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Research article

Towards modelling, and analysis of differential pressure and air velocity in a mechanical ventilation poultry house: Application for hot climates

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ABSTRACT

Due to the broiler house's needs for a healthy environment, efficient control system, and appropriate air, several studies were interested in microclimate and air quality characteristics. However, limited studies are conducted to investigate pressure and air velocity within poultry buildings, which are also significant parameters that impact the breeding environment and productivity. As a reason, the objective of this work was to develop a mathematical model exploring the differential pressure and air velocity inside the house. The peculiarity of this research is the use of thermal balance and air properties to propose a model related to birds' weight which can be translated to birds' age and thermal conditions. The proposed approach acquired experimental measurements (e.g., indoor air temperature and humidity, air velocity, and differential pressure) and performed simulations in a mechanically ventilated Mediterranean broiler house over a summer production cycle. The findings revealed that the observed and modelled differential pressure ranged from a negative to a positive pressure (−5 to 39 Pa), with broilers subjected to air velocity varying from 0.09 to 1.641 m s^{-1} depending on three distinct modes of regulation: nature, power, and tunnel mode. These results confirmed the model's predictive capacity with a relative error of 1.03% of differential pressure and 0.68% of air velocity and a normalised mean square error (NMSE) of −1.06 Pa and 0.19 m s^{-1}, respectively. Consequently, the methodology applied in this paper may be extended to various species of breeding structures in other seasons, allowing simulation tools and system control improvement.

1. Introduction

In the last years, the fast-growing demand for poultry meat has caused worldwide production to explode. This expansion necessitates more efficiency at the production chain level while struggling with customer requirements for quality and animal welfare, climate change, and financial pressures. The combination of rearing house type and control system is essential in generating the best possible growing conditions in the face of these constraints.

In order to provide optimum performance during the production process, buildings must respond to climatic conditions and changes, employing innovative technologies to assist breeders in their daily management. Nowadays, modern control systems are used

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in industrial poultry buildings to maintain the interior living environment. However, poultry houses continue to suffer from significant economic losses as well as a high animal mortality rate, particularly during the summer months, which are marked by a quite hot, humid climate with such a high concentration of polluting gases, which is the case for the Mediterranean climate. Additionally, the processing has further complications in selecting the appropriate mode control with the best performance and the least amount of energy consumption while taking into account the significant effect of the interior environment on the broilers.

Climate control inside poultry houses is the main key to successful production and guaranteed animal welfare. As a result, farmers employ a variety of ventilation strategies for their structures (natural, mixed, and tunnel ventilation). Since the bird's condition is heavily influenced by air temperature, relative humidity, thermal radiation, and air velocity within the poultry house [1], the characteristics and regularity of these environmental parameters are dictated by interior airflow movement [2]. Determining ventilation rate in intensive poultry livestock buildings is typically associated with maintaining only indoor air temperature and humidity [3] -[52] - [4,5] and, in some circumstances, toxic gas concentrations [6]. However, it is also adjusted based on the pressure and air velocity within the house, which, unlike the preceding components, have received less attention in earlier literature. On the one hand, the characteristics associated with air velocity inside the poultry house provide the best findings for determining the airflow rate [7]. On the other hand, the differential pressure within the building considers one of the environmental control parameters to monitor in controlling the inlets and adjusting the slot size, which must be almost constant and equal to the set number [8].

It is against these foundations that we have effectively been interested in production system analysis, processing, and modelling pressure and air velocity parameters. The decision to model these variables mathematically was to understand and generalise the system, apply physical theories, and derive equations applicable in any situation to finally simulate and predict measurements that can assist producers in their management and shift from a reactive to a predictive perspective. Furthermore, by enhancing the quality and precision of the simulation tool, the model will allow us to control the differential pressure and air velocity inside the poultry building.

Several searches have been conducted in the literature to explore these two characteristics. When the outdoor temperature and humidity are extremely high, such as in the Mediterranean, evaporative cooling systems are insufficient to cool all the incoming air. In this circumstance, air velocity becomes quite powerful in lowering the temperature around the birds and boosting their thermal conditions. It is a critical aspect of micro-environmental control [9,10] [11,12]. However, it must remain uniform and stabilized; to prevent animal movement into better ventilated but already populated zones which increase the mortality rate [13]; and consistently high to improve broiler performance, weight gain, growth [14,15], and respiration rate [16]. The static pressure difference is maintained to control inlets, produce airflow configurations inside the house to suit animal growth and incoming air temperature, and maximize airflow rate and velocity in the summer seasons [17].

Santos et al. [55], - [18], in turn, observed that while air velocity can be beneficial and decrease heat stress in moderate to hot conditions, it can also be harmful in cold exposure owing to excessive convective cooling. Therefore, knowing how to handle this property and benefit from the right side is absolutely essential. Regarding the quality of animal meat, this variable has substantial impacts, which Carvalho et al. [53], has addressed.

Bustamante et al. [19], created a computational fluid dynamics (CFD) model of a tunnel ventilated broiler house that predicts airflow behaviour and air velocity distribution under various conditions, intending to avoid the effects of excessive airspeed in the housing. Xue et al. [20], Curi et al. [21], and Cunha et al. [22], also engaged in computational models constructing to analyze airflow distribution in ventilated livestock buildings, which were considered validated with an average normalised mean square error (NMSE) of 0.15, 0.19, and 0.02 for air velocity throughout the house, respectively. Bjerg et al. [23], investigated the possible advantages of employing a ceiling-jet inlet to control the air velocity and heat environment for pigs in finisher unit lying areas and discovered that under Danish climatic conditions, the high indoor temperature can decrease from 40% to 5% of the period.

For the differential pressure between inside and outside the air house, most research that frequently incorporated this parameter focused on determining the system performance and the electrical energy consumption required for heating, cooling, and ventilating the inside livestock buildings. Chai et al. [24], developed fan models to quantify house ventilation, which is a function of differential pressure and fan rotation speed, and verified that this parameter is primarily responsible for fan performance. Using the same approaches, Chen et al. [25], determined the total ventilation rate based on fan operation, differential static pressure, fan rotation speed and performance degradation. Meanwhile, Morello et al. [26], founded a standardized procedure for evaluating and minimizing errors during fan tests utilizing common practice for altering the static pressure within tunnel-ventilated animal housing using the Fan Assessment Numeration System unit. Costantino et al. [27], estimated the electrical energy consumption due to ventilation using Specific Fan Performance, which was defined as a function of the building's static pressure differential.

