# THE APPLICATION OF COMPUTATIONAL FLUID DYNAMICS (CFD) IN THE VENTILATION OF AGRICULTURAL BUILDINGS: A REVIEW

**Ayoola Olawole Jongbo[1]*, Stephen Segun Olajide[1] and Adekunle Temidayo Atta[2]**

[1]Department of Agricultural and Environmental Engineering, School of Engineering and Engineering Technology, Federal University of Technology, PMB 704, Akure, Ondo State, Nigeria.
[2]Institute of Agricultural Research and Training, Obafemi Awolowo University, Moor Plantation, Ibadan, Oyo State, Nigeria
*Corresponding email: aojongbo@futa.edu.ng +234 (0) 8067274621

## ABSTRACT
The effect of heat stress on crop and animal production is immeasurable. The environmental factors majorly influencing heat stress are temperature, relative humidity, and air velocity. The energy required for providing appropriate environments for plants and animals could be reduced through the use of efficient ventilation systems. Appropriate design, evaluation and prediction tools are needed to assess existing systems and determine the changes that are likely to have the most desirable effects on agricultural environments. Improved efficiency of computer systems and the development of better numerical techniques have helped to improve the accuracy of computational fluid dynamics (CFD) techniques and made their application easier. The ability of simulations to represent real situations has also improved. Consequently, CFD has become a common tool in investigating and solving environmental problems within greenhouses and livestock environments. This review provides an up-to-date evaluation of the applications of CFD in the design and improvement of agricultural ventilation systems, outlining the techniques and models used in various studies. The performances of different ventilation systems under various climatic conditions and their ability to meet the environmental requirements of specific crops or livestock were also discussed. In this article as well, the state-of-the-art application of CFD in an agricultural building in Nigeria was discussed. The model equations of the five most commonly used turbulence models in the researches under consideration were likewise itemised.

**KEYWORDS:** Heat stress, Numerical simulation, Greenhouse, Animal environment, Turbulence models.

## 1. INTRODUCTION
Heat stress results in a reduction of voluntary feed intake, leading to a decline in growth rate and production among livestock (King, 2011; Okyere *et al*., 2020). Sohail *et al*. (2012) reported a 16.4% reduction in feed intake, and a 32.6% drop in body weight of 42-day old broilers exposed to chronic heat stress. Effects of adverse climatic conditions on the organs and muscle metabolism of poultry birds, coupled with changes in rearing practices, could significantly affect the meat quality of poultry birds. Heat stress could result in incidences of pale-soft-exudative meat in turkeys, and lower chemical composition and quality of broiler meats, reduced protein content and high fat accumulation (Dia *et al*., 2012; Imik *et al*., 2012; Zhang *et al*., 2012). In the tropical humid climate, animals are mostly exposed to climatic conditions higher than their thermoregulatory zones and this has significant effect on animal health and performance (Jongbo, 2020).

The deleterious effects of heat stress on the mortality of poultry birds have been established by several studies (Yoon *et al*., 2014; Kang *et al*., 2020). These effects could be as a result of the fact that apart from the negative physiological effects of heat stress on the birds themselves, they could suffer the risk of endotoxin and bacterial contamination due to increased permeability of their deficient intestinal integrity (Alhenaky *et al*., 2017). However, an acute increase in temperature- humidity index (THI) was observed to have a more severe negative impact on hen mortality than extended periods of heat stress (Bhadauria *et al*., 2014; Kang *et al*., 2020). Similarly, an extensive study on the effects of heat stress on egg production, shell quality, and hen-day egg production had been carried out and reported by Gwaza *et al*. (2017). Gwaza *et al*. (2017) observed a drop in hen-day production during the five dry season months of November to March. Duduyemi and Oseni (2012) also reported a 0.32 eggs/THI decline in egg-production for the Bovan Nera, and a 0.37 eggs/THI reduction for Isa Brown chickens at THI above 27.5. Abioja *et al*. (2012) and Obidi *et al*. (2008) both reported that fertility and hatchability of eggs laid under different thermal conditions vary, as a result of the effects of thermal stress.

Moderate temperature rise encourages testicular growth in the early stages of a breeder cock's life, however, further rise in temperature and humidity could reduce the productive capacity and fertility of broiler cocks, due to its negative impact on spermatozoa motility (Ameen *et al*., 2014; Noiva *et al*., 2014). The ambient temperature at the moment of inseminating hens could affect the fertility and hatchability of eggs, and prolonged exposure to heat stress could also hinder the process of embryonic growth and development, leading to hatch defects in chicks (Obidi *et al*., 2008; Bhadauria *et al*., 2014).

Several studies have shown that heat stress suppressed the immunity of broilers and laying hens through various physiological responses including a reduced amount of antibodies, a lower liver and lymphoid organ weight (Niu *et al*., 2009; Zhang *et al*., 2012; Ghazi *et al*., 2012). The tendency of climate change to result in an alteration of the distribution of diseases globally has been established; and the result of such an occurrence could be devastating, as previously unexposed humans and animals could come in contact with novel diseases (Guis *et al*., 2011). Climatic factors also affect the transmission of the avian influenza virus, and its ability to survive outside the body of the host animals (Gilbert *et al*., 2008).

Therefore, in this review work, the focus would only be on the ventilation of agricultural buildings and the application of computational fluid dynamics in the simulation of the ventilation of the agricultural buildings.

## 2. VENTILATION

Ventilation involves putting in place measures to regulate the indoor climate of the livestock housing, to provide an adequate supply of oxygen required for their metabolism and reduce the level of waste gases or contaminants such as carbon dioxide, ammonia, dust and odour to a tolerable level (Caroprese, 2008; Weeks, 2008). Ventilation would maintain the appropriate range of temperature and humidity to ensure that the animals feed and grow properly as well as avert the occurrence of diseases that could result from excessively high or low temperature and humidity (Mrema *et al*., 2011).

Ventilation could either be natural or mechanical. The natural ventilation system is generally passive and relies basically on either the stack effect of thermal buoyancy which causes air to rise as it warms up, or air-pressure differentials caused by wind (Dheghan *et al*., 2013). It could be regulated by the use of curtains and vents. Natural ventilation has a limited ability to provide a controlled rate of air change or respond to the varying needs of building occupants (Ohba and Lun, 2012). Despite its limitations, natural ventilation has been designated as a promising method of reducing building energy consumption arising from the use of heating, ventilation, and air conditioning (HVAC) systems (Ohba *et al*., 2012; Oropeza-Perez and Ostergaard 2014; Malkawi *et al*., 2016).

Mechanical ventilation includes the tunnel ventilation system, the cross-ventilation system, and the roof exhaust and side inlet ventilation system. This method involves the use of fans to create a positive or negative pressure inside the building. For positive pressure systems, fans force air through inlets or openings into the building, creating a positive pressure that causes air to move out of the building at the outlet opening. Meanwhile, for negative pressure systems, suction fans expel air from the building, resulting in a pressure drop that causes air to flow into the structure (Mrema *et al*., 2011). The negative impacts of mechanical ventilation cannot be overemphasized, given that it has greatly contributed to global warming as a result of carbon dioxide emissions (Dehghan *et al*., 2013). Hence, architects and designers are turning to natural ventilation, using wind catchers to improve the quality of supplied air, and the efficiency of ventilation systems (Hughes *et al*., 2012).

## 3. VENTILATION PERFORMANCE PREDICTION METHODS

Natural ventilation involves complex physical processes which needs to be simplified by designers to facilitate the study, calculation, and prediction of natural ventilation in buildings (Dehghan *et al*., 2013). Throughout human history, various methods have been adopted in natural ventilation studies, and the evolution of these approaches across various periods is shown in Figure 1. The trend indicates a transition from conventional to computational methods (Ohba and Lun, 2012). Methods used in ventilation performance prediction could either be analytical or experimental (Dehghan *et al*., 2013).

