MODELING AND EXPERIMENTAL VALIDATION TO ESTIMATE THE ENERGY BALANCE FOR A POULTRY HOUSE WITH MISTING COOLING

MODELAMIENTO Y VALIDACIÓN EXPERIMENTAL PARA DETERMINAR UN BALANCE DE ENERGIA EN UN GALPON AVICOLA CON NEBULIZACIÓN INTERNA

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ABSTRACT: The aim of this study was to develop and validate a simplified steady state mathematical model to predict temperature distribution in a commercial poultry house equipped with a negative pressure ventilation system and internal misting. The model was validated with data obtained experimentally during the summer. For external temperature conditions of 26, 27, and 29 °C, the best combinations of energy generated by misting ($q_{misting}$), ventilation rate (V), global heat loss coefficient for the roof (U_t), and global heat loss coefficient for the wall (U_{par}) were encountered to maintain the majority of the installation with temperatures within the optimal thermal comfort range for the birds (24 to 29 °C).

KEYWORDS: evaporative cooling, thermal modeling, tunnel ventilation broiler house

RESUMEN: Este trabajo tuvo como objetivo desarrollar y validar un modelo matemático simplificado en estado permanente, para predecir la distribución de temperatura en un galpón avícola comercial, equipado con sistemas de ventilación de presión negativa y nebulización interna. El modelo fue validado a partir de datos experimentales obtenidos en condiciones de verano. Se encontró para condiciones con temperatura externas de 26, 27, e 29°C, las mejores combinaciones que debe tener el galpón, entre la energía generada por efecto de la nebulización ($q_{misting}$) y por la rata de ventilación (V), el coeficiente global de perdida de calor del techo (U_t) y el coeficiente global de perdida de calor de las paredes (U_{par}), que permitan mantener la mayor parte del galpón con temperaturas que se encuentren dentro de la faja de conforto térmico para las aves de que para temperaturas externas (24 a 29 °C).

PALABRAS CLAVE: resfriamiento evaporativo, modelo térmico, instalaciones avícolas modo túnel

1. INTRODUCTION

The importance of broiler chicken production in Brazil is growing both on a national and international scale, requiring more efficient and intensive production systems in terms of greater yields. Therefore, negative pressure tunnel ventilation buildings are becoming more utilized in tropical countries with the intent of achieving greater productivities.

One of the greatest concerns in poultry production is maintaining temperatures at permitted levels which do not surpass the upper limit of the thermal comfort range which should not exceed 29 °C, where the optimal temperature is 25 °C [1,2]. Therefore, some studies have been performed with the objective of producing models which predict chicken behavior in function of variables including temperature, humidity, and gas concentrations such as ammonia [3,4,5].

When ventilation fans in the poultry buildings are insufficient for diminishing internal temperatures below 29 °C, secondary or artificial modification are used, such as changing the thermal properties of the roofing material [6,7] or incorporating evaporative cooling systems by installation porous plates or cooling pads, or by misting [8,9].

Due to the importance of understanding distribution parameters such as temperature inside poultry buildings, some simple models have been proposed which provide the average temperature inside the installation, but not distribution throughout the building [10,11,12]. Other more complex methods have also been used based on computational fluid dynamics (CFD), which is capable of generating temperature distribution, velocity, humidity, and gas concentrations in a steady state and transient regimes at any point within the installation [2,13,14].

Therefore, the objective of this study was to develop a simplified mathematical model in steady state which allows for calculating the average temperature distribution along the length of a tunnel ventilation building with an adiabatic evaporative cooling system by misting.

2. MATERIAL AND METHODS

2.1 Operating conditions and experimental measurements

The modeled and simulated poultry house is located in the region of Rio Verde, Goiás, Brazil and is part of an integrated system of *Perdigão Agroindústrias S/A*, with a total of 22,700 male Cobb chickens per building, and a housing density of 14 birds per m^2, being part of the experimental work performed by the reference [15]. The installation measures 126 m in length, 12.8 m in width, 3 m in height, a 0.5 m overhang, and a roof with a 25 % inclination. The installation presents two lateral air entrances (Fig. 1).

