ENCIT-2018-0242
STUDY OF THERMAL TRANSMITTANCE OF A BRAZILIAN CONCRETE HOLLOW BLOCK WALL

Marcelo Adriano Fogiatto
Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, 80215-901, Curitiba, Brazil.
m.a.fogiatto@gmail.com

Gerson Henrique dos Santos
Federal University of Technology – Parana (UTFPR), Monteiro Lobato, km 04, 84016-510, Ponta Grossa, Brazil.
gsantos@utfpr.edu.br

Viviana Cocco Mariani
Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, 80215-901, Curitiba, Brazil.
viviana.mariani@pucpr.br

Abstract. The increase in the worldwide energy consumption is an issue that has to be dealt with through the next decades. One of the main concerns on this matter is the energy spent by electric apparatus in residential and commercial buildings. A considerable share of building energy consumption is due to the usage of heating, ventilation and air conditioning (HVAC) systems. Energy consumption can be decreased by minimizing the heat transfer through the building envelope, i.e., reducing the thermal transmittance of the walls. In this work, the thermal transmittance of a typical Brazilian concrete hollow block wall has been studied for a wide range of external environment temperatures. Firstly, thermal transmittance values are obtained for few external wall temperatures using a computational fluid dynamics (CFD) commercial software. Afterwards, it is developed a code using the finite volume method (FVM), to calculate the transmittance for any temperature in the determined range. The results obtained from the CFD analysis and from the FVM written algorithm have reached good agreement, making it possible to perform thermal transmittance evaluation on the designed situation without the use of the CFD commercial software. Furthermore, the simulations have shown that the thermal transmittance of a concrete hollow block may vary up to 18% to different gaps between external and internal wall temperatures.

Keywords: thermal transmittance, concrete hollow block, computational fluid dynamics, finite-volume method.

1. INTRODUCTION

Obtaining thermal comfort has been one of the main objectives of builders since the beginning of construction history. Currently, in most edifices, thermal comfort is often acquired with the use of HVAC (Heating, Ventilation and Air Conditioning) systems. In Brazil, for example, HVAC systems can be responsible for 63% of the total energy consumption in commercial buildings, according to Carvalho *et al*. (2010). One of the main factors which contribute to this high energy consumption of the HVAC systems is the heat transfer through the building envelope. The amount of heat flowing through the wall can be quantified by a variable called thermal transmittance, which is the main parameter of comparison regarding different wall configurations in terms of heat transfer. Thus, the thermal transmittance is an important factor regarding the thermal efficiency of buildings.

Due to interesting features, such as high strength and proper space to fit pipes and wires, concrete hollow blocks have become more popular in Brazil, especially in low buildings, taking the place of traditional ceramic bricks. Modeling the heat transfer which across the wall is a complex process, due to the interaction of different heat transfer phenomena inside the cavities, such as free convection and thermal radiation.

Several studies have been performed regarding the heat transfer through hollow blocks. Sun and Fang (2009) performed CFD (Computational Fluid Dynamics) analysis of equivalent thermal conductivity for several configurations of cavities in concrete hollow bricks. The results obtained have revealed that the use of smaller cavities can reduce the convection and radiation effects on heat transfer through the blocks, contrary to the effect of the choice of bigger ones.

Koci *et al*. (2015) obtained values for the equivalent thermal conductivity of hollow clay bricks with complex geometry cavities, using a finite element method. In their calculations, they presumed the air in the cavities to have a total equivalent conductivity, given by the sum of steady air real conductivity, radiation and convection equivalent ones. The results showed that numerical and experimental values were close.

Santos *et al*. (2017) performed 2D and 3D CFD analysis of thermal transmittance in concrete hollow blocks, considering several different configurations, size and number of cavities. The results obtained led to the conclusions

that large size cavities can enhance the heat transfer phenomenon through the blocks, and that thermal radiation answers for a great part of the heat transfer through the cavities.

Laaroussi *et al.* (2017) studied the thermal transmittance of different multi-holed blocks. They performed the calculations following a simple procedure determined by international standards, and then compared the results with the ones obtained by a more complex CFD analysis. The authors concluded that the procedure of international standards is inaccurate, due to inappropriate correlations of thermal radiation and free convection inside the cavities.