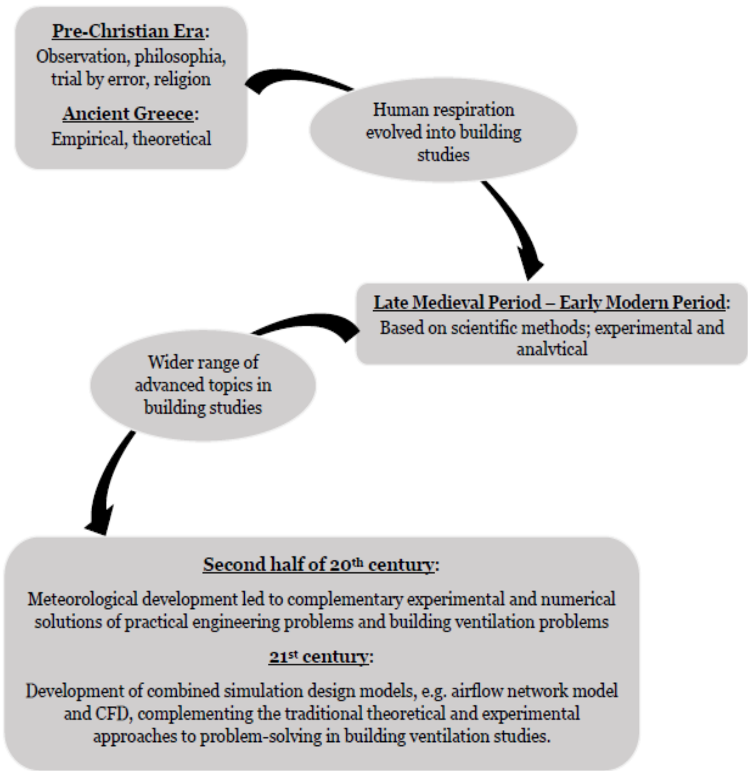


**Figure 1**: Evolution of ventilation study approaches. Source: Ohba and Lun (2012)

### 3.1. Basic Principles of CFD

The CFD approach in this review involves numerically solving Reynolds-averaged form of the Navier-Stokes equations within each cell of the computational domain to obtain complex simulations of turbulent flows, thermal distributions, air velocity and convection within the building (Rojano *et al*., 2014). The Reynolds averaged Navier-Stokes equations (RANS) uses time averaging to determine the effect of turbulence on the mean flow field (Bustamante *et al*., 2013).

The non-linear partial differential equations for the conservation of mass, momentum and energy solved by the simulation software, are given below as Equations 1, 2, and 3, respectively (Lee *et al*., 2007).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{dx_i}(\rho\, u_i) = S_m \quad 1$$

$$\frac{\partial}{\partial t}(\rho\, u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \quad 2$$

$$\frac{\partial \rho}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(K\frac{\partial T}{\partial x_i}\right) - \frac{\partial}{\partial x_i}\sum_j h_j J_j + \frac{\partial}{\partial t} + \frac{\partial p}{\partial x_i} + \tau_{ij}\frac{\partial u_i}{\partial x_j} + S_h \quad 3$$

where:

$S_m$ is mass source in ($kgm^{-3}s^{-1}$); $\rho$ is density in ($kgm^{-3}$); $u_i$ is component of velocity in ($ms^{-1}$); $x_i$ is component of length in (m); t is time in (s); $\rho$ is pressure in (Pa); $\tau_{ij}$ is the stress tensor in (Pa); $F_i$ is external force vector in ($Nm^{-3}$); $g_i$ is gravitational acceleration in ($ms^{-2}$); K is thermal conductivity in ($Wm^{-1}K^{-1}$); h is specific enthalpy in ($Jkg^{-1}$); $J_j$ is the component of diffusion flux in ($kgm^{-2}s^{-1}$); $S_h$ is total entropy in ($JK^{-1}$); and T is air temperature for the livestock building in (K).

Numerous turbulence models have been developed, but the most commonly used ones for studies involving agricultural buildings include the standard k-ε, the renormalization-group (RNG) k-ε, the k-ε realizable, and the Reynolds Stress Model (RSM) (Bustamante *et al*., 2013). As shown in Figure 2, obtaining a solution from the governing equations above involves converting the governing partial differential equations and boundary conditions into a system of discrete algebraic equations using finite difference or finite volume method, then obtaining the solution from the system of linear or non-linear algebraic equations through the application of numerical methods. Currently, all CFD models predict building ventilation performance using approximation, which unavoidably results in a level of uncertainty in the prediction of air flow, velocity and temperature.

## 3.2. Turbulence Models

Commonly used CFD models generally fall into two categories namely those that are based on a finite-volume approach involving the Reynolds-averaged Navier-Stokes (RANS) equations which resolves only the mean (time-averaged or ensemble-averaged) flow, and those that follow the large eddy simulation (LES) methods which filters the Navier-Stokes (NS) equations. Other classes of CFD models are the Direct Numerical Simulation (DNS) which is too computationally demanding since it requires that the exact Navier Stokes equations be solved to the smallest length and time scales, and the hybrid LES-URANS (unsteady RANS) methods (Blocken and Gualtieri, 2012). The satisfactorily high quality of results, and the low computational power requirement of RANS models have led to their continued use both for research and design purposes (Blocken, 2018).

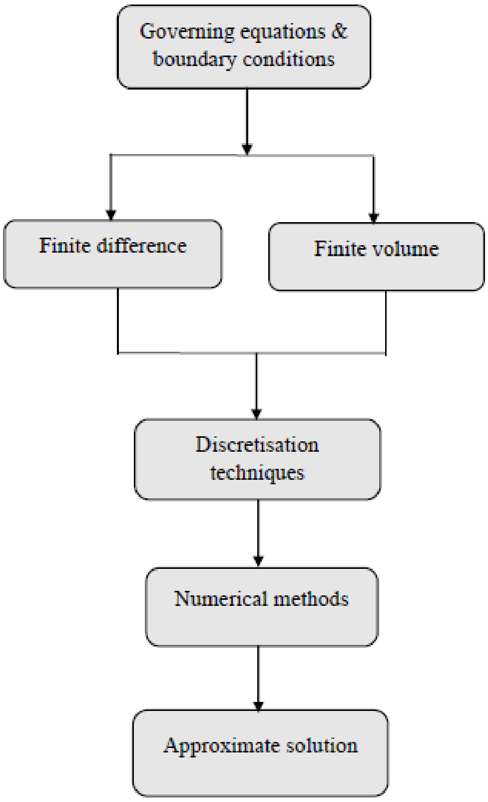


**Figure 2**: CFD solution procedure. Source: Tu *et al*. (2018)

An investigation of the indoor condition in an industrial premises carried out by Rohdin and Moshfegh (2011) where three turbulence models (standard *k-ε*, RNG *k-ε* and realizable *k-ε*) were tested by qualitative and quantitative validation methods revealed that RNG *k-ε* had the best agreements with measurements from the field experiment. The same conclusion was drawn from similar studies where CFD and other turbulence models were evaluated (Lee *et al*., 2007; Liu *et al*., 2013). Along with the three *k-ε* models outlined above, other two-equation RANS models: the standard *k-ω*, and shear stress transport (SST) *k-ω* turbulence models have been extensively used in simulation studies (Kim *et al*., 2017; Oh *et al*., 2019).

### 3.2.1. Standard *k-ε* model

The standard *k-ε* model is a semi-empirical model whose equations were derived from the Reynolds-Averaged Navier-Stokes equations. The major assumptions in this model were that the flow is fully turbulent and the effects of molecular viscosity are negligible, therefore it could only be used for fully turbulent flows. It evaluates the turbulent viscosity ($\mu_t$) from the relationship between the turbulent kinetic energy (κ) and kinetic energy of turbulent dissipation (ε) as defined by equation 4 (Li *et al*., 2016):

$$\mu_t = C_\mu \rho \frac{\varepsilon^2}{\kappa} \qquad 4$$

The values of κ and ε are calculated using equations 5 and 6 (Li *et al*., 2016):

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho\kappa u_i)}{\partial \rho_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial}{\partial x_i}\right] + P_k + P_b - \rho_j\varepsilon - Y_M + S_k \qquad 5$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{\kappa}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \qquad 6$$

The production of turbulent kinetic energy $P_k$ is given by (Li *et al*., 2016) as:

$$P_k = \mu_t S^2 \quad 7$$

The effect of buoyancy forces $P_b$ is given by (Li *et al*., 2016) as:

$$P_b = \beta g_i \frac{\mu_t}{\mathrm{Pr}_t} \frac{\partial T}{\partial x_i} \quad 8$$

where:

$\mathrm{Pr}_t$ is the turbulent Prandtl number,
$g_i$ is the component of the gravity vector in the *i*th direction.
$C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, $C_{3\varepsilon}$ = 1, $C_\mu$ = 0.09, $\sigma_\varepsilon$ = 1.3,
$\sigma_\kappa$ = 1 were adopted as values of the model constants.

### 3.2.2. Renormalization group (RNG) *k-ε* model

The RNG *k-ε* model resolves turbulence by filtering out as much small-scale turbulence as necessary. This is achieved by making the $C_{\varepsilon 2}$ a variable term, and applying a factor "h" which is the ratio between the time scales of the turbulence and the mean flow (Rohdin and Moshfegh, 2011).

