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CFD ANALYSIS OF A TROMBE WALL SYSTEM FOR COOLING IN A SUBTROPICAL REGION

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Abstract. *The Trombe wall system aims to use the solar radiation to provide sustainable energy to air renewal system. While conventional photovoltaic solar panels convert solar energy into electrical energy, the Trombe wall uses thermal inertia and natural convection to perform the thermal conditioning of an indoor environment. Another possible use is heating an environment in a similar way to solar water panels. On the other hand, this device can also been used to create an air flow for cooling the environment, such as a solar chimney or other system passive ventilation. This paper focuses on the study of the second alternative, which is suitable for the intense summer of tropical and subtropical regions, typical for the south and southeast of Brazil. For this study analytical model, available in the literature, is used to evaluate its operation. Subsequently, this analytical model is compared with results from a computational fluid dynamics modeling using solar system load in order to evaluate the model and impacts on the conditions of the room. Results for the temperature and speed profiles in the system showed a good ventilation capacity through the chimney, adequate to the proposed conditions.*

Keywords: *Trombe wall, solar chimney, CFD.*

1. INTRODUCTION

The Trombe wall system consists in a massive wall, usually made of stone, brick or concrete, with high thermal inertia and in black color that is mounted in a short distance from a glass pane. A schematic of this type of device can be seen in Fig. 1. In these devices, solar radiation is absorbed the wall and retransmits part of the thermal energy to the air spacing by natural convection.

The chimney cross wise formed in the space between glazing and the wall itself carries out air upward movement. The heat absorbed the outer surface of the wall also is conducted slowly through the massive wall to the inner surface and then into the room by radiation and convection (YEDDER, 1991). The conduction effect can be minimized using low thermal conductivity materials or phase change material. The Trombe wall system is commonly used for heating indoor environments located in regions with colder climates with good sunlight, such as the European Mediterranean. There are few studies for warmer climates such as tropical and subtropical regions.

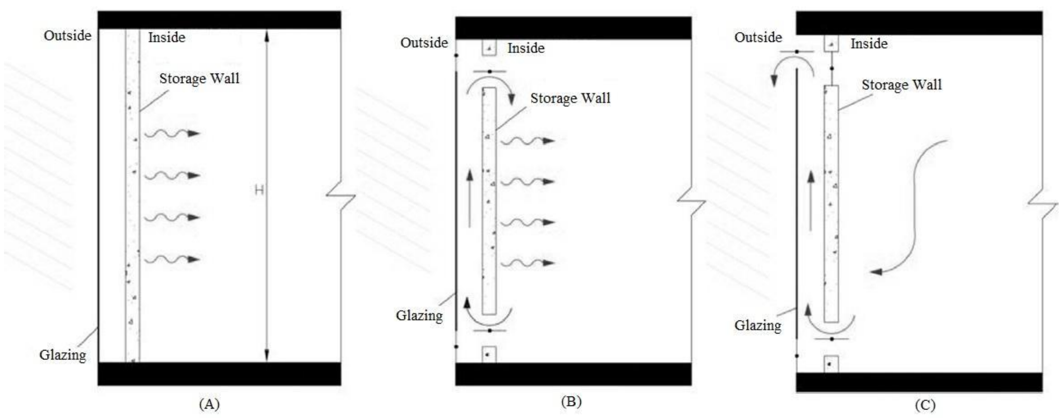

Figure 1 - Examples of cases of the Trombe wall system (Kruger et al., 2013).

This type of system can have different types of operation in winter and summer. During the summer, due to a higher solar elevation, the heating effect is largely neutralized (GAN, 1998). In order to increase the cooling effect through the natural circulation of the chimney, the lower and/or upper air ventilation of the storage wall can be used to extract the hot air from the interior, as shown in Fig.1c. Khanal (2011) studied solar chimneys as passive ventilation system and the effect of geometry and angle of inclination on ventilation performance in the system. Analyzing the results, he concluded that angles between 40 and 60° are more effective. An experimental study of Trombe walls was developed by Kruger et al. (2013) for the city of Curitiba. Various opening configurations for the air inlet and outlet of the system were evaluated. It is possible to highlight the configurations indicated in Fig. 1, with case (B) indicated for winter and case (C) indicated for summer. The air renewal rates in this type of system were assessed by Bansal et al. (1993). The interest was to replace obsolete air with fresh external air and provide a healthy and comfortable indoor environment. In this way, the speed of the average air flow in the chimney could be with the ventilation capacity in the system.