To our knowledge, there is no research work in the literature dealing with differential pressure and air velocity modelling inside poultry livestock buildings using the same approach (i.e., applying Dalton's law and combining thermal equations as physics theories) under the critical Mediterranean summer climatic conditions.

The novelty of this paper is the use of an innovative model for simulating, supervising, and controlling air velocity and differential pressure in broiler houses. Furthermore, the developed approach guarantees accurate prevision over the entire operating range at any place of the building with a tiny deviation error. Moreover, the proposed mathematical model can be applied in the automation and implementation of different controllers in the poultry house.

This study contributes to the literature by applying a novel mathematical model for airspeed and differential pressure inside poultry houses, experimentally assessing its capacity to prevent measurements of these variables, presenting the correlation between the microclimatic parameters, properly controlling the system; and providing some recommendations for further studies.

Based on the preceding, we have concentrated our study on exploring air velocity and differential pressure inside the broiler livestock buildings, which affect the thermal conditions and animal welfare. The specific objectives of this paper were.

1. To measure and monitor temperature, humidity, air velocity, and differential pressure inside the poultry house;
2. To develop a mathematical model of these parameters (i.e., air velocity and differential pressure);
3. And to test and validate the results before starting controlling the microclimate relating to animal comfort and production gain.

A mechanically ventilated broiler house in Morocco (Mediterranean area) was selected as a case study for the analysis; it was tracked over a production cycle during the summer season to provide the needed experimental data for modelling and simulating the predictive parameters.

2. Materials and methods

2.1. Housing

All the animal procedures carried out in this study were performed following the Moroccan guidelines of animal care and use codes (Dahir No. 1-02-119; Law n°49–99) and the European Communities Council Directive 2010/63/EU and comply with the ARRIVE guidelines. The protocol was approved by the National Office of Food Safety Ethics Review Committee (Office National de Sécurité Sanitaire des Produits Alimentaires), in accordance with Superior School of Technology of Salé, Mohammed V University. The experiment was performed in a commercial broiler livestock building in the Mediterranean (Northwest Morocco), supplied with three distinct modes of the ventilation system, as illustrated in Fig. 1. The house dimensions were 120 m in length, 12.4 m in width, and 3,85 m in height. The ventilation configuration of this broiler house depends on the inside and outside climate conditions and the broilers' needs. The two lateral larger walls include air inlets along their length (see Fig. 2.) and are automatically controlled to maintain the recommended air temperature and humidity for young broilers. They provide a constant negative differential pressure between the inside and outside of the house, bring in the proper amount, volume, and speed of air, and achieve the natural ventilation goals employed in the early bird age of the production cycle.

Since the optimum air temperature declines with age, natural ventilation is insufficient to maintain the appropriate climatic conditions. In this scenario, mixed ventilation is used. To provide this power mode, three fans are also located consistently in the lateral walls alongside the inlets to create a positive differential pressure within the house, supplying new clean air through the windows and evacuating the heated guilty one. When the climate conditions become more crucial in the third and final age of the production cycle, tunnel ventilation, which contains six large fans at the end gable wall, and evaporative cooling systems, which are located at the front end of the house, are activated. They ensure a high positive level of pressure to allow a higher flow rate and maximum evacuation of pollutants and moist-warm air along the entire length of the house, delivering a cooling effect, as described in Ref. [27]. During the winter season, 15 propane air heaters are carefully installed all across the house to maintain additional heating.

2.2. Instrumentation and recording

The experiment was carried out over six weeks' cycle, from July 1st to August 15th' 2021, with 23 000 broilers. The recorded measurements concern the indoor air temperature and relative humidity (T_{int}, RH_{int}) and the pressure difference between inside and outside the house (Δp) using twelve sensors (four sensors for each parameter distributed throughout the entire building with a level of 0.35 m from the ground, as shown in Fig. 3) embedded in the data loggers of the building's monitoring system with a setting acquisition of each current conditions. The outside pressure, which correlates to atmospheric pressure, was measured every 1 h using the local

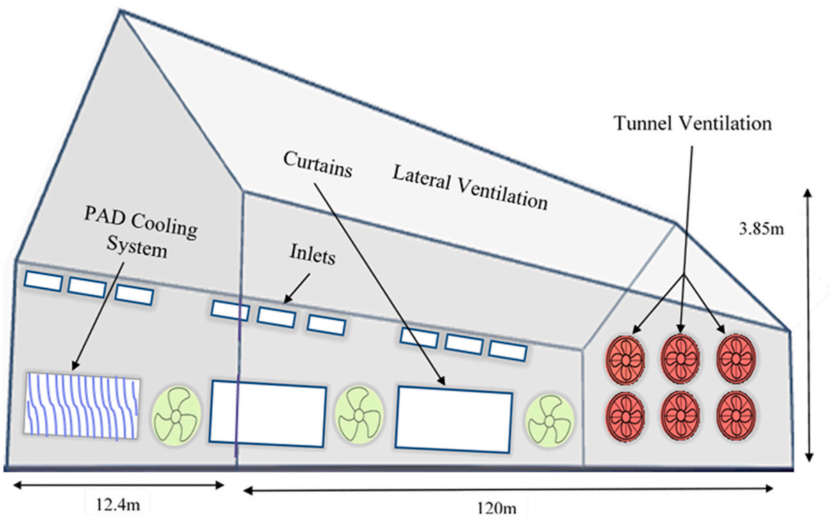

Fig. 1. Schematic drawing of the broilers house's: left view.