The new $C_{\varepsilon 2}$ denoted as $C_{\varepsilon 2n}$ is defined by (Rohdin and Moshfegh, 2011) as:

$$C_{\varepsilon 2n} = C_{\varepsilon 2} \frac{C_\mu \eta^3 (1-\eta/\eta_0)}{1+\beta\eta^3} \quad 9$$

The values of *k* and *ε* are defined by equations 10 and 11 (Mostafa *et al*., 2012).

$$\rho \frac{dk}{dt} = \frac{\partial}{\partial x_i}\left[\alpha_k \mu_{eff} \frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho e - Y_M \quad 10$$

$$\rho \frac{d\varepsilon}{dt} = \frac{\partial}{\partial x_i}\left[\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R \quad 11$$

where:

$k$ is turbulent kinetic energy ($m^2s^{-2}$);
$\mu_{eff}$ is effective viscosity;
$\mu = \mu_t$ ($m^2s$); $\mu$ is viscosity ($m^2s$); $\mu_t$ is turbulent viscosity ($m^2s$);
$\alpha_k$ is the generation of kinetic energy due to the mean velocity gradients ($kgm^{-1}s^{-2}$);
$\alpha_\varepsilon$ is the generation of kinetic energy due to buoyancy ($kgm^{-1}s^{-2}$);
$G_b$ is the generation of turbulent kinetic energy due to the mean velocity gradients ($kgm^{-1}s^{-2}$);
$G_b$ is the generation of kinetic energy due to the buoyancy ($kgm^{-1}s^{-2}$);
ε is turbulent dissipation rate ($m^2s^{-3}$);
$Y_M$ is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate ($kgm^{-1}s^{-2}$);
$C_{1\varepsilon}$and $C_{2\varepsilon}$are constants of 1.42 and 1.68;
$C_{3\varepsilon}$is tanh ($u_1/u_2$), $u_1$ and $u_2$ are components of the flow velocities parallel and perpendicular, respectively, to the gravitational vector, and R is the gas law constant, 8.31447 x $10^3$ $Jkgmol^{-1}K^{-1}$.

The turbulence kinetic energy ($k$) and turbulence dissipation rate ($\varepsilon$), which are important factors for inlet conditions, is calculated using Equations 12 and 13 (Fluent, 2006):

$$k = \frac{1}{2}(u^2 + v^2 + w^2) \tag{12}$$

$$\varepsilon = \frac{C_\mu^{3/4} \times k^{3/2}}{l}, l = \min(k \times z_n, k \times \delta) \tag{13}$$

where:

$C_m$ is an experimental constant;
$z_n$ is height from the ground (m),
and δ is thickness of the turbulent boundary layer (m).

### 3.2.3. Realizable *k-ε* model

The realizable *k-ε* model allows the removal of certain variables such as negative normal stresses from predictions by means of numerical clipping. This realizability effect is achieved by making $C_\mu$ a function of the turbulence field's mean strain and rotation rates. The realizable *k-ε* model's $k$ equation is identical to that of the standard *k-ε* model, while *ε* is derived from equation 14 (Rohdin and Moshfegh, 2011).

$$\frac{\partial(\rho U_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_1\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\rho\varepsilon - C_2\frac{\rho\varepsilon^2}{k + \sqrt{v\varepsilon}} \tag{14}$$

where:

$C_1$= max [0.43, h/(h+5)],
$C_2$= 1.0, $\sigma_k$= 1.0, and
$\sigma_\varepsilon$ = 1.2.

### 3.2.4. Standard *k-ω* model

The standard *k-ω* model is defined by the Equations 15 and 16 (Miroshnichenko and Sheremet, 2015):

$$\frac{\partial K}{\partial \tau} + U\frac{d\xi}{dX}\frac{\partial K}{\partial \xi} + V\frac{d\eta}{dY}\frac{\partial K}{\partial \eta} = \frac{d\xi}{dX}\frac{\partial}{\partial \xi}\left[\left(\sqrt{\frac{Pr}{Ra}} + \frac{v_t}{\sigma_k}\right)\frac{d\xi}{dX}\frac{\partial K}{\partial \xi}\right] + \frac{d\eta}{dY}\frac{\partial}{\partial \eta}\left[\left(\sqrt{\frac{Pr}{Ra}} + \frac{v_t}{\sigma_k}\right)\frac{d\eta}{dY}\frac{\partial K}{\partial \eta}\right] + \bar{P}_k\bar{G}_k - \beta^* WK \tag{15}$$

$$\frac{\partial W}{\partial \tau} + U\frac{d\xi}{dX}\frac{\partial W}{\partial \xi} + V\frac{d\eta}{dY}\frac{\partial W}{\partial \eta} = \frac{d\xi}{dX}\frac{\partial}{\partial \xi}\left[\left(\sqrt{\frac{Pr}{Ra}} + \frac{v_t}{\sigma_k}\right)\frac{d\xi}{dX}\frac{\partial W}{\partial \xi}\right] + \frac{d\eta}{dY}\frac{\partial}{\partial \eta}\left[\left(\sqrt{\frac{Pr}{Ra}} + \frac{v_t}{\sigma_k}\right)\frac{d\eta}{dY}\frac{\partial W}{\partial \eta}\right] + \alpha\frac{W}{K}\bar{P}_k + \frac{W}{K}\bar{G}_k - \beta W^2 \tag{16}$$

where the model constants are $\alpha$ = 0.56, $\beta$ = 0.075, $\beta^*$ = 0.09, $\sigma_k$= 0.5, and $\sigma_\omega$ = 0.5.

### 3.2.5. Shear stress transport (SST) *k-ω* model

The Menter's *k-ω* shear stress transport (SST) model comprises two equations namely, the specific turbulent kinetic energy and the specific turbulent dissipation rate. The specific turbulent kinetic energy *k* could be determined using Equation 17 (Rocha *et al*., 2014):

$$\frac{\partial}{\partial t}(\rho k)\frac{\partial}{\partial x_i}(U_i\rho k) = \frac{\partial}{\partial x_j}\left(\mu_k\frac{\partial}{\partial x_j}k\right) + P_k - \beta^*\rho\omega k \qquad 17$$

The specific turbulent dissipation rate *ω* could be defined by equation 18 (Rocha *et al*., 2014):

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(U_i\rho\omega) = \frac{\partial}{\partial x_j}\left(\mu_\omega\frac{\partial}{\partial x_j}\omega\right) + P_\omega - \beta\rho\omega^2 + 2\rho(1-F_1)\frac{1}{\omega}\frac{1}{\sigma_{\omega 2}}\frac{\partial}{\partial x_j}k\frac{\partial}{\partial x_j}\omega \qquad 18$$

The effective viscosities are given by equations 19 and 20 (Rocha *et al*., 2014):

$$\mu_k = \mu + \mu_t\frac{1}{\sigma_k} \qquad 19$$
$$\mu_\omega = \mu + \mu_t\frac{1}{\sigma_\omega} \qquad 20$$

where:

$\mu_t$is the modified eddy viscosity, and

$\sigma\chi$ ($\chi = k$; ω) is the diffusion constants.

The Reynolds stresses $\tau ij$ are computed using the Boussinesq expression (Rocha *et al*., 2014):

$$\tau_{ij} = -\rho\overline{U'_i U'_j} \qquad 21a$$
$$\tau_{ij} = 2\mu_t S_{ij} - \frac{2}{3}\rho k\delta_{ij} \qquad 21b$$

In equation 21b, $Sij$ is the mean rate of deformation component and $\delta ij$ is the Kronecker delta function. The rate of production of ω denoted as $P\omega$ is derived using equation 22:

$$P_\omega = \gamma\left[2\rho S_{ij}\cdot S_{ij}\frac{2}{3}\rho\omega\left(\frac{\partial}{\partial x_j}U_i\right)\delta_{ij}\right] \qquad 22$$

where γ is the model constant.

## 3.3. Commercial CFD Codes

To satisfy the complex modelling requirements of various disciplines, there has been extensive development of various commercial CFD codes. Those developed for ventilation studies must have the ability to model flow-dependent properties, implement user-defined functions and model flow through porous media among other features (Norton *et al*., 2007). Given the varying performance of different codes under differing applications, as well as the fact that many of them were developed within very specialized research areas, it is necessary to consider the functionality of individual codes before being selected for a study (Norton *et al*., 2007). Some of the most commonly used commercial codes include ANSYS CFX, ANSYS FLUENT, Star CCM+, PHOENICS and CFD 2000. These codes incorporate at least all the aforementioned functionalities, employ graphical user interfaces, and support Windows, UNIX and Linux operating systems. In a further attempt to further ease the process of CFD analysis and open the field up to non-experts, user-friendly, automated simulation programmes have also been developed (Kim *et al*., 2017).