In order to obtain reliable thermal transmittance values, heat transfer through a wall composed by Brazilian standard hollow concrete blocks and cement mortar has been simulated in this work. In the first step, the analysis will be performed using a CFD commercial software with a FVM solver, considering both solid and fluid domains (air inside the cavity), for a few defined external wall temperatures. The objectives of this step are to obtain the values of block's thermal transmittance for the given external wall temperatures, as well as the average temperature in each surface of the cavity, for the same defined external wall temperatures. In the second step, the average temperatures of cavity surfaces obtained in the previous stage are used as some of the boundary conditions in a new FVM code. The objective of this step is to develop a FVM program which can calculate the wall thermal transmittance for any temperature inside the defined range. This new procedure deals only with the solid domain. At last, the values of transmittance obtained by the CFD simulations are compared to those obtained from the FVM code. The main contribution of this study is the development of a computational program useful to calculate the concrete hollow block wall thermal transmittance without the use of commercial CFD software.

2. METHODOLOGY

In this section, the methods employed to reach the results are described. The next subsections explain the physical domain considered, the thermophysical properties of materials, the procedure followed to obtain the CFD analysis results, and also the hypotheses adopted in the FVM program.

2.1 Physical domain

In this study, it is performed the analysis of thermal transmittance in a portion of wall composed by Brazilian Standard (ABNT, 1994) M-15 concrete blocks involved by cement mortar. The main dimensions of the computational domain are represented in Fig.1.
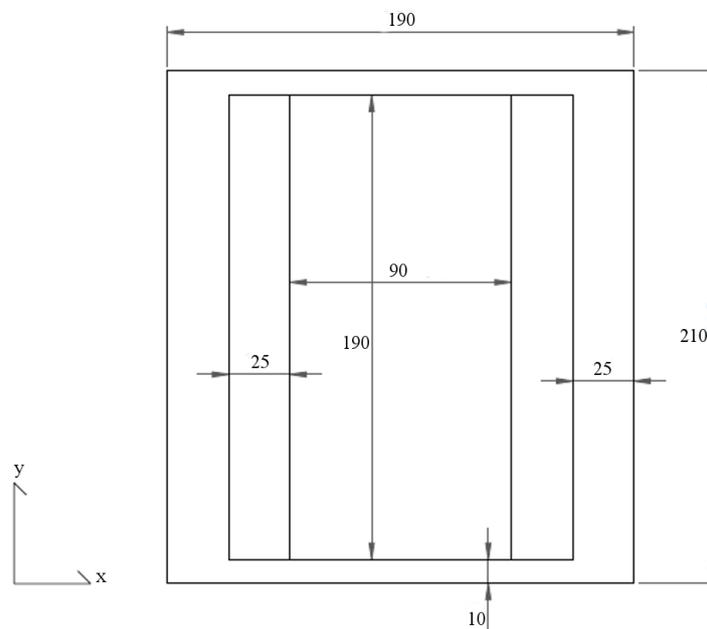

Figure 1. Dimensions of wall section in mm.

2.2 Thermophysical properties

For the solid materials, the properties were considered constant, with their values evaluated at 300 K. The values of the properties – such as density (ρ), specific heat (c), thermal conductivity (k) and emissivity (ε) – which were obtained from Bergman *et al.* (2011) are shown in Tab. 1.

Table 1. Thermophysical properties of solid materials at 300 K.

Material	ρ (kg/m^3)	c (J/(kg*K))	k (W/(m*K))	ε (-)
Cement	1860	780	0.72	0.9
Concrete	2300	880	1.40	0.9

Considering the air properties, important to the CFD analysis, the air density was not taken from the ideal-gas model, but from the real-gas model proposed by Peng and Robinson (1976), already enclosed in the properties section of the CFD software. Other properties necessary for calculation were also extracted from Bergman *et al.* (2011). These air properties were not assumed as constant, but as piecewise linear functions of temperature. Their values for different temperatures can be observed in Tab. 2, where μ represents dynamic viscosity.

