Investigation into an alternative approach of environmental control to enhance sensible heat transfer from broiler chickens during hot weather periods

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DECLARATION

This thesis contains the original research work, carried out by the author and all the materials used in this thesis are well cited and appropriately referenced. To the best knowledge of the author, there is no part of the thesis that has previously been submitted or presented for an application or an award of any degree in another institution.

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ABSTRACT

Climatic conditions within the broiler building play an important role in the performances, health and welfare of broiler chickens. During hot weather periods, farmers in the temperate climates usually open all inlets on the sidewall and operate all the fans in the roof of the broiler building to allow maximum airflow to relieve broilers of heat stress. However, the effects of this practice on the air velocity distribution in the broiler occupied zones of such type of building are not well documented. Therefore, this research work was set up to (1) investigate the impact of wide opened inlet on the airflow characteristics in the broiler occupied zones of an experimental broiler building at Harper Adams University, UK; (2) develop and evaluate the performance of a hot weather ventilation system, incorporating an oscillation baffle, for broiler buildings; (3) examine the impact of the ventilation system on the airflow characteristics in the broiler occupied zones and the sensible heat transfer from broiler model. The results of the study indicated that the act of fully opening the inlets of broiler building during hot weather seasons did not improve the airflow in the broiler occupied zones at all measurement locations, including the sidewall area of the building. However, with the development of the hot weather ventilation system with oscillation baffle, operating at different fan frequencies, baffle oscillation angles and baffle oscillation frequencies, there was a significant improvement in the average air velocity in the broiler occupied zones. At higher inlet turbulence, there was an increase in the sensible heat transfer from broilers in the sidewall area of the broiler building. This indicates that oscillation of inlet baffle instead of keeping it wide opened during the hot weather periods could direct more airflow into the broiler occupied zones and relieve broiler chickens of heat stress.

DEDICATION

This thesis is dedicated to Almighty God, the giver of life. It is also dedicated to my wife, my son and my mother-in-law for their inestimable prayers and supports.

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STATEMENT OF ADVANCED STUDIES

During this research work, there was no paper published in a refereed journal. However, there was a paper presented as poster in a conference and others to be presented in the conference as oral presentation.

Conference presentations:

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variation
CAD	Computer-aided design
CFD	Computational fluid dynamics
CHT	Convective heat transfer (W m^{-2})
DEFRA	Department for Environment Food and Rural Affairs
e	Internal energy (J)
E(f)	Power spectrum
EID	Electronic identification
f	Frequency (Hz)
FAO	Food and Agriculture Organisation of United Nations
FFT	Fast Fourier Transform
HLI	Heat load index
HSD	Honestly significance difference
MATLAB	Matrix laboratory
N	Sample size
OECD	Organisation for Economic Co-operation and Development
p	Pressure (Pa)
PLF	Precision livestock farming
PWM	Pulse width modulation
RHT	Radiative heat transfer (W m^{-2})
SHT	sensible heat transfer (W m^{-2})
T	Temperature (°C)

TG	Turbulence generator
THI	Temperature-humidity index
THVI	Temperature-humidity-velocity index
$^{A, B, C}$	Superscripts
3-D	Three dimensional
$\nabla \cdot \mathrm{V}$	Divergence of the velocity
$\emptyset$	Angle of oscillation (º)
μ_t	Turbulent viscosity (m^2 s^{-1})
u_i	Fluctuating component of velocity in x_i direction
f_f	Fan frequency (Hz)
b_f	Baffle oscillation frequency (Hz)
b_a	Baffle oscillation angle (º)
T_w	Wet-bulb temperature (°C)
T_g	Black globe temperature (°C)
T_a	Dry bulb temperature (°C)
T_i	Turbulence intensity
P_k, P_b	Generated turbulent kinetic energies
D_{ij}	Rate of deformation
C_μ, $C_{1\varepsilon}$ and $C_{2\varepsilon}$	turbulence model constants
τ_{yx}, τ_{zx}, τ_{xy}, τ_{zy}, τ_{xz}, τ_{yz}	Shear stresses (Pa) in the x, y, z directions acting on planes perpendicular to the x, y, z axes
τ_{xx}, τ_{yy}, τ_{zz}	Normal stresses (Pa) in x, y, z directions

$\sigma^2 = \overline{u'^2}$	Mean square of the fluctuating component of the air velocity over a particular period
ν_k	Kinematic viscosity of air (m^2 s^{-1})
ε_b	Surface emissivity of bird
u'	Fluctuating component of the air velocity
T_{surf}	Surface temperature of the bird (ºC)
T_{air}	Indoor temperature (ºC)
Re_b	Reynolds number
$\dot{q}$	Rate of volumetric heat addition per unit mass (kJ)
Nu_b	Nusselt number
$M_{chicken}$	Body weight (kg) of broiler chicken
k_{cond}	Air thermal conductivity (W m^{-1} K^{-1})
$f_{x,y,z}$	Body forces (k N) on a fluid element in x, y, z directions (m)
F_k	Fourier components
A_{surf}	Surface area (m^2) of birds
$\overline{u_x}, \overline{u_y}$ and $\overline{u_z}$	Mean air velocity components along x, y and z directions (m s^{-1})
σ_c	Stefan-Boltzmann constant (W m^{-2}K^{-4})
$D_{poultry}$	Characteristic dimension (m) of a bird
$\bar{u}$	Mean air velocity (m s^{-1})
u, v and w	Components of velocity (m s^{-1})
V	Velocity (m s^{-1})
WBGT	Wet black globe temperature index
β	Slope of the power spectrum curve

ρ	Density (kg m^{-3})
σ	Standard deviation
$\sigma\bar{u}_x$, $\sigma\bar{u}_y$ and $\sigma\bar{u}_z$	Standard deviations of velocity along x, y and z directions
$CoCHT$	Coefficient of convective heat transfer (W m^{-2} K^{-1})
k	Turbulent kinetic energy (kg m^{2} s^{-2})
rH	Relative humidity (%)
t	Time (s)
u	Instantaneous air velocity (m s^{-1})
ε	Rate of dissipation
ω	Specific turbulent dissipation rate

TABLE OF CONTENTS

CHAPTER ONE..1

GENERAL INTRODUCTION 1

- 1.1. Hypothesis...3
- 1.2. Objectives..3

CHAPTER TWO 4

LITERATURE REVIEW 4

- 2.1 Thermal comfort of broiler chickens 4
  - 2.1.1 Thermal tolerance of broiler chickens 6
  - 2.1.2 Ways of assessing thermal comfort of broiler chicken 7
    - 2.1.2.1 Birds’ noise level: 7
    - 2.1.2.2 Behavioural and productive responses:..8
    - 2.1.2.3 Surface temperature: 9
    - 2.1.2.4 Environmental indices: 10
  - 2.1.3. Technology for assessing the thermal comfort of broiler chickens 14
    - 2.1.3.1 Time-lapse video monitoring 17
    - 2.1.3.2 Infrared thermography...17
    - 2.1.3.3 Bioacoustics technique 18
- 2.2 Heat stress in broiler chickens 18
  - 2.2.1. Effects of heat stress on broiler chickens..19
- 2.3 Airflow characteristics and measurements...20
  - 2.3.1. Mean air velocity..20
  - 2.3.2. Turbulence intensity (Ti) and power spectrum Ef..........................20
- 2.4 Ventilation systems in broiler buildings 24

2.4.1. Types of mechanical ventilation system 25

2.4.1.1. Tunnel ventilation system 27

2.4.1.2. Conventional ventilation system 28

2.4.1.2.1. Cross ventilation system 28

2.4.1.2.2. Sidewall inlet and roof exhaust ventilation system 29

2.4.2. Airflow Quality at the Animal Occupied Zone 30

2.4.3 Evaluation of airflow in animal building 31

2.4.4 Hot weather ventilation systems in broiler production 32

2.4.5 Air Inlet control..33

2.4.6 Effect of ventilation on broiler performances 34

2.5 Computational fluid dynamics (CFD) simulation of airflow in animal building 36

2.5.1 Basic physical principles of CFD..36

2.5.2 Turbulence models 38

2.5.2.1 Standard $k - \varepsilon$ model 39

2.5.2.2 Realisable $k - \varepsilon$ model 39

2.5.2.3 Shear stress transport (SST) $k - \omega$ model 40

2.6 Heat transfer from broiler chickens 40

2.6.1 Sensible heat loss in broiler chickens 41

2.6.1.1 Mathematical expression of sensible heat transfer from broiler chickens 42

2.6.1.2 Simulation of sensible heat transfer from broiler chickens.......................44

2.6.1.2.1 CFD application in broiler chicken heat transfer.................................44

2.6.1.3 Effects of air velocity on heat transfer 46

2.6.1.4 Effects of air turbulence intensity on heat transfer 46

2.6.1.4.1 Different ways of generating turbulence in fluid flow 48

2.6.2 Latent heat loss of broiler chickens 53

2.7 Hot weather abatement strategies 53

2.7.1 Nutritional, feeding and intermittent lighting strategies 53

2.7.2 Mixing and ceiling fans 54

2.7.3 Water-cooled perches 54

2.7.4 Ground source heat pump (GSHP) 56

2.7.5 Evaporative cooling systems (ECS) 57

2.7.5.1 Pad cooling system (PCS) 57

2.7.5.2 Surface wetting system (SWS) 59

2.7.5.3 Fogging and misting systems (FMS) 60

2.8 Challenges with the existing cooling systems 61

2.9 Conclusion 63

CHAPTER THREE 65

FIELD EVALUATION OF MICROCLIMATE CONDITION WITHIN AN EXISTING SIDEWALL INLET VENTILATED BROILER BUILDING 65

3.1 Introduction 65

3.2 Materials and methods 66

3.2.1 Experimental broiler building 66

3.2.2. Airflow sensors 67

3.2.3. Airflow characterisation of the inlet of the experimental broiler building 68

3.2.4. Air velocity characterisation at different distances from the sidewall inlet 69

3.2.4.1. Empty experimental broiler building 69

3.2.4.2. Experimental broiler building occupied with broiler models 70

3.2.5 Experimental design and data analysis 72

3.3 Results and discussion 73

3.3.1 Characterisation of inlet airflow 73

3.3.2 Airflow characterisation at different locations from the sidewall inlet of an empty broiler building 73

3.3.3 Broiler building occupied with broiler models. 78

3.3.4 Impact of broiler chickens and indoor equipment on air velocity distribution in the broiler microclimate 80

3.4 Conclusion 82

CHAPTER FOUR 84

COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION OF INDOOR AIR VELOCITY OF A SIDEWALL INLET AND ROOF EXHAUST VENTILATED BROILER BUILDING 84

4.1 Introduction 84

4.2. Materials and methods 85

4.2.1 Experimental building and measurements 85

4.2.2 CFD modelling 86

4.2.2.1. Part 1: CFD modelling preparation and the validation of CFD modelling in an empty broiler building 86

4.2.2.1.1. Development of broiler building geometries 86

4.2.2.1.2. Mesh generation 88

4.2.2.1.3. Turbulence models, measurement planes and convergence criteria 89

4.2.2.1.4. Boundary conditions 90

4.2.2.2. Part 2: CFD modelling and validation of airflow in an experimental broiler building occupied with broiler models, feeder and drinker lines 91

4.3. Results and discussion 93

4.3.1. Verifications of the assumptions in the literature 93

4.3.2. Validation of air velocity in the empty broiler building 97

4.3.3. Validation of air velocity in the broiler building occupied with broiler models 98

4.4 Conclusion.........101

CHAPTER FIVE.........103

DESIGN, DEVELOPMENT AND EVALUATION OF AN ALTERNATIVE HOT WEATHER VENTILATION SYSTEM FOR BROILER PRODUCTION 103

5.1 Introduction.........103

5.2 Materials and methods 104

5.2.1 The design and development of an alternative ventilation system for broiler production.........104

5.2.1.1. Description of the ventilation system.........104

5.2.1.2. Variable speed fan.........105

5.2.1.3. Turbulence generator (TG) 106

5.2.1.4. The operation principle of the ventilation system 107

5.2.2 Performance evaluation of the hot weather ventilation system.........108

5.2.3. Experimental design and data analysis.........109

5.3 Results and discussion 110

5.3.1 The effect of fan frequency (Hz), baffle oscillation frequency (Hz) and the baffle oscillation angle (°) on the output airflow of the ventilation system. 110

5.3.2 Regression model of the ventilation system 113

5.3.2.1 Air velocity (AV) prediction model 113

5.3.2.2 Turbulence intensity ($\mathrm{T}i$) model 115

5.3.2.3 The impact of the interaction between the fan frequency, baffle oscillation frequency and baffle oscillation angle on air velocity and turbulence intensity. 116

5.4 Conclusion.........117

CHAPTER SIX.........119

IMPROVEMENT OF AIR VELOCITY DISTRIBUTIONS IN THE BROILER OCCUPIED ZONES WITH AN OSCILLATING INLET BAFFLE........119

6.1 Introduction........119

6.2 Materials and methods........120

6.2.1. Poultry research room........120

6.2.2. Experimental setup........120

6.2.3. Study 1: Empty experimental room........121

6.2.4. Study 2: Experimental room occupied with broiler models at a stocking density of 33 kg m^{-2}........123

6.2.5. Study 3: Effects of inlet airflow turbulence on the air velocity distribution in the broiler occupied zones at a higher stocking density of 39 kg m^{-2}........125

6.2.6. Experimental design and statistical analysis........125

6.3 Results and discussion........126

6.3.1 Study 1: Air velocity distributions in the empty broiler room........126

6.3.2. Study 2: Effect of inlet turbulence on the airflow characteristics in the broiler occupied zones of a broiler room occupied with broiler models at stocking density of 33 kg m^{-2}........127

6.3.3 Study 3: Effect of inlet turbulence on the airflow characteristic in the broiler occupied zones within a broiler room occupied with broiler model at a stocking density of 39 kg m^{-2}........131

6.3.4 Comparison of the effects of different stocking densities (33 and 39 kg m^{-2}) on the airflow characteristic in the broiler occupied zones........132

6.4 Conclusion........135

CHAPTER SEVEN........136

IMPACT OF INLET TURBULENCE ON THE SENSIBLE HEAT TRANSFER OF ADULT BROILER CHICKENS........136

7.1 Introduction........136

7.2 Materials and methods 137

7.2.1 Broiler experimental room, ventilation system and Instrumentations.........137

7.2.2 Broiler model development 138

7.2.3 The experimental setup 141

7.2.3.1 Exposure of broiler model to hot environmental conditions...................141

7.2.3.2 The impact of inlet turbulence on the surface temperatures of the feathered broiler model 143

7.2.3.2.1 Experimental design and data analysis...146

7.2.3.3 Sensible heat transfer (convective and radiative). 146

7.2.3.3.1 Data analysis..146

7.3 Results and discussion 147

7.3.1 Effects of inlet turbulence on the surface temperature of the broiler model subjected to hot weather conditions..147

7.3.2 Effects of inlet turbulence on the heat transfer of broiler model subjected to hot environmental conditions 149

7.3.2.1 The coefficient of convective heat transfer (CoCHT) 149

7.3.2.2 Convective heat transfer (CHT)..151

7.3.2.3 Radiative heat transfer (RHT) 153

7.3.2.4 Sensible heat transfer (SHT)...155

7.4 Conclusion..157

CHAPTER EIGHT...158

GENERAL DISCUSSION 158

8.1 Future considerations 161

8.2 Conclusions...162

REFERENCES 164

APPENDICES 206

Appendix 1: The estimated torque of the stepper motor 206

Appendix 2: Arduino code for operating the ventilation system..................................208

LIST OF FIGURES

Figure 2.1: Homeostasis zones of market-sized broilers subjected to acute environmental conditions [adapted from (Tao and Xin, 2003a)] 11

Figure 2.2: The power spectral density fluctuations (Kang et al., 2013; Zhou et al., 2006). 23

Figure 2.3: Tunnel ventilation system (Big Dutchman, 2016) 27

Figure 2. 4: Cross ventilation system (Big Dutchman, 2016) 29

Figure 2.5: Sidewall inlet and roof exhaust ventilation system 30

Figure 2.6: Chicken orientations with respect to airflow direction. (a) Head facing the airflow (0 º), (b) side facing the airflow at 45 º, and (c) side facing the airflow at 90 º (Li et al., 2016b)....................45

Figure 2.7: The usage of cooled perches by the laying hens exposed to chronic heat stress (Xiong et al., 2015). 55

Figure 3.1: Schematic representation of a typical sidewall inlet and roof exhaust ventilated broiler building. All dimensions in metres 67

Figure 3.2: Airflow sensors set up at one of the measurement locations. 68

Figure 3.3: Airspeed measurement at the air inlet of an experimental broiler building......69

Figure 3.4: The broiler building showing the measurement heights above the floor. All measurements are in metres. 70

Figure 3.5: The experiment in the occupied broiler building showing the cross-sectional view of the experimental building and measurement height. All measurements are in metres. 72

Figure 3.6: Mean air velocities and turbulence intensities at Broiler height (0.20m), 1.70 m and 2.55 m above the floor at distances 1, 3, 5, 7 and 9 m away from the sidewall. 74

Figure 3.7: Mean air velocities at the broiler height (0.20m) with respect to distance in the broiler building with broiler models. 79

Figure 3.8: Air velocities and turbulence intensities in the broiler occupied zones (0.2 m) within an empty broiler building and the broiler building occupied with broiler models......81

Figure 4.1: Geometries of broiler building with (a) long bottom-hinged sidewall inlets (b) multiple sidewall inlets and (c) drinker and feeder lines. All dimensions are in metres. 87

Figure 4.2: Polyhedral meshes of the computational model used for the verification of airflow in the broiler building with; (a) long bottom-hinged inlet (b) multiple bottom-hinged inlets and (c) internal obstacles..89

Figure 4.3: Measurement planes indicating measurement locations within the sidewall inlet and roof exhaust ventilated broiler building. 90

Figure 4.4: Experimental broiler building occupied with broiler models (spheres). All measurements are in metres. 92

Figure 4.5: Surface and volume meshes of an experimental broiler building...................92

Figure 4.6: The validation of turbulence models [Std $k-\varepsilon$ (red line); Re $k-\varepsilon$ (green line); SST $k-\omega$ (purple line)] predictions with field experiment (blue line). 97

Figure 4.7: Validation of air velocity predictions of standard $k-\varepsilon$ turbulence model (a) all the volume mesh densities [Mesh 1 (red line), Mesh 2 (green line), Mesh 3 (purple line) with the field experiment (blue line) and (b) Mesh 1 (red line) and field experiment (blue line)..100

Figure 5.1: A ventilation system showing the main components and the baffle oscillation angles...105

Figure 5.2: A fan with variable speeds. 106

Figure 5.3: Turbulence generator with an oscillation baffle. 107

Figure 5.4: Operation principles of a ventilation system. 108

Figure 5.5: Airflow measurements at the outlet of the ventilation system 109

Figure 5.6: Airflow characteristics of a ventilation system with oscillation baffle 113

Figure 5.7: A regression plot showing the measured against predicted air velocity (m s^{-1}). 114

Figure 5.8: Regression model showing the measured against predicted turbulence intensity. 116

Figure 5.9: Contour plot of (a) air velocity and (b) turbulence intensity against fan frequency, baffle oscillation frequency and baffle oscillation angle................................117

Figure 6.1: Experimental room with the ventilation system. All dimensions are in metres. 121

Figure 6.2: The experimental set up within an empty experimental room showing measurement locations from the ventilation system at 0.20 m above the floor. All measurements are in metres. 122

Figure 6.3: The experimental set up within an experimental room occupied with broiler models showing the locations of the sensors from the ventilation system. All measurements are in metres. 124

Figure 6.4: Airflow characteristics in the broiler occupied zones of an empty broiler room as a function of inlet turbulence. 126

Figure 6.5: Effect of inlet turbulence on the air characteristics in the broiler occupied zones of an experimental room occupied with broiler models at a stocking density of 33 kg m^{-2}. 128

Figure 6.6: Effect of inlet turbulence on the airflow characteristics in the broiler occupied zones at higher stocking density of 39 kg m^{-2}....................131

Figure 7.1: The broiler model....................139

Figure 7.2: (a) The monitoring of body temperature and energy consumption of broiler model using a thermal camera and a power meter respectively; (b) the body temperature of a broiler model at the thermal comfort zone of 24 ºC indoor temperature....................140

Figure 7.3: The broiler model covered with taxidermy mounts. 140

Figure 7.4: A thermal imager monitoring the body temperature of a broiler model. 141

Figure 7.5: The experimental layout showing the cross-sectional view of the broiler model exposed to different inlet turbulence and indoor temperature. All measurements are in metres. 143

Figure 7.6: The orientations of feathered broiler model (a) 0 º, (b) 90 º and (c) 180 º with respect to the airflow direction. All measurements are in metres....................145

LIST OF TABLES

Table 2.1: The optimum temperature range for broiler growth and production 5

Table 2.2: Summary of the environmental indices for assessing the thermal comfort of farm animals 12

Table 2.3: Animal thermal comfort estimation techniques 15

Table 2.4: Evaluation of air velocities of different mechanical ventilation systems...........26

Table 2.5: Methods of generating turbulence in airflow 50

Table 3.1: Airflow characteristics at the inlet of a sidewall inlet and roof exhaust ventilated broiler building. ux, uy and uz represent the velocity components, σux, σuy and σuz are the standard deviations of the velocity components, u is the mean airspeed, σ is the standard deviation of the airspeed magnitude and Ti is the turbulence intensity.............73

Table 3.2: Mean air velocity (m s^{-1}) and turbulence intensity within an empty broiler building. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the measurement heights (0.20, 1.70 and 2.55 m) according to Tukey-Kramer HSD at a 5 % level of significance. 77

Table 3.3: Mean air velocity (m s^{-1}) and turbulence intensity within the broiler building occupied with broiler models. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the measurement locations (1, 3, 5, 7 and 9 m) according to Tukey-Kramer HSD at a 5 % level of significance...80

Table 3.4: Mean air velocity (m s^{-1}) and turbulence intensity within an empty and an occupied broiler building. 82

Table 4.1: Mesh densities used for model verification...88

Table 4.2: Boundary conditions specifications 91

Table 4.3: Mesh density refinement of broiler building with broiler models.......................93

Table 4.4: Effects of inlet configurations on the air velocity distributions in the broiler occupied zones...94

Table 4.5: Air velocity magnitudes in the broiler occupied zones at the centre of the broiler building from both the right and left sidewall inlets of an empty broiler building. 95

Table 4.6: Effect of obstacles on air velocity distribution in the broiler occupied zones 95

Table 4.7: What happens to the air velocity distribution if inlets are not aligned with the outlets?..96

Table 5.1: The airflow characteristics [mean air velocity, AV (m s^{-1}) and turbulence intensity] of the ventilation system. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the fan frequency (Hz), Baffle oscillation frequency (Hz) and Baffle oscillation angle (º) according to Tukey-Kramer HSD at a 5 % level of significance. 112

Table 6.1: The air velocity distributions in the broiler occupied zone of an empty broiler building at different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 127

Table 6.2: The air velocity distributions in the broiler occupied zone of an occupied building at different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 129

Table 6.3: The air velocity distributions in the broiler occupied zone of an empty and an occupied building at different inlet turbulence. 130

Table 6.4: The air velocity distributions in the broiler occupied zone at higher stocking density and different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance 132

Table 6.5: The impact of stocking densities (kg m^{-2}) on the air velocity distributions in the broiler occupied zone at different inlet turbulence. 134

Table 7.1: The effect of indoor temperature on the body temperatures of a featherless broiler model. 142

Table 7.2: Surface temperatures, $Tsurf$ (ºC) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the means surface temperatures (ºC) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 148

Table 7.3: CoCHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent

the significant differences in the coefficient of convective heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 150

Table 7.4: CHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the convective heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 152

Table 7.5: RHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the radiative heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 154

Table 7.6: SHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the sensible heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance. 156

CHAPTER ONE

GENERAL INTRODUCTION

Broiler chickens are birds specially bred to grow very fast for meat production and usually reach maturity age at 42 days (Goliomytis et al., 2003). Most of the chickens raised for meat production globally are kept under intensive farming systems, with no access to outdoor and natural light. Stocking density levels range from 33 to 42 kg m^{-2}, on the littered floor within a confined environment (European Commission, 2016). In confined environment, broiler chickens find it difficult to adjust to environmental conditions during harsh weather conditions (cold or hot) compared to their counterpart in the natural environment. They are susceptible to welfare and health challenges such as hock burns, lameness and inability to exercise due to excessive body weight gain, breast blister, heart attacks and respiratory problems (Erasmus, 2018). In an intensive broiler building, about 30 % of broilers have leg deformity (Knowles et al., 2008) which has resulted in weight loss due to inability to compete with other healthy birds for food and water. Other research studies have reported the negative impact of broiler intensive production on birds' health and welfare (Ismayilova, 2013; Sorensen and Fraser, 2010).

Poultry production has greatly intensified over the recent years to meet the growing world demand for animal-based products. OECD/FAO (2017) predicted that the global meat consumption will continue to increase by 1.5 % annually between 2017 and 2026 due to higher population growth rates and that chicken will take the largest share of the per capita consumption. As a result of higher population growth rates, poultry farmers have intensified their operations, and now, over 40 billion chickens are annually produced for meat worldwide in highly specialised broiler production operations (Fontana et al., 2014). Poultry meat production has increased by about 17% between 2016 and 2017 in the United Kingdom (DEFRA, 2017). An effort to increase production has led to enhancing the genetic trait of birds for fast growth rate and higher breast muscle yield (Hardiman, 2011). However, these birds are more susceptible to high environmental temperatures, have a low tolerance for heat stress (Watts et al., 2011) and produce higher body heat compared to other genotypes due to their increased metabolic activity (Settar et al., 1999).

Environment plays an important role in birds' welfare and production. In European countries, new housing systems that improve welfare quality of birds are being implemented. However, these systems are only focusing on providing environmental enrichment (such as straw bales) and reducing stocking densities (Compassion in World Farming, 2013) and do not explicitly consider the close management of bird's micro-climate, i.e. temperature, humidity, air quality and airflow, as it is largely considered by poultry growers that control systems achieve this aim. Studies have recognised that the stress felt by birds within current buildings is strongly linked to the type of ventilation system and season of the year (Fontana et al., 2014; Ismayilova, 2013). These factors are more closely linked with bird weight gain (Reiter and Bessei, 2000) and mortality (Dawkins et al., 2004) than stocking density.

Control over temperature, humidity and airflow is essential during intensive poultry production (Glatz and Rodda, 2013; Lara and Rostagno, 2013; Yahav, 2007). It is well known that the distributed environment has consequences on the uniformity of welfare and productivity of the housed birds (Dawkins et al., 2004; Jones et al., 2005). Raising birds in an environment that will not allow them to exhibit their normal behaviours such as feeding, drinking and normal distribution, can impair their welfare and production. There should be a balance between the indoor condition and the thermal comfort of the birds. An ideal thermal condition will allow the birds to expend minimum energy to produce heat by physiological processes (Pereira and Nääs, 2008). Otherwise, the bird will use dietary energy for maintaining body temperature, and this reduces their meat yield, meat quality, body weight gain and muscle growth (Abu-Dieyeh, 2006; Laganá et al., 2007; Quinteiro-Filho et al., 2010). Similarly, subjecting birds to high thermal conditions negatively affects their movement and activity and increases time spent on drinking, panting and sitting (Mack et al., 2013).

The effects of heat stress on livestock production, welfare and health, are well reported (Lara & Rostagno, 2013). To minimise the impact of heat stress in animal production, various heat stress alleviation methods have been investigated. The heat stress alleviation methods, currently available, include nutritional strategies (Lin et al., 2006; Zhou and Yamamoto, 1997; Yalçin et al., 2001; De Basilio et al., 2001), intermittent lighting to regulate bird’s activity (Aerts et al., 2000; Saiful et al. 2002), the use of supplementary cooling systems (Liang et al., 2012; Mutaf et al. 2008, 2009; Saraz et al., 2011; Haeussermann et al., 2007; Liang et al., 2010, Tao and Xin, 2003) and different ventilation systems (Ruzal et al., 2011; Lott et al. 1998; Yahav et al. 2011). However, most of the heat stress alleviating techniques are very expensive and difficult to maintain. Some of them could create an unconducive environment, like increasing indoor relative humidity, for confined birds. As a result, there is a need for an alternative approach to an environmental control system for enhancing sensible heat transfer from broiler chickens during hot weather periods. For birds to be cooled during hot weather periods, air movement provided by fluctuating air velocities (turbulence intensities) at the inlet, seems to be a promising and very cheap strategy (Huang et al., 2012; Zhu et al., 2005) for improving airflow at the microclimate of broiler chickens. During hot weather periods, maximum air movement is expected in the broiler occupied zones. This is difficult to achieve as a result of limited air velocity reaching the broiler occupied zone when the inlets are widely opened (Albright, 1990). Therefore, integrating oscillating baffle, that could generate higher inlet turbulence, into the ventilation system of broiler buildings could direct airflow to the broiler occupied zones that could offset the higher temperature during hot weather periods. Since turbulence increases the cooling effect of airflow (Huang et al., 2014), the impact of air movement in the broiler occupied zones on the sensible heat transfer from broilers could be increased with the incorporation of higher inlet turbulence. As a result, this study intend to investigate the incorporation of oscillating baffle into the ventilation system of broiler building. It applications are further discussed under the literature review.

1.1. Hypothesis

The general hypothesis of this study was that inlet airflow fluctuation can increase air velocity distribution in the broiler occupied zones and also increase sensible heat transfer of broiler chickens during hot weather conditions.

1.2. Objectives

The specific objective of this PhD research work is to investigate an alternative approach to environmental control of broiler building to enhance air distribution at the broiler occupied zone and sensible heat transfer from broiler chickens during hot weather periods. The specific objective is further divided into the following sub-objectives.

1. To understand the air characteristic distribution in the broiler occupied zones in the existing broiler building using field experimentation and computational fluid dynamics approaches.
2. To develop and evaluate the performance of an alternative hot weather ventilation system with oscillation baffle to increase inlet turbulence.
3. To investigate the impact of inlet turbulence of the ventilation system on the sensible heat transfer from broiler model exposed to hot weather conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Thermal comfort of broiler chickens

The thermal environment and production efficiency of livestock are crucial in ensuring better animal welfare and health. The thermal environment within the livestock building could threaten animal survival (Gaughan et al., 2009) during harsh periods if factors such as building topology and ventilation system are not properly designed (Lima et al., 2011). Animal's thermal environment influences their body homeostasis (Cangar et al., 2008), production efficiency and growth performance (Purswell et al., 2012). For animals to survive during hot climatic periods, animals generally alter their behavioural and physiological mechanisms (Arias et al., 2008; DeShazer et al., 2009) by reducing their feed intake in order to regulate body temperature, resulting in lower body growth and meat production (Arias et al., 2008; Gaughan et al., 2009). The core body temperature of broiler chickens is usually maintained between 41.2 and 42.2 °C when the environmental temperature is within the thermoneutral zone (Tao and Xin, 2003a). However, it changes (increases) as the indoor air temperature increases and the inability of broiler chickens to maintain homeothermy could result in death and significant economic losses (Tao and Xin, 2003a). In some hot climate countries, the evaporative cooling system becomes an important heat abatement system adopted, especially when the environmental temperature is higher than the thermoneutral zone of broiler chickens (Cangar et al., 2008). There are indications that at a higher indoor air temperature, increasing the indoor relative humidity of broiler buildings above 60 % could impair heat transmission from the core body to the body surface of broiler chickens (Lin et al., 2005). In addition, increasing indoor relative humidity can exacerbate the impact of high environmental temperature on broilers as they tend to rely on the evaporative heat loss (panting) as the temperature increases (Tao and Xin, 2003b). The implication of this is that birds may not be able to lose body heat through a sensible heat transfer mechanism due to impaired heat transmission to the peripheral surface.

Broiler chickens, being homeotherms, rely on the environmental conditions for their thermal comfort, growth and production. During hot periods, broilers either require supplementary cooling to survive heat stress (Welker et al., 2008) or reduce their feed intake to maintain their body temperature (Cassuce et al., 2013). There are optimum temperatures within which broilers can perform optimally throughout their growing stages. These temperatures are summarised in Table 2.1.

Table 2.1: The optimum temperature range for broiler growth and production

Age	**Air temperature range (˚C)**
Week 1	32 - 34
Week 2	28 - 32
Week 3	26 - 28
Week 4	24 – 26
Week 5	18 – 24
Week 6	18 - 24

Cassuce et al. (2013)

When air temperature exceeds the optimum temperature, broilers find it difficult to exchange heat with the environment and as a result, reduce their feed intake to maintain fairly, constant body temperature (Dozier III et al., 2011). The thermal exchange between broiler chickens and their environment depends on the heat and water vapour demand of broilers, their physical characteristics (feather quantity and quality) and their response to climatic change through thermoregulation (Blanco and Gous, 2006). Birds, during thermoregulation, dissipate heat and moisture. Heat and moisture dissipation will always cause a change in the microclimate conditions. This change will bring about a new thermal response of birds and their thermal response will cause further environmental changes (Gous et al., 2006). Long exposure of broilers to such environmental changes is detrimental to the bird’s welfare, production and the economic growth of poultry growers (Lara and Rostagno, 2013).

The microclimate of the birds is an essential parameter when controlling environmental conditions of the broiler building as it reflects the air temperature felt by the birds (Reiter and Bessei, 2000). Most farmers believe that the indoor conditions measured above the birds reflect the microclimate at the animal zone. However, this has been shown otherwise by the study conducted by Purswell et al. (2008). They found out that in conventionally ventilated broiler building, the temperature above the bird level differed by almost 4 ˚C compared to that at the birds’ microclimate. The study was conducted by attaching a temperature harness containing small data logger with an integral temperature sensor to the back of the chicks to monitor air temperature at bird’s microclimate and thermocouples suspended above the floor to monitor indoor air temperature. The result indicated that the temperature within the microclimate of the chick was higher than that temperature measured above the birds.

Adult broiler chickens are constantly exposed to an environmental temperature higher than their thermal comfort zone (20 to 24 °C) during hot weather periods. To overcome hot weather-related problems in broiler production, there is a need for absolute control over the environmental parameters (air temperature, relative humidity and air velocity) inside broiler houses (Aradas et al., 2005). The major environmental parameters that contribute to heat stress are air temperature and relative humidity (Aradas et al., 2005; Xin et al., 1994) and the cheapest method of controlling them is by increasing airspeed within the broiler building. The combined effects of these factors are critical as the ability of broiler chickens to dissipate body heat is mainly determined by them (Aradas et al., 2005; Xin et al., 1994). Adult broiler chickens find it difficult to dissipate heat quickly during hot weather because of higher body heat production compared to young birds (Czarick and Lacy, 1999). This is because they are well feathered and better insulated than young birds. Another factor contributing to the challenges faced by adult broilers during hot periods is, the reduced space available for broiler chickens as they grow older. This contributes to the increase in heat trapped among older birds and this significantly increase air temperature around broilers at floor level (Czarick & Lacy, 1999). In addition, the surface area per body weight of adult broilers, according to Czarick & Lacy (1999), contributes significantly to their problems during hot weather. Adult broilers have less surface area per body weight compared to young chickens and, therefore, making it difficult for them to lose body heat to the surrounding environment.

2.1.1 Thermal tolerance of broiler chickens

Thermal tolerance is the ability of farm animals to maintain body temperature in heat stressed environments. The extent of heat stress in livestock is determined by the connection between animal’s metabolic heat production and the amount of heat dissipated (Berman, 2012; Bligh, 2006). Environmental heat reduces animal productivity and welfare. Therefore, the reassessment of potential heat tolerant breeds and heat stress relief for optimal animal production is inevitable. Recently, poultry farming has significantly progressed in the genetic selection of fast-growing and high breast muscle developed broiler chickens. But genetically selected broiler chickens, coupled with poor development of visceral organs are unable to cope with extreme environmental conditions (Collin et al., 2007; Piestun et al., 2008a, 2008b). High environmental temperatures are detrimental to broiler welfare and production as they increase metabolic heat production, economic losses, mortality rate, poor meat quality and meat production (Sandercock et al., 2001; St-Pierre et al., 2003).

The occurrence of high body temperature and metabolic heat production of broiler chickens have a direct link with the non-functional nervous thermoregulatory mechanisms and thermoregulatory control system (Janke et al., 2002). The regulation of the body temperature of broiler chicken and the reduction of metabolic heat produced by broilers can be achieved through a well-developed environmental control system. They can be achieved through thermal modification of broiler chicks during embryogenesis when the embryo is being formed and developed (Janke et al., 2002; Tzschentke, 2008; Yahav et al., 2004b). Many studies have shown that exposing broiler chicken to high temperature during embryogenesis would enable broiler chicks to cope with hot environmental conditions up to 10 days post hatch (Janke et al., 2002; Loh et al., 2004; Yahav et al., 2004b), 28 days post hatch (Loyau et al., 2013) and at slaughtering age (Piestun et al., 2011, 2009, 2008a). The report of Collin et al., (2007) indicated that environmental manipulation of broiler chicken during embryogenesis did not improve long-term heat tolerance of broiler rather, it increased the breast muscle yield of broiler chickens at slaughtering age (market size).

2.1.2 Ways of assessing thermal comfort of broiler chicken

There are different ways of assessing the thermal comfort of broiler chickens. Globally, research studies have been carried out to assess the thermal comfort of broiler chickens at various growing stages and to quantify the effect of thermal conditions on poultry health and welfare. This section discusses the thermal assessing methods available in the literature.

2.1.2.1 Birds' noise level:

Vocalisation is very useful for assessing the thermal comfort of broiler chickens. Broiler chickens are capable of producing thirty distinct sounds (De Moura et al., 2008) depending on the situations they are subjected varying from aggression due to social isolation (Marx et al., 2001), thermal distress due to environmental conditions (De Moura et al., 2008), hunger and need (Weary and Fraser, 1995), to feeding frustration due to stress exposition (Zimmerman & Koene, 1998). For broilers' vocalisation to be used as thermal comfort indicator, the sound must predict exact situation of the birds' condition and it must be consistent (Zimmerman and Koene, 1998). The thermal comfort of broiler chicks can be assessed by using both amplitude and frequency of the chick sound (De Moura et al., 2008; Fontana et al., 2014). De Moura et al. (2008) conducted a study to evaluate the thermal comfort of broiler chicks exposed to variable environmental conditions. In the study, 14-day old chicks were exposed to different thermal conditions (warm: 24 – 29 ºC and cold: 15 – 23 ºC). The amplitude and frequency of vocalisation of the chicks were recorded with a microphone while chicks' behavioural response to thermal conditions were monitored with a video camera. It was discovered that the degree of migration (swarm degree) within the building and vocalisation level of chicks were primarily influenced by the thermal conditions to which birds were exposed. They reported that as the chicks' swarm degree increased as a result of high air temperature, there was an apparent increase in chicks' vocalisation. With the temperature dropping below the thermoneutral zone, chicks' vocalisation was recorded to be very low compared to when the temperature was above the thermoneutral zone. In general, high amplitude and frequency of vocalisation occur in broilers when birds are exposed to heat stress due to unbalance heat exchange with surrounding (De Moura et al., 2008).

2.1.2.2 Behavioural and productive responses:

Different genotypes of broiler chickens respond differently to the effects of microclimate. Fast growing broilers adapt to the hot environment through behavioural changes while slow-growing broilers survive cold condition through metabolic changes (Nielsen, 2012). The fast-growing broiler could be seen distributed (behavioural changes) in the cooler areas of the building when the environmental condition is above thermal comfort. Whereas, slow-growing broilers may not be significantly affected by ambient temperature but could be found using metabolic changes (increase in feed intake) when the indoor temperature is low (Nielsen, 2012). The thermal comfort of broiler chickens can be assessed by their behavioural and productive responses. The behavioural and productive responses of broilers chicks exposed to different environmental temperature were evaluated by Ferraz et al. (2014). Broiler chicks were introduced into the environmentally controlled wind tunnel at day one of age with the air temperature set at 33 ˚C. The behaviours of chicks to environmental temperatures, such as birds' clustering, drinking and feeding frequencies and birds' spread within the chamber, were monitored with the video camera installed above the birds. At the same time, the productive response of the chicks was also evaluated based on the feed intake, water intake and body weight gain. They reported that at 27 ˚C, chicks spent about 68 % of the time huddling together while approximately 12 % of the time was spent spreading apart within the chamber. As the temperature increased to 36 ˚C, the percentage of time spent huddling reduced to about 51 % while that of spread increased to around 16 %. Chicks exposed to 36 ˚C were reportedly found spending about 28 % feeding while only about 5 % of the time was spent drinking. They indicated that there was high correlation (96 %) between the behavioural and productive responses and thermal comfort of broiler chicks. With these results, they concluded that huddling time, behavioural and productive responses are useful indicators for assessing the thermal comfort of chicks.

Pereira & Nääs (2008) utilised behaviours of broiler breeders to assess their thermoneutral zone. In the study, electronic identification transponders were implanted in female broiler breeders while radio frequency identity (RFID) transponder reader was positioned in the drinker area to monitor breeders' drinking behaviour. They established that female broiler breeder used drinkers about 67% of the time when environmental temperature and relative humidity were varied between 20 and 29 ˚C and 70 and 80 % respectively. They concluded that the thermoneutral zone of broiler breeders can be assessed using their behavioural pattern and also useful in controlling the environmental conditions within the commercial broiler buildings. Similarly, the thermal comfort of pigs exposed to variable environmental conditions was evaluated using pigs' postural images during resting (Shao et al., 1998). The study indicated that pigs were found lying far from one another when the environmental temperature was above the thermoneutral zone.

2.1.2.3 Surface temperature:

Understanding the importance of thermal comfort in chickens, most especially in the preservation of their homoeostasis throughout the growth period and during thermal variations, will help the farmers to provide a suitable environment for the birds. An important prime parameter in the thermal biology of birds, that contributes to their thermal comfort, is surface temperature (Cangar et al., 2008). The surface temperature of broiler chicken can be measured by a non-invasive and non-destructive testing technology called Infrared thermography. The thermography collects radiation emission from the surface of the birds and converts it into an electrical signal. This creates an image of the surface with different colours expressing numerous temperature distribution ranges of the surface (Naas et al., 2014). The physiological response of broiler chicken to thermal stress leads to the fluctuation of skin temperature (Shinder et al., 2007; Tessier et al., 2003). The blood flow rate in broiler chicken, exposed to dehydration as a result of thermal stress, decreases in order for the birds to exchange heat between the core and the skin surface (Altan et al., 2003; Zhou and Yamamoto, 1997).

The thermal comfort of broiler chickens can be assessed based on the birds' heat production (Nascimento et al., 2011). The authors assessed the surface temperature of 7-day old to 35-day old broiler chickens subjected to variable air temperatures using the infrared thermal camera. They found that surface temperature of broiler chickens increased as indoor temperature was increased from 18 to 32 ˚C. They indicated that age had little or no influence on the surface temperature of the birds. The surface temperature of birds was maximum at 14 days of age and declined as the birds grow to table size at 35 days of age. The thermal comfort of 42-day old broilers was assessed prior slaughtering (Nääs et al., 2010). It was found that featherless regions of the birds respond faster to environmental changes than the feathered regions. The surface temperature of the feathered areas was found to be very close to the environmental temperature. It is clear from these studies that regular assessment of the surface temperature of birds is a control measure for monitoring the thermal comfort of broiler chickens during hot environmental conditions.

Cangar et al. (2008) quantified the spatial distribution of surface temperature of broiler chickens using infrared thermography. They reported that the difference between the surface temperatures of broiler body parts (shanks, feet, wattle, comb, back, and head) was more than 10 ˚C even during steady environmental conditions. They added that there was an increase in blood flow in featherless body parts than well-feathered parts. This simply indicates that where higher the blood flow occurs, there will be more the heat loss from such regions. Surface temperature gradient increased as the birds grew and that there was a significant interaction between the age of the birds and the surface temperature of different parts of the birds. Tessier et al. (2003) reported that variation in skin temperature occurs as a function of the age of birds. Younger birds were recorded to have higher surface temperature than the older birds as a result of the ratio of body size to the total surface area and feather thickness. This shows that heavier/larger birds will find it difficult to dissipate heat if environmental conditions are above their thermoneutral zone.

2.1.2.4 Environmental indices:

Environmental indices are mathematical expressions, containing environmental parameters, used for assessing animals' thermal comfort and for measuring the severity of heat stress on livestock (Marai et al., 2001; Sejian et al., 2012). They can be used as a weather safety indices for monitoring and prevention losses associated with heat stress (Bohmanova et al., 2007; Eigenberg et al., 2007; Hahn et al., 2009). They are used for predicting the impact of environmental conditions on the performances of livestock (Purswell et al., 2012). Different species of livestock have different sensitivity to environmental parameters (Bohmanova et al., 2007). Ruminant animals, such as cattle, can tolerate higher environmental conditions during hot weather than non-ruminant animals like broiler chickens and pigs. The difference is as a result of the ability of ruminant animals to effectively dissipate body heat by sweating because of the presence of sweat glands. Poultry birds lack sweat glands and as a result cannot dissipate heat by sweating, rather resort into panting.

Thermal comfort of broiler chickens can be assessed using environmental indices based on the physiological response and production performances (Tao and Xin, 2003b). Environmental factors such as air velocity, air temperature, relative humidity and solar radiation are the key factors influencing the physiological response and the production performance of farm animals. These factors are integrated together to form the environmental indices for assessing the thermal comfort of livestock. Different forms of environmental indices have been documented (Bohmanova et al., 2007; Hahn et al., 2009; Purswell et al., 2012; Tao and Xin, 2003b). Tao and Xin (2003) developed a temperature-humidity-velocity index (THVI) for assessing thermal comfort of matured broiler chickens (Table 2.2). The index was developed based on the physiological response (body temperature) of adult broilers exposed to different environmental temperatures, relative humidity and air velocity. The index from the integration of the environmental factors was used to determine the homeostasis zones of market-sized broilers. In broiler production, the homeostasis state of broiler chicken is considered to be normal if body temperature rise threshold is 1.0 °C, alert if it is 2.5 °C, dangerous and demands emergency if it is 4.0 °C and above (Figure 2.1).

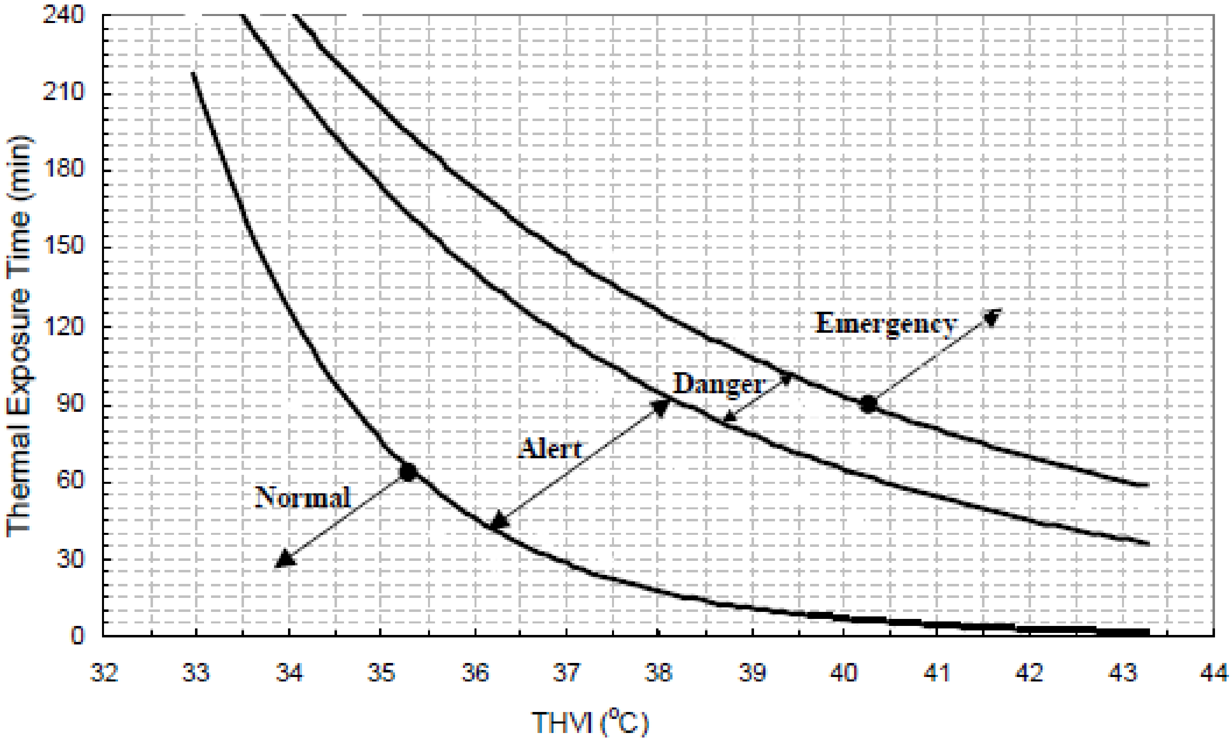


Figure 2.1: Homeostasis zones of market-sized broilers subjected to acute environmental conditions [adapted from (Tao and Xin, 2003a)]

Different indices have widely been developed by various researchers to measure the severity of hot climatic condition on both ruminants (e.g. cattle) and non-ruminant (broiler chickens and pigs) animals. Table 2.2 summarises some of the indices developed and the outcomes of the finding. In Table 2.2, it is clearly shown that severity of heat stress in ruminant animals are generally noticed at higher environmental index while non-ruminant animals are severely heat stressed at low environmental index. In ruminants such as cattle, Index values less than or equal to 70 are considered favourable, from 75-78 are considered distressing, and 79 and above are considered highly severed and require emergency (Sejian et al., 2012; Silanikove, 2000).

Table 2.2: Summary of the environmental indices for assessing the thermal comfort of farm animals

Authors and years	**Indices**	**Animals**	**Remarks**
Ravagnolo & Misztal (2000)	$THI = (1.8T_a + 32) - (0.55 - 0.55rH) \times (T_a - 26)$	Holsteins dairy cattle	The model showed that Holsteins cattle are heat stressed as THI reaches 72 and above.
Marai et al. (2001)	$THI = T_a - [(0.31 - 0.31\, rH) \times (T_a - 14.4)]$	New Zealand white female rabbits	The model indicated that rabbits start to be severely heat stressed at THI = 28.9
Gaughan et al. (2002)	$THI = 0.8T_a + rH(T_a - 14.4) + 46.3$	Cattle	The index indicated that the effects of heat load on cattle are mostly pronounced as THI exceeds 79
Tao & Xin (2003)	$THVI = (0.85T_a + 0.15T_w)V^{-0.058}$	Male broiler chickens	The model was formed based on the core body temperature of broilers exposed to acute environmental conditions.
Amundson et al. (2005)	$THI = T_a - \left(0.55 - \left(0.55 \times \frac{rH}{100}\right)\right) \times (T_a - 58)$	Beef cows	THI higher than 65 negatively affected the pregnancy rate of beef cows within the first 30 days of breeding period
Al-Tamimi (2005)	$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$	Goat kids	The highest WBGT of about 80 was obtained during afternoon period. However, black Bedwin goats were found exhibiting high resistance to heat stress as there was no significant shift in thermoregulation and

Authors and years	**Indices**	**Animals**	**Remarks**
			performances when exposed to harsh environmental condition
Chepete et al. (2005)	$THI = 0.62T_a + 0.38T_w$ for 3-4 weeks old broiler chickens $THI = 0.71T_a + 0.29T_w$ for 5-6 weeks old broiler chickens	Broiler chickens	The indices showed that air temperature had much impact on broiler raised under semi-arid environmental condition
Gaughan et al. (2008)	$HLI = 8.62 + 0.38rH + 1.55T_g - 0.5V + e^{(2.4-V)}$ when T_g>25 °C $HLI = 10.66 + 0.28rH + 1.3T_g - V$ when T_g< 25 °C	Feedlot cattle	The models were used for predicting the panting scores of feedlot cattle when the heat load was high

where THI = temperature-humidity index, THVI = temperature-humidity-velocity index, WBGT = wet black globe temperature index, $HLI_{g>25}$ T_w = wet-bulb temperature (°C), T_g = black globe temperature (°C), T_a = dry bulb temperature (°C), rH = relative humidity (%).

2.1.3. Technology for assessing the thermal comfort of broiler chickens

Precision Livestock Farming (PLF) is a scientific discipline whereby sensor-derived data on animal behaviour and their immediate environment can be integrated into the real-time monitoring and control of livestock welfare and production processes (Ismayilova, 2013). PLF can provide farmers with the opportunity to monitor properly their animals and ensure better care is provided for the animals (Ismayilova, 2013). Non-invasive sensing of animal behaviours is a vital aspect of PLF. Table 2.3 shows the summary of the techniques or instrumentations for assessing thermal comfort of livestock using different thermal comfort indicators. In this section, the use of PLF for assessing animal thermal comfort is discussed.

