STUDY OF THE THERMAL BEHAVIOR OF THE STRUCTURAL HIGH POROSITY BRICK IN BUILDINGS USING THE FINITE ELEMENT METHOD

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Abstract. *Nowadays, in front of the necessity of the economy of the natural recourses, there are a requirements, in relation an economy of electric energy, in habitations, even the most part of this energy are consumed to give thermal comfort, by using air conditioner, ventilators or heating, with the intention to regulate the environmental temperature. The objective of this work is to valuate the thermal behavior of the high porosity structural brick, suitable from Germany technology. This brick must to obtain a mechanical and thermal good performance, simultaneously, fulfilled this both parameters at the masonry of the buildings. This brick, moreover than clay, in its composition there are pore forming agents, which promote the low thermal conductive in the brick. Therefore, the inner geometry of this brick, is composite of cavities that are geometrically distribute by the way, to reduce the global thermal conductive of the brick. This work, presents a methodology based in a model of finite elements, witch is able to simulate the thermal transient behavior of this brick, valuating its capacity of thermal insulate, to cold or heat. This study demonstrate that the use of this brick, in the masonry, proportionate a low dissipation of the inner environmental temperature, economizing energy in comparison with others kind of bricks.*

Keywords: *High porosity structural red ceramic brick, Thermal insulation in habitation, Numerical Simulation, Finite Element Method.*

1. Introdução

In entire planet the wakening of the ecological conscience, has taken a good part of the population to reflect about the lavishness of the natural resources. These resources have being used, into to many years, in exploratory way, and without criteria. Today, a great dial of the man is to search for solutions to reduce the energy consumption. Most of this consumed energy is used to propitiate internal comfort in environments of the habitations. This energy is consumed in the devices, the air conditioning and fans, in the hot countries, and heaters, the cold countries. The purpose of the use of these equipments is to leave the internal temperature, of environments in habitations, in levels of comfort, to human being. In function of this, today increased the requirements in relation to the construction of the habitations, its must have attributes that contribute for the economy electric energy.

The internal temperature of the habitations suffers influences from the external temperature. This influence, in internal environments of buildings, can be reduced, by reducing the heat transmission, from the external environment to the interior of the habitation, using closings, capable to insulate the heat. This can be obtained, constructing with masonry composed of bricks that minimize the heat transfer though the external to internal walls. This is what is intended with the structural red ceramics brick with high porosity, appropriated from the German technology that is resulted of the research carried out for CEFET-RJ, in the technological innovation, in the Red Ceramics Industry in the state of Rio de Janeiro. The main points of this technology are, the use of pore forming agents in composition with the clay mass, studied for Ambrósio (2003), and the proposal of a new design for the geometry of the brick, both contribute to minimize the heat transfer (Faria, Monetto and Brochado 2004).

The objective of this work is to evaluate the thermal behavior of the structural red ceramics brick with high porosity, used in structural masonry. The brick used in this study is resultant of the referring innovation, with the addition of pore forming agents in the clay mass, during the bricks process of production, and a new design for the brick, adapted from the German high porosity technology. Such as the German technology, beyond the clay in the brick composition, is added pore forming agents that are easy to attain for the industry. Moreover, the proposal a new internal geometry design composed by cavities, geometrically ordered, also to contribute for the reduction of the global thermal insulation of the brick, in face of traditionally geometry adopted, for the use in structural masonry in Brazil.

For this study, was used a methodology based on the computational modeling for analysis of structures, by the method of finite elements (MEF), which is possible to carry out the simulation of the transient thermal behavior of an environment constructed with the structural red ceramics bricks with high porosity. Through this methodology, it is possible to evaluate the thermal behavior of this brick, and verify the heat flow transmitted for the interior of environments. This study demonstrated that, with use of this brick in masonry, is possible to keep for more time the internal temperature generated by air conditioning, in the interior of the habitation, due to capacity of the brick to minimize the heat transfer of the external for the internal environment, thus being, saving energy when compared with the traditional bricks used in constructions.

