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Analysis of the dynamics of heat and mass transfer in a naturally ventilated poultry house using CFD

Analyse der Dynamik von Wärme- und Stoffübertragung in einer natürlich belüfteten Stall mit CFD

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Summary

A 2D CFD model was developed to simulate interior climate of a poultry house. To validate the CFD model, an experiment was conducted in West of France during spring 2014. Two cases were evaluated: Case I and II at the early (19th day) and late (69th day) stage of production, respectively. For Case II, the CFD model evaluated three different densities of animals (33 %, 66 % and 100 % of the 10 hens m⁻²). This work was focused on the temperature and humidity gradients, and then, estimate sensible and latent heat losses. With respect to Case I, the model predicted 10.6 air changes per hour (± 0.45 standard deviation) and also estimated that sensible and latent heat losses of 76 % and 24 %, respectively. With respect to Case II, the model predicted 25.2 air changes per hour (± 2.6 standard deviation) and estimated sensible and latent heat losses approximately of 64 % and 36 %, respectively.

Zusammenfassung

Um das Raumklima eines Geflügelstalls zu simulieren, wurde ein 2-D-CFD-Modell entwickelt. Für die Validierung des CFD-Modells wurde ein Versuch im Frühjahr 2014 in Westfrankreich durchgeführt. Zwei Versuchsszenarien wurden dabei evaluiert: in der frühen (19. Tag) und der späten (69. Tag) Produktionsstufe. Im Fall II (späte Produktionsstufe) wurden zusätzlich drei unterschiedliche Besatzdichten (33 %, 66 % und 100 % der 10 m⁻² untersucht. Das Hauptaugenmerk lag dabei auf dem Verlauf der Temperatur und der Luftfeuchte und demzufolge dem sensiblen und latenten Wärmeverlust. Im Fall I wurden mit dem Modell 10,6 Luftwechsel pro Stunde ($\pm 0,45$ Standardabweichung) mit geschätzten 76 % sensiblen bzw. 24 % latenten Wärmeverlusten vorhergesagt. Im Fall II hingegen 25,2 Luftwechsel pro Stunde ($\pm 2,6$ Standardabweichung) mit geschätzten 64 % sensiblen bzw. 36 % latenten Wärmeverlusten.

1 Introduction

Poultry house climate conditions can be studied using modelling techniques that handle the dynamics of heat and mass transport phenomena. The availability of such techniques based on numerical solutions such as Computational Fluid Dynamics (CFD), makes it possible to replicate the micro-climate of a defined domain and also the heat and mass (i.e. humidity) sources interacting with natural ventilation. The CFD model can be enhanced by incorporating the governing equations that describe the animals, heaters and rearing system as the main contributors of sensible and latent heat in the poultry house. In this way, the present work investigates spatial and temporal variability of the indoor temperature and humidity under typical operating conditions of a poultry house. Experimental data was used to support the study's findings, specifically assisting in the validation of a 2D CFD model by means of the thermal and humidity gradients.

The CFD model was established by following a methodology developed by ROACHE (1994) to identify the appropriate mesh to apply to a domain defined accordingly to ROJANO et al. (2014). Subsequently, the model was used to validate the spatiotemporal variability of temperature and humidity. The research was focused on Case I at the beginning of the growing cycle in order to assess the influence of the heaters and animals under low ventilation rates; and a Case II at the end of the growing cycle in order to analyse the influence of three densities of animals under high ventilation rates and heaters turned off. Validation of the 2D CFD model through temperature and humidity served to predict the system's capacity to exchange sensible and latent heat by natural ventilation.

2 Materials and Methods

2.1 Experimental data

An 84-day cycle of organic production in a poultry house at the experimental station "Le Magneraud", located in France (46.15 N, -0.69 W), was selected for this study. All the walls and roof were composed of polystyrene (thickness: 4 cm and thermal conductivity: $0.05 \text{ Wm}^{-1}\text{C}^{-1}$); lateral curtains had maximum opening of 53 cm and composed of polyethylene (thickness: 0.5 mm and thermal conductivity: $0.33 \text{ Wm}^{-1}\text{C}^{-1}$). The building had two heaters uniformly distributed along the length, and each had a heating of 4.8 kW.