Table 2.3: Animal thermal comfort estimation techniques

Authors	Thermal comfort indicators	Instrumentation	Research findings
De Moura et al. (2008)	swarm degree and noise level	Video camera, microphone	In a hot environment, both swarm degree and noise level increased.
Pereira & Nääs (2008)	Drinking behaviour	Video camera	Birds visited drinkers more often when environmental temperature was high
Nielsen (2012)	Migration and feed intake	Video camera	Birds migrated to the cooler region of the building. An indication of non-uniformity of environmental condition.
Nascimento et al. (2011)	Surface temperature	Infrared thermography	Mean surface temperature correlated with the changes in indoor temperature. As temperature increased, the mean surface temperature increased.
Baracho et al. (2011)	Surface temperature	Infrared thermography	Skin temperature of birds was not the same at different locations within the building.
Tao and Xin (2003b)	THVI	Equations	The index is useful for assessing the homeostasis state (normal, alert, danger and emergency) of birds. It is also a managerial guideline for preventing animals from heat stress.
(Rodrigues et al., 2010)	Enthalpy index	Equations	Enthalpy is a useful indicator for assessing the thermal comfort of animals. It indicates the thermal conditions corresponding to the present situation of animals suffering from heat stress.

Authors	Thermal comfort indicators	Instrumentation	Research findings
Pereira et al. (2005)	Aggressive behaviour	Video cameras	At low air temperature, aggressive behaviour of broiler breeders increased when food was offered to the birds.
Nääs et al. (2012)	Broiler distribution	Video camera and algorithm	Birds were found clustering around feeders very early in the morning, when the temperature was low, waiting for a feed. As the temperature increases, birds were found separating from one other in order to increase sensible heat transfer. Birds spent more time drinking water when the temperature was high.
Curto et al. (2002)	Distribution	Electronic identification (EID)	Birds occupied cooler places in the building more frequently when temperature increased.
Cangar et al. (2008)	Skin temperature	Infrared thermography	The difference in skin temperature of birds and environment was at a maximum when birds are four weeks old. As a result, optimal ventilation is highly needed at this stage of growth of broiler chickens.
Pereira et al. (2012)	Cluster index	Video camera	Cluster rate of broiler breeders was found to be influenced by indoor air temperature. It reduces with increase in temperature and increases with a decrease in environmental temperature.

2.1.3.1 Time-lapse video monitoring

Time-lapse video monitoring is a useful PLF tool which has received particular attention in animal husbandry (Ismayilova, 2013). New image processing systems have been developed by researchers and implemented in laboratories studies and the livestock buildings for research and commercial production purposes. Systems have been developed for tracking animals (Kashiha et al., 2014a), monitoring broiler behaviours and health conditions (Kashiha et al., 2013b), assessing hen behaviour in response to ammonia concentration (Kashiha et al., 2014b), monitoring feeding and drinking behaviours of pigs (Kashiha et al., 2013a), monitoring hen growth and activity (Leroy et al., 2006), assessing and controlling thermal comfort of pigs based on their body posture when resting (Xin and Shao, 2005). Commercially, automatic and continual monitoring of real-time activity of broilers is recently made possible with an innovative software called eYeNamic, manufactured by Fancom BV, The Netherlands. The software coupled with video camera helps in remote monitoring and analysing the behaviour of broiler chickens (De Montis et al., 2013) for better broiler welfare and thermal comfort. With the eYeNamic software, it is possible to monitor the influence of microclimate on activity and occupation indices of pigs (Costa et al., 2014), distribution, eating and drinking behaviours of broiler chickens (De Montis et al., 2013), automatic detection of abnormal activity levels in broiler chickens (Kristensen and Cornou, 2011). Among the available PLF equipment, real-lapse video is widely used in the commercial livestock production, such as cattle, pigs and poultry.

2.1.3.2 Infrared thermography

Another useful PLF tool is thermal image monitoring. Infrared thermography is a non-invasive and non-contact heat detection equipment (Knizkova et al., 2007; McCafferty, 2007) that can be used for detection of inflammatory diseases in human beings (Ring and Ammer, 2012), for diagnosing orthopaedic diseases in horses (Knizkova et al., 2007), for assessing pain and health conditions and hoof lesions in cows (Alsaaod and Büscher, 2012; Theurer et al., 2013), for determining heat tolerance of pigs (Brown-Brandl et al., 2013). It is useful for determining the surface temperature and heat production of broiler chickens (Nääs et al., 2010), assessing the stress-induced-hyperthermia in poultry birds (Edgar et al., 2013), and for evaluating animal responses to management methods (Yarnell et al., 2013). Infrared thermography can be used for evaluating metabolic heat loss in poultry birds fed with high energy diet (Ferreira et al., 2011), for quantifying sensible heat transfer between animals and microclimate (Malheiros et al., 2000; Yahav et al., 2001) and for estimating feed consumed by bird when stressed (Zhou and Yamamoto, 1997). The usage of thermography in commercial livestock production has not been successful yet. This could be as a result of its minimal coverage, if better thermal images and surface temperatures are expected.

2.1.3.3 Bioacoustics technique

Communication is an important key to any species' survival. It is useful for conveying information, expressing emotional state, stressful and welfare conditions (Jahns, 2008). Bioacoustics technique (a non-contact instrumentation) is an important PLF tool for assessing animal thermal comfort. It is also an effective management tool for monitoring livestock welfare, health and farm efficiency (Jahns, 2008). When farm animals are stressed, there is a possibility for the sound intensity, sound frequency and duration of acoustic signals (Richards and Wiley, 1980) to change in response to the stress they are being subjected. To recognise the vocalisations of farm animals in order to identify their state and conditions (Jahns, 2008), call recognisers/microphones are very important. A proper understanding of the vocalisation of heat stressed animals would assist livestock growers to provide an enabling environment for their animals most especially during hot weather conditions. Studies have shown that the sound intensity, sound frequency and sound signal duration can be used to predict the state and conditions of the farm animals. Bioacoustics signal was used to detect the excitement, pain and fearfulness in cows, sheep and pigs (Manteuffel et al., 2004; Von Borell et al., 2009; Weeks, 2008), monitoring coughs and sneezes in pigs and dairy calves (Ferrari et al., 2010; Hemeryck and Berckmans, 2015). Surprisingly, there are limited research studies on the application of the technique in broiler production. However, available studies have shown that sound signal can be used for determining the welfare state of broiler chicks (De Moura et al., 2008; Fontana et al., 2015), pipping stage of eggs in incubator (Exadaktylos et al., 2011), measuring of feed intake and monitoring of feeding behaviour of broiler chickens (Aydin et al., 2015, 2014), assessing broiler activity (Aydin et al., 2010), assessing the age and body weight of broiler chickens (Fontana et al., 2015) and assessing vocalisation level of chicks (De Moura et al., 2008). Bioacoustics technique has not been commercially utilised in the broiler production. The low usage of bioacoustics technique in broiler production for assessing broiler welfare could be as a result of interference of sounds produced by other equipment such as fans, feeder auger, surrounding equipment etc.

2.2 Heat stress in broiler chickens

Heat stress, as a result of hot weather (Sejian et al., 2013), is the summation of all external factors that influence the homoeothermic state of an animal and also displace the state of rest of animal's body temperature. It can also be termed as the demand made by the animal within an environment for dissipation of heat (Silanikove, 2000). It disturbs both physiological state and performances of livestock and adversely influences the cellular function of livestock due to increase in body temperature (Sejian et al., 2012; West, 2003). Additionally, heat stress in an animal occurs as a result of a thermal imbalance between net energy outflow from an animal to its environment and the total energy generated by the animal (Lara and Rostagno, 2013). In livestock production, the thermal imbalance is majorly caused by a discrepancy in the combination of environmental parameters, (temperature, relative humidity and air velocity), and the species, metabolism rate and thermoregulatory mechanisms of livestock (Lara and Rostagno, 2013).

2.2.1. Effects of heat stress on broiler chickens

Broiler chickens, in order to survive during hot conditions, alter their body temperature homeostasis by reducing feed intake (Quinteiro-Filho et al., 2010), increasing water intake, elevating wings, increasing panting, reducing movement and spending more time resting on the floor (Lara and Rostagno, 2013; Mack et al., 2013). Heat stress influences the behavioural and physiological responses of livestock (Lara and Rostagno, 2013), animal production and meat quality (Kadzere et al., 2002; Lara and Rostagno, 2013; Lu et al., 2007; Nardone et al., 2010; St-Pierre et al., 2003), increases mortality in animals (Warriss et al., 2005) and reduces animal reproduction (Nardone et al., 2010). Animals, during hot weather reduce their feed intake by about 50 % below their normal feed consumption when an environmental condition is favourable (Sejian et al., 2012). About 0.03 kg reduction in feed consumption per laying bird was reported by (Deng et al., 2012) to cause about 29 % reduction in egg production. Star et al. (2009) reported that exposure of laying birds to heat stress resulted in 36 % and 3 % reduction in egg production and egg weight respectively. In broiler production, exposure of broiler chickens to heat stress can increase corticosterone serum levels and reduce rate of body weight gain (Quinteiro-Filho et al., 2010), increase body temperature and reduces haematocrit values (Altan et al., 2003) and alters blood acid/base balance (Sandercock et al., 2001).

Broiler chickens exposed to acute heat stress are likely to experience oxidative stress in their livers and hearts (Lin et al., 2006a), as a result of imbalance between the production of reactive oxygen species (ROS) and the antioxidants system in animal’s body (Bansal and Bilaspuri, 2011; Lin et al., 2006a). Excess levels of ROS are usually stimulated in livestock when they are subjected to heat stress resulting in oxidative stress in animal cells (Lin et al., 2006a; Lord-Fontaine and Averill-Bates, 2002). Exposure of broiler to heat stress can result in the higher duration of tonic immobility, indicating a higher level of fearfulness in broiler chickens (Altan et al., 2003). The economic losses in livestock production are directly and indirectly associated with the environment under which animals are raised. The losses are majorly pronounced when the environmental conditions are outside animals’ thermoregulatory zone (St-Pierre et al., 2003). St-Pierre et al. (2003) estimated the total annual economic losses in livestock industries to be about

29 % higher due to heat stress. The losses in livestock production will continue to increase if better heat abatement technique is not provided to support animal activities in order for them to cope with the continual climate change (Nardone et al., 2010).

2.3 Airflow characteristics and measurements

Air movement is an important parameter, in addition to air temperature and relative humidity that influences the thermal comfort of broilers. Airflow in broiler building has gained the interest of researchers over the years and many studies have been carried out on it, including its effects on broiler production. Some researchers have studied the air distribution (Blanes-Vidal et al., 2010, 2008; Bustamante et al., 2013; Wheeler et al., 2003) and airflow patterns (Bjerg et al., 2002; Heber et al., 1996) inside broiler building. Regarding its effects on broiler production based on exposure period, (Dozier III et al., 2006) found that broilers exposed to 2.8 m s^{-1} air velocity for 24 hours gained additional body weight of about 0.1 kg compared to those exposed to the same air velocity for just 12 hours. Airflow in livestock building is characterised by the mean air velocity, turbulence intensity and power spectrum. The mathematical expressions of the airflow characteristics are shown in this section of the study.

2.3.1. Mean air velocity

The mean air velocities ($\bar{u}$) over a particular period can be calculated using equations 1 and 2 (Boulard et al., 2000; Heber et al., 1996; López et al., 2011).

$$\bar{u} = \frac{1}{\delta t}\int_{t}^{t+\delta t} u \, dt \tag{1}$$

$$\bar{u} = \sqrt{\overline{u_x}^2 + \overline{u_y}^2 + \overline{u_z}^2} \tag{2}$$

where u represents the instantaneous air velocity (m s^{-1}), t represents time (second), δt represents the period of time over which the air velocity varied, $\overline{u_x}, \overline{u_y}$ and $\overline{u_z}$ represent the mean air velocity components along x, y and z directions. The fluctuating component of the air velocity (u'), which is the difference between the instantaneous air velocity (m s^{-1}) and the mean air velocity (m s^{-1}), can be obtained using the equation 3.

$$u' = u - \bar{u} \tag{3}$$

2.3.2. Turbulence intensity ($\mathbf{T_i}$) and power spectrum $\mathbf{E(f)}$

There are some parameters involved in illustrating the fluctuation characteristics of airflow. These include turbulence intensity, turbulent integral time scale, turbulent integral length scale, power spectral characteristics and slope of power spectral curve. They have been described by researchers using the turbulence statistical theory, stochastic analysis theory, power spectral analysis, chaos and fractional theory (Zhu et al., 2015a, 2005). The significant effect of these parameters according to Zhu et al. (2005) depends on their correlation with the thermal comfort of the occupant and their ability to act independently. Studies conducted in the human-built thermal environment have indicated that the most influential parameters of the fluctuation characteristic of airflow are turbulence intensity, power spectral curve and the slope of the power spectral curve (Zhu et al., 2005).

Turbulence intensity is an important characteristic of airflow and it has a greater impact on thermal comfort (Zhou et al., 2006). Increasing turbulence intensity can result in a very strong cold air draught (Fanger et al., 1988). In general, turbulence intensity can be described as the amplitude of the turbulence of air movement (Zhou et al., 2006). Alternatively, it can also be defined as the variance of fluctuating component of the air velocity over a period of time t (Zhu et al., 2005). Turbulence intensity can be mathematically (Heber et al., 1996; López et al., 2011) expressed;

$$\sigma^2 = \overline{u'^2} = \frac{1}{\delta t}\int_t^{t+\delta t} (u')^2 \, dt \tag{4}$$

where $\overline{u'^2}$ represents the mean square of the fluctuating component of the air velocity over a particular period.

The turbulence intensity (τ_i) could be obtained by dividing the root-mean-square (standard deviation, σ) of the turbulent velocity fluctuations, by the 3D resultant of the air velocity components as shown in equations 5 and 6 (Heber et al., 1996).

$$T_i = \frac{\sigma}{\bar{u}} \tag{5}$$

where

$$\sigma = \sqrt{\frac{1}{3}(\sigma_x{}^2 + \sigma_y{}^2 + \sigma_z{}^2)} \tag{6}$$

The turbulence of air can also “be described as the superposition of various periodic motions caused by differently sized eddies” (Kang et al., 2013). The kinetic energy of the differently sized eddies is determined by their vorticity or the intensity of their frequency fluctuation. In real turbulence, there is no permanent distinct frequency. However, it is possible to uniquely describe the frequency by allocating a certain amount of energy to distinct frequency using power spectral density (Kang et al., 2013). The spectrum illustrating the energy distribution of the airflow with respect to the frequency is known as power spectrum, $E(f)$ which is mathematically presented by Kang et al. (2013) as,

$$E(f) = \frac{2t}{N}|F_k|^2 \tag{7}$$

where t represents sampling interval, N indicates sample size and F_k is the Fourier components obtained through the Fast Fourier Transform (FFT).

$$F_k = \sqrt{\overline{u_x}^2 + \overline{u_y}^2 + \overline{u_z}^2} \tag{8}$$

Where $u_{x,}\, u_y$ and u_z are the mean air velocities (m s^{-1}) in the directions of x, y and z respectively.

The integral version of the power spectrum over all frequencies of airflow as presented by Heber et al. (1996) and Jinping & Yanfang, (2010), is

$$\bar{u}'^2 = \int_0^\infty E(f)\, df \tag{9}$$

The power spectrum density function is simply the inverse of the frequency ($^1/_f$) and its relationship with the slope of the power spectrum curve (β), as reported by Zhou et al. (2006) and Kang et al. (2013) is

$$E(f) = {}^1/_{f^\beta} \tag{10}$$

where f is the frequency (Hz). The power spectral density function is influenced by the value of β. The signal of the power spectrum is classified into three (Figure 2.2).

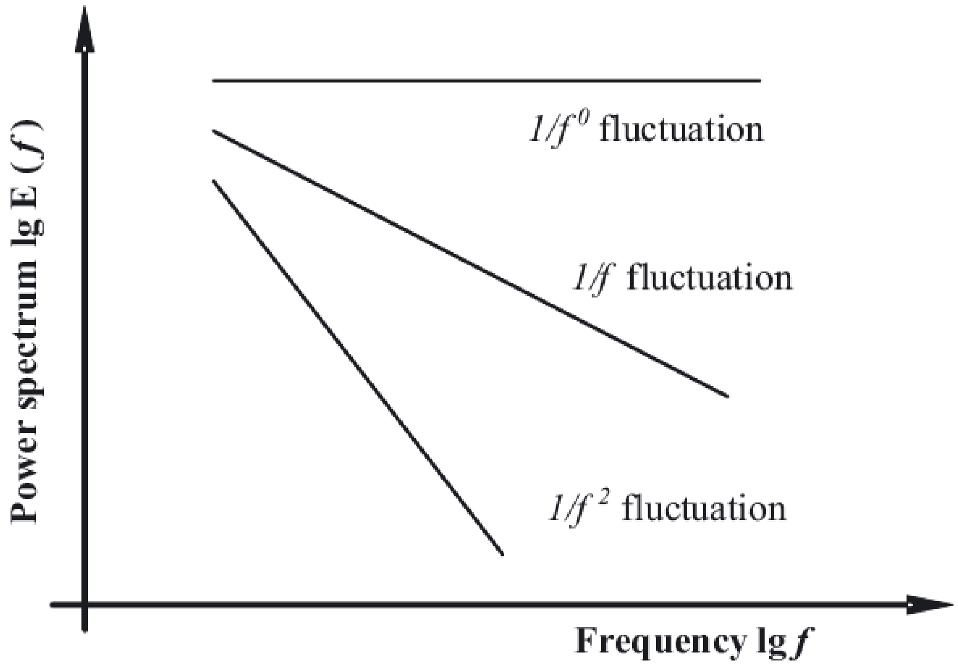


Figure 2.2: The power spectral density fluctuations (Kang et al., 2013; Zhou et al., 2006).

From Figure 2.2, it can be explained that when the value of β is equal to 0, this indicates that signal of the fluctuation has produced a white noise ($1/f^0$). This mostly happens when the power spectrum remains constant irrespective of the frequency. Since power spectrum density function ($1/f$) is naturally everywhere, it tends to produce a comfortable environment for the occupant when the value of β is between 0 and 2. Outdoor wind has been found in the study reported by Zhou et al. (2006) to have $1/f$ fluctuation with β very close to 1.67. The closeness of $1/f$ fluctuation to 1.67 simply means the airflow energy is largely distributed at a low-frequency range (Zhou et al., 2006). A brown noise ($1/f^2$) is produced when the value of β is equal to 2 (Kang et al., 2013; Yu et al., 2006; Zhou et al., 2006).

The power spectral analysis method has been used by many researchers (Cui et al., 2013; Hua et al., 2012; Kang et al., 2013; Li et al., 2007; Ouyang et al., 2006; Toriumi et al., 2000; Yu et al., 2006; Zhou et al., 2006) to characterise the dynamic airflow within an enclosed environment. Zhou et al. (2006) analysed the power spectrums of three airflows (constant airflow, simulated natural airflow and sinusoidal airflow) generated by variable fan speed and turbulence generator in an enclosed environment. It was reported that the airflow parameters produced by different airflows differ. Constant airflow, similar to the airflow in typical broiler building, produced the minimum β-value of 0.28 and simulated natural airflow, similar to outdoor airflow, had the highest β-value of 1.59.

Jinping & Yanfang (2010) also analysed the power spectrum density of an indoor equipped with an underfloor air supplier. Measurements were obtained at different heights

(0.15 and 1.35 m) above the floor where the air supplier was installed. The result showed that β -value differs with distance from the air supplier and heights above the floor. The β -value at 1.35 m above the floor, was shown to be 1.53 while at 0.15 m above the floor, was reported to be 0.36. This simply shows that increasing the distance from the air supplier resulted in 99 % increase in β –value. They concluded that the longer the jet distance, the higher the β -value and the lower the air velocity. Dai et al., (2004) also reported that as the jet distance increased, the power spectral density exponential also increased. Similarly, Ouyang et al. (2006) reported that β -value reduced as the air velocity increased. Relating the result of these study to indoor conditions of broiler building, it is possible to increase the airflow β –value at the centre of broiler building, where it is difficult to obtain higher air velocity, by generating airflow similar to natural wind at the air inlet area of the building.

2.4 Ventilation systems in broiler buildings

Ventilation is crucial in the broiler production as it removes moisture, excessive heat, odours and harmful gases from the building and replaces it with fresh air from outside. For the past four decades, many studies have shown that ventilation plays significant roles in the welfare, performance and production of broiler chicken. Reece & Lott (1982) reported that poor performance of broiler chickens could be as a result of poor ventilation while (Feddes et al., 1984) recounted that ventilation caused 93% of the heat loss in the broiler houses. In turkey production, it was reported by Mendes et al. (2013) that inappropriate design of ventilation can cause drowsiness in young turkey, poor feed and water intakes and high mortality rate due to the sensitivity of turkeys to higher carbon dioxide and ammonia. For transportation of matured broiler chickens to processing factory, there is the possibility of the broilers being exposed to different heat loads if ventilation is below thermal comfort requirement (Knezacek et al., 2010).

There are two major types of ventilation systems in broiler buildings. In the natural ventilation system, airflow is naturally forced in and out of the livestock building while airflow in the mechanically ventilated buildings is provided by the mechanical fans (University of Kentucky College of Agriculture, 2014). These two systems have been reported to have different influences on the broiler's welfare, bird's performance and gas concentrations within the broiler buildings. Alloui et al. (2013) investigated the effects of natural ventilation and mechanical ventilation on the ammonia concentration and broiler performance. It was reported that gas concentration in the mechanically ventilated building at 7th week of broilers' rearing period was 57 % lower than that of the naturally ventilated building. In addition, they reported that the performances of broilers kept in mechanically ventilated building were 11 % higher than those raised in the naturally ventilated building. In designing modern broiler houses, type of fans selected for a mechanical ventilation system is critical. The type of fans used in the broiler building and their performances would determine the ability of the poultry grower to maintain stable environmental condition required by the birds (Czarick, 2015).

2.4.1. Types of mechanical ventilation system

The major types of ventilation system are; the tunnel ventilation system and the conventional ventilation system. They both operate based on the static pressure (that is pressure difference between the inside and outside of the livestock building). This could be negative pressure, forcing air into the livestock building through the inlets; positive pressure, pushing air into the animal building through the mechanical fans; or neutral pressure, forcing air into and out of the animal building through mechanical fans (University of Kentucky College of Agriculture, 2014). The two ventilation systems (tunnel and conventional) are designed to remove heat, moisture and contaminants from the broiler building. However, tunnel ventilation system, as a hot weather ventilation approach, is majorly designed for providing desired air movement in the broiler occupied zones to relieve birds of heat stress (University of Kentucky College of Agriculture, 2014). Some mechanical ventilation systems and their performances are summarised in Table 2.4.

Table 2.4: Evaluation of air velocities of different mechanical ventilation systems

Authors and years	**Ventilation system**	**With/ without animals**	**Comments**
(Blanes-Vidal et al., 2007)	Cross-ventilated	No broiler chicken	Fan combinations influenced air velocity variation in the building
Blanes-Vidal et al. (2010)	Cross-ventilated	With broiler chickens	Fan size and ventilation rates affect air velocity
Bustamante et al. (2012)	Cross-ventilated	No broiler chicken	Fan combinations influenced air velocity variation in the building
Bustamante et al. (2015)	Tunnel-ventilated	No broiler chicken	Air velocity variations were significantly influenced by building sections, operating fans and height above the floor.

2.4.1.1. Tunnel ventilation system

In the tunnel ventilation system (Figure 2.3), fans are located at one end and the inlets are placed at the opposite far end of the broiler building and air is drawn across the length of the broiler building to provide cooling for broiler chickens at an average static pressure of 12 Pa. (Bucklin et al., 2015; Czarick and Fairchild, 2008; Lacy and Czarick, 1992; University of Kentucky College of Agriculture, 2014). Tunnel ventilation system is common in the tropical climate (warm regions) where mean annual temperature generally exceeds 25 ºC (Bhadhauria, 2014; Bustamante et al., 2015; Trewin, 2014). In broiler buildings, tunnel ventilation system usually produce an average air velocity of 1.5 to 3 m s^{-1} at the broiler level to prevent heat stress during hot weather periods (Bustamante et al., 2015; Lacy and Czarick, 1992).

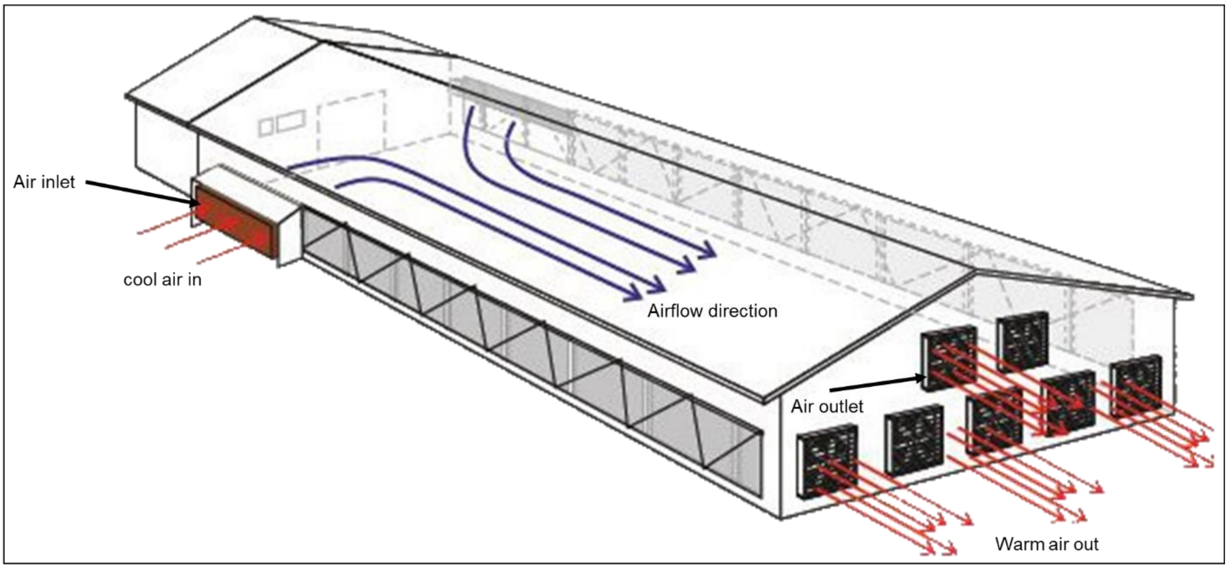


Figure 2.3: Tunnel ventilation system (Big Dutchman, 2016)

Many studies have been carried out on the evaluation of the effectiveness of tunnel ventilation system in providing cool environment for poultry birds. Bustamante et al. (2015) simulated the air velocity distribution in the tunnel ventilated broiler building in the Mediterranean climate to evaluate the performance of the newly introduced tunnel ventilation system over the existing (conventional) ventilation system using computational fluid dynamics (CFD). They indicated that the ventilation within the broiler building was not optimal as a result of dead zones and over ventilation at the ends of the tunnel ventilated broiler building. The performance of broiler chickens raised in a tunnel ventilated broiler building and the operation cost of the tunnel ventilation system were evaluated by Lacy and Czarick (1992). They reported that though the body weight of broiler chickens raised in the tunnel ventilated broiler building increased by 4.3 % compared to the birds raised in a conventional ventilated broiler building, the cost of electricity for running the tunnel ventilated building doubled the cost of running conventional broiler building. The stress conditions within the tunnel ventilated broiler building were spatially analysed by Miragliotta et al. (2006). They indicated that the stress zones are majorly located at the ends of the tunnel ventilated broiler building and that the highest bird mortality was recorded closer to the exhaust fans end. Similar report has also been indicated in the study carried out by Wheeler et al. (2003). They indicated that the microclimate of birds at the exhaust end was the warmest zone within the tunnel ventilated broiler building. It has been shown that birds raised in the tunnel ventilated broiler building tend to migrate towards the inlet area during hot periods which could result in lower performance of the birds and higher body condemnations as a result of overcrowding and poor litter quality (Czarick and Lacy, 1990; Lacy and Czarick, 1992).

2.4.1.2. Conventional ventilation system

The airflow exchange rate of conventional ventilation system in broiler buildings are determined based on the amount of the heat that is expected to be remove from the poultry building (University of Kentucky College of Agriculture, 2014). It has less operation cost compared to tunnel ventilation system (Lacy and Czarick, 1992). The available conventional ventilation systems are discussed below.

2.4.1.2.1. Cross ventilation system

In the cross ventilated broiler building (Figure 2.4), mechanical fans are installed on one sidewall while the inlets are on the other sidewall of the building (Bhadhauria, 2014). The fans could be equally spaced or arranged as a group of 2 or 3 (University of Kentucky College of Agriculture, 2014). Cross ventilation broiler building is usually about 10 m wide and is largely adopted in the hot and humid climate for removing heat during summer periods and contaminants during winter (Bhadhauria, 2014; Bustamante et al., 2013; University of Kentucky College of Agriculture, 2014). Due to high mortality and the heat stress of birds raised in the cross ventilated building, different studies have been carried out to evaluate the airflow within the cross ventilated broiler building. The ventilation efficiency of cross ventilated broiler building was explored by (Bustamante et al., 2013) to understand the air velocity distribution within the building using CFD. The ventilation rate of cross ventilated poultry buildings was evaluated by Calvet et al. (2010). The homogeneousness of the indoor temperature and velocity in cross ventilated broiler buildings were evaluated by Wheeler et al. (2003) and they reported that almost half of the building exhibited air velocity less than 0.25 m s^{-1}. The airflow within the cross ventilated broiler building was predicted using CFD by Blanes-Vidal et al. (2008). All the above studies have indicated that airflow within the cross ventilated broiler building was generally below (< 1.5 m s^{-1}) the required mean air velocity in the broiler microclimate zones. As a result, it can be concluded that cross ventilation system is only suitable for removing indoor heat during cold periods and not an appropriate ventilation system for providing cool environment for broilers during hot weather periods.

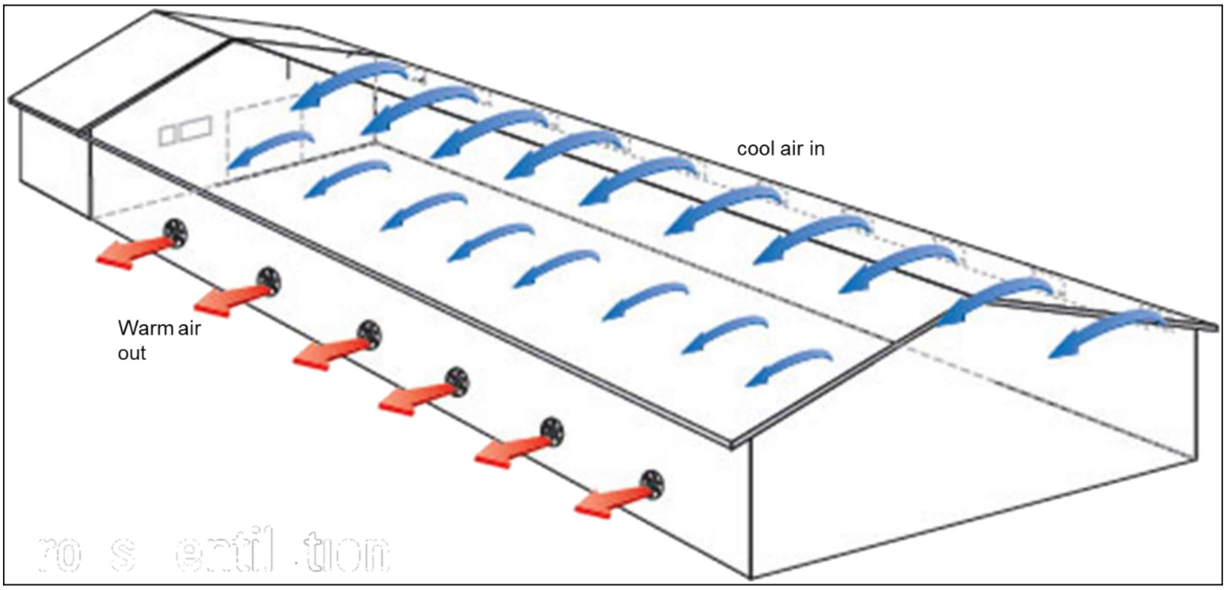


Figure 2. 4: Cross ventilation system (Big Dutchman, 2016)

2.4.1.2.2. Sidewall inlet and roof exhaust ventilation system

In this type of conventional ventilation system (Figure 2.5), automatically adjusted inlets are installed along the two sidewalls and the mechanical fans are mounted in the roof of the building. The fresh air is drawn through the inlet into the building using static pressure while the stale air is vertically expelled out of the building through the roof mounted fans into the atmosphere for better dispersal (AHDB, 2017; Hydor, n.d.). This ventilation system is mainly found in the United Kingdom (AHDB, 2017; Hydor, n.d.). As at when this literature review was written, the information on this type of ventilation system in the literature is scarce. Therefore, not much information could be provided here.

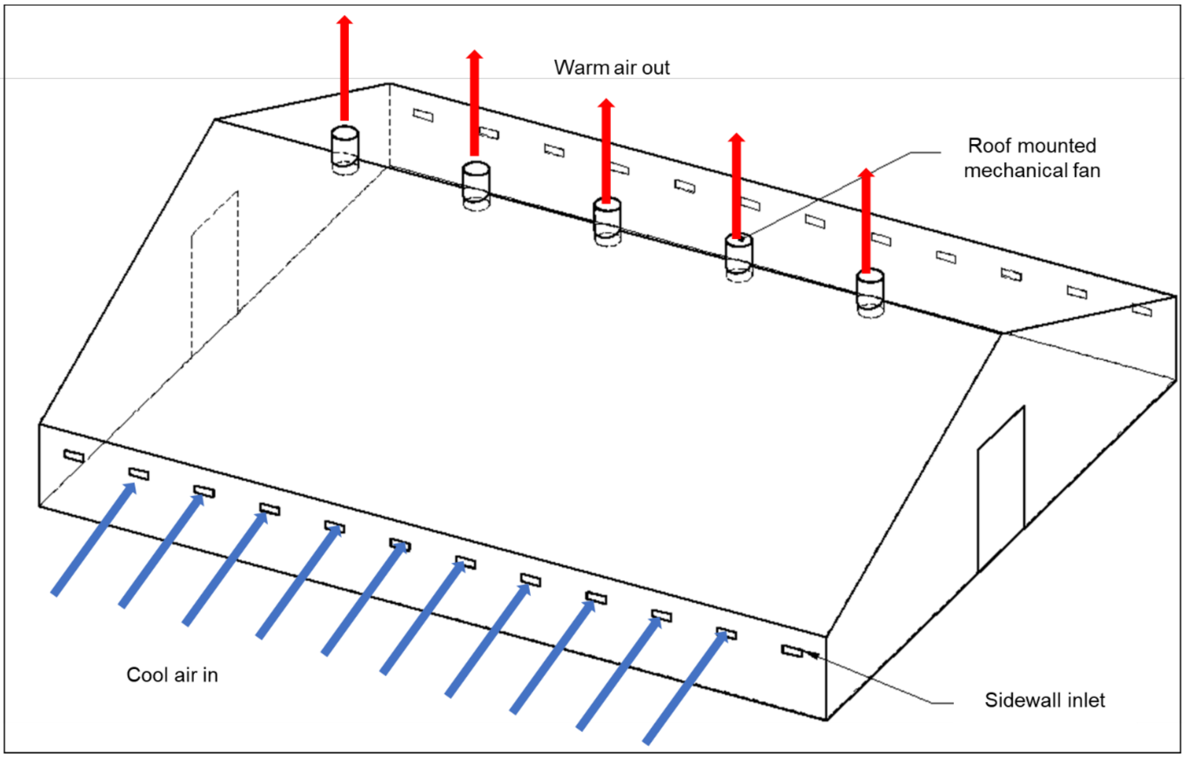


Figure 2.5: Sidewall inlet and roof exhaust ventilation system

2.4.2. Airflow Quality at the Animal Occupied Zone

Broiler buildings are expected to be properly ventilated so as to remove heat and excess moisture, minimise dust and odours and also provide adequate oxygen for broiler respiration. These important purposes of ventilation are sometimes difficult to achieve at the animal occupied zones (AOZ) due to the inappropriate distribution of air within the buildings. The quality of the microclimate in livestock building is characterised by the air temperature, relative humidity, air velocity and the concentration of contaminants in the AOZ (Van Wagenberg and Smolders, 2002). Air temperature and air velocity in the AOZ have a significant effect on livestock health, welfare, behaviour and production (Scheepens et al., 1991a, 1991b; Van Wagenberg and Smolders, 2002). Improvement of ventilation effectiveness in the livestock buildings is an important approach for increasing heat loss from domesticated animals, reducing contamination concentration (Van Wagenberg and Smolders, 2002; Wang et al., 2000; Zhang et al., 2001), ensuring proper distribution of fresh air and improving air exchange rate between inside and outside of livestock building (Mostafa et al., 2012; Wisate et al., 2014).

The effective temperature of animal buildings, welfare and the performances of domesticated animals are mainly influenced by the airflow directions and its intensity at the AOZ (Mistriotis et al., 1997). In order to improve animal building environment towards higher efficiency and also minimise its energy consumption, the performance of the ventilation system in livestock houses was investigated. Some studies have been conducted to investigate the effectiveness of ventilation system in the livestock buildings using field experiments and simulation methods. However, it is difficult to acquire detailed airflow distribution in livestock buildings using field experimentation due to the high instrumentation cost and labour (Boulard et al., 2002; Mistriotis et al., 1997; Norton et al., 2007). To solve the challenges associated with field experimentation, a sophisticated simulation tool (CFD), capable of investigating the large-scale structures of 3D flows, is required. Simulation method gives room for the inclusion of boundary conditions and disturbances (Mistriotis et al., 1997). It has been adopted by agricultural engineers for the explicit simulation of average air velocity, air temperature, airborne particle distribution and the evaluation of ventilation system of livestock buildings (Bustamante et al., 2013; Calvet et al., 2010; Humbert et al., 2014; Mostafa et al., 2012; Norton et al., 2010a, 2010b; Seo et al., 2012).

2.4.3 Evaluation of airflow in animal building

Some studies have evaluated the indoor conditions of animal houses using experimental approach. Van Wagenberg & de Leeuw (2003) measured air velocity at the pig occupied zones within pig building equipped with door ventilated system using ultrasonic anemometers. Two pens (front and back of the room) were selected and all measurements were obtained at the piglets resting area. They indicated that air velocity at the back of the room was 19 % higher than that of the pen in the front of the room. Smith et. al. (1999) investigated the effect of animals on the airflow characteristics (air velocity and air turbulence intensity) in the AOZ of a slot ventilated pig building. Air velocity was measured at 0.2 m and 0.4 m above the floor with ultrasonic anemometers when the building was empty and occupied with live pigs. They reported that air velocity in the empty room was generally higher than that of the room occupied with live pigs. At 0.2 m height (resting height), air velocity in empty and occupied rooms ranged from 0.64 to 0.71 m s^{-1} and 0.23 to 0.51 ms^{-1} respectively. At 0.4 m height (standing height), air velocity in the empty and occupied rooms ranged from 0.20 to 0.67 m s^{-1} and 0.29 to 0.43 m s^{-1} respectively. Air turbulence intensity at 0.2 m above the floor in the occupied room was higher (0.24 to 0.57) than that of the empty room (0.22 to 0.27) due to the upward deflection of airflow by the lying pigs.

Bustamante et al. (2012) developed a multi-sensor system comprising of differential pressure, velocity and temperature sensors to measure indoor climatic conditions at 0.25 m and 1.75 m heights above the floor in an empty cross-ventilated poultry building. Air velocity measurements were obtained at various differential pressure values. Their results indicated that air velocities at 0.25 m and 1.75 m heights were similar in all the experimental conditions. Blanes-Vidal et al. (2007) evaluated the influence of differential pressures (20, 30, 38 and 45 Pa) on the indoor air velocity of a typical Mediterranean broiler house equipped with the conventional cross-ventilation system. Air velocity and temperature, within the building, were measured at different locations and heights (0.2, 0.6 and 2.0 m above the floor). Their results indicated that differential pressure had no significant effect on the air velocity at the broiler occupied zone (0.2 m height above the floor). The authors suggested that pressure values should not be solely used as criteria for controlling airflow at the broiler occupied zones.

All these studies have shown that ventilation systems in the livestock buildings, provide non-uniform air velocity and temperature at the animal level. Likewise, it is also clear from the literature that animals do influence airflow direction. To redesign animal buildings, in order to effectively evaluate, optimise and improve indoor conditions of broiler building, a non-expensive instrumentation is required. This approach is expensive and time-consuming. This has led to the application of computational fluid dynamics (CFD), a powerful simulation tool, in agricultural facilities

2.4.4 Hot weather ventilation systems in broiler production

Broiler chickens cannot sweat and they only depend on sensible (convection and radiation) and latent heat transfer for losing body heat. Increasing air velocity over broilers during hot weather will help them to get rid of excess body temperature (Berry and Huhnke, 2003). However, achieving proper ventilation during hot weather is difficult, most especially in an environmentally controlled broiler building since air distribution depends mainly on the location, design, and adjustment of the air inlet (Berry and Huhnke, 2003; Weaver, 2002a). During cold weather, air inlets are adjusted to direct air along the ceiling towards the centre of the building to remove harmful gases such as ammonia and carbon dioxide and moisture (Lacy, 2002; Weaver, 2002a). But during hot weather, ventilation is needed to remove heat, moisture and harmful gases from the building (Weaver, 2002a). To achieve the purpose of hot weather ventilation, EU farmers tend to open air inlets and doors wide to permit a large volume of air movement into broiler building (Blanes-Vidal et al., 2008). This approach, according to Albright (1990), Czarick & Fairchild (2008), and Weaver (2002) will not cause a noticeable increase in airflow into the building. It will only result in poor air mixture and air distribution. The principle of a sidewall inlet ventilation system, according to Albright (1990) and Czarick & Fairchild (2008), is that if static pressure is between 10 and 30 Pa, the rate of ventilation inside the broiler building is mainly dictated by mechanical fans while air inlets determine the air distribution. Therefore, opening the air inlets wide, with the aim of allowing more air movement into the building during hot periods, may ruin the capability of the ventilation system to produce required ventilation rate and uniform air distribution.

There are many studies on the control of ventilation systems in the broiler building to improve thermal environment of broilers but are majorly centred on cold conditions (Mostafa et al., 2012; Seo et al., 2009). The few studies on hot weather ventilation systems have only evaluated the indoor conditions of broiler building (Blanes-Vidal et al., 2008; Bustamante et al., 2013; Chepete and Tsheko, 2006), while other works have suggested the use of supplementary cooling systems (Chepete and Xin, 2000; Dağtekin et al., 2009; Gates et al., 2014; Liang et al., 2014; Mutaf et al., 2009, 2008; Tao and Xin, 2003c; Xiong et al., 2015) for relieving broilers of heat stress during hot weather periods. There is no comprehensive study reported on how ventilation system, apart from high ventilation rate, in broiler building could be improved to minimise the use of supplementary cooling systems (such as an evaporative cooling pad, surface wetting and fogging) and electrical energy demand for relieving broiler chickens of heat stress during hot weather condition. Therefore, to avoid high initial cost and energy requirement of supplementary cooling systems (Renaudeau et al., 2012) and the resulting high indoor relative humidity (Renaudeau et al., 2012) within broiler building, it could be ideal to investigate other options of providing better thermal environment through the use of existing ventilation system, without additional costs (capital and energy) for broiler chickens during hot weather periods.

2.4.5 Air Inlet control

Many research works have been presented on the air velocity at animals' microclimate over the last decades. In an effort to predict air velocity at animal occupied zones (AOZ), there has been an established study indicating that it depends on the air jet momentum at the inlet and the geometry of the animal building (Ogilvie et al., 1990; Strøm et al., 2002, 2001). The mean air velocity and turbulence intensity at AOZ were reported to be proportional to the inlet air speed and inlet height above the floor (Jin and Ogilvie, 1992). Morsing et al. (2000) showed that, provided a constant airflow pattern is established by an air jet very close to the building ceiling, air velocity at AOZ could be predicted from inlet air velocity and inlet opening size. Hoff (1995) also indicated in the study carried out on the airflow characterisation in an occupied pig building that air velocity at floor level had good correlation with the inlet height and ventilation rate. However, there had been an indication that air jet momentum can be negatively affected because of the large-scale air circulation within the animal building (Albright, 1990) and to maintain high indoor air momentum, it requires that inlet air jet momentum must be constantly kept high in order to stabilise air circulation inside livestock building (Albright, 1990).

Air movement into mechanically ventilated broiler building is determined by the static pressure (the difference between the outdoor pressure and indoor pressure) created within the building. The higher the static pressure (> 25 Pa), the slower the air movement into the building, and as the static pressure drops to between 12 to 25 Pa, there would be an increase in airspeed entering into the animal building (Czarick & Fairchild, 2008). To gain control over the air movement and air distribution inside broiler building, the opening area has to conform to the capacity of the exhaust fans. Blanes-Vidal et. al. (2007) investigated the efficacy of using indoor pressure to control ventilation system of a cross-ventilated broiler building during hot weather. They reported that controlling air inlet, with pressure varying between 20 and 45 Pa, had no significant influence on the air velocity at the broiler level. Ideally, convective cooling of adult broiler chickens during hot weather is expected to be increased by directing air towards the floor (Czarick & Fairchild, 2008) with static pressure being maintained at a variable between 12 to 25 Pa. However, achieving such increase in the convective cooling may be difficult because of the slow air movement at the broiler level. As the distance from the inlet increases, airflow tends to lose it speed, momentum and its ability to properly mix within the broiler building (Weaver, 2002), resulting in drifting aimlessly toward the roof extraction fans" without reaching broiler microclimate (Weaver, 2002).

2.4.6 Effect of ventilation on broiler performances

Ventilation plays a significant role when the ambient temperature is high or above thermal comfort of confined animals. In egg-laying poultry, increasing air velocity from 0.5 to 2.0 m s^{-1} could result in 27 % increase in feed intake and 15 % decrease in water intake of 5 weeks old laying birds when exposed to high indoor temperature (Ruzal et al., 2011). Comparing birds raised in conventional and tunnel-ventilated buildings, Lott et. al. (1998) reported that the body weight gain and feed conversion of broiler chickens raised in the tunnel-ventilated building were higher compared to those in the conventional ventilated building. The difference was identified to have occurred as a result of the high panting rate in conventional ventilated building and high air velocity in the tunnel ventilated building. High air velocity during hot environmental condition was indicated to be helpful in increasing the body weight gain and feed efficiency of young turkeys (Yahav et al., 2011).

Hot weather-related problems can be minimised with adequate air movement over broilers (Czarick & Lacy, 1999). Many studies have shown that air velocity is an important environmental factor for controlling indoor conditions during hot weather. Czarick and Lacy (1999) reported a study conducted by USDA Southern Regional Poultry Research Lab located in Starkville, Mississippi. They indicated that adult broilers exposed to an air velocity of about 2.0 m s^{-1} and 29 °C continued to gain additional 0.45 kg body weight weekly as a result of higher feed intake compared to birds exposed to the same air temperature but no air movement. The growth of birds raised in no air movement environment was found to be slower because of their inability to eat adequately due to higher air temperature. Simmons et. al. (2003) reported that out of adult broilers exposed to still air, 2.0 and 3.0 m s^{-1}, and diurnal cycle of 25-30-25 °C, adult birds exposed to 3.0 m s^{-1} significantly improved in body weight gain and feed: gain ratio compared to that of 2.0 m s^{-1} and still air.

Similarly, May et. al. (2000) conducted a study to determine the effect of air velocity (0.25 and 2.0 m s^{-1}) on feed and water consumption of broiler chickens exposed to a diurnal temperature of 22-32-22 °C. They indicated that broilers that were exposed to higher air velocity (2.0 m s^{-1}) consumed less water (possibly due to a reduction in evaporative heat loss), increased feed intake, gained more body weight and improved in the feed: gain ratio. Mitchell (1985) determined the effects of air velocity on the sensible heat loss from chickens exposed to 20 and 30 °C. He reported that increasing air velocity over chickens exposed to 30 °C facilitated convective heat transfer from the chickens to the surrounding air. Yahav et. al. (2001) studied the effect of air velocity on male broiler chickens exposed to 35 °C air temperature and 60 % relative humidity. They reported that the body weight gain, feed intake and feed efficiency of broiler chickens were 28 %, 15 % and 12 % higher when air velocity was increased from 0.5 to 2.0 m s^{-1}.

Recent genetic selection progress in broilers has resulted in a parallel increase in heat production and this had made it difficult for the fast-growing birds to survive during summer periods (Yahav et al., 2011, 2008). The main environmental parameters influencing the indoor conditions during hot periods are air temperature, relative humidity and air velocity. The influences of air temperature and relative humidity on the heat loss and performance of broiler chicken are well researched (Aerts et al., 2000; Cangar et al., 2008; Lin et al., 2006b; Nascimento et al., 2011; Yahav et al., 2001). Similarly, there are few studies reported on the impact of air velocity on broiler performances when exposed to hot climatic conditions. The available studies have indicated that higher air velocity helps broiler chickens to survive and also increase production when exposed to the hot environment (Ruzal et al., 2011; Yahav et al., 2001).

Furlan et. al. (2000) studied the effect of air velocity from 1.8 to 5.7 m s^{-1} on the surface and rectal temperatures of adult male broiler chickens exposed to 29 °C air temperature. They found out that duration of exposure (0 to 30 minutes) of broiler chickens to air velocity had significant effects on their surface and rectal temperatures. The result indicated that broilers with an initial body temperature of 42 °C lost 2 % body temperature when exposed to 5.7 m s^{-1} air velocity for a period of 30 minutes. They also discovered that head and leg temperatures of broilers, within 30 minutes of exposure to 5.7 m s^{-1} air velocity, were reduced by 1.1 ˚C and 4.2 ˚C respectively while the back temperature was not affected due to postural changes of birds during the study. Yahav et al. (2004) conducted a study to investigate the effect of air velocity on energy and water balance of 4 to 7 weeks old, fast-growing male Cobb broiler chickens subjected to a constant 35 ˚C air temperature and 60 % relative humidity. Water balance, energy balance, body weight, feed intake, feed efficiency and sensible heat loss were all monitored during the study. They reported that there was 16 %, 23 %, 43 %, 57 % increase in energy directed towards growth, body weight, feed intake and feed efficiency respectively as air velocity, to which birds were exposed to, was increased from 0.8 to 2.0 m s^{-1}. The exposure of broiler chickens to higher air velocity (2.0 m $s^{-}1$) resulted in 3 % decrease in body temperature and 88 % increase in convective heat loss as air velocity was increased from 0.8 to 2.0 m s^{-1}.

From the studies, it is clear that increasing air velocity at the animal level can effectively increase convective heat loss, reduce indoor temperature, prevent birds' migration from one region to another, reduce mortality and also improve the animals' thermal comfort (Blanes-Vidal et al., 2010). It has also been identified from the literature that maintaining an average air velocity of 2.0 m s^{-1} within broiler building could be helpful in minimising the impact of high indoor temperature in broiler building. However, it is difficult to achieve such level of air velocity at the broiler level due to the variations in air distribution within broiler building. It is therefore imperative to investigate other available methods of improving indoor conditions of broiler building without unnecessarily increasing indoor moisture level. It would be interesting to know that constant increase in air velocity, to provide a conducive environment for broiler chicken, will lead to the additional energy consumption of more than 29%, according to Estellés et. al. (2012), for a complete rearing cycle of broiler chickens.

2.5 Computational fluid dynamics (CFD) simulation of airflow in animal building

2.5.1 Basic physical principles of CFD

CFD uses computer software such as STAR CCM+ and FLUENT to simulate fluid flow and the quality of its study depends on the available physics in the software and the understanding of the modellers (Norton et al., 2007). CFD software provides modellers with the ability to integrate all interacting forces within livestock buildings (Rojano et al., 2015) to simulate fluid flow. CFD operates on three basic conservation principles governing fluid flow. These principles define the rate of change of fluid within an element as a function of forces (body and surface forces) acting on the element (Norton et al., 2007). The basic physical principles (Anderson, 2014; Norton et al., 2007), are

(1) continuity equation also known as conservation of mass which indicates that the mass inflow into a fluid element is equal to the mass outflow from the fluid element;

(2) conservation of momentum also known as Newton's second law states that the total sum of the forces acting on the fluid element is equal to the rate of change of momentum;

(3) conservation of energy also known as the first law of thermodynamics which shows that the rate of change of energy within a fluid element is equal to the total heat added to the element and the rate of work done on the element as a result of external forces.