2. About Brazilian Climate

Brazil, due to its immense territory, and the fact of its localization is between the line of the equator and the tropic of Capricornia, is a tropical country with varied climate. Being the regions North, Northeast, Center-West and Southeast, that presents a hot climate during almost, all the year. (Goulart, 1994).

The Brazilian bioclimatic letter developed by Givoni (*apud* Goulart, 1994) indicates economic solutions, face to the questions relative to the energy used to minimize the climatic effect of the regions, in the habitations and the people. Givoni still recommends natural methods that can be applied, in the phase of architecture project of the buildings that are base on the internal temperature of the habitations, reducing the inner climatic effect, caused for the external temperature. Being indicated the use of ventilations and circulations, of thermal mass combined, to promote the thermal comfort, thus, preventing the use of household-electric devices for the thermal conditioning of environments, and reducing the use of electric energy.

According to studies of Lamberts, (1998), *"Does exist one strong relation between the comfort and the consumption of energy"*. For the author, there are others variables that influence in this relation of comfort and it must, established the conceptual differences between the weather and climate and influences it of the humidity of air. The weather is the daily variation of the atmospheric conditions, and climate, is the average condition of the time in one given region based on measurements carried out into 30 years.

The temperature and the relative humidity of air, are the most known climatic variable, first, because its effect are felt and second, because they are of easy measurement. The variation of temperature in the surface of the earth results basically, of the great air masses flows and the different reception of the sun radiation, to place by place. According to Mc Quiston, (*apud* ASHRAE, 1992) "Thermal comfort is "a state of spirit" that reflects the satisfaction with the thermal environment that involves the person. If the balance of all heat transfers that the body is submitted, is null, and the skin temperature and sweat, stay inside of certain limits, can be said that the man feels thermal comfort".

For Givoni (*apud* Goulart, 1994), a zone of human comfort exists, that is, the human being, can be in comfort between the limits of temperature of 18 to 29ºC and relative humidity between 20 to 80%.

For Fanger (*apud* Lamberts, 1998), the human being thermal comfort is possible next to 29ºC, if, the people will be dressing light clothes, what is a custom in the tropical countries, and if have been submitted for certain amounts of ventilation. This comes to strengthen Givoni's idea that the allied ventilations to these simple customs allow the people to an amplest limits of temperature and relative humidity, in relation to the cold countries.

The state of Rio de Janeiro is in the latitude 22º 55'S (South) and longitude 43º 12'W (West) ASHRAE (1977). Situated in the Southeastern region, it possess Atlantic tropical climate (Goulart, 1994). This climate is a characteristic of the littoral regions of Brazil. Its main characteristics are abundant rains (1200 mm/year), concentrating in the summer and for the situated regions to the south and in the winter and autumn for the regions next to the Equator. The thermal amplitude varies from region to region, as the latitude an increase, as in the case of Rio de Janeiro, the annual thermal amplitude is raised, making difference into the annual stations.

According to the Climatic Conditions table for Others Countries ASHRAE (1977), in Rio de Janeiro, during the winter, the average temperatures vary between 23ºC and 26ºC (Celsius degrees). In the summer, high temperatures are presented, and oscillate between 33º and 43º C (Celsius degrees), with raised rate, of relative humidity of air (into 85%), what cause an unpleasant thermal sensation.

For Lamberts (1998), the climatic factors act in the nature by an intrinsic form. This simultaneous action will influence in the architectural space, consequently in the energy consumption. When these climatic factors are used in the architecture, with wisdom, can guarantee the thermal comfort of the people and consequently the rationalization of the energy use. One of the contributions for the heat inner the habitations is the solar radiation in the external walls of the buildings.

