THERMAL TRANSMITTANCE EVALUATION OF CONCRETE HOLLOW BLOCKS

Fogiatto M.A.[a], Santos G.H.[a]*and Mendes N.[b]
*Author for correspondence
[a]Federal University of Technology – Parana (UTFPR)
Mechanical Engineering Graduate Program, 84016-510 Ponta Grossa, Brazil
[b]Pontifical Catholic University of Parana (PUCPR)
Mechanical Engineering Graduate Program, 80215-901 Curitiba, Brazil
E-mail: gsantos@utfpr.edu.br

ABSTRACT

Buildings are worldwide responsible for a paramount consumption of energy. Inside them, electrical power is used for a wide range of applications. One of them is directly related to the equipment required to provide thermal comfort to occupants, which may be responsible for a substantial amount of the whole-building energy consumption. The amount of power required by HVAC (Heating, Ventilation and Air Conditioning) systems depends on several factors and, one of the most important, is the conduction load through the building envelope. In this context, a large range of construction elements has been used worldwide. In emerging countries such as Brazil, concrete hollow blocks have become more usual over the past few years. This can be explained by the advantages such as their higher strength, their large cavities – which can be useful for pipes installation –, the faster execution and the small amount of waste produced during the construction process. For the assessment of building energy efficiency, the thermal transmittance evaluation of hollow blocks is required. In this way, this study aims at obtaining values of thermal transmittance for different cavity configurations of concrete blocks, by performing CFD simulations. The transmittance values obtained are compared to those calculated using the methodology presented in international standards. In the results section, it is shown that large cavities provide higher transmittance values and that radiation effect may play an important role on the overall heat transfer through concrete hollow blocks.

NOMENCLATURE

A	[m^2]	Section area
c	[kJ/(kg.K)]	Specific heat
CH	[mm]	Cavity height
CL	[mm]	Cavity length
CW	[mm]	Cavity width
EWL	[mm]	External block wall length
EWW	[mm]	External block wall width
g	[m/s^2]	Acceleration of gravity
h	[W/(m^2.K)]	Average convection coefficient
IWL	[mm]	Inner block wall length
IWW	[mm]	Inner block wall width
k	[W/(m.K)]	Thermal conductivity
L	[m]	Thickness of a layer
Pr	[ ]	Prandtl number
PR	[K/W]	Parallel resistance
R	[K/W]	Thermal resistance of a block
Rn	[K/W]	Resistance of the nth layer of a block
Ra	[ ]	Rayleigh number
RZ	[K/W]	Resistance of the Zth section of a layer
SR	[K/W]	Series resistance
T	[K]	Temperature
U	[W/(m^2.K)]	Thermal transmittance of a block
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction

Special characters

α	[m^2/s]	Thermal diffusivity
β	[K^{-1}]	Expansion coefficient
ε	[ ]	Emissivity
μ	[N.s/m^2]	Dynamic viscosity
ρ	[kg/m^3]	Density
ϑ	[m^2/s]	Kinematic viscosity

Subscripts

A	Hottest cavity surface
Air	Air
B	Coldest cavity surface
C	Concrete
H	Hot boundary surface

INTRODUCTION

Since the ancient past, builders have always searched ways to obtain thermal comfort. Nowadays, thermal comfort is commonly obtained using electrical equipment such as air-conditioners, and only in Brazil, 70% of power consumption in commercial buildings is used for this purpose [1]. HVAC energy consumption depends on several factors. One of the most important factors is the heat transfer through the building envelope. In this context, the building thermal performance can be increased when the thermal transmittance of walls is reduced. In resume, it can be stated that, normally, a well-insulated building has a high thermal performance.

There are several ways to design a well-insulated building taking into account the wall composition. For example, certain types of walls can be built using structural elements, such as concrete blocks and a specific insulation material. In this case, a lower thermal transmittance of the block can reduce the cost associated with the use of insulation.

Many authors have perceived that different configurations of cavities inside hollow blocks can influence their thermal transmittance. Bouchair [2] performed a numerical study on hollow clay bricks, varying the size and number of cavities, and filling them with air or insulating solid materials such as cork and polystyrene. The results obtained have shown that a change in the configuration of cavities could decrease the thermal transmittance in 20%. The reduction of wall emissivity presented better results, as well as the injection of insulating materials, which cancels the radiative and convective effects.

