Numerical modelling of ventilation options of cage-free hen housing for precision environment management

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Abstract

An evolution of ventilation options is underway by the egg industry to keep pace with the advancing transition to cage-free production. The presented study analysed performance of four ventilation schemes within a commercial cage-free hen house using the computational fluid dynamics (CFD) modelling approach. The analysis aimed to refine ventilation design of cage-free hen housing to assure bird welfare and improve the capacity to constrain airborne disease spread. In total, four three-dimensional CFD models of one-eighth portion of a floor-raised hen house were developed in full-scale to compare the performance of a standard ventilation configuration with three alternative designs. To assess challenging indoor environmental conditions within the four ventilation schemes, the performance of ventilation during freezing winter weather was investigated. In addition, a realistic number of birds were modelled individually with simplified geometrical shape with thermal physical settings to account for the sensible heat generated by animals. The dispersal behaviour of surrogate virus particles was analysed coupled with airflow patterns at critical locations. One of the highlights in this study was the emphasis on assessing the environmental conditions at the bird level, in terms of efficient ventilation, airflow, temperature, and disease spread, which provided insights for precision environment management of livestock and poultry facilities.

Keywords: cage-free hen housing, ventilation options, computational fluid dynamics model, precision environment management, airborne disease spread

Introduction

Precision indoor environment management plays a vital role in livestock and poultry farming. In commercial egg production facilities housing thousands of birds, precisely managing indoor environment to satisfy the production demands is always critical and can be challenging. During the transition to cage-free eggs, problems related to indoor environment have increased significantly due to a lack of unified ventilation approaches designated for cage-free housing (Chen et al., 2020; Chen et al., 2021). As a major component of the environment management system, ventilation schemes of hen houses need concurrent evolution to keep pace with the advancements in poultry facilities.

A proper ventilation design should provide hen houses with sufficient air exchanges, to not only maintain satisfactory temperature, humidity, and internal air movement, but fulfilling other requirements such as animal welfare concerns and the capacity to constrain potential disease outbreaks (Chen et al., 2022). Current ventilation designs can benefit from refinements to achieve better environment management in cage-free hen housing.

Computational fluid dynamics (CFD) modelling is a sophisticated mathematical simulation methodology that has been applied to address environmental problems in the field of plant and animal farming systems for decades (Norton et al., 2007; Li and Nielson, 2011). As a representative numerical approach to study ventilation designs with specific aims, CFD models are versatile tools that facilitate the manipulation of input parameters to evaluate ventilation performance at relatively low cost in terms of capital expenses and time (Mistriotis et al., 1997; Pawar et al., 2007; Fabian-Wheeler et al., 2018).

This paper reports CFD investigations of ventilation options for a typical cage-free hen house. One-eighth of a real floor-raised hen house was modelled at full-scale with four different ventilation schemes that include a standard configuration and three alternative designs. To increase the accuracy of models, thermal influences of birds were included in each model (Walserg and King, 1978; Mutaf et al., 2008; Chen et al., 2020). Simulations of airflows during freezing cold weather were conducted to assess the performance of the various ventilation systems by analysing critical parameters, including air velocity, air flow pattern, temperature, static pressure, as well as the mass percentage of surrogate virus particles. The goal aimed to document and compare the performances of multiple cage-free ventilation options to provide practical recommendations on ventilation refinement. More detail of methods and results may be found in Chen et al, (2020, 2021 and 2022) than what can be presented here.

Materials and methods

Software and basic settings used for CFD modelling

Four three-dimensional models were developed by deploying the commercial CFD code in FLUENT (ANSYS v19.1, PA, USA). Simulations were performed using the standard k-ε turbulence model with enhanced wall functions for steady-state calculations. All the computations were conducted on the 'Roar Supercomputer' at the Institute for Computational and Data Science of the Pennsylvania State University.

Modelling the study hen house and ventilation configurations

A 162 m long and 13 m wide floor-raised layer house located in Lititz, Pennsylvania was chosen as the study hen house whose side walls were 273 cm tall (Figure 1a). Roughly 20,000 birds were housed in the study barn.

