

Thermal assessment of ecological tiles in physical models of poultry houses

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Abstract

In countries with tropical climates, such as Brazil, the high summer temperatures associated with high relative humidities are a stress factor in animal production. Excessive heat within a poultry facility causes a reduction in feed intake and production, and increased bird mortality. With the knowledge that about 75% of the radiant heat load within a facility comes from the roof, it is necessary to study alternatives that can minimize this radiation. Thus, the objective of the present work is to analyze the thermal environment inside physical broiler housing models constructed on a reduced scale (1:10), where the thermal comfort was evaluated by the black globe humidity index (BGHI) and radiant heat load (RHL). Five models built with different roofing materials were evaluated. Based on the results, it can be concluded that roofs constructed with the channel clay roofing tile (T_{B30}), natural fiber tiles with their external side painted white (T_{FVP15}) and tiles made of recycled long-life packaging (T_{LV15}), provide better thermal environments within the models.

Keywords: reduced models, thermal environment, alternative materials, thermal capacity.

Evaluación térmica de tejas ecológicas en modelos físicos de galpones avícolas

Resumen

En países con climas tropicales, como Brasil, las altas temperaturas asociadas con altas humedades relativas en el verano contribuyen como un factor de estrés en la producción animal. El calor excesivo dentro de una instalación avícola causa una reducción en el consumo de alimento y en la producción, y aumento en la mortalidad de las aves. Conociendo que el 75% de la carga de calor radiante dentro de una instalación viene desde el techo, es necesario estudiar alternativas que pueden minimizar esta radiación. El objetivo del presente trabajo fue analizar el ambiente térmico dentro de los modelos físicos de instalaciones de pollos de engorde construidos a escala reducida (1:10), donde el confort térmico se evaluó por el índice de humedad y de globo negro (BGHI) y la carga de calor radiante (RHL). Cinco modelos construidos fueron evaluados con diferentes materiales para techos. Basados en los resultados, se puede concluir que los techos construidos con tejas de cerámica (T_{B30}), placas de fibra natural pintadas de blanco con en el lado externo (T_{FVP15}) y placas de fabricadas con envases larga vida reciclado (T_{LV15}), proporcionan los mejores ambientes térmicos.

Palabras clave: modelos a escala, ambiente térmico, materiales alternativos, capacidad térmica.

1. Introduction

The use of ecological tiles is an uncommon practice despite the potential to use industrial and urban waste when manufacturing them.

For many years, in the construction and agricultural

industries, roofs have been built with traditional materials such as fiber-cement, ceramics and aluminum. Current environmental concerns have forced architects and engineers to review the materials used in civil construction, and they now favor the use of renewable and less polluting energy sources [1].

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The roof most commonly used in Brazilian poultry facilities are fiber-cement tiles, which are simple to install, maintain and clean (in comparison to traditional ceramic tiles) in addition to costing less. This is mainly because the support structure is lighter and requires less labor [2,3]. Another advantage is that these tiles may also be combined with other methods, such as a reflective paint and water sprinkling on the external surface in order to decrease the temperature inside the facility [4].

In Brazil, a country with a tropical climate and high summer temperatures that receives intense solar radiation, the materials to construct roofs should provide good thermal insulation for the internal environment of the installations so they are less influenced by the outside climate [5].

According to some researchers [6], of the thermal radiation received from various parts of the installation surrounding an animal in the shade, 28% of the radiant heat load comes from the sky, 21% from the roofing, 18% from the unshaded area and 33% from the shaded area.

The current trend of studies on agricultural projects in South American countries that occupy a prominent place on the world stage, such as Brazil, Colombia and Argentina, is focused on the technical and economic evaluation of technologies seeking to increase efficiency since the global economy requires the poultry industry to be more productive and at the same time more profitable.

In tropical and subtropical countries, the importance of studying new roofing materials and especially ecological materials lies in the wealth of natural resources that these countries possess and the high incidence of direct solar radiation, especially in the summer. According to [7], incident solar radiation generates thermal discomfort, which is mostly related to the roofing material and the type of thermal cooling used, in humans and in animals housed inside production installations.

This discomfort increases the risk of work-related accidents in addition to exposing the body to various conditions such as hyperthermia, dizziness and others. Animal discomfort causes a reduction in growth performance and increased mortality rate [8].