Table 2. Thermophysical properties of air at different temperatures.

T (K)	c (J/(kg*K))	k (W/(m*K))	μ (N*s/m^2)
250	1006	0.0223	$1.596*10^{-5}$
300	1007	0.0263	$1.846*10^{-5}$
350	1009	0.0300	$2.082*10^{-5}$

2.3 CFD analysis procedure

The CFD steady-state analysis was performed using the ANSYS® Workbench package, release 18.2, including the FVM solver ANSYS® Fluent®. The air cavity flow was solved as a 2D laminar flow, and for the thermal radiation simulation, it was chosen the discrete ordinates radiation model, explained in detail by Lu and Wang (2013).

Regarding the boundary conditions, north and south boundaries were considered adiabatic, assuming Neumann type boundary conditions. East and west surfaces were considered Dirichlet type boundary conditions. The east one was simulated as the wall surface inside the building, kept always at T_E=20°C (293 K). The west border was considered the wall surface outside the building, where T_W can vary from -3°C (270 K) to 47°C (320 K). These conditions are represented more clearly in Fig. 2.
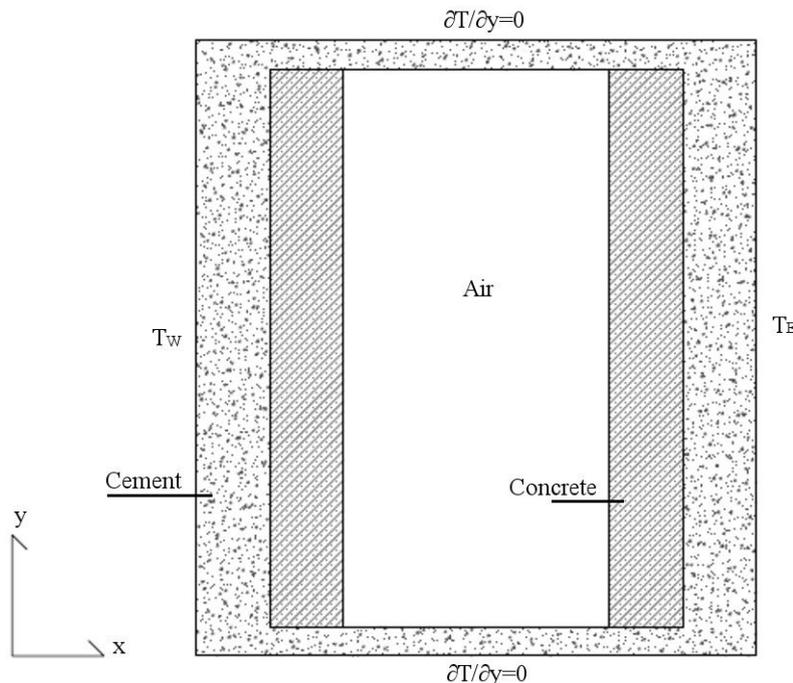

Figure 2. Boundary conditions of the CFD analysis.

The simulations were performed using a structured mesh grid, formed by 1-mm size quadrilateral elements, in both solid and fluid regions, resulting in 190 volumes in x direction by 210 in y direction (39,900 elements). The fluid domain was verified using the benchmark of dimensionless temperature profiles, provided by Wakashima and Saitoh (2004), for flows with Rayleigh number $Ra = 10^5$ in a square cavity with vertical walls at different temperatures and the horizontal ones treated as adiabatic, resembling the situation of the cavity in this analysis. This method of verification