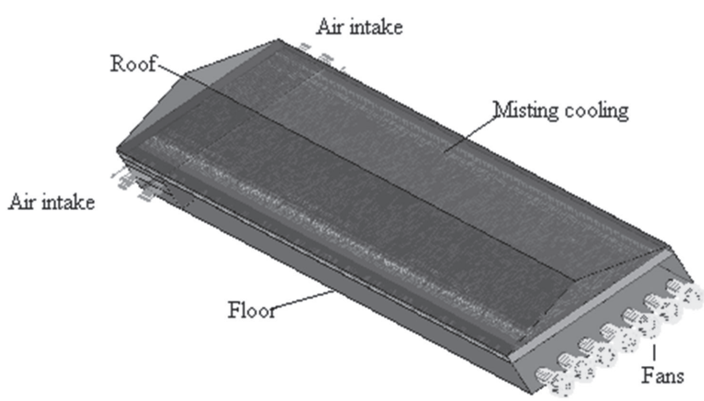


Figure 1. Diagram of the modeled and simulated poultry house

2.2. Thermal analysis

An energy balance was performed considering the following characteristics and adapting the methodology utilized by the references [16,17].

- negative pressure tunnel ventilation building with seven exhaust fans
- zinc roof
- homogeneous sprinkling at the roof height
- lateral air entrance has the same area as the exhaust area
- polyethylene lining
- permanent conditions

2.3 Validation of the model

The variables measured in the experimental part were used to validate the data obtained by the mathematical method (Table 1). Values were registered with a HOBO HO8 datalogger with resolution of 0.5 °C and +/- 1 %, measured in 15 min intervals. Temperatures of the roof were measured with an ICEL model TD 95 infrared thermometer with a resolution of 1 °C and +/- 2 %. The data of the external environment (temperature, velocity, and wind direction) were obtained with a datalogger installed in a meteorological shelter 1.5 m from the ground. Solar radiation data was obtained from a regional meteorological station.

Table 1. Experimental variables utilized to validate the model

Location	Variable	Value
air entrance	external temperature specific heat of the air density of the air	26 °C 1006 J kg^{-1} K^{-1} 1.16 kg m^{-3}.
air outlet	air flow generated by the exhaust fans	46.41 m^3 s^{-1}
roof and walls	global heat transfer coefficient for the roof global heat transfer coefficient for the walls direct solar radiation on the roof, calculated as by reference [18] diffuse solar radiation on the roof, calculated as by reference [18] shading factor of the walls shading factor of the roof	1.5 W m^{-2} K^{-1} 5.5 W m^{-2} K^{-1} 300 W m^{-2} 12.1 W m^{-2} 1.0 0.7
floor	heat flux generated by the birds ($q_{poultry}$) calculated according to reference [19] absorptivity of the chickens [20]	7.68 W $animal^{-1}$ ≈0.45
interior	water flow by the internal sprinkler system at the roof height analyzed as latent heat flux ($q_{misting}$)	1146600 W

2.3.1 Statistical analysis

Results obtained by the mathematical model were verified and compared with the corresponding data obtained experimentally in the field for the negative pressure tunnel ventilation building. Concordance between the measured values and those reported by the model were evaluated, calculating the normalized mean square error (NMSE) according to ASTM (2002) [21,22]. A sample of 25 experimental measurements of all data collected at 10, 50, and 87 m from the air entrance was used. The normalized mean square error (NMSE) values less than 0.25 are accepted as good indicators of concordance.

$$NMSE = \frac{\overline{\left(C_p - C_o\right)^2}}{\left(\bar{C}_{pn} \cdot \bar{C}_{on}\right)} \quad (1)$$

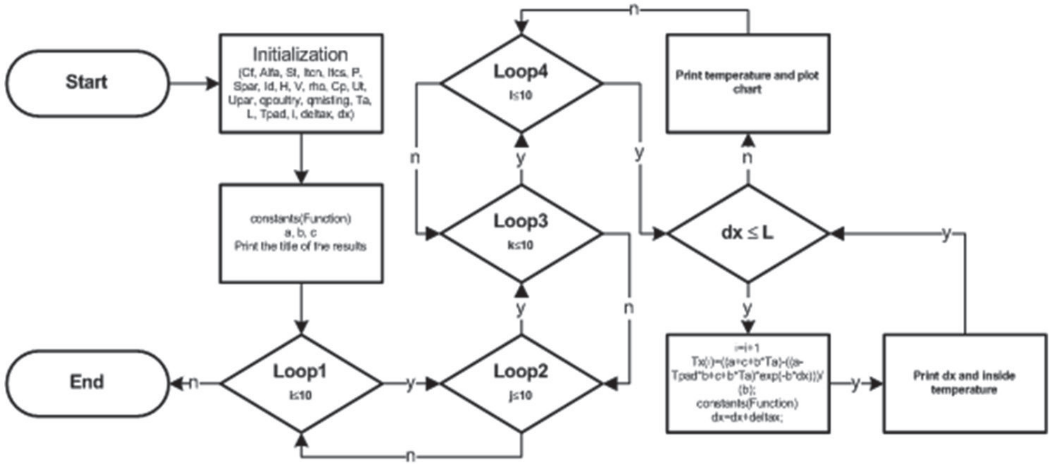
where:

$$\overline{\left(C_p - C_o\right)^2} = \frac{\sum_n \left(C_{\dot{p}} - C_{\dot{o}}\right)^2}{n} \quad (2)$$

2.4 Computational model

A computational routine in Scilab 5.1.1 was developed to simulate the performance of the building based on variation of the parameters $q_{Misting}$ (500,000 to 1,400,000 W), U_T (1 to 10 W m^{-2} K^{-1}), U_{Par} (0.5 to 5.0 W m^{-2} K^{-1}), and V (10 to 100 m^3 s^{-1}), in function of the external temperature (26, 27, and 29 °C). The objective was to encounter an optimized method to calculate temperature distribution along the length of the installation (Fig. 2).

Figure 2. Flowchart representing a computational process for interior temperature distribution



3. RESULTS AND DISCUSSION

The thermal balance was developed considering that temperature inside the installation at a distance X from the lateral entrances is T_x. The temperature can be determined by estimating a differential element at the equilibrium dx (Fig. 3).

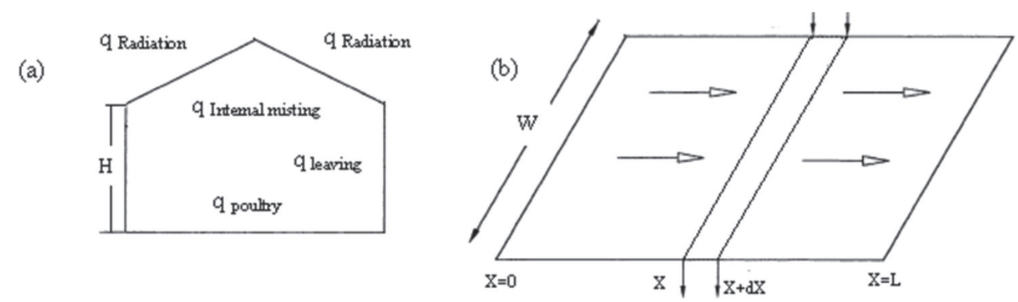


Figure 3. Differential element to function as a control volume

Considering the roof as symmetrical, total heat on the roof for a longitudinal element dx, without shade, is given by:

$$E_{intake} = (I_{tcN} + I_{tcS})\ Pdx + I_{d-par} 2Hdx \quad (3)$$

Considering shade, the total heat within a poultry house for a longitudinal element dx is given by:

$$E_{Leaving} = S_T (I_{tcN} + I_{tcS})\ P\ dx + S_{Par} I_{d-Par} 2Hdx \quad (4)$$

where S_T and S_{Par} are shading factors (1.0 for no shading, and 0.0 for total shading). A part of the heat load within the element is absorbed by the birds and the rest is added to the sensitive heat flow of the element as:

$$E_{Inlet} = (1 - C\alpha)dQ = (1 - C\alpha)(\ S_T (I_{tcN} + I_{tcS})Pdx + S_{Par} I_{d-Par} 2Hdx) \quad (5)$$

Therefore, the heat flux can be estimated as:

$$E_{outlet} = \left[U_T P + 2U_{Par} H)\right] dx(T_x - T_a) \quad (6)$$

Thus:

$$dQ_{neto} = E_{Inlet} - E_{Outlet}$$

$$E_{Inlet} - E_{Outlet} = (1 - C\alpha)(S_T (I_{tcN} + I_{tcS}) P dx + S_{Par} I_{d-Par} 2H dx) - \left[U_T P + 2U_{Par} H\right] dx (T_x - T_a) \quad (7)$$

