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Computational Fluid Dynamics Simulation of the Indoor Microclimate of an Enriched-colony Side Ventilated Commercial Layer House in Southern Ontario

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Abstract—The microclimate inside a layer house is critical to the well-being and egg production performance of laying hens. The objective of this study was to evaluate the feasibility of the computational fluid dynamics (CFD) approach in simulating the indoor temperature and velocity inside an enriched-colony layer barn. The results of this study could provide a foundation for future work to assess alternative ventilation schemes (changing the position & number of inlet baffles & exhaust fans, and the addition of inlet flaps & evaporative cooling pads) using airflow and temperature distribution patterns in layer houses.

Keywords—ventilation, layer house, microclimate, CFD

I. INTRODUCTION

Egg production is a rapidly growing industry with an average yearly increase of 3% over the past 10 years [1]. For commercial egg production, layer hens are kept in large indoor layer houses. Commercial layer houses have different configurations. While traditionally, layer hens were kept in caged systems, due to animal welfare considerations; farmers are gradually transitioning towards alternative systems which include enriched-colony, cage-free (single-tier and multi-tier), and free-range housing designs.

The indoor microclimate of a layer house is critical to birds' well-being and egg productivity. Air temperature, airflow ventilation rate, indoor humidity, and concentration of pollutants (which are mainly dust, NH_3 and greenhouse gases (CO_2, CH_4, N_2O)) remarkably affect laying hens' thermoregulation.

There have been numerous investigations on field measurements of the parameters in layer houses. However, experimental evaluation of these parameters is both costly and time-consuming. As an alternative to field measurements, numerical simulation by computational fluid dynamics (CFD) provides a powerful and cost-effective tool for the prediction of ventilation patterns and dispersion of dust and gaseous pollutants in laying hen houses.

To simulate the indoor microclimate of a layer house by using CFD, the first step is to create a geometry from the barn, discretize this geometry and impose boundary conditions. The type of boundary conditions assigned at the inlets and outlets of the geometry depends on the on-farm measured parameter at those locations (i.e., either pressure or velocity).

In mechanically ventilated layer houses, usually, negative pressure is induced inside the house by operating exhaust fans. Exhaust fans force the contaminated air out of the barn, resulting in a slightly negative pressure inside the house, and fresh air enters the house through inlet baffles or eaves which are located at the top of the barn [2]. The placement of the inlet baffles and exhaust fans inside a layer house leads to different ventilation schemes. Typical ventilation schemes include tunnel and side modes. In tunnel ventilation, fresh air enters from one end of the house (width of the house) and is exhausted by fans located on the other end (width of the house) [3]. In side ventilation, fresh air enters from inlets located at the top of sidewalls (length of the house) and is then discharged by exhaust fans which are located on the sidewalls (length of the house) as well [4].

The next step is to solve the mathematical equations of fluid flow (i.e., conservation of mass, conservation of energy, and the momentum equation) along with two additional transport equations to account for turbulence effects. To model the diffusion of a gaseous contaminant (such as dust, NH_3, CO_2, CH_4, N_2O), the species transport model needs to be considered. Depending on the level of complexity involved, the animal occupant zone (AOZ) is assumed either a solid block or a porous medium.

Due to the complex airflow patterns, turbulent flow is dominant in layer houses. Various turbulence modeling approaches exist, and the choice of turbulence model depends on the specific fluid flow characteristics, the available computational resources, and the desired level of accuracy [5]. The most commonly used turbulence models in layer houses were the standard k-ε, renormalization group (RNG k-ε), and realizable k-ε models.

Then, numerical solution methods and convergence criteria are defined to iteratively solve the equations. Once the simulation is converged, the next step is to visualize and analyze the results by contour plots and data curves.

To ensure the simulated CFD outcomes accurately reflect realistic layer house conditions, the results need to be both verified and validated. The CFD solution method must be verified (a similar previous CFD simulation should be selected and performed, and the acquired results should be compared with the results of that specific study) to ensure the solution method can produce accurate results.

Furthermore, the results of the CFD simulation should be validated (in this regard, field measurements should be taken at sampling locations inside the layer house and the data should be compared with the CFD results). Then, statistical parameters should be used to evaluate the CFD modeling performance. Statistical parameters including fractional bias (FB), normalized mean squared error (NMSE), geometric mean bias (MG), geometric mean-variance (VG), and fraction of two (FAC2) are typically considered as validation criteria [6]. During the last two decades, CFD has been continuously implemented to simulate airflow patterns, temperature distributions, and pollutant concentrations in poultry houses. However more attention was given to broiler facilities than to layer houses [7] and there is still limited data on modeling airflow and pollutant distribution patterns in laying facilities.

In 2007, Pawar et al. [8] carried out a steady-state 2D simulation on two side-by-side caged layer houses which were in a larger domain, representative of the outdoor environment. One of the houses had upward ventilation, while the other had downward ventilation. Airflow was considered a steady state, the k-ε approach was utilized to model the turbulence effects. The diffusion of NH3 was investigated, and the AOZ was assumed to be a solid block with heat flux. The results of their study showed that the upward airflow ventilation could provide better air quality than the downward airflow.

