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Improving poultry system in close house cage through advanced HVAC design: A review of evaporative cooling pads and energy efficiency in broiler cages

Zain Lillahulhaq, Wawan Aries Widodo*, Sutardi, Luthfi Hakim, Anton Nugroho

Department of Mechanical Engineering, Sepuluh Nopember Institute of Technology (ITS), Surabaya, **Indonesia**

✉ wawanaries@its.ac.id

This article contributes to:
7 AFFORDABLE AND CLEAN ENERGY
SUSTAINABLE DEVELOPMENT GOALS

Highlights:
- Closed-house cages with cooling systems improve animal welfare by controlling temperature and airflow.
- Heat stress in chickens reduces food intake, productivity, and overall well-being.
- Simulations help design energy-efficient HVAC systems that balance cost and comfort.

Abstract
Improving the quality and quantity of livestock production can be achieved by creating a comfortable and safe environment for animals. The use of closed-house pens is one of the methods employed to control temperature, humidity, airflow, and the cleanliness of the living space for animals. Close-house pens are equipped with Heating, Ventilation, and Air Conditioning (HVAC), including the combination of an Evaporative Cooling Pad (ECP) and an exhaust fan. The characteristics of the shape and material composition of the ECP components influence pressure drop and the flow pattern entering the room. This research focuses on reviewing papers related to the development of numerical simulation studies of close-house pens and ECP. The design of numerical simulations and the selection of boundary conditions enhance the precision and error level of predicting fluid flow distribution in closed-house cages. In addition to numerical simulations, the application of energy management calculations provides recommendations regarding the combination of HVAC design and environmental control parameters that need to be considered.

Keywords: Close house cage; Evaporate Cooling pad; Numerical Simulation; Heat stress

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1. Introduction

Indonesia actively participates in achieving the Sustainable Development Goals (SDGs) as agreed upon by nations worldwide. The SDGs aim to foster human prosperity while preserving environmental sustainability. Developing the livestock sector is one of the steps toward achieving the SDGs. Livestock development through intensification programs can help reduce hunger and poverty. Chickens are a widely consumed livestock species, serving as an economical and accessible source of animal protein for human nutrition. Poultry farming has been intensively developed using both traditional and modern methods. Poultry farming is divided into broiler chicken farming and laying egg farming. Broiler chickens are raised for their meat while laying hens produce eggs for consumption. To obtain quality chickens, farmers must pay attention to the amount of nutrition, cleanliness, and comfort of the animals in the coop. Some standards used to create comfort for chickens include airflow, Temperature [1], Relative humidity [2], lighting intensity [3], and hazardous gas accumulation [2]. The ideal environmental standards for broiler close-house cages are shown in **Figure 1**. Pollution generated in the coop must be promptly removed to avoid disrupting the development of chickens. Nutritional intake is adjusted according to the chicken's development. Feeding high-protein diets causes chickens to produce higher body heat [4]. However, crude protein feed can reduce the percentage of ammonia the animals produce [5].

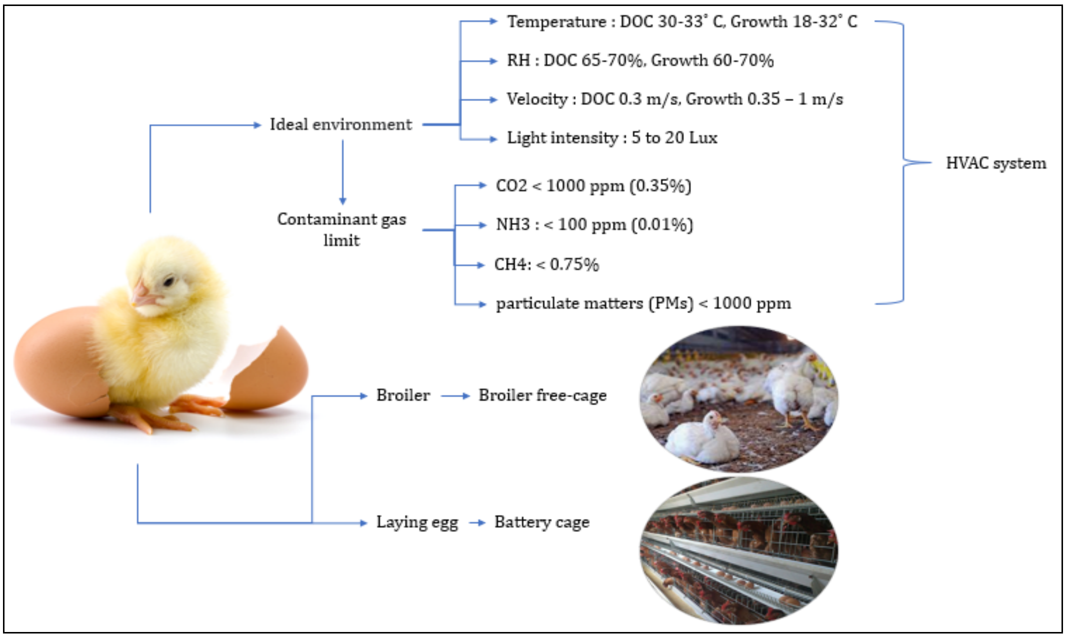

Figure 1. Ideal environmental standards for broiler chickens

Livestock cages are classified into open-house, semi-open-house, and closed-house models. Traditional farmers widely use the open house model with no enclosing walls, so the outside weather influences air circulation. A semi-open cage has a specific height partition wall and accessible windows. This design can reduce the effect of external wind speed on the chickens. However, semi-open cages are not equipped with an insulation system, so the opening and closing of windows must be regulated to prevent an increase in room humidity and temperature. The development of closed-house cages is widely conducted to create an ideal environment for the growth of livestock. Closed-house cage systems have ventilation systems such as misting, heaters, exhaust fans, and ECP. The installation of Heating, Ventilation, and Air Conditioning (HVAC) systems should consider Climate and weather conditions, Electricity consumption, room density, geometry, and room design. HVAC design errors create a non-ideal environment with a low fresh air supply and a high accumulation of contaminant gases. An unsuitable environment leads to increased temperature and heat stress.