The hen house had a ceiling and a ventilation system that included inlets at the top of each sidewall and sidewall exhaust fans, which was modelled as 'Top-Inlet Sidewall Exhaust (TISE)' to represent a standard ventilation configuration in North America. The alternative ventilation schemes, MICE ('Mid-wall Inlet Ceiling Exhaust'), MIRE ('Mid-wall Inlet Ridge Exhaust'), and MIAE ('Mid-wall Inlet Attic Exhaust') were designed with identical inlets positioned 1.5 m above the ground, yet they had different exhaust placement and ceiling features (Figure 2). The MICE model represented a more typical European ventilation design with the exhaust fan positioned at the middle of the ceiling. The MIRE model had the exhaust fan positioned at the ridge directly without any ceiling. The MIAE had a partial ceiling to create an attic space for potential pre- treatment of exhaust air. All inlets in four models were designed with identical opening size to provide adequate airflow during cold weather at a suitable static pressure difference (Figure 1b).

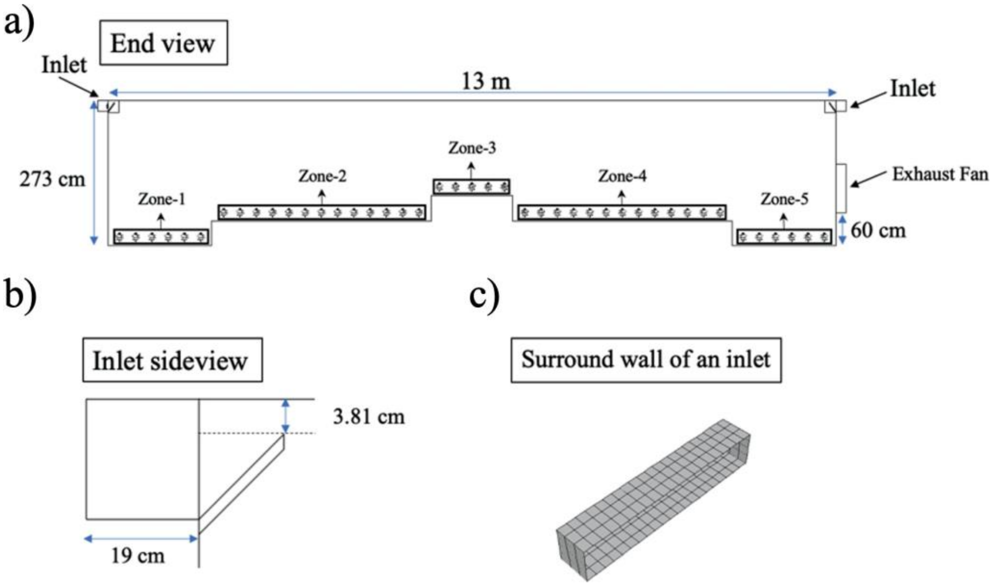

Figure 1: Illustrations of a) the end view cross-section of study hen house including five bird-occupied zones, b) the side view of an inlet showing the opening size and wall thickness, c) surrounding walls of an inlet showing the area where viruses were introduced.