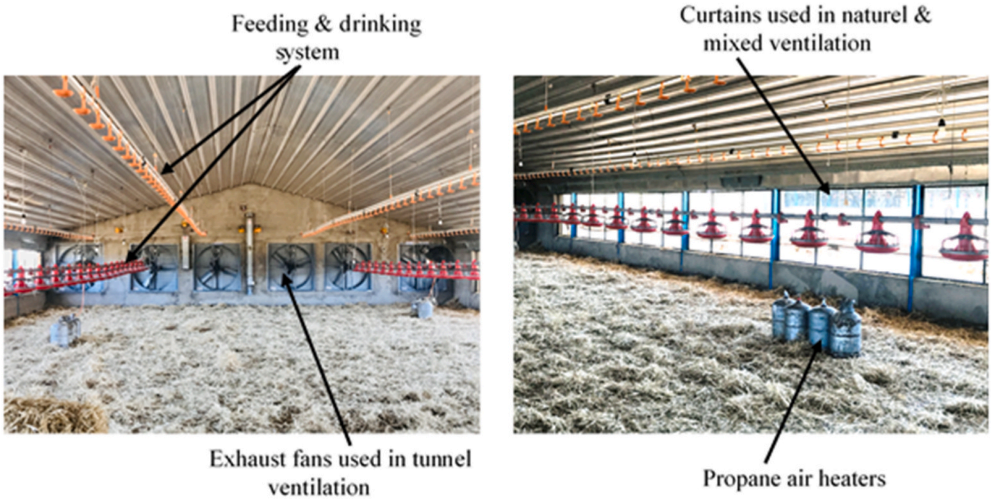

Fig. 2. Broilers house's operational ventilation, feeding and heating system.

weather station. Concerning the air velocity parameter (V_{air}), it was measured by using three calibrated multi-function rotating vane anemometers and recorded with an acquisition every 30 s. The different sensors used in the experience are tabulated in Table 1. The measurements started on the first day of broiler production and continued until the end of the production cycle. All acquired data was communicated to a computer through a central microcontroller and analyzed as requested (Fig. 4).

2.3. Model set-up.

2.2.1. *Air velocity analysis*

As previously mentioned, there is a crucial relationship between thermal conditions and air velocity inside the livestock building. We assume that the broilers are in a state of thermal comfort. Since we are interested in thermal balance, the equation can proceed with the total heat production of the animal and its sensible heat loss.

Referring to Refs. [28,29], the total and sensible heat are expressed as:

$$\varphi_{tot} = 10 * M^{0.75} \tag{1}$$

$$\varphi_s = R * \varphi_{tot} = \frac{T_b - T_{int}}{R_{body}} \tag{2}$$

where:

φ_{tot} is the total heat production by one broiler [W];

φ_s is the sensible heat loss by the broiler [W];

M is the body weight [Kg];

R is the sensible fraction of the heat emission, for more details, check out [27]; T_b corresponds to the deep body temperature of the

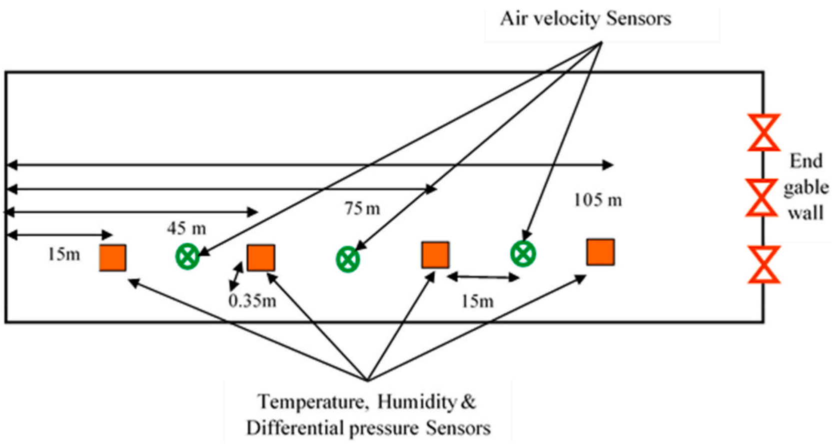

Fig. 3. Schematic drawing sensors location in the broiler house.

Table 1
Detail of the monitored parameters.

Monitored parameter	Symbol	Unit of measurement	Sensor type	Accuracy
Indoor temperature	T_{int}	°C	HOBO UX100-003; Onset Computer Co., USA	±3.5%
Indoor relative humidity	RH_{int}	%		
Air velocity	V_{air}	$m.s^{-1}$	Model 007, PCE, Americas Inc.	±1%
Static pressure difference	Δp	Pa	Model 265, Setra Systems, Inc. Boxborough, MA	±1 Pa

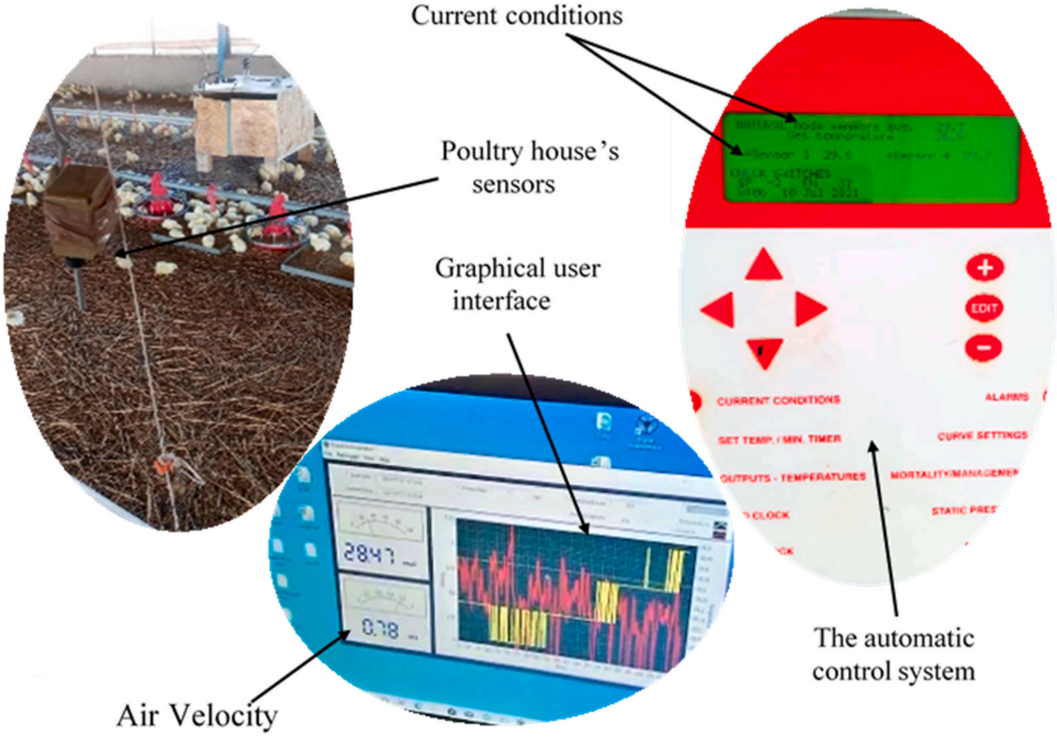

Fig. 4. Illustration of different components used in monitoring system.