In similar study, Fioretti and Principi [3] simulated the heat transfer through clay hollow blocks, considering various designs and configurations of cavities, also with different emissivity. They concluded that a low emissivity treatment in the cavity's wall, reducing the emissivity to approximately 0.2, can reduce the block thermal transmittance, equaling it to the values obtained when the cavities are filled with polystyrene.

In another work, Svoboda and Kubr [4] performed simulations of a vertical heat flux passing through hollow masonry blocks. Among other conclusions, they perceived that the heat transfer in a cavity heated from below is highly dependent on the cavity cross section area, and that the ratio between the transmittance calculated for vertical and horizontal direction is a function of the cavity dimensions and the heat flux direction.

Following the same path, Li *et al.* [5] accomplished a numerical study about the thermal transmittance of multi-holed clay bricks, evaluating the effects of radiation inside the cavities and the number of cavities in each direction. They concluded that more cavities in the brick result in low radiation influence. They also concluded that a great number of cavities reduce the natural convection effect inside the bricks, making the conductivity of the solid material the most important aspect for thermal transmittance.

In a more complex study, Santos and Mendes [6] performed a numerical study on heat, air and moisture transfer through hollow blocks. Different of other works cited above, the block material was not conceived as an impermeable one, but as a porous medium, subject to air and moisture transfer with adsorption and desorption effects.They concluded that when the coupled heat, air and moisture transfer is taken into account, the values of transmittance may considerably differ from those obtained by assuming pure conductive heat transfer.

Generally, it can be stated that different configurations of cavities inside hollow blocks can influence the thermal transmittance of the blocks, due to the interactions between conduction, convection and thermal radiation caused by the hollow geometry. Thus, this study has the objective to find the cavity configuration for a concrete block with defined external dimensions that promotes the lowest thermal transmittance and to verify the influence of each heat transfer mode in this process, considering only the pure transfer of heat.

DIMENSION OF THE BLOCKS

The external dimensions of the blocks were determined accordingly to Brazilian regulation [7], being chosen the M-20 model, which has 390-mm width, 190-mm length and 190-mm height. These dimensions are represented in Figure 1.

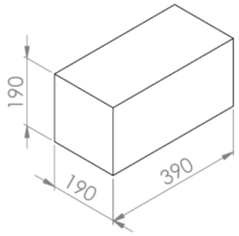


Figure 1 External dimension of the blocks

Considering those external dimensions, the configurations of the blocks conceived for this study are shown in Figure 2. Block #1 was designedbased on Brazilian regulation [7]. Blocks #2 to #9 were designed modifying the size and number of cavities, keeping the same amount of solid material of block #1. Block #10 was conceived without cavities, for comparison and analysis of the cavity effect.

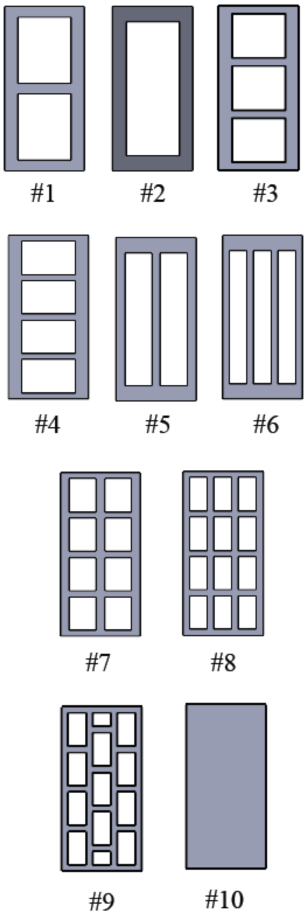


Figure 2 Geometric configurations of the blocks

The block internal dimensions nomenclature is shown in Figure 3, where EWW is the external block wall width, IWW is the inner block wall width, EWL is the external block wall length, IWL is the inner block wall length, CW is cavity width and CL is the cavity length.

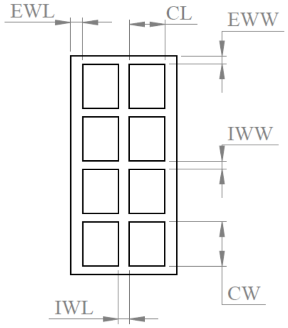


Figure 3 Nomenclature of the internal dimensions

The internal dimensions of each block are shown in Table**1**. The block #9 is the only one with two different values for cavity width.

