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Investigation of gas emissions and spreading inside and outside of a naturally ventilated poultry house using a 3D CFD model

Untersuchung von Gasemissionen und deren Ausbreitung innerhalb und außerhalb eines natürlich belüfteten Stalls mit einem 3-D-CFD-Modell

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Summary

Using Computational Fluid Dynamics (CFD), we investigated the spread of gases inside and around of a poultry house. A 3D CFD model takes account of the natural ventilation combined with heat and water vapour produced by the animals. In order to validate a 3D CFD model a cycle of production for experimental purposes located West of France during the spring, 2014 was used to retrieve data. In the first step, there is a validation of a 3D CFD model based on the interior climate. In the second step, the aim was to identify how the gases might be dispersed in the surrounding environment. Water vapour was accurately logged in space and time for the interior of the building, and then utilized to predict the plume development in the building's surroundings.

Zusammenfassung

Mithilfe der numerischen Strömungsmechanik (Computational Fluid Dynamics; CFD) untersuchten wir die Ausbreitung von Gasen in und um einen Geflügelstall. Ein 3D-CFD-Modell berücksichtigt die natürliche Belüftung in Kombination mit von den Tieren erzeugten Wärme und Wasserdampf. Um dieses 3-D-CFD-Modell zu validieren, wurden während eines Produktionszyklus in einem Betrieb im Westfrankreichs im Frühjahr 2014 Daten erhoben. Zunächst erfolgte die Überprüfung des dreidimensionalen CFD-Modells auf der Basis des Raumklimas. In der zweiten Stufe sollte die Verteilung der Gase in der Umgebung untersucht werden. Dazu wurde der Wasserdampf räumlich und zeitlich genau im Gebäudeinnenbereich registriert, um die Fahnenentwicklung in der Umgebung des Gebäudes vorherzusagen.

1 Introduction

Livestock buildings are a viable alternative to grow animals where a successful production relies on the living conditions such as the climate given to the animals. The design of the building focuses on maximizing contributions of natural ventilation which can reduce operating costs; however, the uncertainties of weather can create in the animal house unfavourable interior climate and potentially high concentration of gases. The animals and rearing system which are the main sources of heat and moisture require ventilation capable to remove excess of them in order to maintain the temperature and humidity that is beneficial for the animals. Otherwise, animals may be exposed to an unfavourable climate and air quality.

The current work has the aim to analyse natural ventilation by means of an enhanced 3D CFD model that includes features of a particular poultry house as well as the heat and moisture sources from animal and rearing system associated to specific natural ventilation regimes. The reliability of the 3D CFD model is demonstrated with the simulation of two operating conditions provided to the poultry house. From those simulations, the aim was to replicate thermal and moisture gradients created by the stagnant and wake regions inside the poultry house; and to validate the climate distribution using experimental data. The experimental setup logged data pertaining to temperature and moisture over two planes (vertical and horizontal) that could assist in the assessment of a 3D CFD model performance. Then, the same model was implemented to estimate the main parameters related to characterize the removal rates and plume of evacuated moisture that would arise. This information can be considered relevant in the dispersion of pollutants, pathogens and particles from poultry house as they have a negative impact in the neighbouring areas.

2 Materials and Methods

2.1 Experimental data

Experimental data was collected from a poultry house in an experimental station “Le Magneraud” West of France (46.15 N, -0.69 W). The dimensions and specifications are provided in Figure 1a. The poultry house had walls and roof made of polystyrene of 4 cm as insulator (thermal conductivity equal to $0.05 \text{ W m}^{-1} \text{ C}^{-1}$) with lateral curtains of plastic (thermal conductivity equal to $0.3 \text{ W m}^{-1} \text{ C}^{-1}$) and traps located along one side of the building as shown in Figure 1a.

Exterior climate was logged with a meteorological station (AWS310, Vaisala, France) located near the building that logged wind velocity and direction, air temperature and relative humidity data. Interior temperature ($\pm 0.1 \text{ }^\circ\text{C}$) and humidity ($\pm 3 \%$) were logged with 13 portable sensors (DL-101T USB, Voltcraft, France) spatially distributed. The data acquisition system placed the sensors distributed over a vertical and horizontal plane that followed the scheme shown in Figure 1a, logging data that covered a half of the building. Vertical plane was defined based on three lines (B, C and D) that were placed at 0.7 m, 1.4 m and 2 m from the floor, also, this plane intersected a trap. Horizontal plane considered three lines (A, C and E) at 1.4 m from the floor and 2.38 m between them.