was already applied by Santos *et al*. (2017) and Svoboda and Kubr (2010) in similar studies. As can be visualized in Fig. 3, the profiles generated with the mesh grid of this analysis are in good agreement with the ones from the benchmark. Thus, this mesh can be used to the CFD analysis.
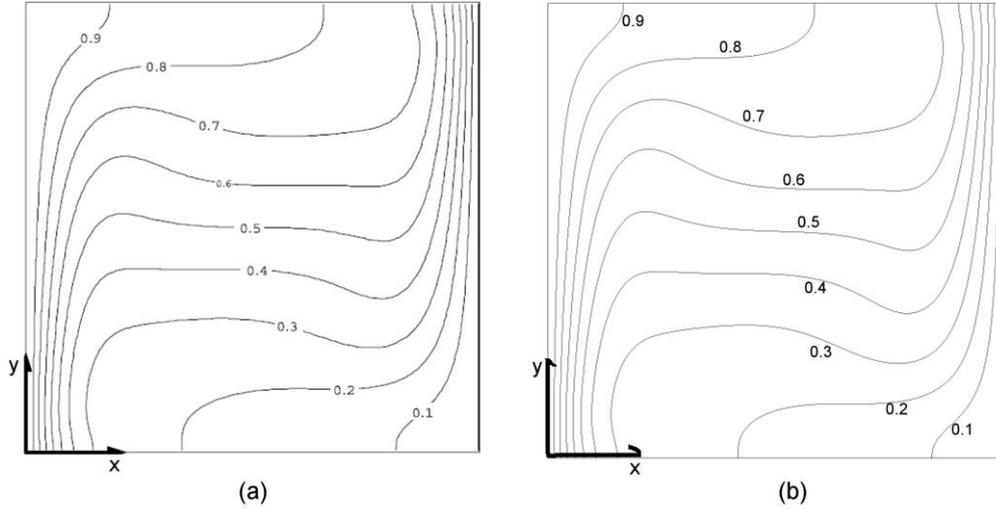

Figure 3. Verification of the mesh grid used for the fluid region in the CFD analysis: (a) Wakashima and Saitoh (2004); (b) mesh used in this study.

2.4 Procedure of the FVM program

The program was written using the software GNU Octave, version 4.2.1 to simulate the heat transfer in the wall solid domain. Considering the problem as steady-state, 2D and without heat generation, Fourier's heat equation has the form of Eq. (1).

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) = 0 \tag{1}$$

In this study, to solve the system of equations of temperature generated by discretization of Eq. (1), it was employed the iterative Gauss-Seidel method. The equation of temperature for a central volume is shown in Eq. (2), where i is the x direction counter, j is the y direction counter, m is the iteration counter, Δx and Δy are the dimensions of the volume in each direction and k is the thermal conductivity in the interface of volumes.

$$T_{i,j,m+1} = \frac{\dfrac{k_{i,j+\frac{1}{2}}\,\Delta x\, T_{i,j+1,m}}{\Delta y} + \dfrac{k_{i-\frac{1}{2},j}\,\Delta x\, T_{i-1,j,m+1}}{\Delta y} + \dfrac{k_{i,j-\frac{1}{2}}\,\Delta x\, T_{i,j-1,m+1}}{\Delta y} + \dfrac{k_{i+\frac{1}{2},j}\,\Delta x\, T_{i+1,j,m}}{\Delta y}}{k_{i,j+\frac{1}{2}}\dfrac{\Delta x}{\Delta y} + k_{i-\frac{1}{2},j}\dfrac{\Delta y}{\Delta x} + k_{i,j-\frac{1}{2}}\dfrac{\Delta x}{\Delta y} + k_{i+\frac{1}{2},j}\dfrac{\Delta y}{\Delta x}} \tag{2}$$

In Eq. (2), special considerations had to be done regarding the values of Δx and Δy in boundary volumes and the values of k in the interface between different solid materials. The initial temperature all over the solid domain was given by Eq. (3):

$$T_{i,j,1} = \frac{T_W + T_E}{2} \tag{3}$$

When the iterative solution has converged and all the temperature values are known, the wall thermal transmittance (U) can be obtained using Eq. (4), where $\bar{T}_{1,j,m}$ is the temperature average value along the first column of volumes:

$$U = \frac{2\,k_{cement}\left(\left|T_W - \bar{T}_{1,j,m}\right|\right)}{\Delta x\left(\left|T_W - T_E\right|\right)} \tag{4}$$

Since the results of transmittance are obtained with this FVM program, they can be compared to those obtained by the CFD analysis described in the previous section. Error value can be calculated using Eq. (5).