Wind direction and velocity, air temperature, relative humidity and solar radiation data were collected by a weather station (AWS310, Vaisala, France) placed 30 m away from the building. Inside the building, a vertical plane was established to monitor climate. The vertical plane was defined based on three lines (B, C and D) placed at 0.7 m, 1.4 m and 2 m from the floor. Along each axis, temperature ($\pm 0.1 \text{ }^\circ\text{C}$) and relative humidity ($\pm 3 \%$) were collected by a data logger (DL-101T USB, Voltcraft, France). Exterior climate data were filtered to retain only cases when the wind was blowing perpendicular to the ridgeline of the building (range $\pm 14.4^\circ$) which had an orientation of 22° NE . Two periods: Case I (19th day) and Case II (69th day) were chosen to be modelled according to the settings of Table 1 and input data shown in Figure 1b. An analysis of a two-dimensional cross-view plane was conducted that included a heater and a trap (Fig. 1a).

Tab. 1: Cases simulated in CFD

Tab. 1: Simulierte Versuchsszenarien im CFD-Modell

	Case I	Case II
Curtain opening	6 cm	30 cm
Traps	Closed	Open
Heater	On	Off
Density of hens	10 hens m ⁻²	Variable
Average outdoors temperature	16.3 °C	25.6 °C
Average floor indoors temperature	34 °C	24 °C
Average shortwave radiation	743 W m ⁻²	835 W m ⁻²
Average longwave radiation	199 W m ⁻²	243 W m ⁻²

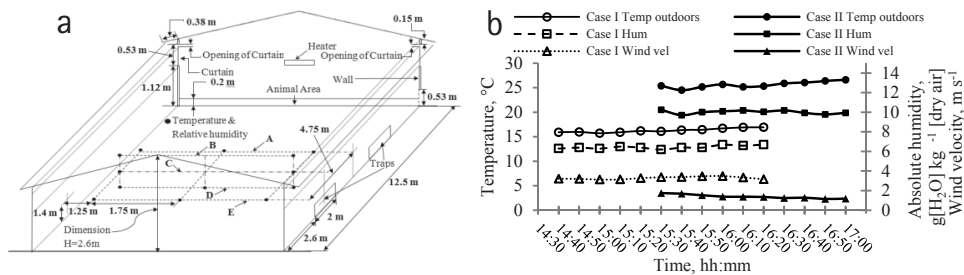


Fig. 1: a) experimental setup and sensor location, b) input data

Abb. 1: a) Versuchsaufbau und Sensorstelle, b) Eingangsdaten

2.2 CFD Modelling

The ridge height (H) equal to 2.6 m was a reference dimension used to define the entire domain, which had a height and length of $7H$ and $12.3H$, respectively (being the poultry house placed $3H$ from the left side); other specifications are indicated in Figure 1a. The modelling followed a finite-volume approach with the Navier-Stokes equations by means of Reynolds-average method. Turbulence quantities relied on two additional equations to determine the kinetic energy k and dissipation rate ϵ . FLUENT of Ansys (2014) was used to find the numerical solutions using the turbulence k - ϵ realizable model as it proved to be consistent in various similar studies dedicated to livestock buildings (BJERG et al. 2013). The long- and short-waves were evaluated by means of the Discrete Ordinate Model (DOM) as the work of BOURNET et al. (2007) wherein accurate predictions were obtained.

