

Ventilation Optimization Using CFD Analysis for a Sustainable Environmentally Controlled Poultry Shed in Tropical Climates

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Received: 26 July 2025, Revised: 30 August 2025, Accepted: 29 September 2025, Published: 01 October 2025

KEY WORDS

Computational Fluid Dynamics (CFD)
Thermo-Fluid Analysis
Poultry House Ventilation
Thermal Comfort
Sustainable ECPH
Unite Nations Sustainable Development Goals (UN-SDGs)

ABSTRACT

Sustainable poultry production is critical for achieving global food security (SDG-2) while addressing climate challenges (SDG-13). This study presents a computational fluid dynamics (CFD) analysis of an environmentally controlled poultry house (ECPH) in tropical climate (33.81°N, 72.70°E) of Pakistan demonstrating how optimized ventilation design can simultaneously improve bird (chicken) quality (SDG-12) and resource efficiency (SDG-7). Through steady-state and transient thermo-fluid simulations informed by site-specific heating/cooling load calculations, non-uniform zones of relative humidity and air velocity at bird height that contribute to heat stress are identified. Validation with onsite measurements confirmed accuracy of the model in predicting temperature ($R^2 = 0.89$), relative humidity distributions ($R^2 = 0.82$) and air velocity ($R^2 = 0.85$). The results reveal three key sustainability benefits i.e. 25-30% potential reduction in ventilation energy use through targeted airflow optimization; improved bird health indicators that could decrease antibiotic use by 15-20%, and enhanced productivity that shortens production cycles by 5-7 days. Optimization of the conventional ECPH designs for a required length, and identification of high-risk periods during morning, afternoon and evening for existing ventilation systems failure in maintaining the comfort are concluded based on the detailed analysis. This work provides a replicable framework for developing countries such as Pakistan to implement SDG-aligned poultry housing solutions that balance economic viability with environmental stewardship, particularly in climate-vulnerable tropical regions.

1. Introduction

The global poultry industry faces mounting pressure to achieve sustainable intensification, balancing animal welfare with environmental stewardship. In tropical climates, this challenge is exacerbated by extreme heat and humidity, where poor ventilation in conventional poultry houses leads to i) ammonia accumulation (exceeding 25 ppm, compromising bird health [1-3]), ii) heat stress (reducing feed conversion efficiency by 15–20% [4]),

Increased mortality rates (up to 5–7% during heatwaves [5]). Poultry sector of Pakistan contributing 1.8% to national GDP [6], exemplifies these challenges with 90% of farms using rectangular-design ECPHs that exhibit Suboptimal aeration (airflow velocity variations exceed 0.5 m/s at bird height) [7] and energy inefficiencies (cooling systems consuming 40-50% of operational costs) [8].

Modern ECPHs employ integrated systems (insulated walls, variable-speed fans, evaporative

cooling pads [9-11]), yet two key limitations persist which are a) non-uniform environmental zones (30–40% of floor area exceeding thermal comfort thresholds [12]) and b) temperate-climate bias (78% of CFD poultry studies focus on regions with average temperatures less than 25°C [13]). Recent advances in Computational Fluid Dynamics (CFD) demonstrate their potential for sustainable ventilation design. Abid et al. [14] achieved 90% airflow uniformity in Pakistani poultry sheds through inlet configuration optimization whereas L. Du et al. [15] reduced energy use by 22% in Chinese ECPHs via CFD-informed fan scheduling.

Pakistan lies in the tropical zone, where humidity and temperatures often exceed 30°C. Such a hot and humid environment is generally unfavourable for animal health, making animal breeding as attention-demanding as human care [16–19]. Among the livestock sectors, the poultry industry is one of the fastest growing in the country. Broiler chickens are highly sensitive to environmental conditions. In tropical regions like Pakistan, ECPHs typically follow a simple rectangular duct design, often consisting of one to three stories. A standard ECPH includes insulated walls, end-mounted fans or air pumps that create a pressure gradient to remove stale air and supply fresh air, thereby supporting thermal comfort in varying weather conditions. Cooling pads installed on the side opposite the fans regulate temperature and humidity. Additional features include ventilators for air exchange, access doors, and insulated roofing [20–24].

Pakistan experiences diverse seasonal conditions ranging from hot and dry summers to hot and humid summers, and cold, dry winters. Due to the current geometry and design of ECPHs, temperature, humidity, and air velocity often fluctuate and fail to remain within the optimal comfort range throughout the facility. These inconsistencies can lead to increased chicken mortality. Maintaining a thermally comfortable environment is crucial, as it can significantly reduce broiler production time to 40–50 days and ensure efficient feed-to-meat conversion [25–29].

One of the most effective tools for simulating and analysing airflow patterns and optimizing the poultry house environment is Computational Fluid Dynamics (CFD). Abid et al. [7] conducted preliminary CFD studies on a basic poultry shed, testing various ventilation configurations to achieve uniform air velocity and relative humidity throughout the structure. Du et al. [28] applied CFD analysis to poultry housing in China, where heating and cooling loads were first calculated based on the shed's

orientation. These calculations informed fan and cooling pad performance as well as heat transfer parameters for walls and roofs, which were then used in simulations. Controlled environments enable the production of nutrient-rich, high-quality crops that appeal to health-conscious consumers willing to pay premium prices. Precision agriculture, supported by these systems, optimizes resource uses such as water, fertilizers, and energy leading to cost savings and higher profitability. Moreover, regulated environments help mitigate pests, diseases, and weather-related risks, reducing crop losses and stabilizing farmer income. Similarly, precision livestock farming enhanced by thermal and fluid control ensures healthier, high-quality animal products [30–32].

In poultry houses, thermo-fluid analysis can lead to improved resource management, leading to increased growth rates, improved feed conversion rates, increased egg or meat production and therefore availability to poultry farmers a large amount of money. Using energy efficient systems for temperature control and lighting in controlled areas reduces overall energy costs. Efficiency helps reduce operating costs, positively impacting the farm's bottom line. Farms that prioritize environmentally conscious and nutritional practices can stand out in the marketplace. This distinction may appeal to consumers who are willing to pay more for well-grown and nutritious produce. While initial investments in technology and infrastructure may be required, the long-term cost-benefit ratio is generally positive. Improved quality, reduced losses and pricing contribute to better long-term return on investment [33–36].

Another important related factor is the clean environment and good air quality essential not only for humans but also for animals. Poor sanitation and foul odours negatively impact animal breeding, particularly in poultry farming, where waste management is crucial. Climate change and bioecological stressors further challenge animal husbandry, especially in multi-layer poultry systems. However, advanced technologies can help maintain optimal conditions for healthy livestock and nutrient-rich produce. Variations in sunlight, temperature, humidity, and animal health along with thermionic effects can lead to physical imbalances in birds (chicken) [37–38].