Higher environmental temperatures lead to heat release from the chicken to the surroundings, indicating the onset of heat stress. Chickens do not have sweat glands; to regulate body temperature and match the environmental temperature, chickens pant by opening their beaks, increasing respiration rate. An increase in respiration rate leads to increased evaporation and decreased body temperature. Elevated respiration due to heat stress disrupts the metabolism of chickens. Heat stress activates the pituitary glands, characterized by increased blood flow, and causes redness in various parts of the chicken's body. Chickens experiencing heat stress undergo behavioural changes, such as increased water consumption. The increased water intake results in reduced food intake in chickens, leading to decreased body

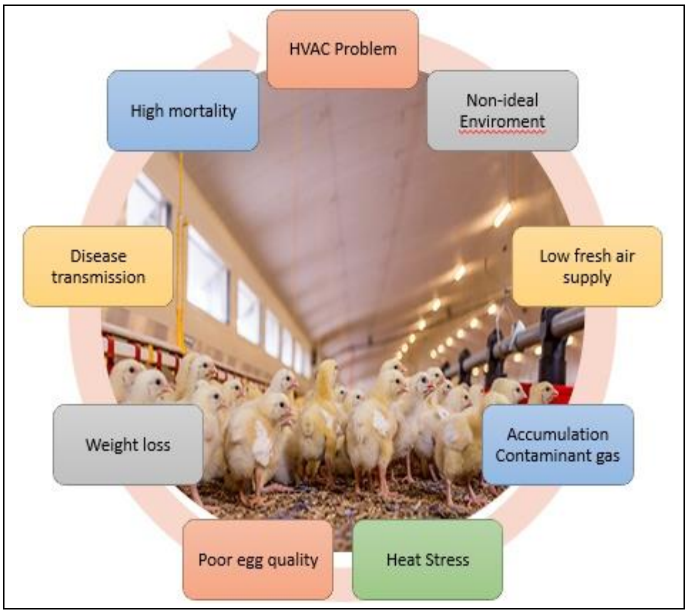

Figure 2. Broiler closed-house cage problems due to inappropriate HVAC system design

weight [6]. Changes in chicken metabolism due to heat stress can result in higher mortality, lower egg production, thinning of eggshells, and reduced egg size [1]. The negative effect of inappropriate HVAC design in close-house cages is shown in **Figure 2**.

There are several expenses to operate an HVAC system in closed-house cages, including heaters, room coolers, exhaust fans, and pumps. Broiler houses' ventilation and heating systems require 75.5% of the total energy consumption. Meanwhile, ventilation and heating systems' electricity requirement for laying hen houses is 58.9%, swine farms 50.2%, and cow farms 28.3% of the total energy needed [7], [8]. In a broiler house, chickens can be kept free-cage or placed in battery cages with multiple levels. The temperature and humidity in the cage affect the chicken's habits and movement patterns. Free-cage chickens gather near the walls when the temperature rises, whereas, in colder conditions, they flock in the middle of the room. The uneven number of flocks causes unbalanced feed consumption distribution, leading to weight loss in chickens. To guarantee that the airflow in the room has uniform temperature and velocity, farmers install HVAC components such as exhaust fans [9], diffusers [10], evaporative cooling pads [11], shutter windows [12], and slot window openings (flaps) [13]. Installing an exhaust fan function to create negative pressure in the closed-house cage ventilation system. The cage has a lower pressure than atmospheric pressure due to exhaust fans. The installation of HVAC components results in a decrease in the speed of incoming air and creates a more uniform airflow pattern [13]. Weather conditions outside the cage also influence airflow patterns inside. The air conditioning system in a multiple-stage battery cage may be hindered due to a decrease in buoyancy force during cold air temperatures. The warm air accumulates around the cage in winter due to the convective process of the chicken's body heat. Contaminant gases (ammonia, carbon dioxide, volatile organic compounds, odor gases, etc.) have a greater mass in cold conditions. In the winter, the air's buoyancy force is less effective in pushing the contaminant gases upward in the cage. As a result, a blocking effect occurs, hindering air circulation. Contaminant gases accumulate around the animals, so the supply of fresh air around the chickens is decreased. The warm air inside the cage must continue to circulate to reduce the blocking effect. Increasing air circulation in the cage can be achieved by using heaters on the roof [14], earth-to-air heat exchangers (EAHE) installed underground [15], [16], and preheating incoming air using double ducting [17].

The energy source required for developing a farm is primarily allocated to improving the nutrition provided to animals. Based on energy audits conducted in the poultry sector, electricity consumption in lowland farms is higher than in highland regions [18]. Electricity consumption contributes the second-largest percentage at 29% [19]. The use of fuel is relatively lower at 11%. Electricity consumption is required to regulate feeding, lighting, ventilation, cooling, and heating systems in closed-house cages. The ventilation system requires the highest electricity consumption due to its high-duty hours around 88% of total electricity consumption [20]. The HVAC design affects the amount of energy consumed, so consideration is needed when choosing the components to be utilized [21]. Therefore, Energy and economic audits are conducted, including assessing the effectiveness of misting and HVAC systems in closed-house cages. A misting system and negative pressure ventilation in closed-house cages can create uniform air and flow at lower temperatures [22]. Sprinkle/misting cooling systems enhance cooling efficiency by up to 15.4% compared to evaporative cooling pad [23]. Cooling systems with intermittent partial surface sprinkle, mist, and fogging models can reduce body temperature by directly contacting the chicken's head, skin, and feathers. However, this cooling system has a negative effect as it makes litter, food, and equipment wet. This condition can lead to the development of bacteria and viruses in closed-house cages [24]. HVAC is forced ventilation, which requires proper design to increase efficiency and minimize electricity consumption. HVAC designs must be audited to achieve an effective HVAC system, minimize energy consumption, and reduce heat loss. The HVAC design process is conducted through numerical simulations to save time and costs in the analysis process. As far as we are aware, there has been no research dedicated to exploring the advancement of numerical studies on closed-house cage poultry, especially concerning evaporative cooling pads. The majority of existing literature reviews primarily address the metabolic systems and health of chickens. This research is conducted to understand the improvement of numerical simulations study related to HVAC systems in closed-house cages. This research aims to give valuable insights for future researchers in developing more precise numerical models with reduced error margins. Additionally, the study aims to explore the development of evaporative cooling pads in HVAC systems.

2. Methods

The review was a study on journals published from 2000 to 2023 to comprehend the progress in research about controlling air conditions in closed-house cages. In current developments, indoor air conditions are more effective when represented by simulation results equipped with contour and vector. The review process focuses on advancing numerical simulations, covering the development of models, methods, boundaries, mathematical equations, and the impact of additional HVAC components.