## 3.4. Credibility of CFD in Ventilation Studies

The accuracy and reliability of predictions of turbulent flows by computational fluid dynamics (CFD) simulation is an issue of great concern to researchers. To convey the validity of CFD model simulations in comparison with field experiments, it is therefore necessary to verify and validate the model solutions. To this end, much detailed validation and verification studies have been conducted over the years, resulting in quite a number of best practices and validation guidelines (Rong *et al*., 2016). There have been numerous published works detailing best practice guidelines for verifying, validating, and reporting CFD investigations of indoor environments (Pelletier, 2010; Roy and Oberkampf, 2011; Blocken and Gualtieri, 2012; Hajdukiewicz *et al*., 2013). Additional guidelines on how to quantify model-form uncertainties and develop credible CFD models have also been developed ( Yao *et al*., 2013; Xiao *et al*., 2016).

### 3.5. Applications of CFD/Numerical models in Agricultural Buildings

Based on the review by Norton *et al*. (2007) and other recent works (Chen, 2009; Wu *et al*., 2012; Lee *et al*., 2013; De Rosis *et al*., 2014; Benni *et al*., 2016; Rong *et al*., 2016), it could be asserted that there has been a shift toward the use of CFD simulation in the study of fluid circulation within agricultural structures. This is perhaps due to the fact that conducting a CFD study requires less time, as well as lower financial and computational cost than full-scale field experiments. These studies also indicate that there has been a significant improvement in the accuracy of CFD simulation results over the years.

#### 3.5.1. Computational domain

Both two- and three-dimensional models have been used in simulating indoor air condition. A two-dimensional study of a layer house failed to show the true ventilation situation within the building due to the fact that the inlet and exhaust fans were located on different two-dimensional planes which could not be accommodated on the model (Fabian-Wheeler *et al*., 2018). Whereas, a three-dimensional model of the same structure presented a more realistic view of the ventilation conditions (Chen *et al*., 2020, 2021). Rojano *et al.* (2015), however, reported a good agreement between the predicted and experimental data in a two-dimension study of the internal environment of a broiler house.

According to Baxevanou *et al*. (2010), two-dimensional models do not precisely represent the situation within a greenhouse. Despite this, Baxevanou *et al*. (2010) also reported that in situations where the transport phenomena are being studied around the centre of a long structure which has ventilation vents along its entire length, two-dimensional models are sufficient for the study of indoor climatic conditions. The work of Benni *et al*. (2016) on greenhouse ventilation followed this assumption, and they reported a high level of correlation between the measured and simulated air speed using both the root squared mean error (RSME) values and an autoregressive model comparison. However, Benni *et al*. (2016) reported that temperature data showed only a fair correlation when compared on the basis of transient analyses and ratio of percentage deviation (RPD) index.

Many recent ventilation studies using three-dimensional models have reported a very good correlation between simulation and the results of field experiments in greenhouses (Chalill *et al*., 2021; Sun *et al*., 2020), cattle barns (Tomasello *et al*., 2019, 2021), piggery (Tabase *et al*., 2020), and poultry houses (Tehinse *et al*., 2020).

#### 3.5.2. Greenhouse Ventilation

Indoor microclimate control is a fundamental issue in greenhouse design since there is a need to maintain the internal temperature within an optimal range, while also replenishing $CO_2$ for photosynthesis through the supply of outdoor air. Natural ventilation is one of the most important indoor climatic control methods (Monila-Aiz *et al*., 2009).

In recent times, the usefulness of CFD in the initial stages of designing ventilation systems, as well as its ability to provide useful insight in estimating the impact of proposed modifications before implementation has been investigated. Computer simulations have also been demonstrated to be useful in optimizing the operations of automated climate management systems (CMS) by assisting designers in determining specific interventions such as degree and combination of vent opening, air circulating fan speed, and specific operations of evaporative coolers and HVAC systems that would effectively counteract the effects of severe variations in heat load under varying weather conditions during the day (Benni *et al*., 2016; Chalill *et al*., 2021). CFD application studies in greenhouse modelling before 2007 have been comprehensively reviewed by (Norton *et al*., 2007). More recent studies in this field are presented below.

In a study of natural ventilation of a side vented solar greenhouse, the effects of thickness, and the spectral, optical and thermal characteristics of the greenhouse cover material and the effects of varying intensities of solar radiation and angle of incidences into account (Baxevanou *et al*., 2010). The standard $k$-$\varepsilon$ turbulence model was used for this study. Cover material that absorbs high intensity solar radiation resulted to an increase in the greenhouse internal heat load due to convective heating of the local air, encouraged secondary recirculation of trapped air, and a significant reduction in the level of photosynthetically active radiation (PAR) available to the plants. Variation in the level of available PAR within the building was however found to be minimal for cover materials with high absorptivity combined with an arched roof design (Baxevanou *et al*., 2010).

Benni *et al*. (2016) studied the effects of various combinations of roof and side vents openings on the temperature within a three-span glass greenhouse in a hot climatic conditions. The effects of various levels of external wind speed on each of the vent configurations were also considered. The authors proposed the incorporation of solar radiation data into the model, as well as investigating the effects of plants on the indoor environment as areas of further study. Using the Standard $k$-$\varepsilon$ turbulence model and the Discrete Ordinates (DO) radiation model, the effects of different positions and combination of windows (three positions and two combinations) on the ventilation efficiency within a naturally ventilated solar greenhouse was studied by Sun *et al*. (2020). The work only considered the effects of thermal interaction between the roofs, walls, floor and the external environment. Investigating the effects of plant matter on internal ventilation was also proposed as a means of improving the accuracy of the model. The result of the study was however only verified using temperature data only, thus limiting the model's utility in the study of airflow and air distribution.

Chalill *et al*. (2021) proposed the use of box-type evaporative cooler (BTEC) units as an improvement on conventional HVAC systems which are usually designed without considering the impact of cover material on the indoor climate resulting in overdesigned systems. A full-scale 3-D CFD study of a greenhouse was carried out using the $k$-$\varepsilon$ turbulence model, and the results showed a good agreement between simulated and measured data. The BTEC systems feedback-based climate management systems (CMS) were thereafter installed, and the ability of the system to adequately keep the greenhouse climate within a range conducive for plant growth on a peak Middle East summer day was confirmed in a 20-hour pilot study which accounts for the total period of solar radiation over an entire day.

### 3.5.3. Cattle Barn Ventilation

Zhaohui *et al*. (2017) used the Realizable *k-ε* model to simulate the performance of a fan-pad evaporative cooling system in a beef cattle barn under summer conditions. Average relative errors of 34.53% and 4.71% between the measured and simulated values of air velocity and temperature respectively indicated that the developed model was adequate for studying ventilation in the building. Based on the simulation results, Zhaohui *et al*. (2017) were able to improve the temperature and airflow and air distribution within the building, thus confirming the model's ability to provide a guide for optimizing the design of a fan-pad evaporative cooling system, and regulating the environment of beef cattle barns.

To alleviate the effects of heat stress on dairy cows within naturally ventilated barns, mixed flow fans (MFF) were commonly used to improve ventilation. By analyzing the effects of three different elevation angles on the length of generated air jet, optimization of improved diffuser shape in an MFF was carried out by Yao *et al*. (2019). The angle of the air inlet was also found to have varying degrees of impact on pressure drop in the three animal occupied zones under study. The simulation was done with the RNG *k-ε* model and results were validated by comparing the simulated and measured values using a t-test.

The configuration of vents and openings, along with the internal building layout has been pointed out to be the primary factors affecting the efficiency of ventilation in naturally ventilated animal housing. (Tomasello *et al.*, 2019) defined a method for modelling and evaluating airflow patterns generated by wind-driven natural ventilation within a free-stall barn for dairy cows. Since there was a good agreement between the modelled air velocity distribution and measured values in the barn, the CFD model was considered reliable for simulating other environmental parameters. Based on the work of Tomasello *et al*. (2021) and using the same steady-state conditions and Standard *k-ε* turbulence model, Tomasello *et al*. (2021) tested five different simulated building layouts which were designed in line with the prevailing principles applied to renovating the layout of free-stall barns in the Mediterranean basin. The simulation results showed possible improvement of the average air velocity in the resting areas, service alley and feeding alley from 0.42 m $s^{-1}$ to 1.38 m $s^{-1}$, while average air velocity in the calf pens could be raised from 0.67 m $s^{-1}$ to 1.42 m $s^{-1}$. These values approach the 1.8 to 2.8 $ms^{-1}$ range of air velocity suggested by Bailey *et al*. (2016) for cattle under heat stress conditions. The investigated case study was considered highly representative of the naturally ventilated barn and the findings of this study could therefore serve as a basis for improving systems used in other countries with hot climates.