Newton and Galileu in XVII century, in relation to the heat transmission, thought as the Greek atomists: "When two systems in different temperatures have been in thermal contact, the heat always flows from hottest system for most cold, until the systems reach the balance, a common temperature". (Tipler, 1978).

That is observed for the external and internal temperatures of constructions. Heat transfer occurs through the walls by conduction, as the external wall receives heat for solar radiation. For Romero (1988), the transference of heat for radiation occurs in five ways:

- Direct solar radiation above the building
- Diffuse solar radiation
- Reflected solar radiation from the around of ground
- Thermal radiation emitted from the heat ground and from the air
- Thermal radiation emitted from the building that hold back the heat

The super heating of the internal environment happens in function of the "stove effect", it is provoked for all these related factors, that combined transmitted the heat for interior of the building, generating this effect because the walls and glasses of the windows, hindered the heat to come back toward the exterior. This effect is what is called thermal transmission: the transmitted solar radiation is transformed into heat in the interior of the habitation.

2.1. The effects of thermal transmission in the buildings

Lamberts (1998) have studied the constructive envelope that related the radiation and the construction materials applied into the construction industries, analyzing the energy changes (light and heat) between the exterior and interior ways. The constructive envelope or closing is the walls that close the buildings and the compartments. It can be made by ceramic brick closing masonry, or ceramic structural brick masonry, gypsum panels, light materials panels, wooden panels, and others. However in the specific case of this work, it relates to the masonry of structural red ceramics bricks with high porosity, adapted of the German technology**.**

The study of Lamberts demonstrated that the relation between the radiation and the kind of construction of buildings can vary enough, and have influence in capacity to transmit the radiation for the internal environment of the building.

The part of radiation transmitted for the interior will act in the conditions of comfort instantaneously, being, therefore, the main fraction of the thermal profits in environments.

For Santos (1989), the external heat, is transmitted to the internal environment of the buildings for the external walls, or the closings. The external heat is transmitted by conduction through the bricks walls and by convection, for the air, that enters in contact with the furniture and the dividing walls of the buildings that also heat and transmit heat. After a time, is in conditions of thermal balance with the external environment, leaving environments discomforted, case, this heating is above of the human being comfort levels. These high temperatures cause great discomfort for the people, who in general, start to use electric devices, the air conditioner or fan to promote the necessary thermal comfort in the buildings.

The consumption of electric energy, of these electric devices, according to Creder (1998), its can be of many models, and in average consumes, generally are:

- Fan of ceiling has as normal rated power 300W, what it means that goes to consume 300W for hour, in 24 hours, the consume are, 300W x 24h = 7.2 KWh, in 30 days of the month are 216 KWh;
- Residential air conditioner device of 7500 BTUs, indicated to cool environments of until 16m², has power of 3/4 HP, (1 Horse Power, is equivalent the 756 W), on during the night, in the period of 7 pm to 7 am, totalizes 12 hours of consumption of (3/4 x 756) W x 12h = 6.804 kW, in 30 days of the month is 204.12 KWh.

This consumption of energy is very expensive, in the monthly budget of the population, and it can be reduced in case that the habitations use in the masonry, bricks capable to promote the reduction of the flow of external heat for the interior of the buildings, keeping the ambient temperature in comfort levels, in relation to the external temperature.

In the countries of the Europe, the question of the energy economy is very important, therefore in function of the cold climate, the consumption of energy with the heating also is high. Mainly after 2^{nd} World Wide War, had much scarcity of resources, due to this necessity, had initiated research in the red ceramic industry of materials that rationalized the consumption of electric energy, to develop a product capable to isolate the cold of the interior of buildings.

2.2 The Germany model

In the years between 1970 and 1980, the crisis of the oil, had great efforts to the reduction of the fossils fuel consumption, in the industrial area, and in the residences, with the heating systems. One of the initiatives of the German government was the research on construction materials that demanded little energy consume, in the manufacture and also provided better thermal insulation in the constructions (Bastos, 2004).

