Ciência Rural, Santa Maria, v.52:11, e20201015, 2022
http://doi.org/10.1590/0103-8478cr20201015
ISSNe 1678-4596
RURAL ENGINEERING

Pre-cooling water applied to porous plates of evaporative cooling systems

João Levi Bastos Fernandes[1] **Tadayuki Yanagi Junior**[2] **Giselle Borges de Moura**[2] **Alex de Oliveira Ribeiro**[3]

[1]Departamento de Engenharia (DEG), Escola de Engenharia (EENG), Universidade Federal de Lavras (UFLA), 37200-900, Lavras, MG, Brasil. E-mail: joão.fernandes@ufla.br. *Corresponding author.
[2]Departamento de Engenharia Agrícola (DEA), Escola de Engenharia (EENG), Universidade Federal de Lavras (UFLA), Lavras, MG, Brasil.
[3]Departamento de Estatística (DES), Instituto de Ciências Exatas e Tecnológicas (ICET), Universidade Federal de Lavras (UFLA), Lavras, MG, Brasil.

ABSTRACT: *This study assessed the ways the thermal environment is influenced by pre-cooling the water employed in wetting the porous plates present in the evaporative cooling systems (ECS). The experiment was performed using two physical models constructed on a distorted and reduced scale, which simulated closed agricultural facilities equipped with ECS made up of porous cellulose panels. In one physical model, the plates were made wet using chilled water (ECS_{cw}), while in the other they were moistened using natural water, at environment temperature (ECS_{nw}). Both inside the physical models and outside, in the external environment, the air dry-bulb temperature (t_{db}), black globe temperature (t_{bg}) and air relative humidity (RH) were measured, at 10 sec intervals. Later, the environmental indices, ECS_{nw} cooling effectiveness and ECS_{cw} performance factor were assessed. When the porous ECS plates were thoroughly wet using pre-cooled water, lowering of the thermal variables and comfort indices was seen to be greater than when wetting the plates was done using water at room temperature. An empirical equation was proposed to determine the cooling performance factor applied to the ECS_{cw} related to water temperature, t_{db} and air wet-bulb temperature.*
Key words: *thermal environment, air cooling, air conditioning, chilled water.*

Efeito do pré-resfriamento da água aplicada em placas porosas de sistemas de resfriamento evaporativo

RESUMO: *Objetivou-se com o presente trabalho avaliar o efeito do pré-resfriamento da água usada no molhamento de placas porosas de sistemas de resfriamento evaporativo (SRE) sobre o ambiente térmico. O experimento foi realizado em dois modelos físicos construídos em escala reduzida e distorcida que simularam instalações agrícolas fechadas, equipadas com SRE composto por painéis porosos de celulose. Em um modelo físico, o molhamento das placas foi realizado por meio de água resfriada (SRAR) e o outro por meio de água natural à temperatura ambiente (SRAN). Mensurou-se a temperatura de bulbo seco do ar (t_{bs}), temperatura de globo negro (t_{gn}) e umidade relativa do ar (UR) no interior dos modelos físicos e no ambiente externo em intervalos de 10s. Posteriormente, foram calculados índices ambientais, a efetividade de resfriamento do SRAN e fator de desempenho do SRAR. O pré-resfriamento da água usada no molhamento de placas porosas de SRE propiciou maior redução nas variáveis térmicas e índices de conforto em relação ao molhamento com água à temperatura ambiente, sendo proposta uma equação empírica para a estimativa do fator de desempenho de resfriamento aplicada ao SRAR em função da temperatura da água, da t_{bs} e da temperatura de bulbo úmido do ar.*
Palavras-chave: *ambiente térmico, resfriamento de ar, condicionamento de ar, água gelada.*

INTRODUCTION

The problems involved in controlling the thermal environment inside agricultural facilities has directed research towards the state of ambience (CURI et al., 2014; WATANABE et al., 2018). This control; although, crucial in regions experiencing hot climates, continues to be stressful for breeders.

However, for the achievement of positive outcomes in the agricultural sector, such control becomes imperative, in order to ensure that the animals throughout their production cycle, can be reared in their thermal comfort zone, thus ensuring higher rates of production (SCHIASSI et al., 2015; LOPES et al., 2020).

This sector has witnessed a gradual transition from the popularly termed conventional

Received 11.19.20 Approved 11.09.21 Returned by the author 06.05.22
CR-2020-1015.R1
Editors: Leandro Souza da Silva Marcia Xavier Peiter

open breeding systems and the employment of artificial temperature control only when required, to systems enclosed by curtains or masonry that, besides the climate control processes, provide the advantages of lowering the internal temperature of the animal growth environments.