Based on these parameters discussed, this study aims to obtain adequate values of the system's operating conditions. The study intends to evaluate the use of this system in cooling indoor environments with passive ventilation through the simulated model. In order to understand the concepts involved and obtain preliminary values of temperature and airflow velocity in the chimney, a mathematical analysis will be carried out before the CFD analysis. To verify its effectiveness, the system will been studied using a heat source inside the room. Another study comparing cases with atmospheric pressure and reduced pressure to analyze the influence of convection in the operational conditions of the chimney. The reduction in pressure minimizes the convective effect and highlights the incident solar radiation ones. This analysis is based on the temperature profile on the Trombe wall. Finally, the parameters necessary to validate the system as use of the solar radiation module are evaluated. The case studies are based on weather conditions in summer in the city of Bauru, in the interior of the state of São Paulo. The climate in this region is characterized as tropical/subtropical, having proximity to the Capricorn tropic, and has low incidence of wind currents as well as predominant part of the Brazilian continental climate.

2. METHODOLOGY

2.1 Mathematical analysis

Ong (2003) proposed a mathematical model for a solar chimney in the form of a Trombe wall as seen in Fig. 2. The system was reformulated according to the proposal of Bansal et al. (2005), where the wall area differs from the glass area, resulting in the system of equations:

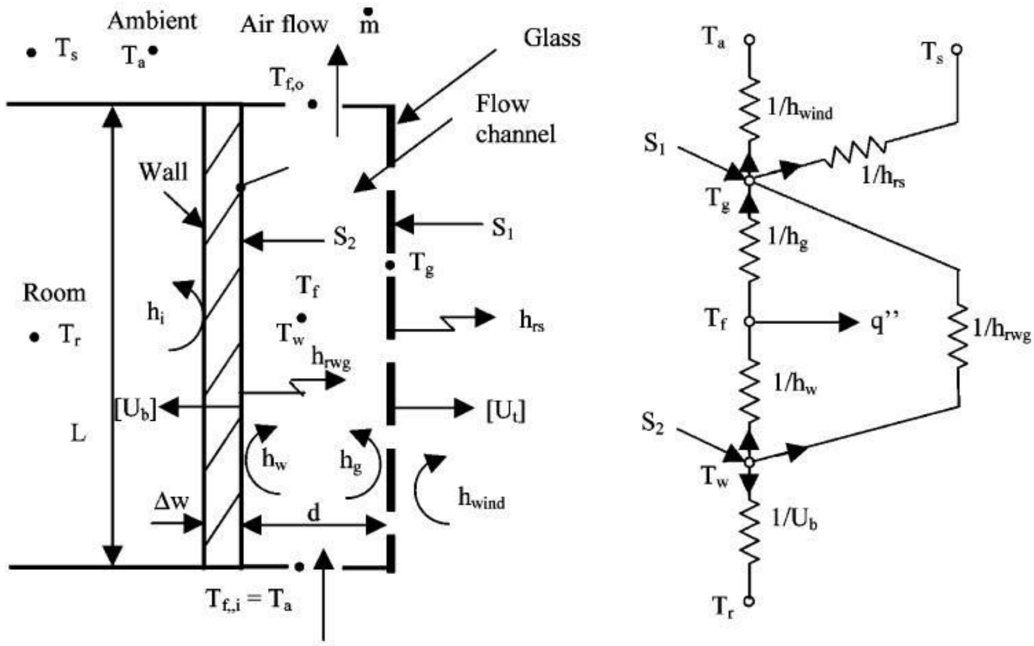

Figure 2 - Solar chimney / Trombe wall and the equivalent thermal circuit proposed by Ong (2003)

$$T_f\text{: } h_w A_t(T_w - T_f) - h_g(T_g - T_f) = MA_t(T_f - T_{fi}) \qquad (1)$$

$$T_g: h_g(T_g - T_f) + h_{rwg}A_t(T_w - T_g) = U_t(T_g - T_a) - S_1 \quad (2)$$

$$T_w: h_wA_t(T_w - T_f) + h_{rwg}A_t(T_w - T_g) + U_bA_t(T_w - T_r) = S_2A_t \quad (3)$$

Thus, the flow heat can be calculated by:

$$\dot{q} = \frac{\dot{m}c_{pf}}{\gamma}(T_f - T_{fi}) \quad (4)$$

being the mass flow calculated according to the expression proposed by Bansal et al., (1993):

$$\dot{m} = C_d \frac{\rho_{fo}A_o}{\sqrt{1+A_r}}\sqrt{\frac{2gL(T_f - T_r)}{T_r}} \quad (5)$$