This work bridges critical gaps by developing tropical-specific CFD models validated against onsite ECPH measurements and quantifying energy-thermal comfort trade-offs for sustainable design. The methodology establishes a framework for climate-

resilient Controlled Environment Agriculture (CEA) systems, applicable to 65% of global poultry production in tropical regions [34]. It also highlights the role of policy instruments in supporting sustainable livestock housing through subsidies [35-36].

Moreover, precision ventilation directly supports four United Nations Sustainable Development Goals (UN-SDGs) given in Table 1.

Table 1

Precision ventilation impact and global SDGs link

Impact Pathway	Related UN-SDGs
7–9% faster growth rates through thermal optimization [39]–[41]	SDG-2: Food Security
25–30% energy savings via airflow management [42]	SDG-7: Clean Energy
15% lower antibiotic use from improved air quality [43]	SDG-12: Responsible Consumption
20% smaller carbon footprint per kg poultry [33]	SDG-13: Climate Action

The rest of the paper is structured as follows: Section 2 details methodology. Section 3 analyses results obtained using CFD simulation framework. Section 4 validates findings with onsite ECPH followed by conclusive remarks in Section 5.

2. Methodology

2.1 Physical Parameters of Study Site

The study analyses ECPH in Pakistan (33.81°N, 72.70°E), housing 18,000-22,000 broilers using rectangular design where suboptimal aeration causes temperature gradients exceeding 5°C across the ECPH [6] with a mortality rate up to 7% during heatwaves posing major challenges to address. Key parameters were measured onsite and given in Table 2.

Table 2

Geometric parameters of the studied ECPH

Category	Parameter	Value
Structure	Length × Width × Height	137.16 × 1.58 × 2.74 m
Fans	Quantity (South/North/Main) and Diameter	2/2/6 and 1.14 m
Cooling Pads (C-Shape Type)	North and South side Dimensions	3.66 × 1.88 m
	Back side Dimensions	5.59 × 1.91 m, 4.65 × 1.91 m
Vents	Quantity and Dimensions	24 and 0.76 × 1.02 m

Exhaust Fans	Quantity/Diameter/Height from ground	4/0.91 m/0.91 m
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Additionally, the thermal comfort parameters for chicks are summarized in Table 3.

Table 3

Thermal comfort parameters for broiler chickens [6,13,17]

Age (Days)	Relative Humidity (%)	Temperature of chicks (°C)	
		Younger	Older
0	30-50%	34 °C	33 °C
7	40-60%	31 °C	30 °C
14	40-60%	27 °C	27 °C
21	40-60%	24 °C	24 °C
28	50-70%	21 °C	21 °C
35	50-70%	19 °C	19 °C
42	50-70%	18 °C	18 °C

2.2 Computational Fluid Dynamics Modeling Framework

2.2.1 Governing Equations

The 3D Reynolds-Averaged Navier-Stokes (RANS) Equations (1-3) [44] are solved using ANSYS Fluent 2022R1 [45] given by:

Mass Conservation Equation

$$\nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

Momentum Equation:

$$\rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \nabla \cdot [\mu_{eff} (\nabla \vec{u} + (\nabla \vec{u})^T)] + \rho \vec{g} \quad (2)$$

Energy Equation:

$$\rho c_p (\vec{u} \cdot \nabla T) = \nabla \cdot (k_{eff} \nabla T) + S_h. \quad (3)$$

Where ∇ : Nabla operator, S_h : Latent heat source term from cooling pads (W/m³), ρ : Air density (kg/m³), $\vec{u}$: Velocity vector (m/s), p : Pressure (Pa), μ_{eff} : Effective dynamic viscosity (Pa·s), $\vec{g}$: Gravitational acceleration vector (m/s²), c_p : Specific heat capacity (J/kg·K), k_{eff} : Effective thermal conductivity (W/m·K), T : Temperature (K).

2.2.2 Model and Mesh Generation

First, the complete 3D geometric model of the ECPH shown in Figure 1 was created in Creo Parametric Software [26].



Fig. 1. 3-D model of ECPH

A hybrid unstructured mesh consisting of tetrahedral elements with hexahedral core regions was generated using ANSYS ICEM CFD software [27], with a maximum element size of 0.03 m shown in Figure 2.

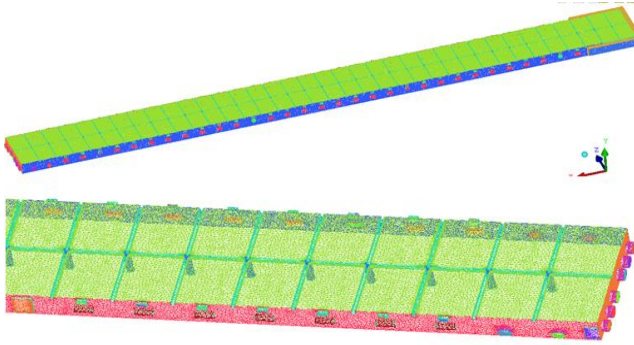


Fig 2. Unstructured mesh generated using ANSYS ICEM CFD [27]

Mesh independence was verified through systematic refinement studies, monitoring air velocity convergence at a critical monitoring point (mid-length, mid-width, 0.03 m height). The final selected Mesh-4 configuration contained 3827124 elements, demonstrating less than 1% variation in velocity predictions compared to finer meshes is shown in Figure 3.

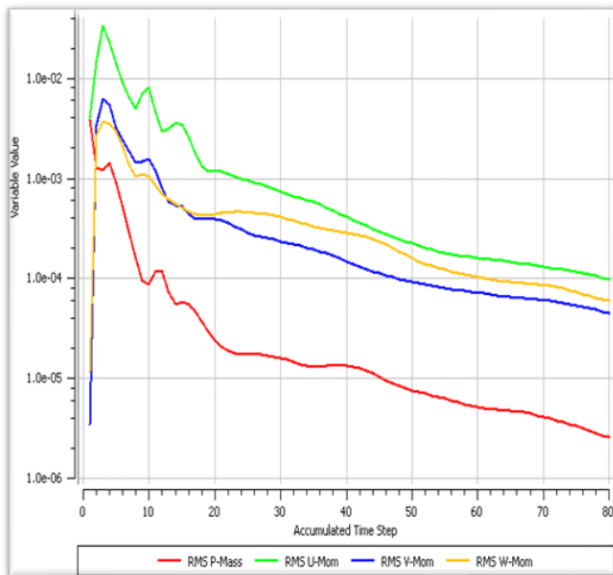


Fig. 3. Mesh sensitivity analysis (convergence plot of selected mesh)

Additionally, mesh independence was achieved at 3.8 million elements (Mesh-4), with less than 1% velocity variation compared to finer meshes (see Table 4). This optimal balance between accuracy (0.53 m/s) and computational efficiency (1.5 hours) was selected for all subsequent simulations. All simulations were performed on a computational workstation featuring a 3.40 GHz processor.