The heat and water vapour emitted by the animals followed the CIGR (2002) equations, computing an empirical basal heat metabolism based on the weight of the animal, which was determined on a weight curve identified in the work of ROJANO et al. (2014). Additionally, the estimations of sensible and latent heat produced by the litter were based on experimental outcomes that established a correlation between total heat produced by the animal and that produced by the litter (MEDA 2011). This author found that the litter's heat generation would equal 10 % of the total heat produced by the animal, which can be split in sensible and latent heat producing 60 % and 40 % respectively.

The amount of heat of the heater was constant with by-products such as water vapour derived from propane. A perfect combustion that followed the stoichiometry equation estimated the sensible and latent heat with 677.6 W and 52.4 W, respectively.

The simulation was conducted under unsteady state conditions; however, the initial conditions were based on the outcomes of the steady state conditions by taking field measurements for Case I and II at 14:40 and 15:30, correspondingly (Fig. 1b) and remaining settings according to Table 1. The left side of the domain was set as the inlet (ventilation inlet) and the right side of the domain as the outlet (pressure outlet) with the same value as that of the operating conditions of 100.4 kPa. The top side of the domain was set as a wall with slip conditions. The indoor floor was set with a constant temperature observed in field measurements and outdoor floor was set as adiabatic. All the walls were treated as “enhanced wall treatment” according to FLUENT (2014) in order to improve calculations pertaining the thermal and convective boundary layer. The simulation considered incompressible ideal gas and influence of buoyancy. The wind profile, kinetic energy and turbulence energy dissipation were calculated based on the equations recommended by RICHARDS and HOXEY (1993).

3 Results

An acceptable grid of 185220 cells was found by following the methodology of ROACHE (1994) with higher density of cells imposed close to the wall. The DOM was set with 15 iterations of the energy equation and the number of angles equal to 7. The incident solar rays angle, to be set as a boundary condition in the top, was found by using the coordinates of the poultry house and time. Heat flux due to longwave was estimated based on the outdoor temperature and emissivity equal to 0.64. FLUENT (2014) found the numerical solution by following the SIMPLEC method with a skewness correction equal to two and a second-order upwind discretization scheme. The convergence had to meet residuals lower than 10^{-6} in continuity, x and y velocity, energy dissipation; and lower than 10^{-12} in water vapour, discrete ordinates and energy.

The validation of the 2D CFD model is summarized in Table 2; where Case II evaluated 33 %, 66 % and 100 % of the 10 hens m^{-2} since in these operating conditions traps were opened and animals could exit the house. Operating conditions of Case I effectively demonstrated the accuracy of the 2D CFD model; however, animals had still low-level of sensible and latent heat emissions as they were in the early growing stage. In Case II, simulations of 66 % and 100 % of the animals had a minimum RMSE according to the experimental data; this result agrees with the number of animals observed in the building which was approximately 75 % of the full population.

Thermal and humidity gradients created by the two operating conditions (Case I and II) are shown in Figure 2. For instance, operating conditions of Case I involved thermal and humidity gradients that are larger than those of Case II due to the operation of the heater; homogeneity was prevalent away of the neighbouring areas of heater and the air entrance and exit. In contrast, operating conditions of Case II attenuated thermal and humidity gradients given that heat produced by animals was distributed across the bottom area and also had higher ventilation than Case I.

Tab. 2: CFD model validation

Tab. 2: Bewertung des CFD-Modells

Case	Temp. RMSE [$^{\circ}\text{C}$]	Hum. RMSE [$\text{g}(\text{H}_2\text{O}) \text{kg}^{-1}(\text{Dry Air})$]
I	1.0	0.26
II (33 %)	1.9	0.48
II (66 %)	1.3	0.37
II (100 %)	0.9	0.58