bird [°C];

$R_{body} = \frac{m_{coat} + \frac{1}{5.4 + 15.7 * \left(\frac{V_{air}{}^{0.6}}{M^{0.13}}\right)}}{0.081 * M^{0.67}}$ is the total thermal resistance of the body [$K \cdot W^{-1}$], determined by the surface area of the body as well as the thermal insulating properties of the tissue, coat, and boundary layers (See more on [30]);

m_{coat} is the thermal resistance of hair–coat layer [$m^2 K \cdot W^{-1}$], see more on [31].

equation (3) is the result of equations (1) and (2):

$$V_{air} = \sqrt[0.6]{\left| \left(\frac{10R}{0.081(T_b - T_{int})M^{-0.08} - 10R * m_{coat}} - 5.4 \right) * \frac{M^{0.13}}{15.7} \right|} \quad (3)$$

2.2.2. Pressure analysis

As the environment within the broiler house contains a mixture of many gases with air, and because these gases have few amounts of a substance compared to air [32,33], they are regarded insignificant, so the combination inside is considered only moist air with presuming that the house is isolated. Based on Dalton's law and considering the mixture of air present in the building as an ideal gas, the differential pressure between indoor and outdoor pressure Δp can be defined through the equation below:

$$\Delta p = P_{int} - P_{out} = \sum_i P_i - P_{out} = \left(P_{int,da} + P_{int,vap}\right) - P_{out} \quad (4)$$

where:

P_{int} is the total indoor mixture pressure inside the poultry house [Pa];

P_{out} is the outdoor atmospheric pressure [Pa];
P_i represents the partial pressure that a gas i would exert if it alone occupied the entire volume [Pa];
$P_{int,da}$, $P_{int,vap}$, design respectively the partial pressure of dry air and water vapor present inside [Pa].
According to Ref. [34], the indoor humidity ratio and relative humidity are represented in equations (5) and (6):

$$H_{int} = 0,62198 \frac{P_{int,vap}}{P_{int,da}} \tag{5}$$

$$RH_{int} = \frac{100.P_{int,vap}}{P_{int,vap,s}} \tag{6}$$

where:
H_{int} is the indoor humidity ratio of air [$kg_{H2O}.kg_{airdry}^{-1}$];
RH_{int} represents the indoor relative humidity [%];
$P_{int,vap,s}$ corresponds to the saturation vapor pressure [Pa], which derived from equation (7) below [35]:

$$ln\left(P_{vap,s}\right) = \frac{C_1}{T_{int}} + C_2 + C_3 T_{int} + C_4 {T_{int}}^2 + C_5 {T_{int}}^3 + C_6\, lnln\, T_{int} \tag{7}$$

where C_1 to C_6 are coefficients derived from the Hyland-Wexler equations detailed as follows in Table 2, and T_{int} is the absolute indoor temperature [K].
From equation (4), equation (8) is derived:

$$\Delta p = \left[0,01 * RH_{int}.e^{\frac{C_1}{T_{int}} + C_2 + C_3 T_{int} + C_4 {T_{int}}^2 + C_5 {T_{int}}^3 + C_6\, lnln\, T_{int}} \left(1 + \frac{0,62198}{H_{int}}\right)\right] - P_{out} \tag{8}$$

2.2.3. Model validation

To validate the mathematical model for the parameters V_{air} and Δp, we followed the same methods adopted by Refs. [19,20], and [22] that were performed on the correlation between the experimental data and simulation results. The first indicator applied in this study is the relative error which determines the differences between these measures. It was calculated as represented in equation (9):

$$E_x = \frac{D_{pi,x} - D_{mi,x}}{D_{mi,x}} * 100\% \tag{9}$$

where:
E_x is the relative error for the parameter x (i.e., air velocity or differential pressure);
$D_{pi,x}$: value of the predicted variable x;
$D_{mi,x}$: value of the measured variable x;
The second indicator's validation was investigated by computing the normalised mean square error (NMSE), obtained by equation (10):

$$NMSE = \frac{\left(\frac{\sum_i \left(D_{pi,x} - D_{mi,x}\right)^2}{n}\right)}{\left(D_{p,x} - D_{m,x}\right)} \tag{10}$$

where:
$D_{p,x}$ is the mean value of the predicted parameter obtained from the model;
$D_{m,x}$ represents the mean value of the measured parameter.
n: number of measurements.
In addition to these statistical analysis methods, the coefficient of determination (R^2), which is a quality measure of linear regression prediction, was performed to determine the precision of the modelling. The closer R^2 to one, the better the model simulation's performance. equation (11) was defined as follow:

Table 2
Coefficients related to saturation pressure over liquid water for the temperature range of 0–200 °C.

Coefficient	Value	Coefficient	Value
C_1	$-5.8002206*10^3$	C_4	$4.1764768*10^{-5}$
C_2	1.3914993	C_5	$-1.4452093*10^{-8}$
C_3	$-4.8640239*10^{-2}$	C_6	6.5459673

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(D_{mi,x} - D_{pi,x}\right)^2}{\sum_{i=1}^{n} \left(D_{mi,x} - D_{m,x}\right)^2} \tag{11}$$

3. Results and discussions

3.1. Air velocity response

Fig. 5 depicts the predicted and measured air velocity inside the poultry house for two days of each production cycle in summer season. In the early bird age, the building employed a natural air system for hot weather conditions. This method was applied to remove heat and moisture and provide fresh air by utilizing temperature variations and natural air movement resulting from side curtains. For this reason, the lowest simulated and experimental air velocity were recorded during this phase and matched 0.09 and 0.1 m s^{-1}, respectively. While the maximum air velocity for both simulated and experimental data is 0.71 m s^{-1} and 0.5 m s^{-1}. This may be explained by the highest indoor temperature observed during the same period; as a result, all side curtains were opened to improve circulation and induce the wind-chill effect on broilers. However, the mean values are 0.28 and 0.3 m s^{-1}, respectively.