The development of the German research resulted in a brick with high quality, that have three functions simultaneously, the function to close the buildings, structural and of thermal isolation, the structural red ceramics brick of high porosity.

These bricks are known in Germany as "Dämmziegel" - Insulating Brick. Commercially, it can be found with different names depending on the company who produces it; as "POROTON", for Wienerberger GAC, and "UNIPOR Ziegel-System" for the Unipor GmbH. This technology was developed by centers of research of construction materials, assisted for enterprise organizations of the ceramic sector, whose intention was the development of constructions of low energy consumption (Brochado, 2000).

The structural red ceramics technology with high porosity consists basically of the combination of one design that retards the flow of heat through the brick, reducing the points of conduction for the density reduction of the ceramic material, with addition of materials that create micro porosities, getting thus, the reduction of the thermal conductivity of the brick and, as consequence, the reduction of the thermal transmission of the masonry.

The pore forming agents are in general organic and inorganic materials, classified into three categories:

- Combustible additives saw dust, expanded polystyrene (EPS);
- Industrial byproducts containing combustible materials and mineral pores forming agents, such as papermaking sludge, cellulose, and fly ashes;
- Mineral pores forming agents, such as, powdered lime or chalk, perlite, diatomaceous earth, hydroxides and aluminum silicate (Hauck, 1998).

Perlite is the denomination of the silicoses rock that found in natural state. What it distinguishes perlite from the other rocks of volcanic origin, is that when this rock is warm in an appropriate point, is softened and become enlarged, twenty times its original volume (Red Co II, 2005). The diatomaceous earth is amorphous sediment, originated from frustules or carapaces of such aquatic vegetal unicellular organisms, microscopically seaweed and lacustrine, normally called diatomite; it presents silicoses nature (Souza, 2005).

The combustible additives also assist during the process of burning of ceramics, helping to keep the heat during this process. After this stage, it extinguishes leaving empty spaces that depending of the granulometry of the used material, generate porosities of different sizes and forms. The inorganic additives, during the burning process, are sinterized together with the clay, that is, the transformation of the clay in ceramic, conferring the hardness to the brick, also contributed for the formation of pores (Brochado, 2000). In both the cases, the pore forming agents contribute for the reduction of the density of the bricks, what also influence on the thermal conductivity of the brick. (Hauck, 1998).

In relation to the German geometry of the bricks, the format of the holes of the brick and its disposal, are projected to make it difficult the conduction of heat. The disposal of the holes is projected thus the heat covers a bigger distance in the interior of the brick, more than closer brick, thus retarding the heat flow in the brick, as showed in the Figure 1.

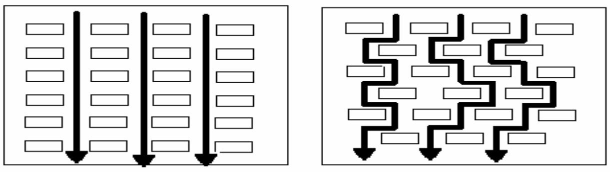


Figure 1. Heat flux in a closer brick and in a structural brick with high porosity (Brochado, 2000).

2.3 The adaptation of the Germany technology and the creation of a Fluminense model

The research directed toward the adaptation of the German model and the creation of a new model to Brazilian brick, had initiated from the research project "a Interdisciplinary Boarding in the Area of Technological Innovation: Study of the of Red Ceramics Industry" it has its origin in 1999, from an accord between the institutions, Federal Center of Technological Education – CEFET-RJ and for the Institute of Technology for Tropics – ITT, and the Fachhochschule/Köln, in Germany, the scope of the interchange CAPES, Brazil, and the DAAD, Germany.

Along of the development of the research, professors and students had the opportunity to know the German technology for the production of structural bricks with high porosity, through techniques visits and periods of supervised training in its industries. Beyond, seminaries and academic quarrels with German professionals, by the way it was possible to evaluate the social-economic and ambient impact, of this production and use in the German constructions.