The heat flux is absorbed by the ventilation air and therefore the difference in temperature by the element is given by the relationship:

$$E_{\text{Accumulated}} = V \rho C_p dT_x$$

$$E_{\text{generated}} = \left(q_{Poultry} N - q_{Misting}\right) \frac{H}{W L} dx \quad (8)$$

$$E_{Accumulated} = E_{Inlet} - E_{Outlet} + E_{\text{generated}}$$

$$V \rho C_p dT_x = (1 - C\alpha)\left[(S_T (I_{tcN} + I_{tcS}) P + S_{Par} I_{d-Par} 2H)\right] dx - \left[U_T P + 2U_{Par} H\right] dx (T_x - T_a) + \left(q_{Poultry} N - q_{Misting}\right) \frac{H}{W L} dx \quad (9)$$

where:

$$A = \frac{(1 - C\alpha)\left[(S_T (I_{tcN} + I_{tcS}) P + S_{Par} I_{d-Par} 2H)\right]}{V \rho C_p}$$

$$B = \frac{U_T P + 2U_{Par} H}{V \rho C_p}$$

$$C = \frac{\left(q_{Poultry} N - q_{Misting}\right)}{V \rho C_p} \frac{H}{W L}$$

Therefore, from Eq. 9, a first order differential equation (Eq. 10) is derived and is solved to arrive at Eq. 11, which is used to determine the average temperature of the installation at any point X.

$$\frac{dT_x}{dx} = A - B(T_x - T_a) + C \quad (10)$$

$$T_x = \frac{A + C + BT_a - (((A - T_a B) + (C + BT_a)) e^{-(BX)})}{B} \quad (11)$$

A comparison among the data shows that the average dry temperature (tbs) values do not significantly differ between those reported by the model and those collected experimentally. They present normalized mean square errors of 0.0011, 0.0018, and 0.0035 for the distances of 10, 50, and 87 meters, respectively; indicating a good correlation between the results (Table 2). It was therefore concluded that the proposed model can be used to predict temperature distribution behavior inside a poultry installation.

Table 2. Comparison of experimental data with temperature and efficiency data from the model

	Temperature (°C) at 10 m		Temperature (°C) at 50 m		Temperature (°C) at 87 m	
	Experimental	**Proposed model**	**Experimental**	**Proposed model**	**Experimental**	**Proposed model**
Mean	26.5	26.9	27.5	28.1	29.4	30.2
NMSE	0.0011		0.0018		0.0035	

Figures 4, 5, and 6 present the best combinations of the variables $q_{Misting}$, U_T, U_{Par}, and V for external temperatures of 26, 27, and 29 °C, respectively, within the thermal comfort range of 24 and 29 °C, at 25, 50, 75, and 100 % of the installation length (31, 63, 94, and 126 m). It can be observed for the lengths of 126 m (typical dimensions for commercial installations) that there is a wide range of the different variables which directly influence the internal temperature of the poultry building; this makes the best combination depending on other technical and economic variables, but the final decision can be supported by tools such as the proposed model. Among these technical factors, $q_{misting}$ is very important since it can cause significant reductions in the internal temperatures; however, it may also cause greater humidities inside the installations which are not beneficial for the health and development of the birds.

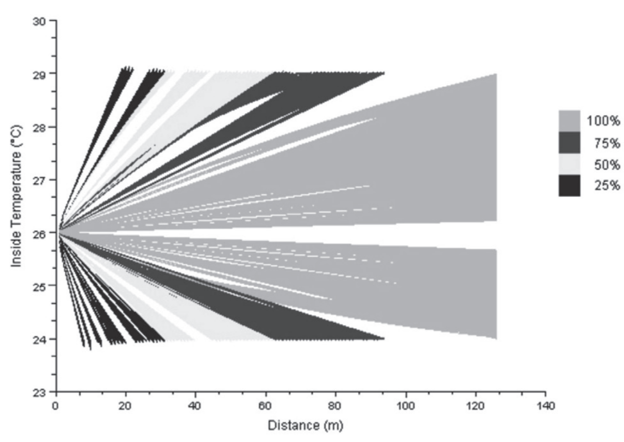


Figure 4. Distribution of internal temperature on installation behavior in function of combinations of $q_{Misting}$, U_T, U_{Par} and V for an external temperature of 26 °C

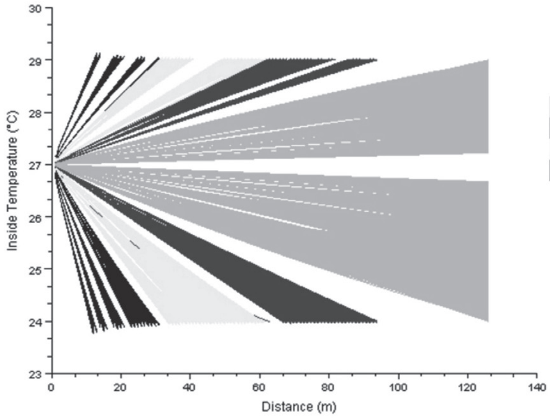


Figure 5. Distribution of internal temperature on installation behavior in function of combinations of $q_{Misting}$, U_T, U_{Par} and V for an external temperature of 27 °C