Table1 Internal dimensions of the blocks (mm)

Block	EWW	IWW	EWL	IWL	CW	CL
#1	25.0	23.3	32.0	-	158.3	126.0
#2	36.7	-	32.0	-	316.7	126.0
#3	18.3	18.3	32.0	-	105.6	126.0
#4	14.7	14.7	32.0	-	79.2	126.0
#5	36.7	-	22.0	20.0	316.7	63.0
#6	36.7	-	16.0	16.0	316.7	42.0
#7	14.7	14.7	22.0	20.0	79.2	63.0
#8	14.7	14.7	16.0	16.0	79.2	42.0
#9	14.7	14.7	16.0	16.0	79.2 32.3	42.0
#10	390.0	-	190.0	-	-	-

BOUNDARY CONDITIONS

Out of the six external surfaces of the blocks, four were established as adiabatic, and two as isothermal. The two parallel isothermal faces had a 4K temperature difference, being the hot surface at T_H=302 K. The temperature difference was considered relatively small to assure laminar air flowinside the cavities. The boundary conditions of the blocks are represented in Figure 4.

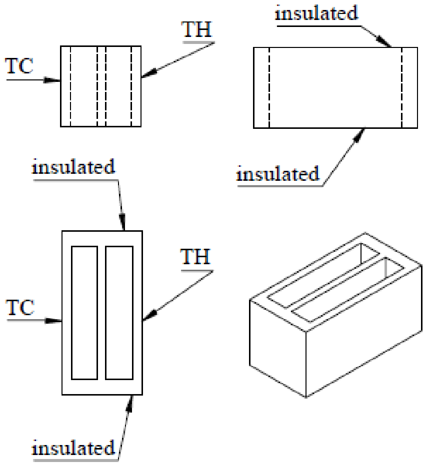


Figure 4 Boundary conditions

THERMOPHYSICAL PROPERTIES

In this kind of study, the choice of the properties for the materials may play an important role in the final results. In this case, the values of thermophysical properties adopted for concrete were the ones provided by the Brazilian regulation [8]. The air density, required in CFD simulations, is assumed to be dependent of pressure and temperature, and varies according to the ideal gas relation.

The other air properties needed in the simulation were gathered from property tables [9], considering the values constant, corresponding to a 300 K temperature. The values adopted for the properties are shown in Table 2.

Table 2 Thermophysical properties

Property	Unity	Air	Concrete
ρ	[kg/m^3]	ideal gas	2300
c	[kJ/(kg.K)]	1.007	1.000
k	[W/(m.K)]	0.0263	1.7500
ε	[ ]	-	0.9
μ	[N.s/m^2]	1.846 * 10^{-5}	-

In Table 2, ρ is the density, c is the specific heat, k is the thermal conductivity, ε is the emissivity and μ is the dynamic viscosity.

CALCULATION OF STANDARD VALUES

In order to verify the validity of the values obtained by simulation, it is necessary to calculate the standard values. The calculation of standardized values of thermal transmittance of blocks was performed following the procedure available in an international regulation [10].

The first step was to calculate the thermal resistance of the blocks. In the calculation, the block can be divided into layers, each one with its own thermal resistance (R1, R2, … , Rn), as shown in the example of Figure 5. If the layer is composed of different materials, each section has its own thermal resistance (RA, RB, … , RZ).

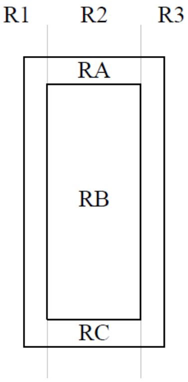


Figure 5 Example of thermal resistances in a block

For a given block, the resistance of a layer is given by the parallel resistance equation (1), and the overall resistance of the block can be obtained by the series resistance equation (2).

$$PR=\left(\frac{1}{RA}+\frac{1}{RB}+\ldots+\frac{1}{RZ}\right)^{-1} \tag{1}$$

$$SR = R1 + R2 + \ldots + Rn \tag{2}$$

If the block layer or section is solid, and made of concrete, its thermal resistance can be obtained by equation (3),

$$R_C = \frac{L}{k_C A_C} \tag{3}$$

where R_C [K/W] is the thermal resistance of the concrete section, L [m] is the thickness of the section, in the direction of the heat flux, k_C [W/(m.K)] is the concrete thermal conductivity and A_C [m^2] is the concrete section area, perpendicular to the heat flux.