Temperature and humidity steadily rose along the broiler growing at the second age. Since natural ventilation could no longer manage these characteristics, the ventilation system switched to a mixed version. This power mode is produced using sidewall fans and curtains. Consequently, the airspeed increased compared to the first period. The mean value air velocity of the predicted and real data were 0.562 and 0.56 m s^{-1}, severally. A slight excess of air velocity corresponds to the maximum with a value of 0.66 m s^{-1}, observed during this phase. This only occurs when lateral fans and side walls are running concurrently when the indoor temperature and/or relative humidity exceed the set point.

In the third age of the production cycle, as the microclimate circumstances got increasingly complicated, the system control converted to tunnel ventilation. Air movement has become one of the most efficient methods for cooling the inside environment during the hot season, providing a wind chill effect to ensure the bird's lower body temperature. At this point, the air velocity had doubled, with the maximum simulated and observed values of 1.641 and 1.5 m s^{-1}, respectively. Since the indoor microclimatic indicators increased, particularly during this summer period, additional ventilation was required; thus, the exhaust fans were activated every 180 s until the required levels were reached. When tunnel ventilation is insufficient, evaporative cooling is activated to supply an additional cooling load preventing deadly heat. Consequently, the average air velocity at bird's level reaches 0.95 m s^{-1}.

These findings are consistent with previous research [36]-[1–37], which found that airspeed at the bird's level in conventional broiler houses did not surpass 0.5 m s^{-1}. However, air velocity averaged 0.8–1.8 m s^{-1} in the other livestock buildings due to variations in maximum ventilation rates and system control. Namely, Wheeler et al [37]. discovered that for the two research houses, the interior air speeds of the tunnel-ventilated house averaged 1.7 m s^{-1} and 2.6 m s^{-1}, compared to the conventionally ventilated house's air speeds of 0.4 m s^{-1} and 0.5 m s^{-1}.

In practice, it was demonstrated that the air velocity should not surpass 0.3 m s^{-1} in breeding young broilers aged from first to fourteen days, range between 0.3 and 0.6 m s^{-1} for broilers aged 15–21 days, and be less than 0.72 m s^{-1} for broilers older than 22 days and not exceed 4 m s^{-1} before slaughter [15–38]. According to Yahav et al. [10] and Al-Dawood et al. [40], an air velocity of 1.5–2 m s^{-1} and 1.5–3.0 m s^{-1}, respectively, are the optimal measurements to achieve a maximum bird performance under high temperatures

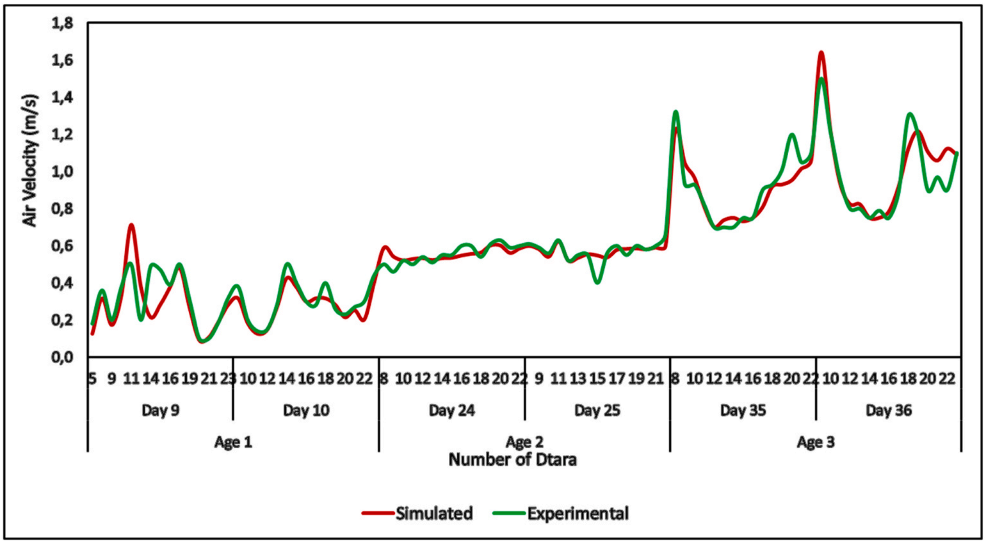

Fig. 5. Simulation of the inside air velocity compared to the experienced measurements.

(<35 °C) between 4 and 8 weeks (i.e., the third age of production cycle). These air velocity requirements provide the highest broiler productivity and maintain the microclimatic conditions below undesirable limit values. In fact, the airflow is controlled such that the concentrations of ammonia and carbon dioxide at the bird's head level are maintained below 20 and 3000 ppm, respectively, and the appropriate indoor temperature and relative humidity are between 20 and 30 °C and 60 and 70%, severally [41].

The measurements made possible by the mathematical model of the air velocity within the poultry house are consistent with the data that has been collected and with recommended standards.

Blanes-Vidal et al. [42], discovered in their study an air velocity of 0.367 ± 0.14 m s^{-1}, 0.547 ± 0.22 m s^{-1}, and 0.337 ± 0.13 m s^{-1} acquired from measurements, CFD simulation, and CFD adjustment in a poultry house with based ventilation and hot conditions. With the same approach, Bustamante et al. [19], concluded, on the one hand, that the highest air velocity in tunnel ventilation was 2.72 ± 0.31 m s^{-1} (CFD) and 2.58 ± 0.29 m s^{-1} (measured), while the minimum was 0.49 ± 0.12 m s^{-1}, and 0.47 ± 0.11 m s^{-1}, respectively. On the other hand, Xue et al. [20], and Curi et al. [21], identified a simulated air velocity between 1.5 and 2.5 m.$s^{-1}$with maximum ventilation. In the case of low air exchange, Kuçuktopcu et al. [43], observed that the airspeed at the bird's level did not surpass 0.6 m s^{-1}. Cunha et al. [22], in their turn, noted a collected mean value of 2.35 ± 1.35 m s^{-1} and a simulated one of 2.50 ± 1.5 m s^{-1}.

