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Special Edition

Numerical evaluation of the earth-air heat exchanger thermal performance in a social housing in brazilian bioclimate zones ZB 3 and ZB 4

Avaliação numérica do desempenho térmico de trocador de calor solo-ar em habitação de interesse social nas zonas bioclimáticas brasileiras ZB 3 e ZB 4

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ABSTRACT

The Earth-Air Heat Exchanger (EAHE) is a device where the external ambient air is cooled or heated when circulating inside ducts buried in the soil, which can bring benefits in terms of reducing energy consumption and providing thermal comfort conditions. This system has been employed in several countries in different climatic contexts, however, little explored in Brazil. The use of this technology in conjunction with bioclimatic strategies benefits buildings, increasing their efficiency. This study aims to evaluate the thermal performance of an EAHE alongside optimization parameters of the building envelope in two Brazilian bioclimatic zones and propose strategies that enhance energy efficiency in buildings. The study consists of the validation and verification of a computational model and the thermal evaluation of a Social Housing (SH), in which characteristics of solar orientation, thermal envelope, and the installation of an EAHE will be modified, combined, and investigated in the proposed models. These evaluations were conducted through dynamic simulation with the EnergyPlus™ software. The results demonstrate that the installation of an EAHE in SH brings improvements in the thermal performance of environments, thus contributing that future projects can rely on validated references and parameters.

Keywords: Numerical simulation; EnergyPlus™; Solar orientation

RESUMO

O Trocador de Calor Solo-Ar (TCSA) é um dispositivo onde o ar ambiente externo é resfriado ou aquecido ao circular dentro de dutos enterrados no solo, podendo trazer benefícios no sentido de reduzir o

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consumo de energia e proporcionar condições de conforto térmico. Esse sistema tem sido empregado em diversos países e em diferentes contextos climáticos, porém, pouco explorado no Brasil. A utilização dessa tecnologia em conjunto às estratégias bioclimáticas favorece as edificações, aumentando sua eficiência energética. Esse estudo tem como objetivo avaliar o desempenho térmico de um TCSA conjuntamente a parâmetros de otimização da envoltória da edificação, em duas zonas bioclimáticas brasileiras e propor estratégias que potencializem a eficiência energética nas edificações. O estudo consiste na validação e verificação de um modelo computacional e nas avaliações térmicas de uma habitação de interesse social (HIS), no qual serão modificadas, combinadas e investigadas características de orientação solar, envelope térmico e a instalação de um TCSA, derivando-o em modelos propostos. Essas avaliações foram realizadas através de simulação dinâmica com o programa EnergyPlus™. Os resultados demonstraram que a instalação de um TCSA em uma HIS traz melhorias no desempenho térmico dos ambientes, contribuindo, assim, para que projetos futuros possam contar com referências e parâmetros validados.

Palavras-chave: Simulação numérica; EnergyPlus™; Orientação solar

1 INTRODUCTION

> The Earth-Air Heat Exchanger (EAHE) is a thermal conditioning technique where the air circulates through a buried pipe; and can be cooled or heated, in the process of exchanging heat with the soil.This exchange takes place due to the thermal inertia of the soil, so that in summer the air circulating through the EAHE comes out at a lower temperature than the outside air; while in winter the external air gains heat when circulating through the EAHE, leaving with a higher temperature (Agostino *et al.*, 2020, p. 2).

> It is a passive strategy for thermal comfort, which takes advantage of the subsoil temperature through the use of air ducts, to preheat environments in winter, or precool them in summer, which can bring benefits in terms of reducing energy consumption and provide thermal comfort conditions (Fonseca *et al*., 2014, p. 538).

The studies by Zajch *et al.* (2021), Agostino *et al*. (2020), and Cuny *et al*. (2020), developed in different places in the world (such as: Canada, Brazil, United Arab Emirates, Italy, and France), demonstrated that the EAHE system achieved good energy performance in any climate, as it reached energy savings in all investigated regions.

According to the study by Lund *et al*. (2004), the cooling and heating capacity of the system is connected with the thermal variability of the location. Therefore, the climate is a very important aspect of the proper functioning of the system.