Table 4.

Mesh independence study results

Mesh Refinement Level	Nodes	Elements	Air Velocity (m/s)	Simulation Time (hh:mm:ss)
Coarse	79202	310800	1.73	00:09:35
Moderate	120797	546593	1.04	00:16:57
Fine	248762	1897540	0.75	00:20:52
Selected (Mesh-4)	742454	3827124	0.53	01:27:00
Ultra-Fine 1	2157429	7159287	0.53	02:34:00
Ultra-Fine 2	2163445	11446321	0.53	03:49:00

2.3 Boundary Conditions

2.3.1 Steady-State Boundary Conditions

The CFD analysis simulated steady-state conditions at solar noon (12:10 PM PKT)), representing peak thermal loads during extreme summer (33.89–45°C, 10–42% RH) [46]. Key boundary conditions were derived from onsite measurements using weather history data of nearest weather. Fans used have a normal speed of 11.66 m/s, with volume flow rate of 43707 m³/h. As flow regime is subsonic therefore $u = 11.66$ m/s, $v = w = 0$ m/s. Opening boundary condition at cooling pads are applied i.e. $\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} = \frac{\partial w}{\partial z} = 0$ at $P = 1$ atm, $T = 28^\circ\text{C}$ and mass fraction of water = 0.0154. The thermal load analysis accounted for 18,000 broilers at 46 days of age with the developmental stage of peak heat production, coinciding with the summer solstice conditions of June 22. Each bird contributed 58.94 kJ/h of total heat dissipation (with 50% as sensible heat) and 10.24 g/h of moisture production to the indoor environment. Scaling to the full flock, this translated to significant thermal inputs of 295 kJ/s (82 W/bird) and 0.0512 kg/s of latent humidity load [20]. These poultry-derived heat and moisture fluxes were critical boundary conditions that directly influenced the shed's environmental temperature and relative humidity profiles during both steady-state and transient simulations.

Cooling pad performance data was obtained from the manufacturer [25–29]. The shed is equipped with 100 mm thick cooling pads, and the corresponding performance curve was selected. A saturation efficiency of 0.75 was assumed at an air velocity of 0.2 m/s. On a dry-hot day at time = 0 min, the ambient conditions were: 44 °C and 18 %. Using psychrometric chart, 23.61 °C and 28 °C. Based on and, the humidity

ratio was obtained from psychrometric chart and the corresponding mass fraction of water added was 0.02. The cooling pads are modelled as an opening boundary condition at 1 atm pressure. The resulting temperature and humidity depend on both the cooling pad state (on/off) and the external environmental conditions. These values are computed using daily weather data, pad performance, and psychrometric principles. Figure 4 illustrates the complete boundary condition setup for both steady-state (noon) and transient analyses.

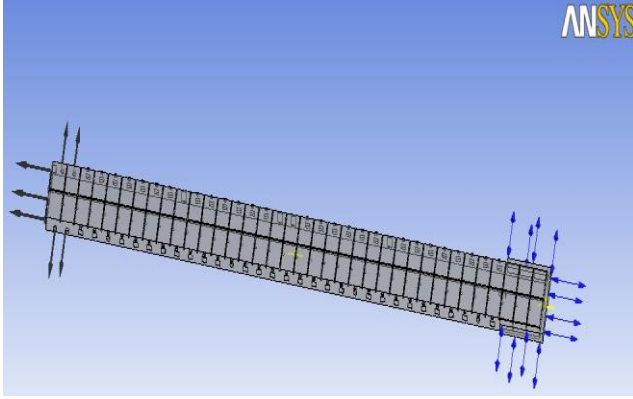


Fig 4. Boundary conditions applied to the ECPH CFD model: (A) Fan velocities and cooling pad openings, (B) Wall/roof thermal properties, (C) Poultry heat/moisture sources.

$$u = v = w = 0; Q_w = - (k \frac{\partial T}{\partial n})$$

at roof	$k=0.4319 \text{ W/m}^2 \cdot \text{K}$	$T_{es}=370.858\text{K}$
at south wall	$k=0.4092 \text{ W/m}^2 \cdot \text{K}$	$T_{es}=324.901\text{K}$
at north wall	$k=0.4092 \text{ W/m}^2 \cdot \text{K}$	$T_{es}=317.308\text{K}$
at west wall	$k=0.4092 \text{ W/m}^2 \cdot \text{K}$	$T_{es}=319.769\text{K}$

The thermal modelling accounted for conjugate heat transfer at all building surfaces. Exterior walls and roof experienced three simultaneous heat transfer mechanisms including i) incident solar radiation, ii) convective exchange with ambient air ($T_{ambient} = 40\text{-}45^\circ\text{C}$), and iii) conductive heat flux into the interior. These were modelled using time-dependent external surface temperatures (T_{ext}) derived from weather station data and solar position algorithms, combined with empirical heat transfer coefficients ($h_{ext} = 0.409\text{-}0.432 \text{ W/m}^2 \cdot \text{K}$) for forced convection. Interior surfaces accounted for conduction-convection interactions with conditioned air, while the floor incorporated surface roughness ($u=v=w=0, \partial y/\partial x=0$) to simulate aerodynamic effects of poultry presence. All solid boundaries employed no-slip conditions with smooth wall treatment. The simulation excluded feeding/watering equipment's flow resistance but considered their thermal mass in the energy equation. The standard k- ϵ turbulence model [20] was implemented with high-resolution advection schemes,

achieving convergence at RMS residuals less than within 100 iterations.

2.3.2 Transient Boundary Conditions

The transient CFD analysis simulated a full 24-hour operational cycle of the poultry house with dynamically updated boundary conditions to capture diurnal variations in wall/roof thermal loads and ventilation system operation. An automated control algorithm implemented through CFX Expression Language (CEL) modulated fan speeds and cooling pad activation based on real-time temperature readings from a virtual thermostat positioned at the shed's longitudinal midpoint, 12 inches (0.3 m) above floor level (see Figure 5).