To simplify the formulation, the parameter is defined:

$$M = \frac{\dot{m}c_{pf}}{\gamma A_w} \quad (6)$$

Considering the expressions presented, it is possible to write the system in the matrix form $[A][T] = [B]$ in the form:

$$\begin{bmatrix} \left(\frac{h_g}{A_t} + h_w + M\right)A_t & -h_g & -h_wA_t \\ -h_g & (h_w + h_{rwg}A_t + U_t) & -h_{rwg}A_t \\ -h_wA_t & -h_{rwg}A_t & (h_w + h_{rwg} + U_b)A_t \end{bmatrix} \begin{bmatrix} T_f \\ T_g \\ T_w \end{bmatrix} = \begin{bmatrix} MA_tT_{fi} \\ S_1 + U_tT_a \\ (S_2 + U_bT_r)A_t \end{bmatrix} \quad (7)$$

where the parameters are defined as:

- h_g and h_w are the coefficients of heat exchange by convection on the surface of the glass and the wall respectively, and the coefficient of heat exchange by radiation between the glass and the wall is $h_{rwg} = \sigma \frac{(T_g{}^2 + T_w{}^2)(T_g + T_w)}{\left(\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right)}$, for $\varepsilon_g = 0.9$ and $\varepsilon_w = 0.94$;
- $U_t = h_{wind} + h_{rs}$ for $h_{wind} = 2.8 + 3V_{wind}$, $V_{wind} = 0.1\ m/s$, and $h_{rs} = \sigma\varepsilon_g \frac{(T_g{}^4 - T_s{}^4)}{(T_g - T_s)}$, $T_s = 0.0552T_{at}{}^{1.5}$ (DUFFIE AND BECKMAN, 2006);
- $U_b = \left(\frac{1}{h_i} + \frac{\Delta w}{k_w}\right)^{-1}$, for Δw the width of the wall, $k_w = 0.0275\ W/mK$, and h_i the coefficient of heat exchange by convection in the environment inside the wall;
- $S_1 = \alpha_1 H$ and $S_2 = \tau\alpha_2 H$ where $\alpha_1 = 0.06$, $\alpha_2 = 0.95$ and $\tau = 0.84$, data found through the solar equations proposed by Kalogirou (2014).

2.2 Numerical analysis

Numerical analysis is performed by OpenFoam code using the *solarLoad* and *viewFactor* radiations models, with the *chtMultiRegionFoam* application, which uses the PIMPLE solution scheme. The RAS k-ε simulation model was used to evaluate the turbulence parameters. The geometry of the problem is based on the separation of distinct fields, and was possible through the use of the *topoSet* tool. The total domain of the problem was defined using *blockMes*h, encompassing all solid regions subsequently separated through *topoSetDict*, as shown in Fig. 3, and air as fluid is the rest of the model. The application of this formulation eliminates frequent turbulence problems in these types of simulations. The mesh is divided so that each cell is 0.1 m each side. and the chimney region is refined in the updated model, measuring 0.05 m sides. This way, the simulation time is reduced compared to the fully refined mesh.

Considering the dimensions shown in Fig. 3, the distance d, as well as the entrance and exit openings of the chimney and the room, is 0.2 m. The hot block has a constant temperature of 313 K and approximate dimensions of a person and the thickness of all other geometries is 0.1 m. Other dimensions are shown in Tab. 1.

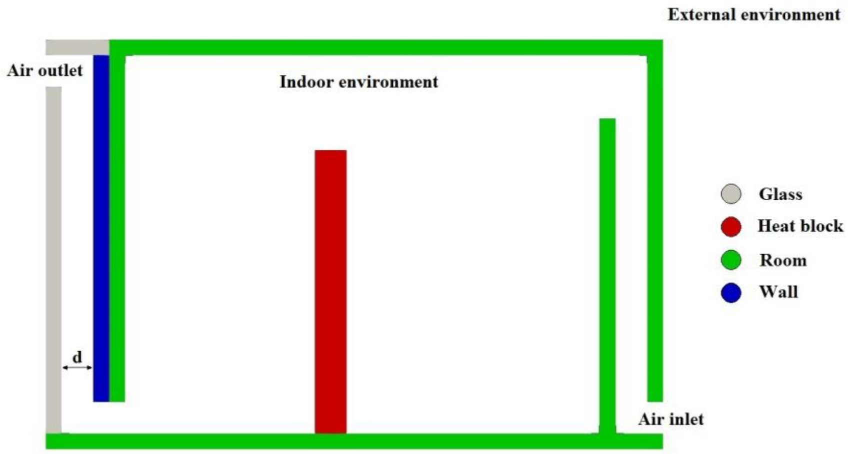

Figure 3 - Geometries of the Trombe wall system used in the problem model.

Table 1. Basic dimensions of the problem model.