Brazil has a very varied climate due to its immense territory and the fact that it is located between the two tropics. The different Brazilian climates are classified through NBR 15220-3 (2005), which establishes the Brazilian bioclimatic zoning, subdividing the country into eight bioclimatic zones. This standard defines the main characteristics and provides constructive guidelines for each of the eight bioclimatic zones in relation to the size of windows, the necessary shading, the ideal type of walls and roofs, and the most recommended bioclimatic strategies for the location.

In accordance with the studies by Rodrigues *et al* (2017), Pakari *et al*. (2021), and Cuny *et al*. (2020) in addition to the climate, other relevant aspects influence the efficiency of the EAHE system, namely: the type of soil, the depth and length of the tubes, and the air velocity.

Complementing these important aspects, in agreement with Pakari *et al*. (2021), the length of the EAHE significantly affected its outlet temperature. For Cuny *et al*. (2020), the most impactful parameters were the radius, length, depth of the tube, air velocity and soil.

> It was found that the EAHE, when installed in clayey soil, has a better thermal performance compared to an installation in sandy soil. Moreover, it is also being observed that the cooling and heating potential of the EAHE does not always increase with the installation depth of the duct (Rodrigues *et al*. (2017, p. 490).

Therefore, it can be seen that the use of surface geothermal energy, for direct use in improving the thermal condition of environments, has shown positive results. Thus, collaborating in thermal performance, with a reduction in energy consumption and pollutant emissions by buildings.

It is also worth mentioning the importance of using this technology, not in isolation, but in conjunction with bioclimatic and energy efficiency strategies; since the sum of them will favor building projects as integrated organisms in their operation. Agrawal *et al*. (2019) affirm such a theory highlighting the fact that the efficiency and usefulness of the system can be increased by coupling it to other systems.

Another relevant aspect "is the relatively low construction and operating cost compared to an air conditioner" (Lechner, 2015, p. 544), which may be an alternative for low-income buildings.

Complementing this situation, one of the serious problems faced in Brazil is the lack of access to housing for a considerable portion of the population, mainly low-income families. According to João Pinheiro Foundation (2021), based on data from the Brazilian Institute of Geography and Statistics, in 2019 the estimated housing deficit was 5.876 million households.

In order to reduce the housing deficit, the Federal Government created in 2009 the Minha Casa, Minha Vida Program - PMCMV (Brasil, 2009) and, currently (in 2021) created the Casa Verde e Amarela Program (Brasil, 2021), in order to facilitate access to homeownership for low-income families.

> The necessity to accelerate the construction process and reduce costs, the social housing project was thought out in a standardized model throughout the country, without concern for regional specificities of climate conditions or building material. The results led to low quality buildings that do not meet the users needs in many ways, including thermal comfort and energy performance. The majority of users of social housing have low purchasing power and, often they do not have the financial resources to afford the expenses of active systems to overcome thermal discomfort (Dalbem *et al.*, 2019, p. 1278).

From these considerations, the research questions that this work seeks to answer arise: (I) do buildings have adequate thermal performance for their use, even if they use a standard design for all regions of Brazil? (II) is the EAHE system efficient for all Brazilian bioclimatic zones? (III) will the use of the EAHE system in conjunction with envelope optimization strategies result in a more energy-efficient building?

Therefore, the present work aims to evaluate the thermal performance of an EAHE, for cooling and heating, together with optimization parameters of the building envelope, in two Brazilian bioclimatic zones (ZB 3 and ZB 4) and propose strategies that enhance energy efficiency in Social Housing (SH). For this, SketchUp 2017 (with the Euclid plugin) and EnergyPlus 9.4 software were used. The computational model, considering the EAHE coupled to the building, was validated and verified, through comparison with the results of Vaz (2011) and Rodrigues *et al*. (2015). Afterward, an evaluation of the thermal performance of the SH was developed. Finally, strategies for the use of EAHE were analyzed together with envelope optimization parameters, aiming at improving the thermal performance of SH.

2 MATERIALS AND METHODS

For the development of the proposed study, the following methodological steps were adopted: (I) to perform a descriptive research based on the literature review on the subject; (II) to determine a building model for analysis of the case study; (III) to define the simulated cases; (IV) to analyze the soil and EAHE system characteristics; (V) to evaluate the thermal performance of the defined cases; and (VI) to compare the defined situations, in order to optimize the thermal performance.

2.1 Building model

The chosen building model is a typology of single-family SH, extracted from the CAIXA Notebooks (Standard project – popular houses), of the *Minha Casa*, *Minha Vida* Program, through the analysis of all the available projects on the CAIXA website (https://www. .caixa.gov.br/site/paginas/downloads.aspx).