### 3.5.4. Pig Barn Ventilation

Kim *et al*. (2017) developed a CFD model to evaluate the ventilation rate in a pig house using thermal distribution data based on the local mean age (LMA) index rather than the Tracer Gas Decay method (TGD). Five commonly used RANS turbulence models (the standard *k-ε*, RNG *k-ε*, realizable *k-ε*, standard *k-ω*, and SST *k-ω*) were tested, of which the standard *k-ω* model performed best with standard error and RSME values of 5.8 and 7.5 respectively. The developed model was considered highly appropriate for conducting ventilation studies in the pig house.

Oh *et al*. (2019) investigated the regional ventilation efficiency at both pig and human height in a pig barn using TGD. Four RANS turbulence models were tested on the developed three-dimensional CFD model, and in stark contrast to the findings of Kim *et al*. (2017), the realizable *k-ε* and the standard *k-ω* models showed the best and least correlations respectively between measured and simulated values of air temperature. The different methods employed in their studies might be a primary factor for this discrepancy.

In a more recent study, a three-dimensional steady-state model for predicting airflow pattern and ammonia emission in a pig negative pressure ventilated building with an underfloor air distribution system was developed and validated (Tabase *et al*., 2020). The SST *k-ω* model was selected based on the recommendations of earlier studies on indoor airflow predictions in enclosed environments with natural convection and buoyancy flows. The modelled air velocity and temperature distribution were validated with the results of a field experiment using mock-up pigs and different ventilation rates. A second experiment involving real pigs was then conducted to validate the modelled airflow patterns, temperature, $CO_2$ and $NH_3$ concentrations. Overall, the model results fit well with the measured data.

Based on the reported benefits of solid floors over the slatted or drained floor in the lying area of pig houses, Bjerg *et al*. (2017) investigated the effectiveness of two ventilation schemes in maintaining the desired level of indoor air temperature in the preferred lying area (PLA). A new effective temperature (ET) model was developed and CFD modelling was carried out using the standard *k-ε* model. The results indicated the period of undesirable indoor temperature in the PLA could be reduced from 40% to 5% even at outdoor temperature levels 11 °C above the reported average of 8 °C.

The influence of several environmental conditions such as air velocity, air temperature, effective draught temperature ($T_{ED}$) and the presence of solid partitions on the lying behavior of pigs was assessed by Jackson *et al*. (2020). The ability of CFD simulations to predict the behavior of pigs with respect to variations in environmental factors, as well as provide valuable insight for designing the internal layout of pig houses were confirmed. The results of the study were however noted to be case-specific.

Gao *et al*. (2021) investigated the impact of summer wet curtains on the temperature and humidity conditions in a pig house and modelled the index of the predicted mean vote (PMV) of thepig body. Based on temperature data and the range of PMV index fluctuation, the use of wet curtains was shown to result in significant improvement in the thermal conditions within the building. Error fluctuation between simulated data and the obtained from sensor measurement was below 6%, which shows that simulation studies could provide accurate insight into the distribution of thermal factors, and serve as a theoretical basis for optimizing environmental control within pig barns.

### 3.5.5. Poultry House Ventilation

Several studies geared toward the improvement of existing ventilation systems and the development of new ones has been carried out. The capability of a negative-pressure ventilation system in a broiler house was assessed by Bustamante *et al*. (2013). Although their experiment was conducted in an empty hen house, air velocity values observed at the animal level were similar to those of Blanes-Vidal *et al*. (2008) and was considered to be representative of real situations. Saraz *et al*. (2013) also observed an insignificant difference between the results of CFD simulation and direct measurements in a broiler farm equipped with misting and negative pressure ventilation system. Temperature distribution within the broiler house, while using different combinations of negative and positive pressure systems with or without misting was also investigated by Saraz *et al*. (Saraz *et al*., 2013) using simulation, thus revealing negative pressure ventilation combined with misting as the most efficient combination for the broiler house, while negative pressure without misting proved the least effective method. This was in concurrence with the findings of (Bustamante *et al*., 2013) whose study likewise indicated the inability of only a negative pressure ventilation system to protect poultry birds from mortality resulting from heat stress. These studies used the standard $k$-$\varepsilon$ turbulence model.

The effects of three ventilation configurations: tunnel, semi tunnel (ST), and improved semi tunnel (IST) on the air velocity and ventilation distribution in the broiler zone within a negative-pressure ventilated poultry house were investigated by Guerra-Galdo *et al*. (2015). The values obtained by Guerra-Galdo *et al*. (2015) were within the range reported by Bustamante *et al*. (2013) in their study on poultry buildings equipped with tunnel mechanical ventilation systems. The study by (Guerra-Galdo *et al*., 2015) indicated the possibility of improving the total area having an index of temperature and velocity (ITV) lower than 25 to about 90.35% using the IST system.

Using CFD techniques employing the RNG $k$-$\varepsilon$ turbulence model, air temperature distribution and ventilation rate in a broiler building equipped with duct ventilation system were analysed by (Mostafa *et al*., 2012). Mostafa *et al*. (2012) also developed four improved ventilation designs which were simulated using CFD, and compared with the standard design to examine the effectiveness of ventilation rates based on maintaining uniformity, stability, and suitability of internal temperature in the broiler zone. The simulation carried out by Mostafa *et al*. (2012) was validated on the basis of air temperature distribution and concentration of ammonia within the broiler housing. The error between the measured and the simulated data for ammonia dilution was 4.3%, while the NSME value for indoor ammonia concentration was 0.2. These values indicated that there was no significant difference between the measured and predicted values of ammonia diffusion, as well as the fact that the model is capable of accurately predicting the efficiency of indoor ammonia concentration and estimating ventilation efficiency of a broiler housing under unsteady-state conditions.

Meanwhile, the limitation of steady-state models in predicting the impact of bird motion on air movement and temperature in a fully automated broiler chamber equipped with five fans and evaporative pads was reported by Fidaros *et al*. (2018). Fidaros *et al*. (2018) noted that a temperature variation of about 2 ºC could exist between measured and simulated temperature values nearer the bird height (0.5 m above ground level), in comparison with those at a height of 1.5 m. They, therefore, suggested that in situations where the sensors for ventilation devices are placed within the broiler house, vertical temperature gradient should be taken into account. Regardless of this, the RSME values for temperature and air velocity, along with error divergence for the respective quantities indicated that the model results were in good agreement with measured values. Thirty-one combinations of different numbers of operating fans, fan position, and operating speed were also investigated.

(Trokhaniak *et al*., 2020) investigated the effects of several modifications including different degrees of fresh-air valve opening, the use of spoilers in controlling air direction, increased building width, decreased floor height, and the effect of valve height in a side ventilated poultry building.

Chen *et al*. (2020) investigated the efficiency of a conventional top-wall inlet, side-wall exhaust (TISE) ventilation system in a cross-ventilated commercial laying hen house under cold conditions (0 ºC); using the standard $k$-$\varepsilon$ turbulence model, enhanced wall functions, and steady-state calculations. They found the system capable of maintaining the temperature between 18 and 24 ºC, while also keeping air speed about 0.26 m $s^{-1}$ on average during cold periods. Their simulated airflow patterns and other air conditions were consistent with other studies (Cheng *et al*., 2018; Saraz *et al*., 2011; Seo *et al*., 2009). Their results showed that conditions at bird level were within comfortable limits. The effect of the hens, their heat production, as well as ventilation features on the indoor air condition was equally observed. Based on the recommendations of Cheng *et al*. (2018), L. Chen *et al*. (2020) represented the hens in their study as individual hen-shaped bodies. This was an improvement on previous studies of laying hen housing, where hens were simply represented either as heated cages, or using other oversimplified geometries. In conclusion, Chen *et al*. (2020) submitted that CFD modelling enables the analysis of ventilation performance and solutions to practical problems related to animal housing.

Similarly, the reliability of CFD in predicting weather conditions within a naturally ventilated poultry building was also demonstrated by Rojano *et al*. (2015) who investigated the heat, mass, and radiative energy transfer between a naturally ventilated broiler house and the environment. They however observed a prevalent underestimation of indoor conditions by CFD in their work, which they opined was as a result of the process of simplifying the heat from the heater in the two-dimensional approach used. The steady-state simulation was carried out using the realizable $k$-$\varepsilon$ turbulence model.

The impact of geometry, spatial distribution and body weight of birds on air flow resistance within the zone occupied by caged laying hens were assessed using six RANS turbulence models of which the RNG k-ε model showed the best performance (Cheng *et al*., 2018). To keep the mesh volume from becoming too large, the animal occupied zone was simplified into a porous media zone. A wind tunnel field experiment was conducted to determine the effect of different inlet wind velocities on the factors being considered. The velocity data obtained from the experiment was also used in validating the simulation results.