This knowledge brought to the team subsidies for the development of diverse sub-projects and research, aiming at the increase of the productivity, reduction of the consumption and energy wastefulness in the state of Rio de Janeiro Red Ceramics Industry and to the magnifying of the ambient comfort in the buildings (Bastos, 2004).

One of the first experiments developed into this Project was carried through in partnership between the CEFET-RJ and the National Institute of Technology - INT, financed for the FAPERJ, resulting in a master dissertation developed for Celeste (2003). In this research the mineralogical composition of argyles of the state of Rio de Janeiro was studied, this is main prime material of the bricks. Have been experimented some mixtures with the incorporation of pore forming agents in the ceramic mass. These mixtures had been tested, for the mineralogical characterization, definition of the technological properties and determination of physical indices as the density, compressive strength and thermal conductivity.

Amongst the gotten results, it was chosen for this work, to accomplishment the simulation, a mixture that incorporates as pore forming agents, the saw dust papermaking sludge, and the brick burning at 1000ºC. The physical indices of this mixture are shown in Tab. 1 (Ambrósio, 2003).

In Brazil, traditionally are used closer bricks in the constructions, that do not have structural function, in general its are seated with the holes parallel to the nesting face, closing the vain between the concrete structures. Also are produced structural bricks, however, used a little, but it are confectioned with the same ceramic mass of the closer brick, presenting with a different internal geometry, with the holes in a vertical, used in a vertical position in relation to nesting face, with structural function.

Table 2 shows the physical indices of the bricks confectioned with the traditional ceramic mass, obtained from the ABNT Standard project (ABNT, 2005) for thermal performance of the constructions.

Table 1. Physical indices for the ceramic mixture, with the pore forming agents, the saw dust and papermaking sludge (Ambrósio, 2003).

Structural Brick - Saw dust/ Papermaking Sludge Mixture	Physical indices
Physical indices	1.16 g/cm³
Compression Strength	6.7 MPa
Thermal Conductivity	0.406 Wm/ºC

Table 2. Physical indices for the conventional ceramic mixture, of the structural traditional brick (ABNT, 2005).

Conventional Structural Brick	Physical indices
Density	1.6 a 1.8 g/cm³
Compression Strength	6.5 MPa
Thermal Conductivity	1.0 Wm/ºC

The structural bricks must possess certain characteristics established by ABNT Standard project (ABNT, 2005). About its geometry, these bricks must possess minimum width of 140 mm, and its size of 290 x 190mm. The bricks must be modular, that is, to respect the minimum measure and its multiples and submultiples. It must possess perpendicular vertical holes to the nesting face. Finally, must offer minimum compression strength of 6.5 MPa.

Figure 2 presents the geometry drawings of the traditional structural brick, the structural brick with high porosity German model, and the brick model proposed by Faria, Monetto and Brochado (2004).

(*a*) (*b*) (*c*)

Figure 2. Structural traditional brick (*a*), Germany structural brick (*b*) and proposed brick model by Faria, Monetto and Brochado (2004) (*c*).

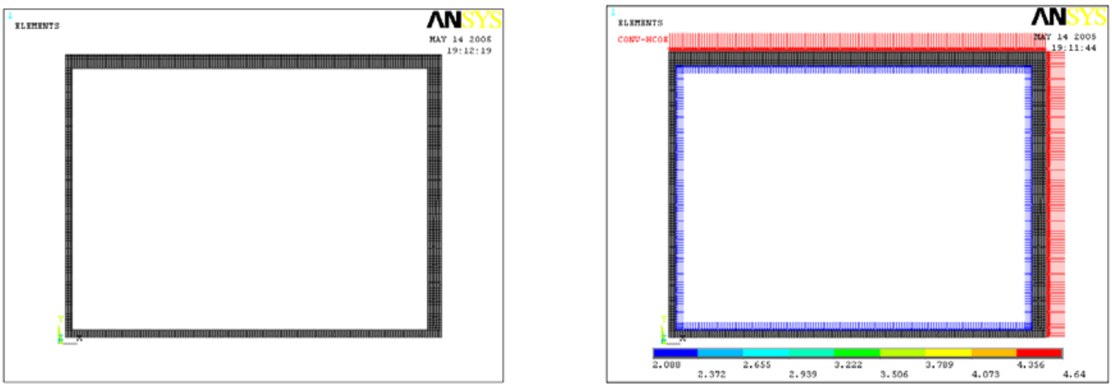
3. Finite Element Model and Numerical Simulations