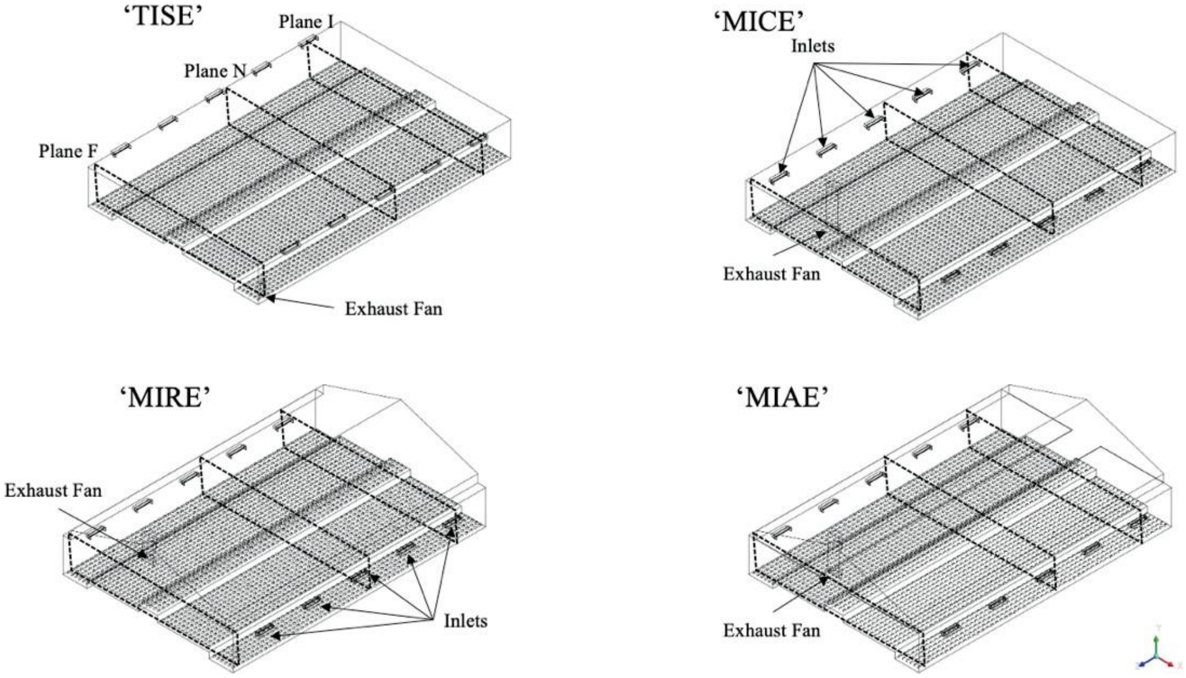

Figure 2: Geometry of four models showing the standard TISE and the three alternative ventilation schemes with arrows pointing to inlets and exhaust fans. Three reference planes used in analysis are presented with dashed lines.

Model boundary conditions, preconditions, and assumptions

The CFD simulations adopted six types of boundary conditions or cell zones, which can be accessed in our previously published article (Chen et al., 2020). The outdoor temperature was defined as 0°C for cold weather simulation, while the wind was presumed constant along positive x-axis at 2 m/s. Gaseous ammonia was selected as surrogate airborne virus species by initially assigning 100% mass percentage of ammonia at the surround walls of upwind inlets (Figure 1c). In total, 2,365 individual hens (approximately one-eighth of the whole flock) were modelled with constant surface temperature to represent bird body heat and to allow ventilation airflow analysis in and around birds.

Bird welfare assessment

Conditions were assessed based upon specific comfort criteria from a bird welfare perspective to evaluate if each ventilation scheme could satisfy the requirements. Those requirements (Chen et al., 2020; Norton et al., 2007) included a desired temperature range between 18 and 24°C; a range between 0.25 and 1.0 m/s of the air speed at hen level; a normal static pressure difference of -25 to -10 Pa (Fabian, 2016a,b) for this type of negative pressure ventilation system. For cold weather, the desirable range of ventilation rate for the modelled layer house ought to be 0.39 to 1.95 m^3/s (Fabian 2016a,b).

Data visualization and statistical analysis

To characterize simulation outputs, three parallel cross-section reference planes were created, representing the indoor locations with inlets (Plane I), no ventilation features (Plane N), and the exhaust fan (Plane F) (Figure 2). Additionally, five bird-occupied zones were created to capture the simulation data at bird level (Figure 1a). Bird zone 3 contained the nest boxes in center of hen house whereas feed and water lines were over an adjacent raised platform with manure scrapers in zones 2 and 4. Bird zones 1 and 5 were floor level areas with litter.

Environmental parameters and mass fraction data were exported from each of the five bird-occupied zones at three reference planes for subsequent statistical analysis. The simulation data were fit to a mixed-effects model to verify whether altering ventilation schemes and the locations had statistically significant effects on the outputs of interest according to the results of ANOVA and Tukey's test, $p < 0.01$)

Results and discussion

The patterns of indoor airflow were evaluated within four ventilation schemes by observing air velocity vectors (Figures 3-5). In general, sufficient indoor air movements were observed in the three alternative ventilation schemes in most regions of the house at all three reference planes.

The alternative designs showed comparable trajectories of incoming air as the standard TISE model at Plane I (Figure 3). Two large circular air eddies that were formed by the incoming air jets in TISE were observed whereas these large eddies along with more numerous, smaller circulation patterns were found in the alternative models. Note some tiny arrows represent air velocity vectors that were oblique or even perpendicular to the plane, indicating lateral airflows moving into or out of the reference plane. Note all arrows have normalized lengths with airflow direction indicated while color (not available here but found in Chen et al., 2021) would indicate velocity magnitude.