The criteria used in this review process are as follows:

a. The journals investigated the optimum environment for chickens in closed-house cages.
b. Simulation of closed-house cages with any livestock inside.
c. Simulation of broiler or laying egg chicken cages in closed-house cages.
d. Air conditioning system in closed-house cages.

The review process continues for journals associated with evolving research on ECP. The implementation design needs to consider energy consumption and its economic viability. To do that, this research also delves into energy audit software papers related to closed-house cages.

3. HVAC in Close House Cage

Climate change negatively affects animal health, welfare, energy consumption, and human labor [25]. Temperature and relative humidity (RH) management is a climate control action required to improve the quality and quantity of livestock production, especially in close-house cages. The fluid streamlines transform due to changes in the installed air conditioning system and external conditions, including weather, wind speed, and direction. Streamline transformation inside close-hose cages can be illustrated through numerical simulation results. The fluid flow in the cage is non-uniform due to the wall friction, fluid interactions with the Animal Occupied Zone (AOZ), and buoyancy forces. When the exhaust fan operates at high speed, damaging and dead zones are formed inside the cage [26]. The damaging zone is a heterogeneous high velocity near the exhaust fan. This area has significant health risks to animals. On the other hand, the dead zone is a low-velocity area trapped near the inlet by the high-speed backflow. This area has a high percentage of harmful gas accumulation.

Several numerical studies were carried out to represent the flow streamlines in a closed enclosure. A numerical Steady was performed to comprehend the effect of the operating condition (on/off) exhaust fans in the closed-house cage. An experiment obtained by measuring velocity within the room was conducted to validate and verify the CFD research model used. Simulation results show that when all exhaust fans are operated, high flow speeds are created, which widespread the damaging zones and dead zones. A simulation conducted by Ma et al. [27] on a two-tier connected cage was run by Airpak software to investigate changes in THVI (Temperature, Humidity, and Velocity Index) levels on each aisle of the cage. This study simulates some cases that combine the location, speed, and size of the exhaust fan to determine the effect of fresh air distribution in the close-house cage. The chicken flocks were defined as 85% porous media. The roof and wall were considered as heat sources. The window was defined as a pressure inlet, and the exhaust fans were set as the velocity outlet. The HVAC system delivered a non-uniform flow. The simulation shows that high-velocity fluid was found near the exhaust fan, window, and air leakage. Meanwhile, the upper floor of the cage has low wind speed, especially at the front wall. Moreover, this study recommended symmetrical installation of exhaust fans at the front and back of the cage in order to decrease speed and temperature to around 22.0% and 88.3% [27].

In the winter, the airflow inside the cage has non-uniform speed and temperature. During winter, air circulation is obstructed due to a weakening buoyancy inside the room. Warm air accumulates around the cage due to the heat generated by the chickens [28]. Contaminant gases have heavier mass friction in cold air, so they can't be lifted out through ventilation. This condition results in less fresh air supply, which leads to stress and health issues for chickens in battery cages, especially in the lower tier [27]. Numerical flow simulations predict THVI conditions that represent a safe and comfortable environment for broilers. Several factors must be considered in numerical simulations:

- Defining the domain and geometry model;
- Selecting boundary conditions; and
- Choosing turbulence models and solvers.

The adjustment of the domain and model geometry affects the type and number of meshes used. The meshing process determines the numerical calculation time and the computer memory capabilities required [29], [30]. Meanwhile, selecting an incompatible turbulence model can propagate errors throughout the solution, impacting the overall accuracy of CFD results, especially when coupled with inappropriate domain and boundary conditions. Moreover, these factors can influence the sensitivity of simulation result estimations [31]–[33]. The use of uncertainty coefficients may be considered to achieve more accurate results [34].

3.1. Defining Domain and Geometry Model

Internal flow in a closed-house cage can be simulated in 2D or 3D domains. A 2D domain model requires less number mesh; thus, it saves cost and computational time. 2D numerical studies illustrate airflow conditions along the centerline cage, representing average conditions inside the room. Generally, the Simulations were conducted as an empty cage model to understand velocity and temperature distribution without considering interactions between airflow and animals [35]. In a steady simulation study by Fabian et al. [35], the airflow distribution in a chicken cage with natural ventilation was investigated using a 2D CFD simulation model. The result also illustrates the condition outside the cage. The tear-drop shape denotes the animal (chicken). The simulations cannot illustrate the turbulence flow comprehensively, especially the Jet flow around the exhaust fan [35]. 3D simulations are conducted to get precise illustrations of air distribution, temperature, and velocity profiles inside a close-house cage. A 3D model can illustrate the impact of HVAC installation with or without depicting the Occupied Animal Zone (OAZ). This simulation was conducted in OpenFOAM to simulate the effect of Heat Exchanger (HX) installation as a substitute for propane lamps in the cage [36]. The results display secondary flow colliding with the wall. The heat generated by HX increases the airflow velocity near the inlet and decreases buoyancy inside the cage. The 3D layout can also highlight different airflow distributions caused by detailed building structure configurations. A study was carried out to illustrate NH3 distribution across empty open cages with and without pillars [37]. The 3D model can display a more uniform flow across the cages with pillars.

The complex geometry model allows the researcher to capture the fluid flow profile around animals. In a study by Wang et al. [38], 3D simulations were conducted to comprehend the fluid flow around cows in different positions: standing, without legs, or sitting. A wall jet zone flow is a wake region that forms around the animal, especially at the bottom of the legs. AOZs with different alignments and animal body postures result in different amounts of drag force. The configuration of the animal positions changes the pressure drop around the animals, which causes differences in velocity and temperature near the animals [39]. Geometric complexity, size and body weight of the animal model also influence the fluid flow profile, which results in differences in drag forces and fluid flow resistance [40]. Simulation study by Li et al. [41] was conducted to determine the convective heat release by chickens based on their size (mass) and the direction of the incoming wind. The chicken was represented as a complex model and a simple spherical model. The research showed that the spherical model could provide simulation results similar to the more complex chicken model. Simplifying the geometry model is recommended to accelerate the meshing and computation process. However, the heat transfer around the model is changed through the size of the geometry surface area. The bigger chicken generates higher heat release during convection. Fluid flow Inside the close-house cage can be simulated in several alternative simple solid geometries, such as using spherical models [42], cuboid [43], cylindrical [39], [44], [45] and rectangular blocks [46], [47]. Simple geometry results in similar flow patterns to complex models and can represent airflow slightly further away from the animals [47].