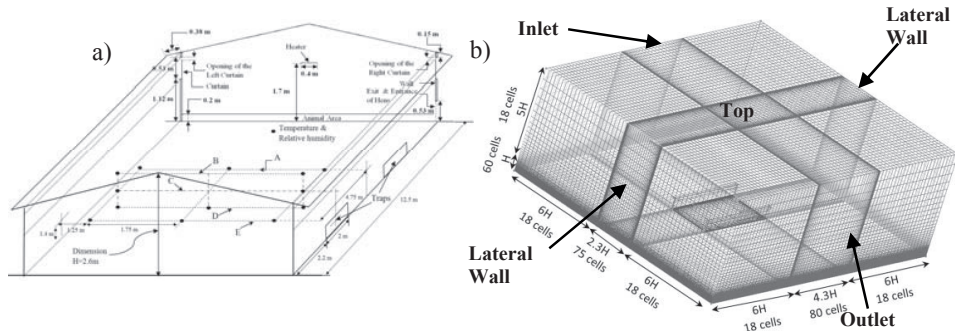


Fig. 1: a) Experimental setup and sensor location, and b) grid and boundary conditions
 Abb. 1: a) Versuchsaufbau und Sensorposition, b) Raster und Randbedingungen

Two typical operating conditions (Case I and II) at the late stage of production were studied with the wind blowing perpendicular to the ridgeline (with a range $\pm 14.4^\circ$), and the poultry house having an orientation of 22° NE. The two operating conditions were primarily differentiated with opened traps during the day for Case I and closed traps during the night for Case II. In both cases, opening of the curtains was the same (30 cm). The two datasets to replicate in the 3D CFD model were chosen based on stability in the temperature (Case I: 25.6 ± 0.6 °C; Case II: 15.6 ± 0.5 °C), humidity (Case I: 10 ± 0.18 g[H₂O] kg⁻¹[Dry Air]; Case II: 10.8 ± 0.34 g[H₂O] kg⁻¹[Dry Air]) and wind velocity (Case I: 1.4 ± 0.2 ms⁻¹; Case II: 0.5 ± 0.15 ms⁻¹).

2.2 CFD Modelling

The grid was built with hexahedral-cell-type using ICEM of Ansys, (2014) that distributed the cells in 60 % and 40 % at the surroundings and interior of the poultry house, respectively. The domain under study was defined based on the ridge height (H) equal to 2.6 m. Figure 1b illustrates the mesh distribution over the domain which implied 1104730 cells. The finite volume approach followed the Reynolds average method of the Navier-Stokes equations because this approach has demonstrated reliability when applied in similar problems (BJERG et al. 2013). The turbulence was replicated by the kinetic energy k and dissipation rate ε through the k - ε realizable model. The equations were numerically solved by using Fluent of Ansys (2014). Animal heat and water vapour emissions followed the empirical equations that CIGR (2002) recommended for correlating total heat and weight of animal under basal heat metabolism. The animal weight was estimated based on a weight curve identified in the work of ROJANO et al. (2014). Also, heat emitted from litter would equal 10% of the total animal heat produced according to MEDA (2011), which can be split in sensible and latent heat by 60 % and 40% respectively.

Initial conditions were found by simulating under steady state conditions and used for the unsteady-state initial conditions. The input data of the steady state conditions were taken from the experimental data (Case I: Temp. Ext = 25.4 °C, Hum. Ext = 10.3 g[H₂O] kg⁻¹[Dry Air] and wind speed of 1.7 m s⁻¹ & Case II: Temp. Ext = 15.5 °C, Hum.