Airflow, internal air temperature distribution, and ventilation efficiency within a naturally ventilated broiler house was investigated by Seo *et al*. (2009) through field experiments. Five modified building models were then simulated alongside the conventional structure using TGD and the RNG k-ε turbulence model to resolve the issues observed through the field experiment. The simulation results for one of the modified structures showed a possible increase in thermal uniformity of 26% and a drop in dust concentration while maintaining the desired air temperature at the animal occupied zone.

The ability of CFD to predict indoor conditions of air temperature and air speed within poultry buildings was attested to by Tehinse *et al*. (2020) who modelled a set of thermally controlled rooms at different temperatures in a study geared toward the initial stages of design in buildings with controlled ventilation and heating. The study was conducted using the standard k-ε model, and a good agreement was reported between the model prediction and measured values of air speed and temperature distribution.

By modelling the temperature, as well as the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) indices of a case study, Sanni (2019) investigated the effects of the Trombe wall system on the internal environment of a poultry house. The results of the analysis indicated the possibility of significantly improving the thermal conditions within the building. However, no information on the model parameters, simulation domain, or validation was provided for this study.

## 4. **CONCLUSIONS**

The applications of CFD simulation in designing agricultural ventilation systems have been discussed. It is obvious from this review that the focus of CFD investigations has shifted from merely analyzing ventilation processes, to implementing the results of these studies in facility design. This highlights the ability of simulation to assist in the initial design phase of building design since it allows the evaluation of alternative designs and configurations, thus ensuring the provision of adequate ventilation from the outset. The usefulness of numerical simulation in the assessment and improvement of already existing ventilation systems to support the real-time monitoring, control and post-occupancy optimization of environmental conditions in buildings has also been demonstrated by the wide range of CFD studies on various types of built environments.

Following their review on the applications of CFD in ventilation studies in agricultural buildings, Norton *et al*. (2007) noted that the standard $k$-$\varepsilon$ turbulence model which was the most commonly used model sometimes gave inadequate results. The standard $k$-$\varepsilon$ model was also the most commonly used in the works under review in this work, and apart from instances where the choice of computational domain detracted from the accuracy of the study, a good correlation was reported between the measured and simulated data. However, in studies where other turbulence models were investigated to determine the right choice of model, the standard $k$-$\varepsilon$ model was outperformed. This indicates that the choice of turbulent model was a critical factor to obtaining good simulation results, and the choice of model should be done carefully.

Unfavourably high temperature and humidity conditions pose serious dangers to animal production in the guise of heat stress and related conditions. These issues could however be alleviated with appropriate ventilation methods. Despite the proven benefits of CFD simulations in the initial design and improvement of existing ventilation systems, along with its widespread use in other countries with hot climates similar to that of Nigeria, there exists a serious dearth of published research on the application of CFD techniques in analyzing ventilation and thermal conditions in animal environments in Nigeria. Only two such studies were reported within the past decade (Sanni, 2019; Tehinse *et al*., 2020). Both of which were carried out in experimental structures which were in no way representative of real poultry houses used across the country. There is therefore a need for more documented research in this field as a means of improving agricultural productivity within Nigeria.

**REFERENCES**

Abioja, M. O., Osinowo, O. A., Smith, O. F., Eruvbetine, D., and Williams, T. J. (2012). Effects of month of lay on egg fertility in layer-breeder flocks in Jos, Nigeria. *Nigerian Poultry Science Journal*, *8*, 70–76.

Abioja, M. O., Williams, T. J., Abiona, J. A., and Iyasere, O. S. (2020). Seasonal variations in egg fertility and hatchability in layer-breeder hens under two climatic conditions. *African Journal of Agriculture, Technology and Environment*, *9*(1), 73–85.

Alhenaky, A., Abdelqader, A., Abuajamieh, M., and Al-fataftah, A. (2017). The effect of heat stress on intestinal integrity and Salmonella invasion in broiler birds. *Journal of Thermal Biology*, *70*, 9–14. https://doi.org/10.1016/j.jtherbio.2017.10.015

Ameen, S. A., Opayemi, O. S., Ajayi, J. A., and Adediwura, M. A. (2014). Evaluation of Semen Quality of Five Different Cockerel Breed Used in Poultry Industry in Nigeria. *Journal of Environmental Issues in Agriculture*, *6*, 30–36.

Bailey, T., Sheets, J., McClary, D., Smith, S., and Bridges, A. (2016). Air Velocity and Fans. In *Heat Abatement* (pp. 22–30). Elanco Dairy Business Unit.

Baxevanou, C., Fidaros, D., Bartzanas, T., and Kittas, C. (2010). Numerical simulation of solar radiation, air flow and temperature distribution in a naturally ventilated tunnel greenhouse. *Agricultural Engineering International: CIGR Journal*, *12*(3–4), 48–67.

Benni, S., Tassinari, P., Bonora, F., Barbaresi, A., and Torreggiani, D. (2016). Efficacy of greenhouse natural ventilation: Environmental monitoring and CFD simulations of a study case. *Energy and Buildings*, *125*, 276–286. https://doi.org/10.1016/j.enbuild.2016.05.014

Bhadauria, P., Kataria, J. M., Majumdar, S., Bhanja, S. K., and Kolluri, G. (2014). Impact of Hot Climate on Poultry Production System-A Review Thermoregulatory Mechanism of Poultry. *Journal of Poultry Scince and Technology*, *2*(4), 56–63.

Bjerg, B., Rong, L., and Zhang, G. (2017). Computational prediction of the effective temperature in the lying area of pig pens. *Computers and Electronics in Agriculture*, 1–9. https://doi.org/10.1016/j.compag.2017.09.016

Blanes-Vidal, V., Guijarro, E., Balasch, S., and Torres, A. G. (2008). Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosystems Engineering*, *100*, 100–116.

Blocken, B., and Gualtieri, C. (2012). Ten iterative steps for model development and evaluation applied to Computational Fluid Dynamics for Environmental Fluid Mechanics. *Environmental Modelling and Software*, *33*, 1–22. https://doi.org/10.1016/j.envsoft.2012.02.001

Blocken, Bert. (2018). LES over RANS in building simulation for outdoor and indoor applications: A foregone conclusion? *Building Simulation*, *11*(5), 821–870. https://doi.org/10.1007/s12273-018-0459-3

Bustamante, E., García-Diego, F. J., Calvet, S., Estellés, F., Beltrán, P., Hospitaler, A., and Torres, A. G. (2013). Exploring ventilation efficiency in poultry buildings: The validation of computational fluid dynamics (CFD) in a cross-mechanically ventilated broiler farm. *Energies*, *6*(5), 2605–2623. https://doi.org/10.3390/en6052605

Caroprese, M. (2008). Sheep housing and welfare. *Small Ruminant Research*, *76*, 21–25. https://doi.org/10.1016/j.smallrumres.2007.12.015

Chalill, S. M., Chowdhury, S., and Karthikeyan, R. (2021). Prediction of Key Crop Growth Parameters in a Commercial Greenhouse Using CFD Simulation and Experimental Verification in a Pilot Study. *Agriculture*, *11*(7), 658. https://doi.org/10.3390/agriculture11070658

Chen, L., Fabian-wheeler, E. E., Cimbala, J. M., Hofstetter, D., and Patterson, P. (2021). Computational Fluid Dynamics Analysis of Alternative Ventilation Schemes in Cage-Free Poultry Housing. *Animals*, *11*(2352), 1–21.

Chen, L., Fabian-Wheeler, E. E., Cimbala, J. M., Hofstetter, D., and Patterson, P. (2020). Computational fluid dynamics modeling of ventilation and hen environment in cage-free egg facility. *Animals*, *10*(6), 1–17. https://doi.org/10.3390/ani10061067

Chen, Q. (2009). Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment*, *44*(4), 848–858. https://doi.org/10.1016/j.buildenv.2008.05.025

Cheng, Q., Wu, W., Li, H., Zhang, G., and Li, B. (2018). CFD study of the influence of laying hen geometry, distribution and weight on airflow resistance. *Computers and Electronics in Agriculture*, *144*(2018), 181–189. https://doi.org/10.1016/j.compag.2017.12.003

De Rosis, A., Barbaresi, A., Torreggiani, D., Benni, S., and Tassinari, P. (2014). Numerical simulations of the airflows in a wine-aging room: A lattice Boltzmann-immersed boundary study. *Computers and Electronics in Agriculture*, *109*(1), 261–270. https://doi.org/10.1016/j.compag.2014.10.010

Dehghan, A. A., Esfeh, M. K., and Manshadi, M. D. (2013). Natural ventilation characteristics of one-sided wind catchers : experimental and analytical evaluation. *Energy* and *Buildings, 61*, 366–377. https://doi.org/10.1016/j.enbuild.2013.02.048

Dia, S. F., Gao, F., Xu, X. L., Zhang, W. H., Song, S. X., and Zhou, G. H. (2012). Effects of dietary glutamine and gamma- aminobutyric acid on meat colour, pH, composition, and water-holding characteristic in broilers under cyclic heat stress. *British Poultry Science, 53*(4), 471–481.