$$error = \frac{|U - U_{CFD}|}{U_{CFD}} * 100\% \tag{5}$$

This FVM program was restricted to the solid domain of the wall. Thus, the cavity air flow was not taken into account in this method. Therefore, the cavity walls were also considered as Dirichlet-type boundary conditions, as represented by T_{Ecv}, T_{Wcv}, T_{Ncv} and T_{Scv} in Fig. 4.
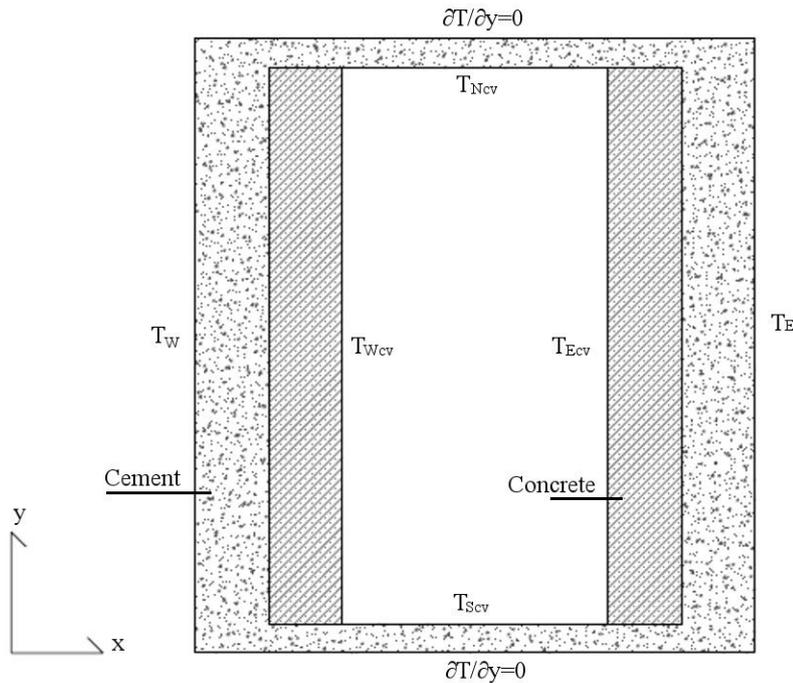

Figure 4. Boundary conditions of the finite-volume analysis.

The mean temperature values of the cavity surfaces T_{Ecv}, T_{Wcv}, T_{Ncv} and T_{Scv} can be obtained directly from the previous CFD analysis for the given temperatures of T_W. And for those and any other temperatures inside the 270-320 K range, they can be obtained using a piecewise linear function of the CFD results for temperature of the cavity surfaces, which is shown with its coefficients values for different temperatures ranges in Tab. 3.

Table 3. Coefficients for calculation of cavity surface temperatures.

$T_{cv} = a + bT_W$								
T_W range	T_{Wcv}		T_{Ecv}		T_{Ncv}		T_{Scv}	
(K)	a	b	a	b	a	b	a	b
270-275	57.279	0.8042	235.67	0.1960	175.07	0.4012	119.86	0.5920
275-280	57.059	0.805	235.94	0.1950	173.20	0.4080	121.34	0.5866
280-285	56.555	0.8068	236.39	0.1934	170.85	0.4164	123.25	0.5798
285-290	55.643	0.8100	237.36	0.1900	167.66	0.4276	125.92	0.5704
290-295	52.795	0.8192	224.37	0.2348	103.39	0.6492	142.69	0.5126
295-300	57.164	0.8050	252.04	0.1410	175.73	0.4040	165.17	0.4364
300-305	60.404	0.7942	232.66	0.2056	125.09	0.5728	166.67	0.4314
305-310	62.722	0.7866	230.28	0.2134	124.11	0.5760	167.21	0.4296
310-315	64.706	0.7802	228.29	0.2198	125.48	0.5716	167.21	0.4296
315-320	66.596	0.7742	226.47	0.2256	121.51	0.5842	166.96	0.4304

3. ANALYSIS OF RESULTS

Firstly it is performed a comparison of the transmittance results obtained by the previous CFD analysis for defined T_W values and the ones obtained by the FVM program for the same values of temperature of that wall. The results obtained are shown in Tab. 4, with different number of volumes tested in the x direction (n_x).