The three fundamental principles of CFD are mathematically expressed in form of partial differential equations. CFD replaces the partial derivatives with discretized algebraic forms to obtain flow field values at the discrete points in time and space (Anderson, 2014). The equations are generally referred to as the Naiver-Stokes equations (Norton and Sun, 2007) and are written as (Anderson, 2014)

The continuity equation (conservation of mass)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \tag{11}$$

The conservation of momentum (Newton's second law)

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{12}$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{13}$$

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{14}$$

The conservation of energy (first law of thermodynamics)

$$\begin{aligned}
&\frac{D}{Dt}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \nabla \cdot \left[\rho\left(e + \frac{V^2}{2}\right)V\right] \\
&\quad = \rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} \\
&\quad - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} \\
&\quad + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} + \rho f \cdot V
\end{aligned} \tag{15}$$

where ρ is density (kg m^{-3}), t is time taken (s), $\nabla \cdot V$ is the divergence of the velocity, V is velocity (m s^{-1}), u, v, w are the components of velocity (m s^{-1}), p is pressure (Pa), $f_{x,y,z}$ are body forces (k N) on a fluid element in x, y, z directions (m), e is the internal energy (J), τ_{xx}, τ_{yy}, τ_{zz} are normal stresses (Pa) in x, y, z directions, τ_{yx}, τ_{zx}, τ_{xy}, τ_{zy}, τ_{xz}, τ_{yz} are shear stresses (Pa) in the x, y, z directions acting on planes perpendicular to the x, y, z axes, $\frac{V^2}{2}$ is the kinetic energy (kg m^2 s^{-2}), T is the temperature (°C), $\dot{q}$ is the rate of volumetric heat addition per unit mass.

Many studies have been carried out on the use of CFD in the evaluation of ventilation performances of livestock building. Norton et al. (2010) conducted a simulation analysis to improve the homogeneity of the indoor environmental condition of naturally ventilated animal buildings in order to optimise ventilation configuration. Their result showed that building geometry and ventilation configuration were key factors influencing indoor environmental heterogeneity of livestock building. Norton et al. (2009) had assessed the ventilation effectiveness, under wind dominated conditions, of the naturally ventilated animal building using CFD. There was an indication that using only air flow rate may not be appropriate for determining the ventilation rate of livestock building. Rather, contaminants decay should also be considered as a measure for assessing the ventilation rate of a naturally ventilated building. Seo et al. (2009) used CFD to improve the ventilation system of a naturally ventilated broiler building during the cold period. They reported that with CFD, installing a diffuser right under the roof inlet enhanced proper mixture of incoming cold air with the hot air at the roof area within the naturally ventilated broiler house. They also indicated that simulating the energy input into the broiler building with CFD helped in saving 47 % energy input at the broiler occupied zones and 30 % energy cost required by additional field experiment. Fidaros et al. (2018) recently studied the ventilation in a broiler building equipped with evaporative cooling pad using CFD. They reported that operating more than three ventilation fans at the same time did not perform better than when 2 or 3 fans were used in the mechanically ventilated broiler building with evaporative cooling pad.

2.5.2 Turbulence models

Ventilation engineers are usually content statistically that environmental parameters, such as air velocity and air temperature, will exhibit a specific value before they can fit into any design plan (Norton, 2010; Norton et al., 2007). However, in ventilated environment, airflow generally has connection with the turbulence motion due to the interactions between high flow rate and heat transfer in flow field (Norton, 2010; Norton et al., 2007) and the effect of turbulence on the flow field is determined by the Reynolds averaged Naiver-Stokes equations (RANS). There are many turbulence models, such as Standard

$k-\varepsilon$, realisable $k-\varepsilon$, SST $k-\omega$ etc, presently available in the literature, including their prediction performances which depend mainly on the turbulence flow conditions, structural geometry and experimental measurements. Only a few turbulence models that are widely applied in the literature will be discussed in the report. For more details of other turbulence model, readers are kindly advised to read more in the literatures (Norton, 2010; Norton et al., 2007). In this report, the three turbulence models mostly applied will be discussed.

2.5.2.1 Standard $\mathbf{k}-\boldsymbol{\varepsilon}$ model

The standard $k-\varepsilon$ model is a semi-empirical turbulence model based on the transport equations for the turbulent kinetic energy (k) and its rate of dissipation (ε) (Launder and Spalding, 1974; Norton, 2010; Norton et al., 2007; Norton and Sun, 2009). Despite its industrial application, it is limited by (1) its assumption that the turbulent energy produced by the large eddies is equally distributed in the energy spectrum. Whereas, energy transfer in the turbulence regime is not automatic as sizable time may exist between when the turbulence is generated and the time it is dissipated (Norton, 2010; Norton and Sun, 2009); (2) It requires wall function due to its inability to determine dissipation rate at the wall (ANSYS FLUENT, 2006). The model could be represented by;

Turbulent kinetic energy (k)

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\partial k}{\partial x_i}.\frac{\mu_t}{\sigma_k}\right)+2\mu_t D_{ij}D_{ij}-\rho\varepsilon \tag{16}$$

Dissipation rate (ε)

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho u_i \varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\partial \varepsilon}{\partial x_i}.\frac{\mu_t}{\sigma_\varepsilon}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t D_{ij}D_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{17}$$

where u_i is the fluctuating component of velocity in x_i direction; ρ is the fluid density; the turbulent viscosity $\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$; $\sigma_k=1.00, \sigma_\varepsilon=1.30$ are Prandtl number for turbulent kinetic energy and dissipation rate equations respectively; D_{ij} is the rate of deformation (strain rate); $C_\mu=0.09$, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$ are turbulence model constants.

2.5.2.2 Realisable $\mathbf{k}-\boldsymbol{\varepsilon}$ model

This model fulfils some mathematical constraints on the Reynolds stresses that are steady with the physics of turbulent flows such as positive standard Reynolds stress terms (ANSYS FLUENT, 2006; Norton, 2010; Norton and Sun, 2009; Shih et al., 1995). In this model, the turbulence model constant C_μ is expressed as a function of mean flow and the properties turbulence and not continuous as in the instance of the standard $k - \varepsilon$ model (Norton, 2010; Norton and Sun, 2009). The model can be represented by;

Turbulent kinetic energy (k)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\partial k}{\partial x_i}\left(\mu + \frac{\mu_t}{\sigma_k}\right)\right] + P_k + P_b - \rho\varepsilon - Y_M \tag{18}$$

Dissipation rate (ε)

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\partial k}{\partial x_i}\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\right] + \rho C_1 D\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} \tag{19}$$

where $C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right]$; $\eta = D\frac{k}{\varepsilon}$; $D = \sqrt{2D_{ij}D_{ij}}$; P_k, P_b are generated turbulent kinetic energies due to mean velocity gradient and buoyancy respectively; $C_2 = 1.90$, $\sigma_\varepsilon = 1.20$

2.5.2.3 Shear stress transport (SST) $\mathbf{k - \omega}$ model

This model is based on the transport equations for the turbulent kinetic energy (k) and the specific turbulent dissipation rate (ω), which is the dissipation rate for every unit of turbulent kinetic energy (Norton, 2010; Norton and Sun, 2009). This model performs better than the $k - \varepsilon$ model at the wall boundary without the application of the empirical log-law wall functions as it gives account for the transport of the principal turbulent shear stress in adverse pressure gradient boundary layers (Menter, 1992). According to Menter (1992), the known problem of the model is its sensitivity to inlet conditions or freestream. However, this problem was addressed by Menter (1992) who transformed the turbulent dissipation rate (ε) in the standard $k - \varepsilon$ into a specific turbulent dissipation rate (ω) by blending the function that includes cross-diffusion term far away from the walls (Norton, 2010; Norton et al., 2010a). As a result, the SST $k - \omega$ model has provided an improved resolution of boundary layer of viscous flow (Menter, 1992; Norton, 2010; Norton et al., 2010a; Norton and Sun, 2009).

2.6 Heat transfer from broiler chickens

The improvement in the genetic selection and feed composition are the key factors that have contributed to the fast growth rate of broiler chickens nowadays. Previously, it took about 100 days for a broiler chicken to reach maturity but due to improvement in genetics and feeding, it takes broilers nowadays to reach table size within 38 - 42 days (Havenstein et al., 2003b). Modern broiler chickens, that are genetically selected for fast growth and higher feed conversion rate, are more susceptible to high environmental temperature, less tolerable to heat stress and produce higher heat and moisture (Watts et al., 2011).

Heat loss from broiler chickens is in the form of sensible heat loss and latent heat loss. Through the sensible heat, heat is transferred from body surface of broiler to the environment while with latent, heat is lost through respiratory evaporation. The density of heat flowing from broiler to the environment depends on the broiler physiological state (size, feather, the rate of respiration). Other factors determining the heat flow are temperature difference (for sensible heat loss) and vapour pressure difference (for latent heat loss) between broiler and the immediate environment (Gous et al., 2006; Simmons et al., 1997). Broilers are homoeothermic and they balance body energy by decreasing heat production, elevating evaporative heat loss and increasing sensible heat loss (Yahav et al., 2004c). However, heat loss by evaporation (latent) has been reported to incur a higher amount of energy expended by birds on maintenance than sensible heat loss. The effects of latent heat on blood acid/base balance, body water balance and energy metabolism (Yahav et al., 2005, 2004c), carbon dioxide levels, blood pH, eggshell mineralisation, and calcium level in blood (Lara and Rostagno, 2013) are well documented. As a result, shifting heat loss from latent to sensible will increase the amount of energy directed towards growth, reduce energy expended for thermal maintenance and also prevent hyperthermia in broilers during the hot period (Yahav et al., 2005). Since sensible heat transfer is very important in ensuring a better environment for broiler chickens, this section will be considering more of sensible heat transfer and less of latent heat transfer.

2.6.1 Sensible heat loss in broiler chickens

The sensible heat loss from the body surface of broiler chickens is majorly through conduction, convection and radiation. The sensible heat transfer from the birds to the environment and vice versa is force driven by the differences between the surface temperature of birds and the environmental temperature. When convective heat loss depends on the temperature difference between the bird’s body surface and the surrounding air, radiative heat loss (the heat transfer through electromagnetic radiation), depends on the temperature difference between the bird and the wall surfaces, emissivity of bird and wall surfaces and the surface area of bird and the wall (Gous et al., 2006; Pedersen and Thomsen, 2000; Yahav et al., 2005).

There are limited research studies on the sensible heat transfer from broiler chickens. The main factor influencing the sensible heat transfer is the air velocity. With the increase in air velocity from 0.8 to 3.0 m s^{-1}, Yahav et al. (2004) reported over 100 % shift in sensible heat transfer from broiler chickens exposed to 35 °C and 60 % relative humidity. Similarly, Simmons et al. (1997) recorded that increasing air velocity from 1.0 – 3.0 m s^{-1} on broiler chickens exposed to high air temperature resulted in an increase in sensible heat loss and a decrease in latent heat loss from birds. Another study (Mitchell, 1985) had also indicated that convective heat transfer from domestic fowl exposed to high air temperature (30 °C) linearly increased with increase in air velocity. However, higher sensible heat transfer in broiler chickens could be difficult to achieve due to the thermal resistance of birds' feather. Heat transfer from the feathered regions varies from that of the featherless regions. It was reported by Furlan et. al. (2000) that while 2.0 m s^{-1} air velocity could significantly reduce broiler's leg (featherless region) temperature, the back (feathered region) temperature could not reduce at air velocity lower than 4.5 m s^{-1}. A similar result was reported by Cangar et al. (2008) that higher surface temperatures were recorded at the regions with no or little feather compared to regions with thicker feather cover.

2.6.1.1 Mathematical expression of sensible heat transfer from broiler chickens

The sensible heat transfer (SHT) between the bird's surface area and it microclimate is usually expressed as:

$$SHT = \mathrm{CHT} + \mathrm{RHT} \tag{20}$$

where CHT is the convective heat transfers (W m^{-2}) between the birds and the surrounding air and RHT is the radiative heat transfer (W m^{-2}) which is the electromagnetic radiation from the bird's surface to its environment due to temperature differences.

The convective heat transfers from birds, which is a means of thermal energy transfer between the bird and its environment, can be estimated using:

$$\mathrm{CHT} = \mathrm{CoCHT} \times A_{surf}(T_{surf} - T_{air}) \tag{21}$$

where CoCHT is the convective heat transfer coefficient (W m^{-2} K^{-1}), A_{surf} is the surface area (m^2) of birds and T_{air} is the air temperature (°C) of the microclimate.

The convective heat transfer coefficient of animals with complicated geometry and the hairy surface can be determined from the convection heat transfer relation containing the dimensionless parameters (Nusselt and Reynolds number) using:

$$Nu_b = \frac{\mathrm{CoCHT} \times \ D_{poultry}}{k_{cond}} \tag{22}$$

$$Re_b = \frac{\bar{u} \ \times \ D_{poultry}}{\nu_k} \tag{23}$$

$$\bar{\mathrm{u}} \ = \ \sqrt{\overline{u_x}^2 + \overline{u_y}^2 + \ \overline{u_z}^2} \tag{24}$$

where Nu_b is the Nusselt number, $D_{poultry}$ is the characteristic dimension (m) of a birds and k_{cond} is the air thermal conductivity (2.5658×10^{-2} W m^{-1} K^{-1}), Re_b is the Reynold number, $\bar{u}$ is the mean air velocity (m s^{-1}) and ν_k is the kinematic viscosity of air (1.460×10^{-5} m^2 s^{-1}), $\overline{u_x}, \overline{u_y}$ and $\overline{u_z}$ represent the mean air velocity components in x, y and z directions.

According to Wathes & Clark (1981), the relationship between the Nusselt number (Nu_b) and the Reynolds number (Re_b) can be expressed as:

$$Nu_b = 2 + 0.79\, {Re_b}^{0.48} \tag{25}$$

As expressed by Mitchell (1930), the characteristic dimension ($D_{poultry}$) of poultry birds can be calculated as a function of broiler body weight using:

$$D_{poultry} = 0.131 \times {M_{chicken}}^{0.33} \tag{26}$$

where $M_{chicken}$ is the body weight (kg) of broiler chicken.

Using the general Meeh equation, Mitchell (1930) derived an expression for determining the surface area of chicken as a function of body weight as:

$$A_{surf} = 0.000819 \times {M_{chicken}}^{0.705} \tag{27}$$

where A_{surf} is the surface area (m^2) of bird.

According to McArthur (1987), the thermal resistance of broiler chicken feathers can be determined using:

$$r_f = \frac{\rho c_p\, D_{poultry}}{k_{cond} Nu_b} \tag{28}$$

where r_f is the thermal resistance of broiler feather (s m^{-1}), ρ is the density of air (kg m^{-3}), c_p is the specific heat capacity of air (kJ kg^{-1} K^{-1}).

The radiative heat transfer between the birds and its environment can be estimated using:

$$RHT = \varepsilon_b\, \sigma_c\, A_{surf}\, ({T_{surf}}^4 - {T_{air}}^4) \tag{29}$$

where ε_b is the surface emissivity of bird (featherless chicken is 0.98 and feathered chicken is 0.94) and σ_c is the Stefan-Boltzmann constant (5.669×10^{-8} W m^{-2}K^{-4}).

2.6.1.2 Simulation of sensible heat transfer from broiler chickens

The application of simulations in the livestock production has recently become more important. The usefulness, accuracy and user-friendly environment offered by the simulation has increased its adoption in the Agricultural Engineering community for solving environmental problems within livestock buildings (Norton et al., 2007). Many research studies have elucidated the benefit of applying simulation in the quantification of heat transfer from livestock. However, with the level of its versatility, it has a major limitation in it accurate predictions due to the uncertainties when specifying boundary conditions (Norton et al., 2007). Therefore, the requirement for experimental work is necessary for validating simulation and also helps in determining the level of agreement that can be achieved between simulation predictions and the experimental results (Norton et al., 2007; Xia and Sun, 2002).

There are few studies on modelling of heat production of broiler chickens. Aerts et. al. (2000) modelled the heat production responses of broiler chickens to step changes in air temperature and light intensity. Kettlewell & Moran (1992) mathematically modelled the heat production and heat transfer from crated broiler chickens to determine the hyper-thermic stress state of broiler chickens during transportation. Aerts et. al. (2003) modelled broiler heat production and growth for developing an integrated management system for managing broiler microclimate. This section will only consider the application of CFD in broiler heat transfer.

2.6.1.2.1 CFD application in broiler chicken heat transfer

CFD is one of the simulation tools used for estimating heat production and heat transfer in animal production. The detailed application of CFD in agricultural buildings has been reviewed (Guerra-Galdo et al., 2017; Norton et al., 2007). Various studies have reported the application of CFD in poultry production (Kumar et al., 2009; Li et al., 2016b; Ozcan et al., 2010; Rojano et al., 2015).

In broiler production, there are a few cases reported in the literature concerning the CFD modelling of sensible heat transfer from broiler chickens most especially during hot weather conditions. Li et al. (2016) employed CFD to evaluate the coefficient of convective heat transfer from broiler chickens. In the study, the authors assumed indoor air temperature to be 20 °C while broiler model was exposed to air velocity ranging from 0.5 – 3.0 m s^{-1}. Measurements on the convective heat transfer coefficient from broiler models based on the angles of orientation, body weights were obtained. The results indicated that convective heat transfer coefficients from chicken were similar for all the angle of orientation (0°, 45° and 90°) with respect to the airflow direction (Figure 2.6).

However, body weight did have significant effects on the convective heat transfer. Birds with higher body weight had higher convective heat transfer coefficient as a result of the ratio of surface area to body weight compared to those with lower body weight.

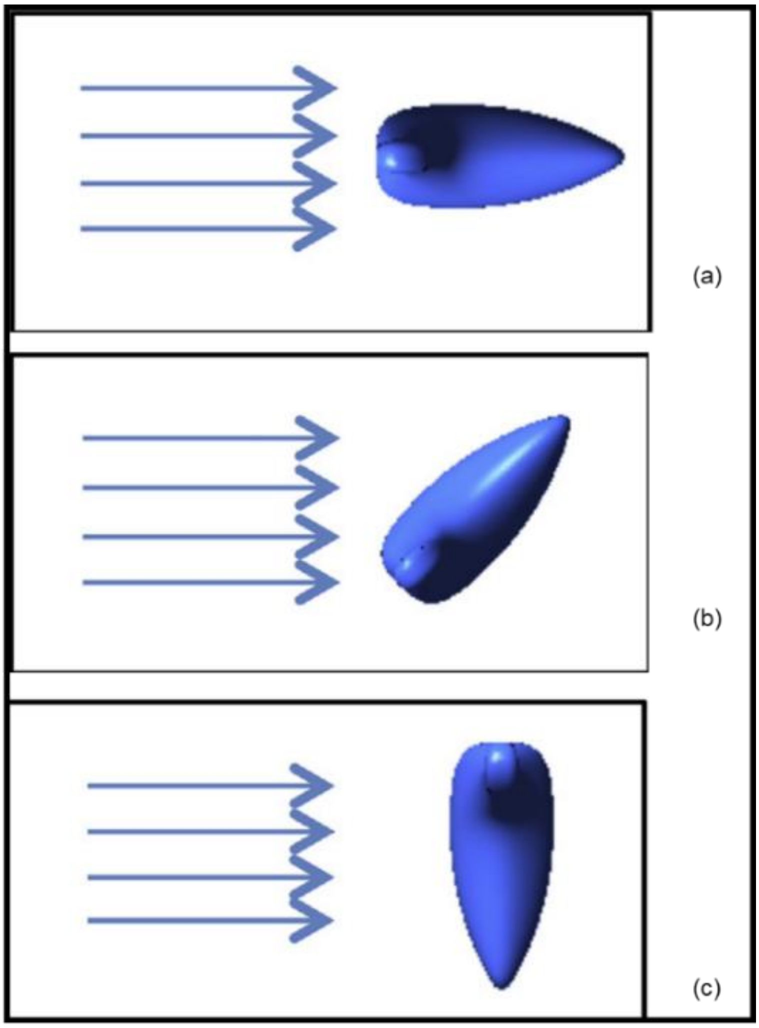


Figure 2.6: Chicken orientations with respect to airflow direction. (a) Head facing the airflow (0 º), (b) side facing the airflow at 45 º, and (c) side facing the airflow at 90 º (Li et al., 2016b).

Although the study was conducted to simulate heat transfer from chicken during hot weather conditions, the indoor air temperature specified in the study (20 °C) was not hot enough to cause heat stress in broilers. The temperature specified was within the thermal comfort zone (18 – 24 °C) of broiler chickens. Exposing broiler chicken to higher air velocity at low air temperature could result in broilers altering behaviours and physiology such as increase feed intake and huddling together in order to cope with the environmental condition (Arias et al., 2008; Blahová et al., 2007; Strawford et al., 2011). These behavioural and physiological responses have been reported to cause an increase in mortality, as a result of birds migration to warm areas during transportation (Di Martino et al., 2017) and a higher metabolic energy loss (an energy required for maintaining body temperature) in laying hens due to lower feed intake (Alves et al., 2012). Studies have indicated that orientations affect the rate of heat transfer from animals (cows and pigs) with respect to airflow direction (Gebremedhin, 1987; Li et al., 2016a) due to their geometrical shape (cylinder). However, orientation has reported by Li et al. (2016) has shown that it does not have any significant effect on convective heat transfer from broiler chickens. The reason may be as a result of the location at which the measurements were obtained. Since there are variations in the body surface temperature of broiler (Cangar et al., 2008), there is a tendency that the direction to which broiler is facing with respect to airflow could influence the rate of heat transfer from different body parts of the bird. Therefore, the influence of orientation on heat transfer from broiler chickens should be further investigated in order to provide a better environment for broilers during hot weather periods.

2.6.1.3 Effects of air velocity on heat transfer

Air velocity is one of the environmental parameters involved in the thermoregulation of broiler chickens during hot periods (Yahav et al., 2004c). Air movement over the body surface of broiler chickens exposed to high environmental temperature is very important to facilitate convective heat transfer between the bird's body surface and its surrounding air (Mitchell, 1985). Studies have shown that high air velocity is a useful parameter in shifting evaporative heat loss to sensible heat loss. High air velocity during hot periods was found by Simmons et al. (1997) to increase sensible heat loss and reduce latent heat loss. The researchers set up a study to investigate the effect of an increase in air velocity on the heat loss of broiler chickens. Birds were subjected to 29, 32 and 35 ˚C air temperatures with air velocity increasing from 1.02 to 3.05 m/s in a tunnel-ventilated broiler house. They reported that with an increase in air velocity from 1.02 to 3.05 m s^{-1}, sensible heat loss increased by about 75 % in 35 days old and 77 % in 36-day old broilers. As for latent heat loss, they found out that heat loss through evaporation was reduced by about 30 % in 35 days old and 12 % in 36-day-old broilers.

2.6.1.4 Effects of air turbulence intensity on heat transfer

The draft provided by fluctuating air velocities (turbulence intensities) seems to be a promising strategy that can be applied in broiler production to improve the environment of broiler chickens. There are indications in the literature (Ahn et al., 2017; Quintino, 2012; Sak et al., 2007; Vlahostergios et al., 2015; Wang et al., 2016) that higher air turbulence intensity, if integrated into the environmental control system of broiler buildings, is an important airflow characteristic for increasing heat transfer from heat-stressed broiler chickens. The impact of air turbulence intensity on heat transfer becomes more pronounced at higher Reynolds number (Kondjoyan and Daudin, 1995) and higher air velocity (Wathes and Clark, 1981). Integration of turbulence intensity into the ventilation system of livestock buildings could help in providing thermal comfort, better environmental control and also in saving energy (Gao and Niu, 2004; Zhao and Li, 2004). Adequate adjustment of the airflow turbulence intensity, through the environmental control system, to the level preferred by livestock could reduce the impact of heat stress which is impossible to achieve with conventional ventilation system (Gao and Niu, 2004) in livestock building. It is also good to know that inducing turbulence in airflow over livestock during hot weather periods could cause an increase in overall Nusselt number values (Wathes and Clark, 1981). The influence of air turbulence intensity on heat transfer has widely been considered in human environment to evaluate human thermal comfort and human sensation (Cao et al., 2013; Cui et al., 2013; Fanger et al., 1988; Gao and Niu, 2004; Huang et al., 2012; Jinping and Yanfang, 2010; Wang et al., 2011; Zhou et al., 2006) and in food and chemical industries (Ghisalberti and Kondjoyan, 1999; Kondjoyan et al., 2002; Sak et al., 2007).

There are reports of the studies carried out on the impact of air turbulence intensity on the thermal responses of different subjects (humans and food packaging materials). Wang et al., (2011) studied the effect of airflow characteristics on thermal response and local skin temperature of humans. They subjected 18 people (male and female) to different air velocities (0.3 and 0.6 m s^{-1}) and turbulence intensities (15 and 30 %) under the same environmental temperature and relative humidity. Questionnaires filled during the study were used to analyse the impact of the airflow characteristics on the subject based on how they felt in each of the environmental conditions they were exposed to over a period of 1 hour. All subjects reported that they felt more cooled when exposed to 30 % turbulence intensity than 15 % turbulence intensity and there was 75 % drop in skin temperature when turbulence intensity was increased from 15 % to 30 %. Similar results were shown by Yang et al., (2013) and Griefahn et al., (2000).

Other researchers (Huang et al., 2012; Todde, 2000; Zhou et al., 2006) have studied the impact of different airflow characteristics on the human thermal response. They have all reported that the higher the turbulence intensity, the cooler the subjects become in a warm environment and vice versa. As to the performances of subjects exposed to higher turbulence intensity, Cui et al., (2013) reported that human performances would keep increasing as long as the subjects are satisfied with the environmental condition. In broiler production, there is a tendency for broilers activities and interest to go on with their normal behavioural responses as long as their microclimate can be improved by increasing the turbulence intensity of the airflow surrounding them.

To the knowledge of the author of this thesis, the only study that has considered the impact of air turbulence intensity on the heat transfer from livestock was carried out by (Li et al., 2016a). The authors showed in the result of their CFD simulation that the exposure of pig model to 3.3 m s^{-1} with air turbulence intensity increasing from 5 % to 30 % resulted in 26 % increase in convective heat transfer coefficient. Similarly, with a lower air velocity of 0.15 m s^{-1}, increasing air turbulence intensity from 5 % to 30 % resulted in only 7 % increase in convective heat transfer coefficient. Turbulence intensity in broiler production could have a significant effect on the thermal resistance offered by the feathers and the boundary layer around birds during hot periods. Higher turbulence intensity could increase heat transfer from feathered broiler chickens by roughening their feathers and also allow energy dissipated by the fluid eddies to penetrate into the boundary layer around birds (Lavender and Pei, 1967).

2.6.1.4.1 Different ways of generating turbulence in fluid flow

Turbulence generators are the transition devices used for changing the laminar flow of fluid (air or liquid) to turbulent flow (Wikipedia, 2015). They are widely used in the industry for instance in the heat exchangers, for mixing fluid and on surfaces of aircraft wings (Wikipedia, 2015). Most of the equipment in use today are equipped with turbulence generators such as air de-stratification fans used in horticultural and other agricultural building, heat transfer ovens, sterilisers etc. (Wikipedia, 2015). For over ten decades, different studies have developed different turbulence generators to change the laminar flow of fluid to turbulent flow. The use of turbulence generator in the ventilation system of broiler building is important most especially when higher air velocity is required for alleviating heat stress in broiler chickens during hot periods. In order to allow a large volume of air into broiler building, farmers usually open all vents (inlets) fully during hot weather. This practice has been reported to be inappropriate (Albright, 1990; Blanes-Vidal et al., 2007). This is because, the practice will not increase ventilation rate rather prevent good ventilation and proper air mixture (Albright, 1990) most especially at the broiler occupied zone (Blanes-Vidal et al., 2007).

The impact of air turbulence intensity on heat transfer in livestock production has only been simulated but how it could be integrated into livestock’s building ventilation is not yet known. Various ways of generating turbulence intensity are available in the literature. Table 2.5 summarises different turbulence generators that have been used in the human environment, aerospace industry, food processing and fluid transportation and the amount of turbulence intensity each turbulence generator could generate. However, it is difficult to adopt any of the methods for increasing turbulence intensity within broiler building as they could impair air flow rate into the building and air circulation at the animal occupied zones. In addition, turbulence promoters/ generators such as screens, grids and perforated plates if used in broiler building could result in downstream decrease in turbulence as a result of degeneration law (Gori and Petracci, 2012; Mikhailova et al., 2005). Therefore, there is a need for an investigation into other possible technique that has little or no negative effect on the airflow rate in broiler building.

Table 2.5: Methods of generating turbulence in airflow

Authors and date	Turbulence generating device	Values of turbulence intensity (%) generated	Results
Zhou et al. (2006)	Controlled fan speed by sending time-series signal through a computer to frequency converter.	51	Higher turbulence intensity increased convective heat transfer from human skin. It also caused skin temperature fluctuation
Fanger et al. (1988)	Increasing the distance from fan to generate different turbulence intensities	12 - 55	Higher turbulence intensity resulted in higher draught compared to low turbulence intensity
Griefahn et al. (2000)	Variation of the on/off time and revolution per minute of four ventilators through computer programme	30 – 70	Draft-induced annoyance increased with increase in airspeed and turbulence intensity. However, only airspeed was found to be correlated with a decrease in human skin temperature.
Hua et al. (2012)	Variable speed air deflector	35	Simulated natural wind with higher turbulence intensity was better in improving human thermal comfort compared with constant mechanical wind
Shy et al. (1997)	Vibration of grids with different geometries	< 25	Turbulent flow was high in the regions very close to the grid but decayed as the distance increased.
Lee & Moon (2002)	Vane-type Swirlers	0 - 12	Combustion mixture increased with increase in turbulence intensity.

Authors and date	Turbulence generating device	Values of turbulence intensity (%) generated	Results
Li et al. (2012)	Agitator with different blade laying angles (45, 60 and 90 °C)	-	Recommended that blade laying angle of the turbulence generator should be from 60 to 75 °C for better performance
Marshall et al. (2011)	Turbulence generating device with fully and partially opened plates	10 - 30	In combustion studies, the generator was found useful in generating turbulence intensity ranging from 10 to 30 %.
Zhou & Cheng (2009)	Oscillating grid	-	Turbulence intensity influenced the settling behaviour of particles
Coppola & Gomez (2009)	Blockage plates	1.6 – 4.5	Turbulence intensity decreased as the distance between the plates and the nozzle increased
Zhao (2007) Zhao & Li (2004)	Rotating disc and swing plate	4 - 25	Human preference for turbulent air was higher than that of constant mechanical wind during warm conditions
Huang et al. (2012)	Semi-circular turntable	30 - 40	Turbulence intensity was found useful in offsetting the increase in indoor temperature.
McIlroy & Budwig (2007)	Active grids and rough surface plates	9 - 16	With realistic rough surface, there was a significant increase in turbulence intensity.
Hasan et al. (2012)	Perforated plates, delta wings, vertically arranged pipes and wire mesh		Turbulence generators appreciably decreased fouling resistance in the water-cooled pipe while the heat transfer coefficient was also increased. But the effectiveness of the generators was correlated to their shapes
Ozono et al. (2006)	Multi-fan in active and quasi-grid methods	< 15	The two methods had similar turbulence characteristics

Authors and date	Turbulence generating device	Values of turbulence intensity (%) generated	Results
Goto et al. (2007)	Rotating sphere along it precession axis		The generator was found to be useful in the laboratory for mixing in place of stirrers.
Eidelman et al. (2006)	Multi-fan turbulence generator		The distribution behaviours of particles in non-isothermal turbulent flow were found to be the same.
Alvarez & Flick (1999a, 1999b)	Perforated grid	10 - 50	Heterogeneity of airflow within the bins was found to influence the cooling of agricultural products. To improve airflow around the products, they suggested re-configuring product packages.

2.6.2 Latent heat loss of broiler chickens

This is the amount of water evaporated from broiler during hot periods. Water evaporates as it passes over the respiratory system of the bird. The moisture produced by birds when losing heat by evaporation contributes substantially to the indoor relative humidity and not to the indoor air temperature. During hot spells, about 60% of heat loss from birds is because of evaporative heat loss. In humid climate countries such as the UK, allowing birds to lose heat by evaporation is inappropriate; it will result in higher humidity within the broiler building. During panting, broiler losses body water and to balance it, they result in increasing water consumption and reduce feed intake. This results in poor growth and respiratory alkalosis because of insufficient carbon dioxide in the blood (Czarick and Fairchild, 2008).

2.7 Hot weather abatement strategies

Heat exhaustion from the animal building is very important for animals to maintain their energy for growth, welfare and production. Likewise, getting rid of heat from the animal during the hot period is as crucial as exhausting heat from the livestock building. The two key ways through which animals dissipate heat to the environment are sensible heat transfer and evaporative heat transfer. The temperature gradient in animal building governs the sensible heat transfer while the vapour pressure governs evaporative heat transfer. Heat transfer mechanisms become more applicable in getting rid of heat from the birds when ambient temperature increases so that birds can maintain their body temperature. (Liang et al., 2012; Mutaf et al., 2008, 2009). There are various heat abatement techniques reported in the literature and they will be discussed in the section of the study.

2.7.1 Nutritional, feeding and intermittent lighting strategies

Nutritionally, studies (Lin et al., 2006b; World Poultry, 2015) have shown that heat stress in broiler chicken can be reduced. The amount of feed consumed by birds can influence heat production in birds (Zhou and Yamamoto, 1997). Temporal withdraw of feed from broiler chicken was reported by Yalçin et al. (2001) to reduce heat stress and mortality in broiler chickens during hot periods. However, withdrawing feed from birds would result in poor growth and performance of broiler chicken. Intermittent lighting has been reported to regulate heat production in broilers due to a reduction in physical activities such as walking, feeding and drinking of birds (Aerts et al., 2000). Surprisingly, these strategies are yet to alleviate the problems caused by heat stress in broiler production because heat stress is majorly influenced by the environmental conditions.

2.7.2 Mixing and ceiling fans

In order to reduce heat stress in broiler buildings during hot weather, Al-dawood & Büscher (2014) conducted a study to investigate the performances of four different fans (mixing and ceiling), used as supplementary cooling system, for providing optimal air velocity (1.5 – 3.0 m s^{-1}) for broiler chicken during hot weather. They tested two different mixing fans (M4E/40 and M2E/40) and ceiling fans (PV60 and PV36). Their results indicated that, with the two fans (mixing and ceiling), air velocity in the vicinity of the fans were generally high but decreased as the distance from the fans increased. Mixing fans were reported to generate 2.0 – 3.0 m s^{-1} air velocity up to a distance of 7 metres away from the fans. While ceiling fans had maximum air velocity of 2.4 m s^{-1} at the distance of 0.3 m from the fan and 0 m s^{-1} air velocity at 1 metre away from the fan. They concluded that fans (mixing and ceiling) are a useful supplementary cooling system for reducing the effects of heat stress in broiler building. However, there was no report on the energy consumption of the fans when tested despite the fact that the fans could be a useful device in the building. In addition, though the authors aimed to use the fans to reduce the heat stress in fowl buildings, the environmental conditions (air temperature and relative humidity) under which the study was conducted were not stated in the study. It is therefore not clear if the result of the study is really applicable under hot weather conditions when heat stress in majorly noticeable.

2.7.3 Water-cooled perches

Over the years, different cooling strategies have been adopted in ensuring that broiler chickens are adequately protected against the effect of heat stress during hot weather. Some researchers have adopted the use of cooling perches to improve broiler welfare and performances during hot weather. Zhao et al., (2012) conducted an experiment to determine the usage of water-cooled perches as a strategy for cooling broiler chickens during hot weather. The experiment was divided into cool perches, normal perches and no perches treatments. They reported that significant numbers of broiler chickens used the cool perches (18 %) more than the normal perches (2 %) and that using cool perches resulted in 5 % increase in feed intake, 8 % increase in body weight and 8 % increase in breast and muscle yields of 6 weeks old broilers compared to normal perches. In addition, they indicated that using cool perches during hot weather reduced panting by 69 % compared to normal perches as the cooled perches offered a thermoregulatory benefit to broiler chickens exposed to high indoor air temperature. Similarly, Hu et al. (2016) assessed the effects of chilled water cooling perches on laying hens production exposed to severe hot weather condition. In the study, chilled water and cool air were distributed into the hen cages through hollow perches when birds were exposed to 4 hours severe hot condition (33 °C). They reported that laying hens used chilled water perches more than the air perches. However, perch cooling (chilled water and cool air) could not influence egg production, body weight and the egg quality as there was no significant difference between the productions of the hens with chilled water cooling perches, air perches and no perches. But as regards panting and wing-spreading (heat stress indicators), those in the chilled water cooling perches cage was found to be highly resistive to acute temperature compared to other treatments.

The usage of cooled perches and air perches by the laying hens during the day and the night was studied by Xiong et al. (2015). They reported that the usage of the cooled perches by birds, as shown in Figure 2.7, increased by over 300 % as the air temperature increased from 29 ºC to 35 ºC at around 1100 hour in the morning. Birds that could not perch were found making body contact with the cooled perches during the day. Laying hens were reported to perch less during the afternoon when there was decrease in the indoor air temperature. However, it was difficult to link the perching behaviour of the birds to cooling as birds would naturally want to exhibit their natural behaviour by jumping on platform higher than other birds to escape from aggressive birds. In addition, it difficult to directly link the total heat gain (conduction, convection and radiation) by the cooled perches to birds usage as the convective and radiative heat loads on the cooled perches were from the cage instead of the birds.

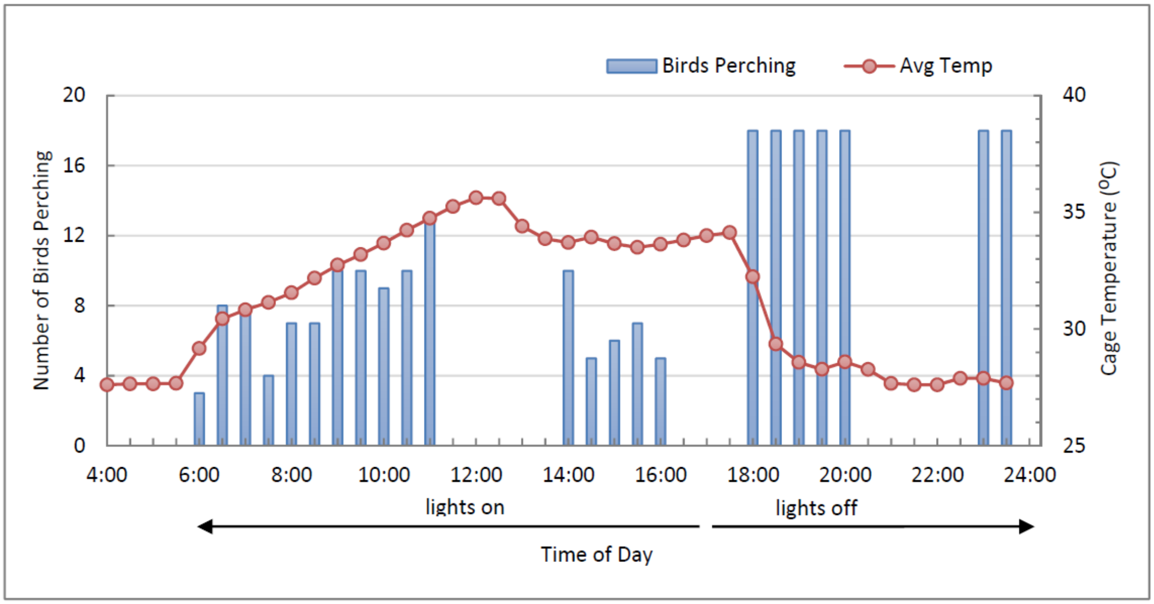


Figure 2.7: The usage of cooled perches by the laying hens exposed to chronic heat stress (Xiong et al., 2015).

Although the authors indicated that using water-cooled perches could minimise the effect of hot weather on the birds, it is still difficult to commercially apply water cooled perches as heat stress relieve technique. The reasons being that; perches were designed for birds so that they can exhibit their natural behaviours like roosting (LeVan et al., 2000), to enrich the indoor environment, increase the usage of spaces above floor by birds, to increase birds' exercise level and for preventing subordinate birds from attacks (LeVan et al., 2000). It was reported by Gunnarsson et al. (2000) that roosting of birds on perches decreases as the age and body weight of birds (broiler chicken) increase. LeVan et al., (2000) indicated that with higher environmental temperature (above 20 °C), perching of broiler chicken decreased. Relatively, Estevez et al. (2002) indicated that broilers that were found using perches were those in the areas where there was higher airflow (better ventilation) compared to other locations within the broiler building and that the use of cool perches had no significant effect on final body weight of 6 weeks old broiler chickens. It is clear that using water-cooled perches to alleviate heat stress in broiler chicken during hot weather may not be an appropriate approach most especially in severe situations. The use of perches may be difficult for cooling broiler, due to limited availability of perches within the broiler houses, floor space and that all birds cannot utilise perches at the same time. It is therefore difficult to use the technique as a cooling method for improving broiler welfare and production during hot weather.

2.7.4 Ground source heat pump (GSHP)

GSHP, as a latest renewable energy technology, is used for heating and cooling of the indoor environment. This technique was recently identified as a means for heating and cooling indoor due to its efficiency in reducing greenhouse gases, energy insecurity and promoting sustainable development (Dincer, 2000; Islam et al., 2016; Kharseh and Nordell, 2011; Liu et al., 2015; Omer, 2008; Wang et al., 2012). GSHP depends on the ground temperature, which is higher than air temperature and lower than the air temperature during winter and summer respectively. The system consists of an earth to air heat exchanger which constantly stores thermal energy from the earth and transfer it through buried pipes and circulate the warm or cool air inside the building with a circulation system depending on the weather conditions (Esen and Yuksel, 2013; Ozgener et al., 2011). Its operational principle is that during summer periods, it transfers warm air out of the building into the ground and replace the warm indoor air with cool air from the earth and during winter, the operation changes as warm air is transferred into the building and cold air is extracted from the building (Liu et al., 2015).

In agricultural buildings, its application for heating and cooling has also been adopted. Some studies have shown its application in greenhouses (Esen & Yuksel, 2013; Ozgener & Ozgener, 2010a, 2010b; Ozgener et al., 2011) and livestock buildings (Choi et al., 2012; Islam et al., 2016; Wang et al., 2012). Kharseh & Nordell (2011) designed a ground source cooling system and tested its sustainability in providing a cool environment for broiler chicken in Syria. They reported that annual operation cost of heating and cooling of broiler shed was reduced by 62 % when GSHP was used to provide heating and cooling for broilers. Although this system has been shown to be highly effective in reducing greenhouse gases and energy consumption, its commercial application in broiler production, most especially in providing a cool environment for broilers during hot periods, may not be economically feasible as a result of its high initial investment (Wang et al., 2012). Another problem confronting the use of GSHP is that increase in ground temperature and the demand of birds for cooling can increase the energy consumption of the system (Kharseh et al., 2011) during hot weather periods.

2.7.5 Evaporative cooling systems (ECS)

ECS is the adiabatic humidification systems that utilise thermal energy from air to evaporate water leading to a reduction in indoor air temperature and increase in relative humidity (Barbari and Conti, 2009; Wang et al., 2008). ECS reduces the amount of sensible heat in the air through the evaporation process. As water evaporates, thermal energy from the surrounding air absorbs the water to cool the environment. Indoor air temperature is reduced by shifting sensible heat to latent heat and as a result increasing the indoor relative humidity (Wang et al., 2008; Xuan et al., 2012). Different evaporative cooling systems have been designed to control adverse effect of high indoor temperature during hot periods. Some of the systems are termed direct evaporative coolers, which include pad cooling system, surface wetting system, fogging and misting systems and they will be discussed in this part of the study.

2.7.5.1 Pad cooling system (PCS)

PCS has been widely used in the tunnel ventilated livestock buildings to effectively reduce indoor temperature most especially in hot and dried climatic condition areas (Kittas et al., 2003; Liao and Chiu, 2002; Tabler et al., 2013; Wang et al., 2008). The maximum cooling efficiency of PCS is determined by the level of relative humidity already present in the air, amount of water used and air flow rate (Dağtekin et al., 2009; Donald, 2000; Tabler et al., 2013). During hot periods, PCS provides cooling for livestock only when the already moisture present in the air is below 80 % (Tabler et al., 2013). As the air reaches saturation level, PCS becomes inapplicable as it lacks the ability to evaporate water due to higher relative humidity already present in the air. Furthermore, heat loss from birds depends on the level of air relative humidity inside the building that the birds breathe in. Birds lose heat through panting when the indoor air relative humidity (RH) is above 80 % and shift to sensible heat when air relative humidity decreases (Czarick and Fairchild, 2009; Tabler et al., 2013). To cool birds during hot periods, fans and PCS are controlled to ensure maximum airflow over birds. Inadequate air velocity at birds level in a building fitted with PCS can cause birds to depend on panting instead of sensible heat transfer, through high air movement, due to higher RH (Tabler et al., 2013). Higher air velocity in poultry buildings fitted with PCS is required as it increases the amount of heat loss from birds to the surrounding air and reduces the dependence of birds on latent heat (Czarick and Fairchild, 2009; Tabler et al., 2013) during hot weather conditions.

Although PCS can be effective in minimising the indoor air temperature in livestock buildings, it has also been shown to have some limitations hindering its application, as a means of supplementary cooling, for birds worldwide. One of the limitations is that it increases indoor relative humidity. It was reported that higher indoor RH causes birds to shift from losing heat through the sensible heat to latent heat (Wang et al., 2008; Xuan et al, 2012) and that it increases the heat stress in birds (Tabler et al., 2013). There has been an indication that the static pressure that the mechanical fans work against in poultry building increases with the installation of PCS. It was reported that with PCS, the mechanical fan performance was reduced by 3 % as a result of the increase in static pressure that the fans were forced to work against (Czarick and Fairchild, 2013). Another limitation is that the use of PCS could result in a decrease in the amount of air velocity along the length of poultry building. Czarick & Fairchild (2013) showed that the air velocity in the poultry house decreased by about 0.1 m s^{-1} when the building was fitted with a cooling pad. An important factor is the capital involved in the use of PCS. PCS are highly expensive to maintain as they require constant cleaning, pad replacement and large water volume for them to be highly efficient (Chepete and Xin, 2000; Czarick and Fairchild, 2013). Since PCS is mostly useful in hot and dried climatic areas (Barbari and Conti, 2009), its application in the highly humidified regions of the world is limited. If used to cool birds in such regions, it will only increase indoor RH, hindering birds from cooling itself by evaporative heat loss through panting (Genç and Portier, 2005; Liang et al., 2014), and this can lead to higher heat stress in birds.

2.7.5.2 Surface wetting system (SWS)

Surface wetting is an evaporative cooling system in which water, in form of droplets, is applied directly to animals to convert sensible heat transfer to latent heat (Tao and Xin, 2003d). Surface wetting gives room for dried air ventilation as water is directly sprinkled on animals and not into the air to provide direct cooling for the animals. It requires less capital (in terms of equipment and installation) and can also be operated at a very low pressure (Tao and Xin, 2003d). The quest for providing a cool environment for livestock has led to the advent of SWS within the last few decades. Pad cooling systems were found to be very expensive, inhibit high air velocity, increase static pressure and also increase indoor relative humidity. Due to all the factors militating against the use of pad cooling systems, a surface wetting method that involves the use of less amount of water (Liang et al., 2014) for providing a cool environment for livestock was adopted. This system involves the use of sprinklers to spray water on livestock body surfaces during extremely hot conditions to cool them so as to prevent heat stress in livestock. SWS has been shown to be cost-effective and easy to retrofit into an existing livestock building with minimal alteration on the building (Yanagi et al., 2002).

It is a technique that has widely been used in the livestock production to abate heat stress during hot weather condition. It has been used in cattle (Berman, 2010, 2008; Brouk et al., 2003; Brown-Brandl et al., 2010; Gebremedhin and Wu, 2002, 2001; Mader et al., 2007; Mader and Davis, 2004; Nienaber and Hahn, 2007), pigs (Banhazi et al., 2009; Huynh et al., 2006, 2005) and poultry productions (Chepete and Xin, 2000; Ikeguchi and Xin, 2001; Liang et al., 2014, 2012, 2010, Mutaf et al., 2009, 2008; Tao and Xin, 2003d). Studies have shown that the application of surface wetting could effectively relieve animals of heat stress and also assist them to cope with thermal challenges (Mutaf et al., 2009; Tao and Xin, 2003d), increase animal production (Mutaf et al., 2009), reduced mortality and have also improved animal welfare.

Chepete & Xin (2000) intermittently sprinkled 8000 mm^3 of water on laying birds exposed to about 40 °C air temperature, 45 % RH and 0.15 - 0.20 $m\ s^{-1}$ air velocities at an interval of 15 minutes. They reported that the use of SWS reduced body temperature, prolonged survival time and reduced mortality of laying birds. They recommended that spraying interval should be reduced to 5 or 6 minutes in order to adequately cool birds when exposed to extremely hot conditions. In a study conducted by Ikeguchi & Xin (2001) and Mutaf et al. (2008, 2009), the efficacy of intermittent surface wetting of laying birds to provide cooling when air temperature exceeds 30 °C was evaluated. Ikeguchi & Xin (2001) reported that intermittent SWS significantly increased egg production by 3 % but had no effect on the egg quality while Mutaf et al. (2008, 2009) reported that SWS significantly reduced surface temperatures (body, head and dorsal) of laying hens exposed to different thermal conditions.

Wolfenson et al. (2001) tested the ability of SWS on providing ventral cooling (on ventral regions) for heat-stressed laying hens in naturally ventilated laying hens building. They reported that the usage of surface wetting for cooling birds ventrally was an efficient method for alleviating birds for heat stress during hot spell periods. Yanagi et al. (2002) and Tao & Xin (2003) optimised SWS by quantifying the amount of water required by the system and the spraying interval. They also developed empirical equations relating spraying interval to indoor conditions for effective cooling of laying birds and broiler chickens respectively during hot periods. Tao & Xin (2003) reported that higher air movement coupled with SWS is very important in order to effectively relieve broiler chickens of heat stress. Liang et al. (2014) compared the cooling efficiencies of PCS and SWS in commercial tunnel-ventilated broiler building during summer periods. They reported that buildings with SWS had higher indoor temperature compared to PCS but relative humidity was substantially reduced in the building with SWS. SWS was found to be more economical in terms of water usage. However, there were no significant differences in live body weight of broilers and litter moisture content.

Though SWS has been reported to be highly effective in providing a cool environment for birds, less expensive and can be easily retrofitted into an existing poultry building, there are challenges hindering its application in deep litter broiler buildings and in the high humid regions. There have been indications that if there are no adequate air movement, the efficiency of SWS could be impaired (Brouk et al., 2003; Collier et al., 2006; Purswell et al., 2013). Another problem created by SWS is the increase in litter moisture level. Higher litter moisture level promotes higher production of Salmonella and Escherichia coli (De Rezende et al., 2001) and other microorganisms, favours the production and release of ammonia and also encourages the widespread of diseases (Homidan et al., 2003; Sethi & Sharma, 2007). Its application in real life situation is still difficult. Getting the exact sprinkling rate and spraying intervals are serious challenges. There is inconsistency in spraying intervals and spraying dosages in all the studies (Chepete and Xin, 2000; Ikeguchi and Xin, 2001; Tao and Xin, 2003d; Yanagi et al., 2002) reported on surface wetting.

2.7.5.3 Fogging and misting systems (FMS)

FMS is an evaporative cooling system that operates on the principle of using the sensible heat in the air to evaporate water directly in contact with it and therefore reduce the indoor temperature and increase indoor RH (Shanmugavelu et al., 2000). It provides cooling by misting the air inside livestock building with higher pressure nozzles to enhance heat and mass transfer of water and the surrounding air (Arbel et al., 2003; Chepete and Xin, 2000; Haeussermann et al., 2007b). The efficiency of FMS is influenced by the rate of ventilation and the mist droplet size (Shanmugavelu et al., 2000). For instance, there may be no significant drop in air temperature if the ventilation rate is high. This was reported to have occurred as a result of the short contact time between the air and evaporated water when ventilation rate is very high (Shanmugavelu et al., 2000).

Studies have investigated the use of FMS as a cooling system for alleviating heat stress in livestock. Shanmugavelu et al., (2000) evaluated the effect of misting on the performance of male broilers. Haeussermann et al. (2007a) investigated the cooling effect of the fogging system on experimental piggery. Panagakis & Axaopoulos (2006) used simulation to compare the efficacy of evaporative pads and fogging system to reduce the indoor air temperature. They reported that evaporative pads showed better performance due to small daily air temperature, higher reduction in heat stress intensity and low water consumption by animals compared to the fogging system. Bridges et al., (2003) assessed the advantages of using misting-cooling systems for pigs based on the environment and the pig placement date. Ju & Lin (2006) evaluated the effect of an evaporative fraction of a misting system in a naturally ventilated broiler building. Haeussermann et al. (2007b) evaluated the control strategies of fogging systems in swine buildings. They have all reported that indoor air temperature was substantially reduced when the fogging system was used for providing cooling for livestock.