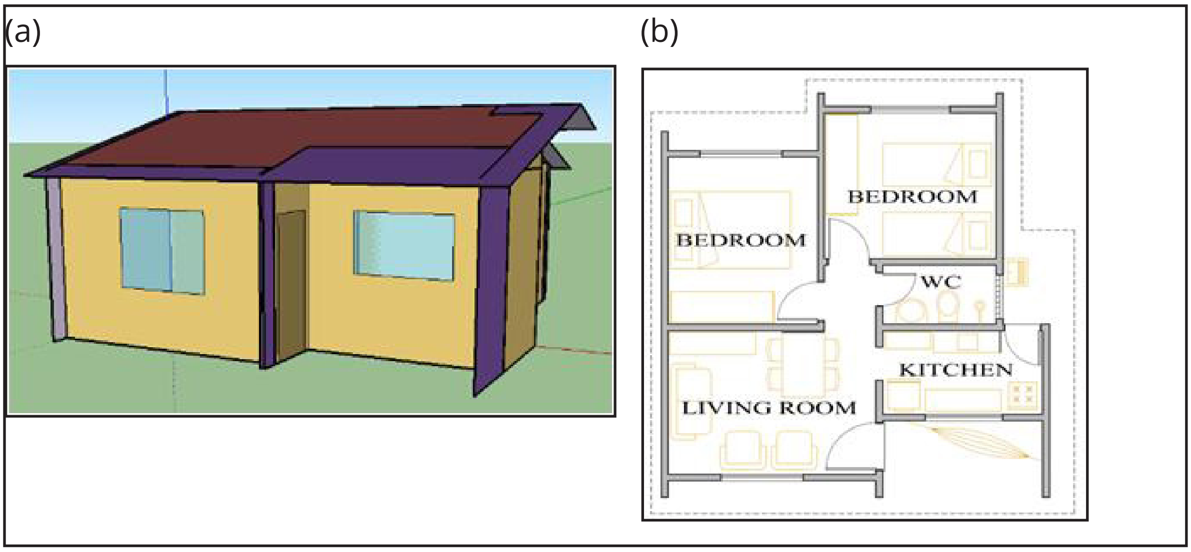
Eight popular housing projects were found, located in four bioclimatic zones (ZB 2, ZB 4, ZB 6 and ZB 8). The estimated areas of popular houses are 40 m², with their openings facing all solar orientations and the distribution is configured in living room, kitchen, bathroom and two bedrooms.

The model that presented more details and constructive information was chosen, in addition to using construction materials commonly used for the execution of popular houses and with lower cost, since it is an SH.

However, the SH model chosen for this study has a total constructed area of 41.87 m², divided into living room, kitchen, two bedrooms and bathroom, as shown in Fig. 1.

All walls are made of ceramic masonry using 6-hole bricks, measuring 20x15x10 cm. The outer faces are roughcast and plastered and the inner faces are made of exposed brick, with the exception of the bathroom and kitchen. The roof is made up of 5 mm fiber cement tiles, inclined at 15° and the ceilings are made of polyvinyl chloride, in all environments. The floor is cemented and the frames are made of wood and glass.

Figure 1 – SH building model



Source: Moura (2022)
Caption: (a) computationally modeled perspective and (b) floor plan.
Note: Paula Wrague Moura private collection (august, 2022)

2.2 Simulated cases

With the building model of SH determined (real model), the following simulated situations were defined: (i) situation 1: real model, with climate file of representative city of ZB 3 (Viamão - RS) and ZB 4 (Brasília - DF) and, with the highest percentage of openings facing each solar orientation (north, northeast, east, southeast, south, southwest, west, and northwest), resulting in 16 simulated cases; and (ii) situation 2: from the point of view of thermal performance, the best results of the real model, referring to solar orientation, with the use of the EAHE system.

2.3 Characteristics of soils and the EAHE system

The characteristics of the soils were analyzed through the Standard Penetration Test (SPT) reports, to obtain information about the type of soil and the level of the water table; while the soils thermophysical properties, such as specific mass, specific heat, and thermal conductivity, were adopted accordingly with Oke (1987, p. 44). This methodology was also used in other studies, such as Hermes *et al*. (2020) and Victoria *et al*. (2020).