As seen in Fig. 5, the air velocity mathematical model generally converges with the actual measurement of the production cycle. Table 3 represents the relative error, NMSE, and R^2 calculated using measurement and simulation data for air velocity inside the building at three distinct stages of the production cycle. The error between the simulated and measured data E for V_{air} did not change substantially, as E was 0.68%, with a maximum value recorded in the third age of 0.99%, which is deemed an acceptable error. The NMSE value reached 0.19 m/s, proving that the mathematical model accurately predicts indoor air velocity under three distinct ventilation mode controls. Since $R^2 = 0.93$ (>0.9), the coefficient of determination also supports the model's adequacy and the good correlation between simulation and real data.

Among the important uses of estimating air velocity at bird's level under hot and/or humid conditions is to provide the temperature-humidity-velocity index (THIV) defined by Tao and Xin [12] for broilers at 46 days of age and 2.8 kg of body weight. The index evaluates the bird's welfare according to severe exposure-time thresholds (as normal, alert, danger, and emergency states) and therefore prevents economic loss caused by potential heat stress during production, live–haul transportation, or abattoir holding of market–size broilers. Exposed to a relative humidity of 65% with a mean predicted air velocity of 0.957 m s^{-1}, broilers would reach danger state of heat stress which is defined as temperature rise of 2.5 °C from the normal in 189, 125, 58 min if the air temperature is 35, 37 and 41 °C, respectively (Table 4).

3.2. Differential pressure response

The static pressure differential between indoor and outdoor of the study broiler house varied throughout three ventilation modes, ranging from −5 to 39 Pa for simulated and measured readings (see Fig. 6). This pressure differential reflects the fans operating and the resistance to the air coming through the inlets, which reaches the house through various types of entrances according to the bird's age. The findings of the first stage of the production cycle indicate a tiny negative to no differential static pressure during the natural mode due to the non-functioning exhausted fans. It happens when the pressure within the building is slightly lower than the atmospheric pressure outside due to the heated air at the bird level rising toward the roof and then ejected outdoors, allowing fresh air to settle at the animal level providing refreshment. The only source of air that enters the building through the open side wall curtains is the outside wind. Consequently, the minimum simulated and experimental Δp obtained are at this level as −5.32 and −5 Pa, respectively. While the average Δp at this age varied from −2.79 Pa for model prediction to −1.78 Pa for observed data, the highest Δp matches −0.7 and 3 Pa, respectively. So, the resulting negative pressure differential draws fresh air into the house through inlets while pulling dirty, moist, and hot air outside as recorded in Fig. 7. The above agrees with Wu et al. [44], findings, which reveal that the pressure distribution in the model research with an inlet velocity of 0.1 m/s in a dairy cattle barn during natural ventilation ranged from −0.6 to 0.2 Pa.

In the power mode, a positive differential pressure was applied, as seen in Fig. 5. This control mode uses lateral fans to exhaust warm used air, and inlets as a source of clean air enter, where their adjustment determines the air exchange rate. The slot width controls positive static pressure according to bird age, density, and microclimate environment. This operation approach typically occurs when the set temperature is near the outside temperature. The poultry building needs just medium ventilation, not too tiny as in the natural mode or too high as in tunnel one. The fans run faster, and the inlets open more when the temperature rises over the set point. Moreover, fan speed reduces, and the inlets close more when the temperature drops below the specified set point. The average predicted and experimental differential pressure were 25.71 and 24.89 Pa, respectively, and the maximum values recorded were 36 and 38.67 Pa, severally. However, this approach is not very widespread since it frequently results in the deterioration of building

Table 3
Comparison of experimental data with simulations of air velocity.

Age	Day	E_{Day} (%)	E_{Age} (%)	E (%)	$NMSE_{Day}$ (m.s^{-1})	$NMSE_{Age}$ (m.s^{-1})	NMSE (m.s^{-1})	R^2
1	9	−4,7921	0.4318	0.6836	−0.5445	−0.338	0.1906	0.9325
	10	5.6557			−0.2156			
2	24	0.6105	0.6219		3.4426	1.0315		
	25	−2.0809			−1.3794			
3	35	−0.8175	0.9971		−0.44	0.0796		
	36	4.0752			0.2807			

Table 4
Exposure time required to transition from normal to danger state during acute exposed thermal condition.

		Simulated Air Velocity (m.s^{-1})		
		Max	Min	Mean
		1.64	0.6	0.957
		Exposure Time (min)		
Temperature (°C)	35	238	155	189
	37	157	102	125
	41	163	47	58

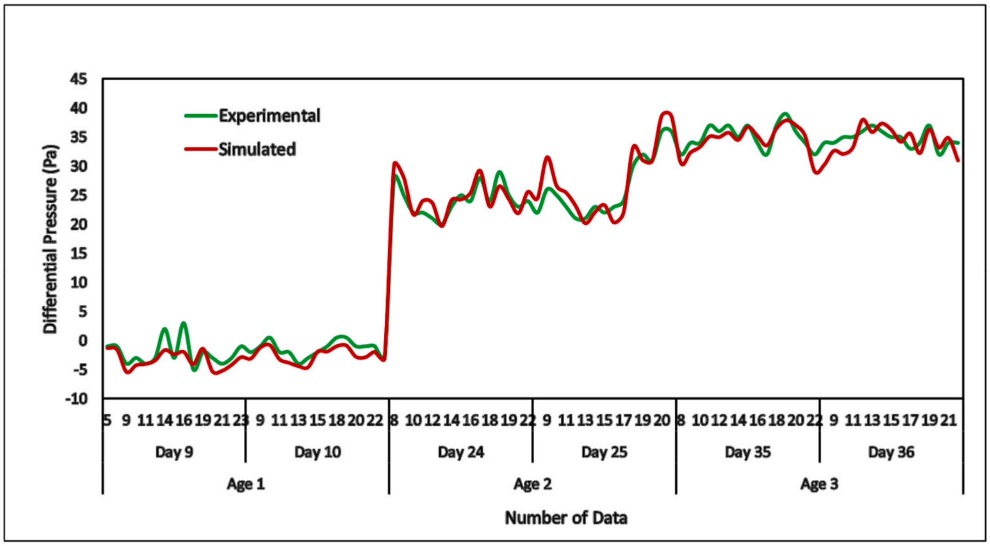

Fig. 6. Simulation of the differential pressure compared to the experienced measurements.