When the section is a cavity fulfilled with air, the calculation is performed differently. For the temperature range and dimensions of the blocks in this study, the equation obtained from regulation [10] and used to calculate the thermal resistance of the cavity R_{Air} [K/W] is shown in (4),

$$R_{Air} = \frac{1}{A_{Air}} \frac{1}{1.25 + \frac{6.12}{\frac{4}{\varepsilon} - 2}\left(1 + \sqrt{1 + \frac{CL^2}{CW^2}} - \frac{CL}{CW}\right)} \tag{4}$$

where A_{Air} [m^2] is the cavity section area, perpendicular to the heat flux.

Calculating the thermal resistance of the block R [K/W] through equations (1) to (4), it is possible to obtain the thermal transmittance of the block U [W/m^2.K] using equation (5),

$$U = \frac{1}{R\,A} \tag{5}$$

where A [m^2] is the area of the block, perpendicular to the direction of the heat flux.

SIMULATION PROCEDURE

The simulations were performed using the software ANSYS® Workbench™, version 16.0, choosing Fluent® Package.

In this three-dimensional study, a structured mesh was considered for each block. The elements had a cubic form, with 1.5 mm of edge length. All the simulations were performed considering steady-state heat transfer.

The air circulation inside each cavity, which promotes the natural convection, was considered as a laminar fluid flow, ruled by the continuity equation, Navier-Stokes equations, and energy equation, that can be obtained from other studies [9, 11].

Besides convection, thermal radiation was also considered. To simulate the thermal radiation heat transfer, it was chosen the discrete ordinates method (DO) since it is applicable for radiation in any kind of gaseous medium. The method is explained in more detail in [12].

VERIFICATION OF THE MESH

The validity of the mesh was verified by comparison using benchmark results [13] for a cavity flow with Rayleigh number Ra=10^5. For a square or rectangular-profile cavity, with four surfaces insulated and two parallel faces at different temperature, the Rayleigh number -*Ra*- equation provided by the literature [9] is shown in (6),

$$Ra = \frac{g\ \beta\,(T_A - T_B)(CL * 10^{-3})^3}{\vartheta\ \alpha} \tag{6}$$

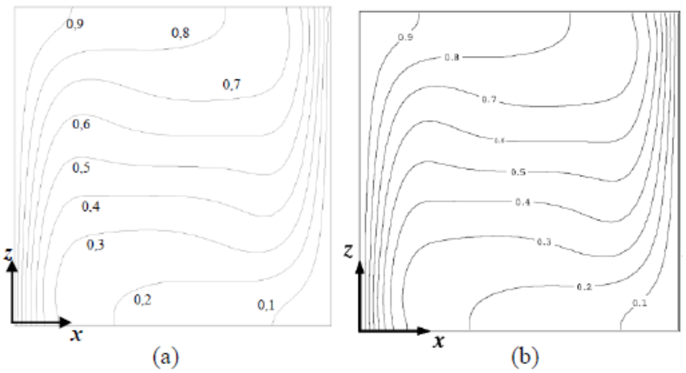
where g [m/s^2] is the gravity acceleration, β [K^{-1}] is the expansion coefficient, T_A [K] and T_B [K] are the fixed temperatures of the two parallel faces, CL [mm] is the cavity length, *i.e.* the distance between the fixed temperature faces, ϑ [m^2/s] is the kinematic viscosity and α [m^2/s] is the thermal diffusivity.

As a pre-test, it was conceived a cubic cavity with four adiabatic faces and two parallel isothermal faces. In Table 3, the air properties at 300 K, obtained from reference tables [9], the temperatures and cavity length established, and the Rayleigh number obtained from (6) are presented.

Table 3 Values for calculation of Rayleigh number

Variable	Units	Value
g	[m/s^2]	9.81
β	[K^{-1}]	0.0033
T_A	[K]	305
T_B	[K]	295
CL	[mm]	48
ϑ	[m^2/s]	1.59 * 10^{-5}
α	[m^2/s]	2.25 * 10^{-5}
Ra	[ ]	≈ 10^5

The pre-test was performed considering the same simulation procedures used in the blocks. The dimensionless temperature profile obtained in the pre-test and the benchmark solution are shown in Figure 6.



(a) (b)

Figure 6 Dimensionless temperature profiles: (a) pre-test; (b) benchmark [13]

In Figure 6, it can be noticed great similarity between the pre-test and the benchmark temperature profiles that validates the mesh used for the tests.

VERIFICATION OF THE LAMINAR FLOW

According to the literature [9], an internal flow is considered turbulent only when the Rayleigh number is higher than 10^9.