From Vaz (2011), the EAHE system was defined with a polyvinyl chloride duct with a diameter of 110 mm and length of 34 m, having an airflow velocity of 3.3 m/s. As for depth, the study by Brum (2013) and Nóbrega (2021) was used, being 2 m and 3 m when the soil is saturated and not saturated, respectively. Finally, as in Pakari *et al*. (2021), Zajch *et al*. (2021), and Alves *et al*. (2015), the ground surface was considered covered by grass, enhancing the EAHE thermal performance, not requiring the ducts to be deeply deepened and facilitating maintenance.

2.4 Evaluation of thermal performance

To evaluate the thermal performance of the real SH model, the computational simulation procedure of NBR 15575 (2021) was adopted in order to meet the minimum level of performance. Moreover, a comparison is made between the real model (CAIXA standard) and a model reference (with thermal properties and compositions of transparent elements, walls and roof specified by the standard).

The parameters analyzed, for the evaluation of the minimum performance, according to NBR 15575 were: (I) calculation of the percentage of occupation hours within an operating temperature range (PHFT) and (II) identification of the maximum annual operating temperatures (*Tomax*) and minimal (*Tomin*), during the occupation.

The computational modeling was developed using the SketchUp 2017 software (see Fig. 1a), with the Euclid plugin, in which the thermal zones were defined. The computational simulation was developed with the EnergyPlus 9.4 software.

According to Melo *et al*. (2009), EnergyPlus is a computational program, created from the BLAST and DOE-2 programs and distributed by the United States Department of Energy, developed for thermal load simulation and energy analysis of buildings and their systems. The software has differentiated simulation capabilities, such as calculation time-step of less than 1 h, modular system, the possibility of calculating differentiated air infiltration for each thermal zone, calculation of thermal comfort indices, and integration with other systems.

EnergyPlus is free, internationally validated, and recognized, and has been widely used in the national context. The input data needed to carry out the simulations are divided between those that characterize the building and the local climate file containing basic information on temperature, humidity, solar radiation, and winds, among others.

The EnergyPlus software employs the concept of the thermal zone, which are spaces that have the same spatial characteristics and the same heating and cooling setpoints, being the parameters used during the modeling and solution of the building. This software calculates the energy required to maintain each zone at a specified temperature for each hour of the day. Each room in the passive house is considered a thermal zone and must be analyzed separately. The software calculates the energy balance for each thermal zone using the prediction-correction method, which uses an explicit scheme to estimate the next result of an iteration and, soon after, an implicit scheme to recalculate this value, seeking to approximate it, more and more of the actual value (Engineering Reference, 2020), using:

$$C_z \frac{dT_Z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_{ext}) + \sum_{i=1}^{N_{zones}} m_i C_p (T_{si} - T_{ext}) + m_{inf} C_p (T_{\infty} - T_{ext}) + Q_{sys} \quad (1)$$

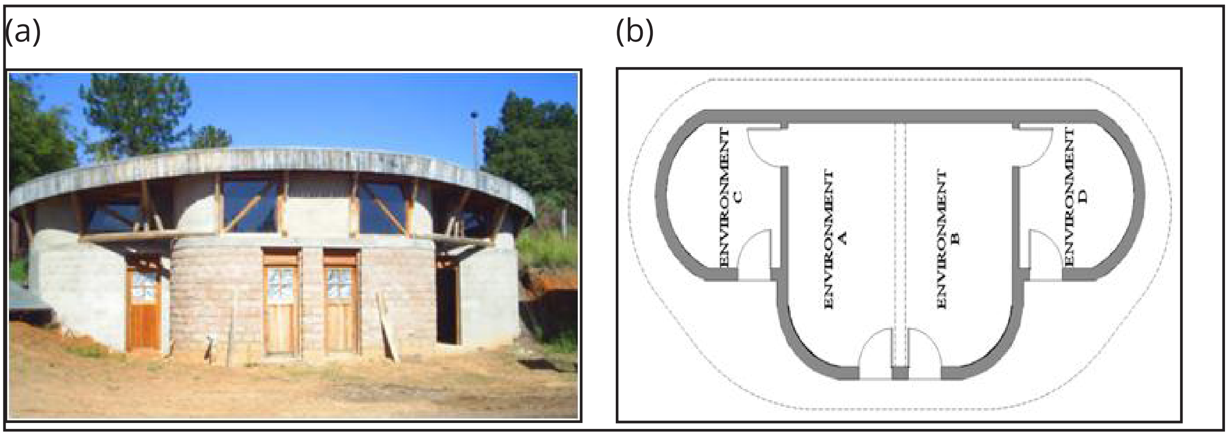
where:
$\sum_{i=1}^{N_{sl}} Q_i$ is the sum of the convective internal charges;
$\sum_{i=1}^{N_{Surface}} h_i A_i (T_{si} - T_Z)$ is the convective heat transfer across the surfaces of the zone;
T_{ext} is the outside temperature, in K;
$m_{inf} C_p (T_\infty - T_Z)$ is the heat transfer due to outside air infiltration;
$\sum_{i=1}^{N_{zones}} m_i C_p (T_{si} - T_z)$ is the heat transfer due to contact between zones;
Q_{sys} is the heat rate with Heating, Ventilation and Air Conditioning (HVAC) systems;
$C_z = \frac{dT_Z}{dt}$ is the rate of energy stored in the thermal zone.
The subscript *i* indicates the *i*-th surface or the *i*-th zone.