In 2013, Wang and Wang [9] performed a steady-state 3D CFD simulation on a tunnel-ventilated caged layer house which used wet cooling pads. The RNG k-ε turbulence model was utilized and the AOZ was considered a solid block with heat flux. By changing the position and size of the cooling pads and exhaust fans, they could achieve a more uniform distribution of temperature and velocity inside the house. The original barn simulation results were validated by comparison with field measurements which indicated a good agreement.

To evaluate the porous medium characteristics of the AOZ of layer houses, in 2018, Cheng et al. [10] carried out CFD modeling on a virtual wind tunnel. They studied the effects of different geometrical models of caged hens (i.e., full-geometry, body only, and ellipsoidal model), hen distribution (three patterns) and hen body weights (1.5, 1.8, and 2 kg) on flow resistance. They conjectured that all the studied parameters impact flow resistance and their calculated viscous resistance coefficients could be considered in further numerical studies when treating the AOZ as a porous medium.

In 2019, Tong et al. [3] performed a 3D transient mode simulation of the indoor thermal environment of a tunnel ventilated two-floor caged layer house. They utilized the RNG k-ε turbulence modeling approach, considered the AOZ as a porous medium with heat flux, and evaluated the diffusion of water vapour inside the house. They validated their model by field measurements and presented numerical results of airflow pattern and thermal environment of the layer house. They concluded that the tunnel ventilation system needed improvement to provide better thermal comfort to prevent birds from suffering heat or cold stresses in extreme weather conditions. In a further study, Tong et al. [11] presented the results of a CFD study on the same layer house, considering mixed mode ventilation (i.e., tunnel ventilation on the upper floor and cross ventilation on the lower floor) and simulated the dispersion of NH_3 as well. They found that adopting a mixed mode ventilation could improve the uniformity of the indoor environment of the house and provide safe NH3 concentrations. The same research group also proposed an upward airflow displacement ventilation scheme to improve the ventilation performance in the same caged layer house [12]. They found that the alternative scheme could provide higher air-exchange effectiveness than the tunnel ventilation system and reduced heat/cold stress. By minimizing airflow pathing across cages, the upward scheme could also limit the transmission of pathogens inside the house.

In 2019, Du et al. [13] carried out a steady-state 3D CFD simulation on a tunnel ventilated caged layer house. The realizable k-ε turbulence modeling approach was utilized and the AOZ was considered a porous medium with heat flux. They studied the impact of optimizing the configurations of air inlets and the addition of sidewall windows on the indoor microclimate. They validated the CFD model with field measurements. In a further study on the same barn in 2019, Du et al. [14] investigated the dispersion of bio-aerosols (with diameters between 1 µm to 100 µm) by implementing the discrete phase modeling approach and found that higher concentrations of bio-aerosols were deposited at the rear part of the house.

In 2020, Chen et al. [4] modeled the indoor microclimate of a cage-free layer house. Similar to the study by Pawar et al., Chen et al.'s barn was located within a larger domain, representative of the outdoor environment. The standard k-ε turbulence model was utilized and the individual hens were treated as individual solid blocks with heat flux. The 3D steady-state simulation demonstrated comfortable temperature and airflow conditions in the barn. In a further study, Chen et al. [15] considered the same cage-free facility and simulated three alternative ventilation schemes to evaluate the effect of changing the position of air inlets and exhaust fans on the indoor temperature and velocity fields. In alternative schemes, the inlet fans were placed on the middle height of the sidewalls, and the exhaust fans were placed on the ceiling of the barn. They found that the alternative designs could provide indoor air movements similar to the standard ventilation, even better at the hen level. However, these three studies did not include any on-farm validation.

In 2021, Cheng et al. [16] simulated a tunnel ventilated layer facility to assess the effect of changing the position of air inlets and the addition of flaps behind the inlets on the distribution of indoor temperature and airflow. The standard k-ε turbulence model was utilized and the AOZ was considered a porous medium. They performed field validation and reported that these two factors have a significant impact on the uniformity of temperature and airflow.