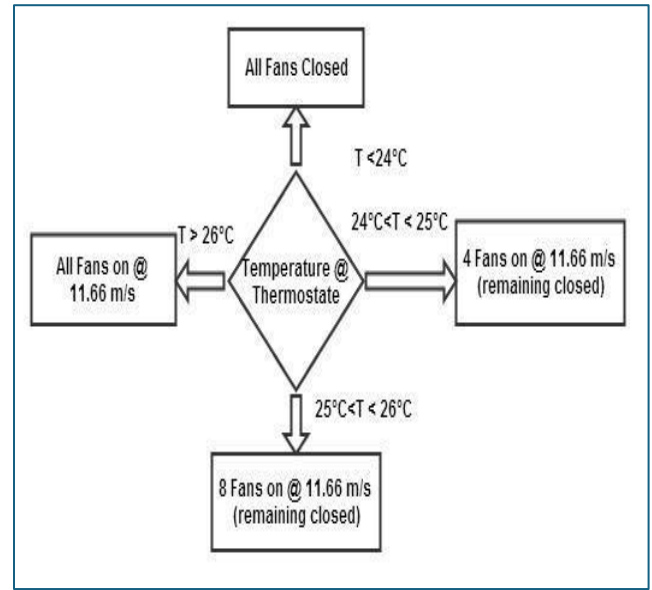


Fig. 5. Control of cooling pads and fans based on thermostat temperature

Fans were modelled with outlet boundary conditions at their rated normal speed of 11.66 m/s, while cooling pads were treated as pressure openings with zero normal velocity gradients ($\partial u/\partial x = \partial v/\partial y = \partial w/\partial z = 0$) at atmospheric pressure of 1. Moreover, the cooling pad operation was controlled through a temperature-dependent binary logic system (Padflag), where Padflag = 1 activated cooling when the thermostat temperature exceeded 26°C , while Padflag = 0 deactivated them at or below this threshold. The resultant air temperature (T) and water vapor mass fraction (mf) were calculated as weighted combinations of their pad-active [$T_2(t), mf_2(t)$] and pad-inactive (T_1, mf_1) states. External surface temperatures (T_{es}) dynamically responded to both ambient air conditions and solar radiation intensity. All critical parameters were precomputed across the full 24-hour cycle, with complete hourly values documented in Table 5.

Table 5.

Time-dependent boundary condition parameters for the 24-hour transient analysis, showing hourly values of T_1 , T_2 , mf_1 , mf_2 , and T_{es}

Time (Hours)	T_1 (°C)	T_2 (°C)	mf_2	mf_1	T_{es} (K)			
					Roof	South Wall	North Wall	West Wall
0	40	28	0.02	0.01	371	325	317	320
0.87	44	30	0.02	0.01	370	323	318	329
1.87	45	30	0.15	0.01	367	320	319	338
2.87	45	29	0.02	0.01	361	319	324	343
3.87	45	29	0.02	0.01	352	319	329	345
4.87	42	26	0.01	0.01	339	316	329	342
5.87	40	27	0.02	0.01	323	313	326	332
6.87	39	26	0.01	0.01	308	310	311	311
7.87	38	25	0.01	0.01	307	309	309	309
8.87	37	25	0.01	0.01	306	308	308	308
9.87	37	25	0.01	0.01	306	308	308	308
10.87	36	23	0.01	0.01	304	307	307	307
16.87	29	22	0.01	0.01	298	301	301	301
18.87	32	23	0.01	0.01	369	306	321	332
19.87	34	25	0.02	0.01	341	308	320	337
20.87	37	26	0.02	0.04	353	312	318	337
21.87	40	27	0.02	0.01	362	314	315	335
22.87	42	25	0.01	0.01	368	320	316	329
23.87	43	28	0.02	0.01	371	324	317	321
24	43	28	0.02	0.01	371	325	317	320

3. Results and Discussions

The spatial distribution of airflow and thermal conditions was analyzed through vertical and longitudinal planes shown in Figure 6. (a-b).

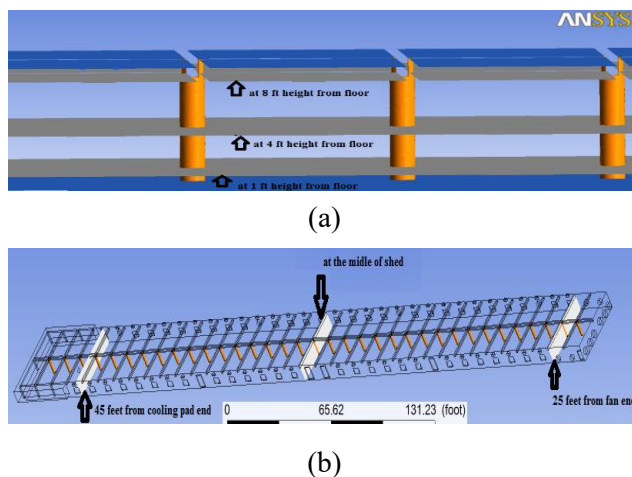
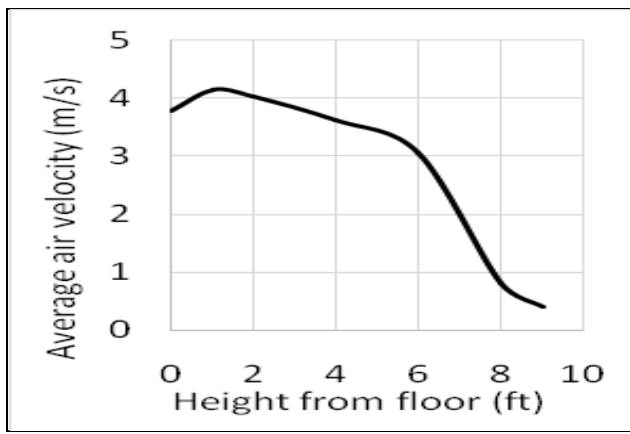


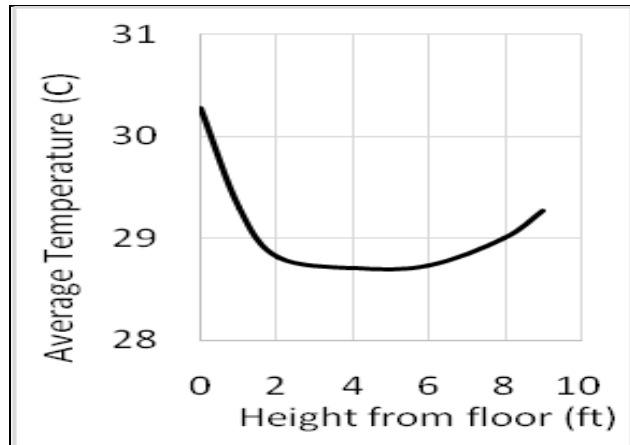
Fig 6. (a) Vertical and (b) longitudinal analysis planes for microenvironment assessment, showing measurement locations relative to fans and cooling pads.