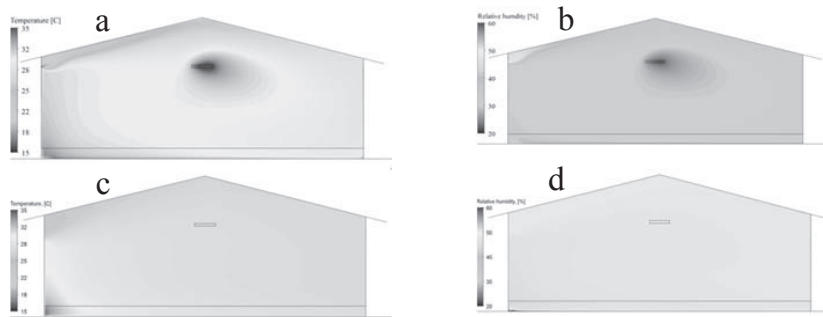


Fig. 2: Predicted thermal (a, c) and humidity (b, d) gradients of the poultry house for operating conditions named as Case I (a & b) and II-100% of animal density (c & d)

Abb. 2: PPrognostizierte Wärmegradienten (a, c) und Luftfeuchtigkeitsgradienten (b, d) des Geflügelstalls für Fall I (a & b) und Fall II -100 % der Besatzdichte (c & d) in den genannten Betriebsbedingungen

From the 2D CFD model, air changes per hour (ACPH) were computed with the virtual tracer gas methodology recommended by OULD KHAOUA et al. (2006). Case I had 10.6 ACPH (± 0.45 standard deviation) and Case II-100 % of animal density had 25.2 ACPH (± 2.6 standard deviation). Thus, temperature and humidity data from experiments and predictions were taken into account to estimate sensible and latent heat losses due to the natural ventilation (Figure 3). For instance, Case I had latent heat losses lower than 25 % of the total, in contrast, Case II had less than 35 % of the total; even though in Case II animals emitted 3.5 times more water vapour than they did in Case I. Nevertheless, in Case I a 25 % of water vapour was emitted by the heater. Variability of the climate was computed as standard deviation to emphasize the impact in the successive calculations related to heat losses. Though there was less climate variability in Case II than in Case I, the ACPH in Case II caused higher standard deviations of heat losses that in Case I.

4 Conclusions

An enhanced 2D CFD model that included natural ventilation, heaters, and animal and rearing system was validated by means of two contrasting operating conditions. Given that temperature and humidity inside the poultry house change spatially and that a representative location for monitoring climate is difficult to define; this work considered distributed temperature and humidity to indicate the bias estimation by means of the standard deviation that could impact in the accuracy of prediction of heat losses. Additionally, the ACPH can also be a significant source of discrepancy when computing

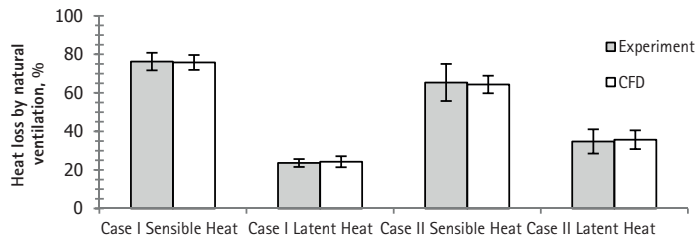


Fig. 3: Experimental and predicted sensible and latent heat losses with the operating conditions for Cases I and II - 100 % as described in Table 1

Abb. 3: Experimentelle und vorhergesagten sensible und latente Wärmeverluste mit den Betriebsbedingungen für Fall I und II - 100 %, wie in Tabelle 1 beschrieben

heat losses. On the basis of two cases considered, this analysis claims that temperature and humidity gradients originated by the operating conditions of Case I are greater than those of the Case II and contributes to a standard deviation in heat losses less than 10% for both, experiments and predictions. In contrast, the ACPH of Case II are greater than those of Case I and caused a standard deviation in heat losses up to 18 % according to the experimental data and up to 13 % based on the predictions. From these two exemplary cases, it was illustrated that heat losses in naturally ventilated poultry houses can be better estimated at low ACPH such as the Case I. However, further work is still needed to optimize the experimental setup and in particular the number of sensors and locations at which they could retrieve meaningful data based on the building's operating conditions.

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