The thermal performance of the bricks is analyzed comparing the results of numerical simulations obtained with a finite element model. Four configurations are considered in the analysis:

- Conventional brick geometry with traditional mixture;
- Conventional brick geometry with S5C10 mixture;
- Proposed brick geometry with traditional mixture;
- Proposed brick geometry with S5C10 mixture.

The *conventional geometry* represents the geometric configuration used in nowadays structural conventional bricks (Fig. 2*a*), while the *proposed geometry* is based in the structural brick geometric configuration from Germany (Fig. 2*c*). In turn, the traditional mixture corresponds currently to the used composition of clays for the confection of bricks, composed of two types of clay: one more plastic (easy molding), and another clay with less plastic characteristic, and the incorporation of water. Mixture S5C10 is a new composition, adding new elements to the clay, the pore forming agents, the papermaking sludge and saw dust.

The four situations associated with the two geometries and the two mixtures are analyzed considering the thermal behavior of a 12 m^2 room (3 x 4 m with a wall thickness of 150 mm) submitted to an external temperature of 40°C (313 K) and an internal temperature of 23°C (296 K) maintained by an air conditioner unit. The room has two walls exposed to the external environment and two internal walls. A simple bi-dimensional finite element model using the commercial software ANSYS® is developed to model the room thermal behavior. The model considers the thermal conduction at the room walls and the thermal convection between the room walls and the internal and external environment. Element PLANE55 (2-D thermal conduction capability - four nodes with a single degree of freedom, temperature, at each node) is employed for spatial discretization of the walls. Convective boundary conditions are applied to the external and internal walls. The final mesh, defined after a convergence analysis, is shown in Fig. 3 with the boundary conditions. Symmetry boundary conditions (adiabatic) are used at the two internal walls. Therefore these walls are represented in the model as having half of the thickness.



(*a*) *b*)

Figure 3. Finite element mesh (*a*) and boundary conditions (*b*) for a 12 m^2 room.

To reduce the computational processing, this model considers a solid homogeneous wall without the holes present in the bricks. To implement this simplification, a previous study is developed to determine the global equivalent thermal properties for the four configurations (two geometries and two mixtures). In this study a temperature gradient is imposed to the brick, prescribing the external and internal wall temperatures. Through a steady-state analysis the heat flux distribution normal to the wall, q_n, is determined. The total heat flux, Q_T, is calculated integrating the heat flux distribution

$$Q_T = \int_0^L q_n \, dx \tag{1}$$

where L is the brick length and x is a coordinate through the brick length. A global equivalent coefficient of thermal conductivity, K_{eq} can be estimated by

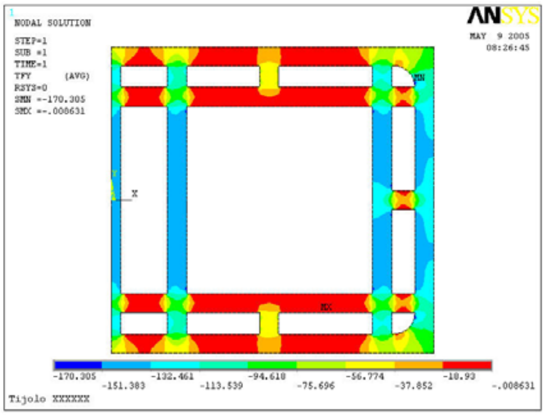
$$K_{eq} = \frac{Q_T}{(T_{ext} - T_{\text{int}})} t \tag{2}$$