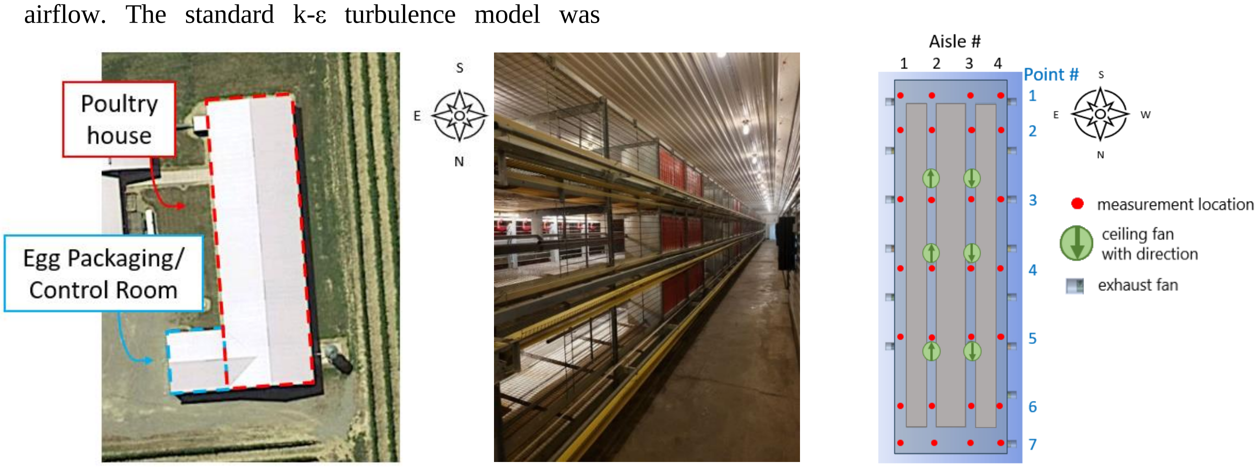
In 2022, Ahmadi et al. [17] verified the layer house model simulated by Wang and Wang [9] and numerically studied the transport of NH_3, CO_2, and H_2O inside the facility.

Based on the reviewed literature, it is evident that the agricultural engineering community has progressively adopted CFD to model the indoor climate of layer barns to assess the transport of pollutants, and to predict the performance of different ventilation schemes. However, most of the previous studies were on traditional caged-layer houses. The present study documents the performance of a side-ventilated enriched-colony layer house in Ontario during the spring season. At first, on-farm measurements of air velocity and temperature were conducted, and then a 3D model of the barn was developed and simulated to predict the airflow and temperature patterns.

II. Materials and Methods

A. Layer house configuration and measurement

The enriched-cage layer house selected for the study is situated in Eastern Ontario (Fig. 1). The house is 45 m long, 12.5 m wide, and 3.8 m high with a side-ventilation system. The field measurements were conducted in an unoccupied barn; hence, chickens were not taken into account. Eight exhaust fans on the west wall and 6 fans on the east wall allow for ventilation through the house, as shown in Fig. 1c. The three rows of cages extend from the north to the south end, consisting of three tiers in each row. Each row is also a collection of three sub-cages that are interconnected.



(a) (b) (c)

Figure 1. The studied enriched-cage layer house's a) top view, b) interior, and c) top-view schematic

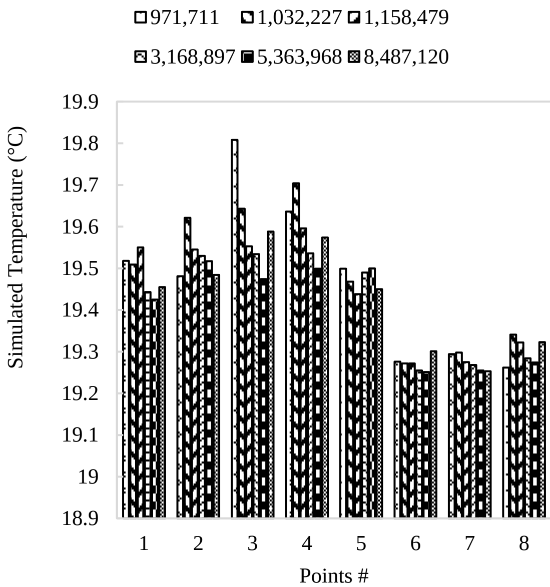


Figure 2. Temperature readings for different grid sizes

Additionally, six recirculating fans are attached to the ceiling at an approximate angle of 45°. Three of the recirculating fans are in aisle 2, while the other three are in aisle 3. Air inlet openings were at the eaves of the east and west walls, across the length of the barn. The fans were operated by a control system based on set-point temperatures and their corresponding fan power level.

Measurements were taken for the ventilation stage where all of the 14 fans operated to replicate peak airflow conditions at the barn. The field measurements were carried out to gain an insight into the environmental parameters inside an empty barn, that can subsequently be compared to a barn full of 9,000 chickens. The data was then utilized for a CFD model validation.

The schematic of the barn (Fig. 1c) illustrates the locations of field measurement devices within the barn. Each measurement was taken at two heights, 1.2 m (top of the first cage tier) and 2.8 m (top of the third cage tier). The air temperature, relative humidity, dust concentration and greenhouse gas readings were recorded at these points during the barn visit on May 30th, 2024. The arrow shapes indicate the position and facing direction of the recirculation ceiling fans in aisles 2 and 3.