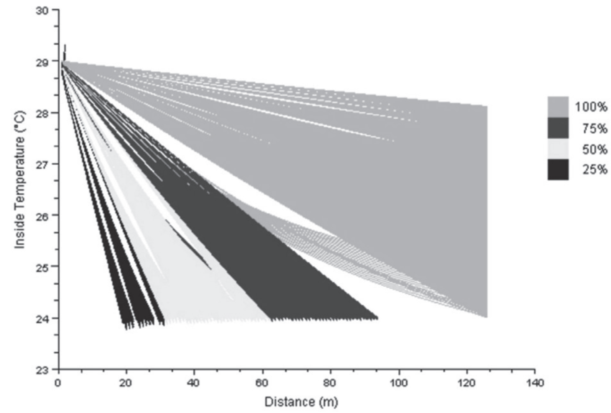


Figure 6. Distribution of internal temperature on installation behavior in function of combinations of $q_{Misting}$, U_T, U_{Par} and V for an external temperature of 29 °C

Given the ample range of combinations that can be presented to maintain the internal temperatures between 24 and 29 °C as presented in Figs. 4, 5, and 6, the amplitude of these ranges can be filtered by seeking the most desired internal temperatures.

Table 3 presents the best heat combinations generated by misting ($q_{misting}$), and ventilation rate (V), where the encountered internal temperatures were 24 and 26 °C (these temperatures being ideal for broiler chickens in the final week before slaughter) [7] for buildings measuring between 63–94 m and 94–126 m with the U_T and U_{par} fixed at 1.0 W m^{-2} K^{-1} and 5.0 W m^{-2} K^{-1}. In the same way new combinations can be obtained depending on the desired temperature within the installation.

Table 3. Intervals between the variables to obtain internal thermal comfort temperatures for different external temperatures

	External temperature 26 °C		**External temperature 27 °C**		**External temperature 29 °C**	
Dist. (m)	**63–94**	**94–126**	**63–94**	**94–126**	**63–94**	**94–126**
$q_{misting}$ (W)	1.2 x 10^6	9 x 10^5–1.1 x 10^6	9 x 10^5–1.3 x 10^6	9 x 10^5–1.3 x 10^6	1.0 x 10^6–1.4 x 10^6	1.0 x 10^6–1.4 x 10^6
V (m^3 s^{-1})	80	20–100	10–100	20–100	10–100	20–100

4. CONCLUSIONS

The results obtained with the energy balance model presented a good relationship with experimental data which permits us to conclude that the model is appropriate to improve broiler poultry buildings operating with negative pressure ventilation and internal misting. The model is also adequate for alterations in variables such as external temperature and material properties when aiming to obtain internal temperatures within the thermal comfort range for the birds.

This model can be used to perform initial dimensioning of tunnel ventilation poultry buildings, encountering suitable relations between building length and width in function of combinations of variables such as internal misting, external temperature, ventilation rate of the exhaust fans, diffuse and direct thermal radiation, the heat generated by the birds, and material thermal properties.

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Nomenclature

C_p	specific heat of the air, J kg^{-1} K^{-1}
C	surface coverage factor of the chickens, %
α	absorptivity of the chickens
H	ceiling height, m
$I_{TCN} = I_{TCS}$	solar radiation intensity on the north and south sides of the roof, W m^{-2}
I_{d-par}	diffuse solar radiation intensity on the wall W m^{-2}
L	building length, m
N	total number of birds
P	perimeter of the roof, m
$q_{poultry}$	heat generated by the chickens, W animal^{-1}
$q_{Misting}$	heat generated by misting, W
S_T	shading factor of the roof
S_{par}	shading factor of the wall
T_a	ambient temperature, °C
U_T	global heat loss coefficient for the roof, W m^{-2} K^{-1}
U_{Par}	global heat loss coefficient for the wall, W m^{-2} K^{-1}
V	ventilation rate for seven exhaust fans, m^3 s^{-1}
W	width of the building, m
ρ	specific mass of the air at the lateral inlets, kg m^{-3}

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