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Physical thermal properties and comparative analysis of the ecological straw constructive modules

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Physical thermal properties and comparative analysis of the ecological straw constructive modules

M C Pérez Rojas[1], J J Mancilla Grimaldo[1], and C X Díaz Fuentes[1]
[1] Grupo de Investigación en Arquitectura y Materiales Alternativos, Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: mariacamilapr@ufps.edu.co

Abstract. Understanding the physical and thermal material properties is important, due to it helps to determine the thermal comfort and how green is an architectural space, decreasing the energy consumption and avoiding the use of artificial cooling systems. This research is based on three stages: the design, simulations, and analysis of the results. The first stage developed three modules made of straw as a core material, wood and cardboard reinforcement. Successively, the thermal analysis simulation of the modules was carried out using the software ANSYS to determine each one thermal performance under extreme solar radiation of San Jose de Cucuta, Colombia. Thus, obtaining the temperature distribution exterior-interior and the heat fluxes for each typology. The results of the simulation show better thermal benefit in one specific module compared to the others, demonstrating that the implementation of an air chamber is the best strategy to reduce heat transfer in the design of the module, encouraging the use of straw as a constructive system. This research promotes the development of widely viable innovative sustainable construction solutions to configure any type of architectural enclosure in rural areas surrounding the city.

1. Introduction

The high solar incidence in areas with a warm tropical climate unquestionably generates a great problem related to intense radiation and overheating in facades that affect the thermal comfort of architectural spaces or enclosures. Which, results in the high energy consumption reflected by the excessive use of artificial cooling, since the buildings do not respond adequately to the needs of the environment [1]. This has prompted architects and engineers to implement strategies that enhance the use of alternative materials and construction solutions [2].

Understanding that the covering of a building is the main element responsible for energy demand [2], it is essential to identify the thermal behavior of the material to be used and its variations, since this determines from the moment it receives the solar incidence on the outer surface, which alters, pro or against, the absorption of energy inside the element [3].

Consequently, this research focuses on the analysis and decisive demonstration to achieve energy efficiency from the influence that design has on the architectural product. In this way, the thermal transmission of three variables of the ecologic straw module is analyzed in order to know and compare their energy efficiency levels, through simulations carried out in the ANSYS software under extreme conditions from San José de Cúcuta, Colombia. As a result, the heat distribution and flux of each is presented.

2. Methodology

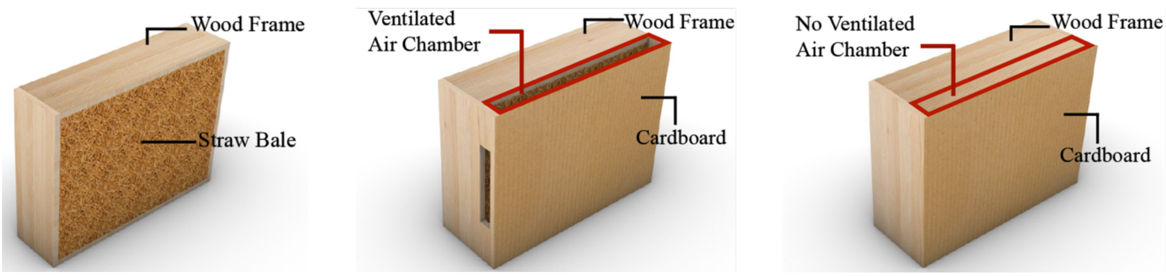
The Methodology purpose mentions different variables of the ecologic straw module as ESM1, ESM2, and ESM3, which are presented in the design proposal first stage. Followed by the physical and thermal analysis from each module, using ANSYS software to simulate the heat temperature and fluxes. Lastly, the comparative result analysis was obtained from simulation to identify which design behaves efficiently.

2.1. Module's design

It starts from the design of a module under three main criteria: thermal insulation, ease of installation of internal networks and versatility in the stacking of modules to be implemented in masonry. In this way, the ecologic straw module is composed of a straw matrix, which is chosen as a noble material for its sustainable characteristics [4]. The straw bale fulfills the function of dividing the exterior from the interior, in order to improve the efficiency related to thermal and acoustic insulation. It is important to mention in this design stage, the straw blades arrangement since they alter the thermal behavior of the straw and consequently the module, due to if they are ordered in the same direction or axis in which the exterior surface absorbs the solar radiation, the heat distribution will take a short time to reach the inner surface. Contradictory, if the straw blades are located in a different direction to the heat flow, minimizing a progressive and rapid heat dissipation attributable to the cavities formed by the straw blades [5,6].