In this context, the construction of ecological roofs has begun to use plant cellulose fiber, paper and recycled long-life packaging. These types of roofs have some advantages including: being eco-friendly, having good thermal and acoustic insulation, good mechanical strength, impermeability, and are socially inclusive and generate employment and income.

As these new eco-friendly materials are being used in the construction of roofing tiles, the agro-industrial sector requires technical information on the damping capacity of the radiant heat load provided by these materials.

Due to limited economic resources and to save time performing studies seeking to evaluate roofing materials, it is common to use physical broiler house models built on a reduced scale [9-14]. According to [12], the use of these physical models is based on the theory of similarity, which intends to establish relationships that allow for real predictions to be made based on observations of smaller models.

Therefore, the objective of this study was to evaluate the efficiency of ecological tiles to reduce the radiant heat load.

It seeks to look for improvements in the thermal environment of facilities for broilers.

2. Material and methods

2.1. Construction and field deployment of the reduced models

In order to undertake this experiment, five models at a reduced scale of 1:10 were constructed, based on the methodology used by [9,11-14] for east-west oriented poultry houses. They had different types of roofing as indicated in Table 1, were constructed according to the cross-section schematic of the models (Fig. 1) and arranged according to the overview of the experimental area (Fig. 2).

The physical models were deployed in the experimental area at the Construction and Ambience Sector of the Engineering Department, Federal University of Lavras, located in southern Minas Gerais - Brazil (21°14' S latitude and 45°00' W longitude, located 918 m above sea level). The local climate, according to the Köppen climate classification, is Cwa: a humid temperate with a dry winter.

In order to construct small-scale models, real dimensions of a commercial poultry house for production of broiler chickens were used as the basis, with a standard that is adopted worldwide (12.0 m wide, 120.0 m long, ceiling height of 3.5 m and distance between roof trusses of 5.0 m).

In the construction, 1 cm thick plywood panels were used that were reinforced by a 3 x 3 cm wood structure. After construction, the models were 1.2 m wide, 1.5 m long and had a distance between roof trusses of 0.5 m. There were three sections of 5 m that represented the distance between pillars. All constructed roofs had 2.0 meter overhangs. The central sector of physical models was used to set the measuring sensors of environmental variables.

The east and west sides of the buildings were completely closed with plywood. The side had a height of 0.5 m, corresponding to the real sheds' existing 5 cm low walls. The buildings' floors were elevated from the soil by 0.4 m, making the air flow at floor height approximately the same, with respect to a real shed [11,12]. All reduced physical models had the ridges of the roofs oriented in the east-west direction since they are located in the southern hemisphere.

Table 1.
Treatments tested in the experiment.

	Description of the Treatments
T _{AL15}	am roof, 0.5 mm thick, 15° inclination, with no louver and a ceiling height of 3.5 m.
T _{B30}	clay roofing tile (Roman), 30° inclination, with no louver and a ceiling height of 3.5 m.
T _{VN15}	tile of cellulose fiber (recycled paper) and bitumen, 0.5 mm thick, 15° inclination, with no louver and a ceiling height of 3.5 m.
T _{VP15}	Roofing tile of cellulose fiber (recycled paper) and bitumen, externally painted with two coats of hydrated lime, 0.5 mm thick, 15° inclination, with no louver and a ceiling height of 3.5 m.
T _{LV15}	tiles made of recycled long-life packaging, with a thickness of 6 mm, ceiling height of 3.5 m and 15° inclination, with no louver.

Source: The authors.