	Total domain [m]	Room dimensions [m]	External dimensions [m]	Chimney [m]
X	8	3	3.9	0.2
Y	5	2.4	2.6	2.2
Z	5	2.4	2.6	2.4

All the boundaries of the numerical domain are defined as *patch* and present the same atmospheric boundary conditions as seen in Tab. 2. The boundary conditions of the fluid for solids are also have seen, except the room which has the adiabatic condition with the type *zeroGradient* for the temperature. Tab. 3 shows the boundary radiation properties of the air domain.

Table 2. Boundary conditions of the problem model.

	Atmospheric Boundaries	Air to solids
alpha	Calculated	compressible::alphatWallFunction
epsilon	inletOutlet	epsilonWallFunction
G	Calculated	Calculated
IDefault	wideBandDiffusiveRadiation	wideBandDiffusiveRadiation
k	inletOutlet	kqRWallFunction
nut	Calculated	nutkWallFunction
p	totalPressure	zeroGradient
p_rgh	fixedMeanOutletInlet	fixedFluxPressure
qr	Calculated	Calculated
T	inletOutlet	compressible::turbulentTemperatureRadCoupledMixed
U	pressureInletVelocity	noSlip

Table 3. Boundary radiation properties of the air field.

	Boundaries	air_to_wall/hot	air_to_room	air_to_glass
Type	transparent	opaqueReflective	opaqueReflective	transparent
Absorptivity	(1 1)	(0.9 0.92)	(0.3 0.7)	(0 0.05)
Emissivity	(0 0)	(0.9 0.92)	(0.3 0.7)	(0 0.05)

The solar radiation model *solarLoad* calculates the direction of the sun according to the location input data, date, start time and model orientation. Bauru's coordinates are 22.3145 ° S, 49.0587 ° W, with meridian -3, Y axis positioned upwards and the wall facing north. Solar irradiation is calculated using the *sunLoadFairWeatherConditions* submodel. The model was configured for the 60th day (March, 1st), which represents a summer day and the angle of solar inclination results in a greater incidence in the wall area, from 7h to 17h.

3. RESULTS AND DISCUSSION

The average flow velocity of air in the chimney can be found through the matrix system (7), along with its relative temperature. Through Fig. 4 it can been seen that the system has better temperature and ventilation values during the winter (N = 180) due to the low solar angles. These results will be subsequently evaluated through numerical analysis and compared to those obtained analytically.

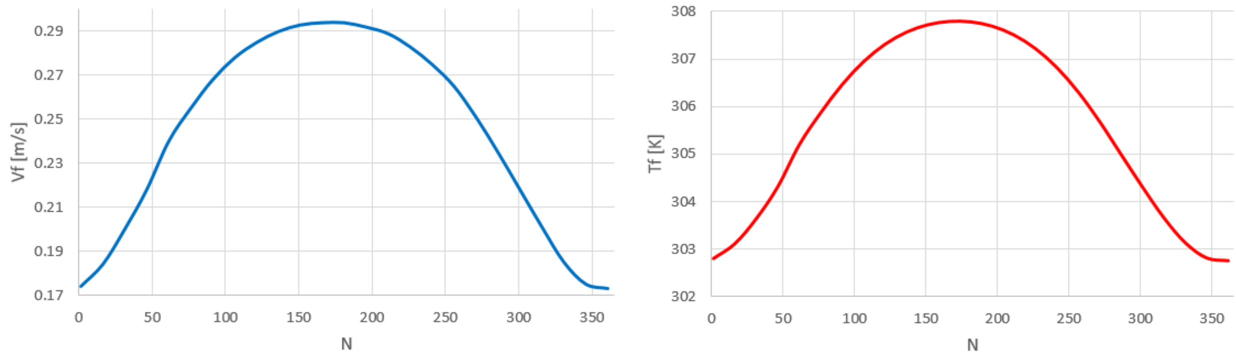

Figure 4. Average airflow speed in the chimney (Vf) and average airflow temperature in the chimney as a function of the day N.

Figure 5 shows the velocity profile [m/s] with the operational conditions on Trombe wall and Fig. 6 shows the same condition for temperature profile [K] on a XY plane.