At the same time, the straw bale is formed into a wooden frame which fulfills the function of modulating the element, making it a more flexible assembly and disassembly system. For the purposes of the study, three similar design options are developed, but with specific characteristics that differentiate them in order to understand how energy is distributed and transported through the shape and arrangement of the materials that make up the ecologic straw module.

In the Figure 1, ESM1 depicts the first design which is the basic pattern for these modules. Consequently, the variations occur in ESM2 and ESM3 models, which have an air chamber that separates the straw bale from the outer lining, generating a space for the installation of internal networks (electrical or hydraulic) where ESM2 allows natural ventilation to the air chamber, contradictory to ESM3, which keeps this space totally hermetic.



(a) (b) (c)

Figure 1. Ecologic straw module design. (a) ESM1; (b) ESM2; (c) ESM3.

2.2. Temperature distribution and heat fluxes

The study relied on the meteorological data from San José de Cúcuta, Colombia where it takes place the proposal; considering the maximum temperature, average maximum solar radiation, time, and the average wind speed [7] of the specific environment necessary to employ finite element method, that describes temperature distribution and heat fluxes of each module using ANSYS software to validate the efficiency of the thermal behavior [8]. Likewise, the coefficient of thermal conductivity of each proposed material: straw, wood and cardboard as observed in Table 1.

On the other hand, the convection data exterior (25.903 Wm^2.°C), and interior (5 Wm^2.°C) ESM surfaces, and heat flow (796.8 Wm^2) [7] are related to the environmental conditions that were taken into account to carry out the simulation settings of each module according to the climatological characteristics of the place to specify the results. For better understanding, the thermal validation in

Figure 2 represents the physical phenomena of each module, where the heat distribution refers to the transferred heat that dissipates progressively from the outer to the inner side, while the heat fluxes build up energy concentration in specific parts of the module, comprehending that the material and the shape are highly bound.

Table 1. Data provided for thermal validation.

Materials	Environment
k Wood =0.115 W/mK [9]	Max T°. Average = 33°C [7]
k Straw = 0.067 W/mK [10]	Max Solar radiation. Average = 796.8 Wh. m^2 [7]
k Confined air = 0.026 W/mK [11]	t = 12: 00 - 13: 00 [7]
k Cardboard = 0.065 W/mK [12]	Q_{solar} = 796.8 Wm^2 [7]
	Average wind speed = 4 m/s [7]