Most of the research studies on the application of fogging systems have been on other livestock and very few on broilers as there are limited reports available as related to broiler housing. However, despite its usage, there have been reports about the problems fogging system might create if used in broiler buildings. The use of fogging and misting systems in poultry production can result in higher indoor air relative humidity and litter moisture causing an increase in ammonia and carbon dioxide emission (Carey et al., 2004; Liu, Wang, et al., 2007; Ni et al., 2010) and bacterial and fungal growth (Wadud et al., 2012).

2.8 Challenges with the existing cooling systems

Studies have shown that the energy requirement of tunnel ventilated broiler building is very high. This could mean that not all farmers would be financially capable to afford it. Similarly, it is majorly used in the tropical climates while its application in the temperate climatic zones is limited due to the fact that it is only suitable for hot weather conditions. This indicates that using it during cold conditions could result in subjecting the birds to wind chill. Similarly, it has been shown that cross ventilation system may not provide adequate air movement that could increase heat transfer from birds during hot periods. In both tunnel and cross ventilated broiler building, exhaust fans are located slightly above the ground floor. This could cause enviromental pollution and poor contaminant dispersion (AHDB, 2017). The ventilation system that is yet to be fully evaluated is the sidewall inlet and roof exhaust ventilation system. There is tendency for the performance of the system to be improved if fully optimised to provide adequate airflow in the broiler occupied zones during hot weather periods.

Supplementary cooling systems are very beneficial to broiler production. It is clear that these cooling systems can drastically reduce indoor temperature, surface temperature and heat production, maintain thermal comfort and productivity of broiler chickens during the summer period. However, there are some problems hindering the successful incorporation of these systems into the commercial broiler buildings. Some of the challenges are, high daily water consumption by the evaporative cooling system (Bucklin et al., 2015; Liang et al., 2010), evaporative cooling works better in regions with high outside temperature and low outside humidity (Bucklin et al., 2015; Tabler et al., 2013). The cost of maintaining evaporative cooling is high and running it for an extended period can cause algae to grow on the pads and reduce the effectiveness of the system (Tabler et al., 2013).

Furthermore, problems associated with the use of fogging and misting systems in broiler production have significantly reduced their usage in poultry production. It was noticed that running foggers in broiler building caused the humidity level to increase, resulting in high mortality. Increasing humidity makes it difficult for the birds to cool themselves and will give in to heat prostration irrespective of air movement of the mechanical fans (Tabler et al., 2013). Moreover, the higher the humidity, the more difficult it becomes to get the water droplets evaporated from the shed. Pulling out the fog outside the building by mechanical fans can cause air movement on the birds to decrease. With time, fan blades and shutters become wet, resulting in higher dust accumulation on mechanical fans and causing the airflow to reduce (Tabler et al., 2013). The cost of maintaining fogging systems is high just like that of the evaporative cooling system as it requires proper water filtration to avoid nozzle orifice clogging (Haeussermann et al., 2007b).

Other disadvantages of fogger are the deterioration of litter conditions. When litter is wet, possible problems that it can cause include, higher heat and ammonia emission (Tabler et al., 2013), challenges of bacterial and coccidial (Phibro Animal Health Corporation, 2013), the occurrence of footpad lesion (De Jong and van Harn, 2012). As regard misting system, the evaporative fraction of the droplets it produces is directly proportional to the indoor temperature and humidity. At higher temperature and low humidity, the evaporative fraction increased and vice versa (Berman, 2008). This in turns leaves the birds with additional moisture to overcome when the misting system is used in poultry production.

Considering the increase in the cost of broiler production as a result of a constant increase in the cost of feed, energy input and power requirement, it is vital to source for other possible ways through which birds can be cooled during the hot period at a minimal cost and at the same time improving broiler production and welfare.

2.9 Conclusion

In a recently published study, it was reported that fluctuating the airflow of mechanical fans produced more acceptable air movement than airflow produced by constant mechanical fans (Zhu et al., 2015). Studies have found out that airflow with β-value equals to $-{}^{5}/_{3}$, similar to that of natural wind, is suitable for providing desirable thermal comfort in an enclosed environment (Hua et al., 2012; Zhou et al. 2006; Zhu et al., 2005; Huang et al., 2012). In order to have air supply systems that can produce airflow with β-value equals to $-{}^{5}/_{3}$, some researchers have designed, developed and tested different dynamic air supplying devices with all having similar operation principles.

Jia (2000) developed a dynamic air supply terminal that produced airflow with β-value equals to $-{}^{5}/_{3}$ by controlling the fan and the rotational speed of a turntable (shunt valve). Zhou et al. (2006) fluctuated air velocity of an axial fan by sending time series signals to a fan motor controller (frequency converter) through a computer. Hua et al. (2012) developed a personalised natural wind fan to produce a simulated airflow by varying the speed of a brushless DC motor and the use of air deflector. Huang et al. (2012) controlled the fan speed by sending time series signals from a computer to a frequency converter and by controlling the opening size of a semicircular turntable to generate a sinusoidal airflow with variable fluctuation frequencies.

At present, limited information (Tao and Xin, 2003a) is available in the literature on the effect of airflow characteristics on the thermal comfort of broiler chickens. The effects of such airflow are well studied in the built environment, and the results have shown that it adequately improved thermal sensation and thermal comfort during hot periods (Hua et al., 2012; Zhou et al. 2006; Zhu et al., 2005; Huang et al., 2012). Presently in typical commercial broiler houses, only constant mechanical wind is available, and all indications have shown that with this airspeed, broilers are still experiencing heat stressed during hot weather periods.

A question needs an urgent answer. What are the plans of the poultry growers to overcome the negative effects of hot weather conditions on poultry birds? In 2003, it was reported by the BBC News that over 80,000 birds were killed by extreme hot weather condition in one of the UK poultry farms when air temperature went above 38 ºC (DEFRA, 2003). The possible cause of their death was linked to ventilation failure when investigated by DEFRA. A recent report by the NHS England has shown that there is a tendency for the UK to experience another extreme hot weather by the year 2040 because of climate change (NHS England, 2015). Though tunnel ventilation system could be employed, but its application is limited in the temperate zones due to higher energy consumption, and higher indoor relative humidity as a result of the incorporated evaporative cooling system. Therefore, there is a need to investigate alternative environmental control system that could be incorporated into the sidewall inlet and roof exhaust ventilation system for providing cool environment for birds during hot periods. Airflow fluctuation, based on the reports in the built environment, if integrated into the environmental control system of the sidewall inlet and roof exhaust ventilated broiler buildings could improve thermal comfort, welfare, health and production of broiler chickens during hot weather periods. In addition, improved ventilation in the broiler microclimate may allow broiler chickens to be housed in climatic conditions which are deemed too hot thereby improving birds’ distribution across the floor space.

CHAPTER THREE

FIELD EVALUATION OF MICROCLIMATE CONDITION WITHIN AN EXISTING SIDEWALL INLET VENTILATED BROILER BUILDING.

3.1 Introduction

Air velocity at the birds microclimate is mainly determined by the opening size of the inlet, air velocity at the inlet, inlet height above the floor, and the building geometry (Hoff, 1995; Jin & Ogilvie, 1992; Morsing et al., 2000; Strøm et al., 2001, 2002). In commercial broiler production, air velocity entering the building is mainly controlled by the static pressure within the building (Bustamante et al., 2013). It was reported by Czarick and Fairchild (2008) that static pressure higher than 25 Pa could cause a decrease in airflow into broiler building. They recommended that static pressure should be maintained between 12 and 25 Pa in order to increase airflow into the broiler building during hot weather periods. To achieve this static pressure, the inlet opening size should conform to the capacity of mechanical fans in operation. However, the efficacy of controlling airflow in the broiler building with static pressure was questioned by Blanes-Vidal et al. (2007) who indicated that the use of static pressure may not be an appropriate approach for increasing air movement around poultry birds raised under hot and humid climatic conditions.

During hot periods, farmers usually open the inlets and doors wide in order to improve indoor ventilation. This practice, as indicated in the literature (Albright, 1990; Czarick and Fairchild, 2008; Weaver, 2002) may not create a noticeable increase in air velocity in the bird occupied zones. Rather, it could ruin the capacity of the ventilation system to produce effective air movement in the birds occupied zones, resulting in poor air mixture and air distribution (Albright, 1990). Therefore, understanding the airflow characteristics (air velocity and turbulence intensity) within broiler building, with wide opened air inlets, is crucial when evaluating the ventilation efficiency and determining the thermal comfort of confined broiler chickens during hot weather periods.

In most commercial broiler buildings, ventilation systems are usually operated at full capacity (100 %) with bottom hinged sidewall inlet fully opened. The current practice of commercial broiler producers, in terms of the opening size of the inlet, has not been widely reported, most especially the sidewall inlet and roof exhaust ventilated broiler building. Most of the available information is on the cross ventilation and tunnel ventilation systems. it is expedient to investigate the indoor air velocity distributions within the empty and occupied sidewall inlet and roof exhaust ventilated broiler building to understand airflow variation as the distance increases toward the centre of the broiler building. As a result, this study was set up to identify the conditions under which broiler chickens are raised in the current commercial sidewall ventilated broiler buildings and how the conditions are related to the cooling capacity of the building. Therefore, the objectives of this study were (1) to evaluate the influence of wide opening of sidewall inlet on the air velocity within the sidewall inlet and roof exhaust ventilated broiler building; (2) to examine the impact of broiler chickens and indoor equipment on the air velocity distributions in the broiler occupied zones.

3.2 Materials and methods

3.2.1 Experimental broiler building

This study was conducted in an experimental broiler building situated in Harper Adams University, United Kingdom located on the latitude and longitude 52. 7795 º N and 2.4271 º W. The building was designed and developed for the experimental purpose and not for commercial broiler production. However, the building is similar to a typical commercial broiler building in terms of indoor equipment such as feeder, drinker lines, automation of inlet, heating system and a state-of-the-art ventilation system. Figure 3.1 shows the details of the experimental broiler building. The building comprises of 24 sidewall inlets of dimension 0.52 m by 0.21 m with 12 inlets on each sidewall of the building and five, equally spaced, mechanical fans of diameter 0.63 m attached to the roof of the building. This means that the experimental broiler building is ventilated by sidewall inlets and roof exhaust ventilation system. The inlets are bottom-hinged and the opening and closing of the inlets and the operation of the mechanical fans are mechanically controlled with a CLIMATEC environmental control system. The number of mechanical fans in operation depends on the ventilation requirement of the birds. During hot weather conditions, all the mechanical fans are fully operated with the bottom-hinged inlets widely opened to allow maximum air movement into the broiler building in order to provide cooling for the birds. The building also contains a heating system (propane gas burner) for warming up the building during cold periods and when the building is stocked with day-old chicks. There were drinking and feeding systems installed in the building.

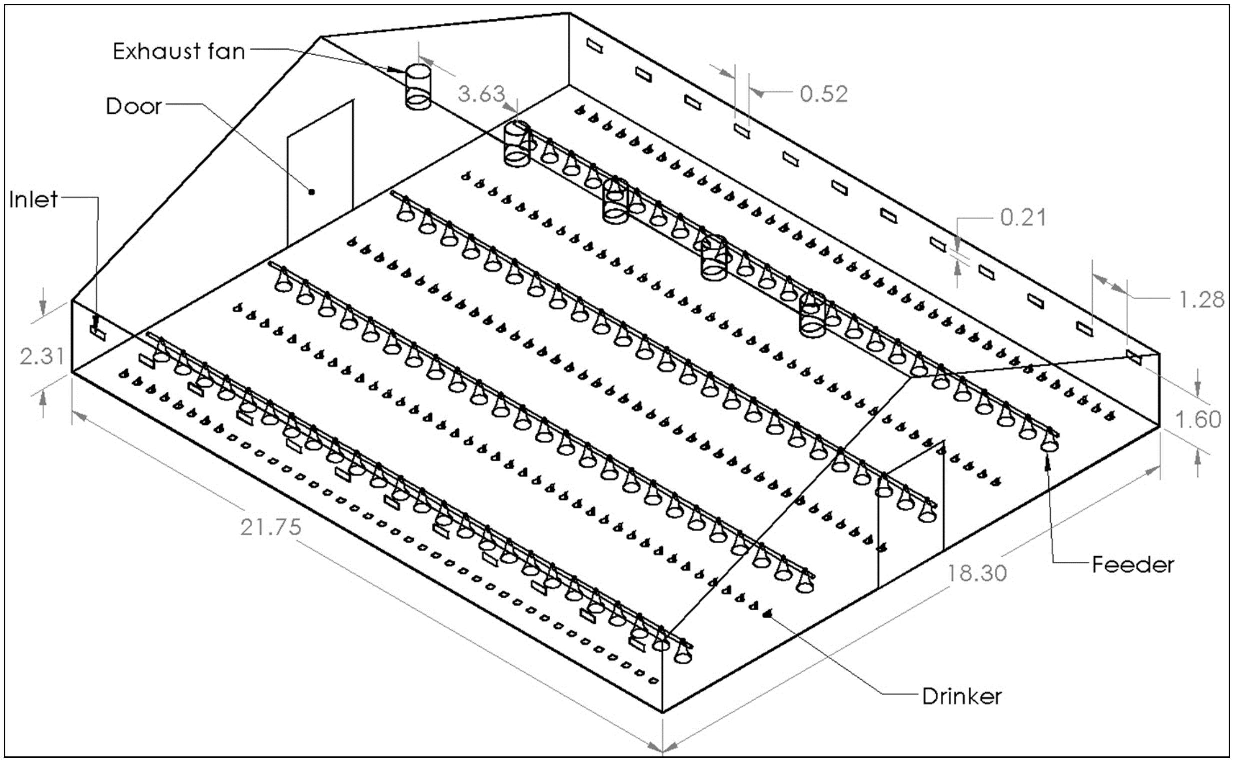


Figure 3.1: Schematic representation of a typical sidewall inlet and roof exhaust ventilated broiler building. All dimensions in metres

3.2.2. Airflow sensors

Four ultrasonic anemometers (WindMaster - Part 1561-PK-020), manufactured by Gill Instrument Limited, United Kingdom, were mounted on tripod stands and used for characterising the air flow within the experimental broiler building. The instruments operate on the principle that the speed of the sound pressure wave changes with the local air velocity. They are suitable for measuring air velocities ranging from 0 to 50 m/s. They have resolution of 0.01 m/s, accuracy of 1.5 % RMS at 12 m/s. In addition, the instruments have the capacity to sample air velocity components $(u_x, u_y \ and \ u_z)$ at 20 Hz (Gill Instruments Limited, 2016). All airflow measurements were logged with a WindView software supplied with the sensor into an HP ProBook 4540s laptop. WindView is a software that displays the data acquired by the anemometer, allows users to query airspeed data in an interactive environment and also enables the user to log the data from the anemometer (Gill Instruments Limited, 2015) on a PC. Figure 3.2 shows the airflow sensor set up at one of the measurement locations.

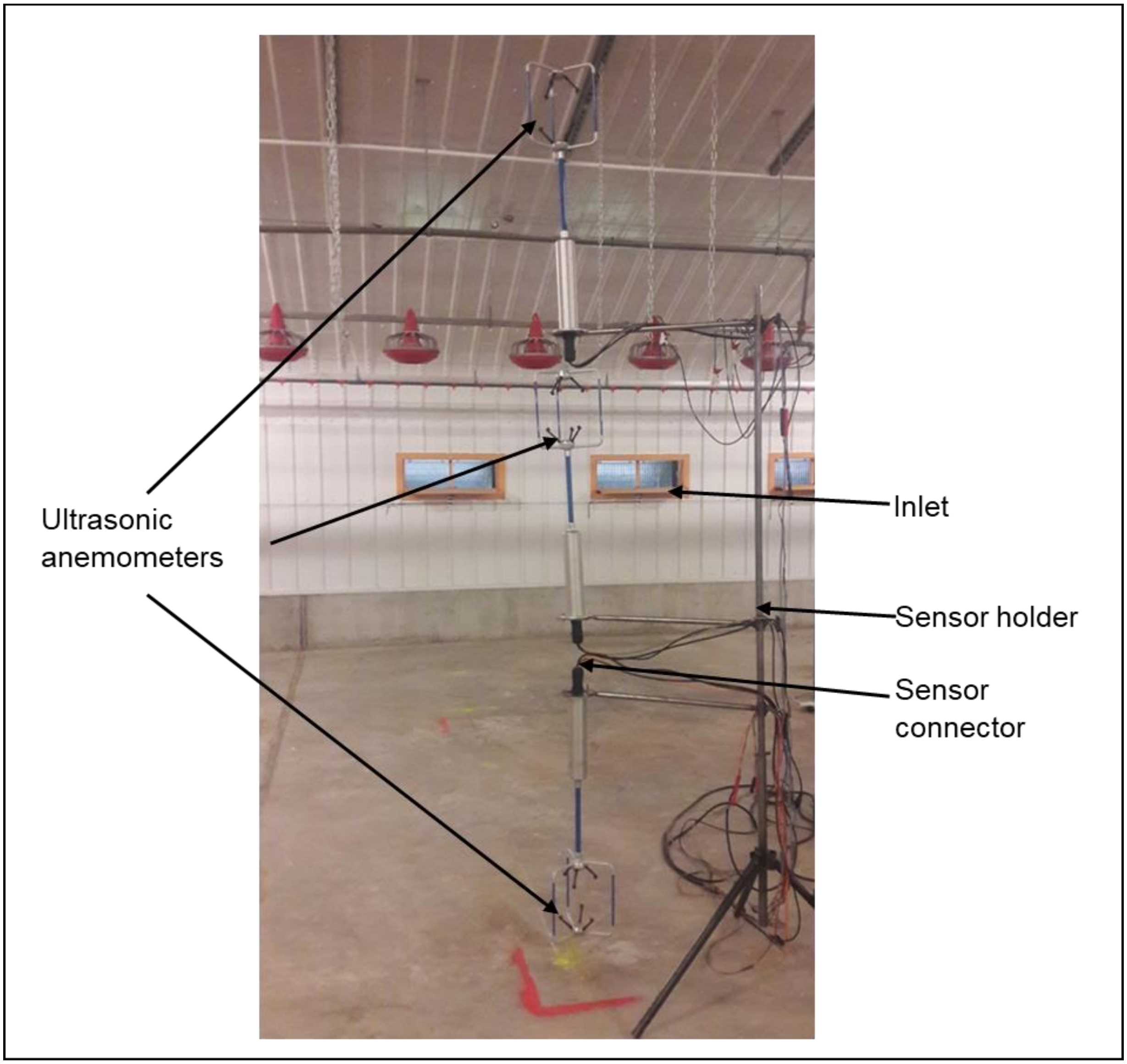


Figure 3.2: Airflow sensors set up at one of the measurement locations.

3.2.3. Airflow characterisation of the inlet of the experimental broiler building

Before the commencement of the study, the bottom-hinged air inlets of the experimental broiler building were fully opened and the five mechanical fans installed in the roof of the building were switched on and operated at 100 % capacity for 30 to 60 minutes to ensure maximum air circulation within the building and at all the measurement locations. This approach was adopted since it is the general method usually practised by the poultry meat producers (farmers) during the hot weather conditions so as to maximise airflow in the broiler occupied zones. The airspeed (m s^{-1}) at the inlet/ opening of the experimental building was measured with an uprightly positioned ultrasonic anemometer and logged with a WindView software on a laptop for a period of 10 minutes. As indicated by Demmers et al. (2000), airflow in the animal building could be conveniently obtained over an average period of 5 minutes. However, in this study, in order to capture all the variations in airflow, air velocities were measured over 10 minutes with the expectation that the airflow would have stabilised within the period. Figure 3.3 shows how the airspeed was acquired at the inlet of the experimental building.

Figure 3.3: Airspeed measurement at the air inlet of an experimental broiler building

3.2.4. Air velocity characterisation at different distances from the sidewall inlet

3.2.4.1. Empty experimental broiler building

Air velocities, within an empty experimental broiler building, were measured at different heights and locations at different distances from the sidewall inlet. In this study, measurements were obtained at the heights 0.2 m (an average broiler's height), 1.70 m (similar to inlet height) and 2.55 m (almost eave height) above the floor. In order to quantify air velocities as the distance from the sidewall inlets increase towards the centre of the broiler building, airflow sensors were placed at 1, 3, 5, 7and 9 m from the sidewall. The heights were selected to evaluate the variations in air flow characteristics with different heights, while different distances were selected to evaluate heterogeneity in air velocity distributions as the distance from the sidewall inlets increases. Figure 3.4 shows the measurement heights and measurement locations in an empty broiler building. Air velocity components acquired through the airflow sensors were logged with a WindView software into a laptop over a period of 10 minutes. It is important to note that this study was primarily set up to examine the air velocity distributions in the broiler microclimate and not air distributions in the entire space within the broiler building.

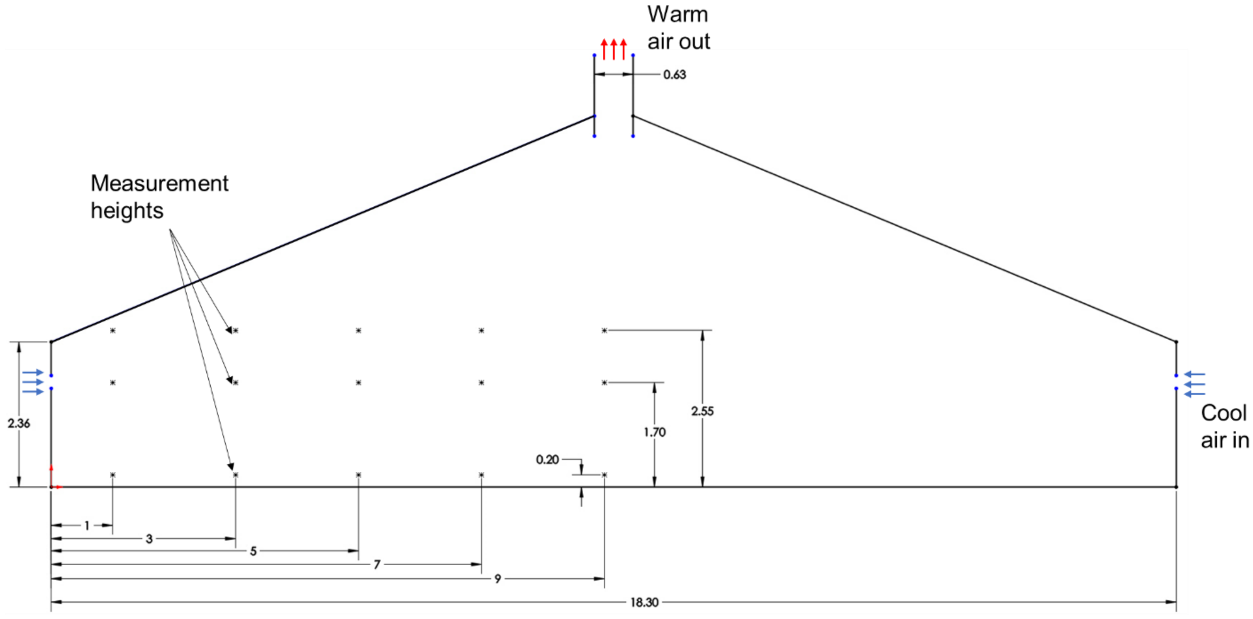


Figure 3.4: The broiler building showing the measurement heights above the floor. All measurements are in metres.

3.2.4.2. Experimental broiler building occupied with broiler models

A study was also set up to evaluate air distribution in the broiler occupied zones within the experimental building when occupied with broiler models. An area of 20 m^2 (10 m long and 2 m wide), in a section of the experimental broiler building, was filled with wood shavings of 0.05 m thickness, plastic footballs, suspended drinkers and plastic feeders. Considering the uncertainties that may arise during a research study, it is difficult to carry out an experiment directly with livestock. As a result, researchers have resulted in using inanimate objects to represent livestock. Plastic footballs were used as broiler chickens as they have been shown to have a characteristic dimension (diameter) similar to that of broiler chickens (Li et al., 2016). The use of broiler models were necessary in order to prevent live broiler chickens from pains, anxiety, suffering and emotional distress during the research studies (Conlee et al., 2009). In addition, since footballs are spherical in shape, they were considered appropriate to replace live broiler chicken in this study. The feeders were placed on the floor and drinker lines were positioned at 0.3 m above the floor. The feeder lines were randomly situated at 2.0 m, 4.0, 6.5 and 8.0 m from the sidewall while the drinker lines were randomly positioned at 3.4, 4.5 and 7.5 m from the wall. The arrangement of the feeders and the drinkers during the study was consistent with the standard practice in typical commercial broiler building.

To prevent poor welfare of broiler chickens a maximum stocking density of 33 kg m^{-2} was set by the European Commission with the expectation that minimum environmental conditions, required by broiler chickens, are provided (Butterworth et al., 2016; European Commission, 2016). In this study, a stocking density of 33 kg m^{-2} of broiler models (plastic footballs) was used to evaluate the impact of broiler chickens on air distribution in the broiler occupied zones. In the commercial broiler production, an average adult broiler chicken of 42 days old is expected to weigh 2.0 to 3.0 kg (Gates et al., 2008). A characteristic dimension with respect to body weight ($M_{chicken}$) of poultry birds ($D_{poultry} = 0.131 \times {M_{chicken}}^{0.33}$) was developed by Mitchell (1930). Based on the equation, an average adult broiler chicken of 2.6 kg was estimated to have a characteristic dimension (diameter) of 0.18 m. All plastic footballs were inflated until their size reached a diameter of 0.18 m and were used as broiler models.

During this study, air velocities in the broiler occupied zones were measured with ultrasonic anemometers at a height of 0.20 m above the floor (the broilers' microclimate). To evaluate air velocity distributions as the distance from the sidewall inlet increases, ultrasonic anemometers were inverted and positioned at different distances 1, 3, 5, 7 and 9 m away from the sidewall inlet. The sensors were inverted because the height at which the measurements were made was lower (0.20 m) than 1 m above the floor. The manufacturer of the sensors recommended that the sensors should be inverted if the measurement height is lower than 1 m above the floor or upright if the measurement height is above 1 m above the floor. Figure 3.5 shows the experimental set up in the occupied broiler building.

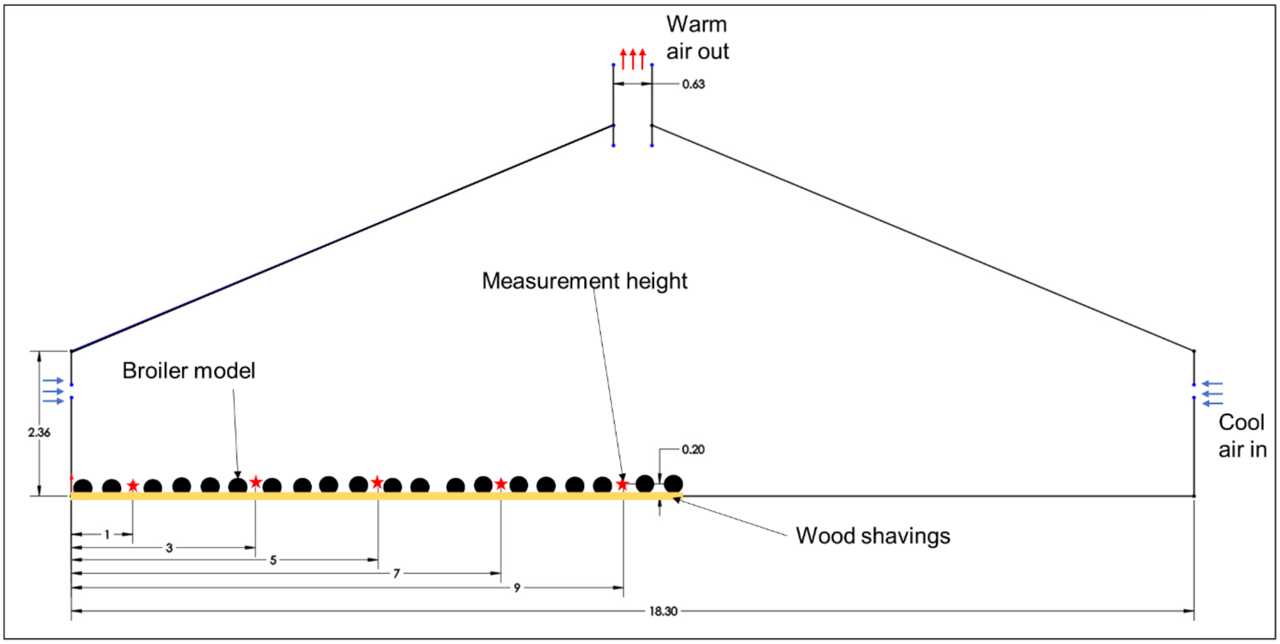


Figure 3.5: The experiment in the occupied broiler building showing the cross-sectional view of the experimental building and measurement height. All measurements are in metres.

3.2.5 Experimental design and data analysis

For the study in the empty broiler building, a 5 x 3 factorial experimental design was adopted. This involved five distances (1, 3, 5, 7 and 9 m) from the sidewall inlet and three heights (0.20, 1.70 and 2.55 m) above the floor. The measurement heights were considered to evaluate vertically, the airflow disparity at difference locations from the sidewall inlets. For the study within an occupied broiler building involving broiler models, stocked at 33 kg m^{-2}, airflow measurements were obtained at five distances and at 0.20 m above the floor. In each of the studies, measurements were repeated three times. This shows that in an empty building, there were 45 experimental observations while in an occupied building, there were 15 experimental observations.

The data obtained from the studies were processed with MATLAB software using equations 1 to 6 in Chapter two. The data analysis was conducted using JMP software from SAS (JMP 14). The data from the empty and occupied broiler building were subjected to ANOVA and t-test respectively. In addition, multiple comparisons, using Tukey-Kramer HSD, were conducted to compare the means of air velocity at different heights and distances. All analyses were performed on $p < 0.05$ level of significance**.**

3.3 Results and discussion

3.3.1 Characterisation of inlet airflow

Table 3.1 shows the airflow characteristic of the sidewall inlet of an experimental broiler building. As indicated in Table 3.1, an average airspeed at the inlet of the building, when the inlets were fully opened and the five roof mechanical fans were in 100 % operation capacity, was 4.91 m s^{-1}. The average turbulence intensity generated by the ventilation system of the building was 0.1. In typical broiler building, studies (Bustamante et al., 2013; Li et al., 2016b) have also indicated that turbulence intensity at the inlet region of broiler building is not more than 0.1 (10 %). The inlets of broiler building are usually covered with gauge wire mesh to protect enclosed birds from predators and wild birds (UMass Extension, n.d.) that could transmit diseases to the birds. However, some studies have also shown that using screens or grids at the inlets could cause a decrease in the turbulence intensity. Groth and Johansson (1988) reported a 5.5 % reduction in turbulence intensity at the region covered with a screen in a wind tunnel. Passive grids, such as the type used in poultry buildings, are limited to a turbulence intensity of 0.1 (Coppola and Gomez, 2009). Similarly, a study conducted by Bartzanas et al. (2002) indicated that the use of screen at the inlet of a greenhouse caused a 50 % decrease in airflow rate and over 100 % increase in indoor temperature within the greenhouse compared to the greenhouse without screen. There is a possibility that grids at the inlet of broiler building have suppressed the turbulence intensity to an average of 10 %.

Table 3.1: Airflow characteristics at the inlet of a sidewall inlet and roof exhaust ventilated broiler building. $\bar{u}_x$, $\bar{u}_y$ and $\bar{u}_z$ represent the velocity components, $\sigma\bar{u}_x$, $\sigma\bar{u}_y$ and $\sigma\bar{u}_z$ are the standard deviations of the velocity components, $\bar{u}$ is the mean airspeed, σ is the standard deviation of the airspeed magnitude and Ti is the turbulence intensity

Mean airspeed (m s^{-1})								Turbulence intensity
$\bar{\boldsymbol{u}}_{\boldsymbol{x}}$	$\bar{u}_y$	$\bar{u}_z$	$\sigma\bar{u}_x$	$\sigma\bar{u}_y$	$\sigma\bar{u}_z$	$\bar{u}$	σ	Ti
-4.402	2.147	-0.281	0.784	0.494	0.445	4.906	0.400	0.082

3.3.2 Airflow characterisation at different locations from the sidewall inlet of an empty broiler building

Figure 3.6 shows the mean air velocities obtained at the broiler level (0.2 m), 1.70 m and 2.55 m above the floor. As shown in Figure 3.6, the mean air velocities at the broiler occupied zones at distances 1 and 3 m from the sidewall differ from that measured at 1.70 m and 2.55

m above the floor while the air velocity measurements at distances 5 m to 9 m from the sidewall inlets are similar. The differences are more pronounced in the areas very close to the sidewall inlets (1 and 3 m from the sidewall). The highest (0.91 m s^{-1}) and minimum (0.26 m s^{-1}) mean air velocities at 1.70 m and 0.20 m respectively were obtained at the region closer to the inlet (1 m from the inlet). A similar result was reported by Bjerg et al. (2002) who indicated that airflow in the animal occupied zone at the areas nearer to the sidewall is usually less than that obtained at other areas away from the sidewall. However, as the distance from the sidewall inlet increases, there is a clear indication that the airflow at heights 1.70 and 2.55 m above the floor lost it energy and began to decrease while airflow at the broiler level (0.2 m) gained momentum and increased to 0.40 m s^{-1} at 5 m away from the sidewall inlet and finally dropped to 0.38 m s^{-1} at the centre of the broiler building (9 m away from the sidewall inlet).

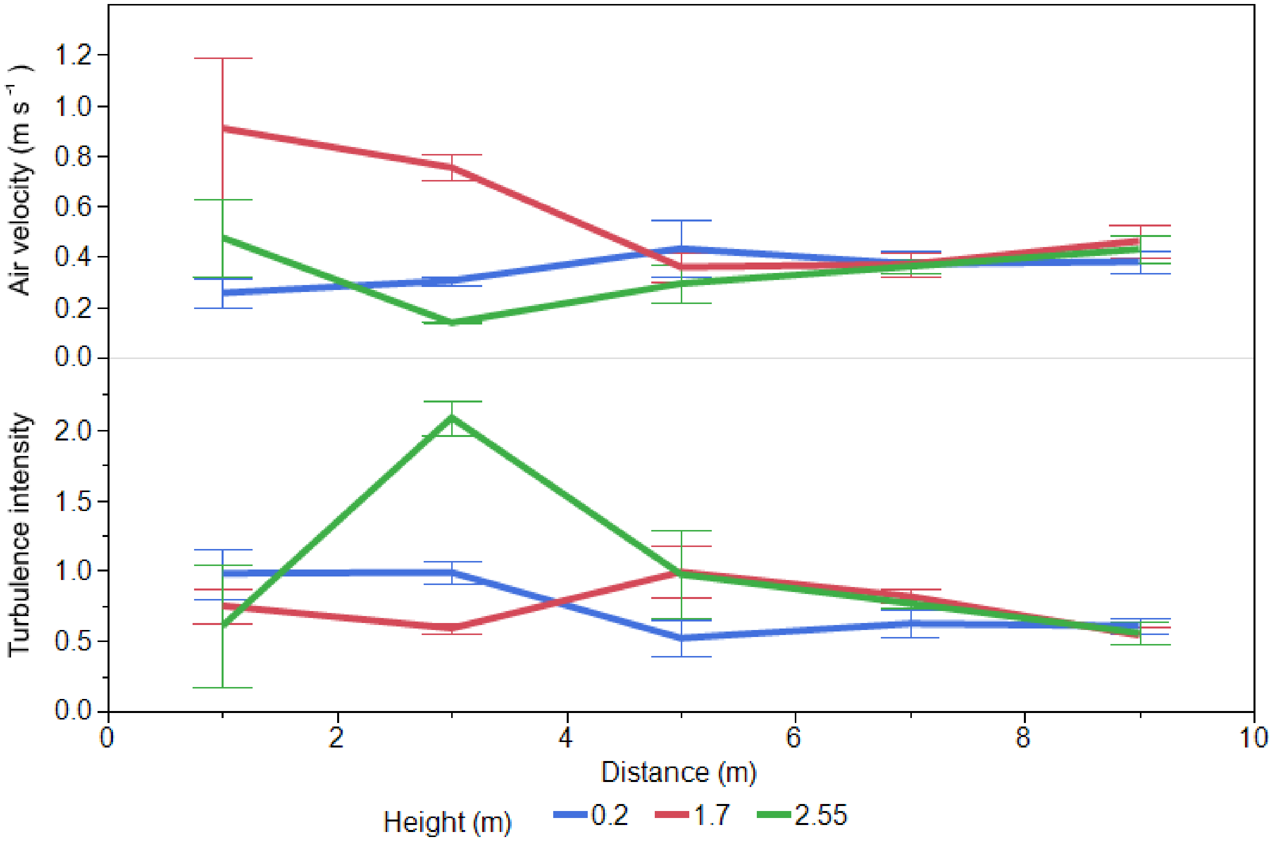


Figure 3.6: Mean air velocities and turbulence intensities at Broiler height (0.20m), 1.70 m and 2.55 m above the floor at distances 1, 3, 5, 7 and 9 m away from the sidewall.

Air velocity at 1.0 m away from the sidewall in the broiler occupied zone is lower than that at the centre (9 m) of the building. This corresponds with the result of Blanes-Vidal et al. (2007) who reported that air velocity at the centre of an environmentally controlled broiler building was significantly higher than the air velocity obtained very close to the inlet wall. The decrease in air velocity at the areas closer to the sidewall could be attributed to the wall barrier due to the height of the inlet above the floor. Similar results have been reported in some studies that air velocity in the animal occupied zones is determined by the building configuration, inlet opening size and the height of inlet above the floor (Jin and Ogilvie, 1992; Ogilvie et al., 1990).

Although higher airspeed (4.91 m s^{-1}) was produced at the sidewall inlet, lower air velocities, ranging from 0.25 to 0.43 m s^{-1}, were recorded at broiler occupied zones. This indicates poor air velocity distribution within the broiler building despite the fact that sidewall inlets were fully opened to allow a higher volume of airflow into the building. This finding supports the report of Albright (1990) who indicated that opening inlet widely would not produce noticeable air movement in the animals occupied zones and that ventilation capacity could be affected, causing the poor distribution of air velocity at the level of the animal. From Figure 3.6, it could be seen that as the distance increased towards the centre of the building, the mean air velocity in the broiler occupied zone first increased to 0.43 m s^{-1} at 5 m from the sidewall before dropping to 0.38 m s^{-1} at the centre of the broiler building. Other studies (Norton et al., 2007; Shklyar & Arbel, 2004) have shown that air velocity at the centre of livestock building is usually lower than other regions within the livestock building.

Figure 3.6 also illustrates the turbulence intensity at the heights of 0.2, 1.7 and 2.55 m above the floor and at the distances 1, 3, 5, 7 and 9 m from the sidewall. In Figure 3.6, the turbulence intensity at the broiler level (0.20 m) is 0.98 at 1 m from the wall while at 5 m from the sidewall, it is 0.52. At the centre of the building, the turbulence intensity, as shown in Figure 3.6 is 0.61. At 1.70 m above the floor, turbulence intensity decreased from 0.75 at 1 m to 0.59 at 3 m from the wall. It increased to 0.99 at 5 m from the wall and decreased to 0.54 at the centre of the building. At 2.55 m above the floor, turbulence intensity was found to increase from 0.61 at 1 m to 2.09 at 3 m from the sidewall. As the distance increased further towards the centre of the building, the turbulence intensity at height 2.55 m above the floor dropped to an average of 0.56 at the centre of the building. Generally, Turbulence intensities within the building were found decreasing as the distance increases towards the centre of the broiler building. Previous studies (Kozioł et al., 2017; Liu et al., 2004) have also indicated that turbulence intensities decreased at the downstream with an increase in distance. The decrease in turbulence intensity with respect to the distance could be linked to the decrease in its kinetic energy and energy dissipation as the distance of travel of incoming air jet increases towards the centre of the building (Heber et al., 1996). Another noticeable effect is the effect of mean air velocity on the turbulence intensity. According to Airflow Instruments

(2008), there is a possibility that the low air velocity in the broiler occupied zones had contributed to the large mean airflow fluctuation. Therefore, the higher turbulence intensity recorded in this study was as a result of very low air velocity obtained in the broiler occupied zones. A similar result has also been reported in the literature (Airflow Instruments, 2008; Xia et al., 2000).

The result of the one-way ANOVA, as shown in Table 3.2, indicated that there was a significant difference in the mean air velocities between the three heights (0.2, 1.7 and 2.55 m) above the floor at 1 m and 3 m away from the sidewall. However, the results of the analysis did indicate that at distance 5 m to 9 m from the sidewall, there was no significant difference in the mean air velocities between the heights (0.2, 1.7 and 2.55 m) considered. Furthermore, a multiple comparisons test, using Tukey-Kramer HSD, was conducted to compare each pair of the means of air velocities at heights 0.20, 1.7 and 2.55 m above the floor at distance 1 to 9 m from the sidewall. The result of the multiple comparisons indicated that there was no significant difference in the mean air velocity between three heights at 5 m to 9 m from the sidewall. However, there was an indication that the mean air velocities at 3 m from the sidewall were significantly different from one another at all the heights considered. The results of Tukey-Kramer HSD at 1 m from the sidewall indicated that there was a significant difference in the mean air velocities between the heights 0.20 m and 1.70 m above the floor.

The results of the one-way ANOVA conducted on the turbulence intensity at the heights 0.2, 1.7 and 2.55 m above the floor and at 1, 3, 5, 7 and 9 m away from the sidewall are shown in Table 3.2. It could be observed in Table 3.2 that it is only at a distance of 3 m away from the sidewall that the analysis indicated that there was a significant difference in the mean turbulence intensities between the heights 0.2, 1.7 and 2.55 m above the floor. At all other locations from the sidewall, the results of the one-way ANOVA indicated that there was no significant difference in the mean turbulence intensities between the heights 0.2, 1.7 and 2.55 m above the floor. Similar results were indicated by the multiple comparisons test that was conducted with Tukey-Kramer HSD.

Table 3.2: Mean air velocity (m s^{-1}) and turbulence intensity within an empty broiler building. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the measurement heights (0.20, 1.70 and 2.55 m) according to Tukey-Kramer HSD at a 5 % level of significance.

Distance (m) from the sidewall	**Mean air velocity (m s^{-1}) at different heights (m)**			**P- value**	**Turbulence intensity at different heights (m)**			**P- value**
	0.20	1.70	2.55		0.20	1.70	2.55	
1	0.26^{B}	0.91^{A}	0.48^{AB}	0.0145	0.98^{A}	0.75^{A}	0.60^{A}	0.3275
3	0.31^{B}	0.75^{A}	0.14^{C}	< 0.0001	0.99^{B}	0.59^{C}	2.09^{A}	< 0.0001
5	0.43^{A}	0.36^{A}	0.29^{A}	0.2216	0.52^{A}	0.99^{A}	0.97^{A}	0.0684
7	0.37^{A}	0.37^{A}	0.36^{A}	0.9592	0.62^{B}	0.81^{A}	0.76^{AB}	0.0364
9	0.38^{A}	0.46^{A}	0.43^{A}	0.2615	0.61^{A}	0.54^{A}	0.56^{A}	0.4747

3.3.3 Broiler building occupied with broiler models.

Figure 3.7 shows the mean air velocities and turbulence intensity obtained at the broiler level (0.2 m) when exposed to airflow from a widely opened sidewall inlet with the mechanical fans in full operational capacity. At all measurement locations, mean air velocities varied from 0.05 to 0.18 ms^{-1}. Raising live broiler chickens in an environment with lower air velocity can be detrimental as birds can be heat stressed. Blanes-Vidal et al. (2007) have also shown that environmental conditions under which broiler chickens are raised during the summer period are not appropriate as mean air velocity is generally low and non-uniform. The adverse effect of lower air velocity (poor ventilation) within the building is that birds are found migrating from the areas with poor ventilation to another region with better air movement, resulting in high mortality (Tabler et al., 2002).

As shown in Figure 3.7, air velocity increased from 0.05 m s^{-1} at the inlet area (1 m from the sidewall) to 0.18 m s^{-1} as the distance increases to 3 m. Air velocity later dropped to 0.13 m s^{-1} at 5 m and remained almost constant up to the distance 7 m from the wall. At 9 m (centre of the broiler building), air velocity can be seen dropping to 0.05 m s^{-1}. At all the measurement locations, there is a wide variation in the air velocity measured as shown by the error bars in Figure 3.7. This might have happened as a result of the effects of the broiler models (plastic footballs) on the air movement at the broiler occupied zones (Bjerg et al., 2000; Fiedler et al., 2013; Smith et al., 1999). This simply means that broiler models, closer to an air source, deflected airflow in the broiler occupied zones upward and variably resulted in wide variations in air velocity.

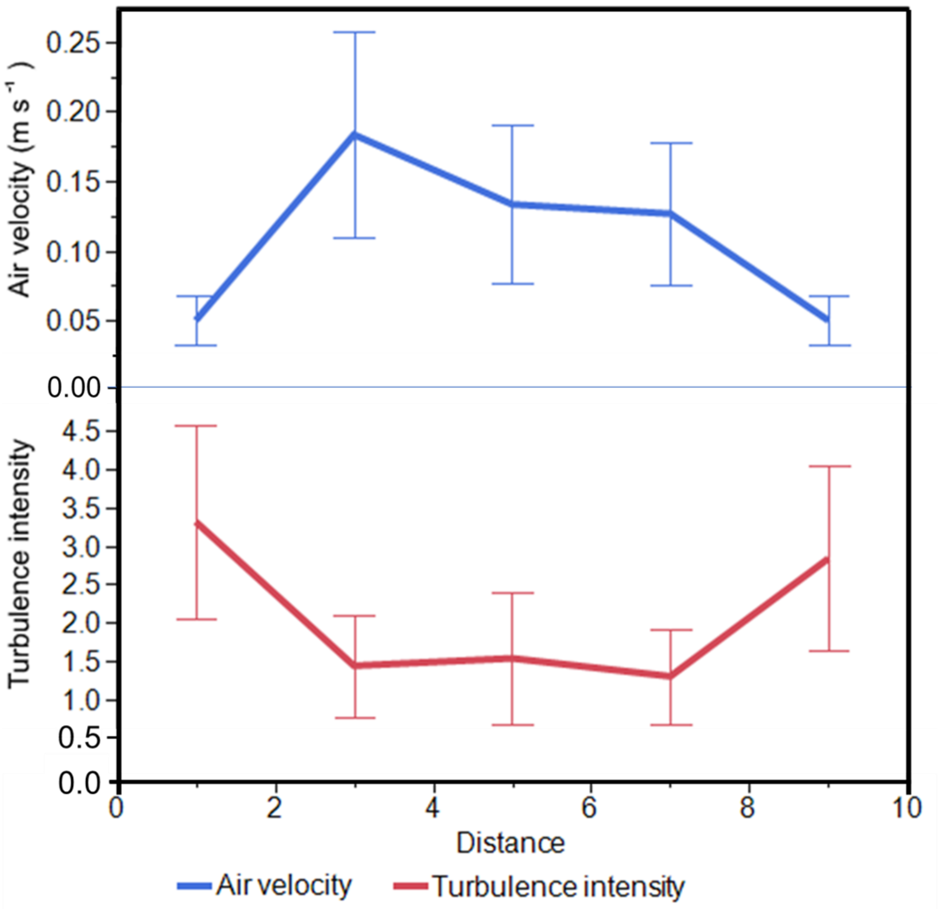


Figure 3.7: Mean air velocities at the broiler height (0.20m) with respect to distance in the broiler building with broiler models.

The turbulence intensities at the measurement locations were also determined. Higher turbulence intensities ranging from 1.31 to 3.31 were obtained at all the locations. The minimum turbulence intensity (1.31) was obtained at 5 m from the sidewall while the highest turbulence intensity (3.31) was obtained at the area very close to the sidewall (1 m). Higher turbulence intensities at the inlet area and the centre of the building were as a result of the lower air velocity (0.05 m s^{-1}) at the regions. As indicated by Xia et al. (2000), turbulence intensity increased as the air velocity decreased. Similar to mean air velocity, turbulence intensities can be seen to also vary widely at all the measurement locations. This study in conjunction with the findings of Smith et al. (1999) has shown that broiler chickens, feeders and drinker lines can act as an obstruction to airflow in an occupied broiler building. As shown in Figure 3.7, the presence of broiler models, feeders and drinker lines have been shown to cause the increase in the turbulence intensity in their occupied zones and the decrease in the air velocity.

Table 3.3: Mean air velocity (m s^{-1}) and turbulence intensity within the broiler building occupied with broiler models. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the measurement locations (1, 3, 5, 7 and 9 m) according to Tukey-Kramer HSD at a 5 % level of significance.

Distance (m) from the sidewall	**Mean air velocity (m s^{-1}) at the broiler level**	**Turbulence intensity at the broiler level**
1	0.05^{B}	3.31^{A}
3	0.19^{A}	1.44^{A}
5	0.13^{AB}	1.54^{A}
7	0.13^{AB}	1.31^{A}
9	0.05^{B}	2.84^{A}
P- value	0.0295	0.0871

As shown in Table 3.3, the one-way ANOVA indicated that there was a significant difference in the mean air velocity (m s^{-1}) between the distances 1, 3, 5, 7 and 9 m from the sidewall. The results of the Tukey-Kramer HSD test indicated that there was a significant difference in the mean air velocity between distance 1 m and 3 m and distance 3 m and 5 m from the sidewall. The results of one-way ANOVA analysis and Tukey-Kramer HSD test on the turbulence intensity indicated that there no significant difference in the mean turbulence intensity between the all the distances (1, 3, 5, 7 and 9 m) from the sidewall.

3.3.4 Impact of broiler chickens and indoor equipment on air velocity distribution in the broiler microclimate

Figure 3.8 shows the differences between the mean air velocities measured in an empty and an occupied experimental broiler building. These results illustrate the effects of obstacles within broiler building on the distribution of air velocity in the broiler occupied zones. In Figure 3.8, it is clearly shown that occupied broiler models (plastic footballs), feeders and drinker, contributed majorly to the lower mean air velocities obtained at all the measurement locations (1, 3, 5, 7 and 9 m). A similar result has earlier been reported by Smith et al. (1999) who indicated that the occupants of pig building influenced the air velocity distribution in the pig occupied zones and airflow characteristics inside the building. In their study, they indicated that active pigs in the area closer to the sidewall reduced air velocity distribution in the pig occupied zones by 37 % while inactive pigs, in the same location, reduced the mean air velocity by 30 %. Since broiler models were used in this study, it was impossible to examine the effects of active broilers on the airflow distributions in the broiler occupied zones.

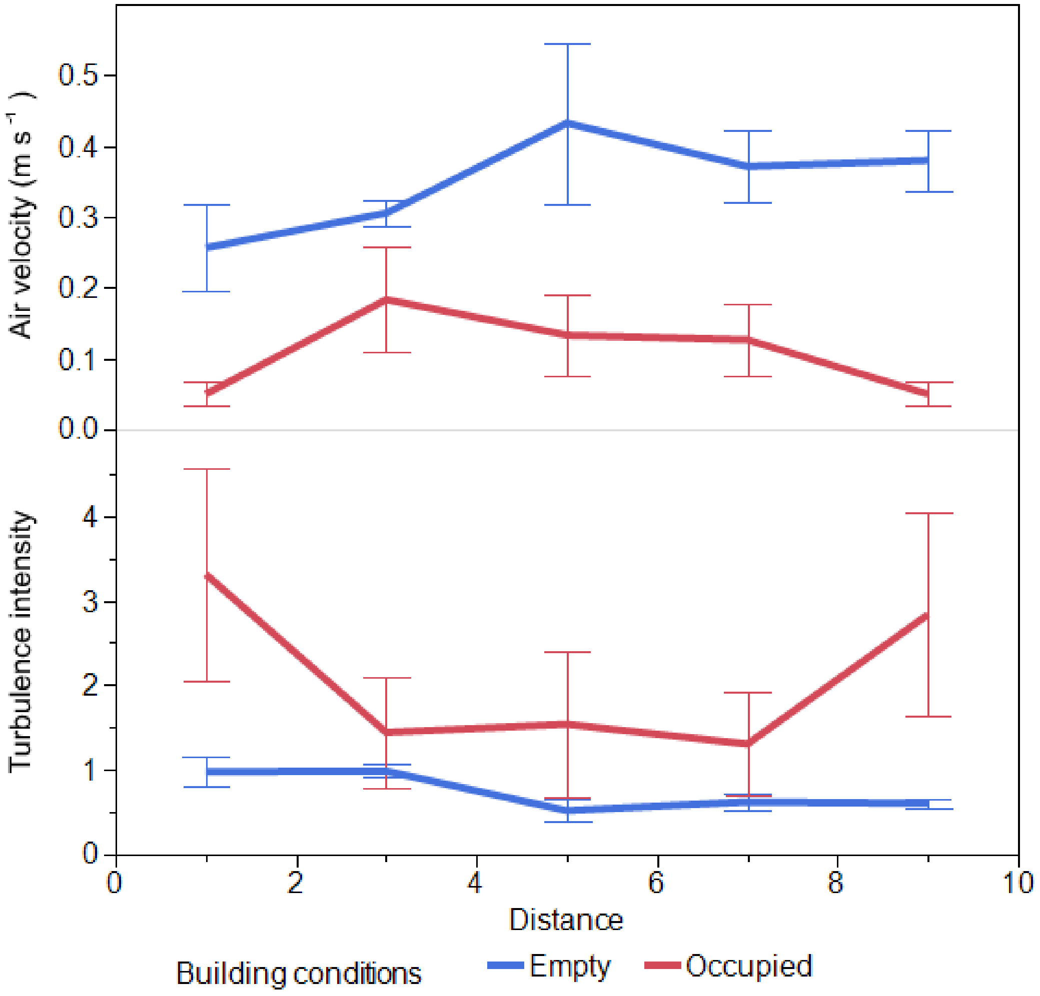


Figure 3.8: Air velocities and turbulence intensities in the broiler occupied zones (0.2 m) within an empty broiler building and the broiler building occupied with broiler models.