Duduyemi, O. A., and Oseni, S. O. (2012). Modelling heat stress characteristics on the layers' performance traits in south-western Nigeria. *TROPENTAG 2012*, *14*, 1.

Fabian-Wheeler, E., Chen, L., Hofstetter, D., Patterson, P., and Cimbala, J. (2018). Modeling hen house ventilation options for cage-free environment: Two-dimensional case. *10th International Livestock Environment Symposium, ILES 2018*, 2–8. https://doi.org/10.13031/iles.ILES18-145

Fidaros, D., Baxevanou, C., Bartzanas, T., and Kittas, C. (2018). Numerical study of mechanically ventilated broiler house equipped with evaporative pads. *Computers and Electronics in Agriculture*, *149*, 101–109. https://doi.org/10.1016/j.compag.2017.10.016

Gao, Y., Wang, Y., Lu, S., Lei, M., Luo, J., and Li, X. (2021). Thermal Comfort Evaluation of Pigsty and CFD Simulation of Wet Curtain in Summer. *Journal of Agricultural Science and Technology*, *23*(7), 125–135.

Ghazi, S. H., Habibian, M., Moeini, M. M., and Abdolmohammadi, A. R. (2012). Effects of different levels of organic and inorganic chromium on growth performance and immunocompetence of broilers under heat stress. *Biological Trace Element Research*, *146*, 309–317.

Gilbert, M., Slingenbergh, J., and Xiao, X. (2008). Climate change and avian influenza. *Revue Scientifique Et Technique*, *27*(2), 459–466.

Guerra-Galdo, E. H., Sanz, S. C., Barber, F. E., and López-Jiménez, P. A. (2015). CFD Model for Ventilation Assessment in Poultry Houses with Different Distribution of Windows. *International Journal of Energy and Environment*, *6*(5), 411–424.

Guis, H., Caminade, C., Calvete, C., Morse, A. P., Tran, A., and Baylis, M. (2011). Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe. *Journal of Rural Sociology Interface*, *9*, 339–350.

Gwaza, D. S., Ukwu, H. U., Ochefu, J., and Gbor, V. (2017). Genotype by Environmental Interaction Effects on Laying Characteristics of Genotype by Environmental Interaction Effects on Laying Characteristics of Lohman Brown in Sub-Humid Tropics of Nigeria. *Journal of Genetics and Genetic Engineering*, *2*(1), 25–35.

Hajdukiewicz, M., Geron, M., and Keane, M. M. (2013). Formal calibration methodology for CFD models of naturally ventilated indoor environments. *Building and Environment*, *59*(August), 290–302. https://doi.org/10.1016/j.buildenv.2012.08.027

Hughes, B. R., Calautit, J. K., and Ghani, S. A. (2012). The development of commercial wind towers for natural ventilation: a review. *Applied Energy*, *92*, 606–627.

Imik, H., Ozlu, H., Gumus, R., Atasever, M. A., Urgar, S., and Atasever, M. (2012). Effects of ascorbic acid and alpha-lipoic acid on performance and meat quality of broilers subjected to heat stress. *British Poultry Science*, *53*, 800–808.

Jackson, P., Nasirahmadi, A., Guy, J. H., Bull, S., Avery, P. J., Edwards, S. A., and Sturm, B. (2020). Using CFD Modelling to Relate Pig Lying Locations to Environmental Variability in Finishing Pens. *Sustainability*, *12*, 1–16.

Jongbo, A. O. (2020). Evaluation of the environmental parameters of battery-caged poultry house in the humid tropical climate. *Colombian Journal of Animal Science*, *12*(2), 2020.753. https://doi.org/10.24188/recia.v12.n2.2020.753

Kang, S., Kim, D., Lee, S., Lee, T., Lee, K., Chang, H., Moon, B., Ayasan, T., and Choi, Y. (2020). An Acute , Rather Than Progressive , Increase in Temperature-Humidity Index Has Severe Effects on Mortality in Laying Hens. *Frontiers in Veterinary Science*, *7*(November), 1–8. https://doi.org/10.3389/fvets.2020.568093

Kim, R., Lee, I., Ha, T., Yeo, U., Lee, S., Lee, M., Park, G., and Kim, J. (2017). Development of CFD model for Predicting Ventilation Rate based on Age. *Journal of the Korean Society of Agricultural Engineers*, *59*(6), 61–71.

King, A. M. (2011). Review of the Factors That Influence Egg Fertility and Hatchabilty in Poultry. *International Journal of Poultry Science*, *10*(6), 483–492.

Lee, I. B., Bitog, J. P. P., Hong, S. W., Seo, I. H., Kwon, K. S., Bartzanas, T., and Kacira, M. (2013). The past, present and future of CFD for agro-environmental applications. *Computers and Electronics in Agriculture*, *93*, 168–183. https://doi.org/10.1016/j.compag.2012.09.006

Lee, I. B., Sase, S., and Sung, S. H. (2007). Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house. *Japan Agricultural Research Quarterly*, *41*(1), 53–64. https://doi.org/10.6090/jarq.41.53

Li, D., Zheng, Y., Liu, C., Qi, H., and Liu, X. (2016). Numerical analysis on thermal performance of naturally ventilated roofs with different influencing parameters. *Sustainable Cities and Society*, *22*, 86–93. https://doi.org/10.1016/j.scs.2016.02.004

Liu, W., Wen, J., Lin, C., Liu, J., Long, Z., and Chen, Q. (2013). Evaluation of various categories of turbulence models for predicting air distribution in an airliner cabin. *Building and Environment*, *65*, 118–131. https://doi.org/10.1016/j.buildenv.2013.03.018

Malkawi, A., Yan, B., Chen, Y., and Tong, Z. (2016). Predicting thermal and energy performance of mixed-mode ventilation using an integrated simulation approach. *Building Simulation*, *9*(3), 335–346. https://doi.org/10.1007/s12273-016-0271-x

Miroshnichenko, I., and Sheremet, M. (2015). Comparative study of standard k -ε And k -ω lence models by giving an analysis of turbulent natural convection in an enclosure. *EPJ Web of Conferences*, *82*, 1–4. https://doi.org/10.1051/epjconf/20158201057

Monila-Aiz, F. D., Valera, D. L., Peña, A. A., and Lopez, A. (2009). A study of natural ventilation in an Almería-type greenhouse with insect screens by means of tri-sonic anemometry. *Biosystems Engineering*, *104*, 224–242.

Mostafa, E., Lee, I. B., Song, S. H., Kwon, K. S., Seo, I. H., Hong, S. W., Hwang, H. S., Bitog, J. P., and Han, H. T. (2012). Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. *Biosystems Engineering*, *112*(4), 293–303. https://doi.org/10.1016/j.biosystemseng.2012.05.001

Mrema, G., Gumbe, L., Chepete, H., and Agullo, J. (2011). Ventilation. In *Rural Structures in the tropics: Design and development* (pp. 329–342). Food and Agricultural Organization.

Niu, Z. Y., Liu, F. Z., Yan, Q. L., and Li, W. C. (2009). Effects of different levels of vitamin E on growth performance and immune responses of broilers under heat stress. *Poultry Science*, *88*, 2101–2107.

Noiva, R. M., Menezes, A. C., and Peleteiro, M. C. (2014). Influence of Temperature and Humidity Manipulation on Chicken Embryonic Development. *Veterinary Research*, *10*, 2–10.

Norton, T., Sun, D. W., Grant, J., Fallon, R., and Dodd, V. (2007). Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review. *Bioresource Technology*, *98*(12), 2386–2414. https://doi.org/10.1016/j.biortech.2006.11.025

Obidi, J. A., Onyeanusi, B. A., Rekwot, P. I., Ayo, J. O., and Dzenda, T. (2008). *Seasonal Variations in Seminal Characteristics of Shikabrown Breeder Cocks*. *7*(12), 1219–1223.

Oh, B.-W., Lee, S.-W., Kim, H.-C., and Seo, I.-H. (2019). Analysis of Working Environment and Ventilation Efficiency in Pig House using Computational Fluid Dynamics. *Journal of the Korean Society of Agricultural Engineers*, *61*(2), 85–95.

Ohba, M., and Lun, I. (2012). Overview of natural crossventilation studies and the latest simulation design tools used in building ventilation-related research. In *Advances in Building Energy Research* (Issue 4, pp. 128–166). CRC Press.