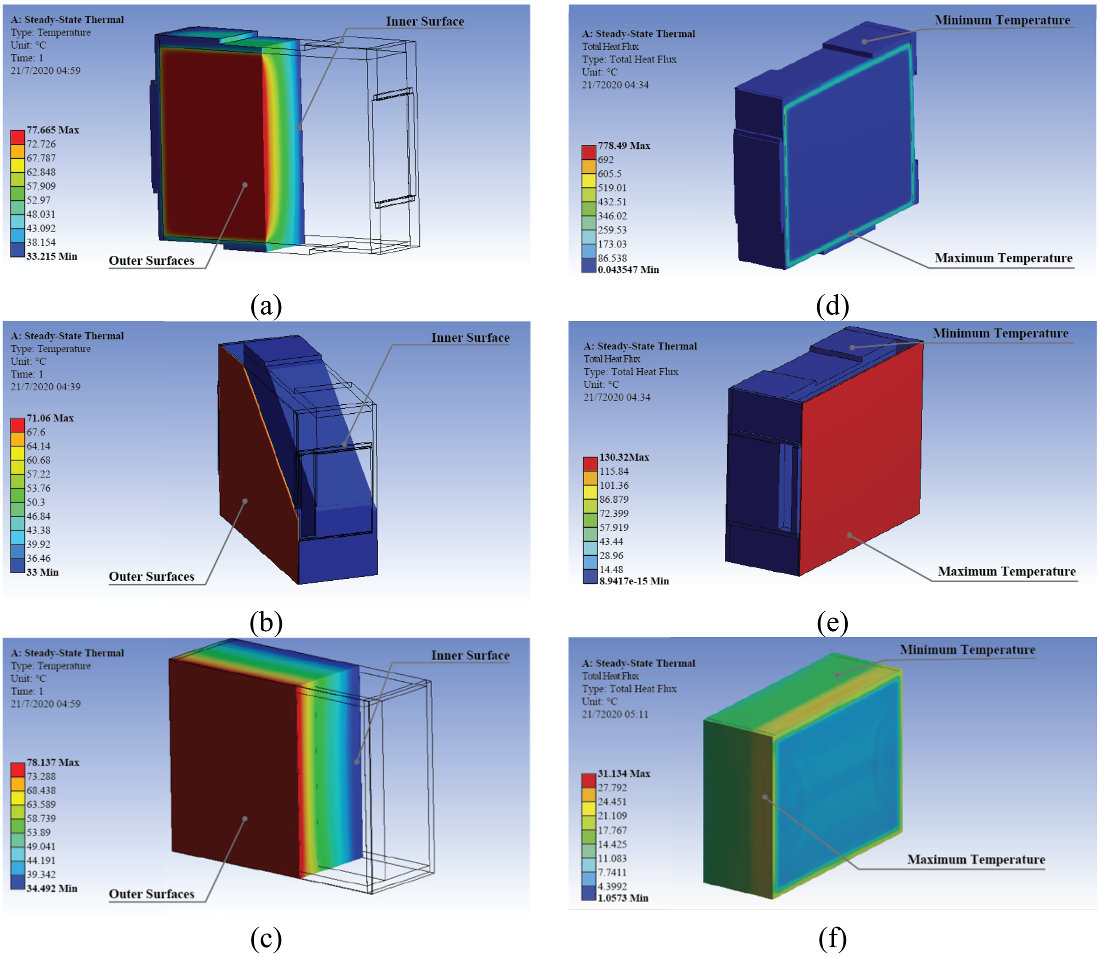


Figure 2. Thermal validation in ecologic straw module. (a) ESM1 temperature distribution; (b) ESM2 temperature distribution; (c) ESM3 temperature distribution; (d) ESM1 heat fluxes; (e) ESM2 heat fluxes; (f) ESM3 heat fluxes.

Regards to the module's proposal, it is important to point out the different variations that occur in each one, standing out two with air chamber ESM2, AND ESM3, which makes it a fundamental aspect to analyze. As reported in Figure 2(a) a progressive heat distribution is noticed in the matrix material of the module (straw) where the outer surface reaches the maximum temperature and the wooden frame helps to regulate the heat once it has touched the surface as conveyed in Table 2.

The module from the middle to the inner surface can stabilize the total distribution with favorable results. In this order, Figure 2(c) despite having a complementary air chamber as Figure 2(b), shows similar behaviors to Figure 2(a) since the air chamber is no ventilated and works as a thermal bridge that facilitates the temperature towards the interior.

The heat fluxes represent the way in which energy is distributed, in this way, it is possible to identify which are the points with the highest and lowest concentration of heat. According to Figure 2(d), The module manages to have an almost uniform control of the heat flux except for the corners where the wood frames and the straw bale meet. Therefore, the energy concentration arises due to the geometry while Figure 2(f) shows that the cardboard does not keep heat, but it builds up in the air chamber due to is a confined space.

From another perspective, the Table 3 shows the maximum energy concentration values are found in the cardboard sheet that configures the ventilated chamber in Figure 2(e), increasing by 89% with respect to the values recorded in the distribution of thermal energy in Figure 2(d) module. At first glance, the energy distribution values suggest that the proposal in Figure 2(e) can accumulate the energy in the cardboard sheet uniformly and with higher concentration. However, if the information is carefully analyzed, it is observed in the image of the heat fluxes in Figure 2(e), it manages to dissipate the transfer of energy towards the interior, thanks to the ventilated air chamber that works as an insulating barrier, avoiding direct heat contact to the straw bale. The values shown in Table 2 demonstrate the analysis presented in Figure 2.

Table 2. Thermal validation by heat transfer and heat flux.