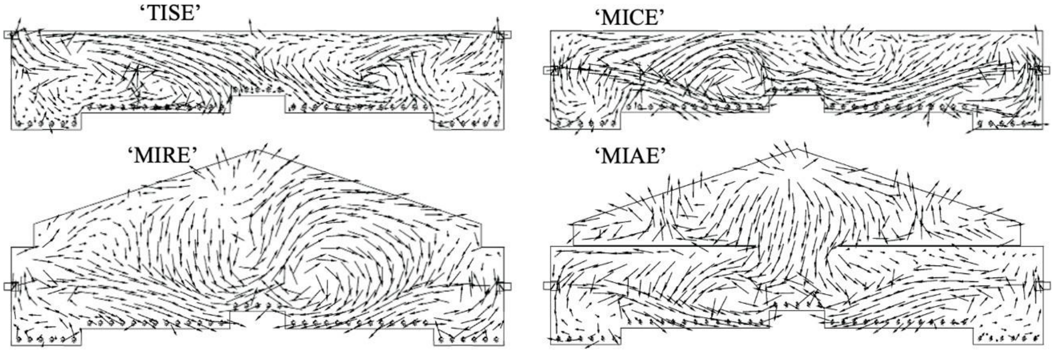

Figure 3: Indoor airflow patterns represented by air velocity vectors at inlet cross-section reference Plane I in the four CFD models. TISE= Top-Inlet Sidewall Exhaust; MICE= Mid-wall Inlet Ceiling Exhaust; MIRE= Mid-wall Inlet Ridge Exhaust; and MIAE= Mid-wall Inlet Attic Exhaust

At Plane N, airflow patterns within each model suggest overall sufficient air mixing even though no ventilation features were present. Airflows in the standard TISE model traveled from the upper right to the lower left with two obvious air eddies forming at both sides of the house (Figure 4). Several scattered air swirls were observed at this plane within the three alternative models plus strong air jets traveling towards the nest-box bird zone 3 area, which implied strong air movement inside the barn. Considering Plane N represents the majority of cross-sections of the entire layer house, the patterns within MICE, MIRE, and MIAE are valuable to assess the predominant airflows.

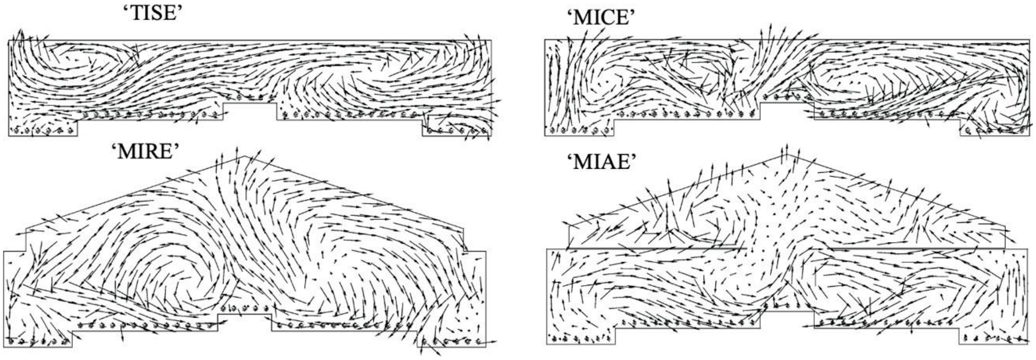

Figure 4: Indoor airflow patterns presented by air velocity vectors at Plane N that has no ventilation features. TISE= Top-Inlet Sidewall Exhaust; MICE= Mid-wall Inlet Ceiling Exhaust; MIRE= Mid-wall Inlet Ridge Exhaust; and MIAE= Mid-wall Inlet Attic Exhaust

Airflow patterns at reference Plane F suggested significant impact of the exhaust fan on indoor air movements very near the fan (Figure 5). Due to sidewall exhausting, indoor air traveled horizontally to both sides within the TISE model, which was different from the observations within the three alternative schemes where airflow moved upwards in MICE, MIRE, and MIAE resulted from driving force from the ceiling/ridge fan.