Evaporative techniques, using nebulization or moistened porous plates have been proven as the most effective and economically feasible options in closed aviaries to decrease the internal temperatures (DAMASCENO et al., 2010). The wet porous plates, more than the nebulization method, have higher air-cooling capacity, which may differ, based on the various materials used in their construction (TINOCO et al., 2002; PANAGAKIS and AXAOPOULOS, 2006).

From the commercial perspective, cellulose is the most prominent of the different materials used to manufacture the evaporative cooling plates. However, good alternative substitutes for these pads, are expanded clay and vegetable fibers, to ensure higher performance or lower expenditure (TINÔCO et al., 2002; ROSA et al., 2011).

As the air temperature increases and the air humidity outside the premises decreases, the cooling effectiveness also rises. However, works that assessed the temperature of the water used to wet the porous plates employed in animal husbandry to facilitate better thermal indices are very few in the literature.

Therefore, the goal of this research was to determine the effect on the thermal environment, which pre-cooling the water utilized to wet the porous plates of the evaporative cooling systems could exert (ECS).

MATERIALS AND METHODS

The experiment was carried out using two identical physical models constructed on a site, at the geographic coordinates of 21º13' 45.2'S latitude; 44º58'32.85''W of longitude and 918 m of altitude. Experiencing the Cwa type of climate (based on the Köppen classification), the place revealed rainy and temperate weather conditions (mesothermal), with dry winters and rainy summers, subtropical, with higher than 22 °C temperature during the warmest month (DANTAS et al., 2007).

Physical models and experimental treatments

The two physical models, identical in their construction properties, are typical of the enclosed agricultural facilities in animal husbandry (Figure 1). The physical models were constructed on the scales mentioned: width (W), length (L) and height (H) of 1:10, 1:25 and 1:2, respectively, thus ensuring the internal dimensions of 1.5 m (W) x 6 m (L) x 1.5 m (H). The physical models had roof ridges oriented in the true East-West direction. The main aim of the physical models, constructed in a suitable site, was to facilitate the placement of evaporative porous plates and exhaust fans, ensuring free airflow through them.

The first physical model had a cellulose pad cooling system using natural water (ECS_{nw}), while the second had the cellulose pad cooling system but with chilled water (ECS_{cw}) being used instead.

Acclimatization systems installed on physical models

Each physical model had, at one end, a porous commercial cellulose pad (1 m wide x 1 m high x 0.15 m thick) installed, while at the other end three exhausts (flow rate of 4200 m^3 h^{-1} each) were provided. This acclimatization system is normally employed in the agricultural sector, as in the wind tunnel type commercial aviaries. The evaporative cooling system was designed based on VANTRESS (2018).

In the ECS_{cw}, the water-cooling system installed included a hermetic compressor, air condenser (0.56 W), thermal box (77 L capacity) and a pump (0.37 kW and 2400 L h^{-1}). Water flow rates of 0.17±0.004 L s^{-1} and 0.17±0.003 L s^{-1}, respectively for the ECS_{cw} and ECS_{nw}, were pumped to the upper part of the cellulose pad. Water volume in excess was returned to the reservoir to be reused. In the ECS_{cw} physical model, water cooling was controlled using the digital thermostat model TIC-17RGTi), manufactured by Full Gauge Controls (±1 °C accuracy).

Measurements and instrumentation

To analyze the cooling capacity of the air flow through the moistened porous plates, the internal and external thermal environments were evaluated, for each physical model.

Inside the physical models, constructed on a reduced scale, five recording thermo-hygrometers were positioned, model U12-001, manufactured by Onset, to ensure the measurement of the air dry-bulb temperature (t_{db}, °C) and air relative humidity (RH, %), with ±0.35 °C and ±2.5% accuracy for the RH values in the 10 to 90 % range, respectively. The black globe temperature (t_{bg}, °C) was measured at the center of the porous plate alone (Figure 1), while an external temperature sensor, model TMC6-HD, manufactured by Onset, was positioned in the center of a black plastic globe, 3.6 cm in diameter (SANTOS et al., 2005), and painted with matte black paint on the outside. This external temperature sensor was hooked up to the external channel of the recording thermo-hygrometer. The responses from the thermometers