Once the Rayleigh number is obtained, the average convection coefficient h [W/m^2.K] can also be calculated. It can be obtained from equations suggested for the Nusselt number [9, 14]. The equation for blocks #1 to #4 is represented in (7), and for blocks #5 to #9, in (8),

$$h=\frac{k}{(CL*10^{-3})}0.18\left(\frac{Pr}{0.2+Pr}Ra\right)^{0.28} \tag{7}$$

$$h=\frac{k}{(CL*10^{-3})}0.22\left(\frac{Pr}{0.2+Pr}Ra\right)^{0.28}\left(\frac{CH}{CL}\right)^{-0.25} \tag{8}$$

where k for air is obtained from Table 2, Pr is the Prandtl number, which is equal to 0.707 for air at 300 K, and CH [mm] is the cavity height, which has the value of 190 mm to all the blocks. The results for Ra [ ] and h [W/m^2.K] for each block are shown in Table 4.

Table 4 Rayleigh number and convection coefficient

Block	CL[mm]	T_A[K]	T_B[K]	$Ra*10^5$	h[W/m^2.K]
#1	126	301.6	298.4	5.792	1.439
#2	126	301.6	298.4	5.792	1.439
#3	126	301.6	298.4	5.792	1.439
#4	126	301.6	298.4	5.792	1.439
#5	63	301.9	300.5	0.317	1.183
#6	42	301.9	301.0	0.060	1.008
#7	63	301.9	300.5	0.317	1.183
#8	42	301.9	301.0	0.060	1.008
#9	42	301.9	301.0	0.060	1.008
#10	-	-	-	-	-

The flow inside the cavities of all blocks did not reach the limit of Rayleigh number for laminar flow. Thus, the laminar flow hypothesis is valid. The regulation [10] estimates the convection coefficient inside the cavities as approximately 1.25 W/m^2.K, which is very close to the values obtained, considering that Nusselt number relations usually have approximately 20% of inaccuracy.

The higher the cavity length the higher the convective heat transfer coefficient. It can be explained by the higher velocities reached by the air inside those cavities. The velocity profiles obtained for different cavity lengths are illustrated in Figure 7.

For the 126-mm length cavity, the maximum air velocity calculated was 45 mm/s, while for the 42-mm one the highest velocity was 26 mm/s, causing, respectively, the highest and the lowest convective heat transfer coefficients.

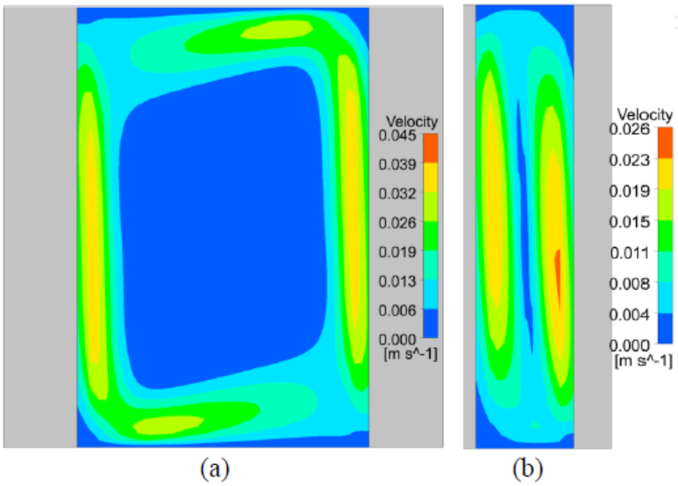


Figure 7 Velocity profiles: (a) *CL=126 mm*; (b) *CL=42 mm*

THERMAL TRANSMITTANCE ANALYSIS

The calculation was performed to obtain the standard value of transmittance for each block. The heat transfer simulation, including the radiation model, was also performed. The results are shown in Table 5.

Table 5 Standard values and simulation results

Block	U [W/m^2.K]		RelativeDifference
	Standard	Simulation	[%]
#1	5.342	5.363	0.39
#2	5.597	5.510	-1.55
#3	5.185	5.255	1.35
#4	5.083	5.157	1.46
#5	4.205	4.041	-3.90
#6	3.656	3.391	-7.25
#7	3.956	3.889	-1.69
#8	3.515	3.328	-5.32
#9	3.614	3.296	-8.80
#10	9.211	9.802	6.42

The transmittance values obtained by simulation were close to the calculated standard values, which are proportional to the cavity length. This can be explained by the importance of that length on the Rayleigh number. As expected, the cavity effect plays a major role on thermal transmittance, when comparing the higher value for block #10 with the other nine ones.