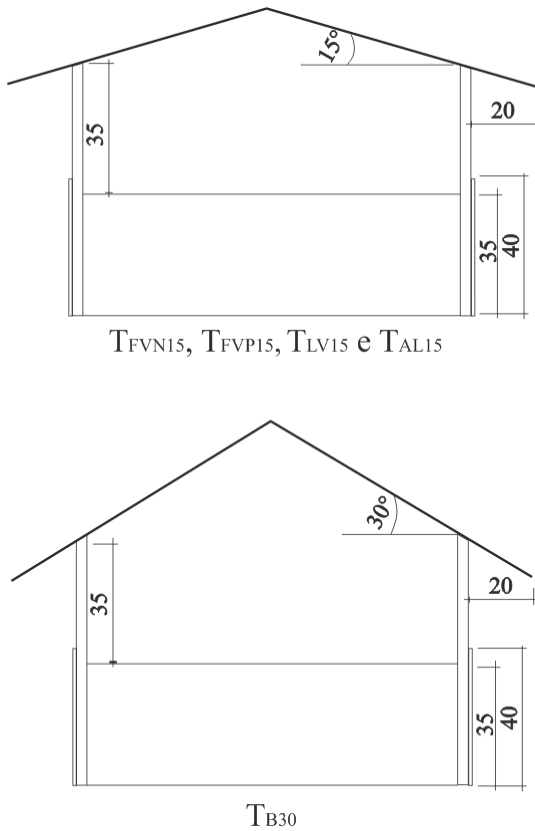


Figure 1. Schematic illustration of the cross sections of the physical models built on a reduced scale (unit: cm).
Source: The authors.

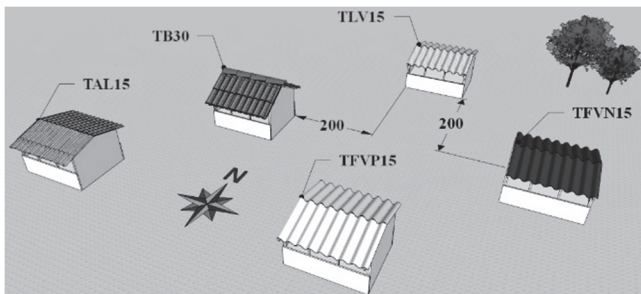


Figure 2. Overview of the experimental area and distribution of the physical models (unit: cm).
Source: The authors.

2.2. Instrumentation and measurements

The dry bulb temperature (T_{db}), black globe temperature (T_{bg}), relative humidity (RH) and air velocity (V) variables were measured in the constructed physical reduced scale models and in the external environment over a period of seven non-consecutive typical summer days, with a clear sky, between 12 and 16 h. These conditions present severe thermal discomfort conditions, at 15-minute intervals. After this process, the respective values of BGHI and RHL were calculated for the measurement times.

Inside the reduced scale physical models, sensors were installed at the height corresponding to the geometric center of the birds, i.e., 3 cm from the floor (30 cm in the actual

buildings). In the external environment, climate data was collected in a weather shelter that was installed in the experimental area, except for T_{bg} and V , whose sensors were allocated at the height corresponding to the geometric center of the birds.

2.2.1. Dry bulb, wet bulb and black globe temperatures

The thermal environment was assessed by the T_{db} , T_{bg} and RH, in which these three variables were measured by means of sensors / recorders (Hobo®, mod. U12-013, accurate to $\pm 3\%$). In each reduced model, one sensor / T_{db} , T_{bg} and RH recorder were installed. These sensors were housed inside a perforated protective container in order to prevent damage to equipment. Readings were compared to a sensor outside of the protection in order to verify any interference that the protective container had on equipment measurements. In the case of T_{bg} , only the recorder was housed in the protective container, since the temperature sensor was inserted into a plastic sphere measuring 3.6 cm in diameter and painted matte black. The recorder-sensor assembly was calibrated against a standard made of copper, with a 15 cm diameter and 0.5 mm thickness, painted black.

2.2.2. Air velocity

The air velocity was measured using a digital propeller anemometer (Kestrel® mod. 4000, accurate to $\pm 3\%$). Measurements were obtained in the vicinity of each black globe, on the same days and at the same times.

2.2.3. Climatic variables of the external environment

External climate data was collected using a weather shelter installed in the experimental area. In this shelter, sensors were installed to measure air temperature and humidity. Thus, T_{db} and RH data could be developed using measurements at 15-minute intervals, indicating the average, maximum and minimum. A black globe thermometer was installed in the external environment to quantify the BGHI and RHL of the external environment.