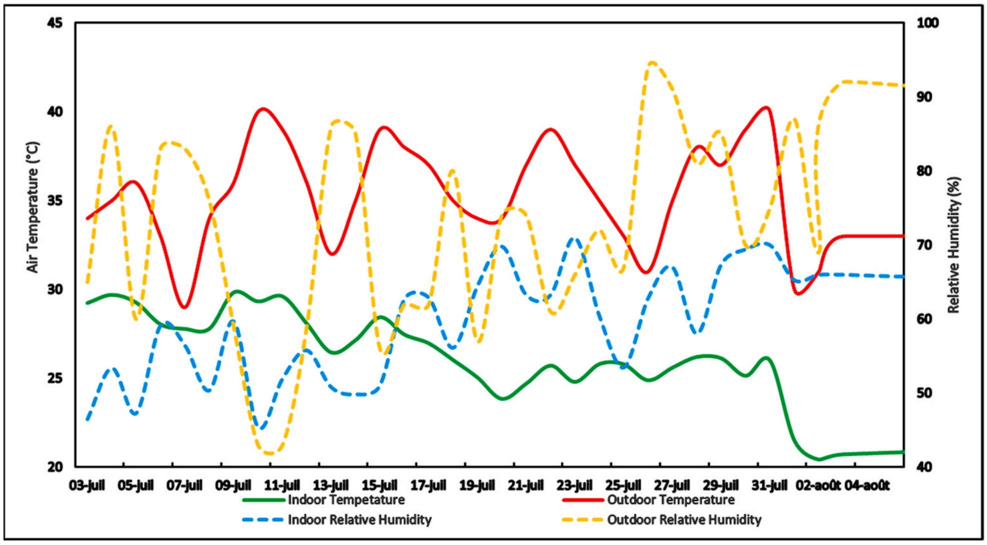

Fig. 7. Monitored indoor and outdoor air temperature and relative humidity.

components because moisture seeps through the building's cracks [54]. While using the same ventilation mode but choosing negative pressure, the Δp of the layer house studied in Ref. [1] varied slightly over four distinct lateral fans operation with a total range from −30 to 0 Pa.

Due to the summer season's cycle and the broilers' needs rising at the third and final age, a positive static pressure system was used in the tunnel ventilation, drawing air through tunnel inlets at the end of the house. As the ventilation rate climbed to its highest load, as illustrated in Fig. 8, a maximum positive pressure was observed of 39 and 37.98 Pa, and an average value of 34.37 and 34.9 Pa for the simulated and observed parameter, respectively. In fact, the more the building needs airspeed, the more the pressure must be increased to blow more air into the barn. During a complete production cycle, Rosa et al. [45] performed a study in a mechanically ventilated laying hen facility in a Mediterranean environment and discovered that the differential pressure value varied between 12.4 and 49.7 Pa across nine ventilation stages from 97 004 to 239 220 m^3 h^{-1}. The ventilation system was expanded when the Δp level of the house was raised. Generally, the mechanically ventilated broiler houses have a static pressure differential between 10 and 25 Pa [17]. Chai et al. [24], discovered an average Δp of −36.5 and −48.9 Pa in two separate houses, during a two-year monitoring period in tunnel ventilation layer hen house, and confirmed that the highest Δp was caused by the insufficient opening of the ceiling air inlets. Whereas, Park et al. [46], discovered that the static pressure at most locations, in tunnel ventilation broiler house, distant from the exhaust fans was constant at −14.0 Pa and similar in all simulation cases. The static pressure, and hence the airflow rate of each slot opening, were approximately equal. While Luck et al. [47] studied the air velocity distribution, and quantified the floor area in three facilities and found that the differential static pressure at all fans of the poultry house ranged from 36.3 to 39.6 Pa, and the total airflow varied from 329 270 to 512 730 m^3 h^{-1} in the three experiences.

The trend of the total actual ventilation rate during the monitored period and selected days of each production cycle age is presented in Fig. 8. Depending on the bird's age and the climatic conditions, the airflow value steadily increased from the beginning to the end of the production cycle. On day 34, there was a noticeable increase in ventilation rate, reaching a peak of roughly 99 m^3 s^{-1}, the highest number ever recorded. These findings are consistent with those of [48], who discovered a maximum ventilation rate of 15 m^3 h^{-1}. animal^{-1} at the end of the production cycle and an average value of 5.8 m^3 h^{-1}. animal^{-1} in the summer. In most cases, the required and appropriate ventilation rate is set as the minimum ventilation rate for livestock housing. The recommended values should be 1.8 m^3 h^{-1} kg^{-1} in the summer and 0.18 m^3 h^{-1} kg^{-1} in the winter to remove moisture, heat, and toxic gases and deliver fresh air [49]. In Northern Europe, the average ventilation rates are 1.78 m^3 h^{-1} kg^{-1} in the summer (range from 0.78 to 2.94), and 0.89 m^3 h^{-1} kg^{-1} in the winter (ranging from 0.60 to 1.76) [50].

According to Fig. 6 and Table 5, the model's differential pressure diverges perfectly from the real conditions throughout the third ages of the production cycle. Table 5 represents the model validation process. According to the value of E, the average percentage difference between measured and simulated differential pressure was 1.03%, with a maximum error of 3.3% observed in the second age. The mean NMSE of the mathematical model was −1.06 Pa, and the coefficient of determination R^2 was 0.98, reflecting the efficiency of estimating the indoor pressure under house settings.

