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Research Paper

Modelling heat and mass transfer of a broiler house using computational fluid dynamics

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Improvements to the living conditions in semi-enclosed spaces such as broiler houses can be achieved by better control of the heat and mass transport that occur in climate and air quality. This study shows that computer-aided modelling, and in particular computational fluid dynamics (CFD), can provide to researchers the ability to integrate the primary forces that interact at the interior environment. A two dimensional CFD model was used to assess the dynamics of a broiler house by investigating sensible and latent heat, as well as mass transport and radiative transfer energy, as these relate to the environment of the broiler house. Validation data related to temperature, absolute humidity and CO_2 were collected both inside and outside of a naturally ventilated broiler house. Inside data was logged at various locations to identify the degree of homogeneity throughout space. The CFD model replicated two contrasting cases: an early stage and a late stage of production. The predicted values for temperature, absolute humidity and CO_2 were in good agreement with experimental data. For instance, the first case had a ventilation rate of 10 air changes h^{-1}, and obtained a root-mean-square error (RMSE) of 1.0 °C, 0.3 g [H_2O] kg^{-1} [dry air] and 134 ppm for temperature, absolute humidity and CO_2, respectively. The second case had ventilation rates of 25 air changes h^{-1}, and obtained a RMSE of 0.9 °C and 0.48 g [H_2O] kg^{-1} [dry air] for temperature and absolute humidity, respectively.

1. Introduction

The shift from traditional to modern animal production has helped to meet the increasing demand for meat whilst also minimising production costs and incrementing productivity. Raising animals in buildings has also enabled producers to locate operations on smaller plots of land closer to large markets. Also, livestock buildings solve a number of the living-condition issues associated with high-density, accelerated weight gain and reduced mortality rates. All these

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Nomenclature

a	absorption coefficient, m^{-1}
AH	total animal heat, W
AH_L	latent heat from animal, W
AH_S	sensible heat from animal, W
C	gas concentration, ppm
d	nth day of production cycle, day
e	water vapour pressure, Pa
H	characteristic height of the broiler house, m
h	absolute humidity, g[H_2O] kg^{-1} [dry air]
HH_L	latent heat from heater, W
HH_S	sensible heat from heater, W
HF_{fo}	heat flux from outdoor floor, W m^{-2}
I	radiance, W m^{-3} sr^{-1}
k_z	turbulence kinetic energy, m^2 s^{-2}
LH_L	latent heat from litter, W
LH_S	sensible heat from litter, W
m	mass of hen, kg
N	ventilation rate decay, h^{-1}
n	refractive index
p_o	atmospheric pressure, Pa
q	atmospheric radiative flux, W m^{-2}
$\bar{r}$	Position vector, m
RMSE	root-mean-square error
$\bar{s}$	unitary vector along the propagation of radiation
$\bar{s}'$	scattering direction vector
S_R	solar radiation, W m^{-2}
S_ϕ	source term (i.e. buoyancy effects)
T	air temperature, °C
T_{fi}	temperature from indoor floor, °C
T_i	indoor temperature, °C
T_o	outdoor temperature, °C
t	time, s
u_j	velocity in direction j (i.e. for two-dimensional domain $j = 1, 2$), m s^{-1}
u_o	wind velocity, m s^{-1}
x_j	coordinate in direction j, m
α	wind direction, °
ε	emissivity [from 0 to 1]
ε_z	turbulence energy dissipation, m^2 s^{-3}
ϕ	denotes velocity, temperature, turbulent kinetic energy, dissipation kinetic energy and mass transport
Γ_ϕ	diffusion coefficient of the variable ϕ
σ	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} C^{-1})
σ_s	scattering coefficient, m^{-1}
Φ	Diffusion phase function
Ω^t	solid angle, sr

changes make the understanding of the climate and air quality conditions within the buildings an imperative. To analyse the living-conditions, we chose to investigate broiler production because the system has a high ratio (2:1) for converting feed mass into weight gain (Gerber et al., 2013). Also, broiler houses can be operated in a way that saves water for cleaning purposes, in contrast to the operation of livestock buildings for pigs or cows where a significant amount of water is required.

1.1. *Environment control in broiler houses*

Operating a broiler house efficiently depends on controlling the climate at an early stage of production because the young broilers are susceptible to temperature changes. Typically, in mild climates, heaters burning propane are used to maintain the required interior temperatures during the early stages. As the broilers gain weight, they become more resistant to climatic changes and produce more heat, which helps to regulate the temperature inside the building and thereby reducing the heat provided by the heaters.

Although temperature is the main climatic parameter, the overall climate indoors is determined by the dynamics of the sensible and latent heat present in the building. Consequently, the water vapour released from various sources such as the broilers, the rearing system, the heaters and the degree of natural ventilation should all be included when calculating heat and mass balances. Also gases derived from the dynamics of heat and water vapour generation such as CO_2 should be incorporated since they impact on the environment and animal welfare.

Furthermore, the climatic conditions that must be provided in order to keep the broilers within the particular ranges of temperature and humidity that enhance rapid weight gain and optimal welfare also provide favourable conditions for the bacteria found in the rearing system to increase the emissions of heat, humidity and various gases. As more humidity and gases are generated, the air quality deteriorates unless appropriate ventilation is maintained.

1.2. *Use of CFD modelling to assess livestock building environment*

Broiler-house environmental conditions can be studied using modelling techniques that handle heat and mass transport phenomena. The availability of advanced modelling tools, based on numerical solutions such as computational fluid dynamics (CFD), analyses heat and mass sources (i.e. gases) simultaneously, as these sources fluctuate due to the exchange of indoor and outdoor air that is occurring by natural ventilation.

The quality of the CFD model generated from data taken inside a livestock building depends on features such as the accuracy of the numerical solution obtained, which in turn depends on choosing the proper turbulence model, turbulence intensity, grid quality and discretisation scheme, and convergence settings of the numerical solution. These features can be achieved using the method deployed by Ramponi and Blocken (2012) that involves scaling down the livestock building and relies on particle image velocimetry to validate the velocity field.

Various CFD studies validated by field experiments have analysed methods of modifying the interior of livestock buildings to improve their atmospheric environment. Specifically, CFD modelling has been used to consider air properties, airflow conditions and the physical features of particular