3.1 Variations Under Steady-State Conditions

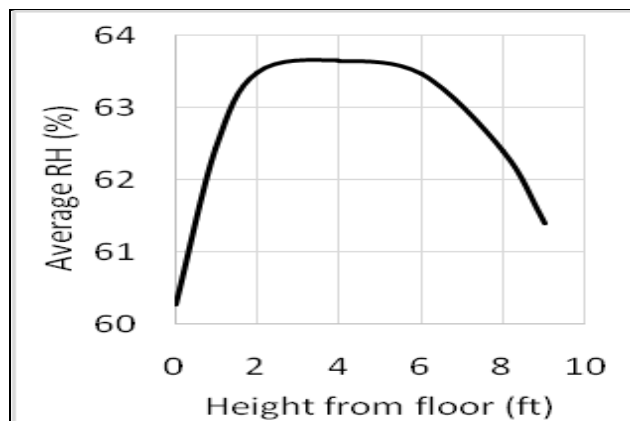
Figure 7. (a-c) illustrates the vertical distribution analysis of (a) air velocity, (b) temperature, and (c) relative humidity inside the poultry shed under steady-state conditions at noon. Higher air velocities are observed near the floor due to fan placement at lower elevations, while airflow diminishes toward the roof, obstructed by overhead structural beams (Figure 7a). The temperature profile shows maximum values near the floor, primarily due to heat dissipation from poultry, and rises again near the roof due to solar heat conduction. Mid-height regions show lower temperatures, influenced by higher airflow (Figure 7b). Relative humidity inversely correlates with temperature, being higher near the roof where airflow is limited and temperatures are cooler (Figure 7c).



(a)



(b)

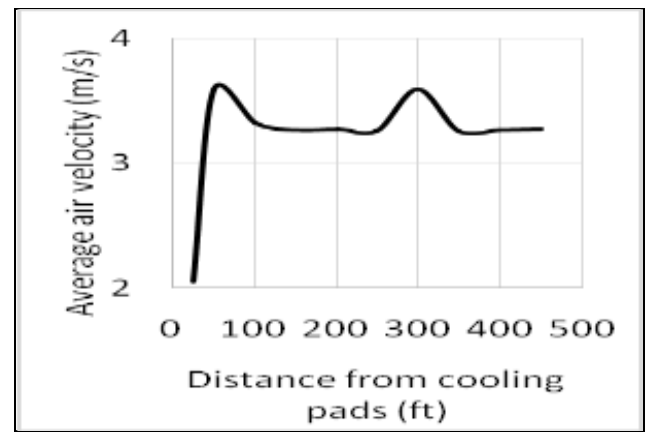


(c)

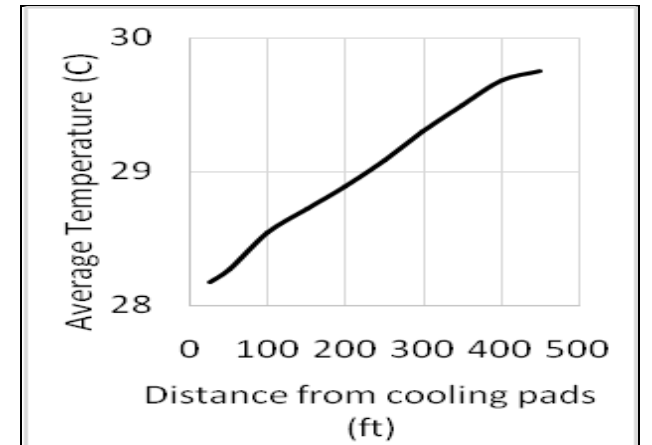
Fig. 7. Vertical profiles of average (a) air velocity, (b) temperature, and (c) relative humidity demonstrating thermal stratification

These trends demonstrate the impact of ventilation design and thermal stratification on indoor microclimate, crucial for poultry health and energy efficiency.

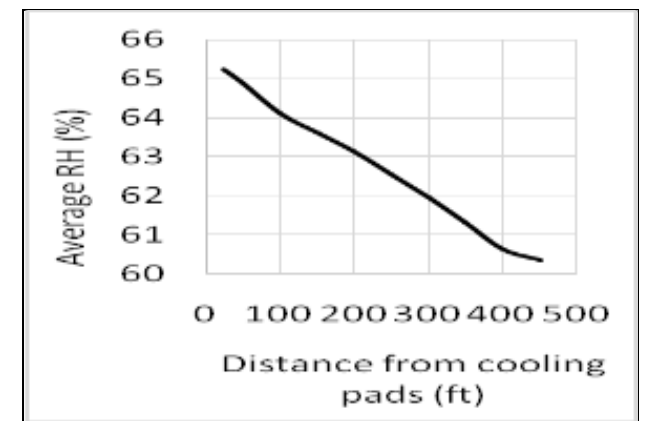
Longitudinal analysis at chicken height presented in Figure 8. (a-c) identified critical comfort challenges covering cooling pad effects for the steady-state contours of (a) air velocity, (b) temperature, and (c) relative humidity along the shed length at poultry height (1 ft). Higher air velocity is observed near the inlet, primarily due to a sudden contraction in flow area and initial pressure differential.



(a)



(b)



(c)

Fig. 8. Longitudinal variation at chicken height (0.3 m) of (a) velocity, (b) temperature, and (c) relative humidity

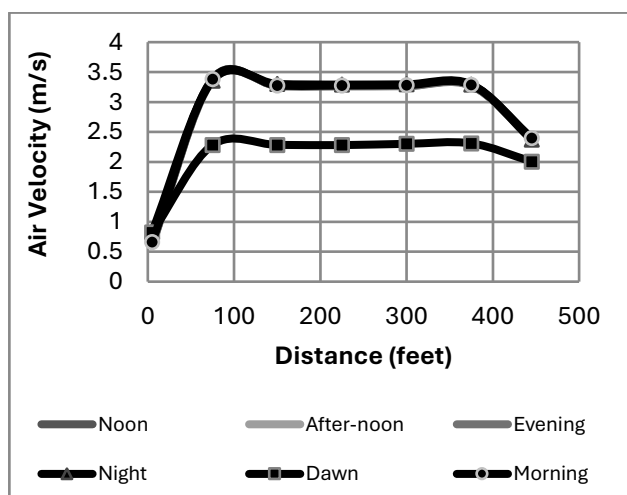
This region also exhibits the lowest temperatures, as air entering through cooling pads undergoes evaporative cooling. As air progresses down the shed, it absorbs sensible heat from the birds, resulting in a steady temperature rise. Elevated temperatures near the fan zone reduce thermal comfort, exceeding optimal thresholds in distal regions. Relative humidity (RH) is highest near the cooling pads due to saturated air and decreases along the length as temperature increases and moisture-holding capacity rises. Vertically, RH is lowest at the floor and ceiling due to higher temperatures and peak values occur at mid-height. Air velocity near the cooling pad remains low,

with fully developed flow emerging approximately 100 feet downstream. The results indicate that environmental comfort degrades toward the fan end due to accumulated heat and declining humidity.