Okyere, K., Kagya-agyemang, J. K., Annor, S. Y., Asabere-ameyaw, A., and Kyere, C. G. (2020). Influence of Season and Day Length on Production and Reproductive Traits and Egg Characteristics of the Guinea Fowl ( Numida meleagris ). *Asian Journal of Research in Zoology*, *3*(1), 26–34. https://doi.org/10.9734/AJRIZ/2020/v3i130081

Oropeza-Perez, I., and Østergaard, P. A. (2014). Energy saving potential of utilizing natural ventilation under warm conditions–a case study of Mexico. *Applied Energy*, *130*, 20–32.

Pelletier, D. (2010). Verification, validation, and uncertainty in computational fluids dynamics. *Canadian Journal of Civil Engineering*, *37*, 1003–1013. https://doi.org/10.1139/L10-032

Rocha, P. A. C., Rocha, H. H. B., Carneiro, F. O. M., Vieira da Silva, M. E., and Bueno, A. V. (2014). K-ω SST (shear stress transport) turbulence model calibration: A case study on a small scale horizontal axis wind turbine. *Energy*, *65*, 412–418. https://doi.org/10.1016/j.energy.2013.11.050

Rohdin, P., and Moshfegh, B. (2011). Numerical modelling of industrial indoor environments: A comparison between different turbulence models and supply systems supported by field measurements. *Building and Environment*, *46*(11), 2365–2374. https://doi.org/10.1016/j.buildenv.2011.05.019

Rojano, F., Bournet, P. E., Hassouna, M., Robin, P., Kacira, M., and Choi, C. Y. (2015). Modelling heat and mass transfer of a broiler house using computational fluid dynamics. *Biosystems Engineering*, *136*, 25–38. https://doi.org/10.1016/j.biosystemseng.2015.05.004

Rojano, F., Bournet, P., Robin, P., Hassouna, M., Choi, C. Y., and Murat, K. (2014). Test of two different schemes through CFD to include heat and mass transfer induced by animals inside a broiler. *International Conference of Agricultural Engineering, Zurich, Switzertland July 6-10*, *January*, 1–8.

Rong, L., Nielsen, P. V., Bjerg, B., and Zhang, G. (2016). Summary of best guidelines and validation of CFD modeling in livestock buildings to ensure prediction quality. *Computers and Electronics in Agriculture*, *121*, 180–190. https://doi.org/10.1016/j.compag.2015.12.005

Roy, C. J., and Oberkampf, W. L. (2011). A comprehensive framework for verification, validation, and uncertainty quantification in scientific computing. *Computer Methods in Applied Mechanics and Engineering*, *200*, 2131–2144. https://doi.org/10.1016/j.cma.2011.03.016

Sanni, Z. O. (2019). Improving Indoor Temperature in a Poultry Building Using a Trombe Wall in a Hot Dry Climate, Kaduna. *AARCHES National Comference*, 185–192.

Saraz, J. A. O., Martins, M. A., Rocha, K. S. O., Machado, N. S., and Velasques, H. J. C. (2013). Use of computational fluid dynamics to simulate temperature distribution in broiler houses with negative and positive tunnel type ventilation systems. *Revista U.D.C.A Actualidad* and *Divulgación Científica*, *16*(1), 159–166.

Saraz, O. A. J., Rocha, O. S. K., Tinoco, F. D. F. I., Gates, R. S., Mendes, O. L. Z. M., and Damasceno, F. A. (2011). Use of CFD modeling for determination of ammonia emission in non-insulated poultry houses with natural ventilation. *Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting*, 4409–4418.

Seo, I. H., Lee, I. B., Moon, O. K., Kim, H. T., Hwang, H. S., Hong, S. W., Bitog, J. P., Yoo, J. I., Kwon, K. S., Kim, Y. H., and Han, J. W. (2009). Improvement of the ventilation system of a naturally ventilated broiler house in the cold season using computational simulations. *Biosystems Engineering*, *104*(1), 106–117. https://doi.org/10.1016/j.biosystemseng.2009.05.007

Sohail, M. U., Hume, M. E., Byrd, J. A., Nisbet, D. J., Ijaz, A., Sohail, A., Shabbir, M. Z., and Rehman, H. (2012). Effect of Supplementation of Prebiotic Mannan-Oligosaccharides and Probiotic Mixture on Growth Performance of Broilers Subjected to Chronic Heat Stress. *Poultry Science*, *91*, 2235–2240.

Sun, Y. C., Bao, E. C., Zhu, C. M., Yan, L. L., Cao, Y. F., Zhang, X. H., Li, J. M., Jing, H. W., and Zou, Z. R. (2020). Effects of window opening style on inside environment of solar greenhouse based on CFD simulation. *International Journal of Agricultural and Biological Engineering*, *13*(6), 53–59. https://doi.org/10.25165/j.ijabe.20201306.5734

Tabase, R. K., Van linden, V., Bagci, O., De Paepe, M., Aarnink, A. J. A., and Demeyer, P. (2020). CFD simulation of airflows and ammonia emissions in a pig compartment with underfloor air distribution system: Model validation at different ventilation rates. *Computers and Electronics in Agriculture*, *171*(February), 105297. https://doi.org/10.1016/j.compag.2020.105297

Tehinse, T. O., Falayi, F. R., Aduewa, T. O., Alatise, M. O., and Osho, B. I. (2020). Analysis of Thermally Controlled Poultry Housing Using CFD. *Journal of Engineering Research and Reports*, *10*(3), 40–48. https://doi.org/10.9734/jerr/2020/v10i317042

Tomasello, N., Valenti, F., Cascone, G., and Porto, S. M. C. (2019). Development of a CFD model to simulate natural ventilation in a semi-open free-stall barn for dairy cows. *Buildings*, *9*(8), 1–15. https://doi.org/10.3390/buildings9080183

Tomasello, N., Valenti, F., Cascone, G., and Porto, S. M. C. (2021). Improving natural ventilation in renovated free-stall barns for dairy cows: Optimized building solutions by using a validated computational fluid dynamics model. *Journal of Agricultural Engineering*, *52*(1). https://doi.org/10.4081/jae.2021.1135

Trokhaniak, V. I., Rogovskii, I. L., Titova, L. L., Dziubata, Z. I., Luzan, P. H., and Popyk, P. S. (2020). Using CFD Simulation to Investigate the Impact of Fresh air Valves on Poultry House Aerodynamics in Case of a Side Ventilation System. *INMATEH - Agricultural Engineering*, *62*(3), 155–164. https://doi.org/10.35633/INMATEH-62-16

Tu, J., Yeoh, G.-H., and Liu, C. (2018). Computational fluid dyanmics: a practical approach. In *Elsevier Ltd.* (3rd ed.). Elsevier.

Weeks, C. A. (2008). A review of welfare in cattle, sheep and pig lairages, with emphasis on stocking rates, ventilation and noise. *Animal Welfare*, *17*, 275–284.

Wu, W., Zhang, G., Bjerg, B., and Nielsen, P. V. (2012). An assessment of a partial pit ventilation system to reduce emission under slatted floor - Part 2: Feasibility of CFD prediction using RANS turbulence models. *Computers and Electronics in Agriculture*, *83*, 134–142. https://doi.org/10.1016/j.compag.2012.01.011

Xiao, H., Sun, R., and Roy, C. J. (2016). *Accepted Manuscript*. *July*. https://doi.org/10.1016/j.jcp.2016.07.038

Yao, C., Shi, Z., Zhao, Y., and Ding, T. (2019). Effect of mixed-flow fans with a newly shaped diffuser on heat stress of dairy cows based on CFD. *Energies*, *12*(22), 1–14. https://doi.org/10.3390/en12224315

Yao, Z. Q., Shen, H. C., and Gao, H. (2013). A new methodology for the CFD uncertainty analysis. *Journal of Hydrodynamics*, *25*(1), 131–147. https://doi.org/10.1016/S1001-6058(13)60347-9

Yoon, H., Hwangbo, J., Yang, Y., Kim, J., Kim, Y., Park, B., and Choi, Y. (2014). Effects of Early Heat Conditioning on Performance in Broilers exposed to Heat Stress. *Korean Journal of Poultry Science*, *41*(4), 297–303.

Zhang, Z. Y., Jia, G. Q., Zuo, J. J., Zhang, Y., Lei, J., Ren, L., and Feng, D. Y. (2012). Effects of constant and cyclic heat stress on muscle metabolism and meat quality of broiler breast fillet and thigh meat. *Poultry Science*, *91*, 2931–2937.

Zhaohui, C., Yichang, M., Rui, L., Fei, G., JIjun, L., and Shitang, Y. (2017). Numerical simulation of environmental conditions for fan-pad evaporative cooling system of beef cattle barn in summer. *Transactions of the Chinese Society of Agricultural Engineering*, *33*(16), 211–218.