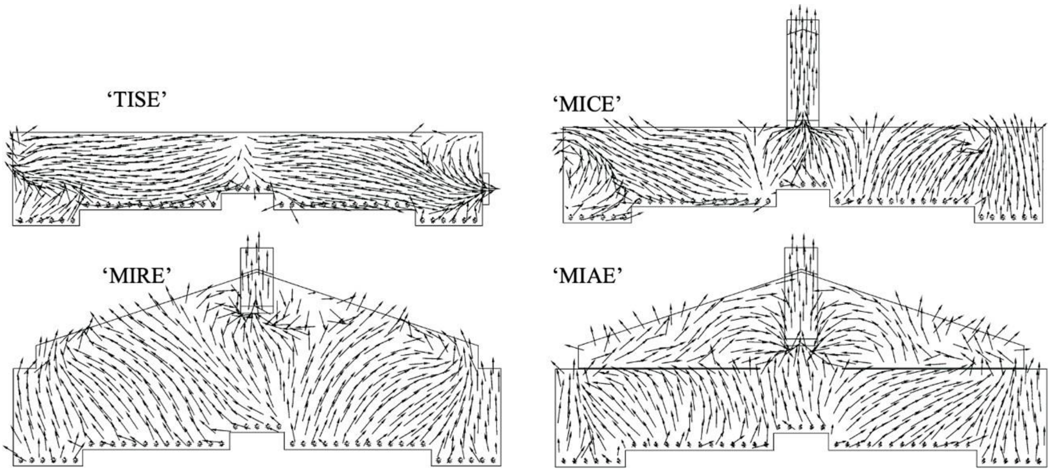

Figure 5: Indoor airflow patterns presented by air velocity vectors at Plane F in the four CFD models. TISE= Top-Inlet Sidewall Exhaust; MICE= Mid-wall Inlet Ceiling Exhaust; MIRE= Mid-wall Inlet Ridge Exhaust; and MIAE= Mid-wall Inlet Attic Exhaust

The means of predicted environmental parameters (air speed, temperature, static pressure) and mass percentage of virus particles at the three reference planes are summarized separately in Table 1 based on statistical analysis. The simulation results provided reasonable environment patterns, based on our field experiences with bird welfare assessments, and agreed with the field validation data from other relevant studies (such as, Küçüktopcu et al., 2022).

Table 1: Means of environmental parameters at the three cross-sectional reference planes in four models based on the simulation outputs from the five bird-occupied zones. All the differences at a specific reference plane without annotations have statistical significance, $p < 0.01$. TISE= Top-Inlet Sidewall Exhaust; MICE= Mid-wall Inlet Ceiling Exhaust; MIRE= Mid-wall Inlet Ridge Exhaust; and MIAE= Mid-wall Inlet Attic Exhaust.

Plane	Model	Air Speed (m/s)	Temperature (°C)	Static Pressure Magnitude (Pa)	Mass Percentage of Virus Particles (%)
Plane I	TISE	0.26	22.90	24.67	1.82 a
	MICE	0.28	20.64	21.87	0.96
	MIRE	0.31	21.16	22.45	1.81 a
	MIAE	0.34	21.53	21.05	1.36
Plane N	TISE	0.35 ab	20.84 c	24.53	1.59
	MICE	0.27	21.40	21.91	1.31
	MIRE	0.34 a	21.04 d	22.43	1.67
	MIAE	0.35 b	20.91 cd	21.05	1.58
Plane F	TISE	0.19 a	20.10	24.45	1.60
	MICE	0.19 a	23.05 b	21.96	1.68
	MIRE	0.17	23.65	22.47	1.56
	MIAE	0.18	22.97 b	21.02	1.35

Among four models, the maximum average air speed at bird level was observed in MIAE at the cross-sectional location with inlets (Table 1), whereas TISE had the slowest air speed overall and the warmest bird-level temperature.

The MICE model had the smallest average air speed at Plane N compared to the other three, which was consistent with the evidence that the warmest air temperature was found within MICE due to relatively slower air movement (Table 1). At Plane F, average temperature of four models increased slightly because of reduced air speeds on average and the accumulation of warmed air prior to exhaust.

As expected, indoor static pressure was quite uniform within each ventilation scheme at each of the three reference planes with rather small variations throughout the hen house. However, the concentration of virus varied among models at each reference plane, demonstrating the circulation of airborne contaminants was influenced by both the ventilation scheme and the location within the house. In general, the models of MICE and MIAE showed advantages of reducing the internal level of airborne particles over the standard TISE model.

Conclusions

The CFD results reported herein revealed the three alternative ventilation schemes were capable of maintaining a comparable indoor environment similar to the standard scheme. The present study demonstrates CFD modelling is a robust approach to refine ventilation systems and assess animal comfort and welfare conditions that can contribute to more insights for precision environment management of animal housing.

Acknowledgments

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