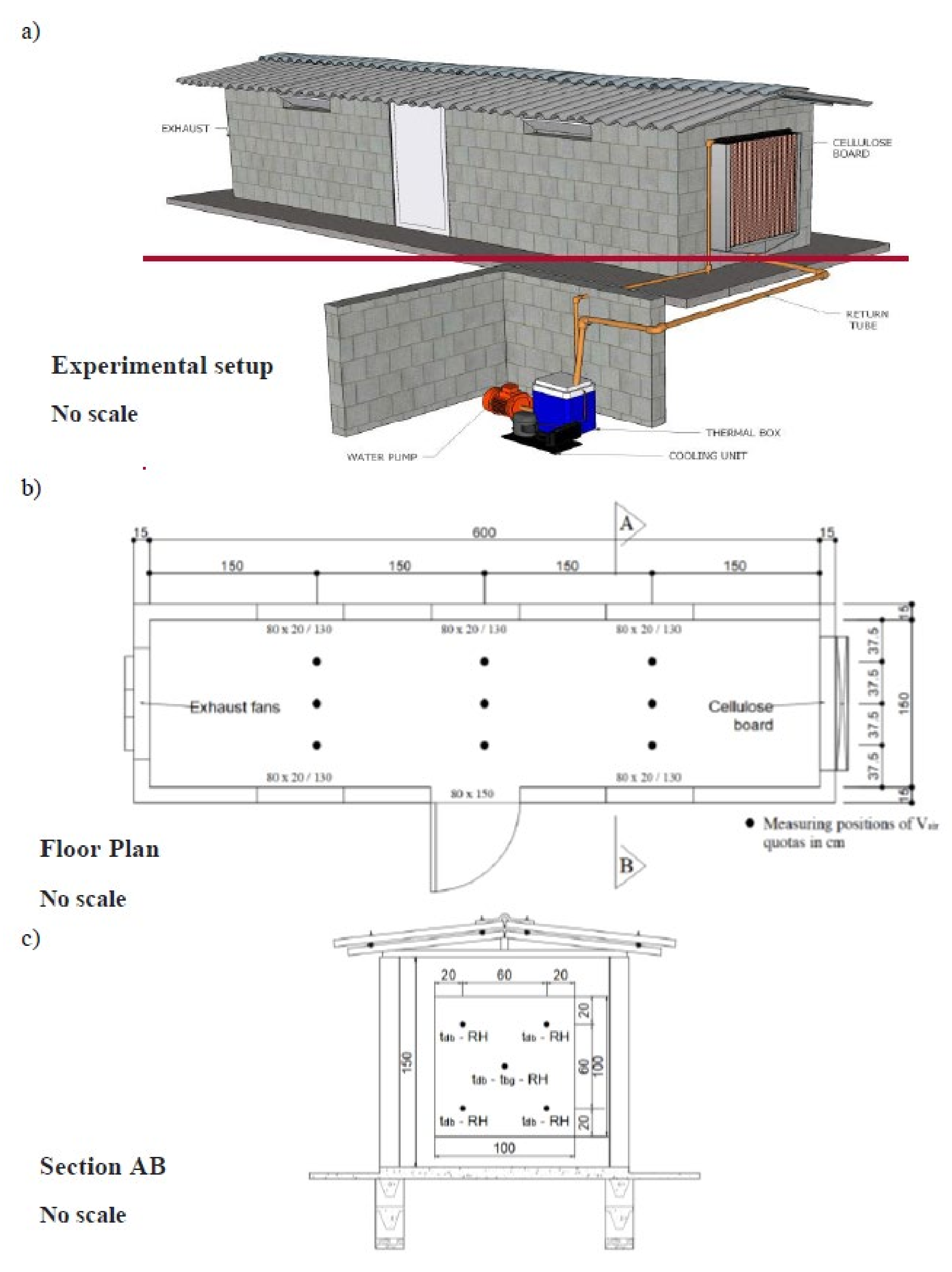

Figure 1 - Experimental setup in perspective (a), Floor Plan (b) and Section AB (c) of the physical model of aviaries constructed with a cellulose board cooling system using natural water (ECS_{nw}) and chilled water (ECS_{cw}). The dots in Section AB indicate the measurement positions of the temperatures on the air dry-bulb and black globe (t_{db} and t_{bg}, respectively) and air relative humidity (RH). Detailing without scale.

installed in the plastic black globe were confirmed against a standard black globe thermometer, built using a copper plate 15 cm in diameter and 0.5 mm thick, painted in matte black color.

Five thermo-hygrometers were fitted 30 cm from the porous plate, one each at 20 cm from both ends and one in the center. The thermo-hygrometers were placed 30 cm from the porous plates to ensure that the condition of the air immediately post cooling after passing through the wet porous plates, is not wet with the water droplets from the plates. Apart from the external channels of these logging instruments, the wetting water temperatures (t_{water}) of the cellulose plates inside both the ECS_{cw} and ECS_{nw} reservoirs were also recorded. Using the recording thermo-hygrometer in the external environment, the t_{db}, t_{bg} and RH were determined. All the specified measurements cited earlier were taken at 10 second intervals.

Using a Highmed manufactured model HM-385, hot-wire anemometer (accuracy ±5% +0.1 m s^{-1}) the values of V_{air} were noted in nine distinct positions, within each physical model (Figure 1) at 75 cm height, always at the commencement of each experiment day.