4. Conclusion

In this study, field experience and mathematical model simulations were performed to explore air velocity and differential pressure within a mechanical ventilation broiler house in the Mediterranean area. The experience was conducted to measure the micro-climate characteristics associated with these elements of a summer production cycle. During the first age of the production cycle, a natural ventilation mode was operated, using natural forces to move air into and out of the building. As a result, the measured and modelled data related to air velocity ranged from 0.1 to 0.5 m s^{-1} for real measurements with a mean of 0.3 m s^{-1}; and 0.09–0.7 m s^{-1} for predicted ones with an average of 0.28 m s^{-1}. While the average differential pressure at this age varied from −2.79 Pa for model prediction to −1.78 Pa for observed data.

As the microclimatic conditions become more critical with the broiler needs, the mode control switches to mixed ventilation characterised by the combination of wall fans and inlets in its operational mode. Comparing this stage to the previous one, the findings have marginally risen. The highest airspeed for both measurements is 0.66 m s^{-1}, while the average velocity for experimental and simulated data is respectively 0.52 and 0.562 m s^{-1}, and the mean Δp corresponds to 24.89 and 25.71 Pa, severely. During the last age of the production cycle, the air velocity and differential pressure have increased with maximum recorded and simulated values of 1.5 and 1.641 m s^{-1}, and 39 and 37.98 Pa, with an average airspeed of 0.95 m s^{-1}, and a mean Δp of 34.9 and 34.37 Pa, respectively.

The model's performance was assessed statistically, with relative errors of 0.68% and 1.03%, respectively, and normalised mean square errors (NMSE) of 0.19 m/s and −1.06 Pa for air velocity and differential pressure. A linear regression model revealed that the coefficient of determination R^2 for air velocity was 0.93 and 0.98 for static pressure difference, validating the accuracy of estimating these components under house conditions.

Consequently, this new proposed mathematical model can provide a valuable reference for predicting and controlling air velocity and differential pressure inside livestock buildings. Future work will develop, design, and implement an optimal controller to track and stabilize these parameters inside the poultry house system. This study's technique was intended to be extended to other mechanically ventilated agricultural buildings in various climatic conditions with different geometries, locations, or designs under the condition that the parameters associated with the equations are modified in accordance with the properties of the selected poultry house.

The findings of this study have to be seen in the light of some limitations. The first one relates to broiler management. Data collection was a little challenging since it was required to shorten intervention durations and times of access and leave from the building to minimise animal stress. This made it more challenging to keep track of the maintenance instruments. The second limitation concerns time constraints. The production cycle, which lasted exactly 45 days, and the time allotted for the study constrained the amount of time that could be used to measure every parameter. In order to avoid missing anything and to have a basis for comparison, it is highly advised that future research begin, if possible, with many simulations or experiments in various poultry houses simultaneously and under the same conditions.

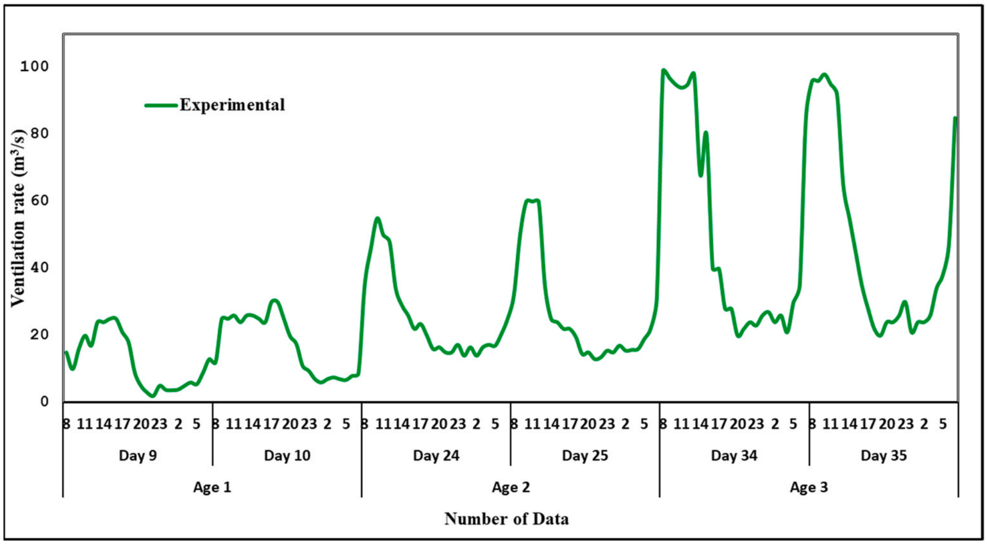

Fig. 8. Monitored ventilation rate variation during the rearing period.

Table 5
Comparison of experimental data with simulations of differential pressure.

Age	Day	E_{Day} (%)	E_{Age} (%)	E (%)	$NMSE_{Day}$ (Pa)	$NMSE_{Age}$ (Pa)	NMSE (Pa)	R^2
1	9	2.8566	1.2875	1.0369	−3.3519	−2.3643	−1.0632	0.9884
	10	−0.2816			−1.3767			
2	24	2.7244	3.3031		4.5422	4.7315		
	25	3.8817			4.9208			
3	35	−1.4972	−1.4798		−3.523	−5.5568		
	36	−1.4624			−7.5906			

The actual fan airflow efficiencies are unknown, may considerably drop the recommended and desired value, and may vary over time. Due to dust accumulation on fan blades and shutters, motor efficiency decline, fan imbalances, belt wear and slippage, and other factors, fan performance might gradually decline under field conditions [51]. Consequently, the ventilation rate is impacted as well as the air velocity, differential pressure, indoor temperature, and relative humidity … It is recommended to utilise a handheld tachometer to evaluate and regulate fan performance, spot unexpected issues related to fans, and prevent possible calculation errors in the house ventilation rate.

This study evaluated the methodology by assuming that the broilers are in comfortable thermal conditions. Therefore, it is suggested that future work could assess the mathematical model by considering the relative animal activity that shows the actual animal's daily cycles, depending on animal actions during the day (feeding, moving, resting, etc.).

Author contribution statement

Narjice Elghardouf: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Ilyas Lahlouh: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Ahmed Elakkary; Nacer Sefiani: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare no conflict of interest.

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