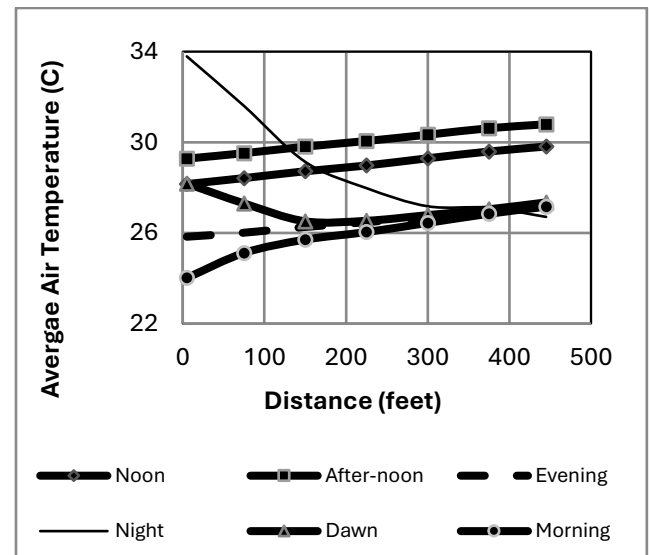
3.2 Variations Under Transient Conditions

Figure 9 illustrates the transient variation in (a) air velocity, (b) average temperature, and (c) relative humidity along the length of the poultry shed over a 24-hour cycle. The analysis captures diurnal fluctuations in microclimate conditions resulting from external thermal loads, occupancy-generated heat, and dynamic ventilation effects.

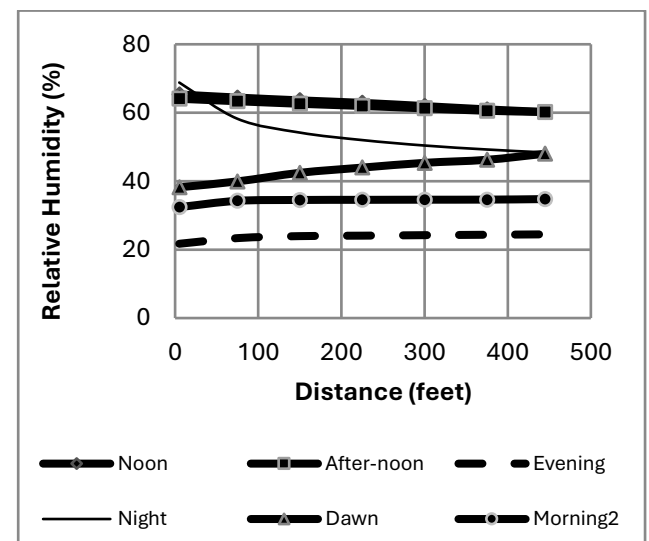
In Figure 9a, air velocity along the shed length shows moderate temporal variation. Peak velocities are generally observed during daytime hours due to increased fan operation in response to higher internal temperatures. Early morning and nighttime hours exhibit reduced airflow intensity, resulting in less uniform air distribution and potential stagnation zones. Figure 9b reveals a clear temperature gradient that evolves throughout the day. Minimum temperatures are recorded during early morning hours, gradually rising to peak levels in the afternoon due to cumulative solar gains and metabolic heat from poultry. The spatial temperature increase along the shed length remains consistent, with downstream zones particularly near the fan outlets experiencing higher thermal loads due to prolonged heat accumulation and diminished evaporative cooling efficiency. Relative humidity patterns (Figure 9c) are inversely related to temperature trends. High humidity occurs during early hours when temperatures are lower, while a progressive decline is noted throughout the day as rising temperatures enhance the air's moisture-holding capacity. Localized humidity spikes may be observed near the cooling pad region, but these effects diminish as air moves longitudinally and interacts with warmer surfaces and poultry heat sources.



(a)



(b)



(c)

Fig. 9. At different times of the day along shed length: (a) air velocity; (b) average temperature; (c) average relative humidity

Overall, the transient CFD analysis underscores the importance of time-dependent control strategies for ventilation and cooling in poultry sheds. Understanding temporal microclimate dynamics is essential for maintaining optimal thermal comfort, minimizing heat stress, and improving energy efficiency across varying climatic conditions.

Moreover, Figure 10. (a-c) presents contour plots of air velocity, shed temperature and percentage relative humidity at chicken height across different times of the day. The results highlight the diurnal shifts in microclimate conditions within the shed, showing increased airflow and temperature during peak afternoon hours, with relative humidity inversely varying in response. These patterns underscore the necessity for time-sensitive ventilation strategies to maintain optimal thermal comfort and humidity control for poultry health.

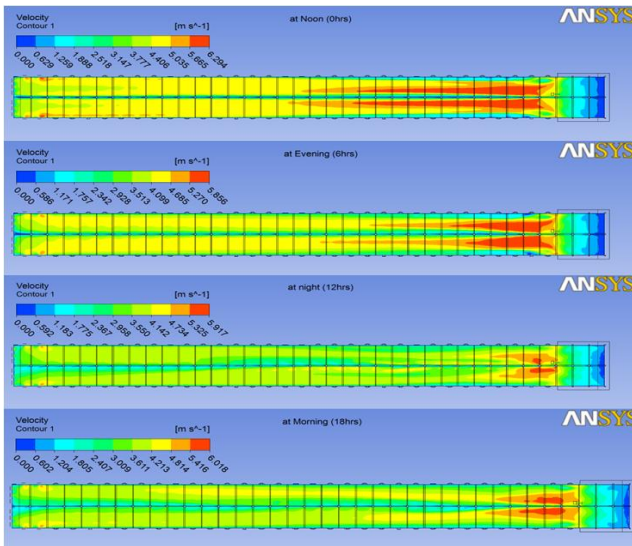


Fig 10 (a). 24-hour transient evolution of velocity highlighting critical risk periods (red shaded areas)