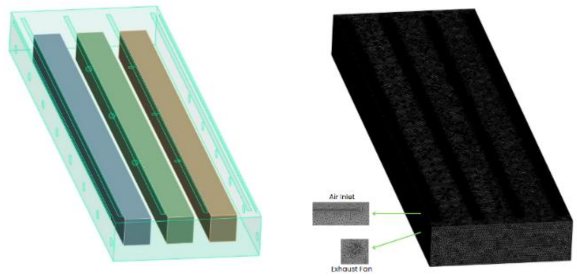


Figure 3. Geometry (left) and mesh (right) of the enriched-cage layer house

B. *CFD modeling*

3D CFD simulation of the indoor microclimate of a commercial enriched-cage layer house with a side-ventilation system was conducted using ANSYS Fluent 2023 R2.

1) *Geometry and mesh independence test*

To minimize the influence of the number of mesh sizes on the accuracy of numerical results, a mesh independency test was conducted to find the optimal mesh size which is reasonable in terms of computation resources and time, while still giving results with acceptable accuracy. Six different mesh sizes consisting of mixed pyramid, tetrahedron and hexahedron shapes in the computational domain were generated and the temperatures at 8 locations at a height of 1.2 m were compared (Fig. 2). Since a higher number of mesh elements usually correspond to higher accuracy, the results for the 8-million mesh have been taken as the basis to calculate the mean relative error % for other grid sizes as presented in Table I. It was observed that grid sizing of 1,158,479 and 3,168,897 elements had mean relative errors of less than 0.2%. Thus, to reduce computational time and cost, mesh elements of 3,168,897 have been considered in the study.

Refined meshes have been used at the air inlet/outlet and surfaces with heat fluxes, to better capture their effects on the velocity and thermal fields respectively inside the barn (Fig. 3).

2) *Boundary and input conditions*

Accurate CFD modeling requires defining correct boundary conditions. However, quantifying and determining the boundary conditions in the actual barn boundaries can be very difficult. According to the in-situ measurements, exhaust fans on the walls were modeled as velocity inlets with a constant negative

TABLE I. MEAN RELATIVE ERROR FOR DIFFERENT GRID SIZES

Grid Size	971,711	1,032,227	1,158,479	3,168,897	5,363,968
Mean Relative Error (%)	0.34	0.32	0.18	0.19	0.26

velocity measured in the house at the entrance of each exhaust fan.

Cages were modeled as free-surface cell zones with porosity to account for the airflow hindrance by the cages. A porosity of 0.5 and an inertial resistance coefficient of 1 m^{-1} along all directional components were assigned based on previous studies in the literature [3]. Since turbulent flow is dominant, the viscous resistance coefficient has been ignored as it is very small compared to the inertial resistance [10,3]. The boundary and input conditions of the model are summarized in Table II.

3) Numerical solution and assumptions

For the numerical study, an incompressible, turbulent, 3D steady-state flow was assumed. The mass, momentum (Navier-Stokes), energy, turbulent kinetic energy and turbulent dissipation rate equations were discretized using a second-order scheme. Air properties were considered to be constant. Based on the previous investigations [8,4,15,16], the standard k-ε turbulence model with enhanced wall functions was utilized to capture turbulence effects. The solution for this study was fully converged by 1000 iterations. For steady-state flow problems, the SIMPLE algorithm was employed to handle coupling between the pressure and velocity fields [18]. To ensure the convergence of the solution, the residual convergence criterion's absolute error tolerances were set to 10^{-6} for temperature, and 10^{-3} for velocity, continuity, and turbulent parameters.

C. Model verification

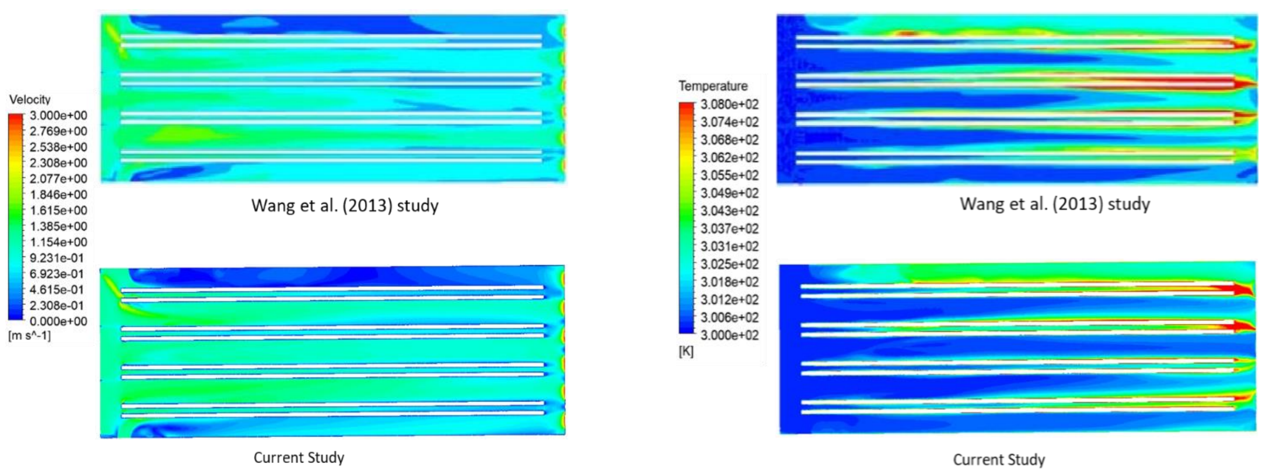
It is essential to perform model verification to ensure the accuracy of the solution method. For comparison, the thermal and velocity field contours have been recreated (Fig. 4) from the study by Wang and Wang [9], which was conducted in a typical commercial laying hen barn located in Southeast China. The barn housed approximately 15,000 layers and featured a structure with concrete foundations and plastered walls, a roof with color plates and aluminium-coated polystyrene foam, and four rows of cages. The simulation focused on optimizing the ventilation and cooling system of the laying hen barn using CFD. As observed in Fig. 4, the velocity and temperature distributions from their study are consistent with the results recreated by the current study.