Simulations of free-cage close-house chicken farms were depicted per individual to obtain realistic results. Chickens are portrayed as a heat source wall with a 3D solid model featuring aligned necks and tails [48]. Simulations were conducted to investigate the effect of inlet water supply position in closed cages. The chickens are modeled individually as walls to obtain the distribution of harmful gases from the chicken's nostrils. These fluent simulations illustrate concentrations of harmful gases such as CO_2, NH3, and specific humidity (ω) [44]. The 3D ANSYS software was conducted in steady conditions to determine the cage construction type that most significantly reduces the spread of viruses among chickens [49]. Individual-based animal modeling was employed to obtain detailed particle distribution from a specific point. Some researchers also employed an individual chicken model with aligned rows [44], [49]. A single porous media can be used to represent a group of animals. Using porous media can reduce the number of meshes and the time required in the 3 Model computational process. A 3D simulation was conducted in a cattle cage to analyze changes in Air Change Hour (ACH) and animal density. Animal density refers to the density of livestock within cages. The number of Animal density is used to calculate the values of internal and viscous resistance. Livestock was defined as a box-shaped porous media generating heat flux. Animal density was varied: AOZ Empty = 0 cow (empty cages condition), AOZ Low = 12.0 m^2/cow, and AOZ High = 1.56 m^2/cow. The simulation results show that airflow around livestock has a lower velocity than inlet air. A cage with a high AOZ requires a higher ACH to create an adequate environment for the livestock [50]. A porous media model was used as a substitute for the Occupied Animal Zone (OAZ) and tested in a 2D simulation. The simulation showed that using porous media to represent animals resulted in longer computational times for the 2D model. However, porous media could better illustrate the aerodynamic force interactions around the animal. A porous media can be combined with the DPM method to evaluate molecular distribution in the cage. A Simulation was conducted to determine the distribution of aerosols in a cage with 4 rows [51]. This Simulation aims to understand the effect of wind speed on which enter the close-house cage. The Solid building was defined as Porous Media: 96%. The barn door openings and wind direction significantly affect the fluid flow inside the cage. Structural mesh can provide more detailed and significant results [52]. The simplified geometry results in differences of up to 10% compared to the complex geometry that is like actual conditions. However, the complex geometry simulation requires a longer computation time [53], [54]. Based on these considerations, adjustments to the model geometry selection should be made in aligned with the research objectives. If the study aims to assess the general flow distribution, a simple 2D model may be sufficient for the simulation. However, if the researcher intends to simulate the conditions of a room in 3D, it may be recommended to represent the geometry using a symmetry model or apply model simplifications to reduce computation time. Complex geometric representation in a 3D model can be considered if the researcher aims to analyze the effect of airflow distribution around livestock, particularly the turbulence changes around the animal surfaces.

3.2. Boundary Condition

The configuration of boundary conditions is the most crucial aspect of defining the limits of mathematical computation. The preference for boundary conditions includes describing the computational domain and inputting initial data. The preference of boundary conditions determines the originality of the computation results. The selection of the type of boundary condition in 2D and 3D simulations is influenced by the parameters and data measured from the field. The size and dimensions of the geometry do not affect the type of boundary condition used. In general poultry cases, both 2D and 3D geometries have similar boundary conditions. In the simulation of a close-house cage, the inlet of the computational domain is defined as a "velocity inlet" to describe the specific velocity of outside wind entering the room. The inlet boundary condition is represented as "interior" to describe the plane of incoming wind traverses along the domain room. "Pressure outlet" boundary condition is utilized when the air exits to atmospheric pressure and interacts directly outside the simulation domain. The outlet is defined as a "fan" if the air flows through to the exit plane of the cage model, but it is still inside the simulation domain [35]. Another Boundary condition of inlet-outlet configuration in previous research is shown in **Table 1**.

Table 1. The Boundary condition of inlet – outlet configuration in previous research

Inlet	Outlet	Refences	Frequency
Velocity Inlet	Pressure Outlet	[35], [38], [41], [42], [44], [52], [55]–[60]	|||||||||||||||||||||||||||||||||||||||
Velocity Inlet	Mass flux rate	[26]	|||||
Pressure Inlet	Velocity Inlet	[28]	|||||
Pressure Inlet	Outflow	[17]	|||||
Pressure outlet	Exhaust Fan	[27]	|||||
Pressure Inlet	Pressure Outlet	[51]	||||||||||
Pressure atm	Negative Velocity Inlet	[61], [62]	||||||||||
Velocity Inlet	Velocity Outlet	[46]	|||||
Velocity Inlet	Pressure Jump	[48]	|||||
Volumetric Flow	Velocity outlet	[36]	|||||

The boundary condition Velocity inlet–pressure outlet configuration is most often used in close-house cage research. However, this configuration is difficult to apply to close-house cages equipped with Evaporative cooling pads as porous media. Fresh air entering the ECP inlet creates a uniform low-velocity airflow as the pressure drop effect.

In a simulation that conducted to understand the impact application of input-output boundary condition configuration [63]. The simulations concern 4 close house cage models and 7 cases. The boundary conditions applied to each model were as follows:

- Case I: Atmospheric pressure at inlets; velocity inlet at outlets; fan as an outlet.
- Case II: Velocity inlet at inlets; atmospheric pressure outlet at outlets.
- Case III: Atmospheric pressure at inlets; pressure outlet at outlets.
- Case IV: Air velocity at inlets; fan at outlets.

In this simulation, the chickens are represented as heat source porous media. The Hosmer–Lemeshow and chi-square (χ^2) method tests the simulation results. The chi-square (χ^2) values are under the specified standard, which indicates that all configurations of boundary conditions are a good fit to represent the actual condition. Scenario III, with the boundary conditions of Inlet - atmospheric pressure inlet and Outlet - pressure outlet, has the lowest chi-square (χ^2) value than another boundary. This boundary is most suitable to be applied in the following CFD studies [63].

Another CFD simulation was conducted to validate the accuracy of the boundary condition configuration, initial value, and solution in numerical simulation [64]. The statistical analysis of the stepwise second-order method was accomplished to determine the error between the real measured of wind speed and the simulation result. The variations of boundary conditions used were:

- Case I: Velocity Inlet (uniform) - Airflow
- Case II: Velocity Inlet (Real Measurement) - Airflow
- Case III: Pressure Inlet (atmospheric) - Velocity (outlet), the outlet velocity value was calculated in Cubic feet/minute (CFM)
- Case IV: Velocity Inlet (uniform) - Pressure Outlet: The pressure value was obtained from field measurements.