Measurements of the surface temperature of the external surface of the moistened cellulose panels (t_{ps}) were taken at 1-minute intervals, with an infrared thermographic camera, model Ti 55 manufactured by Fluke (accuracy of 0.05 ºC).

To record the thermal values inside the reduced models provided with ECS, the temperature-humidity index (THI) (THOM, 1958), as well as black globe-humidity index (BGHI) were determined from the recorded meteorological variables and t_{bg} (BUFFINGTON et al., 1981), besides the specific enthalpy (h) (ALBRIGHT, 1990 and adapted by RODRIGUES et al., 2011), cooling effectiveness (ε) (RIANGVILAIKUL & KUMAR, 2010), performance factor of evaporative cooling (F) (ASHRAE, 1997) and the vapor pressure deficit (VPD) (ASHRAE, 2005). All the equations are cited in table 1.

The THI is a thermal comfort evaluation index dependent upon the t_{db} and air dew-point temperature (t_{dp}) (THOM, 1958). In a single value, the BGHI surveys the effects of t_{db}, radiation and air flow via the t_{bg} and air humidity through the t_{dp}

Table 1 - Equations for calculation of the thermal environment evaluation indices, thermodynamic properties of the air and effectiveness of the evaporative cooling of the air.

Nº	Equation	Legend
1	$THI = t_{db} + 0.36 \cdot t_{dp} + 41.5$	THI: Temperature humidity index (dimensionless); t_{db}: air dry-bulb temperature (º C); t_{dp}: air dew-point temperature (° C)
2	$BGHI = t_{bg} + 0.36 \cdot t_{dp} + 41.5$	BGHI: black globe temperature index and humidity (dimensionless); t_{bg}: black globe temperature (° C); t_{dp}: air dew-point temperature (° C)
3	$h = 1.006 \cdot t_{db} + \frac{RH}{p_B} \cdot 10^{\left(\frac{7.5 \cdot t_{db}}{237.3 + t_{db}}\right)} \cdot (71.28 + 0.052 \cdot t_{db})$	h: specific enthalpy of air (kJ $kg_{dry\ air}^{-1}$); t_{db}: air dry-bulb temperature (ºC); RH: air relative humidity (%); p_B: local barometric pressure (mmHg)
4	$\varepsilon = \frac{t_{dbi} - t_{dbo}}{t_{dbi} - t_{wbi}}$	ε: Evaporative cooling effectiveness; t_{dbi}: air dry-bulb temperature at the evaporative plates' inlet (°C); t_{dbo}: air dry-bulb temperature at the evaporative plates'outlet (°C); t_{wbi}: air wet-bulb temperature at the evaporative plates' inlet (°C)
5	$F = \frac{h_i - h_o}{h_i - h_a}$	F: Evaporative cooling performance factor (decimal); h_i: enthalpy of the air at the evaporative plates' inlet (kJ $kg_{air\ dry}^{-1}$); h_o: enthalpy of the air at the evaporative plates' outlet (kJ $kg_{air\ dry}$-1); h_a: saturated air enthalpy calculated considering t_{db} equal to the water temperature at the evaporative plates'inlet (kJ $kg_{air\ dry}^{-1}$)
6	$VPD = \left(1 - \frac{RH}{100}\right) \cdot P_{ws}$	VPD: vapor pressure deficit (kPa); RH: Relative air humidity (%); Pws: air saturation pressure proposed by Tetens for air dry-bulb temperatures above 0º C (equation 6);
7	$P_{ws} = 6.1078 \cdot 10^{\left(\frac{7.5 \cdot t_{db}}{237.3 + t_{db}}\right)}$	Pws: air saturation pressure (mbar); t_{db}: air dry-bulb temperature (ºC); Note: 760 mmHg = 1013.25 mbar

(BUFFINGTON et al., 1981). Enthalpy is a physical quantity, expressed in the realm of thermodynamics, which quantifies the energy of a system (ALBRIGHT, 1990). The cooling effectiveness or saturation efficiency indicates the ratio between the lowered t_{db} recorded and the maximum that can be theoretically achieved (CAMARGO, 2008; RIANGVILAIKUL & KUMAR, 2010). The performance factor F, pertinent to non-adiabatic cooling processes is the ratio between the enthalpy reduction observed and the maximum theoretically achievable (ASHRAE, 1997). The VPD refers to the difference between the water vapor pressure during saturation conditions and the current water vapor pressure at a specific temperature (YUAN et al., 2019).

The air wet-bulb temperature (t_{wb}) was calculated analytically by the equations that define the psychrometric properties of the air (WILHELM, 1976).

Experimental phases, experimental design and statistical analysis

To confirm the presence of equivalence between the two ECS fitted in the physical models, experiments were conducted prior, for three non-consecutive days, where similar conditions required for the system to function were maintained. This step was termed the 'pre-test phase'.