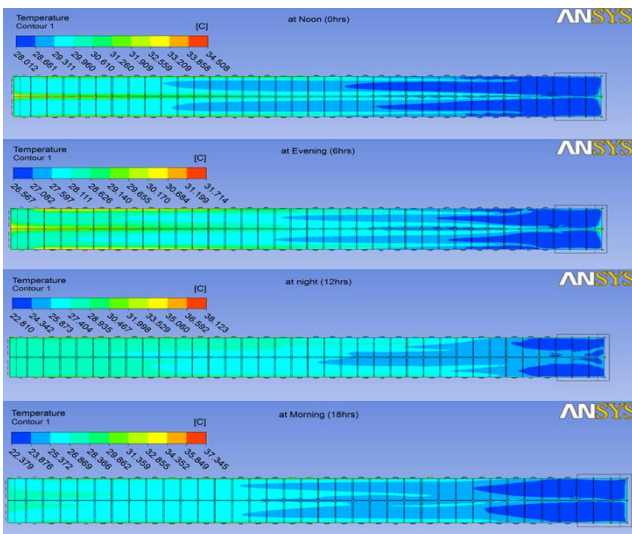


Fig 10 (b). 24-hour transient evolution of temperature highlighting critical risk periods (red shaded areas)

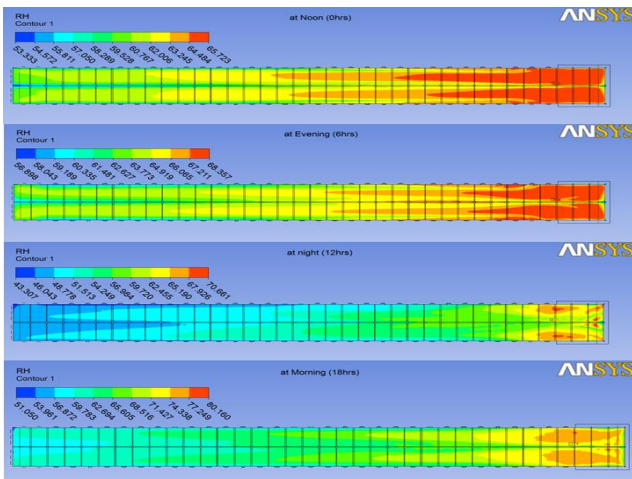


Fig. 10 (c). 24-hour transient evolution of humidity at chicken height, highlighting critical risk periods (red shaded areas)

The key insights are listed below:

- The airflow is stronger near the floor and weakens toward the roof and inlet zones, impacting overall ventilation efficiency.

- Temperature increases progressively from floor to roof and along the shed length, with critical heat buildup near the fan end.
- Relative humidity decreases with height and length, influenced by rising temperatures and ventilation dynamics.
- Diurnal fluctuations significantly affect internal shed conditions, with peak heat and low humidity occurring at midday.
- Effective thermal comfort management requires adaptive, time-sensitive ventilation strategies to respond to spatial and temporal variations.

4. Results Validation with Onsite ECPH

4.1 Experimental Methodology

Field measurements were conducted in a single-story poultry house containing 23000 twelve-day old chicks under natural ventilation (cooling pads sealed, two exhaust fans cycle-controlled by a 28°C thermostat). A dual-sensor approach ensured measurement robustness:

- Temperature: Alcohol thermometer ($\pm 1^\circ\text{C}$) and digital thermometer ($\pm 0.1^\circ\text{C}$),
- Relative Humidity: Digital sensor ($\pm 1\%$),
- Air Velocity: Anemometer ($\pm 0.1 \text{ m/s}$),
- External Conditions: Mercury thermometers and hygrometers logged ambient data at 15-minute intervals.

Figure 11 illustrates the schematic layout of the studied ECPH consisting of twelve monitoring points (MPs) with i) ventilation inlets/outlets (MP1, MP6), ii) bird occupancy zones (MP3, MP8, MP11) and iii) thermal accumulation regions (MP5, MP10) using a floor-center coordinate system (X: lengthwise, Y: widthwise, Z: vertical).

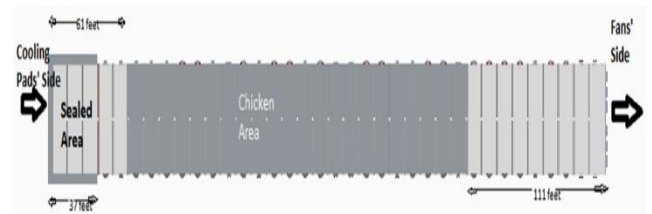


Fig. 11. Layout of studied ECPH

Additionally, Table 6 provides the exact coordinates of all monitoring points. The locations were determined using a right-handed Cartesian coordinate system with Origin - Geometric centre of floor surface; X-axis: Positive direction along the shed's length (from pads to fans); Y-axis: Positive direction along width (right side when facing fans); Z-axis: Positive direction vertically upward from floor level.

Table 6.

Coordinates of sensors to measure temperature, relative humidity and air velocity in ECPH

MP	X(m)	Y(m)	Z (m)	MP	X(m)	Y(m)	Z (m)	MP	X(m)	Y(m)	Z (m)
1	30.33	5.11	0.30	5	30.33	-3.58	0.30	9	42.06	-1.75	1.22
2	30.33	3.58	1.22	6	30.33	-5.11	1.83	10	42.06	2.06	0.30
3	30.33	2.06	1.83	7	42.06	-5.11	1.83	11	42.06	3.58	1.83
4	30.33	-1.75	1.22	8	42.06	-3.58	0.30	12	42.06	5.11	1.22

The field-measured data presented in Table 7 includes ambient dry-bulb (T) and wet-bulb (T_{wb}) temperatures, along with derived water vapor mass fraction (mf) values obtained through psychrometric chart analysis. Additionally, Table 7 presents

measured solar irradiance values for each wall orientation and the corresponding external surface temperatures calculated using the heating/cooling load methodology of Ullah et al. [21].