Also, in Figure 3.8, the turbulence intensities in the occupied broiler building are higher than that in the empty broiler building. The higher turbulence intensities recorded in the occupied building, most especially in the areas closer to the sidewall, could have occurred as a result of the wall deflecting the air movement away from the area. As the distance increased, broiler models, which the air stream from the inlet reached first (that is at 3, 5 and 7 m from the sidewall), had higher air velocity and while the broiler models at the centre of the building experienced lower air velocity with larger airflow fluctuation (Bjerg et al., 2000; Smith et al., 1999). In this study, it has been shown that the airflow characteristics in an empty broiler building would not specifically state the air velocity that the bird would experience. Using only the results of the airflow in an empty broiler building to determine the available air movement in the broiler occupied zones could be misleading (Smith et al., 1999).

A statistical analysis, using the t-test, was performed on the mean air velocities obtained in the empty and occupied broiler building. The result of the analysis, as shown in Table 3.4, indicated that there was a significant difference in the mean air velocities (m s^{-1}) between the empty broiler building and the occupied building at all the measurement locations (1, 3, 5, 7 and 9 m from the sidewall). The same t-test analysis was conducted on the turbulence intensities in the empty broiler building and the occupied broiler building. The result of the test indicated that there was a significant difference in the turbulence intensity between the empty broiler building and the occupied broiler building at 1 m and 5 m from the sidewall. At distance 3 to 7m from the sidewall, the analysis indicated no significant difference in the turbulence intensity between the empty broiler building and the occupied broiler building.

Table 3.4: Mean air velocity (m s^{-1}) and turbulence intensity within an empty and an occupied broiler building.

Distance (m) from the sidewall	**Mean air velocity (m s^{-1})**		**P- value**	**Turbulence intensity**		**P- value**
	Empty	Occupied		Empty	Occupied	
1	0.26	0.05	0.0047	0.98	3.31	0.0333
3	0.31	0.19	0.0470	0.99	1.44	0.2992
5	0.43	0.13	0.0136	0.52	1.54	0.1119
7	0.37	0.13	0.0036	0.62	1.31	0.1319
9	0.38	0.05	0.0003	0.61	2.84	0.0328

3.4 Conclusion

This study was conducted to evaluate the air distribution in the broiler occupied zones based on the ventilation system operations during the hot weather periods. In this study, it has been identified that air distribution in the broiler occupied zones depends on the inlet opening technique, the distance at which measurements are obtained and the building conditions (empty or occupied). This study has also discovered that air distribution in the broiler occupied zones is majorly influenced by the indoor obstacles such as broiler chickens, feeder lines, drinker lines and other mechanical equipment within the broiler building. This is because, broiler chickens which the air stream reached first deflected the airflow upward, resulting in lower air velocity and higher turbulence intensity downstream.

Therefore, in order to adequately understand the airflow pattern and air distribution within an empty and an occupied broiler building, application of computational fluid dynamics (CFD) for airflow simulation is necessary. This simulation technique would assist in optimising the air distribution within the building. Also, considering the fact that ventilation system, mostly used during hot weather condition (wide opening of bottom-hinged inlets) could not provide adequate air movement in the broiler occupied zones, there is a need for the development of hot weather ventilation system capable of increasing inlet turbulence intensity and also directing airflow from the inlet towards the birds so as to relieve birds of heat stress during hot weather periods.

CHAPTER FOUR

COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION OF INDOOR AIR VELOCITY OF A SIDEWALL INLET AND ROOF EXHAUST VENTILATED BROILER BUILDING

4.1 Introduction

To provide thermal comfort and a healthy environment for livestock, it is important to ensure that adequate air movement is provided in the animal occupied zones (Li et al., 2017; Van Wagenberg et al., 2004; Bustamante et al., 2013). The ability to maintain required climatic condition within the animal building is dependent on the design of the ventilation system and its performances (Norton et al, 2007). There are many benefits reported in the literature that are associated with understanding the air velocity distributions within the animal building (Norton et al, 2007). Due to the complexity of the indoor conditions of the animal building, it is difficult to accurately quantify the indoor environmental conditions (Norton et al, 2007). However, there has been significant progress in computational fluid dynamics (CFD) for quantifying and analysing indoor and outdoor climate parameters. This tool has been widely used in the aviation industry, food industry and the built environments.

There are many advantages of CFD in the agricultural industries most especially in the climate control of animal buildings. These include its control over the influencing factors within an enclosed environment, it’s less expensive and it has ability to process environmental parameters in lesser time (Li et al., 2017). Other advantages include non-requirement of instrumentation, building and measurement assistants, prevention of interference with the indoor airflow and unlimited measurement points (Blanes-Vidal et al., 2008; Bustamante et al., 2015). These advantages might have contributed to its recent wide usage in livestock buildings (Norton et al., 2007, 2009, 2010; Li et al., 2016, 2017). However, there are a few limitations facing CFD applications. Its predictions are not credible or considered accurate until they are validated with the field experiment. It also requires technical expertise in the handling the boundary conditions and meshing of the fluid domain (Bjerg et al., 2002; Blanes-Vidal et al., 2008).

CFD is an engineering tool applicable in the design of structural facilities, numerical calculation of the fluid flow field and simulation of fluid flow patterns (Blanes-Vidal et al., 2008). CFD has been used by many engineers as a tool for simulating flow field within agricultural facilities such as greenhouses (Benni et al., 2016; Bournet & Boulard, 2010; Norton et al., 2007), broiler buildings (Blanes-Vidal et al., 2008; Bustamante et al., 2013; Seo et al., 2009), cattle buildings (Norton et al., 2007, 2010) and pig houses (Li et al., 2017; Seo et al., 2012). Despite the application of CFD in poultry production, information on the airflow analysis of sidewall inlets and roof exhaust ventilated broiler building, during hot weather periods, is scarce. During hot weather periods, farmers usually open the sidewall inlets wide to allow maximum air movement into the broiler occupied zones (Albright, 1990). To understand the impact of the wide opening of inlets on air velocity distribution at the broiler occupied zones, there is a need for numerical simulation using CFD. This will contribute significantly to the improvement of hot weather ventilation of sidewall inlet and roof exhaust ventilated broiler building and also assist the ventilation engineers to provide appropriate hot weather ventilation system for sidewall inlet and roof exhaust ventilated broiler buildings.

Broiler buildings, compared with other agricultural buildings such as pig and cattle buildings, have lesser indoor obstacles in the broiler occupied zones (Blanes-Vidal et al., 2008). The implication of this is that there is a minimal number of obstructions to airflow in the broiler occupied zones except for the birds, feeder lines, drinker lines and farm workers. It is expected that the air velocity in the broiler occupied zones is sufficient to provide cooling for the birds during hot periods. It was suggested by Albright (1990) that fully opening of sidewall inlet, for the purpose of increasing airflow into the livestock building, could hinder air circulation in the animal occupied zones. This is yet to be scientifically supported using CFD simulation. Therefore, this study was set up to evaluate the impact of the wide opening of sidewall inlets on the indoor air velocity in the broiler occupied zones using CFD. The objectives of this study were (1) to verify some assumptions in the literature concerning the CFD simulation of livestock buildings; (2) to simulate air velocity in the broiler occupied zones within a sidewall inlet and roof exhaust ventilated broiler building with wide opened air inlets; (2) to determine suitable turbulence model for subsequent evaluation of indoor conditions of the broiler building and; (3) to validate the CFD simulation against field experiments conducted in an experimental broiler building in the poultry unit of Harper Adams University, UK as described in chapter 3.

4.2. Materials and methods

4.2.1 Experimental building and measurements

A detailed description of the experimental building and the measurements for validating the prediction of the CFD can be found in chapter 3. The experimental measurements were necessary because the credibility of CFD predictions depends on how close or similar the predictions are to the field experimental results. All necessary precautions were observed when performing field experiments, such as measurement locations and the directions of the head of airflow sensors to ensure that the experimental procedures are as similar as possible to the CFD simulation.

4.2.2 CFD modelling

In this study, CFD modelling is divided into three parts. The first part of the modelling considered the verification of some assumptions in the literature. The second part looked into the validation of the CFD predictions of airflow in an empty broiler building. Lastly, the third part evaluated air velocity distributions in the broiler occupied zones within an occupied broiler building.

4.2.2.1. Part 1: CFD modelling preparation and the validation of CFD modelling in an empty broiler building

For a proper understanding of the simulation processes, there were various verification processes undertaken in this study to confirm the assumptions made in the literature as regards the use of CFD for indoor simulations of livestock buildings. The verification processes were considered necessary in order to critically assess the applicability of the assumptions and the accuracy of the CFD predictions in this study. The framework of the verifications in this study include; (1) the inlet configurations, (2) airflow through the inlets on right and left sidewalls, (3) addition of indoor obstacles such as drinker and feeder lines in the CFD simulation and (4) finally the positioning of measurement planes. Previous studies have indicated that multiple sidewall inlets can be represented by a long sidewall inlet (Bjerg et al., 2002; Blanes-Vidal et al., 2008), airflows through the sidewall openings are identical (Harral and Boon, 1997) and indoor obstacles such as drinker and feeder lines can be neglected during the CFD simulation based on their negligible effect on the airflow (Blanes-Vidal et al., 2008). These assumptions were first verified to determine appropriate broiler building geometry and building set up for further CFD simulations.

4.2.2.1.1. Development of broiler building geometries

Figure 4.1 shows the geometries of broiler buildings with different inlet configurations and indoor obstacles. The geometries were developed with SolidWorks 2016. The building is 21.75 m long, 18.30 m wide, 2.36 m eave height and the inlets are 1.60 m above the floor. The detailed description of the experimental building can be found in chapter 3. Figure 4.1a shows a broiler building with two long sidewall inlets with the dimension 20.36 m by 0.21 m placed at 1.60 m above the floor. Figure 4.1b shows a typical broiler building with twenty-four 0.52 m by 0.21 m sidewall inlets. Figure 4.1c shows a broiler building with feeder and drinker lines raised to the height of 0.3 m above the floor with their locations from the sidewall as they are in the experimental broiler building. These geometries were used in the CFD simulations to verify the assumptions earlier discussed and for simulating the indoor air velocities of the empty broiler building.

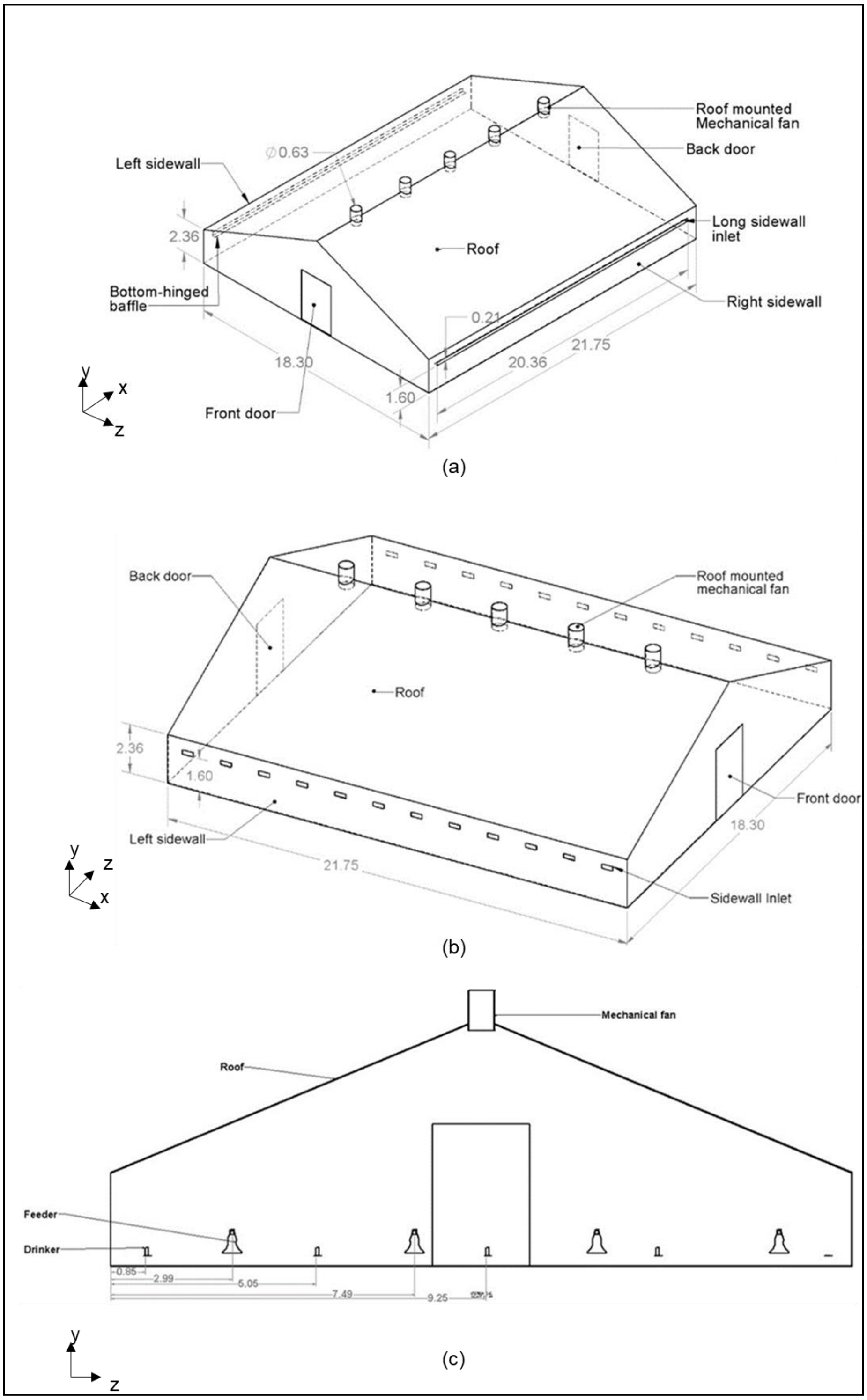


Figure 4.1: Geometries of broiler building with (a) long bottom-hinged sidewall inlets (b) multiple sidewall inlets and (c) drinker and feeder lines. All dimensions are in metres.

4.2.2.1.2. Mesh generation

The CAD geometries of the broiler building (shown in Figure 4.1) were imported into the Star CCM+ 12 (Siemens, 2017), a CFD software package, for simulations. The software was adopted in this study based on it wide usage in the agricultural industry by previous researchers (Ji et al., 2013; Norton et al., 2013, 2009). The internal parts, which represents the computational domain, of the imported CAD geometry were extracted for surface and volume discretisation. The discretised surfaces and volume were used by the solver (turbulence models) to obtain the physical solutions of the airflow in the broiler occupied zones within the sidewall inlet and roof exhaust ventilated broiler building.

For each of the building geometries, three unstructured coarse mesh densities were generated to discretise the computational domain (see Table 4.1). The mesh density refinement was done based on the number of cells within the prism layer. The successive growth rate of prism layer was maintained at a stretch ratio of one and a half from the wall surface. For the inlet mesh size, 25 % of the relative target size was used as the inlet relative minimum mesh size. As shown in Table 4.1, Mesh 3 has the highest mesh densities in all the building geometries test than Meshes 1 and 2. Therefore, in order to ensure that CFD predictions were precise and accurate for all the turbulence models, Mesh 3 has been used in all the CFD simulations.

Table 4.1: Mesh densities used for model verification

Case	Multiple inlets	Long inlets	Internal obstacles
Mesh 1	656,983	605,335	656,724
Mesh 2	791,754	738,144	853,522
Mesh 3	925,448	870,795	1,050,996

Figure 4.2 shows the meshes of the broiler building with different inlet configurations and internal obstructions. During volume meshing, unstructured polyhedral grids were used to improve and optimise the overall quality of the cell surfaces and the volume mesh model. Polyhedral grids were adopted based on it high accuracy, lesser computational time, fewer cells and the allowances it gives for conformal mesh interface between separate regions (Siemens, 2017). A prism layer mesh was used to generate prismatic cells near wall surfaces to improve the accuracy of the flow solution closer to all wall surfaces.

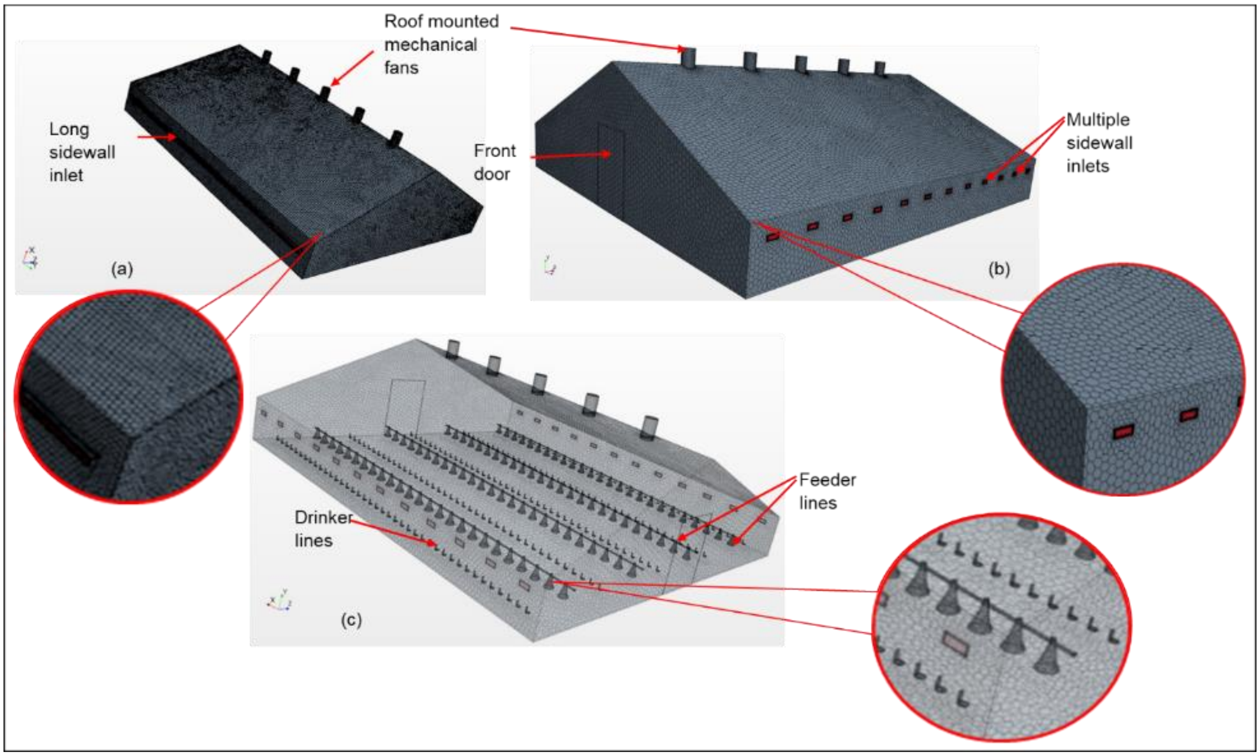


Figure 4.2: Polyhedral meshes of the computational model used for the verification of airflow in the broiler building with; (a) long bottom-hinged inlet (b) multiple bottom-hinged inlets and (c) internal obstacles.

4.2.2.1.3. Turbulence models, measurement planes and convergence criteria

To verify the conditions under which indoor conditions of broiler building were simulated, three, widely adopted turbulence models were selected (Bjerg et al., 2002; Li et al., 2016a; Norton et al., 2009; Rong et al., 2016). Their selection for the evaluation of airflow in the broiler building was necessary in order to determine the most appropriate turbulence model for the indoor environment of a sidewall inlet and roof exhaust ventilated broiler building. These models include standard (Std) $k - \varepsilon$, realisable (Re) $k - \varepsilon$, and shear stress transport (SST) $k - \omega$ turbulence models. The model that predicted the closest air velocity magnitude to the mean air velocities obtained in the field experiments has been used for further CFD simulation.

The fundamental principles (continuity and momentum and energy) of Naiver-Stoke equations governing the fluid flow in a sidewall inlet and roof exhaust ventilated broiler building were solved using the turbulence models. The indoor environment of the broiler building was simulated based on inlet configurations and internal obstacles as reported in the literature. Four measurement planes were created in the simulated broiler building to verify the assumptions reported in the literature. Figure 4.3 represents the measurement planes created to determine airflow variations at different locations from the sidewalls. The locations of the measurement planes, irrespective of the building geometry, are similar. Planes A, B, C and D are 4.50 m, 7.30 m, 10.88 m and 17.20 m from the front door respectively. Plane C represents the plane of symmetry of the building. The planes were created to represent the locations where inlets are not aligned with the outlets and places closer to the door walls. These were very important as they would enable the ventilation engineers to strictly consider the effects that inlets and outlets locations could have on the air distribution within the broiler buildings.

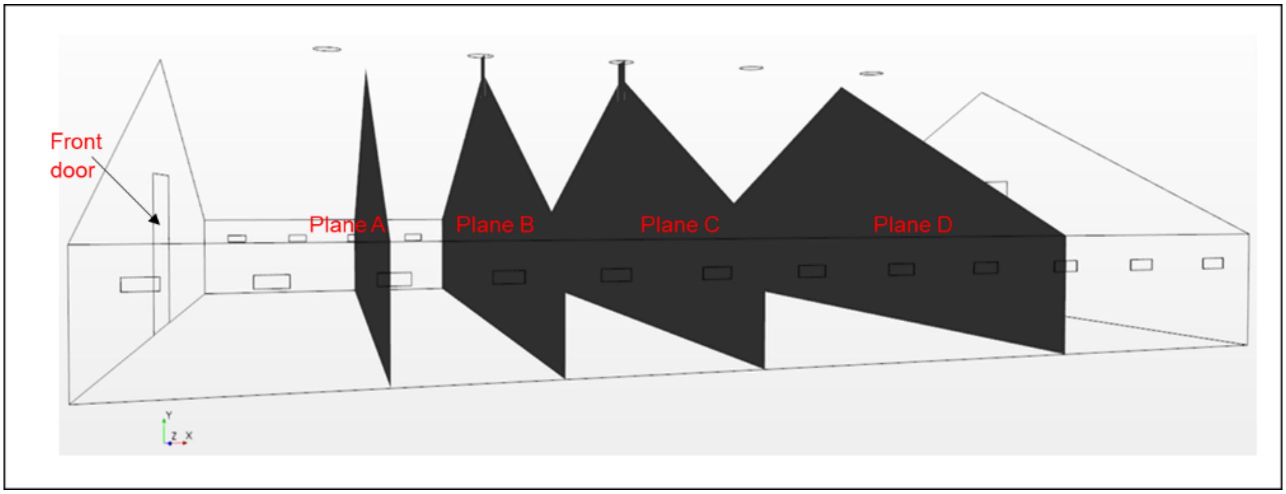


Figure 4.3: Measurement planes indicating measurement locations within the sidewall inlet and roof exhaust ventilated broiler building.

For the purpose of solution monitoring and convergence criteria, a global residual of 0.001 (0.1 %), for all fundamental equations (conservation of mass, momentum and energy) was defined. The computations were not terminated until the residuals were lesser than 0.001 and the air velocity magnitudes in the broiler occupied zones were also stabilised. The air velocity magnitudes in the broiler occupied zones, where broiler chickens experience heat stress during hot weather periods, were only considered in this study.

4.2.2.1.4. Boundary conditions

The boundary conditions specified in this study are shown in Table 4.2. These include the air velocity at the inlet, pressure at the outlet and building wall surfaces. Air turbulence intensity of 0.10 was imposed at the inlet. Similar inlet turbulence intensity in the broiler building has been reported in the literature (Blanes-Vidal et al., 2008; Li et al., 2016b). The same turbulence intensity was obtained during the field experimentation at the inlet of the sidewall inlet and roof exhaust ventilated broiler building.

Table 4.2: Boundary conditions specifications

Building surfaces	Boundary conditions
Inlet	Velocity inlet Air velocity of 4.91 m s^{-1} at the inlet Inlet turbulence intensity of 0.10
Outlet	Pressure outlet Pressure (0 Pa)
Building walls, floor and roof	No-slip and smooth wall

4.2.2.2. Part 2: CFD modelling and validation of airflow in an experimental broiler building occupied with broiler models, feeder and drinker lines

Similar to the empty broiler building, an experimental broiler building, occupied with broiler models, was developed with SolidWorks 2016 (Figure 4.4) and imported into Star CCM+ for turbulence modelling. For CFD simulation purpose, the building was filled with broiler models of a characteristic dimension of 0.18 m, exactly as the size of the plastic footballs used during the field experiment in chapter 3. The building used for the simulation was filled with broiler models similar to real life situations in the commercial broiler buildings. This approach is necessary to ensure uniform indoor conditions within the building during the CFD simulations. The broiler chickens were modelled as spheres (1) to simulate plastic footballs that were used for the field experiment and (2) to represent broiler chickens since it has been reported that there is a correlation between broiler chickens and spheres (Li et al., 2016b). The fluid domain (internal part of the building) was extracted and the surface and volume meshing were performed (Figure 4.5).

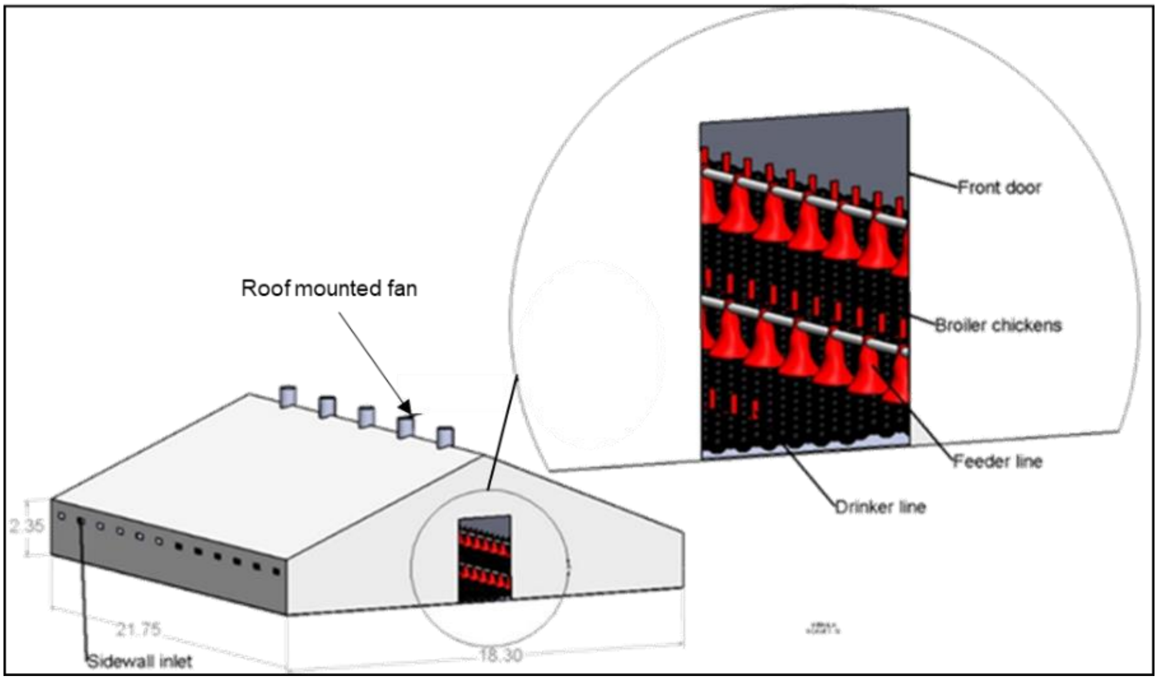


Figure 4.4: Experimental broiler building occupied with broiler models (spheres). All measurements are in metres.

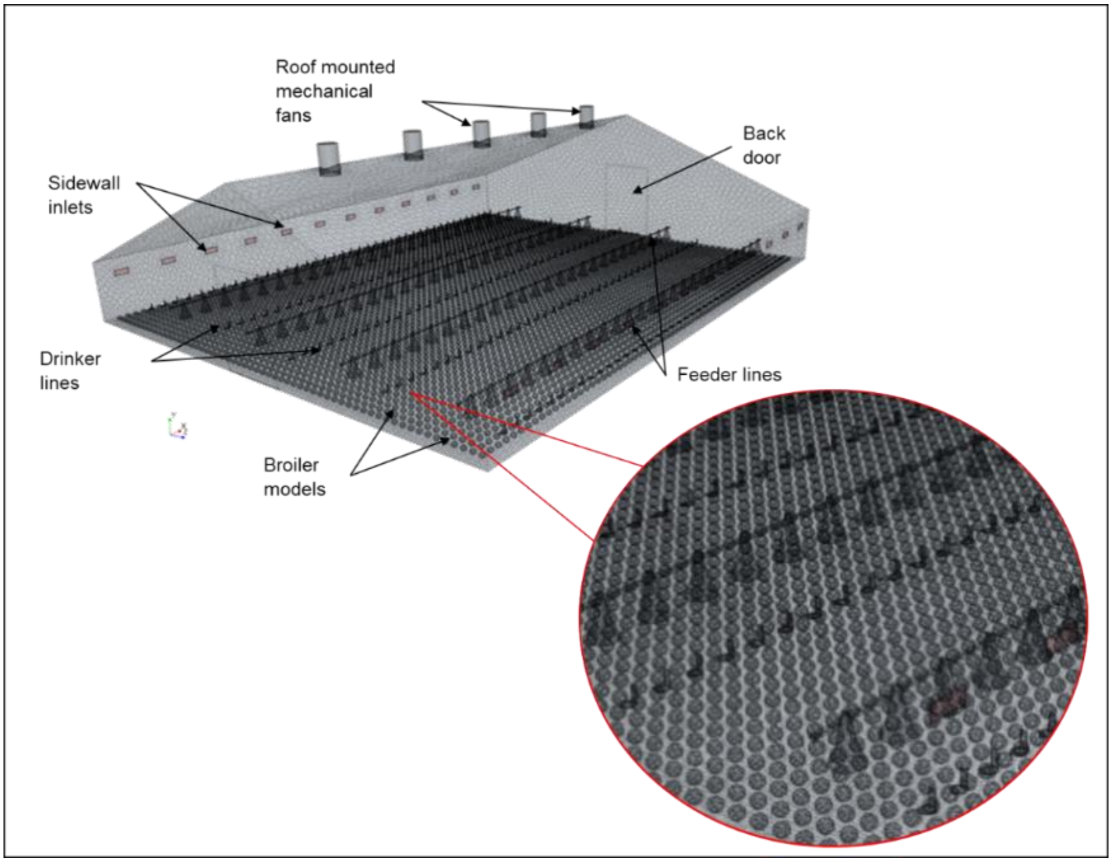


Figure 4.5: Surface and volume meshes of an experimental broiler building

In this study, three mesh densities (Meshes 1, 2 and 3) refinements were performed based on the number of cells in the prism layers (Table 4.3).

Table 4.3: Mesh density refinement of broiler building with broiler models

Case	**Mesh densities (cells)**
Mesh 1	808,805
Mesh 2	976,541
Mesh 3	1,095,753

The three mesh densities were used for the CFD simulations and were validated with the field experimental results in order to determine the appropriate volume mesh that would predict the airflow distributions in the broiler occupied zones using standard $k - \varepsilon$ turbulence model. In this section, only standard $k - \varepsilon$ turbulence model was used to simulate airflow in the broiler building occupied with broiler models based on its predictive capability in the simulated empty broiler building in section 4.3.2. Air velocity magnitudes in the broiler occupied zones were obtained from the left sidewall inlets towards the centre of the broiler building on the measurement Plane B situated at 7.3 m from the front door.

4.3. Results and discussion

4.3.1. Verifications of the assumptions in the literature

a. Assumption 1- Inlet configurations.

To verify the assumption of Bjerg et al. (2002) and Blanes-Vidal et al. (2008) who have indicated that multiple sidewall inlets can be replaced with one long sidewall inlet, a symmetry plane was set up at 10.88 m from the front door and used for assessing the CFD predictions of air velocity magnitudes in the broiler occupied zones (0.2 m above the floor). The effects of the inlet configurations on the air velocity distributions in the broiler occupied zones were accessed from the right sidewall inlets at distance 5 m from the sidewall inlet. Table 4.4 shows the effects of inlet configurations on the air velocity distributions in the broiler occupied zones.

Table 4.4: Effects of inlet configurations on the air velocity distributions in the broiler occupied zones.

Inlet configurations	**Distance (m) from the sidewall**	**Air velocity ($m\ s^{-1}$) in the broiler occupied zones**		
		Std $k-\varepsilon$	Re $k-\varepsilon$	SST $k-\omega$
Long bottom-hinged inlet	5	0.678	2.267	2.563
Multiple bottom-hinged inlets	5	0.452	0.389	0.108

It is clear from Table 4.4 that the assumptions of Bjerg et al. (2002) and Blanes-Vidal et al. (2008), that multiple sidewall inlets can be replaced with a long sidewall inlet, may not be applicable for the CFD design of the sidewall inlet and roof exhaust ventilated broiler building considered in this study. Replacing multiple sidewall inlets with a long sidewall inlet could result in over predictions and wrong estimation of airflow in the broiler occupied zones. It is therefore advised that the CAD geometry used for CFD simulation should be the same with the livestock building used for field experimentation in order to properly assess the CFD results.

b. Assumption 2: Airflow from right and left sidewalls are similar.

The assumption that airflow through the sidewall inlet is the same according to Harral and Boon (1997) was verified using the symmetry plane created in the CFD simulation at 10.88 m from the front door and the measurements were obtained at the centre of the broiler building (9 m from the sidewall). Table 4.5 illustrates the airflow predictions in the occupied zones of broiler at the centre of the broiler building (9 m from the sidewall inlets).

Table 4.5: Air velocity magnitudes in the broiler occupied zones at the centre of the broiler building from both the right and left sidewall inlets of an empty broiler building.

Inlet configuration	**Distance (m) from the sidewall**	**Air velocity ($m\ s^{-1}$) in the broiler occupied zones**					
		Std $k-\varepsilon$		**Re $k-\varepsilon$**		**SST $k-\omega$**	
		Right inlet	Left inlet	Right inlet	Left inlet	Right inlet	Left inlet
Multiple bottom-hinged inlets	9	0.611	0.611	0.495	0.495	0.055	0.055

Table 4.5 support the assumption of Harral and Boon (1997). As shown in Table 4.5, the predicted magnitudes of the mean air velocity at both sides of the broiler building are the same. Therefore, in the subsequent airflow measurements, air velocity at the sidewall and towards the centre of the broiler building were evaluated from only one side of the sidewall inlet and roof exhaust ventilated broiler building.

c. Assumption 3: Negligible effect of indoor obstacles on air velocity distributions.

The effects of indoor obstacles such as feeder and drinker lines on the indoor air velocity distribution were evaluated based on the assumption that they have negligible effect on the air velocity distributions in the broiler occupied zones (Blanes-Vidal et al., 2008). To verify the assumption, airflow inside broiler building with multiple sidewall inlets were used. There were no obstacles in one of the buildings while obstacles, such as feeder and drinker lines, were installed in the second building (Figures 4.1 and 4.2). Airflow distributions from the right sidewall inlet at distance 5 m from the sidewall inlets of the broiler building along the symmetry plane were used for the evaluation. Table 4.6 shows the airflow measurements in the broiler occupied zones at distance 5 m from the sidewall inlets of the building.

Table 4.6: Effect of obstacles on air velocity distribution in the broiler occupied zones

Indoor obstacles	**Distance (m) from the sidewall**	**Air velocity ($m\ s^{-1}$) in the broiler occupied zones**
		Std $k-\varepsilon$
With obstacles	5	0.311
Without obstacles	5	0.452

Considering Table 4.6, it is clear from the CFD predictions that feeder and drinker lines do have an effect on the airflow distribution in the broiler occupied zones. These results indicate that the assumption of Blanes-Vidal et al. (2008) that indoor obstacles such as feeder and drinker lines have a negligible effect on the airflow distributions in the broiler occupied zones may not be suitable for the broiler building considered in this study. In this study, indoor obstacles were considered to have effects on the air velocity distributions in the broiler occupied zones. With the standard $k - \varepsilon$ turbulence model, it can be seen from Table 4.6 that airflow distributions within the building without indoor obstacles are more than that of the building with indoor obstacles.

d. Assumption 4: Airflow measurements depend on the alignment of the inlet with the outlet.

For a further understanding of the CFD predictions, an assumption that the results of air velocity within the broiler building depend on the alignment between the inlets and the outlets was evaluated. To test the assumption, measurements were obtained from the right sidewall inlet at 3 m from the sidewall inlets of the broiler building on the Plane A, B, and C. For the purpose of this section, this assumption was examined based on the air velocities predicted by the standard $k - \varepsilon$ turbulence model within a broiler building with indoor feeder and drinker lines. Table 4.7 shows the predicted values of air velocity in the broiler occupied zones along the Planes A, B, and C.

Table 4.7: What happens to the air velocity distribution if inlets are not aligned with the outlets?

Indoor obstacles	**Distance (m) from the sidewall**	**Air velocity (m s^{-1}) in the broiler occupied zones**		
		Plane A	Plane B	Plane C
With obstacles	3	0.179	0.177	0.167

The results shown in Table 4.7 indicates that the alignment of the inlet with the outlet has a negligible effect on the air velocity distributions in the broiler occupied zones within the sidewall inlet and roof exhaust ventilated broiler building. It is therefore suggested that inlet-outlet alignment should not be the criteria for determining measurement locations in the sidewall inlet and roof exhaust ventilated broiler buildings.

4.3.2. Validation of air velocity in the empty broiler building

As indicated in the Assumption 3 above, indoor obstacles such as feeder and drinker lines within broiler building do have an effect on the airflow distributions in the broiler occupied zones. As a result, the air velocity predictions of the CFD simulation conducted with the broiler building with the indoor obstacles were used in this section and validated with field experiment results. Similarly, Assumption 4 has shown that the alignment of the inlet with the outlet has a negligible effect on the air velocity distributions in the broiler occupied zones. Therefore, the air velocities predicted on the Plane A (4.5 m from the front door) were used and validated with a field experiment. Figure 4.6 shows the comparisons of the results of the turbulence modelling conducted in broiler building with the results of the field experiment.

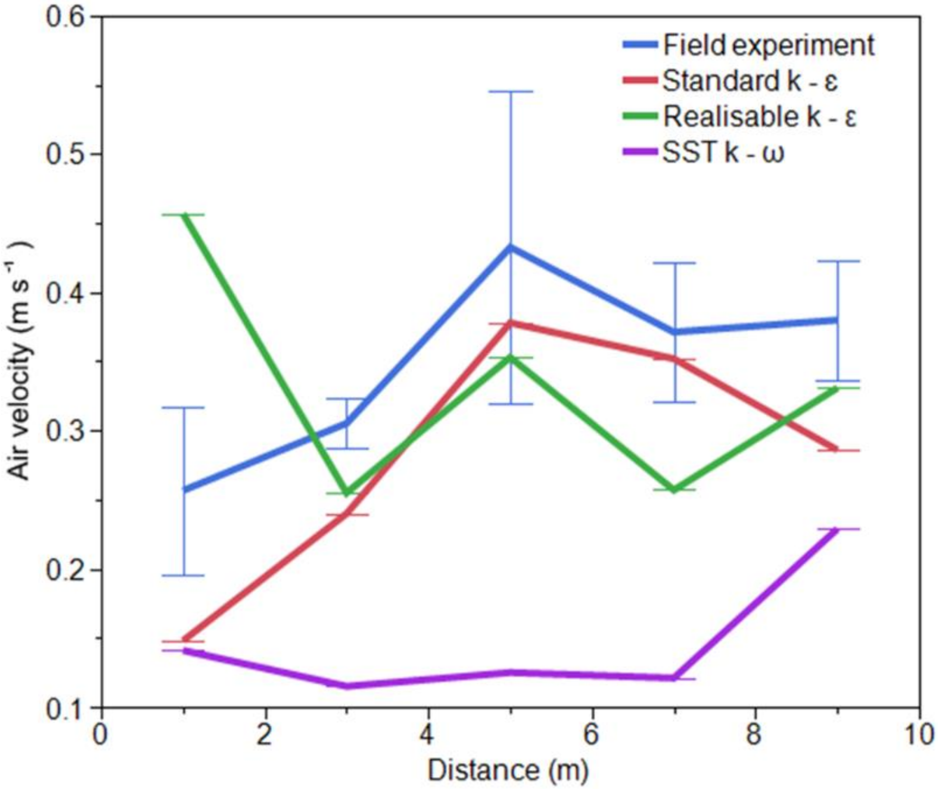


Figure 4.6: The validation of turbulence models [Std $k-\varepsilon$ (red line); Re $k-\varepsilon$ (green line); SST $k-\omega$ (purple line)] predictions with field experiment (blue line).

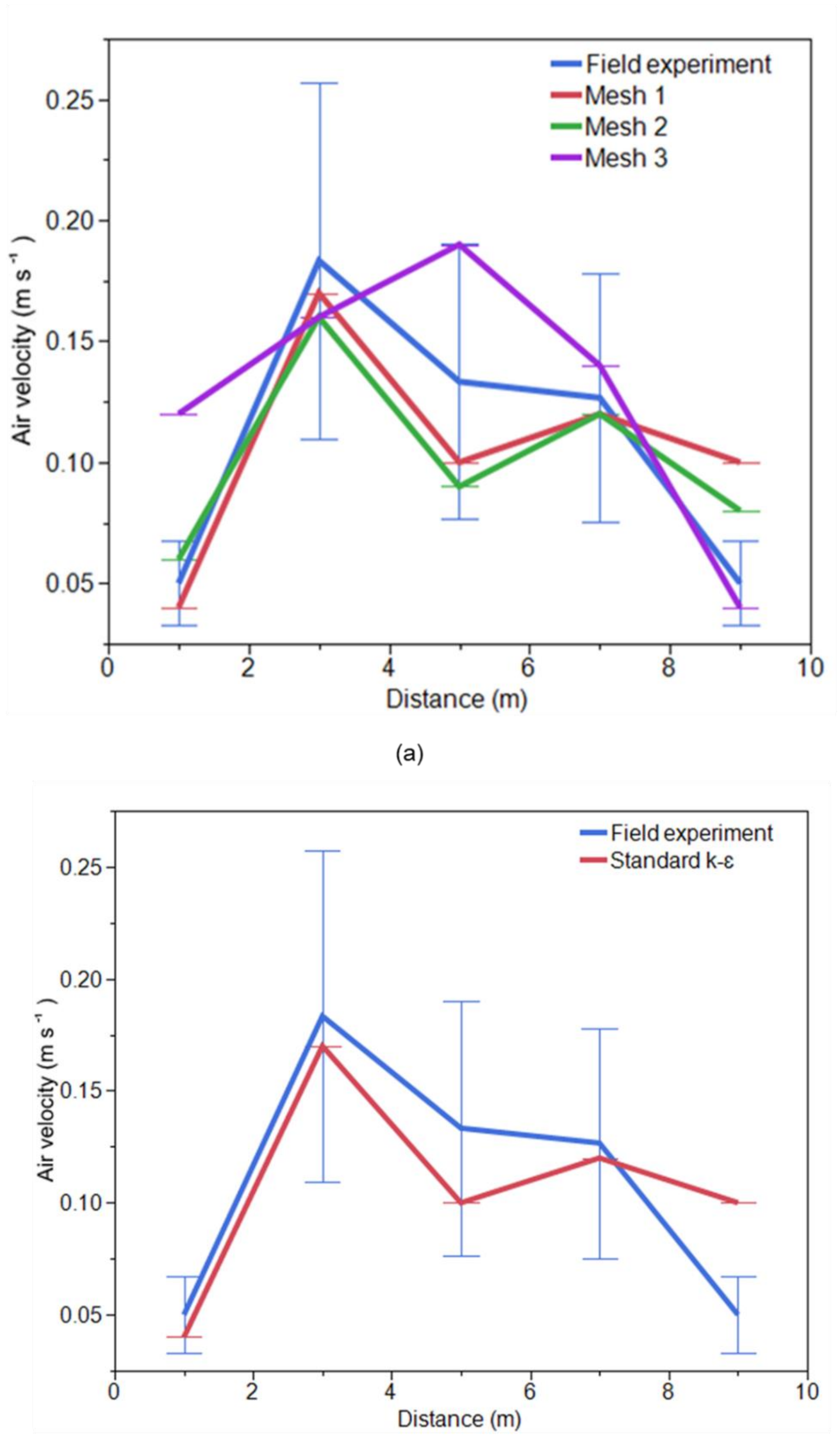
As shown in Figure 4.6, the best CFD turbulence model that predicted close streamwise velocity in the broiler occupied zones was Standard $k-\varepsilon$ (red line). Standard $k-\varepsilon$ turbulence model has been indicated as a good predictive turbulence model in some studies (Bustamante et al., 2013; Norton, 2010; Norton et al., 2013). The results of this simulation have shown that the assumption (Blanes-Vidal et al., 2008) that obstructions such as feeder and drinker lines have no effect on the airflow in the broiler occupied zones is not applicable in this study. In the study conducted by Blanes-Vidal et al. (2008), it was reported that there were higher discrepancies between the CFD predictions and field experiment. The higher discrepancies in the study of Blanes-Vidal et al. (2008) could have been as a result of the CFD simulation of an empty broiler building with no indoor obstruction. Similar higher discrepancies were also noted in the verification under the Assumption 3 of this study. In the present study, the discrepancies between the Standard $k-\varepsilon$ (red line) and the field experiment are ±0.10 m s^{-1} at all measurement locations. The CFD predictions of Standard $k-\varepsilon$ can be considered as very good for the purpose of this study. The lower predictions of the CFD could be attributed to the height of the feeder and drinker lines which were designed and located at 0.3 m above the floor in the simulation. The results of other turbulence models were ignored due to their poor prediction of the indoor airflow in the broiler occupied zones. In the study carried out by Norton (2010, p.53) in the naturally ventilated calf building, he indicated that standard $k-\varepsilon$ and realisable $k-\varepsilon$ were good turbulence models for predicting indoor environment of livestock. However, in this study, realisable $k-\varepsilon$ has not shown to be a good turbulence model for simulating sidewall inlet and roof exhaust ventilated broiler building because realisable $k-\varepsilon$ turbulence model predicted that air velocity at the sidewall (1 m from the inlet) is 0.46 m s^{-1}, higher than that at 5 m away from the sidewall (0.36 m s^{-1}).

A t-test was conducted with SAS JMP 14 to analyse the differences between the predictions of the standard $k-\varepsilon$ turbulence model and the field experiment at the distance 1, 5 and 9 m from the sidewall. The result of the analysis indicates that at 1 m from the sidewall, there is a significant difference (p = 0.045) between the standard $k-\varepsilon$ turbulence model prediction and the field experiment. At distance 5 m, there is no significant difference (p = 0.245) between the standard $k-\varepsilon$ turbulence model prediction and the field experiment. At the centre of the building (9 m from the sidewall), the result of the t-test indicated that there is a significant difference (p = 0.032) between the air velocity predicted by standard $k-\varepsilon$ and the air velocity measured in the experimental broiler building. Previous studies (Blanes-Vidal et al., 2008; Mostafa et al., 2012) have also shown that turbulence model may not predict the exact results as they were obtained during the field experiment. However, the prediction of CFD, though not exactly as field experiment, could roughly follow similar pattern of field experiment.

4.3.3. Validation of air velocity in the broiler building occupied with broiler models

As indicated in Figure 4.7a, it can be seen that Mesh 1 and 2 perform better than Mesh 3. However, Mesh 1 was considered appropriate based on its contributions to the close results predicted by the standard $k-\varepsilon$ turbulence model. The mesh density with minimal details showed closer results to that obtained during the field experimentation. This indicates that too many details may not be necessary as the indoor conditions of the broiler building become complicated (higher number of indoor equipment). This also suggests that it is unnecessary for ventilation engineers to increase the number of cells in the prism layers when simulating the airflow in the broiler occupied zones so as to improve the predictive capability of the turbulence model used during the CFD simulation.

For better understanding, Mesh 1, which is considered to be appropriate, was separated from other mesh densities for further discussion (Figure 4.7b). As shown in Figure 4.7b, there is no significant difference ($p < 0.05$) between the prediction of standard $k - \varepsilon$ and the field experiment at all locations except at the centre of the building (9 m from the sidewall) where the standard $k - \varepsilon$ turbulence model predicted higher air velocity in the broiler occupied zone. Similar to the previous study (Blanes-Vidal et al., 2008), this study has shown that CFD could be used as an engineering tool to give an estimation of indoor conditions of sidewall inlet and roof exhaust ventilated broiler building which could direct further field experiments.



(a)

(b)

Figure 4.7: Validation of air velocity predictions of standard $k - \varepsilon$ turbulence model (a) all the volume mesh densities [Mesh 1 (red line), Mesh 2 (green line), Mesh 3 (purple line) with the field experiment (blue line) and (b) Mesh 1 (red line) and field experiment (blue line).

4.4 Conclusion

This study has shown through various verifications that inlet configurations used in the CFD simulation have an important role in the prediction capability of turbulence models. It has also been found out that it is important to consider indoor equipment in the broiler building when simulating the airflow conditions inside the building with the CFD. In like manner, this study has supported the earlier reports on the assumption that airflow through the sidewall inlets (right and left) into the mechanically ventilated livestock buildings is similar and that measurements from one of the two sides could be used to represent the airflow from the sidewall inlets. In order to further understand how the inlet-outlet alignment could influence indoor airflow across the broiler building, this study has shown that measurements obtained on any measurement plane irrespective of its location from the same origin are similar.

Airflow in the broiler occupied zones, within an empty broiler building, was validated with the field experiment. The results of this study have shown that an estimation of the indoor air velocity of the sidewall inlet and roof exhaust ventilated broiler building could be predicted by using CFD simulation and that standard $k - \varepsilon$ turbulence model showed better results compared to other turbulence models (realisable $k - \varepsilon$ and SST $k - \omega$) considered in this study. However, in order to simulate airflow in an empty broiler building, it is advisable to increase the mesh density during the surface and volume discretisation so as to improve the prediction capacity of the CFD modelling.

Further study with an occupied broiler building was conducted to evaluate the impact of current inlet opening technique used during the hot weather conditions by the commercial poultry farmers. The standard $k - \varepsilon$ turbulence model averagely performed well in predicting the airflow distributions in the occupied zones of broiler chickens when validated with the results of field experiment. However, comparing the mesh densities of occupied broiler building with that of the empty broiler building, this study has shown that the higher number of cells in the prism layer may be avoided due to the design complexity and longer computation time. With lesser design details of broiler building occupied with broilers, the CFD could accurately predict the airflow distributions in the broiler occupied zones when the building is occupied with broiler chickens.

This study, in conjunction with the report findings of Albright (1990) has shown that the current method used in the sidewall inlet and roof exhaust ventilated broiler building needs to be re-evaluated. It has clearly shown that the method may not provide a better airflow in the broiler occupied zones where higher air movement is needed during hot weather periods. Therefore, this study suggests that the ventilation engineers need to investigate other appropriate hot weather ventilation system for broiler production so as to alleviate the heat stress challenges faced by broiler chickens during hot weather periods.