2.3. Determination of the thermal indices

From the T_{db} data, dew point temperature (T_{dp}), T_{bg} and V measured at the predetermined times, the respective BGHI and RHL values for each measurement time were calculated according to eq. 1 and 2, respectively.

$$BGHI = T_{bg} + 0.36 \cdot T_{dp} - 330.08 \quad (1)$$

where:

T_{bg} : black globe temperature, K;

T_{dp} : dew point temperature, K.

$$RHL = \sigma \cdot (T_m)^4 \quad (2)$$

where:

σ : Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$);
 T_m : mean radiant temperature, calculated by eq. 3.

$$T_m = 100 \cdot \left[2.51 \cdot v^{0.5} \cdot (T_{bg} - T_{db}) + \left(\frac{T_{bg}}{100} \right)^4 \right]^{\frac{1}{4}} \quad (3)$$

Classification of materials used in the roofs or their designs was performed by effectiveness (ϵ), which may be defined in relation to the BGHI [18, 3, 28, 11] by eq. 4.

$$\epsilon = \frac{BGHI_{sun} - BGHI_{tested\ roof}}{BGHI_{sun} - BGHI_{aluminium\ roof}} \quad (4)$$

2.4. Experimental design and statistical analysis

We used a randomized block design (RBD), in which the treatments were arranged in a split-plot design, with seven repetitions (measurement days) The plots were attributed to the constructed reduced scale models with the different roofs, and subplots with the measurement times. The mean BGHI and RHL for the treatments were compared with the Skott-Knott test at a 5% probability. The Sisvar 4.6 software [14] was used for statistical analysis.

3. Results and discussion

Results from the analysis of variance for the response variables BGHI and RHL ($W \cdot m^{-2}$) are presented in Table 2. It was verified that for both the BGHI and RHL there was a significant difference ($p < 0.05$) for the treatments and measurement times. However, no significant difference was observed for the interaction of treatments x measurement time ($p > 0.05$).

Regarding the BGHI, the coefficients of variation for the plots and subplots were 2.64% and 1.33%, respectively; and for the RHL they were 3.37% and 2.65%. This demonstrated little variability of the observed models in relation to the means.

For both the RHL and BGHI (Table 3), the treatments that resulted in the best thermal comfort conditions inside the reduced physical models were T_{B30} , T_{FVP15} and T_{LV15} , which are statistically equal (Skott-Knott test, $p < 0.05$). The other treatments presented poorer results (Skott-Knott test, $p > 0.05$).

The results obtained for the BGHI and RHL are in accordance with those observed by [16] and [17], where T_{B30} presented the best efficiency when compared with the other materials due to its reflective capacity and porosity. It is therefore statistically equal to T_{FVP15} and T_{LV15} and different in relation to T_{FVN15} and T_{AL15} .

When considering tiles constructed of natural plant fiber sealed with bitumen, a better efficiency was observed when they were painted with two coats of hydrated lime on the external surface. This effect was similar to that encountered when using white paint on fiber-cement tiles, as observed by [16,18,19], where it was shown that the use of reflective paint on the tiles resulted in improved thermal performance.

Mean BGHI values observed in treatments T_{B30} and T_{FVP15} were in agreement with those found by [20], from 69.0 to 77.0, where adult birds have the highest productivity and best performance parameters.

Table 2.

Summary of the analysis of variance for the temperature index response variables: black globe humidity index (BGHI) and radiant heat load (RHL).

FV	Mean square		
	DF	BGHI	RHL
Blocks	6	55.34*	3330.45*
Treatments	4	22.29*	1110*
Error (a)	24	4.17	256.86
Times	16	2.36*	143.81*
Treatment x Time	64	0.33 ns	18.41ns
Error (b)	240	1.06	61,81
C.V. Error (a) %		2,64	3,37
C.V. Error (b) % =		1,33	2,65

*: significant at 5% probability (F test); ns: non-significant (F test).

Source: The authors.

Table 3.

Mean values of the radiant heat load (RHL), reduction of the RHL and black globe humidity index (BGHI) and reduction of the BGHI in relation to the external environment for the various treatments tested.

Trea t.	BGH I	Reduction of BGHI (%)	RHL ($W \cdot m^{-2}$)	Reduction of RHL (%)
	76.61			
T_{B30}	a	7.09	471.23 a	20.24
T_{FVP15}	76.68			
5	a	7.01	472.75 a	19.98
	77.07			
T_{LV15}	a	6.54	475.49 a	19.52
T_{FVN15}	77.72			
5	b	5.75	480.45 b	18.68
	77.84			
T_{AL15}	b	5.6	479.47 b	18.84
T_{EXT}	82.46		590.82	

Source: The authors.