TABLE II. SUMMARY OF BOUNDARY CONDITIONS AND INPUTS OF THE MODEL.

Housing structure	Boundary condition type	Value	
Ambient	Constant temperature	19°C	
Walls	Constant temperature no-slip walls with zero heat flux	East: 19.5°C	West: 20°C
		South: 19.5°C	North: 20°C
Roof		19.5°C	
Floor		19.5°C	
Air Inlets	pressure-inlet	-	
Air inlet Baffle Angle	45° upward	Inlet Angle	
Exhaust Fans	velocity-inlet	- 8 m/s	
Cage walls	No-slip, zero heat flux		
Cage units	Porous medium		
Circulation Fans	pressure drop: 5 Pa, max velocity: 5 m/s		
Ceiling Lights	Constant Heat flux: 450 W/m^2		

D. On-farm measurement and model validation

The performance of the CFD model was evaluated by comparing the simulation results with the on-farm measurements of air velocity and temperature. Measurements of air temperature and air velocity were conducted in the commercial enriched-cage side-ventilated layer house from the morning till afternoon on 05/30/2024 at different sampling locations (as



(a) (b)

Figure 4. Comparison of (a) velocity and (b) temperature contours at a height of 0.9 m between Wang and Wang [9] and the current study

shown in Fig. 1c). Indoor air velocity was measured at each sampling location one at a time using Ultrasonic Anemometer Model 81000 which has an accuracy of ±0.05 ms^{-1}. The sensor of the air velocity meter was placed perpendicular to the airflow direction. The readings of the air velocity meter took about 2-3 min to get stabilized at each location. Air temperature was recorded continuously at each sampling location using the Thermo Recorder Datalogger TR-73U device which has an accuracy level of ±0.3°C for air temperature.

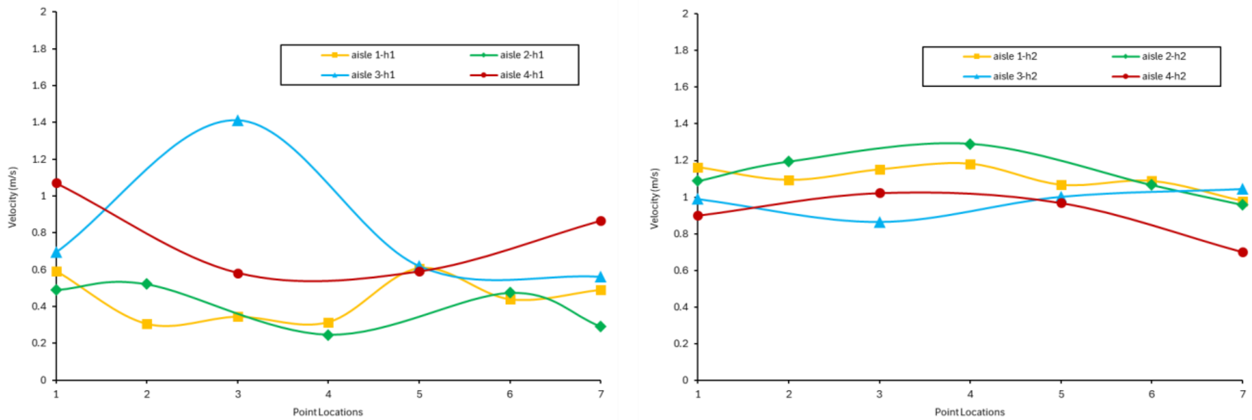
For validation purposes, five statistical parameters, including fractional bias (FB), geometric mean bias (MG), geometric mean-variance (VG), fraction of two (FAC2), and normalised mean square error (NMSE) were used to evaluate the model performance [6]. The numerical model is considered adequate if more than half of the parameters meet the following criteria: $|FB| < 0.3$; $0.7 < MG < 1.3$; $VG < 4$, $0.5 < FAC2 < 2$, and $NMSE < 0.25$.