3 RESULTS

3.1 Validation and verification of the computational model

For the validation and verification of the proposed computational model, the Casa Ventura building (Fig. 2) was used, where the thermal behavior was analyzed, through the values of the average daily temperature, of duct A and of Environment A, in agreement with the experiment performed by Vaz (2011). The results obtained from this model were compared with the numerical study by Rodrigues *et al*. (2015), for verification purposes and with experimental data from Vaz (2011) for validation purposes.

Figure 2 – Casa Ventura building



Source: Vaz (2011)
Caption: (a) facade and (b) floor plan.
Note: VAZ private collection (november, 2010)

The EAHE computational model was verified through comparison with the numerical study by Rodrigues *et al*. (2015), who used the Fluent software, which resulted in a relative difference of 0.83%, in duct A. It was validated from the comparison with the experiment by Vaz (2011), reaching a relative error of 0.87% for duct A. In these comparisons, the temperature variation at the outlet of the EAHE was analyzed in the period of one year, from 2007.

On the other hand, the Environment A was only validated since there are still no numerical studies that have developed such a simulation. So, the relative error when comparing the numerical result obtained to the experimental one by Vaz (2011) was 3.40%, in environment A. In this comparison, the temperature variation of the computational model that numerically simulated the EAHE, coupled to Environment A was analyzed.

Therefore, it is clear that the results obtained with the computational model developed in the EnergyPlus software are coherent and similar to those presented in Rodrigues *et al*. (2015) and Vaz (2011). In other words, it can be said that the computational model developed was duly validated and verified.

3.2 Thermal evaluation of the SH, in ZB 3 and ZB 4, with the installation of the EAHE

For each bioclimatic zone, a parametric simulation was developed, in eight solar orientations (north, northeast, east, southeast, south, southwest, west, and northwest), in order to identify the orientation with the best thermal performance, for the analyzed model.

As the computational simulation procedure of NBR 15575 (2021) was adopted, aiming to meet the minimum level of performance, a real model and a reference model were simulated, with different parameters, as shown in Table 1.

In Table 1, it can be seen that when the real model is compared to the reference model, it presents walls and roofs with lower transmittances, that is, the real model presents greater thermal insulation. In addition, the real model also has lower absorbances, that is, it absorbs less heat into the building.