The RHL values for all treatments were lower than those found in [19], 498.3 ($W \cdot m^{-2}$), and [21], 502.7 $W \cdot m^{-2}$ (average of the times) for sheds with clay tiles. Reduction of the BGHI by the roofs varied from 7.09 to 5.60% for the best (T_{B30}) and worst (T_{AL15}) treatment, respectively. For the RHL, the change was 20.24% to 18.68% for the best (T_{B30}) and worst (T_{FVN15}) treatment. The RHL reduction results are within the range suggested by several authors, which is from 20 to 40% [22-25].

Fig. 3 shows the average internal and external behaviors of the BGHI and RHL, depending on the time of day for the tested treatments, and the lower and upper limits of thermal comfort for the BGHI. The lower and upper limits of BGHI that prevented the broilers from suffering stress had values of 69.1 and 77.5, respectively, and were in accordance with the recommendations reported by other studies [21,27,28].

The classification of effectivities (ϵ) of the roofs is presented in Table 4. Behavior was observed similar to that found for [11,28]. These results complement the information in the literature related to the classification of roofs made of different types of materials, especially those obtained by [3,11].

Through analysis of the BGHI, RHL and ϵ , it was verified that the roofs T_{B30} , T_{FVP15} and T_{LV15} provided the best thermal comfort conditions inside the physical reduced-scale models. This is due to the increased thermal resistance of the roof, an effect of the thickness of the material and the light color, as shown by [11].

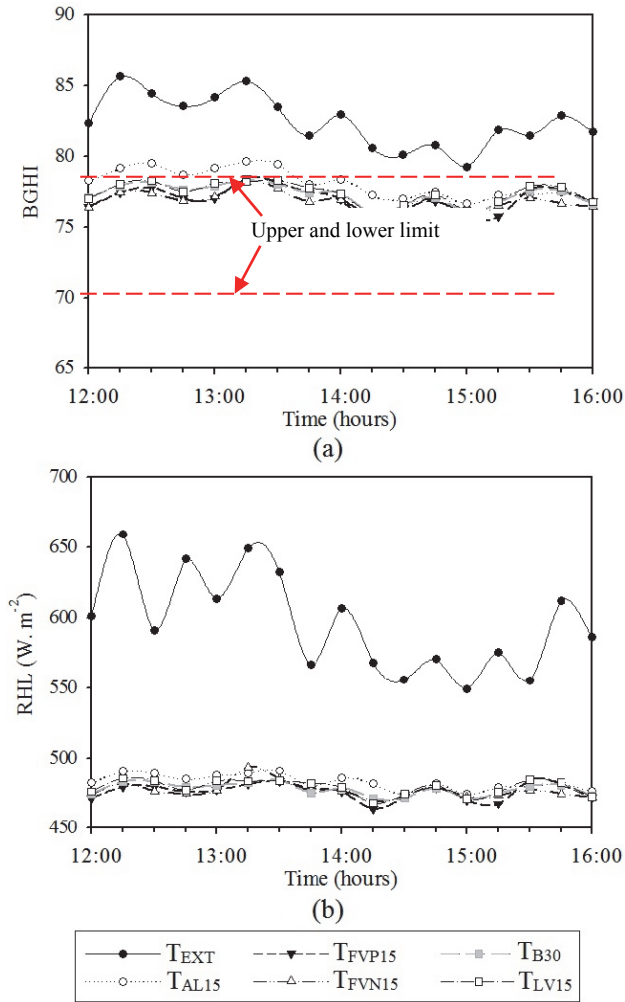


Figure 3. Mean values of the black globe humidity index - BGHI (a) and radiation heat load - RHL (b), corresponding to the height of the birds. Source: The authors.

Table 4.

Mean values and standard deviations of the effectiveness (ϵ) of the roofs in reducing the black globe humidity index (BGHI) in relation to the roof constructed with aluminum sheets.

Treatments	Effectiveness (ϵ)
T _{FVN15}	1.28 ± 0.13
T _{FVP15}	1.26 ± 0.18
T _{B30}	1.18 ± 0.12
T _{LV15}	1.16 ± 0.14
T _{AL15}	1.00 ±

Source: The authors.

4. Conclusions

The roofs constructed with tiles made of ceramic, plant fiber, painted bitumen and recycled long-life packaging provided the best thermal comfort conditions inside the physical broiler housing models built on a reduced scale (1:10). Statistically equal results were obtained. Average reduction of the black globe humidity index (BGHI) and radiant heat load (RHL) were 6.88% and 19.91%, respectively.

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