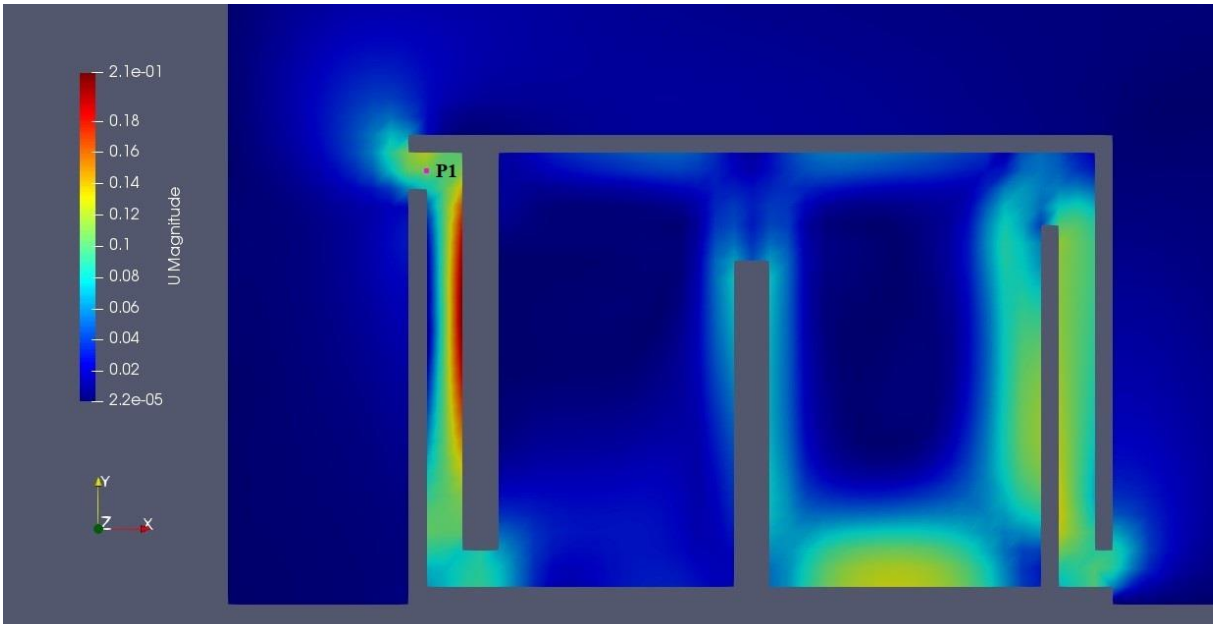

Figure 5. Air flow speed distribution [m/s] of the Trombe wall model with a hot block inside of the room for day N = 60, at 17h.

Analyzing the results, one can verify the formation of an upward air current on the wall surfaces, with higher temperature values at the top of the chimney and the room. So, an inlet flow is formed at the right side of the room. This air flow is able to renew the heated air after 10h (10800 s), when the speed increases and the air temperature reduces considerably, as shown in Fig. 7. Figure 5 and 6 also indicate the positioning of the points presented in Fig. 7. Such behavior could been explained by the accumulated thermal load and the increases in solar irradiation.

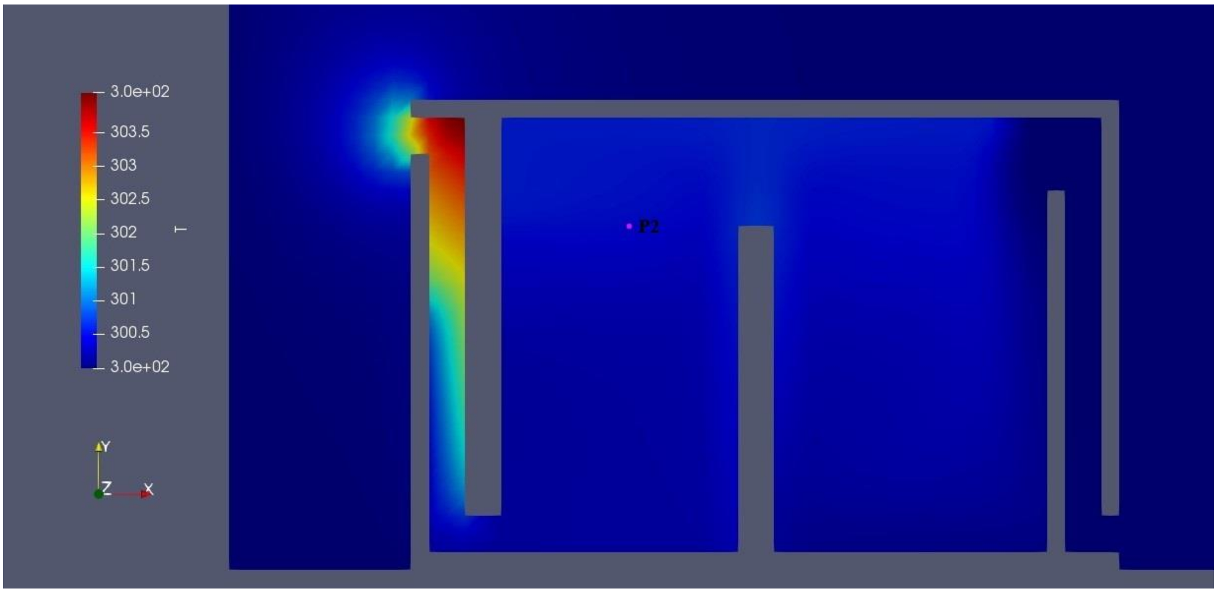

Figure 6. Air temperature distribution [K] of the Trombe wall model with a hot block inside of the room for day N = 60, at 17h.