III. Results and Discussion

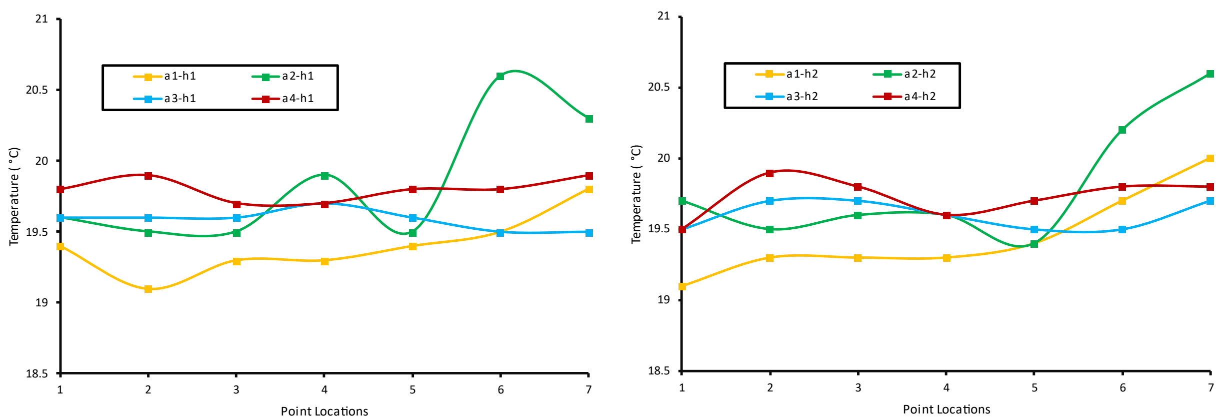
A. Experimental Results

From the field measurement data, the air velocity and temperature patterns observed along the different aisles for heights h1 (1.2 m) and h2 (2.8 m) have been presented in Fig. 5. The velocities at the upper height h2 were roughly around 1 m/s, nearly double the values measured at the lower height h1 (Fig. 5a). The disparity was expected as the height h2 is closer to the unobstructed open space above the cages, allowing airflow without any resistance. An outlier was also recorded in aisle 3-h1, where the velocity reading reached 1.4 m/s, resulting from directly facing one of the ceiling-mounted recirculation fans.

Temperature readings throughout the barn remained consistent, with the variations occurring mostly within the measuring device accuracy limits. They ranged from 19ºC to 21ºC, showing a very slight increase in temperatures from aisle 1 to aisle 4 (Fig. 5).



(a)



(b)

Figure 5. Distribution of (a) air velocity and (b) temperature from field measurements along different aisles & heights