Material: wood, cardboard, straw				
Design	Heat transfer (°C)		Heat flux ($\mathrm{Wh/m^2}$)	
	Ext.	Int.	Max.	Min.
MEP 1	77.66	33.21	778.49	0.04
MEP 2	71.06	33.00	130.32	8.94
MEP 3	78.13	34.49	31.13	1.05

Table 3. Thermal benefit by heat transfer and heat flux.

Eco straw product		
Design	Heat transfer (°C)	Heat flux (Wh/m^2)
MEP1	Pattern	
MEP2	− 0.21	+ 8.90
MEP3	+ 1.23	+1.01

3. Results

ESM1 registers 77 °C of outside temperature, while ESM2 decreases this value by 6.6 °C, that is, the outer surface of cardboard and ventilated chamber heats up less even when its energy concentration is higher. However, the ESM3 temperature values were not positive, showing the highest temperature both outside and inside, since the confined air chamber acts as if it were a solid body that becomes a thermal bridge and facilitates the conduction of heat inside. Thus, ESM1 and ESM2 are favored products, with the best advantage being significantly found in ESM2 by presenting the lowest interior temperature 33 °C and by having the ventilated chamber that brings added value to the construction design, due to its possibility of using that space for electrical, hydraulic, maintenance and/or repair installations, among other functions. Because it has the highest temperature value on the interior surface 34 °C, ESM3 is ruled out of any future consideration to develop as a construction system in the configuration of walls of an enclosure.

Knowing that the geometry and shape of the element improve the thermal efficiency in Figure 3(a), and Figure 3(b) the module does not have any variant that delays the heat transfer to the interior, and if it does, it does not cause any effect, therefore, one of the most relevant strategies is to include the ventilated air chamber in the geometry of the module as shown in Figure 3(c) to improve the thermal comfort of space at the same time solve the problem of installations in conventional walls. The advantage of the air chamber lies in the generation of an expansion space that delays the indirect heat distribution from the outside to the inside of the element and that can additionally be used for functional elements of the wall. Next, we will compare the geometry, shape, and material settings of ESM1, ESM2, and ESM3 (Figure 3).

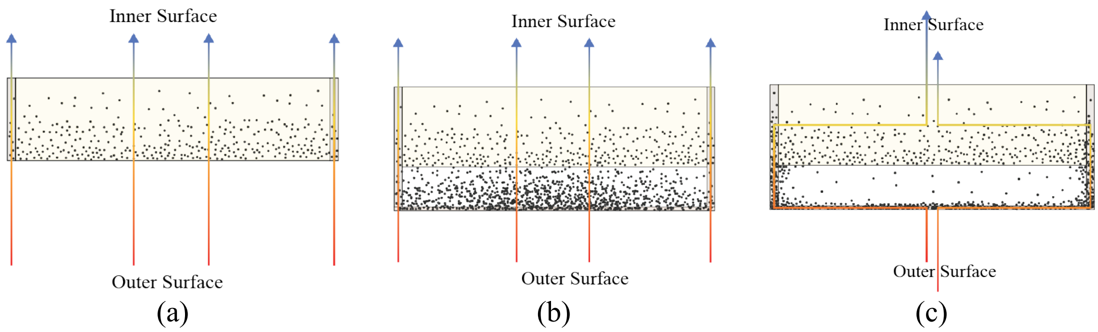


Figure 3. Heat transfer and formal diagram of the ecological straw module. Heat transfer by conduction, (a) ESM1, and (b) ESM3; heat transfer by convection, (c) ESM2.

4. Conclusions

Analyzing ESM1, ESM2, and ESM3 thermal behavior, it must be highlighted that besides of physical and thermal properties of a material, in this case, straw can be improve its performance as long as its geometry, shape and material settings of the Module is considered, it is identified that the strategy to thermally isolate a space delimited with ecological straw module is the blocking of thermal bridges through the ventilated chamber. According to the table of thermal benefit by heat distribution and heat fluxes, the confined air chamber does not bring any benefit in relation to the ventilated air chamber. The product with the greatest insulation has been the one that integrates the ventilated chamber to block the direct conduction of energy to the rest of the parts that make up the module, while the ESM1 and ESM3 section geometries configure products with direct thermal bridges that transfer energy from the outside to the inside more easily.

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