The initial values for inlets and outlets are obtained from experimental measurements. The study indicates that the best boundary for "Inlets" is "air velocity," and for "Outlets," it is represented as "% Airflow."

3.3. Turbulence Viscous Model

The Reynolds-Averaged Navier-Stokes (RANS) equations are mathematical equations derived to approximate turbulence phenomena of mean flow. The turbulence model has 4 equations consisting of 3 momentum equations and 1 mass conservation equation. These equations are used to find 10 unknown variables, including 3 mean velocities, 1 pressure, and 6 Reynolds stresses. The equations utilize a mathematical approach to solve and illustrate the velocity profile. Various turbulence models have been developed by the ANSYS program, including Spalart-Allmaras (One-Equation), Standard k-ε, RNG k-ε, Realizable k-ε (Two-Equation Models), Standard k-ω, SST k-ω (Three-Equation Models), 4-Equations v2f, Reynolds Stress Model k-kl-ω Transition Model, SST Transition Model, Detached Eddy Simulation, and Large Eddy Simulation.

The numerical simulation model of a close-house cage can detail temperature, humidity, and velocity distribution. A simulation was performed by Gebremedhin and Wu [65] to compare the impact of different turbulence viscous model selections on the airflow distribution. The cattle are modeled as solid geometry in a randomly patterned standing position using PHOENICS 3.2 software. The simulations were conducted on turbulence models, including Standard k-ε, RNG k-ε, Low-Reynolds number k-ε, k-ω, and the Reynolds Stress Model. The study results show that the RNG k-ε turbulence viscous model is most relevant to apply, especially in heat exchange cases. A study by Cheng et al. [40] was conducted to compare turbulence models: standard k-ε, RNG k-ε, realizable k-ε, low-Re k-ε, standard k-ω, and SST k-ω. The pressure-velocity equations were discretized using the SIMPLE second-order scheme. The flocks are simulated as oval-shaped, chicken-shaped, and oval-necked chicken models. The flock was also simulated in regular and irregular chicken positioning during feeding. The research concluded that the RNG k-ε turbulence model is well-suited for simulating simple models with detailed, high-density meshing.

A star CCM+ simulation investigates the impact of fluid flow in the barn on variations in porosity [56]. The turbulence models used were Standard k–ε, realizable k–ε, SST k–ω, and v2f k–ε. Simulation results of Standard k–ε and realizable turbulence viscous models are like actual measured velocity. However, the realizable k–ε, SST k–ω, and v2f k–ε turbulence models did not provide adequate results. The simulation by Küçüktopcu & Cemek [66] compares velocity and temperature distribution by applying different turbulence viscous models Standard k-ε, RNG k-ε, and Realizable k-ε. The results show that the RNG k-ε model accurately predicts velocity. The RNG k-ε offers higher accuracy than the Standard k-ε model [1], [66], especially in obtaining species transportation distribution, such as CO_2, NH3, and water vapor. However, the accuracy of temperature distribution prediction of RNG k-ε is inadequate [56]. The standard k-ε turbulence viscous model proposes suitable precision and manageably convergence [26], [67]. This turbulence viscous model can accurately predict areas far from the wall. However, this turbulence viscous model provides up to 30% dissimilarities in close wall areas. The standard k-ε turbulence model is acutely sensitive to grid density transformations. Modifying the standard k-ε model provides better accuracy in approaching predictions of the actual velocity [68]. An The turbulence viscous model in previous research is shown in **Table 2**.

Table 2. The turbulance viscous model and discritation model in previous research

Category	Turbulence viscous	References
Poultry	The turbulence model used is SST k-ε. The pressure-velocity method SIMPLE is employed with a second-order upwind scheme discretization approach.	[10], [17], [26], [27], [38], [41], [42], [44], [50], [52], [53], [55], [57], [61], [64], [66], [69]–[73]
Poultry	The turbulence model used is k-ε SIMPLE first order.	[28]
Poultry	The simulation is carried out using the k-ε Standard SIMPLE method.	[74]
Poultry	The simulation was carried out using the RNG k-ε turbulence model with standard wall functions and the SIMPLE method.	[36]
Poultry	The turbulence model used is k-ω SIMPLEC. The discretization equations for momentum and radiation are solved using the Second Order Upwind (SOU) method, while the turbulence and energy equations are solved using the First Order Upwind (FOU) method.	[2]
Cattle	The RNG k-ε turbulence model combined with SIMPLE was used in the simulation.	[75]

Solving the Navier–Stokes equations in livestock farming cases requires an additional equation. The additional algorithm commonly used to solve this problem is SIMPLE or SIMPLEC. This algorithm is employed to solve pressure and velocity coupling. In various studies, closed-house cage simulations are completed mainly by a pressure-velocity coupling-based solver and a second-order scheme for discretizing governing equations. However, employing a second-order scheme discretization causes unstable results and time-consuming simulation than first-order schemes. The instability is presumed to be caused by the high turbulence jet flow created by the incoming fluid hitting the roof and wall. To enhance computational stability and achieve more precise results, some researchers combine both first- and second-order discretization methods [2], [48], [49]. Additional equations manage more complex cases, such as when considering radiation and buoyancy in heat exchange calculations. For instance, solar radiation is solved using the Discrete Ordinate Method (DOM) equation [64]. The distribution of dust and hazardous particles such as PM can be calculated through the Discrete Element Method (DEM) or Discrete Parcel Method (DPM) [76], [77].

4. Water Sprinkle in Close-house Cage

Heat stress is a series of conditions experienced by the body that cannot get rid of excess heat. In animals, this condition negatively affects the metabolism, including behavior changes, food intake decrease, health disorders, and mortality. The effects of heat stress can be mitigated through feeding strategies adaptation, genetic approaches, and housing system improvement. Hot-humid air can raise cage temperature and potentially accelerate animal heat stress conditions. Several steps are taken to control temperature and RH in the close-house cage, choosing the type of litter [78], determining the number of exhausts [55], open and close window scheduling [1], [28], setting inlets position [79] and determining the on/off system of exhaust fans [1], [26].