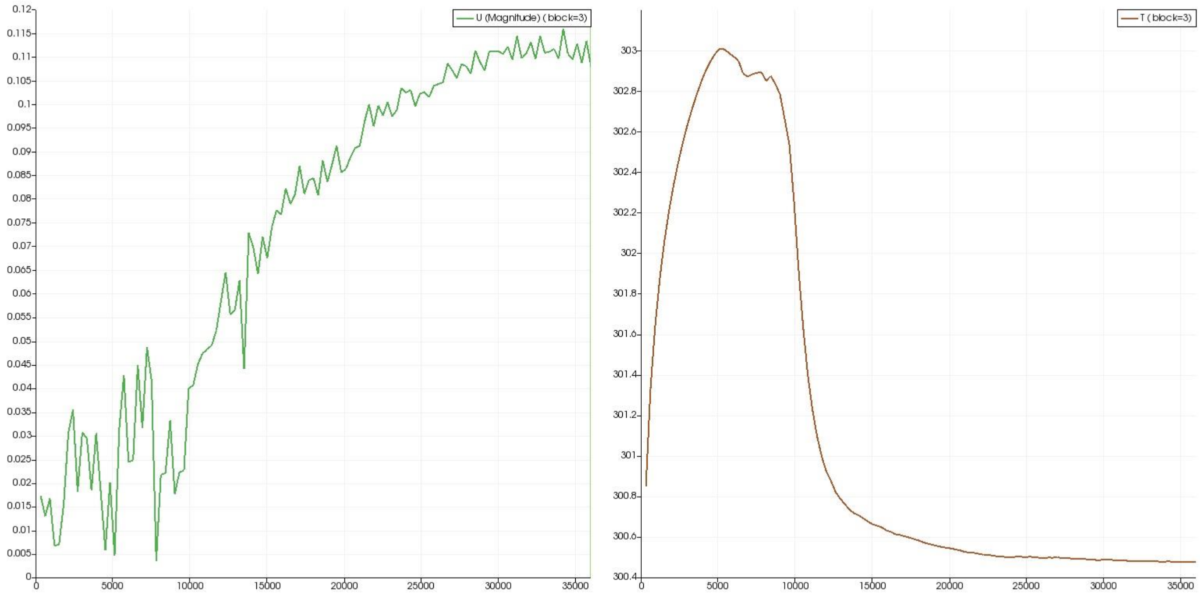

Figure 7. Air flow speed [m/s] and air temperature [K] distribution over time of the respective points P1 and P2 indicated in Fig. 5 and 6.

The influence of the free convection on the Trombe wall is also evaluated using different physical models for the numerical simulation. So, models using normal atmospheric pressure and reduced pressure (100 Pa) were compared. In these models, the heat generation in the central block is removed, since it implies greater interference in the air intake of the chimney. Figure 8 shows that the air flow velocity profile along the chimney for both cases. One can note the reduction in velocity value for atmospheric pressure condition. Despite this effect, it is important to detach that the air mass flow is too much lower in reduced pressure due to its density decrease. So, the air temperature next to the wall has higher and constant values over most parts of the heated wall for reduced pressure, as can be seen in Fig. 9. This effect is due to the reduction on upward air mass flow previously discussed. The higher temperature values are verified at the beginning of the wall, where the solar radiation incidence is more intense throughout the day.

The air flow velocity in the chimney region formed by the wall (x = 0) and the glass (x = 0.2 m) for the normal pressure condition was shown in Fig. 10. The velocity profile in the entrance region is relatively uniform but, as it develops, one can note higher ascending values near to the hot wall surface.