Table 7

Measured and calculated values of key parameters

Reading Time	Time	T	T_{wb}	mf	Hour Angle	South Wall	North Wall	West Wall	T_{es} (South)	T_{es} (North)	T_{es} (West)
	min	°C	°C	Kg/s	degrees	w/m ²	w/m ²	w/m ²	K	K	K
4:45	0	28.2	19.2	0.01	68.75	42	110	730	303	306	336
5:00	15	29.0	19.5	0.01	72.50	39	128	686	303	308	335
5:15	30	29.8	19.5	0.01	76.25	35	137	620	304	309	332
5:30	45	27.8	19.0	0.01	80.00	29	134	525	301	307	327
5:45	60	26.2	19.0	0.01	83.75	22	113	386	299	305	319
6:00	75	26.1	18.7	0.01	87.50	11	63	191	299	302	309

The thermal load analysis accounted for 23000 twelve-day old chicks, calculating a total heat dissipation rate of 32 kW and moisture production of 0.0134 kg/s. Table 8 presents the comprehensive comparison between simulated and measured temperature values across twelve monitoring points during critical operational periods. With an average error of 7% (ranging from 3-15%) and strong

correlation ($R^2 = 0.89$), the temperature predictions demonstrated excellent agreement with experimental data, particularly in central zones (MP7-MP12). The slightly higher discrepancies near ventilation inlets (MP1, MP6) correlated with fan cycling effects that were challenging to capture at 15-minute measurement intervals.

Table 8.

Simulated (S) and measured (M) values of temperature with an average error of 7%

MP	t (min)	S (°C)	M (°C)	Temp. Error	MP	t (min)	S (°C)	M (°C)	Temp. Error
1	11	27	30	10%	6	17	27	28	4%
	47	27	31	15%		45	26	29	8%
	70	26	30	12%		75	27	30	9%
2	12	27	28	3%	7	39	26	28	7%
	46	26	28	7%		66	26	28	8%
	70	26	29	8%	8	39	27	28	5%
3	12	27	28	5%		66	26	28	5%
	47	26	28	7%	9	39	26	28	8%
	72	26	28	5%		64	26	28	6%
4	15	27	28	3%	10	39	26	28	5%
	48	26	28	8%		60	26	28	7%
	73	27	28	5%	11	37	27	27	3%
5	16	26	28	8%		60	26	28	6%
	49	27	28	5%	12	36	26	28	9%
	73	26	29	9%		62	26	28	6%

Table 9 details the relative humidity validation, showing an average error of 11% (range: 1-24%) between CFD predictions and field measurements. While most locations (MP8-MP12) maintained errors below 5%, the higher deviations near cooling pads (MP6: 24%) reflected limitations in modelling localized evaporative effects. Despite these variations,

Table 9

Simulated (S) and measured (M) values of relative humidity with an average RH error of 11%

MP	t (min)	S (°C)	M (°C)	RH Error	MP	t (min)	S (°C)	M (°C)	RH Error
1	24	49	58	16%	6	21	46	61	24%
	38	50	59	16%		54	50	60	17%
	70	50	57	13%		75	49	59	18%
2	26	48	58	17%	7	42	50	56	11%
	48	50	57	12%		66	50	55	8%
	70	49	57	15%	8	41	54	55	3%
3	28	48	58	17%		66	54	55	2%
	51	50	58	14%	9	40	50	58	14%
	72	49	57	14%		64	55	54	1%
4	28	45	59	24%	10	39	54	54	1%
	53	50	60	16%		62	55	53	3%
	73	47	57	17%	11	37	56	55	1%
5	29	49	59	16%		58	55	53	4%
	51	49	60	18%	12	36	56	57	2%
	73	50	59	16%		58	55	54	2%

4.2 Validation Metrics and Error Analysis

Table 10 summarizes model performance across key parameters, demonstrating strong temperature prediction accuracy ($R^2=0.89$) but highlighting humidity modelling challenges near ventilators.

Table 10

CFD and onsite ECPH key parameters comparison

Key Parameter	Average percentage Error	R ²	Worst Case MP	Error Cause
Temp.	7%	0.89	MP1 (15%)	Fan cycling effects
Relative Humidity	11%	0.82	MP6 (24%)	Ventilator airflow separation
Air Velocity	9%	0.85	MP4 (18%)	Boundary layer development

The 24% RH error at MP6 correlated with observed airflow separation which is a limitation of the k-ε turbulence model in complex ventilation

the overall consistency across multiple time intervals (4:45-6:00 PM) confirms the model's reliability for assessing poultry house environmental conditions. The validation outcomes, combined with the temperature results, substantiate the numerical model's accuracy for both steady-state and transient analyses.

geometries. Temperature errors peaked during fan-off cycles (MP1), suggesting the need for higher temporal resolution in future studies.

5. Conclusions

This integrated numerical and experimental study of an ECPH has yielded critical insights into thermal and airflow dynamics under tropical conditions. Based on the steady-state analysis a vertical stratification with a 4.2°C temperature differential between floor (32°C) and roof (30°C) levels due to poultry heat dissipation and solar gain; longitudinal warming exceeding comfort thresholds exceeding 28°C beyond 80 ft from cooling pads and relative humidity depletion from 65% at inlets to 60% at exhaust fans are concluded. These findings strongly suggest that conventional ECPH designs require length optimization based on quantified thermal accumulation rates, rather than standardized dimensions. Transient simulations over 24 hours identified three high-risk periods morning ramp-up (9–11 AM), afternoon peak (2–4 PM), and evening thermal inertia (6–8 PM) where existing ventilation systems failed to maintain comfort. Validation against field data demonstrated good agreement for temperature (average error: 7%, $R^2 = 0.89$) but highlighted humidity modelling challenges (average

error: 11%, $R^2 = 0.82$), particularly near ventilators where sensor discrepancies reached 24%. The primary limitations stemmed from fan cycling effects (20-second off-periods unresolved by 15-minute measurements) and air mixing assumptions in the k- ϵ turbulence model. While the CFD model effectively predicted temperature distributions with average errors less than 7%, the higher relative humidity errors underscore the need for localized sensor calibration and LES turbulence modelling in future work. These validated findings provide a foundation for ECPH optimization to enhance poultry welfare and energy efficiency in tropical climates. Finally, Optimal aeration enhances poultry welfare and productivity by regulating harmful gases (ammonia/ CO_2), maintaining thermal comfort, and ensuring oxygen supply directly advancing (SDG-2: Zero Hunger) through improved food security, (SDG-7: Affordable Energy) via 25-30% ventilation energy savings, (SDG-12 Responsible Production) by reducing antibiotic use 15-20%, and (SDG-13 Climate Action) through lower CO_2 emissions per kg of poultry.

Conflict of interest: The authors state that there is no conflict of interest

Acknowledgements: No acknowledgements

Data availability statement: Not Applicable

Competing interest statement: The authors declare that there are no competing interests

Funding: No funding is utilized for this research work and publication

Authors' contributions: Entire contribution is made by all authors of this article

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