Natural ventilation of the housing system is improved by adjusting the building design based on local climate conditions. The improvement involves adjusting the cage's height, roof slope, and selection of insulation materials to suit the temperature of the animal's comfort level. Advanced technology can be added to enhance animal comfort, including using exhaust fans, fogging roofs, sprinkler systems, interior fans, air conditioners, cooling pads, and cooling perches [80]. Sprinklers are considered more effective in reducing animal heat stress due to less energy consumption up to 60% less than evaporative systems [81]. The installation of sprinkle spray in broiler close-house cage is shown in **Figure 3**. Operating misting sprinklers requires a pump to circulate water as a cooling medium. Sometimes, the farmer used water mixed with disinfectants or medications in the sprinkle to effectively circulate into the air. Various equipment can be used to reduce the mist size, as indicated in the following **Table 3** [82].

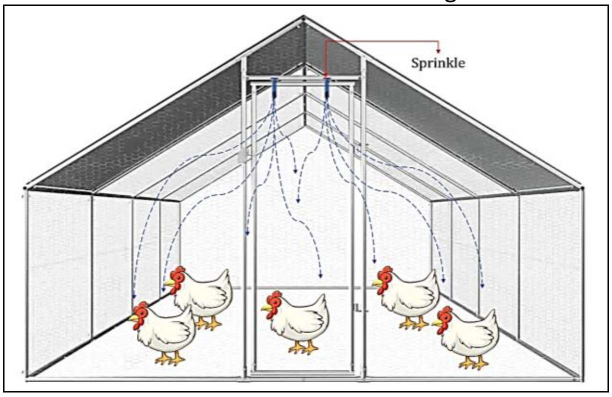

Figure 3. The application of sprinkle spray in broiler close-house cage

Table 3. Water particle size from spinkle spray

Device	Types of water particles	Size
Humidification	Dry fog	<10 µm
Disinfection	Semi-dry fog	10 ~ 30 µm
Venturi	Fine mist	10 ~ 100 µm
Pest Control	Fine drizzle	100 ~ 300 µm

Indoor cage temperature reduction is achieved through the misting process. Sprinklers are more suitable to apply in high temperature open-house cage regions [83]. In a closed-house cage, applying sprinklers causes wet walls and litter, which triggers fungi and bacteria growth. Hence, ECP installation is more effective in improving animal comfort in closed-house cages [84]. The sprinkles system can be modified to archive similar ECP effect. The study conducted by Çaylı et al. [85] compares the use of the Fan-Pad Evaporative Cooling System (FPES) with the Water Spray Evaporative Cooling Systems (WSES). In this method, the fresh air is streamed into a chamber outside the cage and sprayed with water mist to reach a certain humidity level. Then, the humid air blows into the room through the windshield to achieve an effect similar to the ECP. Applying a Fan-Pad Evaporative Cooling System (FPES) sometimes causes failures in the wetting process due to blockages in the pipe holes. However, the use of the original Evaporating pad (FPES) is considered more effective because it can reduce temperatures by up to 5.4–6.4 °C without a drastic increase in Relative Humidity (RH) [85].

5. Evaporative Cooling Pads (ECP)

ECPs are used to decrease the room temperature after the chicken passes through DOC age. ECP is a porous layer made of cellulose, and each layer is positioned at a specific angle. The cellulose layer is coated with chemicals to improve strength, decomposition resistance, and wind resilience. ECP Installation is carried out to reduce room temperature and create uniform low-speed airflow inside the close-house cage. The structure of the evaporative cooling pad is shown in **Figure 4**. Generally, ECP is installed in a closed-house cage with a negative-pressure ventilation system [86]. Humid air is pulled into the closed house cage by a high-pressure exhaust fan installed on the outlet side. This conditioning system is also known as tunnel ventilation. The tunnel ventilation system with ECP cannot operate in the DOC ages or indoors below 15 °C. In the DOC stages, particularly within the first week, it is advisable to place the chickens in a new cage with fresh litter. During this stage, they require a warm environment to facilitate their growth. Implementing a positive ventilation system is more suitable due to the low emission rate at this stage [87]. The ECP tunnel ventilation system is highly recommended for dry and hot regions like the Mediterranean because the wet air circulates inside [88]. Climate and weather characteristics in each area also result in differences in ECP cooling performance [89]. The ECP system's pump was activated when the indoor air temperature exceeded 30 °C and deactivated when it fell below 29 °C. By employing this control method, fluctuations in indoor air temperature could be limited to 4 °C [90]. The stability of temperature and RH in ECP closed-house cages decreases mortality rates, raises egg production, and improves egg weight. However, eggshells produced by chickens in ECP close-house cages are more susceptible to cracking [91].