Table 4. Thermal transmittance values U for the wall found with both methods.

T_W (K)	CFD analysis	FVM code					
		$n_x \times n_y$					
		38 ×84		76 × 84		152 × 84	
	U (W/(m²*K))	U (W/(m²*K))	error (%)	U (W/(m²*K))	error (%)	U (W/(m²*K))	error (%)
270	3.6436	3.7902	4.0	3.7688	3.4	3.7634	3.3
275	3.6237	3.7701	4.0	3.7527	3.6	3.7474	3.4
280	3.5940	3.7405	4.1	3.7211	3.5	3.7158	3.4
285	3.5455	3.6940	4.2	3.6704	3.5	3.6652	3.4
290	3.4447	3.5609	3.4	3.5454	2.9	3.5406	2.8
295	3.4374	3.4589	0.6	3.4436	0.2	3.4390	0.0
300	3.6290	3.7818	4.2	3.7532	3.4	3.7479	3.3
305	3.7435	3.8830	3.7	3.8660	3.3	3.8604	3.1
310	3.8326	3.9699	3.6	3.9504	3.1	3.9445	2.9
315	3.9085	4.0440	3.5	4.0263	3.0	4.0202	2.9
320	3.9759	4.1102	3.4	4.0921	2.9	4.0859	2.8

It can be noticed that the error between the results of both methods decrease when the number of volumes in x increases. However, this error does not decrease substantially when increasing from 76 to 152 volumes. Thus, in analysis of thermal transmittance involving the finite volume method in this study, it will be used 76 volumes in 'x' direction, in order to avoid unnecessary computational costs.

From Tab. 4, it can be noticed the variation of thermal transmittance values as a function of the external wall temperature. The behavior of the function can be better observed in Fig. 5, where the values of transmittance were obtained for 50 different temperatures, using the FVM code.
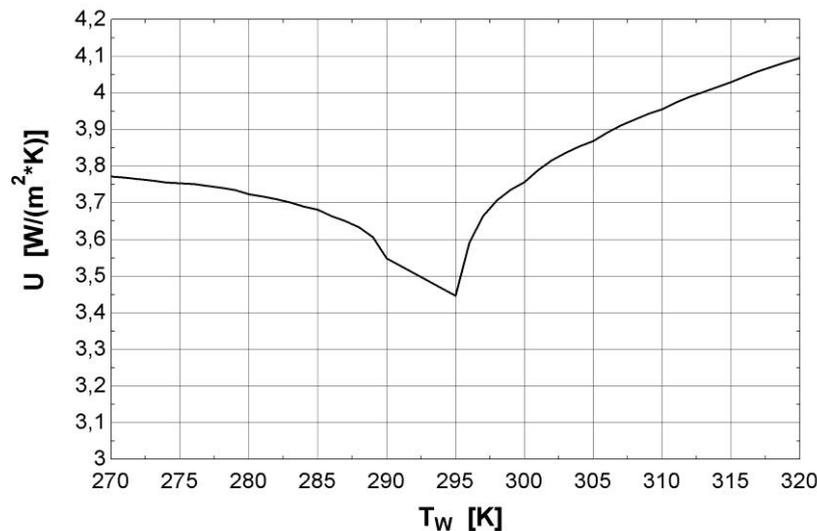

Figure 5. Thermal transmittance values as function of the external wall temperature.

In the temperature range considered, the thermal transmittance presented an average value of 3.807 W/(m²*K). The lowest values occur when the external wall temperature (T_W) is close to the internal wall one (T_E). Regarding the lowest transmittance value computed, there is an increase of 9.4% in thermal transmittance at the lowest temperature of 270 K and an 18.8% increase at the highest temperature of 320 K.