CHAPTER FIVE

DESIGN, DEVELOPMENT AND EVALUATION OF AN ALTERNATIVE HOT WEATHER VENTILATION SYSTEM FOR BROILER PRODUCTION

5.1 Introduction

Control over temperature, humidity and airflow is essential during intensive broiler production. It is well known that the distributed environment has consequences on the welfare and productivity of the confined birds (Dawkins et al., 2004; Jones et al., 2005). Raising birds in an environment that would prevent them from exhibiting their normal behaviours such as feeding, drinking and normal distribution, could impair their welfare and production. As a result, there should be a balance between the indoor condition and the thermal comfort of the birds. An ideal thermal condition will allow the birds to expend minimum energy to produce heat by physiological processes (Pereira and Nääs, 2008). Otherwise, the bird would resort to using dietary energy for body temperature maintenance, and this could affect their meat yield, meat quality, body weight gain, muscle growth and activities (Quinteiro-Filho et al., 2010; Ruzal et al., 2011; Mack et al., 2013).

An important airflow characteristic that is yet to be considered in the design of the ventilation system of broiler building is the higher inlet turbulence (that is inlet air fluctuation). Many studies have indicated the importance of an air fluctuation in increasing the convective heat transfer of different objects (see chapter two). Integrating air fluctuation into the hot weather ventilation system in broiler production could significantly increase the heat transfer of poultry birds and also shift heat transfer from latent (panting) to sensible (convective and radiative) heat transfer (Yahav et al., 2005). This integration could also provide broiler chickens with an opportunity to reduce the energy they expend on body maintenance, acid/ base and body water balances and also improve the thermal comfort of birds during hot weather periods (Yahav et al., 2005).

In the built environment, studies (Hua et al., 2012; Huang et al., 2012; Zhu et al., 2015) have shown that air fluctuation with $-5/3$ power spectrum exponent (a parameter for analysing the fluctuation characteristics of airflow) could provide desirable thermal comfort. Heat loss from food products was increased with higher air fluctuation (Ghisalberti and Kondjoyan, 1999). Li et al. (2016a) simulated with computational fluid dynamics (CFD) and reported that an increase in the turbulence intensity within the pig unit from 0.15 to 0.30 improved the heat loss of pig models by 2.6 % at an air velocity of 3.3 m s^{-1}. Presently in the typical commercial broiler houses, ventilation system with constant running fans are available which are only operated based on the assumed ventilation required within the building. The air turbulence intensity provided at the air inlets in the broiler building is usually 0.1 (Bustamante et al., 2013; Li et al., 2016). To improve air distribution within the broiler building, there is a need for the development of an alternative ventilation system capable of generating higher inlet turbulence so as to improve airflow distributions in the broiler occupied zones during hot weather periods.

Therefore, the objectives of this study were: (1) to design and develop an alternative hot weather ventilation system for broiler production; (2) to evaluate the performances of an alternative hot weather ventilation system and (3) to develop predictive models for air velocity and turbulence intensity of the system.

5.2 Materials and methods

5.2.1 The design and development of an alternative ventilation system for broiler production

A hot weather ventilation system was designed and developed. The system was designed to increase the air turbulence at the inlet of broiler building and to improve the air velocity distributions in the broiler occupied zones. The ability of the system to achieve these purposes could result in minimising the energy required for broiler production and also alleviate heat stress in broiler chickens. This ventilation system could be used as a supplementary cooling system in a naturally ventilated livestock building to increase air velocity and turbulence intensity at the animal level during hot weather periods, or integrated into the ventilation system of a mechanically ventilated broiler building to improve inlet turbulence intensity and air velocity in the broiler occupied zones. In this study, the main focus was the integration of the ventilation system into mechanically ventilated broiler building.

5.2.1.1. Description of the ventilation system

To investigate how the turbulence intensity at the air inlet can be increased during hot weather conditions, a ventilation system with an oscillation baffle was developed with SolidWorks 2016 edition and fabricated in the engineering workshop, Harper Adams University, UK. The system comprised of two major parts; a variable speed fan of 0.50 m diameter, a turbulence generator (TG) of 0.58 × 0.58 m dimension and a flexible duct of 0.55 m diameter. The first part contains a three-variable speed fan that produces airspeed while the second part, TG, contains a baffle operating at variable oscillation speeds and angles to fluctuate the airspeed produced by the fan so as to increase output air turbulence intensity. Figure 5.1 presents the main components of the ventilation system. An option to either operate the ventilation system as a unit or operate the fan and the TG independently was provided in the ventilation control system. This was considered necessary so that turbulence intensity would only be adjusted when needed without necessarily altering the operations of the fan or the whole unit could be operated together to fluctuate airflow of the ventilation system.

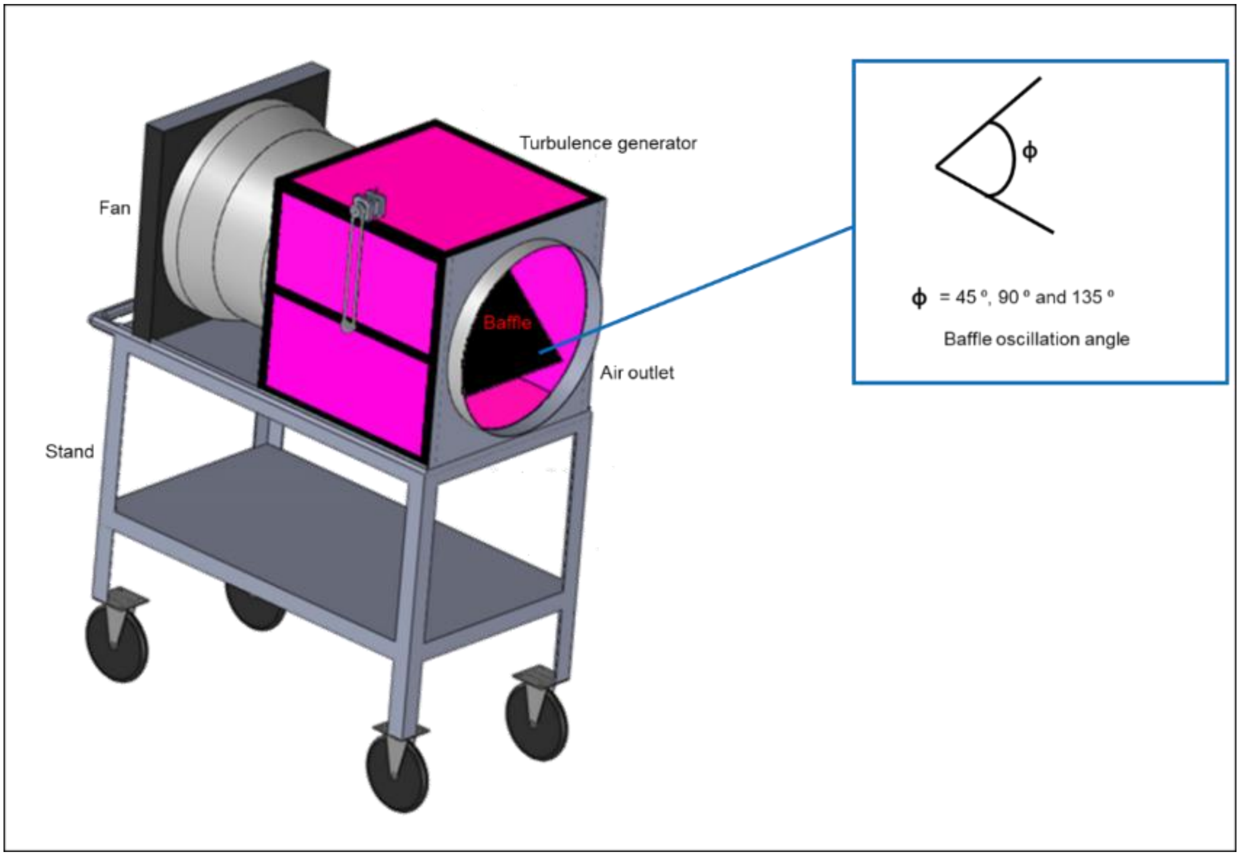


Figure 5.1: A ventilation system showing the main components and the baffle oscillation angles.

5.2.1.2. Variable speed fan

The variable speeds of the fan were achieved by sending a pulse width modulation (PWM) signal to a single-phase frequency converter (0.37-1.1kW) through a microcontroller (Arduino UNO). Three variable fan frequencies (12.7, 16.0 and 19.3 Hz) were obtained by using a retro-reflective type infrared photoelectric sensor (OPB725A-18Z model). In this design, the average airspeeds of 2.5, 3.5 and 4.5 m s^{-1} were needed and they were achieved with the fan frequencies (f_f) 12.7, 16.0 and 19.3 Hz respectively. To increase the airflow fluctuation of the fan, response times of 0.5 s and 2.0 s were set on the single-phase frequency converter for fan acceleration and deceleration respectively. Figure 5.2 shows the variable speed fan of the system.

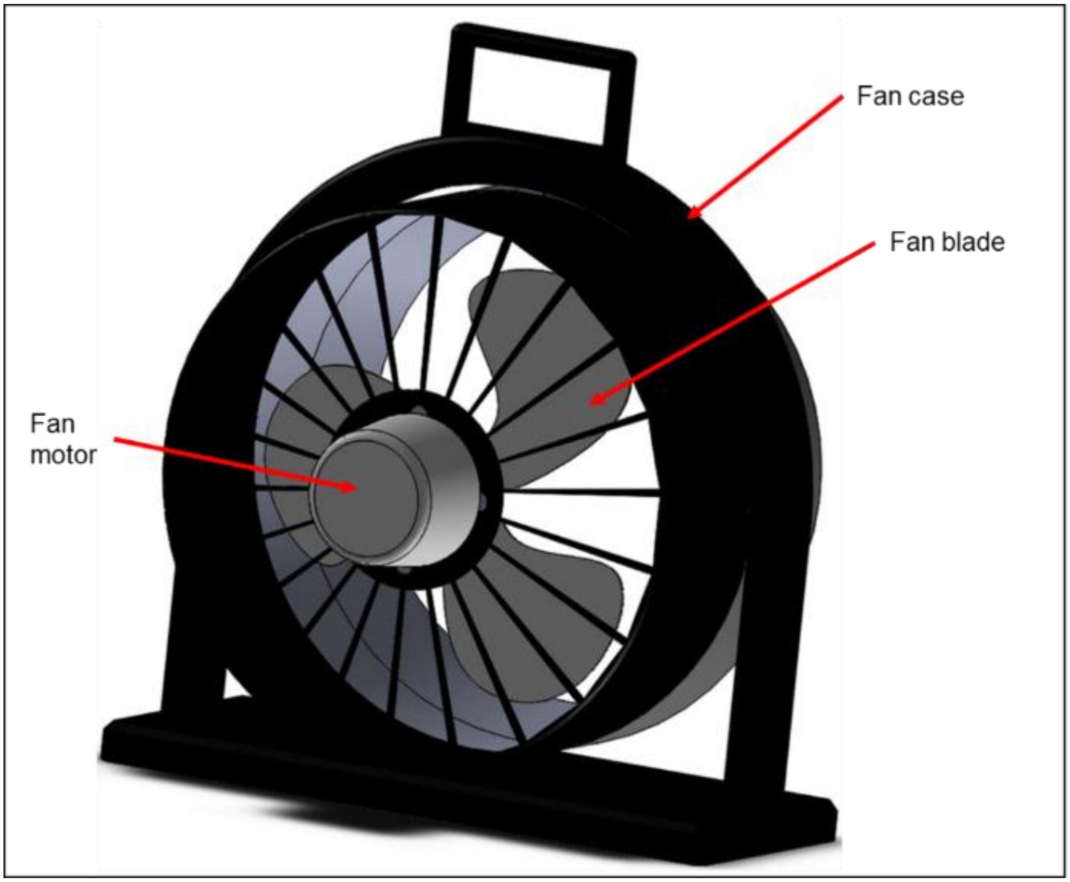


Figure 5.2: A fan with variable speeds.

5.2.1.3. Turbulence generator (TG)

The baffle oscillation frequencies and the baffle oscillation angles of the TG were achieved by sending timed phase, a control signal, to a stepper motor with 1.8 ° stepping angle and 2.8 N m holding torque (see Appendix 1 for calculation details). The signal was sent to the motor from a computer through a microcontroller (Arduino UNO) and an L298N DC dual H-bridge motor driver. Figure 5.3 shows the turbulence generator with oscillation baffle. TG was used to produce three oscillation frequencies, b_f, (0.25, 0.75 and 1.10 Hz) and oscillation angles, b_a, (45 ^{o}, 90 ^{o} and 135 ^{o}). These parameters were generated from a series of tests on the ventilation system to produce the required air turbulence intensity expected from the ventilation system. An oscillatory motion of the baffle was used to prevent swirling airflow that could occur as a result of the rotational motion of the baffle.

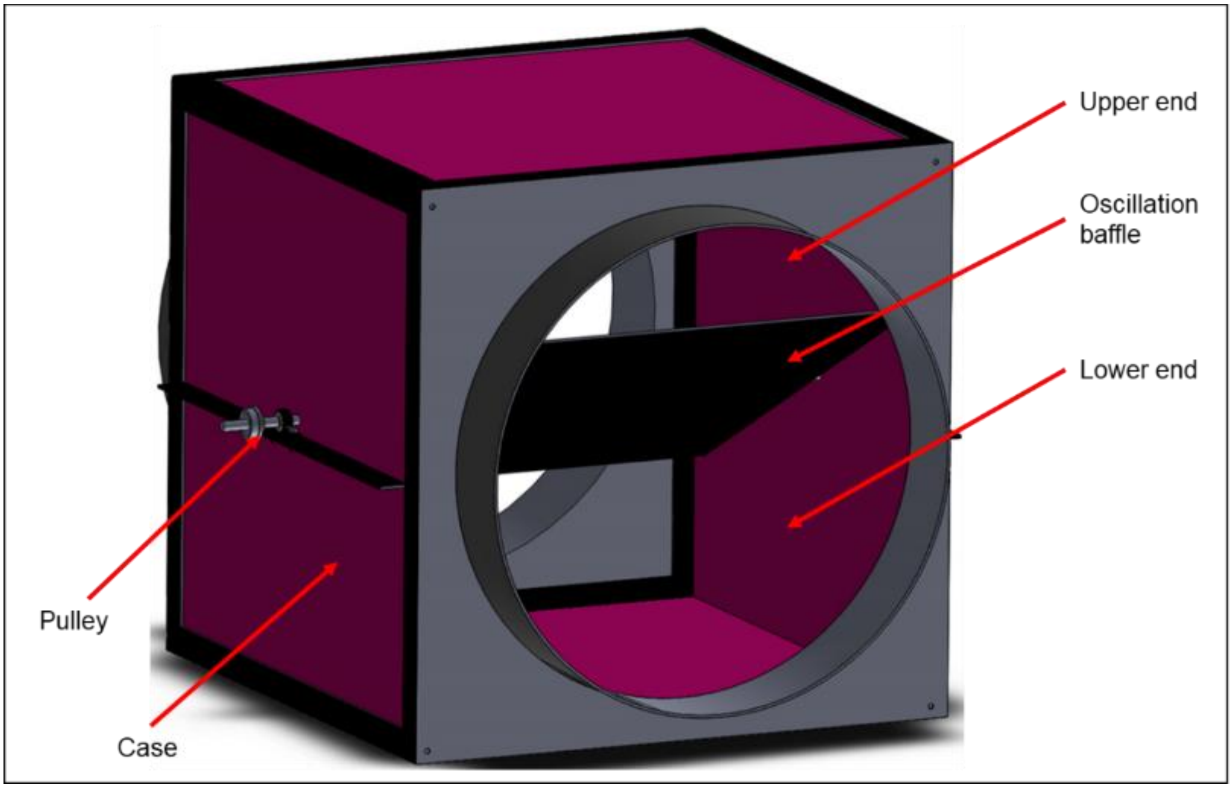


Figure 5.3: Turbulence generator with an oscillation baffle.

5.2.1.4. The operation principle of the ventilation system

Figure 5.4 presents the operation principle of the ventilation system. Arduino codes (for fan and stepper motor) were developed on a personal computer (PC) and communicated with ATMega 328P microcontroller using an Arduino UNO interface via a USB port (see Appendix 2 for the Arduino codes). The microcontroller was powered by a 0 – 5V power supply or the PC. The microcontroller sends pulse width modulation (PWM) signal to the frequency converter while a command pulse was sent to the stepper motor driver. Frequency converter controls the frequency and the voltage supplied to the fan motor while the stepper motor driver controls the magnitude and direction of current flowing into the stepper motor. The performance of the ventilation system was evaluated based on the level of airspeed and turbulence intensity it produced using an ultrasonic anemometer. The data acquired by the ultrasonic anemometer were logged on the PC using a WindView software supplied with the anemometer.

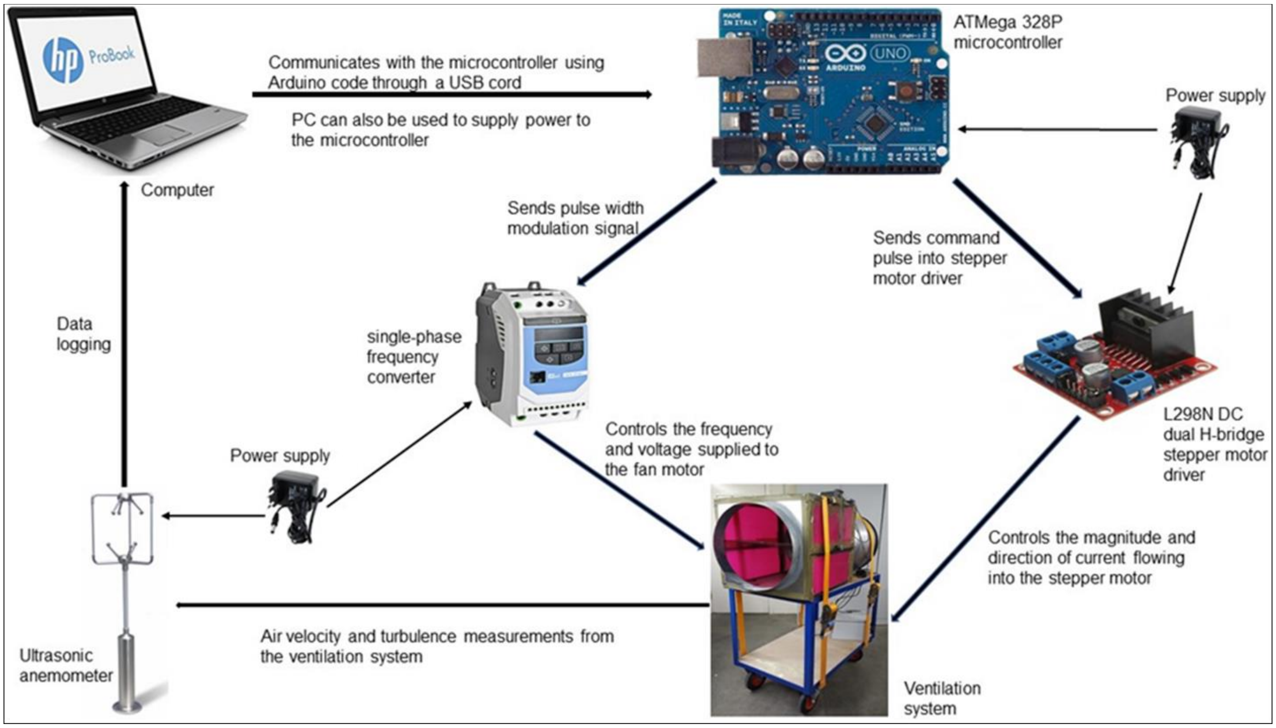


Figure 5.4: Operation principles of a ventilation system.

5.2.2 Performance evaluation of the hot weather ventilation system

To test the capacity of the ventilation system, 3-dimensional air velocities $(u_{x,}u_{y}\ and\ u_{z})$ at the outlet of the ventilation system were characterised by using two 3-D ultrasonic anemometers mounted on rigid tripod stands and placed at the upper and lower ends of the outlet of the ventilation system (Figure 5.5). This method of characterisation was considered as an appropriate approach based on the following reasons.

1. Airflow from the system, as the baffle oscillates, differs during the pre-test due to baffle opening size at the upper and lower ends.
2. Airspeed measurement at the centre of the system was not possible as airflow hardly occurs at the centre due to the baffle oscillation angle. Airspeed measurement at a 0.3 -0.5 m away from the system could have been possible, but it will result in poor capturing of exact airflow from the outlet of the system due to airflow loss to the immediate environment.
3. An averaged airflow from the two sensors was considered as a suitable approach for determining the airflow characteristic of the system as it represents the total airflow at the system outlet.

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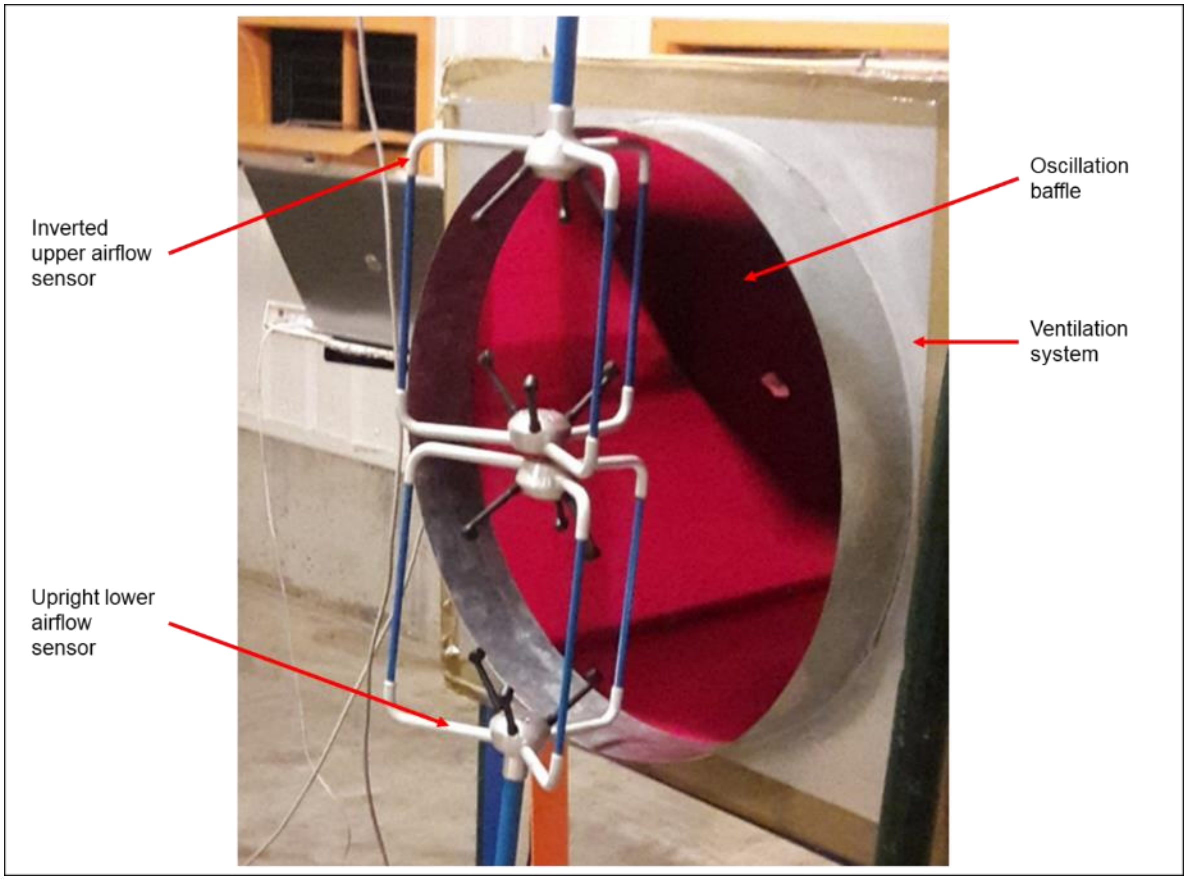

Figure 5.5: Airflow measurements at the outlet of the ventilation system

The anemometers were positioned in a way that one was positioned with the head inverted and the second positioned upright. The two positions were necessary to adequately determine the average airflow characteristics of the ventilation system. The two sensors were configured in accordance with their head positions to acquire airspeed at different fan speeds, baffle oscillation angles and baffle oscillation frequencies. As recommended by the manufacturer and also used by Taylor et al. (2004), the instrument was positioned with its u-axis (north spar) pointing towards the ventilation system. The airspeed (m s^{-1}) and the turbulence intensity of the ventilation system were obtained with the fan frequencies (f_f) set at 12.7, 16.0 and 19.3 Hz, baffle oscillation angles (b_a) set at 45 °, 90 ° and 135 ° and baffle oscillation frequencies (b_f) set at 0.25, 0.75 and 1.10 Hz. Air speeds were logged on the PC with a WindView software over a period of 10 minutes per observation.

5.2.3. Experimental design and data analysis

In this study, a 3x3x3 full factorial design was adopted for the performance evaluation of the ventilation system. This shows that there were three fan frequencies (12.7, 16.0 and 19.3

Hz), three oscillation angles (45 º, 90 º and 135 º) and three oscillation frequencies (0.25, 0.75 and 1.10 Hz). The operations of the ventilation system were repeated three times resulting in 81 observations in total. The air velocity components ($u_{x,}u_y\ and\ u_z$) acquired from the system were processed using equations 1 to 6 in section 2.3 and analysed with SAS JMP 14. The mean air velocities and the turbulence intensities were subjected to one-way ANOVA and a multiple comparison analyses using Tukey-Kramer HSD. Regression models were developed for the air velocity and turbulence intensity of the system. All analyses were performed on a 5 % significance level**.**

5.3 Results and discussion

5.3.1 The effect of fan frequency (Hz), baffle oscillation frequency (Hz) and the baffle oscillation angle (º) on the output airflow of the ventilation system.

Table 5.1 shows the mean air velocities (AV) and the corresponding turbulence intensities (Ti) produced by the ventilation system at different fan frequencies, baffle oscillation frequencies and baffle oscillation angles. It could be deduced from Table 5.1 that at different fan frequency, baffle oscillation frequency and baffle oscillation angle have significant impact on the airflow characteristics of the ventilation system. For instance, at a fan frequency (f_f) of 12.7 Hz and a baffle oscillation frequency of 0.25 Hz, increasing baffle oscillation angle (b_a) from 45 º to 135 º resulted in a 22.82 % decrease in the mean air velocity and 94.12 % increase in the turbulence intensity produced by the ventilation system. Similarly, at a fan frequency of 16.0 Hz and a baffle oscillation frequency of 0.75, an increase in baffle oscillation angle from 45 º to 135 º resulted in 20.92 % decrease in mean air velocity and 66.67 % increase in turbulence intensity. Finally, at a fan frequency of 19.3 Hz and a baffle oscillation frequency of 1.10 Hz, an increase in the baffle oscillation angle for 45 º to 135 º lead to a decrease of 18.79 % in the mean air velocity and an increase of 63.16 % in the turbulence intensity of the ventilation system. From the results, it could be observed that as the fan frequency increased, there is a continuous decrease in the percentage loss of the air velocity and the percentage gain in the turbulence intensity of the ventilation system.

The one-way ANOVA analysis performed on the airflow characteristics of the ventilation system indicated that there was a significant difference (p < 0.0001) between the mean air velocities and the turbulence intensities of the ventilation system. Further analysis with the Tukey-Kramer HSD indicated that there was a significant difference in the mean air velocities and the turbulence intensities between the fan frequency (Hz), baffle oscillation frequency (Hz) and the baffle oscillation angle (º) of the ventilation system. The results of this study supports the findings of Huang et al. (2012) who indicated that airflow characteristics of ventilation systems could be altered by simply integrating a turbulence generator (oscillation baffle) to the ventilation system. Furthermore, it could be observed from Table 5.1 that as the mean air velocity increased, there was a decrease in the turbulence intensities. Similar results have also been reported in the previous research studies (Melikov et al., 2005; Sun et al., 2007; Xia et al., 2000). Figure 5.6 shows the airflow characteristics of the ventilation system as a result of the combined effect of the fan frequency (Hz), baffle oscillation frequency (Hz) and the baffle oscillation angle (º).

Table 5.1: The airflow characteristics [mean air velocity, AV (m s^{-1}) and turbulence intensity] of the ventilation system. The superscript letters represent the significant differences in the mean air velocity (m s^{-1}) and mean turbulence intensity between the fan frequency (Hz), Baffle oscillation frequency (Hz) and Baffle oscillation angle (º) according to Tukey-Kramer HSD at a 5 % level of significance.

Fan frequency (HZ)	**Baffle oscillation frequency (Hz)**	**AV (m s^{-1}) at different baffle oscillation angle (º)**			**P-value**	**Ti at different baffle oscillation angle (º)**			**P-value**
		45	90	135		45	90	135	
12.7	0.25	2.98^{A}	2.78^{B}	2.30^{C}	< 0.0001	0.17^{C}	0.22^{B}	0.33^{A}	< 0.0001
	0.75	2.95^{A}	2.49^{B}	2.13^{C}	< 0.0001	0.17^{C}	0.26^{B}	0.33^{A}	< 0.0001
	1.10	2.85^{A}	2.43^{B}	2.01^{C}	< 0.0001	0.19^{C}	0.27^{B}	0.38^{A}	< 0.0001
16.0	0.25	3.61^{A}	3.36^{B}	2.86^{C}	< 0.0001	0.17^{C}	0.22^{B}	0.30^{A}	< 0.0001
	0.75	3.49^{A}	3.01^{B}	2.76^{C}	< 0.0001	0.18^{C}	0.26^{B}	0.30^{A}	< 0.0001
	1.10	3.43^{A}	2.94^{B}	2.55^{C}	< 0.0001	0.19^{C}	0.26^{B}	0.35^{A}	< 0.0001
19.3	0.25	4.61^{A}	4.42^{B}	3.55^{C}	< 0.0001	0.17^{C}	0.23^{B}	0.35^{A}	< 0.0001
	0.75	4.57^{A}	4.11^{B}	3.64^{C}	< 0.0001	0.18^{C}	0.26^{B}	0.31^{A}	< 0.0001
	1.10	4.47^{A}	4.09^{B}	3.63^{C}	< 0.0001	0.19^{C}	0.25^{B}	0.31^{A}	< 0.0001

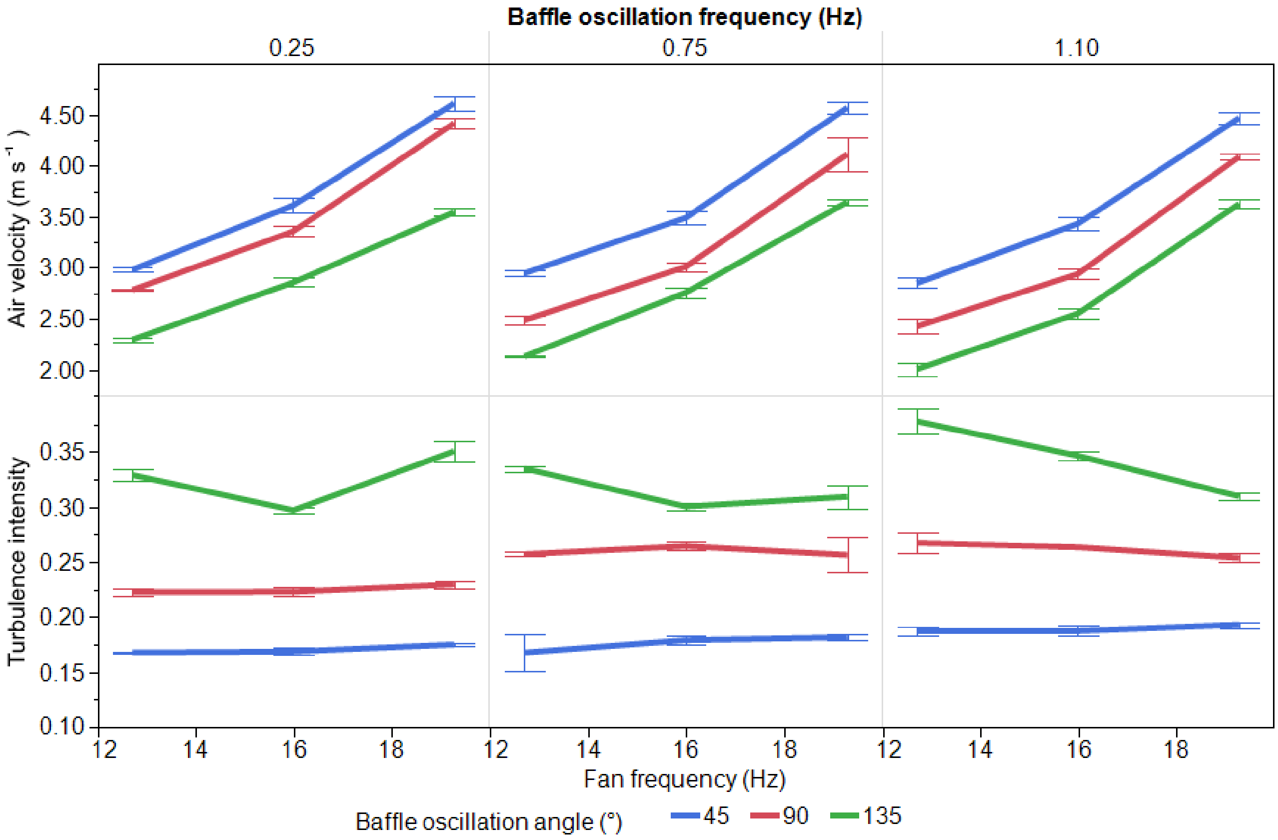

Figure 5.6: Airflow characteristics of a ventilation system with oscillation baffle

5.3.2 Regression model of the ventilation system

Two regression models were fitted for the air velocity and turbulence intensity produced by the ventilation system using Standard Least Square. The models were developed based on the effects of fan frequency (Hz), baffle oscillation frequency (Hz) and the baffle oscillation angle (º).

5.3.2.1 Air velocity ($\mathbf{AV}$) prediction model

Equation (30) shows a regression model for the prediction of expected air velocity from the ventilation system. The equation shows that for every additional unit of fan frequency (f_f), the mean air velocity of the system is expected to increase by an average of 0.24 m s^{-1}. A unit increase in baffle oscillation frequency (b_f) and baffle oscillation angle (b_a) would negatively affect the average air velocity produced by the ventilation system. According to the model, the baffle oscillation frequency and the baffle oscillation angle were predicted to cause an average decrease of 0.27 m s^{-1} and 0.01 m s^{-1} in the mean air velocity respectively. The results of the analysis of variance indicated that fan frequency, baffle oscillation frequency and baffle oscillation angle have significant effect ($p < 0.0001$) on the mean air velocity of the ventilation system.

$$AV\ (m\ s^{-1}) = 0.47 + 0.24 * (f_f) - 0.27 * (b_f) - 0.01 * (b_a) \qquad (30)$$

where f_f is the fan frequency (Hz), b_f is the baffle oscillation frequency (Hz) and b_a is the baffle oscillation angle (º).

Figure 5.7 shows the plot of measured against predicted mean air velocity. From the Figure 5.7, it is clear that the model accurately predicted the air velocity of the ventilation system as there is a strong correlation between the predicted values of the model and the values of the measured air velocity of the ventilation system. The model also fits the data appropriately as the differences between the measured and predicted values of air velocity are small (± 10 %) and unbiased. This was also supported by the coefficient of determination ($R^2 = 0.97$) which indicates that the prediction model explained 97 % of the variability of air velocity around its mean values.

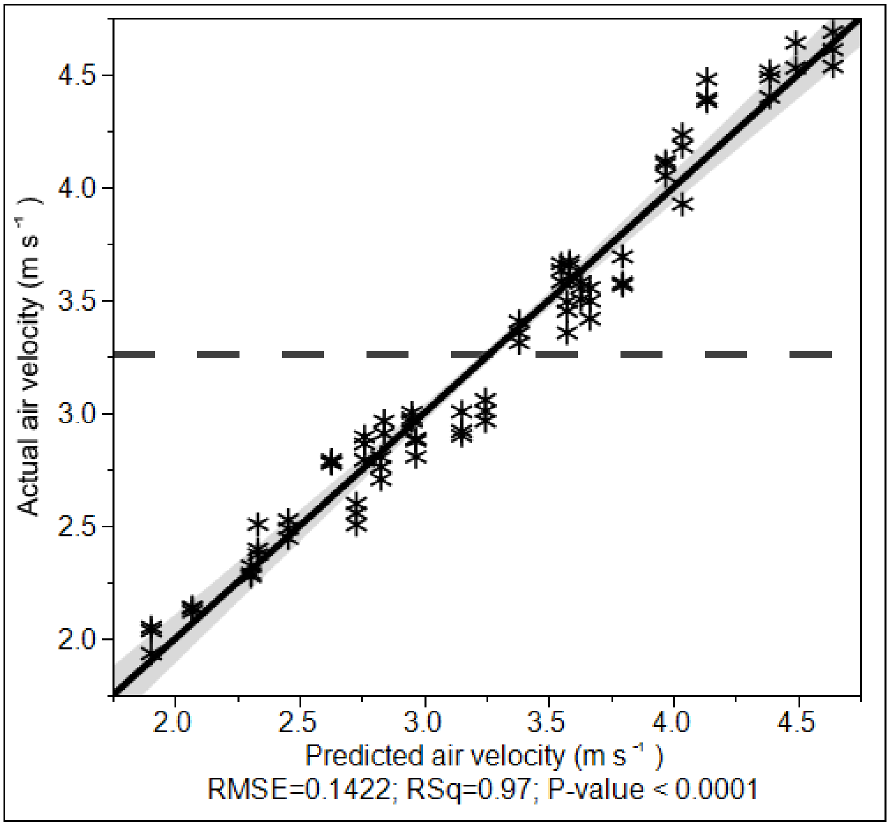

Figure 5.7: A regression plot showing the measured against predicted air velocity (m s^{-1}).

5.3.2.2 Turbulence intensity (T_i) model

Equation (31) shows a regression model for predicting the turbulence intensity of the ventilation system. The equation shows that for a unit increase in baffle oscillation frequency, the turbulence intensity of the system is expected to increase by an average of 0.027 (2.7 %). A unit increase in baffle oscillation angle would result in an average increase of 0.002 (0.2 %) in the turbulence intensity. Furthermore, a unit increase in the interactions between fan frequency and baffle oscillation frequency would reduce the turbulence intensity by 0.01 (1 %). In addition, a unit increase in the interaction between fan frequency and baffle oscillation angle could reduce the turbulence intensity by 0.0000556 (5.56x10^{-3} %) while the interaction between the fan frequency, baffle oscillation frequency and baffle oscillation angle would reduce the turbulence intensity by 0.0002 (0.02 %). The results of the analysis of variance indicated that the fan frequency, baffle oscillation frequency and baffle oscillation angle have a significant effect ($p < 0.0001$) on the turbulence intensity of the ventilation system.

$$\begin{aligned} T_i = {} & 0.096 + 0.028 * (b_f) + 2e^{-3} * (b_a) - 0.01 * (f_f - 16)(b_f - 0.7) - 5.56e^{-4} \\ & * (f_f - 16)(b_a - 90) - 2e^{-4} * (f_f - 16)(b_f - 0.7)(b_a - 90) \end{aligned} \tag{31}$$

where f_f is the fan frequency (Hz), b_f is the baffle oscillation frequency (Hz) and b_a is the baffle oscillation angle (º).

Figure 5.8 shows the regression plot of measured against predicted turbulence intensity of the ventilation system. From Figure 5.8, it is clear that the model accurately predicted the turbulence intensity of the ventilation system as there is a strong correlation between the predicted values and the values of the measured turbulence intensity. The model also fits the data appropriately as the differences between the measured and predicted values of turbulence intensity are small (± 10 %) and unbiased. This was also supported by the coefficient of determination ($R^2 = 0.96$) which indicates that the prediction model explained 96 % of the variability of turbulence intensity around its mean values.

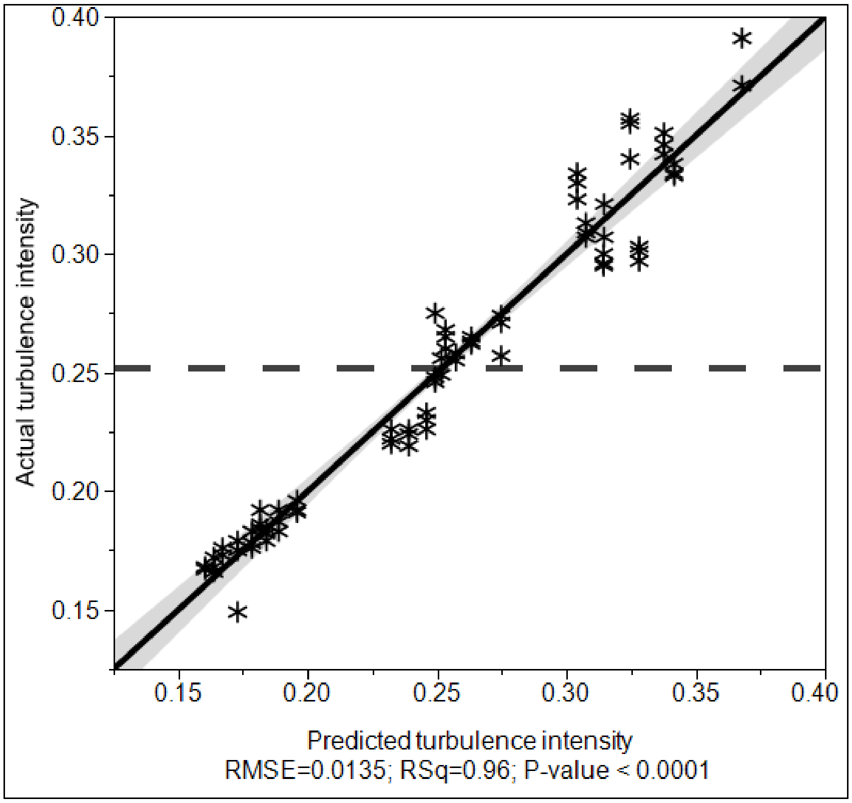

Figure 5.8: Regression model showing the measured against predicted turbulence intensity.

5.3.2.3 The impact of the interaction between the fan frequency, baffle oscillation frequency and baffle oscillation angle on air velocity and turbulence intensity.

Figure 5.9 show cube and contour plots illustrating the effects of fan frequency, baffle oscillation frequency and baffle oscillation angle on the air velocity and turbulence intensity. It shows the impact of the interaction between the fan frequency (Hz) and baffle oscillation angle (º) and the fan frequency (Hz) and the baffle oscillation frequency (Hz) on the air velocities and turbulence intensities of the ventilation system. As shown in Figure 5.9a, there is an indication that as the fan frequency increases and the baffle oscillation angle and baffle oscillation frequency decrease, there is a probability that air velocity of the ventilation system would increase. However, in Figure 5.9b it could be observed that as the fan frequency reduces and the baffle oscillation angle and baffle oscillation frequency increase, there is a probability that the turbulence intensity of the ventilation system would increase. Furthermore, it could be seen from the plots in Figure 5.9a that the effect of fan frequency was greater than the effect of baffle oscillation frequency and baffle oscillation angle on the air velocity of the ventilation system. However, in Figure 5.9b, the effects of fan frequency, baffle oscillation frequency and baffle oscillation angle on the turbulence intensity changed. It could be detected in Figure 5.9b that the effect of baffle oscillation frequency and baffle oscillation angle were larger than the effect of fan frequency on the turbulence intensity of the ventilation system.

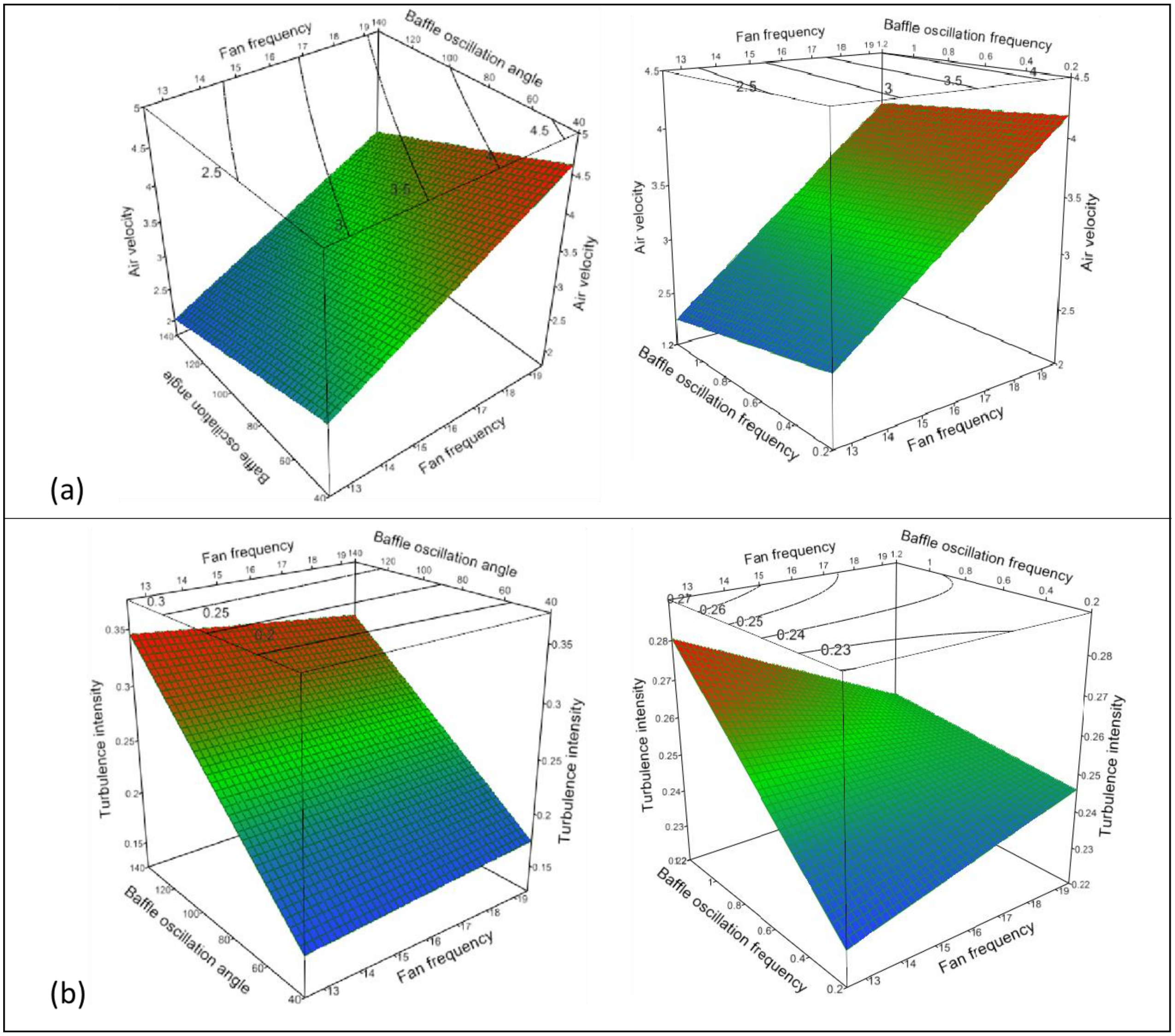

Figure 5.9: Contour plot of (a) air velocity and (b) turbulence intensity against fan frequency, baffle oscillation frequency and baffle oscillation angle.

5.4 Conclusion

This study has shown that turbulence intensity of a ventilation system could be increased with minimal effect on the average air velocity. For instance, at 19.3 Hz fan frequency, which generated approximately 4.5 m s^{-1}, integrating turbulence generator with baffle oscillation frequency set at 1.10 Hz and baffle oscillation angle set at 45 º, resulted in 0.2 % reduction in final air velocity output of the ventilation system. However, it has been shown that the reduction in the output air velocity of the ventilation could be compensated with the increase in the turbulence intensity as the baffle oscillation frequency and baffle oscillation angle increased. The ventilation system developed in this study is capable of producing 2.5 to 4.5 m s^{-1} air velocity and 0.15 to 0.35 turbulence intensity at variable fan frequency (12.7, 16.0 and 19.3 Hz), baffle oscillation frequency (0.25, 0.75 and 1.10 Hz) and baffle oscillation angle (45, 90 and 135 º).

The air velocity model [$AV = 0.47 + 0.24 * (f_f) - 0.27 * (b_f) - 0.01 * (b_a)$] could lead to improving air velocity in the broiler occupied zones. It could also be used to estimate the output air velocity of the ventilation system at lower or higher fan frequencies, baffle oscillation angles and baffle oscillation frequencies. With the model, the ventilation engineers could be guided on the control of similar ventilation system based on the air velocity and turbulence intensity requirement in the livestock buildings. This ventilation system was developed to generate air velocity ranging from 2.5 to 4.5 m s^{-1} and the turbulence intensity ranging from 0.15 to 0.35. In order to produce air velocity and turbulence intensity different from the air velocity and turbulence intensity discussed in this study, there is a need for the ventilation engineer to also modify the fan frequency, baffle oscillation frequency and baffle oscillation angle of the ventilation system. However, the air velocity model in this study could be used as a design tool for generating or estimating the air velocity required in the animal buildings by the ventilation engineers. Further research study is need to examine the performance of the ventilation system on the airflow distributions in the broiler occupied zones of the broiler building.

CHAPTER SIX

IMPROVEMENT OF AIR VELOCITY DISTRIBUTIONS IN THE BROILER OCCUPIED ZONES WITH AN OSCILLATING INLET BAFFLE

6.1 Introduction

Proper ventilation of livestock building is crucial in ensuring thermal uniformity in livestock occupied zones (Mostafa et al., 2012). The ventilation system in the livestock buildings should be able to provide a suitable, stable and uniform indoor environmental conditions across the livestock building. However, this is difficult as the indoor conditions of the livestock building are mainly influenced by the outdoor conditions. Air movement at the broiler occupied zones is important as it does not only determine the thermal comfort of birds, it also determines the quality of the litter and the health of livestock depends on the design of livestock ventilation systems (Jiang et al., 2003; Mostafa et al., 2012). Therefore, while it is important to improve the homogeneity of airflow within the broiler building, it is equally necessary to ensure adequate air distributions in the broiler occupied zones during hot weather conditions.

There was a directive by the European Commission (EC) allowing the farmers to raise the broiler chickens up to a maximum of 42 kg m^{-2} (European Commission, 2016) against the initial maximum stocking density of 33 kg m^{-2} without affecting the welfare of broiler chickens (Estevez, 2007; European Commission, 2016). This higher stocking density was allowed in the broiler production under the condition that the farmers are capable of providing minimum environmental conditions required by the broiler chickens. Prior to the recent directive of the EC in 2016, many studies have been carried out to investigate the effect of high stocking density on broiler welfare and performances. Buijs et al. (2009) indicated that a high stocking density significantly influenced leg health ($p = 0.02$) and hock dermatitis ($p < 0.001$) of broiler chickens. A high stocking density could result in lower feed intake, poor feed efficiency, poor growth and higher ventilation requirement (Yani et al., 2014). As at the moment, all studies on the impacts of stocking density on the wellbeing of broiler chickens have only been evaluated based on the mortality and footpad dermatitis (European Commission, 2016) with less consideration on the immediate microclimate around broiler chickens (Estevez, 2007; Jongbo et al., 2016). There is no explicit study on the effects of stocking density on the air distribution in the broiler occupied zones. Therefore, while higher stocking density could influence broiler welfare and performances, it is also important to evaluate air distribution in the broiler occupied zones with respect to higher stocking density of 39 kg m^{-2} allowed in the United Kingdom (European Commission, 2016).

Globally, some studies have shown the importance of airflow turbulence on the heat transfer from humans, cylinder and pig models (Cui et al., 2013; Gori and Petracci, 2012; Li et al., 2016a; Yang et al., 2013). Although airflow turbulence has been reported to aid higher heat transfer from warm objects, it is still difficult to integrate turbulence into the ventilation system of livestock buildings. Therefore, this study was set up to investigate the impact of inlet turbulence generated by an oscillating inlet baffle on the indoor airflow characteristics. The objectives of the study were; (1) to study the effect of inlet turbulence, generated by oscillating baffle on the airflow distributions in the broiler occupied zones in an empty and occupied experimental broiler room; (2) to examine the impact of inlet turbulence on airflow characteristics in the broiler occupied zones with higher stocking density.

6.2 Materials and methods

In this study, a hot weather ventilation system with oscillating inlet baffle was tested in a broiler experimental room. This was necessary because conducting this study in a larger broiler building could cause the airflow of the ventilation system to spread out to areas not needed for the study. It is also essential to ensure that maximum airflow reached all the measurement locations.

6.2.1. Poultry research room

This research work was carried out in one of the poultry research rooms at Harper Adams University, United Kingdom. This was necessary as the room allowed maximum control over the indoor climatic conditions with minimal impact from the outdoor conditions. The dimensions of the room are; Length = 7.3 m; width = 5.44 m; sidewall height = 2.35 m; roof slope = 22.6 °; maximum height of the room = 5.22 m. The room is equipped with a water source for birds' drinking and bell-type feeders. The ventilation system of the room comprises a 0.45 m diameter mechanical fan, a rectangle (0.46 X 0.29 m) inlet and a climate control system (CLIMATEC). There are four 3 kW wall-mounted electric fan heaters in the room for heating. The room was washed and sanitised before it was used for the experiment. It is necessary to indicate that the ventilation system in the room was not used throughout this study.