Ext = 11.08 g[H₂O] kg⁻¹[Dry Air] and wind speed of 0.5 m s⁻¹), in conjunction with remaining settings according to Table 1. The left side of the domain was set as the inlet (ventilation inlet) whereas the right side of the domain as the outlet (pressure outlet) at atmospheric pressure of 100.4 kPa. The top side as well as the lateral walls of the domain were set as walls with slip conditions with a magnitude of the wind velocity (Fig. 1b). 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 of Ansys (2014) to improve calculations of the thermal and convective boundary layer. The simulation considered incompressible ideal gas and buoyancy effects. The wind profile, kinetic energy and turbulence energy dissipation were calculated based on the equations recommended by RICHARDS and HOXEY (1993).

Tab. 1: Operating conditions for Case I and II
 Tab. 1: Betriebsparameter für Fall I und II

	Case I	Case II
Day of production	69	45
Time	15:30–17:00	22:40–00:10
Traps	Open	Closed
Average floor indoors temperature	24 °C	22.3 °C

3 Results

The solver Fluent of Ansys (2014) found the numerical solution using SIMPLE method and a second-order upwind discretization scheme. The convergence had to meet residuals lower than 10⁻⁵ in the continuity, x, y and z velocity, energy dissipation; and lower than 10⁻⁸ in water vapour and energy.

The 3D CFD model was validated under the two operating conditions (Case I and II) and overall results were as follows: Case I had a RMSE of 0.8 °C and 0.64 g[H₂O] kg⁻¹[Dry Air] for temperature and humidity, respectively, in contrast, Case II had a RMSE of 1.02 °C and 1.15 g[H₂O] kg⁻¹[Dry Air] for temperature and humidity, respectively. Despite Case I had the minimum RMSE, the operating conditions implied traps open where animals could have left the poultry house thus causing a misrepresentation of the heat and moisture originated by them. Then, operating conditions of Case II served to evaluate the governing equations for the heat and moisture originated by the animals

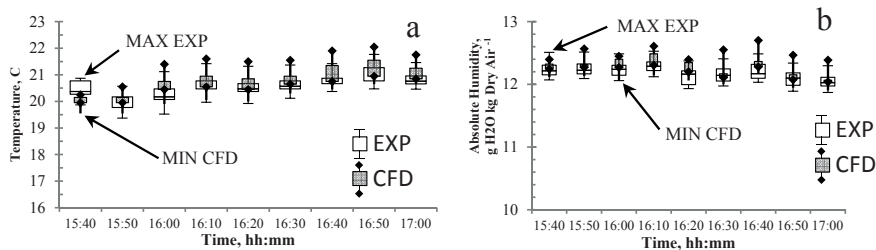


Fig. 2: Three-dimensional CFD model validation using Case II for a) temperature and b) humidity
 Abb. 2.: Validierung des dreidimensionalen CFD-Modells in Fall II, a) Temperatur und b) Luftfeuchtigkeit

and rearing system; even though the night time simulation implied that animal emissions might be reduced due to less physical activity. With these conditions, changes over time for Case II are shown in Figure 2. As there were 13 locations spatially distributed, data were summarized with standard deviation, maximum and minimum values. Thus, capability of the 3D CFD model to replicate thermal and humidity gradients can be verified in terms of accuracy and consistency along the time. Over 9 time steps, the thermal and humidity gradients did not undergo significant changes. Figure 2 shows temperature, humidity and streamlines at the level of the vertical plane (Lines B, C and D, accordingly to Fig. 1a) that also included an opened trap. Even though the two cases were dissimilar in the operating conditions, the wind originated whirls at the interior and downstream area of the building which were dominated by the freestream from the surroundings of the building. The top and right sides of the building were predominantly governed by the freestream (Fig. 3 c & f) that pushed to the floor the air exiting the building due to the roof angle. This fact was found in the two cases demonstrating that regardless of the curtain and/or traps opening for air discharge, heat and gases will mainly spread horizontally, following the dominant exterior air currents. The 3D CFD model considered only 15 m downstream the poultry house where plume spreading was identified. For instance, in Case I dispersion was near the floor whereas in Case II, it occurred lifting of the plume as heat and gases moved away of the building.