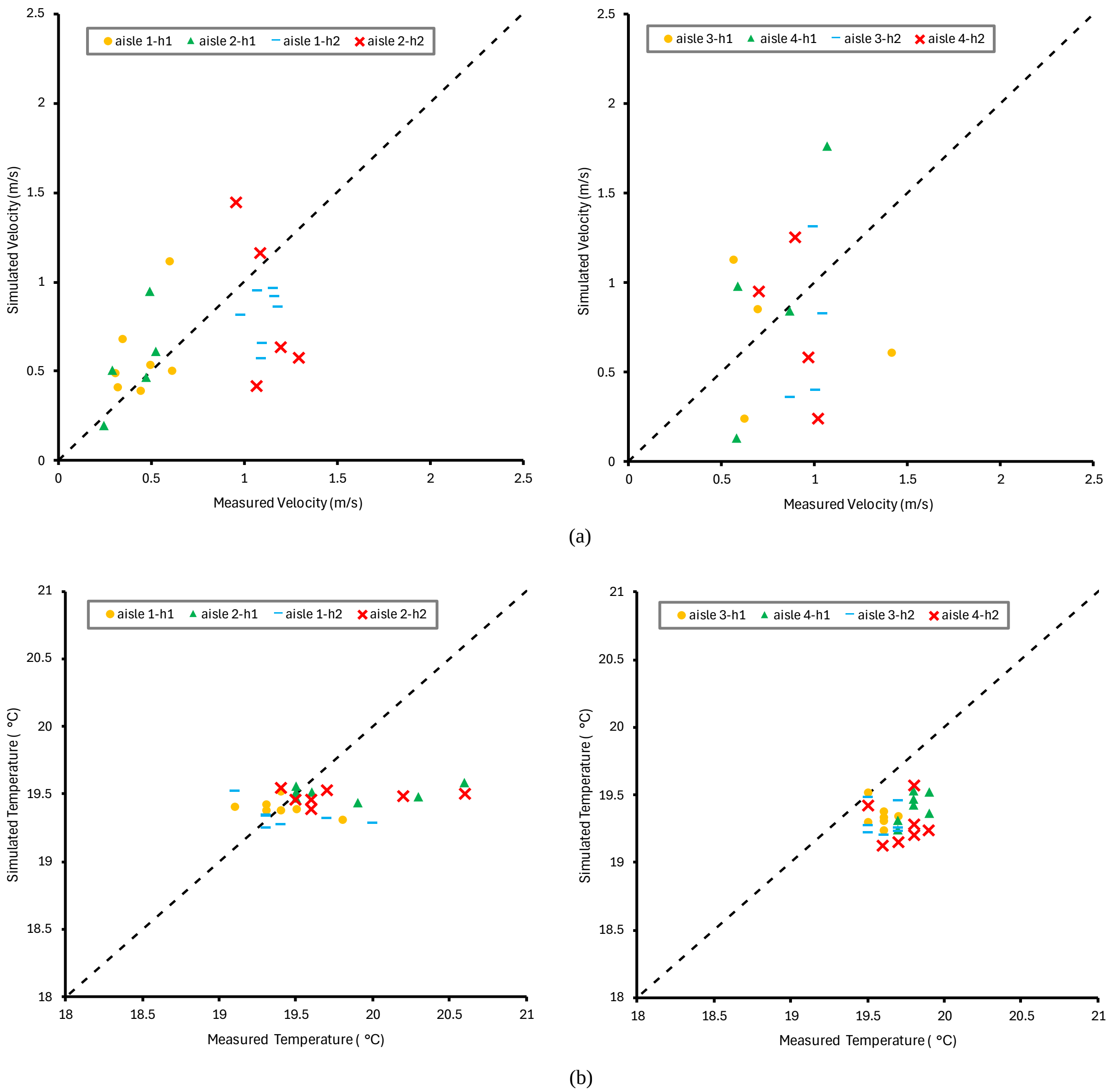


Figure 6. Comparison between simulated results and on-farm measurements in aisles 1, 2, 3 & 4 at both heights for (a) air velocity and (b) air temperature

Two outliers have been identified toward the north end in aisle 2, which could have been possibly because of interference from a frequently opening entrance door near that north-east corner, or the high-bird density in the 2nd aisle.

B. On-farm model validation

The comparisons between the numerical results and field measurements for air velocities and temperatures are shown in Fig. 6a and Fig. 6b respectively, along all the four aisles at different heights. The 45° line indicates the ideal scenario where both the simulated and measured values match each other. Fig. 6 suggests that good agreements are observed between the simulation results and field measurements for air velocity and temperature.

The statistical parameters for model performance evaluation are presented in Table III. The simulated temperature and velocity readings showed good

TABLE III. STATISTICAL ANALYSIS RESULTS FOR MODEL PERFORMANCE EVALUATION.

Statistical Parameters	Velocity	Temperature
|FB| (<0.3)	0.297	0.023
MG (0.7-1.3)	1.548	1.023
VG (<4)	2.017	1.001
FAC2 (0.5-2)	1.243	1.191
NMSE (<0.25)	0.486	0.001

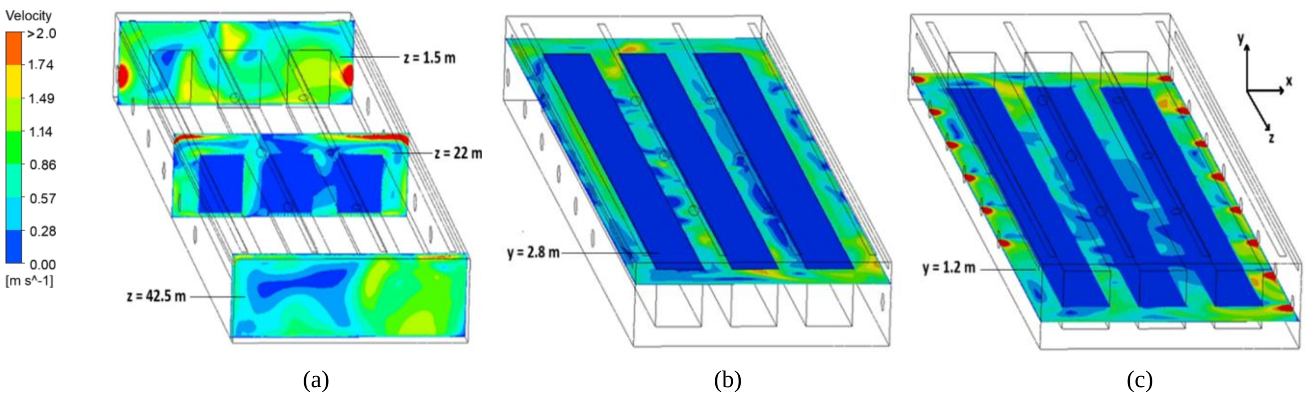


Figure 7. Air velocity contours in vertical and horizontal planes inside the simulated layer house

agreement with the field measurements, with more than half of the parameters satisfied.

C. *Air velocity contours*

The air velocity distributions in the enriched-cage side-ventilated layer house are shown in Fig. *7*. The analysis is done in terms of three vertical planes considered at y = 1.5 m, 22 m and 42.5 m (Fig. *7*a), and two horizontal planes at y = 2.8 m (Fig. *7*b) and y = 1.2 m (Fig. *7*c). According to Fig. *7*a, the average velocity in the central z = 22 m plane is higher than those obtained for the planes z = 1.5 m and z = 42.5 m, which is reasonable as the presence of the cages significantly hinders the airflow. However, strong streamlines from the air inlets are noticeable at the top corners of the central plane. This indicate the incoming air that is directed over the top of the side cages.