6.2.2. Experimental setup

Before the commencement of the experimental study, the ventilation system of 1.05 m long was raised to a height similar to the inlet height in the typical sidewall inlet and roof exhaust ventilated broiler building by mounting it on a flat surface cart of 0.96 m high. The ventilation system was placed at the front of the inlet sidewall at a distance of 0.5 m. The clearance between the wall and the ventilation system was necessary to give room for the mechanical adjustment and operations of the ventilation system. The ventilation system with the oscillating inlet baffle was switched on and allowed to operate at the maximum fan frequency of 19.3 Hz for an average period of 30 minutes. This was essential to ensure maximum air distribution within the room and most especially at the measurement locations. The fan frequency generated an average air velocity of 4.5 m s^{-1}. The oscillation frequencies (0.25, 0.75 and 1.1 Hz) and the oscillation angles (45 º, 90 º and 180 º) of the inlet baffle were combined to generate an inlet turbulence 0.15, 0.25 and 0.35 needed for this study. The combination details of the oscillation inlet can be found in chapter 5. Figure 6.1 shows the schematics of experimental room with the ventilation system.

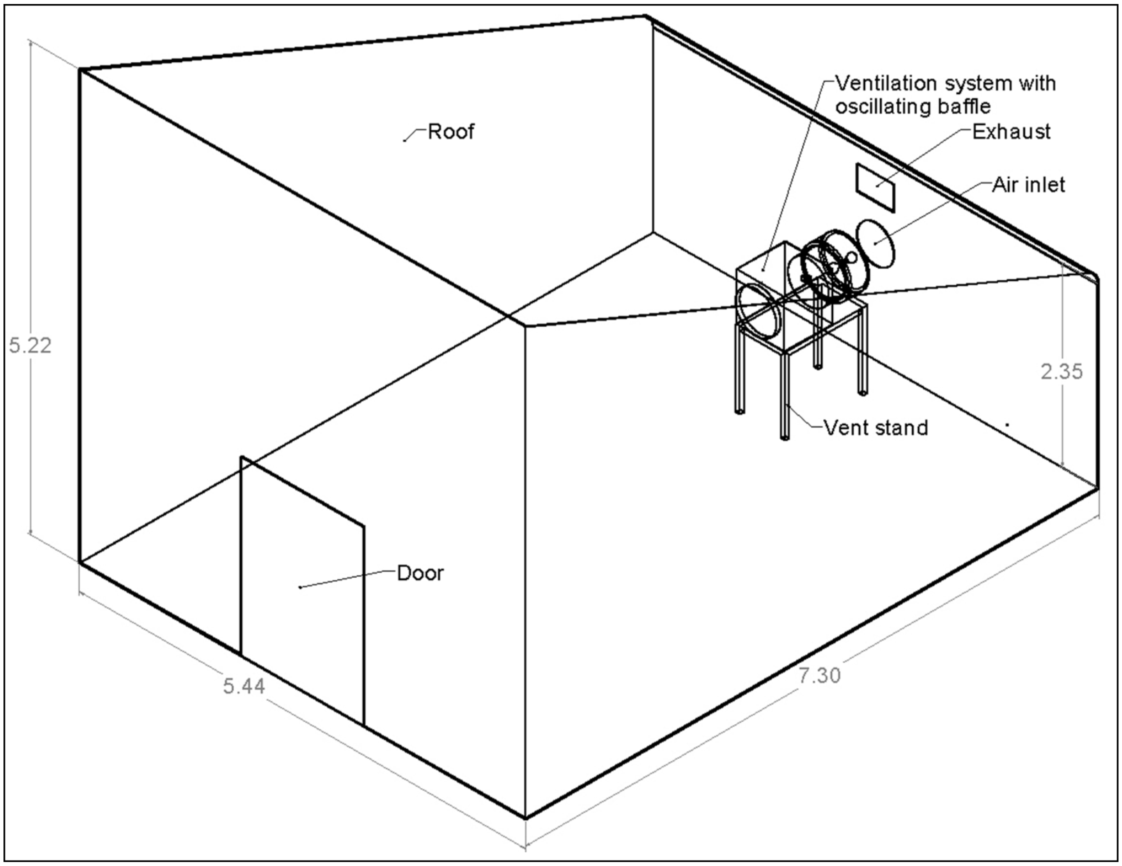

Figure 6.1: Experimental room with the ventilation system. All dimensions are in metres.

6.2.3. Study 1: Empty experimental room

The ventilation system was tested in an empty experimental room to evaluate the air distributions of the system at different distances. Figure 6.2 shows the experimental set up within an empty broiler experimental room. In order to characterise the air velocity distributions in the broiler occupied zones, three 3-dimensional ultrasonic anemometers were mounted on three rigid tripod stands and used. The anemometers were mounted with its head inverted to measure air velocity at the broiler height (0.2 m above the floor) as recommended by the sensor manufacturer for measurements below 1 m above the floor. The anemometers were positioned with the u-axis (north spar) on them pointing towards the direction of the ventilation system (Taylor et al., 2004). The airflow sensors were positioned at 1, 3 and 5 m from the ventilation system to acquire air velocity measurements. The air velocity measurements at these locations were necessary to fully understand the impact of inlet turbulence on the airflow distributions in the broiler occupied zones (0.20 m above the floor) as the distance from the ventilation system increases. All measurements data from the airflow sensors were logged using WindView over a period of 10 minutes on an HP ProBook 4540s laptop.

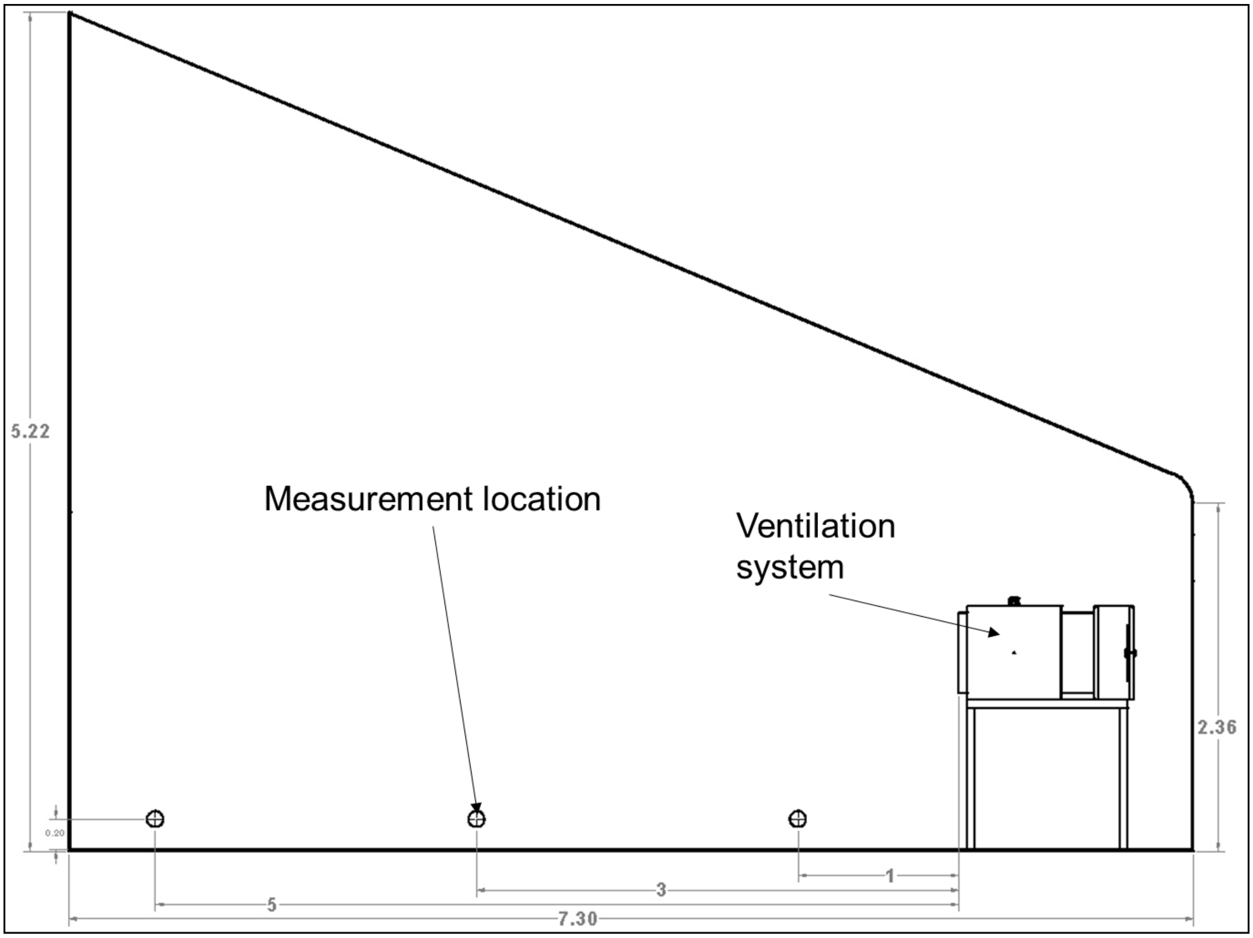

Figure 6.2: The experimental set up within an empty experimental room showing measurement locations from the ventilation system at 0.20 m above the floor. All measurements are in metres.

6.2.4. Study 2: Experimental room occupied with broiler models at a stocking density of 33 kg m^{-2}

This study evaluated the performance of the ventilation system with the room occupied with broiler models (plastic footballs), feeder and drinker lines. The models were used based on the fact that birds are considered to be spherical in shape (Li et al., 2016b). The room was not equipped with a feeder and drinker lines. Therefore, three bell-type and two 5-nipples triangular drinkers with water lines were used in place of the feeder and drinker lines typically found in the modern broiler buildings. The bell-type feeders were placed 1.0 m apart while the drinker lines were positioned 2.0 m apart. The first feeder was positioned at 1.0 m from the ventilation system while the first drinker was 0.50 m from the ventilation system. For this study, a floor space of 10 m^{2} (5 m by 2 m) was marked out and covered with 0.05 m thick wood shavings in order to simulate floor condition of a typical commercial broiler building and to keep the plastic footballs stationary when exposed to high airflow. In this study, broiler models representing an adult broiler chicken of body weight ($M_{chicken}$) 2.0 kg were used. The number of broiler models used within the marked floor space was based on the stocking density recommended by the European Commission. It is recommended that the maximum stocking density of broiler chickens, to protect the welfare of birds, should not be more than 33 kg m^{-2} (European Commission, 2016). Therefore, a total of 165 broiler models, with each having a characteristic dimension (diameter) of 0.165 m were placed on the 10 m^{2} floor space. It is necessary to indicate that the broiler models were randomly placed on the litter (wood shavings) and no arrangement pattern was followed. The characteristic dimension ($D_{poultry}$) of the models (0.165 m) was determined by using $D_{poultry} = 0.131 \times M_{chicken}{}^{0.33}$ (Mitchell, 1930). Figure 6.3 shows the indoor arrangement of the experimental room occupied with broiler models.

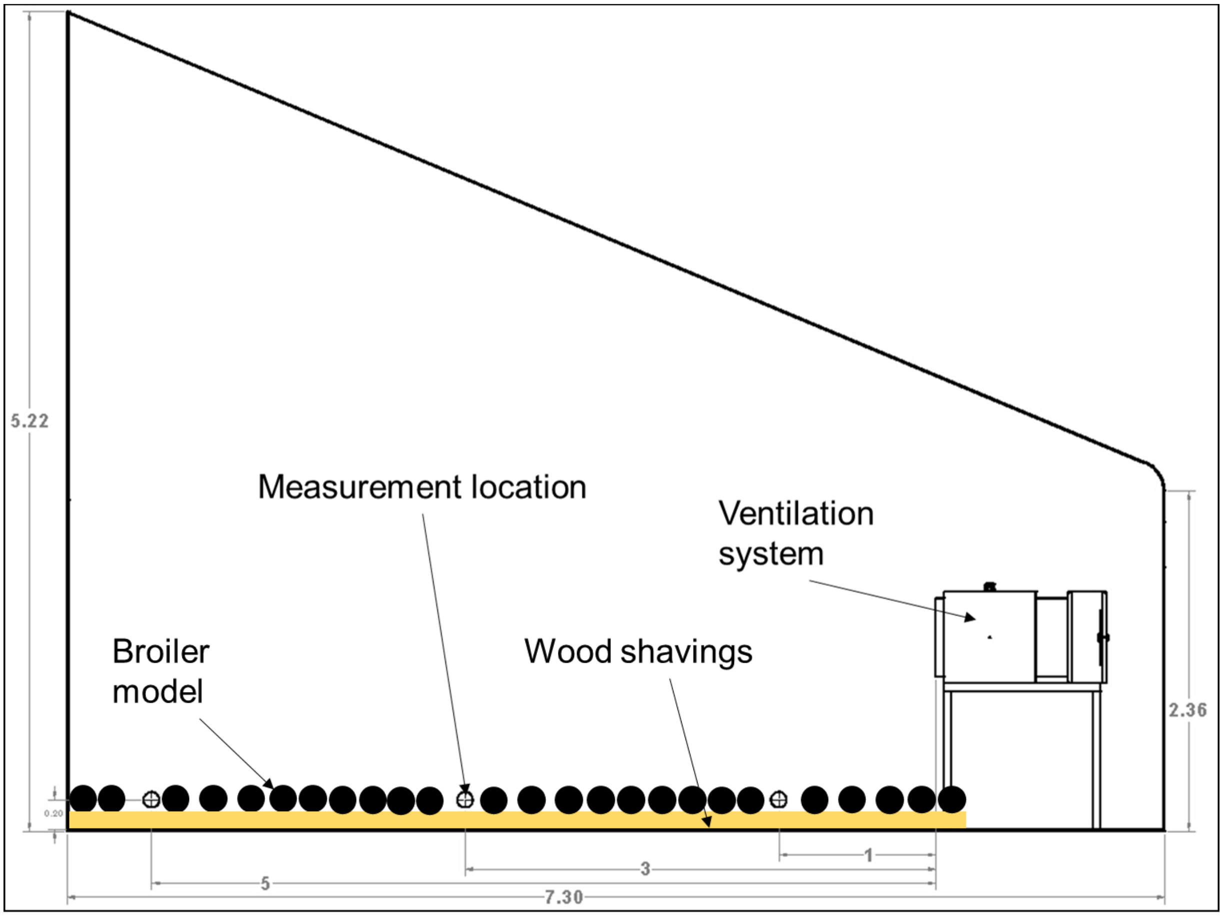

Figure 6.3: The experimental set up within an experimental room occupied with broiler models showing the locations of the sensors from the ventilation system. All measurements are in metres.

In order to observe, measure and log the air velocity distributions in the broiler occupied zones, three ultrasonic anemometers were used. They were mounted on rigid tripod stands with their heads inverted. For accuracy, the sensor's manufacturer advised that the anemometers should be configured based on the head's position (that is upright for measurements at over 1.0 m above the floor and inverted for measurements at a height below 1.0 m above the floor). In this study, measurements were obtained in the broiler occupied zones (0.20 m above the floor). The sensors were positioned with their head inverted and configured appropriately to acquire air velocity measurements. The airflow sensors were stationed at 1, 3 and 5 m from the ventilation system and data were obtained over a period of 10 minutes.

6.2.5. Study 3: Effects of inlet airflow turbulence on the air velocity distribution in the broiler occupied zones at a higher stocking density of 39 kg m^{-2}

In Europe, farmers are permitted to increase the stocking density of broiler chickens provided that adequate environmental conditions are provided (European Commission, 2016). In some countries such as the UK and Germany, more stringent legislation have implemented and the stocking density is set at 39 kg m^{-2} (European Commission, 2016). With this higher stocking density (39 kg m^{-2}), which is about 20 birds per square metre of 2.0 kg body weight adult broiler chickens, there is a possibility that the air distribution in the broiler occupied zones would be reduced compared to the stocking density of 33 kg m^{-2} (16.5 birds per square metre). There is no adequate information on the effect of stocking density on air velocity distributions in the broiler occupied zones. Similarly, no report is available on how the effect of stocking density can be minimised by the inlet turbulent. This study was therefore set up to investigate the effect of inlet turbulent on the air velocity distributions in the broiler occupied zones with higher stocking density.

In this experiment, the stocking density of plastic football was increased to 39 kg m^{-2}. The characteristic dimensions of the plastic footballs are similar to that discussed in the Study 2. The ultrasonic anemometers were set up at distance 1, 3 and 5 m from the ventilation system to measure the instantaneous air velocities at the broiler level (0.20 m above the floor) over a period of 10 minutes. It is also essential to emphasise that the broiler models used were randomly placed on the wood shavings and no arrangement pattern was followed.

6.2.6. Experimental design and statistical analysis

The impacts of inlet air fluctuation on the mean air velocities in the broiler occupied zones within empty broiler room, occupied broiler room with 33 kg m^{-2} and the broiler room with higher stocking density of 39 kg m^{-2} were investigated with a 3x3 full factorial experimental design. This indicates that there were 3 inlet turbulence intensities (0.15, 0.25 and 0.35) and 3 distances (1, 3 and 5 m) from the ventilation system and the airspeed of the fan was maintained at 4.5 m s^{-1}. The airspeed used in this study has been discussed in Chapter 5. The experiments were repeated three times, resulting in a total of 27 experimental observations each. The data were processed using equations 1 to 6 in section 2.3 and subjected to a one-way ANOVA, t-test and multiple comparisons (Tukey-Kramer HSD) analysis using SAS JMP 14. The analyses were performed on a 5 % significance level.

6.3 Results and discussion

6.3.1 Study 1: Air velocity distributions in the empty broiler room

Figure 6.4 shows the effects of inlet turbulence on the airflow characteristics in the broiler occupied zones within an experimental room. At a distance of 1 m from the ventilation system, the results shown in Figure 6.4 indicate that an average air velocity of 0.58, 0.24 and 0.41 m s^{-1} were obtained in the broiler occupied zones at 0.15, 0.25 and 0.35 inlet turbulence respectively. As the distance increased to 3 m from the ventilation system, the average air velocity recorded in the broiler occupied zones at the inlet turbulence of 0.15, 0.25 and 0.35 were 0.64, 0.63 and 0.61 m s^{-1} respectively. At the downstream (5 m from the ventilation system), an average air velocity of 0.33, 0.38 and 0.34 m s^{-1} were obtained at the inlet turbulence of 0.15, 0.25 and 0.35 respectively. The results also shown in Figure 6.4 are the turbulence intensities in the broiler occupied zones. The turbulence intensities of 0.35 to 0.77 were generated in the broiler occupied zones at the inlet turbulence of 0.15. At inlet turbulence of 0.25, the turbulence intensities in the broiler occupied zones were between 0.32 and 0.83. At higher inlet turbulence of 0.35, the turbulence intensities in the broiler occupied zones were between 0.28 and 0.66.

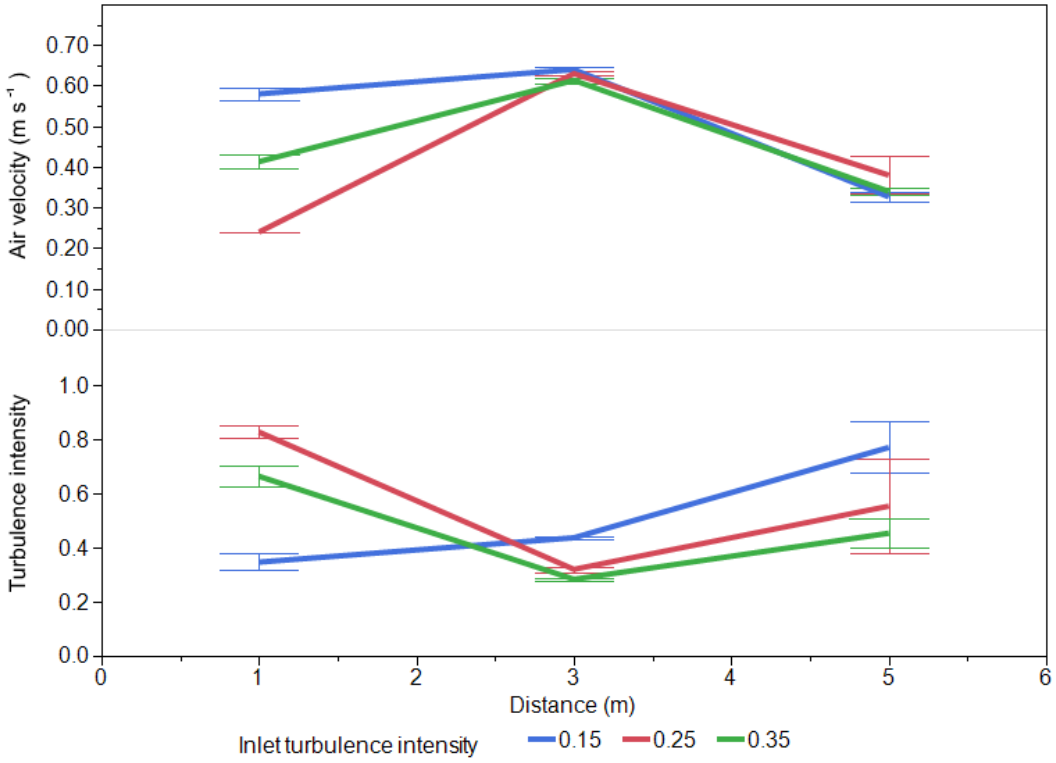

Figure 6.4: Airflow characteristics in the broiler occupied zones of an empty broiler room as a function of inlet turbulence.

In typical commercial broiler building, air velocity in the areas closer to the walls are usually very low or almost zero due to the effect of wall barrier (Bjerg et al., 2002). However, the results of this study have shown that the air movement in the broiler occupied zones, closer to the wall areas could be improved with the integration of an oscillating inlet baffle into the ventilation system of broiler building. As shown in Figure 6.4, there is an indication that the mean air velocity in the broiler occupied zones was also restricted by the distance from the ventilation system (Lau and Ritzer, 2005).

The results of the one-way ANOVA and the Tukey-Kramer HSD analysis are shown in Table 6.1. The analysis indicates that there was a significant difference in the mean air velocities between the inlet turbulence at a distance of 1 m from the ventilation system. At 3 and 5 m from the ventilation system, there was no significant difference in the mean air velocities between the inlet turbulence.

Table 6.1: The air velocity distributions in the broiler occupied zone of an empty broiler building at different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m) from the ventilation system	**Air velocities (m s^{-1}) in the broiler occupied zones at different inlet turbulence**			**P-value**
	0.15	0.25	0.35	
1	0.58^{A}	0.24^{C}	0.41^{B}	< 0.0001
3	0.64^{A}	0.63^{AB}	0.61^{B}	0.0548
5	0.33^{A}	0.38^{A}	0.34^{A}	0.4353

6.3.2. Study 2: Effect of inlet turbulence on the airflow characteristics in the broiler occupied zones of a broiler room occupied with broiler models at stocking density of 33 kg m^{-2}

Figure 6.5 shows the effects of inlet turbulence on the airflow characteristics in the broiler occupied zones. As shown in Figure 6.5, at 1.0 m from the ventilation system, the average air velocities obtained at inlet turbulence of 0.15, 0.25 and 0.35, were 0.24 m s^{-1}, 0.17 m s^{-1} and 0.32 m s^{-1} respectively. At a distance of 3.0 m from the ventilation system, the average air velocities produced by 0.15, 0.25 and 0.35 inlet turbulence were 0.61 m s^{-1}, 0.55 m s^{-1} and 0.45 m s^{-1} respectively. Farther away from the ventilation system (5.0 m), the average air velocities of 0.09 m s^{-1}, 0.06 m s^{-1} and 0.11 m s^{-1} were obtained with the inlet turbulence at

0.15, 0.25 and 0.35 respectively. The turbulence intensities at each location (1, 3 and 5 m) were evaluated. The results shown in Figure 6.5 indicate that 0.15, 0.25 and 0.35 inlet turbulence generated 0.51 to 2.66, 0.44 to 3.34 and 0.45 to 1.34 turbulence intensities in the broiler occupied zones respectively.

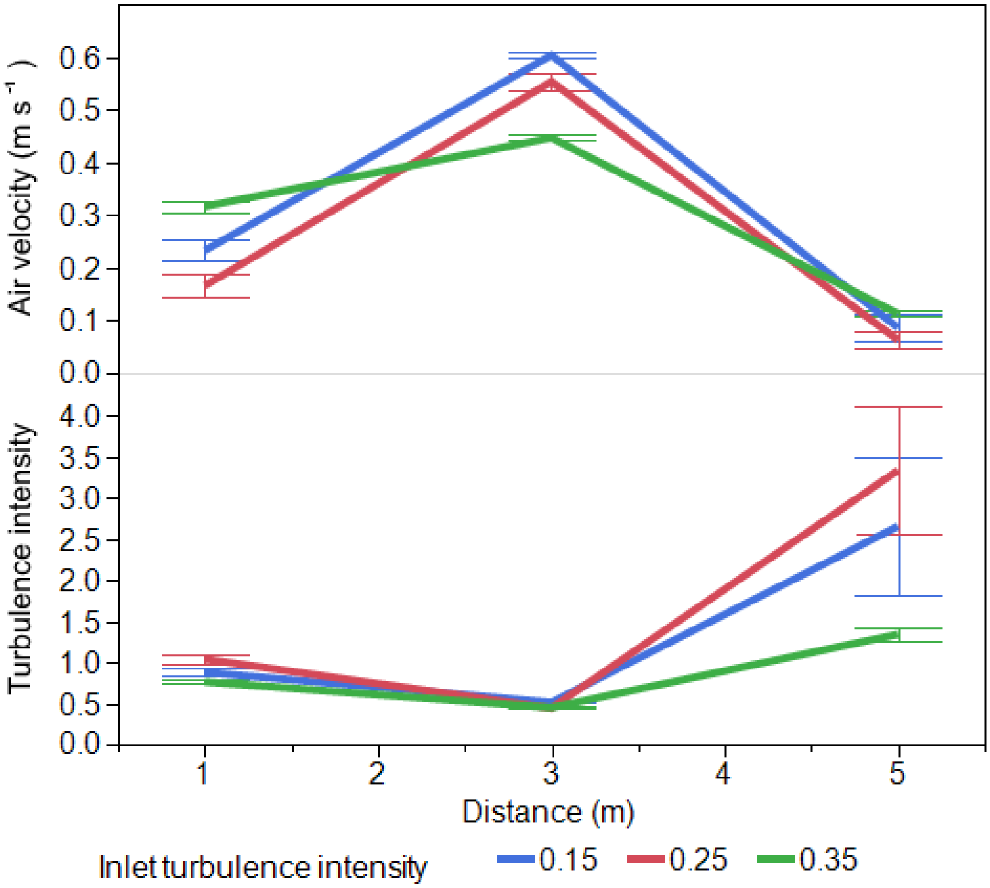

Figure 6.5: Effect of inlet turbulence on the air characteristics in the broiler occupied zones of an experimental room occupied with broiler models at a stocking density of 33 kg m^{-2}.

As shown in Figure 6.5, higher inlet turbulence intensity (0.35) performed better in the area closer to the ventilation system (1 m) compared to the inlet turbulence of 0.15 and 0.25. In a typical commercial broiler building, broilers in the areas closer to the sidewall inlets usually experience lower or almost zero air velocity as a result of wall barrier (Bjerg et al., 2002; Norton et al., 2007; Shklyar and Arbel, 2004). However, with higher inlet turbulence of 0.35, the mean air velocity in these areas could be improved to provide a cool environment for broiler chickens. The integration of oscillating inlet baffle that could produce inlet turbulence of 0.35, into ventilation systems of broiler building might reduce broiler migration from warmer areas within the broiler building to cooler areas which could result in higher mortality. The results show that there was an improvement of 33.3 % in the mean air velocity obtained at the area closer to the ventilation system (1 m) at higher inlet turbulence (0.35) over the mean air velocity at lower inlet turbulence (0.15).

Table 6.2 shows the results of the statistical analysis carried out with one-way ANOVA and Tukey-Kramer HSD. The results indicate that there was a significant difference in the mean air velocities between the inlet turbulence of 0.15, 0.25 and 0.35 at all the locations from the ventilation system.

Table 6.2: The air velocity distributions in the broiler occupied zone of an occupied building at different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m) from the ventilation system	Air velocities (m s^{-1}) in the broiler occupied zones at different inlet turbulence			P-value
	0.15	0.25	0.35	
1	0.24^{B}	0.17^{C}	0.32^{A}	0.0003
3	0.61^{A}	0.55^{B}	0.45^{C}	< 0.0001
5	0.09^{B}	0.06^{AB}	0.11^{A}	0.0329

The mean air velocities obtained in the occupied broiler room were compared with the mean air velocities in the broiler occupied zones of the empty broiler room. From Table 6.3, the result of the unpaired t-test analysis showed that there was a significant difference in the mean air velocities in the broiler occupied zones between the two building conditions (empty and occupied broiler rooms) at all measurement locations. Also, from Table 6.3, it could be observed that the mean air velocities in the broiler occupied zones of the empty broiler room are higher than the mean air velocities in the occupied broiler room at all measurement locations. This implies that indoor obstacles such as broiler models, drinkers and feeders did have significant influence on the mean air velocity distributions in the broiler occupied zones of the broiler room which is similar to the results of the study conducted by Smith et al. (1999). They indicated that pigs obstructed the airflow in the animal occupied zones within the pig building.

Table 6.3: The air velocity distributions in the broiler occupied zone of an empty and an occupied building at different inlet turbulence.

Distance (m) from the ventilation system	Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.15			Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.25			Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.35		
	Empty	Occupied	P- value	Empty	Occupied	P- value	Empty	Occupied	P- value
1	0.58	0.24	< 0.0001	0.24	0.17	0.0048	0.41	0.32	0.0082
3	0.64	0.61	0.0056	0.63	0.55	0.016	0.61	0.45	<0.0001
5	0.33	0.09	0.0003	0.38	0.06	0.0025	0.34	0.11	<0.0001

6.3.3 Study 3: Effect of inlet turbulence on the airflow characteristic in the broiler occupied zones within a broiler room occupied with broiler model at a stocking density of 39 kg m^{-2}

Further study was carried out at a higher stocking density of 39 kg m^{-2} and the airflow characteristics in the broiler occupied zones were evaluated (Figure 6.6). As shown in Figure 6.6, the mean air velocities of 0.19, 0.23 and 0.43 m s^{-1} were obtained at 1 m from the ventilation system at the inlet turbulence of 0.15, 025 and 0.35 respectively. At the inlet turbulence of 0.15, 0.25 and 0.35, the mean air velocity at 3 m from the ventilation system were 0.61, 0.59 and 0.61 m s^{-1} respectively. At 5 m from the ventilation system, the mean air velocity in the broiler occupied zone of 0.15, 0.09 and 0.16 m s^{-1} were obtained at inlet turbulence of 0.15, 0.25 and 0.35 respectively. From Figure 6.6, the mean turbulence intensities in the broiler occupied zones generated by 0.15, 0.25 and 0.35 inlet turbulence were 0.50 to 1.30, 0.38 to 1.72 and 0.30 to 0.83 respectively. These results have shown that inlet turbulence of 0.35 improved the mean air velocities in the broiler occupied zones more than another inlet turbulence (0.15 and 0.25).

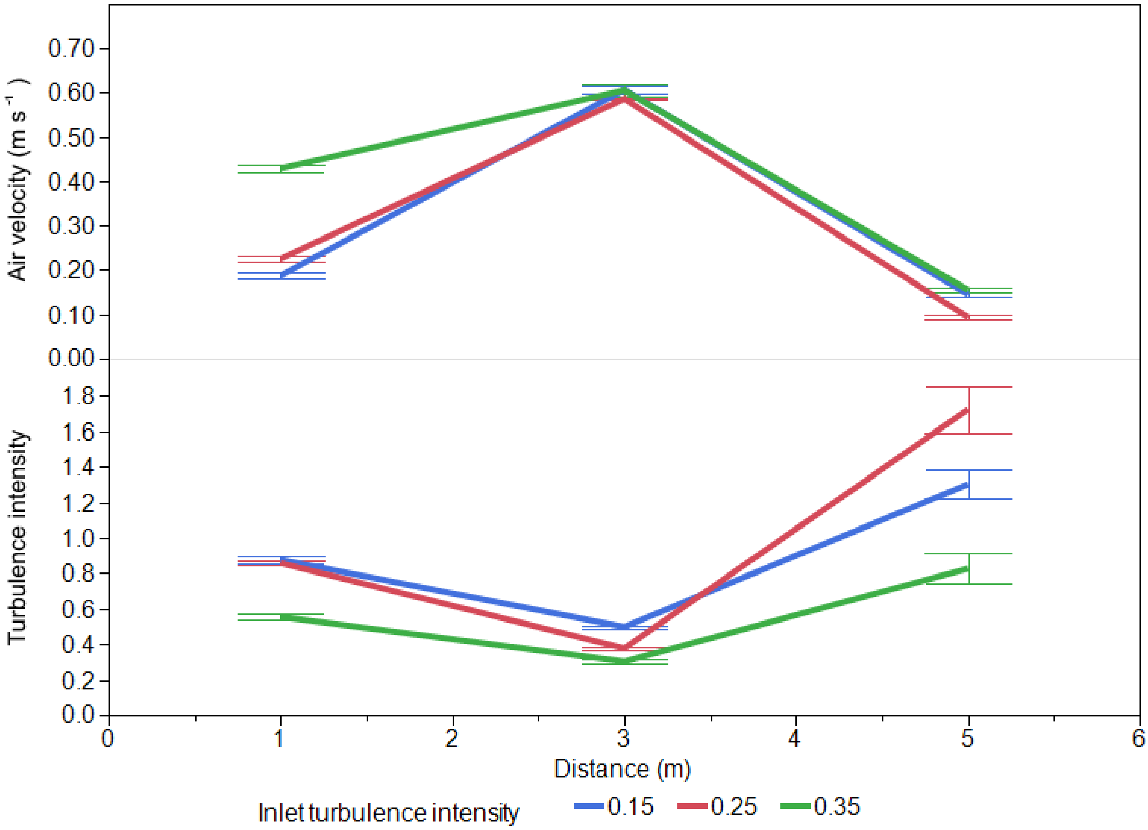

Figure 6.6: Effect of inlet turbulence on the airflow characteristics in the broiler occupied zones at higher stocking density of 39 kg m^{-2}.

Table 6.4 shows the statistical analysis carried out with one-way ANOVA and Tukey-Kramer HSD. From Table 6.4, there is a significant difference in the mean air velocities between the inlet turbulence of 0.15, 0.25 and 0.35 at all the measurement locations from the ventilation system except at 3 m where there is no significant difference in the mean air velocities between the inlet turbulence.

Table 6.4: The air velocity distributions in the broiler occupied zone at higher stocking density and different inlet turbulence. The superscript letters represent the significant differences in the means air velocities (m s^{-1}) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance

Distance (m) from the ventilation system	**Air velocities (m s^{-1}) in the broiler occupied zones at different inlet turbulence**			**P-value**
	0.15	0.25	0.35	
1	0.19^{C}	0.23^{B}	0.43^{A}	< 0.0001
3	0.61^{A}	0.59^{A}	0.61^{A}	0.2762
5	0.15^{B}	0.09^{C}	0.16^{A}	0.0004

6.3.4 Comparison of the effects of different stocking densities (33 and 39 kg m^{-2}) on the airflow characteristic in the broiler occupied zones.

The impact of higher stocking density (39 kg m^{-2}) on the mean air velocity distributions in the broiler occupied zones within the broiler room was compared to the impact that the lower stocking density (33 kg m^{-2}) had on the air velocity in the broiler occupied zones. The results are shown in Figure 6.7 and Table 6.5. As shown in Table 6.5, the higher inlet turbulence (0.35) performed better at all measurement locations than the lower inlet turbulence (0.15 and 0.25). Contrary to the author’s expectation, the mean air velocities in the broiler occupied zone within the broiler room with higher stocking density were higher than the mean air velocities inside the room with lower stocking density. It was expected that the air velocity in the room with higher stocking density would be lower than the air velocities within the room with lower stocking density. The reason for this was not known. However, the possible reason could be because of the arrangement of the broiler models (plastic footballs). The models were randomly placed on the wood shavings with no particular arrangement pattern. In addition, the difference could be because the broiler models had no porous medium. However, the results of this study have shown that the effect of higher stocking density on the performance of broiler chickens could be minimised during hot weather with increase in the inlet turbulence. This indicates that farmers could increase the number of broiler chickens per floor space during hot weather periods so as to increase their economic gains without necessarily stressing the birds. The results of the t-test analysis indicated that there was a significant difference in the mean air velocity at all measurement locations between the stocking densities 33 and 39 kg m^{-2} except at 3 m from the ventilation system under the influence of inlet turbulence intensity of 0.15 that there was no significant difference in the mean air velocities between the stocking densities of 33 and 39 kg m^{-2}.

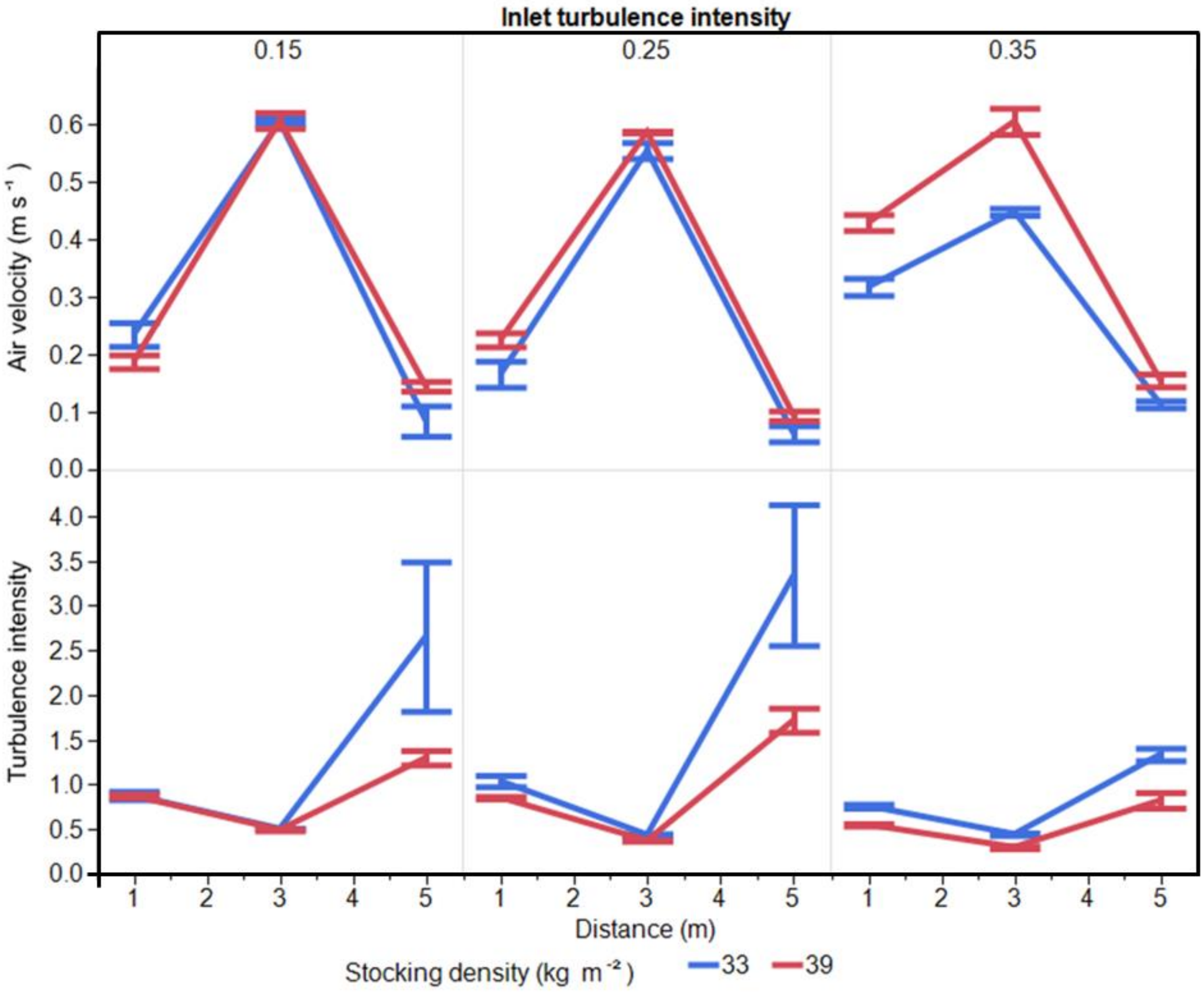

Figure 6.7: Comparison of the impact of different stocking densities (33 and 39 kg m^{-2}) on the airflow characteristics in the broiler occupied zones at different inlet turbulence (0.15, 0.25 and 0.35).

Table 6.5: The impact of stocking densities (kg m^{-2}) on the air velocity distributions in the broiler occupied zone at different inlet turbulence.

Distance (m) from the ventilation system	**Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.15**			**Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.25**			**Air velocities (m s^{-1}) in the broiler occupied zones at inlet turbulence of 0.35**		
	33 (kg m^{-2})	39 (kg m^{-2})	P- value	33 (kg m^{-2})	39 (kg m^{-2})	P- value	33 (kg m^{-2})	39 (kg m^{-2})	P- value
1	0.24	0.19	0.0266	0.17	0.23	0.0154	0.32	0.43	0.0007
3	0.61	0.61	0.8272	0.55	0.59	0.0166	0.45	0.61	0.0003
5	0.09	0.15	0.0192	0.06	0.09	0.0274	0.11	0.16	0.0046

6.4 Conclusion

In this study, the results of different inlet turbulence tested on the ventilation system have shown that the integration of inlet turbulence, through oscillating inlet baffle, into the ventilation system of broiler building could have a significant effect on the mean air velocities in the broiler occupied zones. In an empty broiler building, this study has shown that higher inlet turbulence of 0.35, when compared to lower inlet turbulence of 0.15, may not necessarily increase the mean air velocities in the broiler occupied zones as expected. However, with the room occupied with broiler model, there were indications that higher inlet turbulence (0.35) had significant effect on the mean air velocity distributions in the broiler occupied zones at the areas closer to the ventilation system than in the other locations. This indicates that air movement in the broiler occupied zones at the areas closer to the sidewall could be improved during hot period by directing airflow on the birds at higher inlet turbulence.

In this study, it has also been shown that higher stocking density may not reduce the mean air velocity in the broiler occupied zones if inlet turbulence is integrated into the ventilation system of broiler building. The mean air velocities in the broiler occupied zones within the room with stocking density of 39 kg m^{-2} were higher than the mean air velocities within the room with the stocking density of 33 kg m^{-2} most especially at the inlet turbulence of 0.35. This simply shows that farmers could increase their birds stocking density to an average of 39 kg m^{-2} throughout the year, including the hot weather seasons, without necessarily subjecting the birds to heat stress as long as the ventilation system is equipped with oscillating inlet baffle and that the inlet turbulence is increased to 0.35. Also, the incorporation of oscillating inlet baffle into the ventilation system of broiler building could reduce, to some extent, the migration of birds to a cooler region within the building, which could result in higher mortality. Similarly, there could be possibility to improve the distribution of birds across the floor space during hot weather periods with the integration of oscillating baffle into the inlets of the broiler building.

CHAPTER SEVEN

IMPACT OF INLET TURBULENCE ON THE SENSIBLE HEAT TRANSFER OF ADULT BROILER CHICKENS

7.1 Introduction

Absolute control over the environmental parameters (air temperature, relative humidity and air velocity) within broiler buildings is very important in order to alleviate problems such as heat stress, poor performances and poor growth associated with the hot weather conditions (Aradas et al., 2005; Van Buggenhout et al., 2005). During hot weather conditions, adult broiler chickens find it difficult to dissipate body heat quickly because of their higher body heat production, high body surface insulation, lesser floor space and lower surface area to body weight ratio (Czarick and Lacy, 1999). One of the cheapest methods of controlling heat stress in livestock is by increasing air movement in the animal occupied zones (Aradas et al., 2005). As a result, poultry growers usually alter the inlets' opening size and a number of fans in operation in order to allow a large volume of airflow into the broiler building (Bustamante et al., 2013). However, this practice has not significantly improved the airflow in the broiler occupied zone due to the height of the inlet above the floor and the inlet configuration (Strøm et al., 2002, 2001). Therefore, providing higher airflow at the inlet is incomplete if the airflow is not properly directed towards the broiler occupied zones so as to provide broiler chickens with the effective air velocity.

Broiler chickens are capable of losing body heat through sensible and latent heat transfer mechanisms. However, heat loss by latent heat could incur higher energy expended on body maintenance, blood acid/ base imbalance and body water imbalance (Yahav et al., 2005). It could also increase the risk of hyperthermia in broiler chickens (Yahav et al., 2005). Though latent heat transfer has been widely reported as the fastest mechanism for heat transfer in poultry birds (Weaver, 2002), increasing air movement at the broiler occupied zones has also been shown to shift heat transfer from latent heat to sensible heat transfer, resulting in higher energy directed towards body growth of broiler chickens, risk of hyperthermia prevention and blood acid/ base imbalance in broiler chickens (Simmons et al., 1997; Yahav et al., 2005). In the last two decades, many research works (Boulard et al., 1997; McCafferty et al., 1997; Simmons et al., 1997; Yahav et al., 2008; Yahav et al., 2005) have shown that exposure of poultry birds to higher air velocity have significantly contributed to the sensible heat transfer of birds. Most of the studies were either conducted in the respiration chamber, laboratory or in a small-scale livestock facility. There are limited reports on heat transfer of the confined animals in the commercial livestock buildings.

Airflow turbulence has been reported to have a significant effect on the heat transfer. Huang et al. (2007) indicated that the upstream wake generator and turbulence grid produced additional regular instantaneous velocity fluctuations, further comprehensive velocity profiles, and a higher turbulence intensity which enhanced the heat transfer from the heated cylinder. Li et al. (2016a) carried out a study using the computational fluid dynamics (CFD) to simulate the convective heat transfer of a pig model exposed to different airflow turbulence. They reported that the coefficient of convective heat transfer increased by 9 % when turbulence intensity to which the pig model was exposed to increase from 0.15 to 0.30. There is no study on the effect of turbulence intensity on the heat transfer of broiler chickens. In addition, no study has ever suggested how the turbulence intensity could be integrated into the ventilation system of livestock buildings. Therefore, this study was set up to investigate an alternative ventilation system, incorporated with turbulence, for improving the heat transfer of broiler chickens during hot weather periods.

The objectives of this study were to; (1) investigate the effect of inlet turbulence and broiler orientations on the surface temperatures of broiler chicken subjected to hot environment; (2) determine the effect of inlet turbulence and broiler orientations on the sensible heat transfer of the broiler chicken exposed to the hot environmental condition.

7.2 Materials and methods

7.2.1 Broiler experimental room, ventilation system and Instrumentations

The experimental room used for this study has been described in the section 6.2.1. The experimental room contains four 3 kW electric heaters, mounted on the wall and were controlled by the climate control system. For this study, the heaters were used to generate 28 ºC and 31 ºC indoor temperatures which were assumed to provide a hot environment and also cause heat stress for broiler chickens. The ventilation system in the room was not used during this research work. Instead, a ventilation system capable of generating airflow turbulence was used. The details of the ventilation system have earlier been discussed in chapter five (section 5.2.1).

The instrumentations used in this study are as follow. The airflow sensors (ultrasonic anemometers) used have been earlier discussed in the chapters 4 to 7. In this study, the airflow sensors were positioned at each measurement location (1.0, 3.0 and 5.0 m from the ventilation system) at 0.20 m above the floor to measure the effective air velocities at the level of the broiler model. The effective air velocities were needed to adequately quantify the sensible heat transfer of the broiler model. A thermal imager (Optris PI400) was used to monitor and measure the body and surface temperatures of the broiler model. The thermal imager has a 25x25 µm FPA uncooled detector, a spectral range of 7.5 to 13 µm, a temperature range of -20 to 100 ºC, and an accuracy of ± 2 %. The thermal imager was mounted on a table tripod stand based on the height at which measurements were to be obtained on the broiler model (0.17 m above the floor). During the study, a bucket was filled with cold water and placed in the room in order to provide the room with appropriate relative humidity needed for the experiment. The relative humidity of the room was monitored with a digital hygro-thermometer (HTC-1 model). The sensor has a temperature range of -10 ºC to 50 ºC, a relative humidity range of 10 % to 99 %, a resolution of 0.1 ºC (temperature) and 1 % (relative humidity). The accuracy of the sensor is ± 0.1 ºC for temperature and ± 5 % for relative humidity. The sensor indicated that the indoor relative humidity of the room varied between 41.8 % and 51.2 % throughout the study. The same digital hygro-thermometer was used to monitor the indoor temperatures of the experimental room.

7.2.2 Broiler model development

A broiler model was developed with a hollow wrought iron sphere (Figure 7.1). The surface area of the sphere ($1.61\text{x}10^{-3}$ m^2), which is a function of the body weight of a broiler chicken (2.6 kg), was estimated using $A_{surf} = 0.000819 \times {M_{chicken}}^{0.705}$ (Mitchell, 1930). The characteristic dimension of the broiler model (0.180 m), which also depends on the body weight of broiler chicken (2.6 kg) was determined using $D_{poultry} = 0.131 \times {M_{chicken}}^{0.33}$ (Mitchell, 1930). The chicken model was mounted on two cylindrical rods, 90.7 mm long and 13.5 mm diameter to represent the legs of a typical broiler chicken (Fayeye et al, 2006). Two metal plates of length 177 mm (an average length of broiler wing) were attached to the two sides of the sphere to simulate the wings of a heat-stressed broiler chicken. The inner and outer surfaces of the model were painted black to obtain approximately a unity emissivity for thermal radiation.

Figure 7.1: The broiler model.

The core body temperature of a typical broiler chicken in a thermal comfort zone (18 to 24 °C) varies between 41.2 to 42.2 ºC (Tao and Xin, 2003a). In this study, a body temperature of 42 °C was selected as the core body temperature of the broiler model at the thermal comfort zone of 24 ºC indoor temperature. To achieve this body temperature, a heating lamp of 100 watts was installed in the broiler model and the current flowing into the lamp was regulated with a lamp dimmer switch while the energy consumption of the heating lamp of an average of 30.2 Watts was monitored and measured with a power meter (PM231). The meter has a measuring power range of 0.2 to 3120 Watt at an accuracy of ± 0.2 W. The body temperature of the broiler model was monitored with the thermal imager (optris PI400) inside a controlled environment at zero airspeed until an average temperature of 42 °C was reached (Figure 7.2a). The energy consumption of the heating lamp was recorded for the purpose of subsequent experimental observations. Figure 7.2b shows the body temperature of the broiler model at the thermal comfort zone.

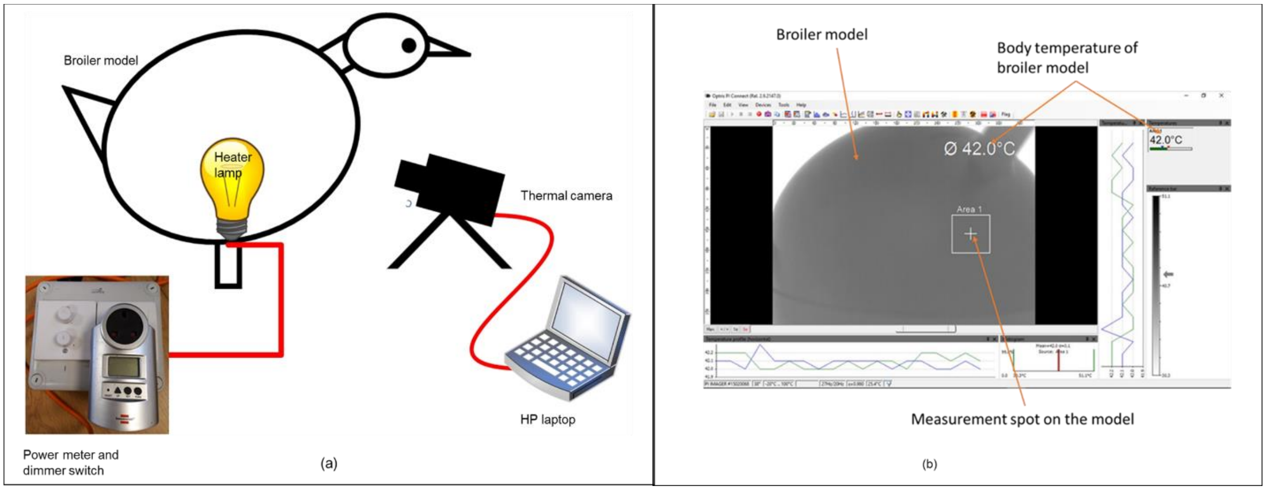

Figure 7.2: (a) The monitoring of body temperature and energy consumption of broiler model using a thermal camera and a power meter respectively; (b) the body temperature of a broiler model at the thermal comfort zone of 24 ºC indoor temperature.