Subsequently, nine non-consecutive days, the systems (ECS_{nw} and ECS_{cw}) were evaluated, during the hottest part of the day (from 12:00 to 15:45), termed the 'test phase'. The t_{water} values during the course of the tests were in the 18.3 to 21.5 °C range for the ECS_{nw} and from 8.8 to 16.1 °C for the ECS_{cw}. Analysis was done each day, for three operating cycles of the ECS, with and without cooling the water used to wet the plates. Each cycle took 1 hour to complete, which included 15 min of ECS operation and 45 min of waiting, to cool the water down to as close to the desired temperature as possible.

From among all the 15 min of data collected, only the data drawn during the intermediate 5 min were statistically analyzed. This procedure enabled higher stabilization of the ECS because in the initial stage the evaporative cooling plate was kept wet and, during the final 5 minutes, there was a trend of the surface temperature of the plate to rise due to the inability of the water cooling system to maintain the water at constant. All the data recording was done in 10 second intervals.

The completely randomized design was adopted (CRD) with the water temperature represented as a single factor, subdivided into two levels (ECS_{nw} and ECS_{cw}), used in the physical models. The response variables, pertaining to the thermal comfort in these two situations, were evaluated, giving 27 repetitions in all, for each one.

Using the Student's t test for the independent data with 5% significance level these variables were analyzed between the two levels of the factor. The fit of the models was assessed based on the regression analysis of variance and the coefficient of determination (R^2). Adjustment was done for the multiple linear regression models to evaluate the cooling performance factor for the ECS_{cw} as a function of the t_{water}, thermal environment variables, thermal environment evaluation indices and enthalpy, and the correlation coefficients were determined.

Employing the R statistical computational system (R DEVELOPMENT CORE TEAM, 2019), all the statistical analyses were done.

RESULTS AND DISCUSSION

The equivalence present between the cellulose board cooling system using natural water (ECS_{nw}) and the cellulose board cooling system utilizing chilled water (ECS_{cw}) was obvious during the pre-test phase (Table 2) because, on analysis, all the variables were statistically equal ($P > 0.05$, t test). The reduction of t_{db}, THI, BGHI and h showed values of -7.1 and -6.7 ºC, -6.2 and -6.0, -10.0 and -10.4, -3.5 and -3.1 for the ECS_{nw} and ECS_{cw}, respectively. The ε values for the ECS_{nw} and ECS_{cw} were 79.7 and 75.5, respectively, clearly indicating that the responses of the cooling systems were similar and that it is the exclusively the water temperature variations that induce the changes.

During the test phase, statistical differences were confirmed, revealing improved ECS_{cw} performance when the means of the t_{db}, t_{dp} and t_{water} variables, and the THI and BGHI indexes and the thermodynamic property h ($P < 0.01$, test t) were analyzed. The t_{bg} also displayed identical profile ($P < 0.05$, t-test). In turn, the variables UR and t_{ps} were statistically equal ($P > 0.05$, t test).

During the days that the experiments were performed, when the t_{db} and RH mean values of the external environment were 31.2 ºC and 40.9%, respectively, the ECS_{nw} induced a 6.8 ºC decrease in the t_{db}, with a corresponding 29.1 % increase in the RH, while the ECS_{cw} caused the t_{db} to decline at 8.1ºC and the RH to show a rise of 28.3 % in (Table 2). For a closely similar thermal condition (32 ºC and 40 %), a system made up of a cellulose evaporative plate can lower by 7.7 ºC the internal temperature of aviaries, while causing a 34.6% increase in the RH (VANTRESS, 2018).

Table 2 - Student's t test applied to compare thermal and cooling effectiveness of scaled-down models equipped with evaporative cooling of the wetted porous plate type, in the pre-test and test phases.

Phase	Variables and Indices	---------------Avarage------------------		-----Standard Deviation------		P(T<=t) uni-caudal
		ECS_{nw}	ECS_{cw}	ECS_{nw}	ECS_{cw}	
Pre-test	Δt_{db}	-7.1	-6.7	1.039	0.962	0.2127
	ΔRH	31.3	29.6	3.336	3.504	0.1505
	ΔTHI	-6.2	-6.0	0.641	0.579	0.2699
	ΔBGHI	-10.0	-10.4	2.538	2.489	0.3760
	Δh	-3.5	-3.1	0.678	0.709	0.1362
	Δt_{bg}	-11.0	-11.1	2.658	2.597	0.4445
	Δt_{dp}	2.6	2.0	1.177	1.113	0.1532
	ε	79.7	75.5	7.321	7.039	0.1113
	t_{ps}	28.1	27.8	3.803	3.788	0.4369
	t_{water}	17.7	17.4	0.681	0.873	0.1994
Test	Δt_{db} **	-6.8	-8.1	0.886	1.077	2.8586*10-6
	ΔRH	29.1	28.3	2.541	2.904	0.1231
	ΔTHI **	-5.8	-7.9	0.803	1.077	6.0195$^{*}10^{-11}$
	ΔBGHI **	-9.3	-11.5	2.513	2.536	0.0014
	Δh **	-3.0	-7.0	1.457	1.781	3.9887$_{*}10^{-12}$
	Δt_{bg} *	-10.3	-11.7	2.539	2.547	0.0241
	Δt_{dp} **	2.7	0.6	1.292	1.183	4.9292$^{*}10^{-8}$
	ε **	72.5		8.385	-	-
	F	-	0.237	-	0.054	-
	t_{ps}	30.1	29.5	3.637	3.713	0.2517
	t_{water} **	19.4	12.9	0.775	1.860	1.0742$^{*}10^{-18}$