In order to assess gas profiles, moisture concentration was computed after leaving the building. Figure 4 summarizes the two cases and also illustrates the profile of the

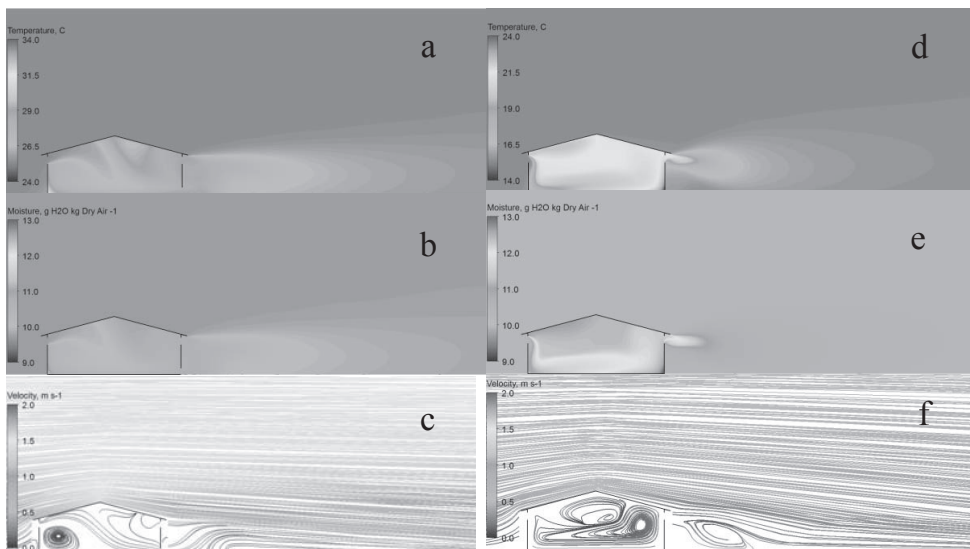


Fig. 3: CFD results for case I (a, b & c) at time 16:20 h (19/06/2014) and Case II (d, e and f) at time 23:20 h (05/06/2014); both cases with 100 % of the animals indoors. Predicted temperature (a and d) humidity (b and e) and stream lines, (c and f) of the two cases

Abb. 3: CFD -Ergebnisse für Fall I (a, b und c) zum Zeitpunkt 16:20 h (19/06/2014) und Fall II (d, e und f) zum Zeitpunkt 23:20 h (2014.05.06); in beiden Fällen mit 100 % der Tiere im Innenbereich. Vorhergesagte Temperatur (A und D), Luftfeuchtigkeit (B und E) und Stromleitungen (c und f) für beide Fälle

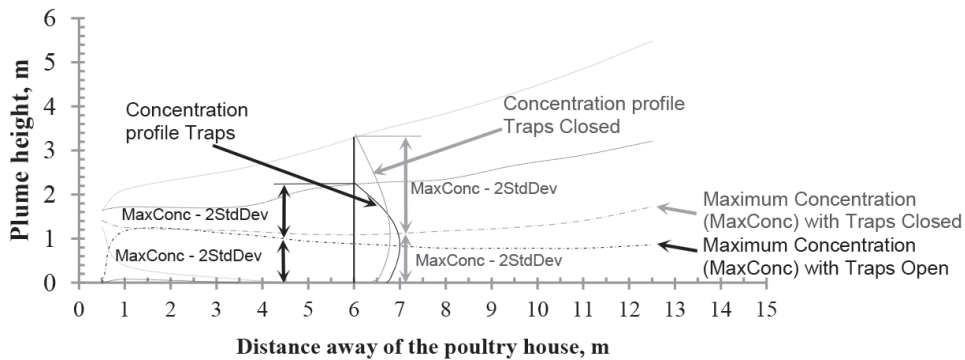


Fig. 4: Estimated gas dispersion for traps open and closed

Abb. 4: Geschätzte Gasdispersion für offene und geschlossene Fallen

dimensionless concentration expected at 6 m away of the building. The plume development was identified over the same vertical plane illustrated in Figure 1a (lines B, C and D). According to Figure 4 opened traps incremented the concentration at the bottom part and plume rising did not happen, but closed traps had a profile concentration with a tendency to rise.

4 Conclusions

1. A 3D CFD model of a naturally ventilated poultry house was validated with spatio-temporal experimental data under two contrasting operating conditions: traps opened (Case I) and closed (Case II).
2. Natural ventilation assisted in the discharge of heat and moisture and moisture profile was considered to analyse plume development.
3. Estimated plume development/spreading of the two cases was identified downstream the poultry house.

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