To simulate a typical live broiler chicken, the broiler model was covered with taxidermy mounts (skin with feathers) of broiler chicken. The taxidermy mounts were obtained from three six-weeks old broiler chickens used in another regulated research study running at Harper Adams University, UK. To obtain the taxidermy mounts, the birds were sacrificed by cervical dislocation which was performed by a poultry technician. The mounts were carefully removed from the dead birds without tissues and placed on the outer surface of the broiler model (Figure 7.3).

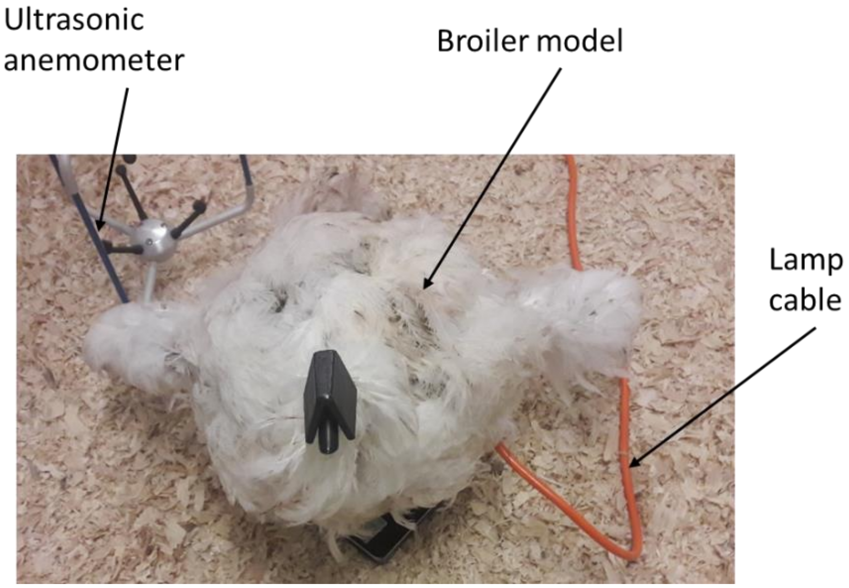

Figure 7.3: The broiler model covered with taxidermy mounts.

7.2.3 The experimental setup

7.2.3.1 Exposure of broiler model to hot environmental conditions

The broiler model was exposed to high indoor temperatures of 28 ºC and 31 ºC in order to estimate the body and surface temperatures of broiler model that were used in this study. The body temperature of the broiler model was determined based on the classification of homeostasis states of birds reported by Tao and Xin (2003). They indicated that the alert homeostasis state of broiler chickens was reached when the body temperature rise threshold was 2.5 ºC and the danger homeostasis state was attained as the body temperature rise threshold approached 4.0 ºC. Therefore, to achieve these homeostasis states, the broiler model was placed at the centre of the experimental room (2.72 m from the sidewall and 3.50 m from the door) and exposed to different indoor temperatures of 28 ºC and 31 ºC. The broiler model was first exposed to an indoor temperature of 28 ºC until the broiler model gained additional body temperature of 2.6 ºC (an alert homeostasis state) and the time was recorded as approximately 10 minutes 48 seconds. Figure 7.4 shows a thermal camera measuring the body temperature of the broiler model.

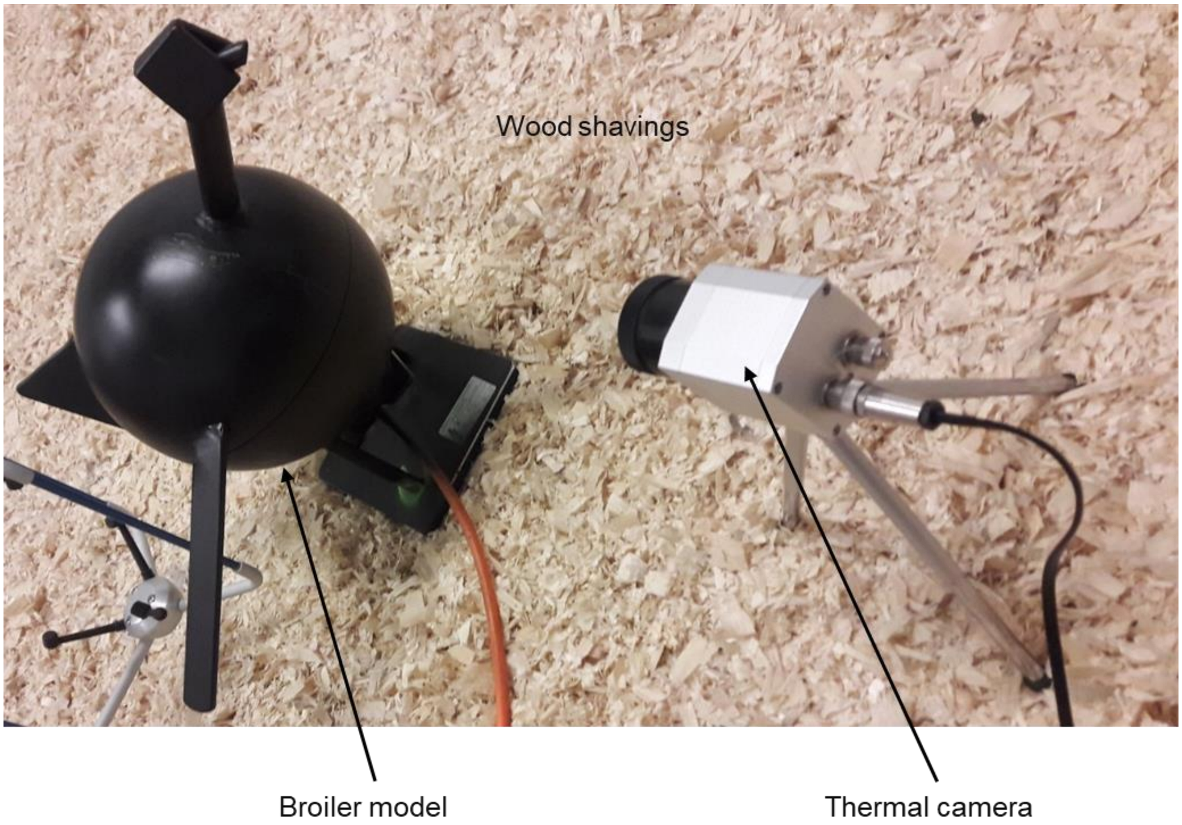

Figure 7.4: A thermal imager monitoring the body temperature of a broiler model.

The process was repeated with a higher indoor temperature of 31 ºC. The broiler model was exposed to 31 ºC indoor temperature until its body temperature rise threshold approached 3.8 ºC which was classified as danger homeostasis state at an average period of 10 minutes. The body temperature of the broiler model was monitored when the model was not yet covered with a taxidermic mount. This approach was used based on the report that there is a correlation between the core body temperature of broiler chickens and the featherless body surface (Czarick et al., 2017). The emissivity on the thermal imager was set at 0.98 as suggested by Nascimento et al. (2013) for featherless birds in order to adequately estimate the body temperature of the broiler model. The estimated body temperatures of the broiler model are shown in Table 7.1.

Similarly, the surface temperatures of the broiler model, covered with a taxidermic mount and placed at the centre of the experimental room, were measured. The emissivity on the thermal imager was set at 0.94 for feathered birds, as suggested by Nascimento et al. (2013). The surface temperature of the feathered broiler model was measured and recorded as 32.3 ºC when it was kept at the thermal neutral zone of 24 ºC indoor temperature and a body temperature of 42 ºC. The indoor temperature of the room was first increased to 28 ºC and the feathered broiler model was placed in the room and exposed to 28 ºC indoor temperature for an average period of 10 minutes 48 seconds. The surface temperature of the model was measured at the end of the exposure period with a thermal imager. Similarly, the feathered broiler model was subjected to an indoor temperature of 31 ºC and the surface temperature was also measured at the end of 10 minutes of exposure. Table 7.1 shows the body and surface temperatures of the broiler model exposed to the indoor temperatures of 28 ºC and 31 ºC.

Table 7.1: The effect of indoor temperature on the body temperatures of a featherless broiler model.

Indoor temperature (ºC)	Body temperature (ºC)	Surface temperature (ºC)
24	42 (thermal comfort zone)	32.3 (thermal comfort zone)
28	44.6 (alert)	33.6 (alert)
31	45.8 (danger)	35.8 (danger)

7.2.3.2 The impact of inlet turbulence on the surface temperatures of the feathered broiler model

To conduct this study, the experimental room was pre-heated to a temperature of 28 ºC and was periodically monitored with a digital hygro-thermometer. The ventilation system was operated for 30 minutes prior to the test to ensure adequate air circulation within the room. Thereafter, the feathered broiler model, with an initial surface temperature of 33.6 ºC, was placed at different measurement locations (1, 3 and 5 m from the ventilation system) and was exposed to the minimum and maximum inlet turbulence (0.15 and 0.35) and an average airspeed of 4.5 m s^{-1} for a maximum period of 30 minutes (Figure 7.5). The details of how the turbulence intensities were generated have been discussed in chapter 5. The broiler model was allowed to regain its initial surface temperature of 33.6 ºC at all orientations before it was exposed to different inlet turbulence and an average airspeed of 4.5 m s^{-1} at all measurement locations.

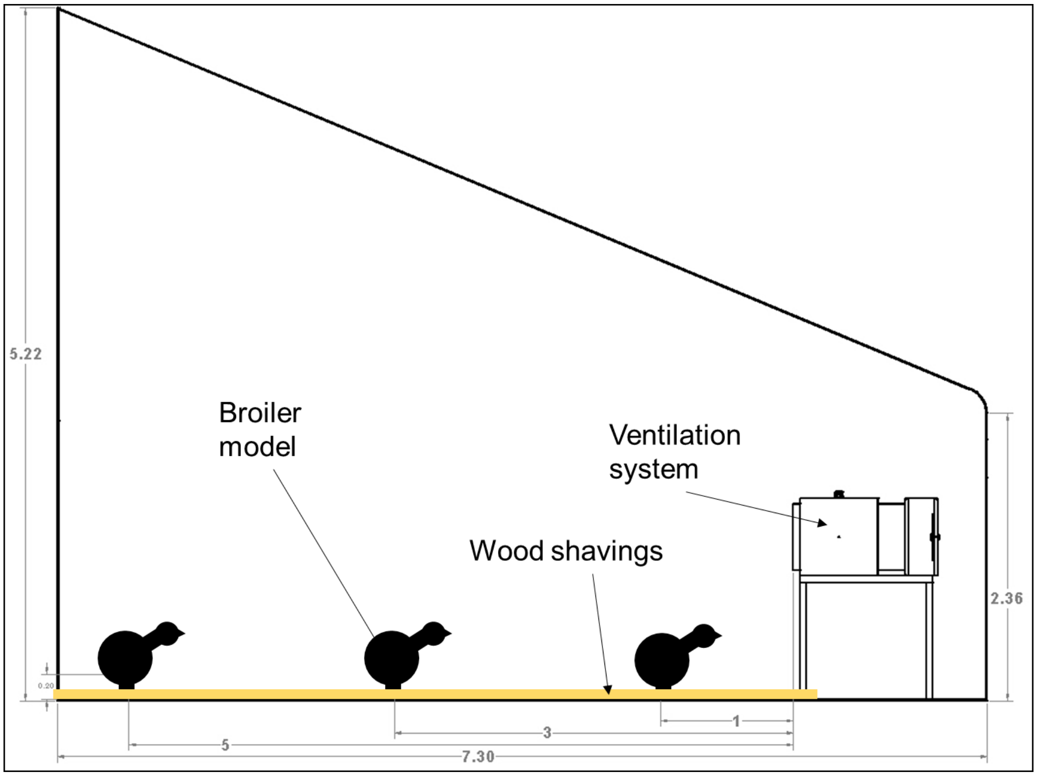

Figure 7.5: The experimental layout showing the cross-sectional view of the broiler model exposed to different inlet turbulence and indoor temperature. All measurements are in metres.

A general behaviour of a typical broiler chicken is that it changes its posture from time to time during feeding, drinking, standing and walking. In this study, the orientations of the broiler model were changed with respect to the airflow direction. The three orientations considered in this study, based on the orientations used in previous studies (Gebremedhin, 1987; Li et al., 2016a, 2016b), were; (1) the head of the broiler model facing the airflow direction (0 °), (2) the side of the model facing the airflow direction (90 °) and finally (3) the tail facing the airflow direction (180 °) and the surface temperatures of the feathered broiler model were obtained. The indoor temperature of the room was thereafter increased to 31 ºC and the above procedures were repeated. However, the surface temperature of the feathered broiler model was allowed to reach 35.8 ºC before it was exposed to different inlet turbulence at different orientations with respect to the airflow direction and mean airspeed of 4.5 m s^{-1}. The surface temperature measurements, at the breast region, were acquired using the thermal camera.

The measurement spot (breast region) on the broiler model was selected based on the assumption that different body regions of bird (back and breast) would have different surface temperatures depending on the bird’s orientation with respect to airflow direction. Since birds are considered to be spherical in shape (Li et al., 2016b), the back surface temperature of broiler chicken may not significantly change (Li et al. 2016b) when it changes its posture with respect to the airflow direction. However, there is a tendency for the breast surface temperature of broiler chicken to change as the bird alters its orientation with respect to the airflow direction due to obstruction to airflow created by the nearest birds. In this study, the breast region was considered as the measurement spot for evaluating the surface temperatures of the broiler model exposed to different inlet turbulence intensities at different orientations. The camera was configured to record the surface temperature of the feathered broiler model at every 30 seconds and logged the data as text (*.cvs) files on a laptop for a period of 30 minutes. The orientations of the broiler model are shown in Figure 7.6.

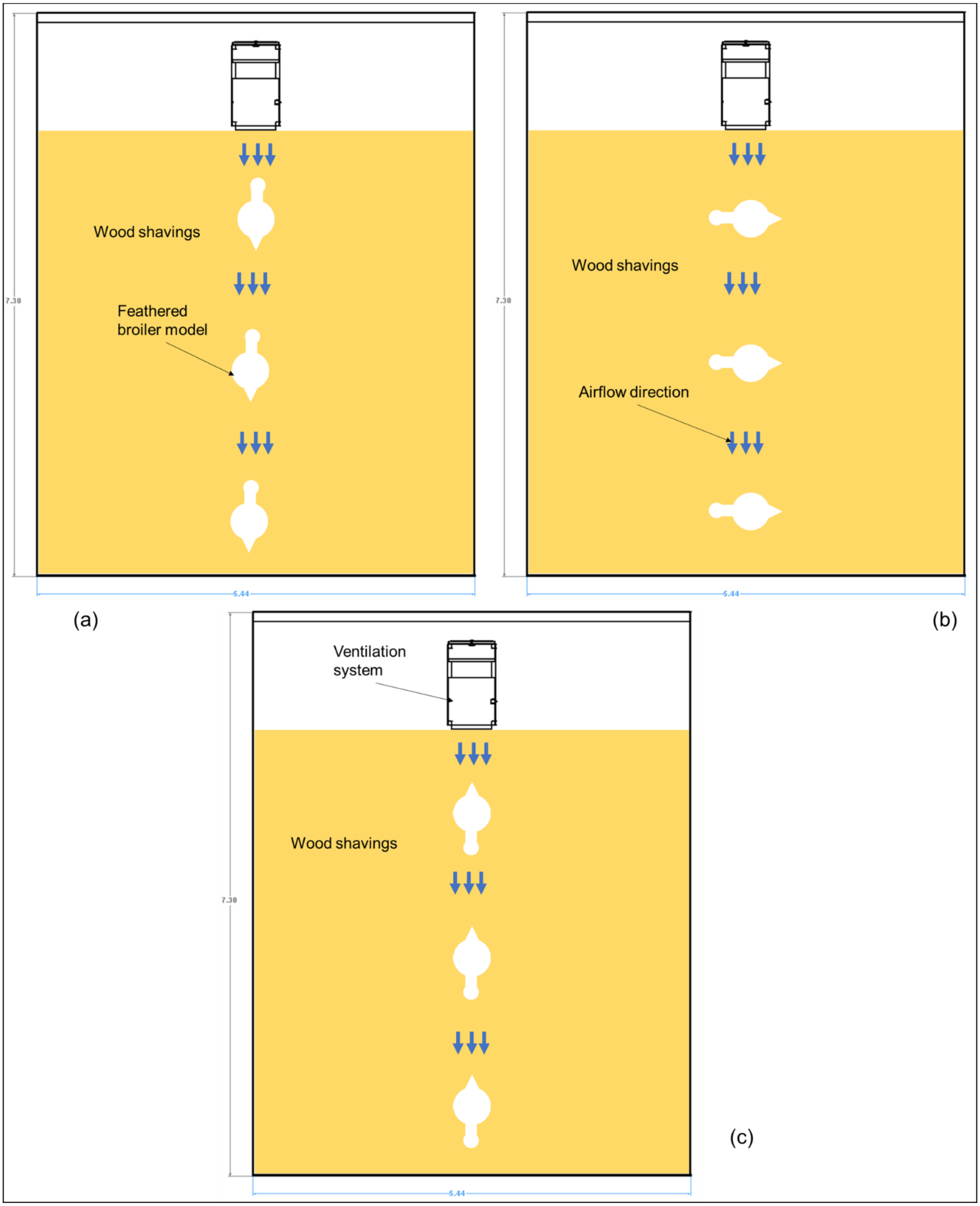

Figure 7.6: The orientations of feathered broiler model (a) 0 º, (b) 90 º and (c) 180 º with respect to the airflow direction. All measurements are in metres.

7.2.3.2.1 Experimental design and data analysis

In this study, a 2x2x3x3 full factorial experimental design was adopted. This means there were 2 indoor temperatures (28 ºC and 31 ºC), 2 inlet airflow turbulence intensities (0.15 and 0.35), 3 orientations (0 º, 90 º and 180 º), 3 distances (1.0, 3.0 and 5.0 m) and a mean airspeed of 4.5 m s^{-1}. The study was repeated three times resulting in 108 experimental observations in total. The results of the study were subjected to one-way ANOVA to determine the significant effect of broiler orientations on the surface temperatures of the broiler model. All analyses were performed at a 5 % significance level.

7.2.3.3 Sensible heat transfer (convective and radiative).

The effect of inlet turbulence intensities on the sensible heat transfer of feathered broiler model was appraised. The sensible heat transfers of the broiler model were estimated as the summation of the convective and radiative heat transfers of the broiler model with respect to the model orientations (0 º, 90 º and 180 º with respect to the airflow direction), indoor temperatures (28 ºC and 31 ºC), the effective mean air velocity the broiler model experienced at each location (distance of 1.0, 3.0 and 5.0 m from the ventilation system) and the surface temperatures of the broiler model. In this study, the mathematical expressions for heat transfer in the equations 20 to 29 (section 2.6.1.1) were adopted and used for the estimation of the convection, radiation and sensible heat transfers of the broiler model. The effective mean air velocities at the level of the broiler model were obtained by an ultrasonic anemometer placed at each measurement location (1.0, 3.0 and 5.0 m from the ventilation system). To accurately measure the effective mean air velocities at the broiler level, the anemometer was positioned with its head inverted as recommended by the manufacturer for the heights lesser than 1 m above the floor and the u-axis (north spar) pointing towards the direction of the ventilation system.

7.2.3.3.1 Data analysis

The data obtained were processed and substituted into the expressions in equations 20 to 29 in section 2.6.1. The analysis was performed with SAS JMP 14. The processed data were subjected to one-way ANOVA analysis. All analyses were performed at a 5 % significance level.

7.3 Results and discussion

7.3.1 Effects of inlet turbulence on the surface temperature of the broiler model subjected to hot weather conditions

Table 7.2 shows the result of the mean surface temperatures of the broiler model exposed to the different inlet turbulence and an indoor temperature of 28 and 31 ºC at different orientations with respect to the airflow direction. From Table 7.2, compared to the initial surface temperatures (33.6 ºC and 35.8 ºC) when the broiler model was exposed to 28 ºC and 31 ºC in still air, it could be observed that using oscillating inlet baffle to generate different turbulence did have an effect on the surface temperatures of the broiler model. Comparing the impact of inlet turbulence on the surface temperatures of broiler model subjected to 28 ºC, it could be observed that the higher inlet turbulence of 0.35 has higher effect on the surface temperatures of the broiler model nearer to the ventilation system. As it could be expected, with increase in distance (3 and 5 m) from the ventilation system, the impact of higher inlet turbulence reduced and the broiler model gain additional body temperature instead of losing heat. However, different scenario was noticed at a higher indoor temperature (31 ºC). The impact of higher inlet turbulence (0.35) was higher at 3 m and 5 m from the ventilation system compared to the impact of the inlet turbulence of 0.15. The results shown in Table 7.2 indicate that broiler orientations did not have effect on the surface temperatures of broiler models exposed to different indoor temperatures (28 ºC and 31 ºC). However, the results of the analysis indicated that there were significant differences between the effect of inlet turbulence (0.15 and 0.35) on the surface temperatures of broiler model at different at 1 m from the ventilation system when broiler model was exposed an indoor temperature of 28 ºC. As the distance increased to 3 and 5 m from the ventilation system and at 31 ºC indoor temperature, there was no significant difference between the surface temperatures of broiler model.

Table 7.2: Surface temperatures, T_{surf} (ºC) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the means surface temperatures (ºC) between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m)	**Orientation (º)**	**Inlet turbulence**	**28 ºC indoor temperature**		**31 ºC indoor temperature**	
			T_{surf} (ºC)	*P-value*	T_{surf} (ºC)	*P-value*
1	0	0.15	33.03^{A}	0.0212	34.46^{A}	0.4103
		0.35	31.05^{B}		34.79^{A}	
	90	0.15	34.28^{A}	0.0264	35.71^{A}	0.4458
		0.35	30.76^{B}		36.91^{A}	
	180	0.15	33.42^{A}	0.0098	33.72^{A}	0.3471
		0.35	29.62^{B}		35.31^{A}	
3	0	0.15	28.54^{A}	0.1868	32.72^{A}	0.8181
		0.35	29.48^{A}		33.07^{A}	
	90	0.15	30.02^{A}	0.1588	33.59^{A}	0.7707
		0.35	32.86^{A}		33.12^{A}	
	180	0.15	32.77^{A}	0.3102	35.54^{A}	0.9113
		0.35	33.74^{A}		34.88^{A}	
5	0	0.15	31.53^{A}	0.4604	36.39^{A}	0.1366
		0.35	32.16^{A}		34.59^{A}	
	90	0.15	31.59^{A}	0.4069	36.16^{A}	0.1217
		0.35	32.23^{A}		34.09^{A}	
	180	0.15	29.62^{A}	0.6695	35.53^{A}	0.1693
		0.35	32.57^{A}		33.92^{A}	

7.3.2 Effects of inlet turbulence on the heat transfer of broiler model subjected to hot environmental conditions

The impact of inlet turbulence on the heat transfer of the broiler model was estimated. The heat transfers estimated were the coefficient of convective heat transfer (CoCHT), the convective heat transfer (CHT), the radiative heat transfer (RHT) and the sensible heat transfer (SHT). The following results were presented based on the indoor temperatures and the inlet turbulence intensities the broiler model was subjected to.

7.3.2.1 The coefficient of convective heat transfer (CoCHT)

Table 7.3 shows the results of the impact of inlet turbulence (0.15 and 0.35) on the coefficient of convective heat transfer (CoCHT) of broiler model when exposed to 28 ºC and 31 ºC indoor temperatures at different orientations (0 º, 90 º and 180 º) with respect to airflow direction using equation 22. The results shown in Table 7.3 indicate that orientations did not have an effect on the CoCHT of broiler model at both indoor temperatures. However, it could be observed from Table 7.3 that inlet turbulence did have effect on the CoCHT of broiler model. The results of the analysis indicated that there was a significant difference between the impacts of inlet turbulence on the CoCHT of broiler model at various orientations. These results support the report of Li et al. (2016b) who indicated that broiler orientations had no significant effect on the coefficient of convective heat transfer of broiler chickens. In Table 7.3, it could also be noticed that at both indoor temperatures of 28 ºC and 31 ºC, the inlet turbulence did have an effect on the CoCHT of broiler model. Similar results have been reported in previous studies (Ahn et al., 2017; Li et al., 2016a, 2016b) who have all indicated that turbulence had a significant effect of the CoCHT of circular cylinder, broiler and pig models respectively.

Table 7.3: CoCHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the coefficient of convective heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m)	**Orientation (º)**	**Inlet turbulence**	**28 ºC indoor temperature**		**31 ºC indoor temperature**	
			CoCHT (W m^{-2} K^{-1})	*P-value*	CoCHT (W m^{-2} K^{-1})	*P-value*
1	0	0.15	6.20^{B}	< 0. 0001	4.76^{B}	< 0. 0001
		0.35	6.91^{A}		6.31^{A}	
	90	0.15	6.20^{B}	< 0. 0001	4.76^{B}	< 0. 0001
		0.35	6.91^{A}		6.31^{A}	
	180	0.15	6.20^{B}	< 0. 0001	4.76^{B}	< 0. 0001
		0.35	6.91^{A}		6.31^{A}	
3	0	0.15	8.44^{B}	0.0038	7.27^{B}	< 0. 0001
		0.35	8.90^{A}		8.59^{A}	
	90	0.15	8.44^{B}	0.0038	7.27^{B}	< 0. 0001
		0.35	8.90^{A}		8.59^{A}	
	180	0.15	8.44^{B}	0.0038	7.27^{B}	< 0. 0001
		0.35	8.90^{A}		8.59^{A}	
5	0	0.15	4.03^{B}	< 0.0001	4.35^{B}	0.0180
		0.35	5.87^{A}		3.87^{A}	
	90	0.15	4.03^{B}	< 0. 0001	4.35^{B}	0.0180
		0.35	5.87^{A}		3.87^{A}	
	180	0.15	4.03^{B}	< 0. 0001	4.35^{B}	0.0180
		0.35	5.87^{A}		3.87^{A}	

7.3.2.2 Convective heat transfer (CHT)

Table 7.4 shows the result of CHT of broiler model exposed to the indoor temperatures of 28 ºC and 31 ºC at different orientations (0 º, 90 º and 180 º) with respect to airflow direction using equation 21. From Table 7.4, it could be found that the impact of lower inlet turbulence (0.15) on the CHT of the broiler, closer to the ventilation system is generally greater than that of the higher inlet turbulence (0.35) at an indoor temperature of 28 ºC. However, at an indoor temperature of 31 ºC, the CHT of broiler model exposed to higher inlet turbulence (0.35) at the area closer to the ventilation system (1 m) is greater than that of the lower inlet turbulence (0.15). The results of the one-way ANOVA analysis carried out indicated that there was no significant difference in the CHT of broiler model between the inlet turbulence, orientation and distance considered except when the broiler model was exposed to an indoor temperature of 28 ºC at 1 m from the ventilation system with the broiler model's orientation at 180 º ($p = 0.0312$) and at 3 m from the ventilation system with its orientation at 90 º ($p = 0.0496$) to the direction of the airflow. This indicates that irrespective of the orientation of broiler chickens with respect to the airflow direction, the CHT of broiler chickens exposed to the hot environment may rarely be influenced by the orientations of broiler chickens.

Table 7.4: CHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the convective heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m)	**Orientation (º)**	**Inlet turbulence**	**28 ºC indoor temperature**		**31 ºC indoor temperature**	
			CHT (W m^{-2} K^{-1})	*P-value*	CHT (W m^{-2} K^{-1})	*P-value*
1	0	0.15	0.050^{A}	0.0574	0.026^{A}	0.1433
		0.35	0.034^{A}		0.039^{A}	
	90	0.15	0.062^{A}	0.1087	0.036^{A}	0.1478
		0.35	0.031^{A}		0.060^{A}	
	180	0.15	0.054^{A}	0.0312	0.021^{A}	0.1225
		0.35	0.018^{B}		0.044^{A}	
3	0	0.15	0.070^{A}	0.0952	0.021^{A}	0.8907
		0.35	0.021^{A}		0.029^{A}	
	90	0.15	0.027^{B}	0.0496	0.031^{A}	0.9040
		0.35	0.069^{A}		0.029^{A}	
	180	0.15	0.065^{A}	0.1597	0.053^{A}	0.8247
		0.35	0.082^{A}		0.054^{A}	
5	0	0.15	0.023^{A}	0.2043	0.037^{A}	0.2575
		0.35	0.039^{A}		0.022^{A}	
	90	0.15	0.023^{A}	0.1160	0.035^{A}	0.2507
		0.35	0.040^{A}		0.019^{A}	
	180	0.15	0.022^{A}	0.3167	0.031^{A}	0.2937
		0.35	0.043^{A}		0.018^{A}	

7.3.2.3 Radiative heat transfer (RHT)

Table 7.5 shows the RHT of the broiler model exposed to indoor temperatures of 28 ºC and 31 ºC at different orientations with respect to the airflow direction and different inlet turbulence (0.15 and 0.35) at distance 1, 3 and 5 m from the ventilation system using equation 29. As shown in Table 7.5, it could be observed that RHTs of broiler model subjected to 28 ºC indoor temperature and an inlet turbulence of 0.15 at a distance of 1 m from the ventilation system are higher than that of the broiler model exposed to an inlet turbulence of 0.35. However, at a higher indoor temperature of 31 ºC, the exposure of broiler model to higher inlet turbulence (0.35) resulted in higher RHT compared to that of inlet turbulence of 0.15. In this study, it was observed that the heat transfers of broiler model by radiation were as much as the heat transfers of the broiler model by convection. This contradicts the report of Luthra (2017), who indicated that the heat transfer of confined broiler chickens is majorly by convection. The results of the one-way ANOVA analysis conducted on the RHT of broiler model indicated that there was a significant difference in the RHT of broiler model at 1 m from the ventilation system as result of the impact of inlet turbulence. However, at distance 3 and 5 m from the ventilation system, there was no significant difference in the RHT of broiler model between the orientations and the inlet turbulence intensities considered.

Table 7.5: RHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the radiative heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m)	**Orientation (º)**	**Inlet turbulence**	**28 ºC indoor temperature**		**31 ºC indoor temperature**	
			RHT (W m^{-2} K^{-1})	*P-value*	RHT (W m^{-2} K^{-1})	*P-value*
1	0	0.15	0.048^{A}	0.0197	0.034^{A}	0.4283
		0.35	0.029^{B}		0.037^{A}	
	90	0.15	0.061^{A}	0.0256	0.046^{A}	0.4389
		0.35	0.026^{B}		0.059^{A}	
	180	0.15	0.052^{A}	0.0093	0.027^{A}	0.3494
		0.35	0.015^{B}		0.042^{A}	
3	0	0.15	0.002^{A}	0.2018	0.017^{A}	0.8012
		0.35	0.014^{A}		0.020^{A}	
	90	0.15	0.020^{A}	0.1668	0.026^{A}	0.7872
		0.35	0.047^{AB}		0.021^{A}	
	180	0.15	0.046^{A}	0.3262	0.045^{A}	0.9154
		0.35	0.055^{A}		0.038^{A}	
5	0	0.15	0.034^{A}	0.4770	0.053^{A}	0.1258
		0.35	0.040^{A}		0.035^{A}	
	90	0.15	0.034^{A}	0.4124	0.051^{A}	0.1215
		0.35	0.041^{A}		0.030^{A}	
	180	0.15	0.032^{A}	0.6809	0.045^{A}	0.1642
		0.35	0.044^{A}		0.029^{A}	

7.3.2.4 Sensible heat transfer (SHT)

Table 7.6 shows the sensible heat transfers (SHT) of the broiler model subjected to 28 ºC and 31 ºC indoor temperature, different inlet turbulence (0.15 and 0.35) and orientations (0 º, 90 º and 180 º) with respect to the airflow direction using equation 20. From Table 7.6, it could be observed that at an indoor temperature of 28 ºC, the impact of higher inlet turbulence (0.35) on the SHT of broiler model was higher at 3 and 5 m distances from the ventilation system than in the area closer to the ventilation system (1 m) when compared to the SHT of broiler model obtained at an inlet turbulence of 0.15. However, at a higher indoor temperature (31 ºC), higher inlet turbulence (0.35) has a higher effect on the SHT of broiler model at an area closer to the ventilation system (1 m) than that of lower inlet turbulence. As shown in Table 7.6, the results of the one-way ANOVA indicated that there was no significant difference in the effect of inlet turbulence on the mean of SHT of broiler model except at 1 m from the ventilation system when broiler model was exposed to an indoor temperature of 28 ºC at orientations 0 º and 180 º with respect to the airflow direction. This indicates that SHT of broiler chickens may not be determined based on their orientations with respect to the airflow direction but the condition of inlets' airflow. In addition, there is a tendency that inlet turbulence may significantly influence the sensible heat transfer of broiler chickens in the areas closer to the sidewalls when subjected to hot weather conditions.

Table 7.6: SHT (W m^{-2} K^{-1}) of broiler model subjected to 28 and 31 ºC indoor temperature at different inlet turbulence and orientations. The superscript letters represent the significant differences in the sensible heat transfer (W m^{-2} K^{-1}) of broiler between the inlet turbulence according to Tukey-Kramer HSD at 5 % level of significance.

Distance (m)	**Orientation (º)**	**Inlet turbulence**	**28 ºC indoor temperature**		**31 ºC indoor temperature**	
			SHT (W m^{-2} K^{-1})	*P-value*	SHT (W m^{-2} K^{-1})	*P-value*
1	0	0.15	0.098^A	0.0320	0.060^A	0.2427
		0.35	0.063^B		0.076^A	
	90	0.15	0.123^A	0.0544	0.082^A	0.2498
		0.35	0.057^A		0.118^A	
	180	0.15	0.106^A	0.0167	0.047^A	0.2050
		0.35	0.034^B		0.086^A	
3	0	0.15	0.013^A	0.1326	0.038^A	0.9634
		0.35	0.035^A		0.049^A	
	90	0.15	0.047^A	0.0833	0.056^A	0.9493
		0.35	0.116^A		0.050^A	
	180	0.15	0.110^A	0.2150	0.098^A	0.9552
		0.35	0.137^A		0.092^A	
5	0	0.15	0.057^A	0.3124	0.091^A	0.1792
		0.35	0.079^A		0.058^A	
	90	0.15	0.057^A	0.2135	0.086^A	0.1737
		0.35	0.081^A		0.049^A	
	180	0.15	0.053^A	0.4591	0.076^A	0.2134
		0.35	0.087^A		0.046^A	

7.4 Conclusion

The surface temperatures, the coefficient of convective heat transfer, the convective heat transfer, radiative heat transfer and sensible heat transfer of broiler model subjected to hot environmental conditions (28 ºC and 31 ºC), inlet turbulence intensities (0.15 and 0.35) and inlet airspeed of 4.5 m s^{-1} were evaluated. In the evaluations, the interactions of the broiler model orientations with respect to airflow direction were considered. It has therefore been found that broiler orientations do not play an important role in the estimation of the surface temperatures, the coefficient of convective heat transfer, convective heat transfer, radiative heat transfer and sensible heat transfer of broiler chickens. It is therefore suggested that it should be considered as an insignificant factor when estimating the heat transfer of broiler chickens in the future research.

In a typical broiler building, the maximum inlet turbulence obtainable at the inlet is 0.1. In this study, it has been found that the integration of oscillating inlet baffle, capable of generating higher inlet turbulence of 0.15 and 0.35, could be possible and that it could reduce the surface temperatures of broiler chickens and increase the heat transfer from broiler chickens subjected to hot environmental conditions. Therefore, the integration of oscillating inlet baffle should be considered by ventilation engineers as a promising hot weather ventilation technique for providing a cool environment for broiler chickens during hot weather conditions. In this study, the surface temperatures, the coefficient of convective heat transfer, convective heat transfer, radiative heat transfer and the sensible heat transfer were, to some extent, affected by the inlet turbulence using oscillating inlet baffle. An optimisation of the ventilation system would improve its performances and also provide adequate environmental conditions for broiler chickens during hot weather seasons. Therefore, further research works would require investigating how the inlet airspeed could be increased in addition to the inlet turbulence in order to increase the output airflow characteristics of the ventilation system to other locations beyond the areas closer to the sidewall inlets of the broiler buildings.

CHAPTER EIGHT

GENERAL DISCUSSION

The welfare, health and production of broiler chicken depends on the environmental conditions that are provided for them and the outdoor conditions. During hot weather periods, it is usually difficult for broiler chickens to adapt and they tend to resort to altering their behavioural and physiological mechanisms by lowering feed intake and increase water intake (Dozier III et al., 2011). This survival strategy of broiler chickens has resulted in farmers' economic losses through slower growth and high mortality of broiler chickens. For farmers to improve the indoor conditions of broiler buildings during hot weather, they often tend to open all available inlets and even doors with all mechanical fans fully in operation (Albright, 1990). Unfortunately, the challenges facing the broiler chickens during the hot weather periods are yet to be solved with the method, full opening of inlets, adopted by the poultry growers. To date, the wide opening of inlets of broiler building, during hot periods, is yet not fully appraised. Therefore, this research work was set up to examine the indoor air velocity distributions of sidewall inlet and roof exhaust ventilated broiler building. Furthermore, a plan was developed to investigate an alternative ventilation system for improving the air velocity in the broiler occupied zones during hot weather periods and to evaluate the effect of the ventilation system on the sensible heat transfer from broiler chickens.

In the first experimental study, which was centered on the evaluation of the indoor air velocity in the broiler occupied zones, it was shown that the air velocity is generally below the airflow required for providing appropriate environment for broiler chickens during hot weather periods at all measurement locations. At the inlet, the mean air velocity was 4.91 m s^{-1} while the air velocity distributions in the broiler occupied zones was below 0.6 m s^{-1} (within an empty broiler building) and below 0.2 m s^{-2} (within a broiler building occupied with broiler models). This indicates that wide opening of inlets during hot weather periods does not necessarily mean that higher air movement would occur in the broiler occupied zones (Albright, 1990). There are possible factors contributing to the poor air distributions within the broiler building when the bottom-hinged inlet baffles were fully opened. It could be that the bottom-hinge baffles deflected away the airflow from the broiler occupied zones, resulting in airflow drift towards the roof exhaust fans which has also been indicated in a study conducted by Smith et al. (1999). Another important factor contributing to the lower air velocity distributions in the broiler occupied zone is the height of the inlet above the floor which have been shown in some studies (Jin and Ogilvie, 1992; Ogilvie et al., 1990). The indoor air velocity distributions of a sidewall inlet and roof exhaust ventilated broiler building was simulated using the computational fluid dynamic (CFD). The simulation was conducted with three turbulence models (standard $k-\varepsilon$, realisable $k-\varepsilon$, and shear stress transport $k-\omega$) to determine the best predictive model for the hot weather ventilation of the sidewall inlet and roof exhaust ventilated broiler building. Before the simulation was carried out, some assumptions in the literature were validated to ensure that they were applicable in this study. The validation indicated that the structural details and the boundary conditions of the building to be simulated are crucial factors that the ventilation engineers need to consider when carrying out livestock building simulation in order to improve the accuracy of CFD predictions (Norton et al., 2007). The results predicted by the turbulence models were validated with the experimental results. It was discovered that standard $k-\varepsilon$ turbulence model, which has also been shown in another study (Norton et al., 2010a) predicted the indoor air velocity distributions, almost similar to the air velocity distributions obtained in the experimental study except at the centre of the broiler building where the CFD predicted higher air velocity.

Sequel to the results of the evaluation of the indoor air velocities of the broiler experimental building and that of the CFD simulation, an alternative hot weather ventilation system was developed to improve the air velocity distributions in the areas closer to the sidewalls where some studies have shown to have very low or almost zero air velocity distributions (Hoff, 1995; Norton et al., 2007). The ventilation system comprises of two major parts: a mechanical fan and a turbulence generator. The fan produces an airflow of an average of 2.5 m s^{-1} to 4.5 m s^{-1} air velocity and the turbulence generator fluctuates the airflow at an average of 0.15 to 0.35 turbulence intensities before discharging the air out of the system. The results of the study showed that as the inlet turbulence increased, there was a reduction in the mean inlet air velocity. Similar result has also been reported by Xia et al. (2000) who indicated that as the air velocity increased, there was a decrease in turbulence intensity. The highest mean air velocity and the least inlet turbulence of the ventilation system were observed at an oscillation baffle angle of 45 º. The least mean inlet air velocity and the highest inlet turbulence were noticed at an oscillation baffle angle of 135 º. This indicates that the mean inlet air velocity and the mean inlet turbulence of the system were mainly influenced by the angle of oscillation of the inlet baffle. This is the first study considering the integration of higher inlet turbulence in the broiler building ventilation.

The effect of the ventilation system on the air velocity distributions within an experimental broiler room was also evaluated. The study indicated that inlet airflow turbulence, using oscillating inlet baffle, improved air movement in the areas closer to the wall in both the occupied and the empty broiler rooms. For instance, the inlet airflow turbulence of 0.15 improved airflow in the occupied broiler zones by 360 % over the wide opened bottom-hinged baffle. Likewise, there was an increase of 540 % in air velocity distributions in the broiler occupied zones when inlet airflow turbulence was set at 0.35 over the wide opened bottom-hinged baffle. This indicates that integration of airflow turbulence in the ventilation system of broiler building would improve the air movement in the broiler occupied zones and also could help relieve broiler chickens of heat stress during hot weather periods. Further study on the impact of stocking densities (33 and 39 kg m^{-2}) on the airflow movement in the broiler occupied zones showed that higher stocking density of 39 kg m^{-2} did not reduce the effect of inlet airflow turbulence on the air distributions in the broiler occupied zones within the experimental room.

The impacts of inlet airflow turbulence on the surface temperatures, coefficient of convective heat transfer, convective heat transfer, radiative heat transfer and sensible heat transfer of broiler chickens were examined. The study was conducted with a modelled broiler chicken covered with taxidermy mount. In a study conducted by Li et al. (2016), they indicated that broiler orientations did not have any effect on the convective heat transfer of broiler chickens exposed to variable airflow. The possibility of orientations not having effect in their study could be that heat transfer measurements were made at the back (dorsal region) of the broiler. Therefore, in this study, there was an assumption that the heat transfer at the breast (pectoral) region of broiler could vary as the broiler orientations change with respect to airflow direction. As a result, the model was exposed to variable inlet airflow turbulence at different orientations [head facing the airflow direction (0 º), side facing the airflow direction (90 º) and the tail facing the direction of the airflow (180 º)] and surface temperatures of broiler model were obtained at the breast region with a thermal imager. This study showed that orientations did not have significant effect on the surface temperatures and all the heat transfers of the broiler model considered. However, the result of the study did indicate that inlet airflow turbulence had significant effect on the coefficient of convective heat transfer of broiler model similar to the results reported by other researchers (Gebremedhin, 1987; Li et al., 2016b, 2016a). As indicated in other studies (Li et al., 2016a; Sak et al., 2007), it has also been found in this study that inlet airflow turbulence has effect on the heat transfer and the surface temperatures of broiler chickens in the areas closer to the inlet. In the literature, it has been indicated that broiler chickens located in the sidewall areas in the broiler building suffer from heat stress during hot weather periods due to lower air velocity distributions in these areas which has also been indicated in another study (Blanes-Vidal et al., 2007). In this study, it has been demonstrated that problems associated with the sidewall inlet areas could be minimised with the integration of inlet oscillation baffle into the broiler ventilation system, which could generate higher inlet airflow turbulence that would improve air movement in the broiler occupied zones during hot weather periods.

8.1 Future considerations

The studies conducted with the alternative hot weather ventilation system have shown for the first time that the heat stress experienced by the broiler chickens, during hot weather periods, could be potentially reduced. Though the air movement in the wall areas was improved by increasing the inlet turbulence, achieving higher air movement as the distance increased was a problem. In this study, only an average airspeed of 4.5 m s^{-1} was tested as the inlet airspeed due to its closeness to the mean airspeed of 4.91 m s^{-1} obtained in the experimental building. Additional studies could have been tested using the computational fluid dynamics (CFD) so as to guide the direction of the further research study. However, it was challenging to conduct such studies due to the limited knowledge of the author of this work in the handling of CFD package. It would have been good if the CFD could be employed to investigate different angles of inlet openings with variable inlet airspeeds and turbulence intensities and their effects on the air velocity distributions in the broiler occupied zones. Therefore, it would be of interest to investigate the impact of inlet oscillation baffle with variable inlet airspeed and turbulence intensities on the air velocity distributions in the broiler occupied zones of broiler building and the heat transfer from broiler chickens when exposed to higher indoor temperatures.

Although the effect of sidewall on the air movement in the areas closer to the wall was reduced by increasing the inlet turbulence to 0.15 and 0.35 using inlet oscillation baffle, it could have been of interest if the impact of inlet height above the floor was considered during the experimental study. It was reported that during the hot weather periods, higher air movement ranging between 1 to 3 m s^{-1} should be provided in the broiler occupied zones (Defra, 2005). However, this air velocity could be difficult to achieve as inlet height tend to have significant effect on the air velocity in the broiler occupied zones (Hoff, 1995). It has been observed that the same inlet height above the floor is used for both cold weather and hot weather ventilations in typical broiler buildings. During cold weather, exposure of birds to cold air could result in draft. Therefore, airflow is usually directed towards the ceiling before it falls on the birds at the centre of the building using bottom-hinged inlet baffles. However, for hot weather, birds are expected to be exposed to higher airflow to relieve them of heat stress. Birds' exposure to maximum airflow during hot weather periods could be difficult if no new inlet height is designed for the hot weather ventilation. Therefore, the information on the impact of inlet heights using CFD would be useful in the design of new hot weather inlets for broiler buildings so as to increase air movement in the broiler occupied zones.

An important aspect to be investigated would be the CFD simulation of heat transfer from single bird and group of birds as found in the typical commercial broiler productions. In this study, only one broiler model was used during the evaluation of the heat transfer from broiler model subjected to variable hot environment conditions and different inlet airflow turbulence. Though inlet airflow turbulence had significant effect on the air velocity distributions in the occupied broiler building, it was difficult to estimate the effects of many birds on the heat transfer from each broiler chicken due to the fact that only one broiler model was used during the study.

8.2 Conclusions

This study has shown that wide opening of the inlets in the broiler building would not necessarily improve the air movement in the broiler occupied zones. The situation becomes more critical when the building is occupied with broiler chickens as air velocity in the broiler occupied zones dropped below an average of 0.2 m s^{-1}. It has also been shown in this study that the broiler building used in CFD simulation should be a close representative of real-time broiler building and that standard $k - \varepsilon$ turbulence model is very useful in the prediction of air velocity distributions with the broiler building with sidewall inlet and roof exhaust ventilation system compared to other turbulence models.

The indoor airflow in the broiler occupied zones has been shown in this study to be improved by the integration of inlet oscillation baffle that could generate higher inlet turbulence, in the ventilation systems of broiler buildings. The introduction of higher inlet turbulence in the ventilation system in this study has shown that air movement in the areas closer to the sidewall could be improved in both occupied and unoccupied broiler buildings. Furthermore, it has been shown in this report that it is of no importance to estimate surface temperatures and heat transfers of broiler chickens based on their orientations. This indicates that irrespective of the orientation at which measurements are obtained, the surface temperatures and the heat transfers would be similar. Nevertheless, the results of this study have showed that sensible heat transfer of broiler chickens could be enhanced during hot weather periods with the introduction of higher inlet turbulence, generated by the inlet oscillation baffle, in the ventilation system of broiler building.

This study is the first to show that the inlet of the broiler buildings could be oscillated to generate higher inlet turbulence that could improve air distributions in the broiler occupied zones within broiler building during hot weather periods. The fact that inlet turbulence can be generated in the broiler ventilation system by oscillating the inlet baffle at different angles and frequencies has never been previously reported. This study has laid an important research framework for the possible hot weather ventilation for the ventilation engineers.

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APPENDICES

Appendix 1: The estimated torque of the stepper motor

1. Force of baffle

Mass of the baffle = 0.75 kg

$g = 9.81\ m/s^2$

$$F_1 = mg \tag{32}$$

$$= 0.75 \text{ x } 9.81 = 7.358 \text{ N}$$

2. Force of air that will act on the baffle

Dynamic pressure of air (Pd)

$$P_d = {}^1/_2\, \rho V^2 \tag{33}$$

Where ρ is air density (1.225 kg m^{-3}), V is velocity of air from the fan (5 m s^{-1})

$$P_d = 0.5 \text{ x } 1.225 \text{ x } 5^2$$

$$= 15.313 \text{ Pa}$$

Area (A) of flap on which the force of air acts to rotate it

$$A = {}^1/_2\, A \tag{34}$$

$$A = {}^1/_2 \text{ x } 0.545 \text{ x } 0.545$$

$$= 0.149 \text{ m}^2$$

Force (F_2) of air from the fan = Area x dynamic pressure

$$F_2 = A \text{ x } P_d \tag{35}$$

$$=0.149 \text{ x } 15.313$$

$$= 2.282 \text{ N}$$

3. Total force ($\mathrm{F_{total}}$) acting on the baffle

$$\mathrm{F_{total}} = \mathrm{F_1} + \mathrm{F_2} \tag{36}$$

= 7.358 + 2.282

= 9.640 N

4. Torque of the oscillating baffle

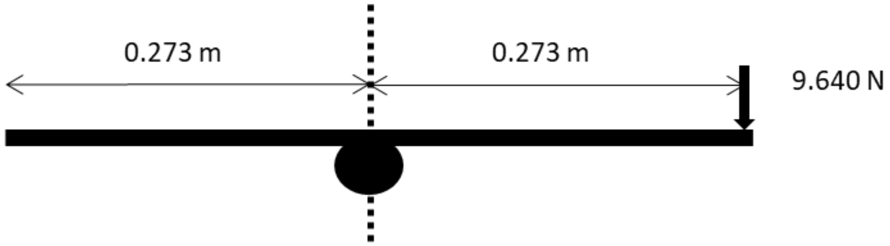

Figure A1: The force acting on the baffle of the turbulence generator

D = width of flap = 0.545 m

d = Distance at which the force would act on the baffle from the shaft = $\frac{1}{2}\mathrm{D}$ = 0.273 m

Torque = F × d

Torque = 9.640 x 0.273 = 2.621 Nm

Appendix 2: Arduino code for operating the ventilation system

```
#include <Stepper.h>

const int stepsPerRevolution = 100; // set stepsperrevolution at 50, 75 and 100

                                    // which are equal to 90, 135 and 180 degree

                                    //flap opening angle

// set pin numbers:

const int twentySwitch = 2;        // the bit-number of the pushbutton

const int sixtyfiveSwitch = 3;       // the bit-number of the pushbutton

//const int eightySwitch = 4;    // the bit-number of the pushbutton

//const int onehundredSwitch = 5;     // the bit-number of the pushbutton

int stepperSpeed;

int buttonState = 0;               // variable for reading the pushbutton status

Stepper myStepper(stepsPerRevolution,8,9,10,11);  // initailise the stepper, pins 8 9 10 11

void setup() {

  pinMode(13, OUTPUT);              // initialize digital pin 13 LED output.

  pinMode(twentySwitch, INPUT);      // initialize the pushbutton pins as an inputs:

  pinMode(sixtyfiveSwitch, INPUT);

  //pinMode(eightySwitch, INPUT);

  //pinMode(onehundredSwitch, INPUT);
```

```
 stepperSpeed = 0; // Stepper motor speed is rpm.
}
void loop() {
   buttonState = digitalRead(twentySwitch);
  if (buttonState == LOW) {
    stepperSpeed =20;
    myStepper.setSpeed(stepperSpeed);
    flashLED();
  }
  buttonState = digitalRead(sixtyfiveSwitch);
  if (buttonState == LOW) {
    stepperSpeed =65;
    myStepper.setSpeed(stepperSpeed);
    flashLED();
  }
  // buttonState = digitalRead(eightySwitch);
  // if (buttonState == LOW) {
  //  stepperSpeed =80;
   // myStepper.setSpeed(stepperSpeed);
    //flashLED();
 // }
   //buttonState = digitalRead(onehundredSwitch);
```

```
   //if (buttonState == LOW) {
   // stepperSpeed =100;
    //myStepper.setSpeed(stepperSpeed);
   // flashLED();
  //}
  Serial.println("Clockwise");
  myStepper.step(stepsPerRevolution);
  delay(0);
  Serial.println("Counter Clockwise");
  myStepper.step(-stepsPerRevolution);
  delay(0);
}
void flashLED(){
  digitalWrite(13, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(500);               // wait for a second
  digitalWrite(13, LOW);    // turn the LED off by making the voltage LOW
  delay(500);
```