Table 1 – Parameters analyzed in the reference model and in the real model

			Conductivity	Specific heat	Absorbance	Emissivity	Density	Transmittance
REFERENCE MODEL								
			W/(m.K)	J/(kg.K)			(kg/m³)	W/(m².K)
FLOORS			1,75	1000	0,70	0,90	2200	
WALLS	EXTERNAL		1,75	1000	0,58	0,90	2200	4,40
WALLS	INTERNAL		1,75	1000	0,20	0,90	2200	
ROOF	Roof tile 6 mm		0,65	840	0,65	0,90	1700	2,06
ROOF	Slab 100 mm		1,75	1000	0,70	0,90	2200	
ROOF			Thermal Resistance		Absorbance	Emissivity		
ROOF	Thermal insulation		0,67		0,70	0,90		
REAL MODEL								
			Conductivity	Specific heat	Absorbance	Emissivity	Density	Transmittance
FLOORS	Cemented 20 mm		1,75	1000	0,70	0,90	2200	
FLOORS	Radiator 100 mm							
WALLS	EXTERNAL	Ceramic brick 6 holes	0,90	920	0,20	0,90	1600	2,82
WALLS	EXTERNAL	Air chamber	Thermal Resistance ((m².K)/W)= 0,0961					
WALLS	EXTERNAL	Ceramic brick 6 holes	0,90	920	0,20	0,90	1600	
WALLS	EXTERNAL	Mortar	1,15	1000	0,20	0,90	2000	
WALLS	INTERNAL	Ceramic brick 6 holes	0,90	920	0,20	0,90	1600	
WALLS	INTERNAL	Air chamber	Thermal Resistance ((m².K)/W)= 0,0961					
WALLS	INTERNAL	Ceramic brick 6 holes	0,90	920	0,20	0,90	1600	
ROOF	Fiber cement tile		0,95	840	0,57	0,90	1900	1,76
ROOF	Air chamber		Thermal Resistance ((m².K)/W)= 0,21					
ROOF	Polyvinyl chloride lining		0,071	960	0,20	0,90	273	

Source: Paula Wrague Moura (2022)

To represent the ZB 3, the city of Viamão - RS was chosen, which was the same for the verification and validation of the computational model, while for the ZB 4, the city of Brasília - DF was chosen.

The ZB 3 also includes the cities of Porto Alegre, Rio Grande, São Paulo, Belo Horizonte, among others. It is recommended for this zone, as constructive guidelines, according to NBR 15575 (2021): (I) light and reflective external walls; (II) the need for cross ventilation in summer; (III) medium-sized openings for ventilation; (IV) shading to allow sun in winter; (V) isolated cover.

In turn, the ZB 4 comprises the cities of Viracopos, Ribeirão Preto, Jau, Franca, Pirapora, Pitangui, among others. Based on NBR 15575 (2021), the main constructive recommendations are: (I) openings with medium dimensions, for ventilation; (II) opening shading throughout the year; (III) heavy walls; (IV) light cover with thermal insulation.

According to NBR 15575 (2021), for these climate files (Viamão and Brasília) the operating temperature in the range of 18°C to 26°C is considered acceptable, that is, it is within the comfort range. Above and below this temperature range a discomfort due to heat and cold will occur, respectively.

Comparing the results of the real model simulation with the reference model in the ZB 3, one can note that the real model of the SH presented more discomfort due to cold than due to heat. This happens because the real model is more insulated and absorbs less heat, and with that, not allowing heat to enter the rooms. In the reference model, less insulated and with materials with higher absorbance, there is greater discomfort due to heat.

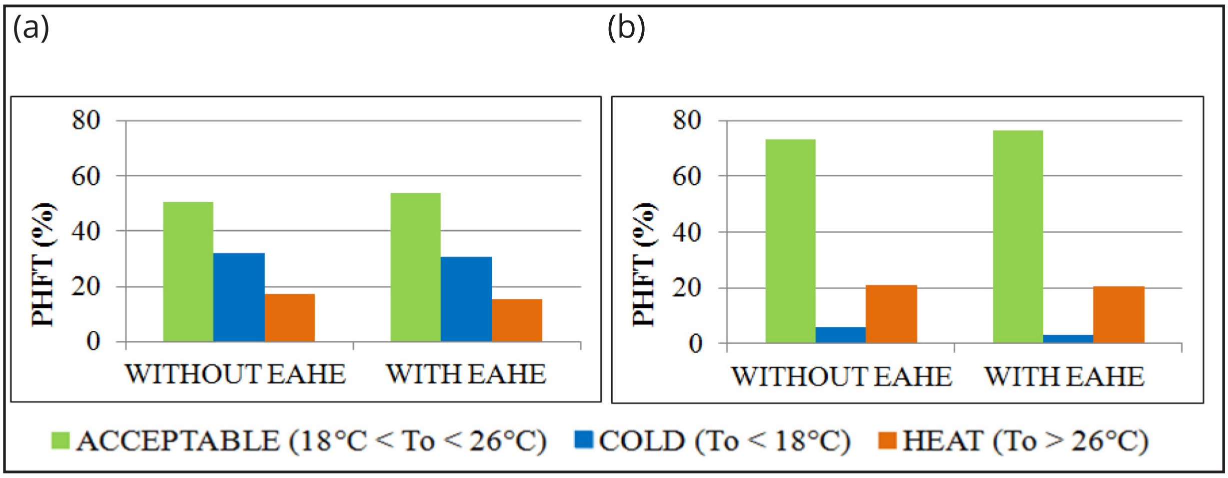
However, the real model presented a better thermal performance, when compared to the reference one, reaching 8% difference, within the acceptable range, that is, materials with lower transmittances and absorbances allowed a better performance, for this SH model on ZB 3.