Such increases in thermal transmittance can be explained by the enhancement of the heat transfer inside the cavity, especially by free convection. This can be perceived by air velocity profile inside the cavities in the case of the extreme temperatures of the determined range. It can be observed in the velocity profiles of air inside the cavities for different values of T_W, as shown in Fig. 6.
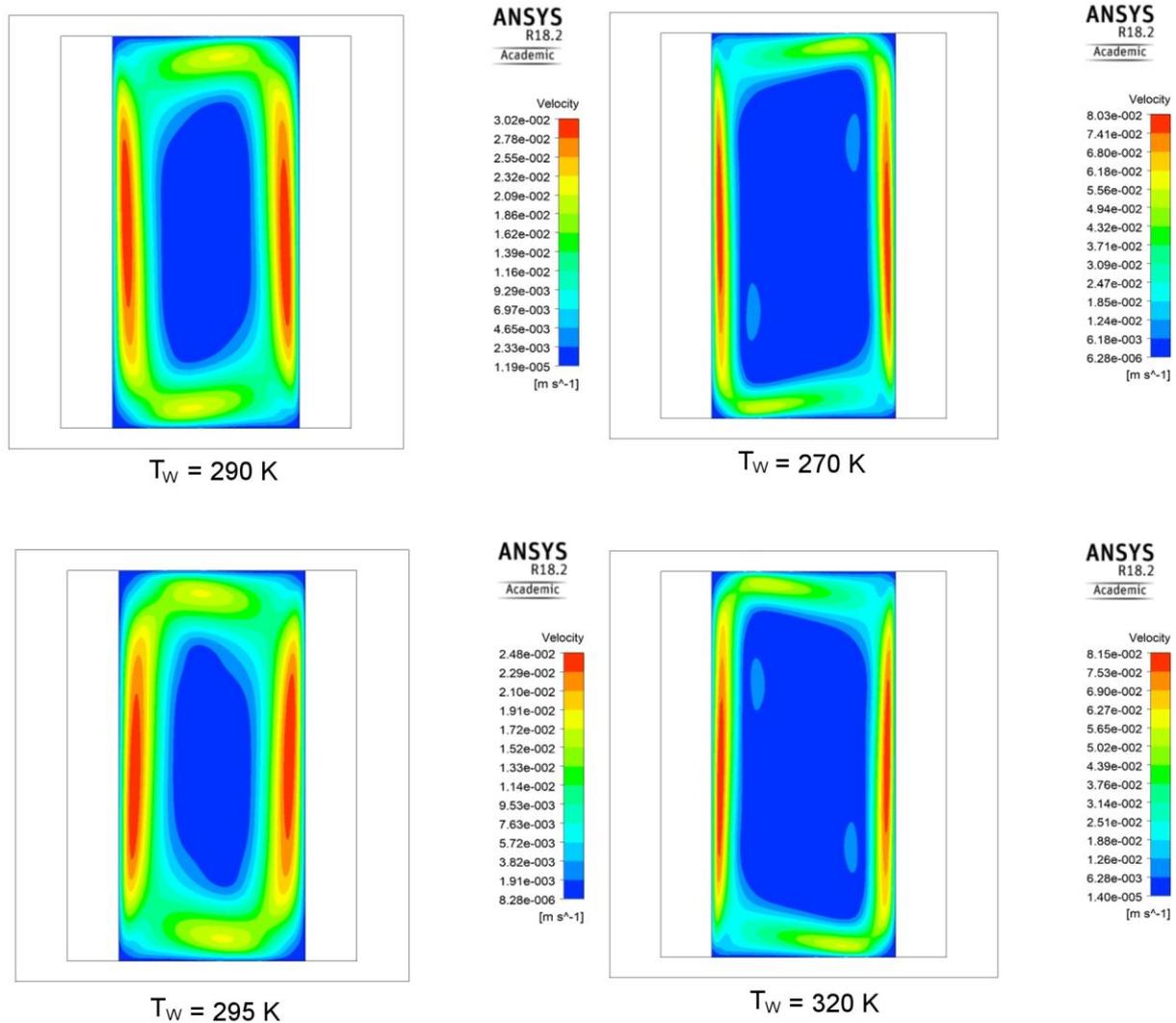

Figure 6. Air velocity profiles of the cavity air for different external wall temperatures, when T_E=293 K.