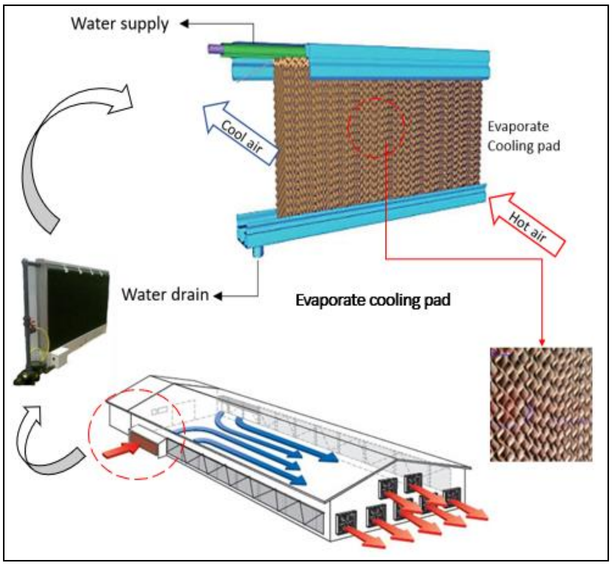

Figure 4. Evaporative cooling pad in broiler close house cage

5.1. The Characteristic Evaporative Cooling Pads (ECP)

The performance of ECPs can be evaluated through some indicators, including Coefficient of Performance (COP), power consumption, and cooling effectiveness [89]. Evaporative cooling pads made from cellulose layers have a cooling effectiveness of up to 75.9% and effectively reduce temperatures up to 4.4 °C in subtropical climates [92]. Several natural sources have been developed as the ECP base material, such as wood shavings, aspen, loofah, specialized fibers, palm, jute, and straw [93]. The Cooling Efficiency (η) values for natural cooling pad materials are as follows: Aspen 71.6–97.7, Palm 38.9, Jute 57.0–87.0, Khus Fibre 64.2–82.0, Straw Fibre 71.9–90.0, and Wood Savings 25.0–65.8, respectively [94]. The criteria of ECP alternative material selection including porosity, permeability, water-holding capacity, thickness, and material structure. Pressure differences on both sides of the ECP can cause deformation of the layers. Therefore, some researchers suggest high-strength materials as ECP alternative materials, such as Coconut shell pads, Burnt clay hollow brick pads, and Pumice stone. These materials endure high-pressure flow from both sides despite having lower cooling effectiveness than cellulose ECPs. Lower cooling effectiveness ECP has a lower pressure drop that minimizes the energy consumption for indoor air circulation [94]. Porous Concrete Evaporative Cooling Pads (PCECP) is an advanced material developed by porous concentrate brick with 21.6% and 22.45% porosities. These materials can reduce surface temperatures by up to 20 °C and 12 °C, respectively [95]. Porous Concrete PCECP were invented to obtain strong materials with high porosity with cooling effectiveness of up to 97% [96].

The ECP performance is affected by the inlet velocity, thickness, reduction in pressure drop, and the water evaporation used to wet the ECP [97]. The increment of inlet air velocity reduces the time for the air to absorb sufficient water content flow into the closed-house cage. High-velocity fresh air minimizes the heat transfer inside the cage, which gives adequate time for contaminant gas to leave the cage rapidly without causing any condensation. Meanwhile, ECP thickness indicates pressure drop rise, causing lower saturation efficiency and relative humidity

(RH). The deviation of saturation efficiency and RH is rising due to velocity increase in the frontal area [98].

5.2. Evaporative Cooling Pads (ECP) Installation Position

The installation of ECP significantly influences the fluid flow patterns within the ECP barn [42][99]. In a study by Wang et al. [99], the installation of ECP was varied in three models. Typically, ECP installation is carried out at the back and beside the close house barn. The exhaust fan is installed at the front of the house barn (model A). This model was compared with installing ECP only at the back with the exhaust fan at the front (model B). In another model, ECP was installed on both sides of the closed-house barn with exhaust fans placed at the front and back (model C). 3D simulations were conducted using the K-epsilon RNG turbulence model. The Evaporative Cooling Pad (ECP) is described as an inlet velocity, and the exhaust fan is a pressure outlet. Simulation results indicate that model B is more suitable for application in closed-house barns because the temperature and air velocity inside the room are more uniform. The mass flow of water wetting the ECP affects the saturation efficiency. An increase in the flow rate of water indicates an improvement in saturation efficiency until the ECP is adequately moist. A lower mass flow of water during the wetting of the ECP indicates an increase in saturation efficiency and results in a high cooling energy value [100].

Increasing water contained in the ECPs layer can be done by direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) methods. The DEC method uses a small pipe that drips an amount of water from the upper part of the ECP. DEC can be applied to single or multiple ECPs arranged perpendicular to the direction of the wind. On the other hand, IEC is a configuration of ECPs stacked parallel to the direction of the wind [101]. The installation of DEC is recommended due to increased humidity and reduced temperature effectively. Besides, the DEC method has lower energy consumption than the IEC.

The temperature and RH level of the close-house cage must be set up in ideal conditions, around 26 °C and RH of 70%. A high-temperature level inside a close-house cage causes heat stress for animals. Humid conditions indicate high-level RH creates an ineffective heat transfer from animal body heat load and the surrounding air. Several scenarios can be implemented to maintain ideal temperature and humidity. The combination of ECP and intermediate sprinklers is recommended to operate when the temperature starts to warm up [102]. When the temperature rises in the summer, the sprinkler operates at low pressure to create coarse water droplets. Chickens bury their bodies in wet litter to reduce the heat load due to the heat stress. The combination of ECP and intermediate sprinklers serves to wet the litter. Adding chemical substances as a water mixture has a better cooling effect in wetting the ECP. The chemical substances reduce reaction time between water vapour and indoor humidity to avoid dank conditions. The chemical substances that can be mixed with water include CaCl and LiCl. Research determinations show that LiCl is more effective [103]. Additionally, using ECP can be combined with a dehumidifier to reduce humidity levels in the close-house cage [104].

5.3. The Setup of Evaporative Cooling Pads (ECP) Numerical Simulation

Research on ECP is conducted through experimental and numerical simulation methods to understand the characteristics of cooling performance. Seasonal changes affect chickens' health in close-house cages. The rising temperature makes them susceptible to heat strokes during the summer. In the winter, they are at high risk of a lack of fresh air supply due to air circulation obstruction. A simulation by Küçüktopcu et al. [66] illustrates the temperature distribution in a contour inside a close-house cage during winter and summer. The cage has an HVAC system that includes a heating system, an evaporating pad, and a circulating fan. The evaporative cooling pad is an inlet humidity source with 94.7% porosity. The chickens are described as a heat source with 90% porosity. The result shows that ECPs can reduce the temperature up to 3 °C during summer. Further, an exhaust fan is recommended to operate in order to eliminate stagnant air during the winter. Another CFD simulation was conducted to illustrate the airflow in a multi-level pig barn. Animals are represented as heat sources in porous media AOZ. In this study, the assumed outside air conditions were 38.0 °C and 80.0%. After passing through the wet ECP, the conditions became 35.1 °C and 96.7% (assuming a cooling efficiency of 85%). Installing exhaust on each floor was more effective in supplying clean air in a closed-house barn [71].