In addition to these results, as expected it was also observed that the best orientation was the north, reaching a 2% difference when compared with the worst solar orientations, which were the southwest and west. Finally, in the criterion for evaluating the thermal performance of the envelope regarding the PHFT of the SH in ZB

3, all solar orientations reached the minimum level; while in the criterion of maximum and minimum annual operating temperatures, only the southwest orientation did not reach the minimum performance level.

After this analysis, the real model of SH in ZB 3 was evaluated, with the best solar orientation and with the installation of the EAHE system. It resulted in a performance improvement of 3.2%, when compared to the model without the EAHE (Fig. 3a), proving that this system improves the thermal performance of the building. This difference is equivalent to twelve days more in the year, with the feeling of comfort of the users, that is, in the acceptable range, according to the current regulation.

Figure 3 – PHFT variation chart for Viamão and Brasília



Source: Moura (2022)

Caption: Variation of PHFT (a) Viamão - RS and (b) Brasília - DF.

Note: Paula Wrague Moura private collection (august, 2022)

Comparing the numerical simulation for the real and reference models in ZB 4, it was observed that both models presented discomfort only due to heat. This fact occurs because Brasilia has a climate with higher temperatures when compared to Viamão. However, the real model presented a better thermal performance when compared to the reference one, reaching 20% of the difference within the acceptable range. That is, the materials with lower transmittance and absorbance enabled a better performance, for this SH model and on this ZB 4.

In addition to these results, it was observed again that the best orientation was the north, reaching a 2.5% difference when compared with the worst solar orientation (the southeast). Finally, in the evaluation criterion of the thermal performance of the envelope regarding the PHFT of the SH in ZB 4, all solar orientations reached the minimum level. Nevertheless, in the criterion of maximum and minimum annual operating temperatures, no solar orientation reached the minimum level of performance, by the minimum annual operating temperature. Therefore, even improving 20% of the thermal performance between the real and reference models, it was not enough to reach all the criteria of the minimum level of the NBR 15575 (2021), being necessary to modify its envelope to obtain the minimum level, according to the current standard of performance.

After this analysis, the real model of SH in ZB 4 was evaluated, with the best solar orientation and with the installation of the EAHE system. This resulted in a performance improvement of 2.9%, when compared to the model without the EAHE (Fig. 3b). Thus, proving that this system improves the thermal performance of the building. This difference is equivalent to eleven days more in the year, with the feeling of comfort of the users, that is, in the acceptable range, according to the current norm.

4 CONCLUSIONS

The portrayed results made it possible to conclude that the computational model, through the EnergyPlus software, was satisfactorily validated and verified, both for the EAHE and for the thermal condition of the built environment. Furthermore, the EAHE installation coupled with the building enhanced the thermal performance of the environments, improving the thermal comfort condition.

The SH with the installation of the EAHE reached an acceptable PHFT of 3.2 more than the SH without the EAHE, equivalent to twelve days more in the year with the feeling of comfort of the users, that is, in the acceptable range according to current regulations.

As expected, another important consideration is that solar orientation is a fundamental parameter in the thermal performance of buildings. For the SH and the considered operational conditions, it was possible to obtain up to 2.5% improvement in thermal performance, if compared the best and the worst cases. It is important to highlight that there is no additional construction cost to reach this gain, being just the result of an appropriate design strategy.

Another relevant factor observed was the possibility of identifying suit bioclimatic strategies for each bioclimatic zone, respecting the climatic conditions and favoring better thermal performance.

Therefore, it is concluded that this study fulfilled its objective of evaluating the thermal performance of an EAHE, together with optimization parameters of the building envelope, in two different Brazilian bioclimatic zones. In addition, it proposed strategies that enhanced the thermal performance of building, so that future projects can count on validated references and parameters.

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