As noticed, higher temperature differences maximize the air velocity inside the cavities and, consequently, the heat transfer. There are some ways to minimize the heat transfer, such as: filling the cavity with insulating material (Pavlik et al., 2015), reducing the emissivity of cavity walls (Principi and Fioretti, 2012) or designing the cavities with baffles (Alhazmy, 2010), to decrease the air velocity.

4. CONCLUSION

The thermal transmittance of a concrete hollow block wall has been evaluated in this work. The first step of the study was to perform the thermal transmittance for a few external wall temperatures using a CFD software. In this analysis, it was also obtained the average temperature of the cavity surfaces for each external wall temperature simulated. In a second step, a FVM program for analysis of thermal transmittance has been written, using the temperature of the cavity surfaces, previously obtained, as Dirichlet-type boundary conditions at the cavity surfaces.

The good agreement found between the results obtained by the CFD analysis and the ones obtained through the FVM code has shown that this program can be used to evaluate the transmittance of concrete hollow block walls in any external temperature, without the necessity to use the CFD software. It is highly beneficial for the user, since CFD software has a longer setup time and, in case of commercial ones, costs are also involved.

The analysis performed using the FVM code have shown that the difference in thermal transmittance can reach 18%, with higher values occurring at higher temperature differences between external and internal surfaces of the wall.

5. ACKNOWLEDGEMENTS

6. REFERENCES

ABNT, 1994. *NBR 6136: Bloco vazado de concreto simples para alvenaria estrutural*. ABNT, Rio de Janeiro.

Alhazmy, M. M., 2010. "Internal baffles to reduce the natural convection in the voids of hollow blocks", *Building Simulation*, Vol. 3, pp. 125-137.

Bergman, T.L., Lavine, A.S., Incropera, F.P., Dewitt, D.P., 2011. *Fundamentals of Heat and Mass Transfer*. Wiley, Hoboken, 7th edition.

Carvalho, M.M.Q., la Rovere, E.L. and Gonçalves, A.C.M., 2010. "Analysis of variables that influence electric energy consumption in commercial buildings in Brazil". *Renewable and Sustainable Energy Reviews*, Vol. 14, p. 3199-3205.

dos Santos, G.H., Fogiatto, M.A., Mendes, N., 2017. "Numerical analysis of thermal transmittance of hollow concrete blocks". *Journal of Building Physics*, Vol. 41, p. 7-24.

Koci, J., Madera, J., Cerny, R., 2015. "A fast computational approach for the determination of thermal properties of hollow bricks in energy-related calculations". *Energy*, Vol. 83, p. 749-755.

Laaroussi, N., Lauriat, G., Raefat, S., Garoum, M., Ahachad, M., 2017. "An example of comparison between ISO Norm calculations and full CFD simulations of thermal performances of hollow bricks". *Journal of Building Engineering*, Vol. 11, p. 69-81.

Lu, X., Wang, T., 2013. "Investigation of radiation models in entrained-flow coal gasification simulation". *International Journal of Heat and Mass Transfer*, Vol. 67, p. 377-392.

Pavlik, Z., Jerman, M., Fort, J., Cerny, R., 2015. "Monitoring thermal performance of hollow bricks with different cavity fillers in difference climate conditions.", *International Journal of Thermophysics*, Vol. 36, pp. 557-568.

Peng, D.Y., Robinson, D.B., 1976. "A new two-constant equation of state". *Industrial & Chemical Engineering Fundamentals*, Vol. 15, p. 59-64.

Principi, P., Fioretti, R., 2012. "Thermal analysis of the application of pcm and low emissivity coating in hollow bricks", *Energy and Buildings*, Vol. 51, pp. 131-142.

Sun, J., Fang, L., 2009. "Numerical simulation of concrete hollow bricks by the finite volume method". *International Journal of Heat and Mass Transfer*, Vol. 52, p. 5598-5607.

Svoboda, Z., Kubr, M., 2010. "Numerical simulation of heat transfer through hollow bricks in the vertical direction". *Journal of Building Physics*, Vol. 34, p. 325-350.

Wakashima, S., Saitoh, T.S., 2004. "Benchmark solutions for natural convection in a cubic cavity using the high-order time–space method". *International Journal of Heat and Mass Transfer*, Vol. 47, p. 853-864.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.