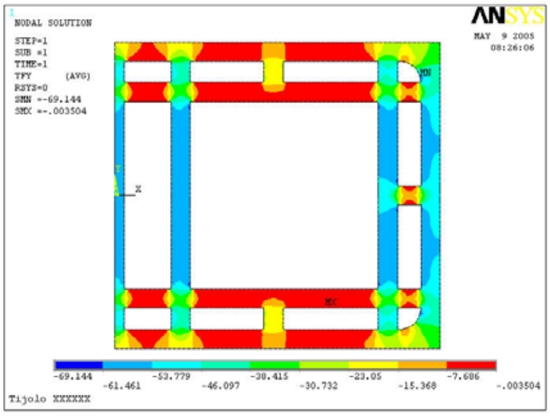
where T_{int} is the internal temperature, T_{ext} is the external temperature and t is the brick thickness. In the numerical simulations the following values are used: T_{int} = 23 °C, T_{ext} = 40 °C, t = 140 mm for the conventional brick geometry and t = 150 mm for the proposed brick geometry. Figure 4 presents the heat flux for the four brick configurations. The global equivalent thermal conductivity coefficients obtained from the numerical analysis are presented in the Tab. 3.

Table 3. Global equivalent thermal conductivity coefficients, K_{eq}, for the four situations.

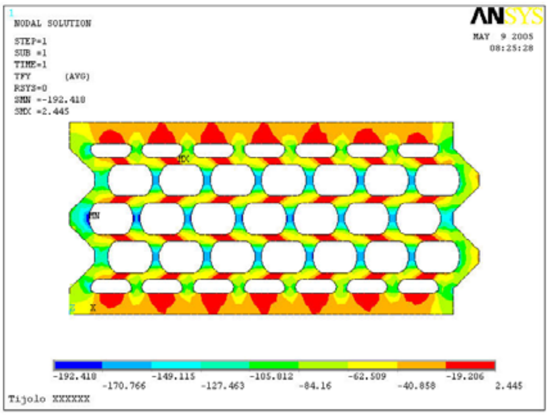
CONFIGURATION	K_{eq} **(Wm/°C)**
Conventional brick geometry with traditional mixture	0.233
Conventional brick geometry with S5C10 mixture	0.090
Proposed brick geometry with traditional mixture	0.259
Proposed brick geometry with S5C10 mixture	0.107

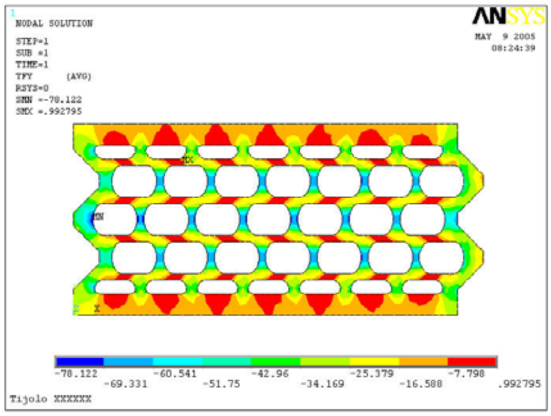
Note that, as expected from the material thermal conductivity values presented in Tabs. 1 and 2, the equivalent conductivity coefficient values for the new mixture (S5C10) are considerable lower than the ones for the traditional mixture. This shows that this mixture can produce a reduction in the amount of heat transfer through the walls of approximately 350%. For the same material, the proposed geometry presents a higher value (approximately 20%) when compared with the conventional geometry. However the proposed geometry can be considered superior to the conventional one in the structural aspect, as his net cross area (in a horizontal plane) is approximately 30% higher.