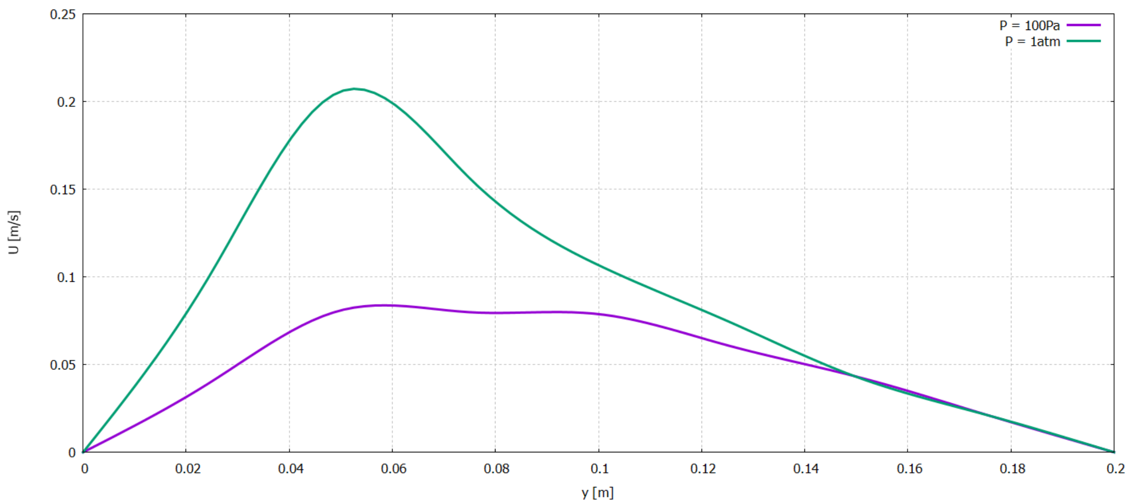

Figure 8. Comparison of upward air flow speed [K] across Trombe wall system for atmospheric pressure and reduced pressure for y = 2.3 m at 17h.

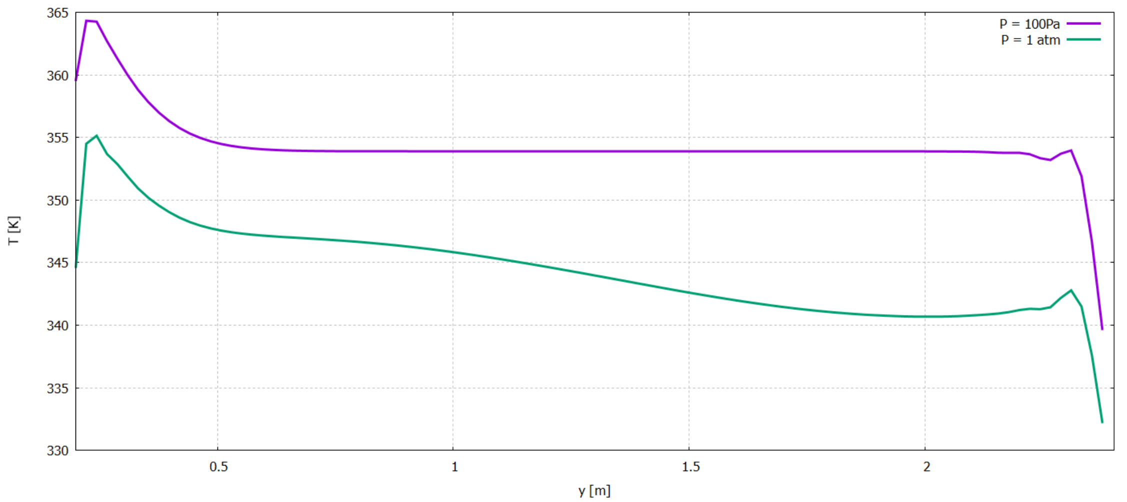

Figure 9. Comparison of the temperature [K] along the chimney with atmospheric pressure and reduced pressure, for x = 0 at 17h.

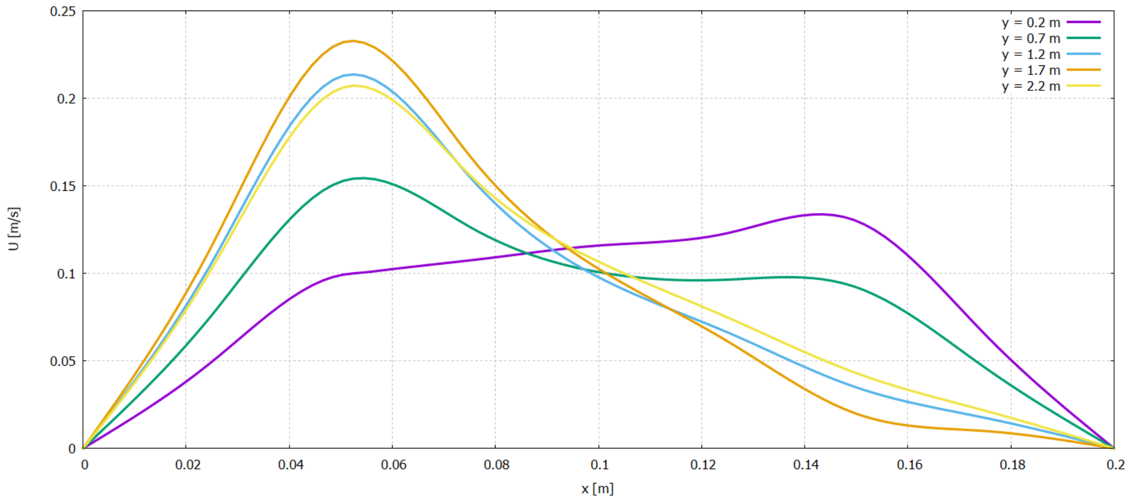

Figure 10. Upward air flow speed [m/s] distribution across Trombe wall system for 17h.