Δt_{db}: Difference between indoor and outdoor air dry-bulb temperature (°C). ΔRH: Difference between indoor and outdoor air relative humidity (%). ΔTHI: Difference between indoor and outdoor temperature-humidity index. ΔBGHI: Difference between internal and external black globe-humidity index. Δh: Difference between internal and external enthalpies (kJ $kg_{dry\ air}^{-1}$). Δt_{bg}: Difference between internal and external black globe temperatures (°C). Δt_{dp}: Difference between internal and external air dew-point temperatures (°C). ε: Evaporative cooling effectiveness (%). F: Evaporative cooling performance factor (%). t_{ps}: Surface temperature on the external surface of the wet porous plate (°C). t_{water}: Water temperature (ºC). Significance levels by Student's t test: * (P < 0.05) ** (P < 0.01).

In their investigations of a variety of configurations for the evaporative cooling system using computer simulations, CARVALHO et al. (2009) concluded that in September, for the study duration, a tunnel mode ventilation system related to a porous material type evaporative cooling system, moistened at 70% efficiency, lowered the THI by 1.8±1.4 when compared to a negative pressure wind tunnel ventilation system lacking the evaporative cooling. In the current study, the ECS_{cw} induced a 2.0±0.8 reduction when compared to the ECS_{nw}, for the same index being investigated.

In their research, in Brazil, TINÔCO et al. (2002) compared a few of the available alternative porous materials, and reported BGHI values roughly 2.5 lower in the expanded clay-filled slabs than for those filled with sawdust, vegetable fiber and charcoal. A difference of 2.2, on average, was achieved favoring the ECS_{cw}, suggesting this as another possibility to boost the cooling performance.

In their endeavor to determine the distribution of illuminance and enthalpy in two aviaries used for rearing broilers, FAUSTINO et al. (2021) recorded a 0.5 kJ kg^{-1} reduction, induced by a clay tile-covered brick shed when compared to a straw-covered wooden shed. In this study, the ECS_{cw} registered a 3.9±0.8 kJ kg^{-1} reduction compared to the ECS_{nw} for the same index investigated.

For ECS_{nw}, the mean value of ε was found to be 72.5 % (Table 2), the range being 52.4 to 83%. ROSA et al. (2011), recorded 78.1 % as the average value of ε for cellulose. Of note, that the value of ε shows variations as a function of the air that flows through the porous plates, the water mass that flows over the porous material surface and its uniformity, besides other variables.

For the ECS_{cw}, the mean performance factor (F) was found to be 0.237±0.054. During the tests, the outdoor and indoor air dry-bulb temperatures were in the 28.2 to 35.6 °C range (average of 31.2° C) and from 21.5 to 27.1° C (average of 23.1° C), respectively. The relative humidity of the outdoor air was in the range of 25.8 to 51.4 % (average 40. %) while, for the indoor air, the variation hovered between 53.2 and 76.8%, with 69.1% as the average value. The water temperature was in the 8.8 to 16.1 °C range, with the average at 12.9 °C. In fact, AL-BADRI & AL-WAALY (2017), in their assessment of a direct evaporative cooler for inlet air temperatures from 24.5 to 33.6 °C (average 31.0° C) and water temperatures from 15.8 to 21.0 °C (average 18.7° C), observed that F values occurred between 0.10 and 0.41, showing a mean of 0.214. Thus, among other factors, the greatest value achieved by the average performance factor acquired in this research can be credited to the lowest values attained by the wetting water temperature on the porous plates. Further, these results imply an escalation in the performance factor with lowering of the water temperature, findings which concur with those reported by these authors.