A further look will reveal that in the z=22 m plane, there is barely any airflow across the middle cage, i.e., the air does not really flow from one side to the other in this configuration, rather it exits through the exhaust on the same side just as its inlet. The other two end planes z=1.5 m and 42.5 m show a fair degree of free flow due to the open space. However, the latter faces a dead zone towards the left side wall (east) as there are only 6 exhaust fans on that side, compared to the 8 on the other. Hence the lack of symmetry and two less fans on that corner generate a stagnation zone.

The horizontal contours mostly highlight the significant airflow obstruction within the cages. Velocities as high as 8 m/s are obtained near the exhaust fans in the horizontal plane y = 1.2 m (Fig. 7c). As for the airflow in-between the aisles, Fig. 7b and Fig. 7c indicate that the velocities range from 0.5 m/s to roughly 1 m/s, with negligible airflow across the cages. The velocities in the cage zone were extremely low, especially because of the porous boundary effect applied to it.

D. *Temperature contours*

The distribution of temperature was analyzed at the same planes used for the velocity contours, which include the three vertical planes (Fig. 8a), and two horizontal planes (Fig. 8b and Fig. 8c). The temperatures were observed to be mostly uniform at the planes z = 1.5 m and z = 42.5 m, as it was seen earlier that there is better heat dissipation in those spaces due to the free airflow. The higher temperatures (greater than 20°C) were spotted near the ceiling lights because of their heat flux boundary conditions (Fig. 8a). At z = 22 m, lower temperatures can be seen especially within

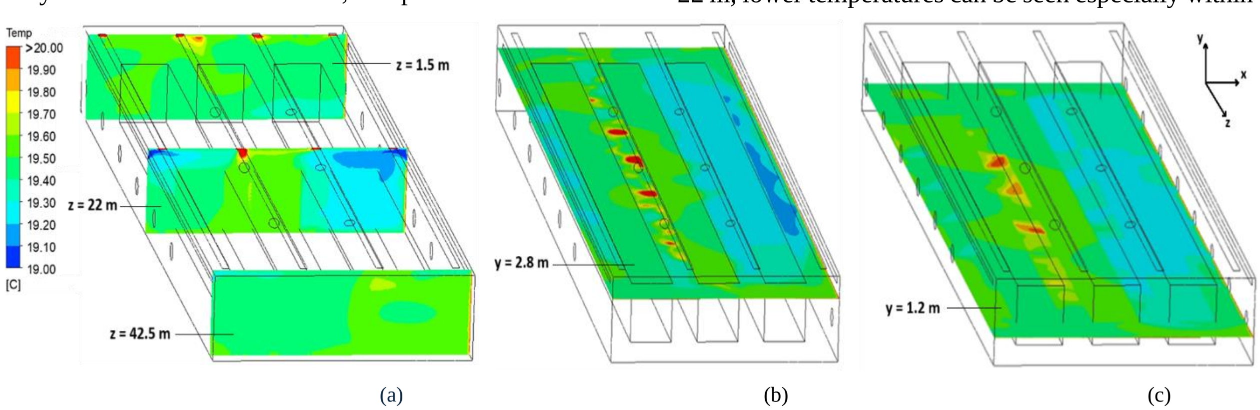


Figure 8. Temperature contours in vertical and horizontal planes inside the simulated layer house

and around the right cage (near west wall), meaning that there is better airflow and heat transfer on the right half of the barn. This can be attributed to the fact that there are higher number of exhaust fans (8) on that side compared to the other end (6 fans), thus enabling higher ventilation in that region.

The horizontal planes are also consistent with this asymmetric ventilation pattern as they exhibit cooler air on the right half (Fig. 8b and 8c). Some warm thermal regions are noticeable on the 2nd aisle just by the left cage. This is caused by the incoming air warming up near the ceiling that subsequently dips in the aisle to create a vortex around the left cage before exiting through the exhausts. Overall, the temperature variations in the barn were within the desired comfort range of 18 to 24°C for birds [15].

IV. Conclusions

This research was intended to evaluate the feasibility of using CFD techniques to simulate airflow and temperature fields in a commercial enriched-cage side-ventilated layer house in spring. The performance of the model was successfully validated using on-farm measurements of air velocity and temperature based on statistical criteria. As experimental research can be expensive and time-consuming, CFD simulation could play an effective role in optimizing layer house designs and pave the way for exploring alternative ventilation schemes for barns to improve airflow and temperature uniformity. In future, the study will be expanded to include the outdoor effect of different seasons, as well as the distribution of dust, greenhouse gases, and relative humidity inside the barn. The addition of relative humidity to the study can help apply the temperature humidity velocity index (THVI) for assessing the indoor microclimate. Moreover, the present study was conducted in an empty barn, focusing mainly on the ventilation performance. Future studies would contain animal-occupied zones, which can help establish a comprehensive and comparative analysis of the indoor environment with the presence of chickens.

V. Acknowledgements

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