The simulation on ECP was run using the "porosity" menu on ANSYS to describe porosity characteristics and pressure differences on both sides. Viscous and inertial resistance numbers determine the porosity characteristic. The viscous and inertial resistance values were obtained by experimental studies, which assembled quadratic equations graphs of the pressure drop as a function of velocity [104]. The quadratic equation is shown in **Figure 1** to **Figure 3**. The pressure drop that occurs between the evaporating pads is expressed in the equation [74].

$$\frac{\Delta P_i}{\Delta x_i} = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v|v_j\right) \tag{1}$$

$$\frac{\Delta P_i}{\Delta x_i} = -\left(\sum_{j=1}^{3} \frac{\mu}{\alpha} v_j + \sum_{j=1}^{3} C_2\rho|v|v_j\right) \tag{2}$$

$$\frac{\Delta P_i}{\Delta x_i} = -\left(\sum_{j=1}^{3} a v_j + \sum_{j=1}^{3} b|v|v_j\right) \tag{3}$$

Where viscous ($1/\alpha$) and inertial (C_2) resistance:

$$C_2 = \frac{a}{t.\rho}\, m^{-1} \tag{4}$$

$$\frac{1}{\alpha} = \frac{b}{t.\mu} m^{-2} \tag{5}$$

Where, *D* is matrices for viscous coefficients (m^{-2}), *C* is matrices for inertial resistance coefficients(m^{-1}), t is thickness (m), $\Delta P/\Delta x$ is pressure drop (Pa), α is viscous ($1/m^2$), b is inertial resistance (1/m), μ is kinematic viscosity, ρ is density(kg/m^3), v is velocity (m/s), and $1/\alpha$ is viscous resitance($1/m^2$). The viscous ($1/\alpha$) and inertial (C_2) resistance values which shown in equation 4 -5 will be incorporated into the available "porosity" menu in ANSYS Fluent.

Another simulation assessed the changes in pressure drop for fluid flow from various brands. Numerical simulations were used to obtain mathematical models for inertial factors in evaporative cooling pads with the following brands: 45–45° (100 mm) by G&R; 45–45˚ (100 mm) by Munters; 60–30° (100 mm) by Munters; 60–30˚ (50 mm) by Munters. Each brand has a design with specific ECP angle characteristics. The simulation resulted in equations for pressure drop, permeability, and cubic law inertial factor as follows [105].

$$\Delta P = av^3 + bv \tag{6}$$

$$K = \frac{\mu.l}{b} \tag{7}$$

$$\gamma = \frac{\mu.a}{l.\rho^2} \tag{8}$$

Where :

ΔP	: Pressure drop (Pa)	b	: Inertial resistance (1/m)
K	: Forchheimer's permeability (m^2)	γ	: inertial factor
μ	: kinematic viscosity	l	: ECP thickness (m)
ρ	: density(kg/m^3)	1/α	: Viscous resitance($1/m^2$
υ	: Velocity (m/s)		

The simulation result Eq. (6) from the Franco et al. [106] is similar to Eq. (3) from the Cheng et al. [74] experiment. Model quadratic (Eq. 3) dan cubic law equation (Eq. 6) resulting in a difference of up to 10% [106]. Consequently, the quadratic law model is considered more suitable for application in numerical simulations

In an experiment conducted by Salins et al. [107] to integrate experiment and numerical study. There are several variations reviewed in this study, including ECP positioning ducting (cross and counterflow), thickness and porosity in 0.062 - 0.083 kg/s. This experiment uses ECP with 100 x 100 x 100 mm wire filled with materials including Celdek, Wood Shavings, and Coconut Coir. The experiment concluded that installing ECP in counterflow has better performance and cooling efficiency coefficients than the crossflow type. The experimental result shows that Cellulose has the highest cooling effectiveness than Wood Shaving and Coconut Coir pad. Simulation research was conducted based on experiment results to compare the performance of ECP made of cellulose material with variations in porosity and thickness. In this simulation, the geometry model consists of a block of a cooling pad and a test box. The 3D simulation applied the standard k-ε model turbulence. The simulation indicates that differences in the number of porosities have no significant effect on cooling performance. The cooling performance varies due to the increased speed and thickness of the ECP [93], [108].

6. Energy Management Calculation

Most energy consumption in broiler house farming is 32% for electricity and 35% for food supply. The energy requirements increase along with the growing metabolism of broilers. Metabolic requirements can be predicted based on weight, environmental temperature, and egg mass [109]. A mathematical model of the energy equations required for broiler growth is essential for understanding the total net energy consumed and the animal's metabolic system [110]. Animals need a comfortable environment characterized by ideal temperature and RH to develop optimally. A comfortable environment for animals can reduce heat stress and mortality rates. Animal comfort is indicated by the temperature humidity velocity index (THVI) level. THVI can be determined from Eq. (9) [27]:

$$THVI = (0.85t_{db} + 0.15t_{wb}).v^{-0.058} \tag{9}$$

or [83]:

$$THI = (1.8 \times T_{db} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26)] \tag{10}$$

Based on THI calculations, the heat stress is divided into four categories: Normal (≥74), Alert (75-78), Danger (79-83), and Emergency (≤ 84). Farmers can operate HVAC equipment to maintain ideal conditions, such as exhaust fans and evaporative cooling pads equipped with pumps or heaters. The number of HVACs operated affects the electrical energy consumption. An energy audit must be carried out to minimize electricity consumption. Farmers can decide on the HVAC equipment to operate through an energy audit process. Energy use efficiency (EUE) is analyzed by considering energy input and output. Energy consumption calculations are carried out by considering mass and energy balance [15], [44]. The total energy consumption required by farmers takes into heating energy requirement [8], [16], water flow rate [9], cooling capacity [104], heat load produced by chickens [103], water evaporation rate[95], water consumption [100], lighting [103] and heat loss [111]. Energy analyses can be calculated based on the pressure drop value of the inlet and outlet mass airflow in a close-house cage [13], [23]. Profit (net return) is obtained from the deviation between total energy and production costs [101].

7. Conclusion

An Evaporative Cooling Pad (ECP) is one of the HVAC systems that can be applied to increase relative humidity (RH) and temperature in close-house cages. Using ECP can also create conditions of uniform and low velocity air flow. The combination of ECP and exhaust fans suits dry and hot environments. The impact of using ECP in closed-house cage can be depicted through numerical simulation results. Some researchers use the k-epsilon RNG turbulence model to achieve high accuracy. However, this turbulence model is highly sensitive to changes in mesh density, requiring a dense mesh around the walls. Combining first- and second-order upwind discretization models is recommended to obtain more stable results. The characteristics of the components making up the ECP affect the pattern and pressure drop of fluid flow in close-house cages. Increasing the thickness of the ECP arrangement leads to an increase in pressure drop, causing a decrease in saturation efficiency and relative humidity (RH) as the flow velocity increases. Wetting the ECP is recommended when the air temperature is above 28 °C and RH is below 75%. Economic efficiency of the combination of HVAC design and ECP needs to be considered. The HVAC design in closed-house cages results in differences in energy consumption. An energy audit of the HVAC design is necessary to predict the incurred costs.

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Authors' Declaration

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