On investigating the multiple regression models among the variables, the best fit model identified to determine the F values was seen as a function of the t_{water}, t_{db} and t_{wb} (equation 8), achieving R^2 of 0.9753 and with all the variables showing a minimum of 97.52% significance. The standard errors corresponding to the coefficients of the equation for t_{water}, t_{db} and t_{wb} were 0.004267, 0.004019 and 0.005922, respectively.

$$F = - 0.010218 \cdot t_{water} - 0.017841 \cdot t_{db} + 0.042595 \cdot t_{wb}$$

CONCLUSION

In the present study, under the specific conditions, pre-cooling the water used to wet the porous plates present in the evaporative cooling systems induced an additional drop in the thermal variables (of 1.4 °C and 1.4 °C for t_{db} and t_{bg}, respectively). With respect to the evaluation of the indices of the thermal environment and the thermodynamic property of the air values of 2.1, 2.2 and 4.0 kJ kg dry air^{-1} (for THI, BGHI and h, respectively) were observed, related to the wetting of the porous plates, using water at room temperature.

In order to estimate the evaporative cooling performance factor as a function of the temperature of wetting water of the porous plates, as well as the air dry- and wet-bulb temperatures, an empirical equation was fitted.

The electrical energy consumed for cooling the water in the chilled water cellulose board cooling system (ECS_{cw}) was not determined in the current study because the investigations were performed only on a small-scale model; however, in future it has been suggested to conduct the research in commercial aviaries.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

ACKNOWLEDGEMENTS

We are grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the finantial incentive for the second (CNPq, Grant no. 310729/2018-1) and financial support for the third (CNPq, Project no. 462095/2014-2) authors. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

AUTHORS' CONTRIBUTIONS

Conceptualization: GBM and TYJ. Data acquisition: JLBF. Design of methodology and data analysis: GBM, TYJ, JLBF and AOR. JLBF, TYJ, GBM and AOR prepared the draft of the manuscript. All authors critically revised the manuscript and approved of the final version.

REFERENCES

AL-BADRI, A. R; AL-WAALY, A. A. Y. The influence of chilled water on the performance of direct evaporative cooling. **Energy and Buildings**, v.155, p.143-150, 2017. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0378778817319977>. Accessed: Jun. 10, 2020. doi: 10.1016/j.enbuild.2017.09.021.

ALBRIGHT, L. D. **Environment control for animals and plants**. ASAE Textbook, 4. American Society of Agricultural Engineers Michigan, St. Joseph, 1990.

ASHRAE. **Handbook of fundamentals**. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA 30329. 2005.

ASHRAE. **Handbook – fundamentals (SI)**. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA.1997.

BUFFINGTON, D. E. et al. Black globe-humidity index (BGHI) as comfort equation for dairy cows. **Transaction of the ASAE**, St. Joseph, v.24, n.3, p.711-714, 1981. Available from: <https://www.tandfonline.com/servlet/linkout?suffix=CIT0005&dbid=16&doi=10.1080%2F09291016.2018.1526499&ke

y=10.13031%2F2013.34325>. Accessed: Oct. 17, 2019. doi: 10.13031/2013.34325.

CARVALHO, V. F. et al. Mapping of potential use of evaporative cooling systems in Southeastern Brazil. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, PB, v.13, n.3, p.358-366, 2009. Available from: <https://www.scielo.br/scielo.php?script=sci_arttext&pid=S1415-43662009000300020>. Accessed: Oct. 17, 2019. doi: 10.1590/S1415-43662009000300020.

CURI, T. M. R. de C. et al. Geostatistic to evaluete the environmental control in different ventilation systems in broiler houses. **Engenharia Agrícola**, Jaboticabal, SP, v.34, n.6, p.1062-1074, 2014. Available from: <https://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-69162014000600004&lng=en&nrm=iso>. Accessed: May, 11, 2020. doi: 10.1590/S0100-69162014000600004.

DAMASCENO, F. A. et al. Evaluation of broiler welfare in two air-conditioned commercial sheds. **Science and Agrotechnology**, Lavras, MG, v.34, no.4, p.1031-1038, 2010. Available from: <https://www.scielo.br/scielo.php?pid=S1413-70542010000400033&script=sci_arttext>. Accessed: May, 11, 2020. doi: 10.1590/S1413-70542010000400033.

DANTAS, A. A. A. et al. Climatic classification and tendencies in Lavras region, MG. **Ciência e agrotecnologia, Lavras**, v.31, n.6, p.1862-1866, 2007. Available from: <http://dx.doi.org/10.1590/S1413-70542007000600039>. Accessed: Oct. 10, 2019. doi: 10.1590/S1413-70542007000600039.

FAUSTINO, A. C. et al. Spatial variability of enthalpy and illuminance in free-range broiler sheds. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, PB, v.25, n.5, p.340-344, 2021. Available from: <https://www.scielo.br/j/rbeaa/a/CBdbpVJpKg7F8W87Ry4Mmvk/?lang=en&format=html>. Accessed: Oct. 10, 2019. doi: 10.1590/1807-1929/agriambi.v25n5p340-344.