The effect of thermal radiation on thermal transmittance for the blocks can be seen in Table 6, which shows the comparison for the values obtained considering the DO radiation model and no radiation in the simulations. The influence was calculated with the difference between the two cases divided by the DO model result.

Table 6 Influence of radiation on each block

Block	U [W/m^2.K]		Influence [%]
	DO model	No radiation	
#1	5.363	3.228	39.8
#2	5.510	3.127	43.2
#3	5.255	3.321	36.8
#4	5.157	3.397	34.1
#5	4.041	2.390	40.9
#6	3.391	2.137	37.0
#7	3.889	2.526	35.0
#8	3.328	2.245	32.5
#9	3.296	2.175	34.0
#10	9.802	9.802	0.0

Thermal radiation has a remarkable importance for the heat transfer inside the cavities, even for a low temperature difference, thus, it should not be neglected. Therefore, this result agrees with statements from previous works [2, 3,5].

CONCLUSION

The building thermal performance is highly dependent on the thermal transmittance of their walls. In this study, it has been demonstrated that results of thermal transmittance for concrete hollow blocks obtained through CFD simulations are accurate, comparing them to standard values provided by international regulations.

Thermal radiation is responsible for a very significant part of the overall heat transferred in block cavities, but the major part is due to free convection. Therefore, one possible way to minimize the thermal transmittance of the concrete hollow blocks is by reducing the length of cavities.

ACKNOWLEDGEMENTS

The authors thank CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico - of the Secretary for Science and Technology of Brazil - and Fundação Araucária by financial support.

REFERENCES

[1] Carvalho, M. M. Q., La Rovere, E. L., Gonçalves, A. C. M. Analysis of variables that influence electric energy consumption in commercial buildings in Brazil, *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 9, December 2010, pp. 3199-3205.

[2] Bouchair, A. Steady state theoretical model of fired clay hollow bricks for enhanced external wall thermal insulation, *Building and Environment*, Vol. 43, No. 10, October 2008, pp. 1603-1618.

[3] Fioretti, R., Principi, P. Thermal performance of hollow clay brick with low emissivity treatment in surface enclosures, *Coatings*, Vol. 4, October 2014, pp. 715-731.

[4] Svoboda, Z., Kubr, M. Numerical simulation of heat transfer through hollow bricks in the vertical direction, *Journal of Building Physics*, Vol. 34, No. 4, April 2011, pp. 325-350.

[5] Li, L. P., Wu, Z. G., Li, Z. Y., He, Y. L., Tao, W. Q. Numerical thermal optimization of the configuration of multi-holed clay bricks used for constructing building walls by the finite volume method, *International Journal of Heat and Mass Transfer*, Vol. 51, No. 13-14, July 2008, pp. 3669-3682.

[6] Santos, G. H., Mendes, N. Heat, air and moisture transfer through hollow porous blocks, *International Journal of Heat and Mass Transfer*, Vol. 52, No. 9-10, April 2009, pp. 2390-2398.

[7] Associação Brasileira de Normas Técnicas. *NBR 6136: Bloco vazado de concreto simples para alvenaria estrutural*. Rio de Janeiro, 1994.

[8] Associação Brasileira de Normas Técnicas. *NBR 15220: Desempenho térmico de edificações: Parte 2: Métodos de cálculo da transmitância térmica, da capacidade térmica, do atraso térmico e do fator solar de elementos e componentes de edificações*. Rio de Janeiro, 2003.

[9] Bergman, T. L., Lavine, A. S., Incropera, F. P., Dewitt, D. P. *Fundamentals of heat and mass transfer*. 7th ed. Hoboken: Wiley, 2011.

[10] International Organization for Standardization. *ISO 6946: Building components and building elements - Thermal resistance and thermal transmittance - Calculation method*. Geneva, 1996.

[11] White, F. M. *Viscous fluid flow*. 2nd Ed. New York: McGraw-Hill, 1991.

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

[13] Wakashima, S., Saitoh, T. S. 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, No. 4, February 2004, pp. 853-864.

[14] Catton, I. Natural convection in enclosures, *Proceedings of the 6th International Heat Transfer Conference*, Toronto, Canada, Vol. 6, 1978, pp, 13-31.