Near to the wall, for x = 0.05 m, the air temperature profiles are evaluated throughout the day, as seen in Fig. 11. One can observe that the maximum values are achieved around 15h. This behavior indicates that the heat stroke peak on the wall occurs before this time. The temperature increases due to thermal inertia and decays smoothly, which is according to experiments in the literature. It is also observed that the maximum values are consistent with those calculated during the mathematical analysis and shown in Fig.4.

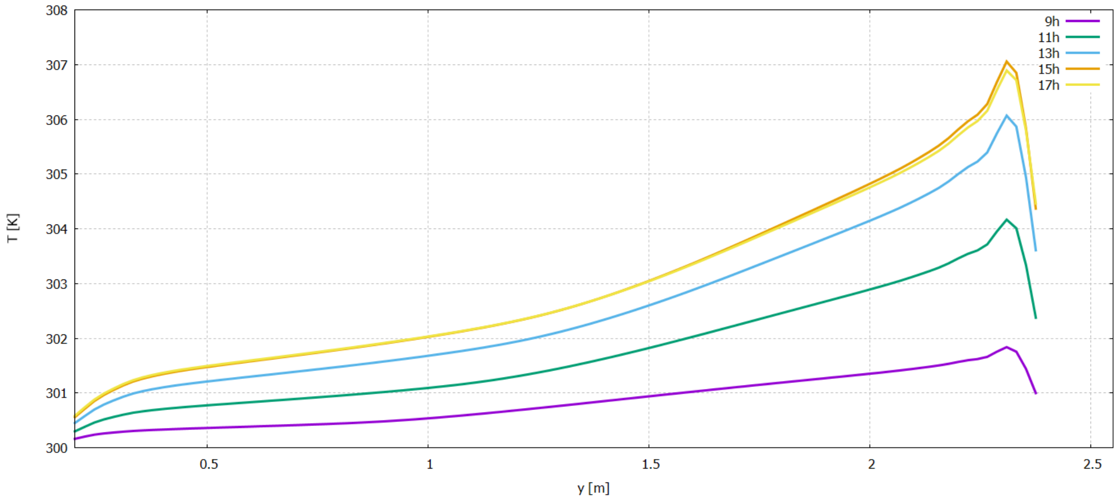

Figure 11. Air flow temperature [K] distribution across Trombe wall system along a day for x = 0.05 m from the wall.

Considering the simulation results, the average airflow velocity at the chimney outlet was calculated for different times. The sum of the room and the chimney volumes is 20.748 m³ and the exit area of the chimney is 0.48 m². Thus, the volumetric air flow at the device outlet and the time required to renew the environment air volume were shown in Table 4. It can be observed in the table that the time reduces considerably throughout the day, inversely proportional to the temperature profile of the wall. In this way, after 13h. So, the system can renew the ambient air in less than 10 minutes, which implies 6 complete renovations of the room air per hour.

Table 4. Calculated data for the Trombe wall system output over a day.

Hour of a day	9h	11h	13h	15h	17h
Average airflow speed [m/s]	0.028	0.052	0.071	0.081	0.081
Volumetric flow [m³/s]	0.014	0.025	0.034	0.039	0.039
Renewal time [min]	25.28	13.88	10.18	8.91	8.88
Renewal rate [cycle/h]	2.37	4.32	5.90	6.74	6.76

4. CONCLUSION

The analysis indicates that the Trombe wall device is interesting way for inducing the renewal of the air in a room. The results for the proposed arrangement show that the convective flow draws air out of the room in less than 10 minutes for the most time in the afternoon. As the renewal rate increases it also increases the air renew, as seen in Fig. 7. This effect causes a temperature drop after 10h and the renovation is sufficient to keep the room temperature near to the air room entrance. New simulations, with a larger number of data are being carried out to complete this study. For now, it is known that the ideal sustainable system for the cooling function of an indoor environment is the inclined solar chimney, for this reason, future analyzes will have the comparison of the proposed standard model (90°) with inclined models.

The *solarLoad* radiation module is suitable for use, requiring comparative experiments to define precisely the radiation parameters used. The code also provides application of this module using the fvDOM module, which could been evaluated in the future. Still, it is known about the importance of the greenhouse effect for this type of environment, so new studies must be done to apply it in the current simulation model.

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