LOPES, I. et al. Geostatistics applied to the environmental mapping of aviaries. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, PB, v.24, n.6, p.409-414, 2020. Available from: <https://www.researchgate.net/profile/Iug_Lopes/publication/341134200Geostatisticsapplied_to_the_environmental_mapping_of_aviaries/links/5eb0645245851592d6b8c20f/Geostatistics-applied-to-the-environmental-mapping-of-aviaries.pdf>. Accessed: Jun. 10, 2020. doi: 10.1590/1807-1929/agriambi.v24n6p409-414.

PANAGAKIS, P.; AXAOPOULOS, P. Simulation comparison of evaporative pads and fogging on air temperatures inside a growing swine building. **American Society of Agricultural and Biological Engineers**, v.49, n.1, p.2019-2015, 2006. Available from: <https://elibrary.asabe.org/abstract.asp?aid=20240>. Accessed: Apr. 19, 2021. doi: 10.13031/2013.20240.

R DEVELOPMENT CORE TEAM. **R**: A Language and Environment for Statistical Computing. Vienna: R Foundation for Statistical Computing, 2019. Available from: <http://www.R-project.org/>. Accessed: Apr. 19, 2021.

RIANGVILAIKUL, B.; KUMAR, S. An experimental study of a novel dew point evaporative cooling system. **Energy and Buildings**, v.42, n.5, p.637-644, 2010. Available from: <https://doi.org/10.1016/j.enbuild.2009.10.034>. Accessed: Oct. 10, 2019. doi: 10.1016/j.enbuild.2009.10.034.

RODRIGUES, V. C. et al. A correct enthalpy relationship as thermal comfort index for livestock. **International Journal of Biometeorology**, v.55, n.3, p.455-459, 2011. Available from: <https://doi.org/10.1007/s00484-010-0344-y>. Accessed: May, 03, 2019. doi: 10.1007/s00484-010-0344-y.

ROSA, J. F. et al. Analysis of the cooling efficiency of porous panels filled with expanded clay compared to cellulose, using a wind tunnel. **Engineering in Agriculture**, Viçosa, MG, v.19, no.6, p.516-523, 2011. Available from: <https://periodicos.ufv.br/reveng/article/view/96/80>. Accessed: Dec. 28, 2019. doi: 10.13083/reveng.v19i6.107.

SANTOS, P. A. D. et al. Thermal environment inside small scale poultry house models with natural and artificial roof ventilation. **Agricultural Engineering**, Jaboticabal, v.25, no.3, p.575-584, 2005. Available from: <http://dx.doi.org/10.1590/S0100-69162005000300002>. Accessed: Jun. 15, 2019. doi: 10.1590/S0100-69162005000300002.

SCHIASSI, L. et al. Behavior of broilers subjected to different thermal environments. **Agricultural Engineering**, Jaboticabal, SP, v.35, no.3, p.390-396, 2015. Available from: <https://www.scielo.br/scielo.php?pid=S0100-69162015000300390&script=sci_arttext>. Accessed: May, 11, 2020. doi: 10.1590/1809-4430.

THOM, E. C. **Cooling degree-days air conditioning, heating and ventilating**. Transactions of the ASAE, Atlanta, vol. 55, no. 7, p. 65-72, 1958.

TINÔCO, I. F. F. et al. Evaluation of alternative materials used in the manufacture of porous plates for adiabatic evaporative cooling systems. **Brazilian Journal of Agricultural and Environmental Engineering**, v.6, no.1, p.147-150, 2002. Available from: <http://dx.doi.org/10.1590/S1415-43662002000100026>. Accessed: Oct. 15, 2019. doi: 10.1590/S1415-43662002000100026.

VANTRESS, Cobb. **Cobb broiler management guide**. Cobb-Vantress, Siloam Springs, AR, USA, 2018.

WATANABE, P. H. et al. Cooling ventilation at forrowing for sows from firstto third parturition. **Comunicata Scientiae Horticultural Journal**, Bom Jesus, PI, v.9, n.4, p.556-564, 2018. Available from: <https://www.comunicatascientiae.com.br/comunicata/article/view/1098/592>. Accessed: Jun. 09, 2020. doi: 10.14295/CS.v9i4.1098.

WILHELM, L. **Numerical calculation of psychrometric in SI units**. Transactions of the ASAE, v.19, n.2, p.318-321, 325, 1976. Available from: <https://elibrary.asabe.org/abstract.asp?aid=36019>. Accessed: Jan. 14, 2020. doi: 10.13031/2013.36019.

YUAN, W. et al. Increased atmospheric vapor pressure deficit reduces global vegetation growth. **Ecology**, v.5, n.8, eaax1396, 2019. Available from: <https://www.science.org/doi/10.1126/sciadv.aax1396>. Accessed: May, 7, 2021. doi: 10.1126/sciadv.aax1396.