(*a*) (*b*)

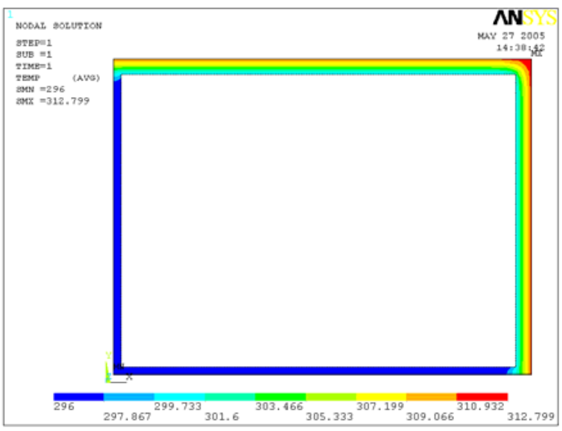


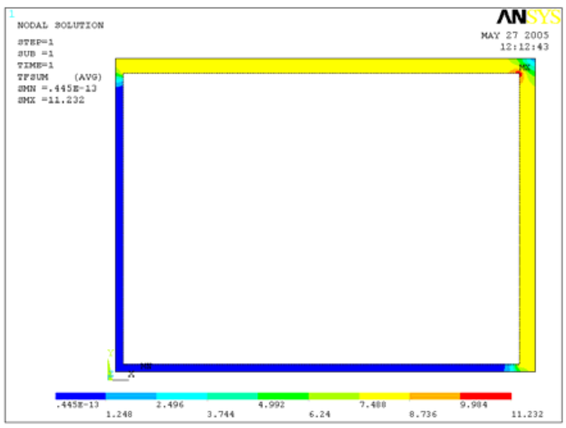


(*c*) (*d*)

Figure 4 – Heat flux for the four configurations: conventional brick geometry with traditional mixture (*a*) and with S5C10 mixture (*b*) and proposed brick geometry with traditional mixture (*c*) and with S5C10 mixture (*d*).

Now that the global equivalent thermal conductivity coefficients are obtained for the four configurations, the thermal behavior of the 12 m^2 room is analyzed. The study consist in prescribe an external temperature of 40 ºC (313 K) and an internal temperature of 23 ºC (296 K) and observing the heat flux in a steady-state condition. The room is constructed from bricks with the proposed geometry. The two mixtures (traditional and S5C10) are considered in this analysis. Figure 5 shows the temperature distribution and the heat flux for the S5C10 mixture after the steady-state is established. At this instant, an average heat flux from external to internal environment of 8 W/m² is observed and the internal wall temperature is at 27 ºC (300 K). For the traditional mixture, the corresponding values are: a heat flux of 14 W/m² and an internal wall temperature of 30 ºC (303 K).





(*a*) (*b*)

Figure 5. Temperature distribution (*a*) and heat flux (*b*) in the steady-state regime for the proposed brick geometry with the S5C10 mixture.

The room constructed from bricks with the C5S10 mixture presents a heat flux 1.8 times smaller than the one constructed from bricks with the traditional mixture. This indicates that a reduction by this amount in the energy consumption needed to maintain the same comfort condition can be achieved.

4. Conclusion

The methodology proposed in this work uses a simple numerical model based in the finite element method to study the thermal behavior of a new geometry for a structural brick with pore forming agents. Four configurations are analyzed involving two geometric configurations and two mixtures. The numerical results show that the new brick has a good thermal insulation provided by the combination of the thermal properties of the mixture with a brick cross section geometry with holes positioned in a pattern to reduce the heat flow. Also, a superior structural condition is observed as the new brick cross section has a 30% higher effective area. The model is used to study the transient thermal behavior of a room with two exposed walls. The methodology has proved to be effective and can be applied to more complex situations involving other room geometries and thermal loads as people and electronic equipments present in the room.

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