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Modeling the Thermal Behavior of Egyptian Perforated Masonry Red Brick Filled with Material of Low Thermal Conductivity

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ABSTRACT

Frequently, there is an international call for energy savings in all aspects of life due to the annoying continuous increase in energy consumption. One of the highly energy consumption sectors in a community is the residential sector. In summer, a significant amount of heat is usually gained through building's envelope due to the used type of construction materials. In Egypt, a perforated red brick with different configurations is commonly used in building constructions. In the present study, the thermal analysis of an Egyptian perforated masonry red brick filled with material of low thermal conductivity is carried out numerically. A finite volume model was developed and a FORTRAN computer program that uses the line-by-line over relaxation method was built to predict the temperature distribution and heat transmission through a wall mounted of this type of brick. A grid-independent solution was proved. The results quantitatively showed that increasing brick thermal resistance results in a lower wall inner surface temperature, and accordingly this reduces the amount of heat convected to the indoor space. Filling the holes with polyurethane foam or cork showed a reduction in the heat transmitted through the brick due to a decrease in the equivalent thermal conductivity by almost 45%, and accordingly an increase in the thermal resistance.

1. Introduction

Increasing the energy consumption in any country is a crisis that importantly requires the integration of efforts in over all sectors to save energy. The electrical energy consumption in buildings' lighting, ventilating, and air conditioning is a major problem. According to Fig. 1, the residential sector almost consumes 50% of electrical energy [1]. The way the residential buildings are constructed and oriented plays a major role in increasing or decreasing this energy consumption. The properties of the construction are of great importance since they enclose the buildings and form its envelope. The masonry brick is usually used in the building construction in Egypt. Brick properties contribute to the transmitted load and accordingly determine the building interior thermal comfort. Therefore; it is necessary to have an appropriate understanding of the thermal performance of brick behavior to propose modifications to minimize the transmitted thermal load.

ASHRAE [2] reported that thermal insulation in building envelopes conserves energy by reducing heat loss or gain of the building in addition of reducing temperature fluctuation s in unconditioned or partly conditioned spaces. Diaz et al. [3] carried out a non-linear complex heat transfer analysis of light concrete hollow brick walls. The non-linearity is due to the radiation boundary condition inside the inner holes of the bricks. The authors took into consideration conduction and convection phenomena for three different values of the conductivity mortar and two values for the brick. Finally, the numerical and experimental results were compared and a good agreement was shown.

Al-Hazmy [4] studied the coupled convective and conduction heat transport mode in a common hollow building brick to assess suitable brick insulation configuration. Three different configurations for building bricks were considered: a typical brick of three identical hollow cells (air cavities), cells were filled with ordinary polystyrene bars and finally hollow polystyrene bars were used. A computational model, using fluent software, showed that the cellular air motion inside blocks' cavities contributes significantly to the heat loads. Insertion of polystyrene bars reduced the heat rate by a maximum of 36%. Using a hollow polystyrene bars reduces the heat rate by 6% only due to the air motion inside cells.

Conjugate heat transfer across a hollow block was numerically investigated by Antar and Baig [5]. The authors reported that increasing the number of cavities while keeping the block width constant decreases the heat loss significantly. Further, a maximum number of six cavities are recommended and hence; no insulation would be needed to fill the cavities as a result of the reduced effect of natural convection.

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Nomenclature

A, a	Area, m^2, coefficients in Eq.[4]
h	convective heat transfer coefficient, W/(m^2 K)
k	Thermal conductivity, W/m K
L, ℓ	brick length, domain of interest length, m
q”	heat flux, W/m^2
S	source term with constant part, S_c, and slope, S_P
T	temperature, °C
W	brick width, m
x, y, z	local coordinate axes

Greek letters

δ	diffusion length, m
Δ	geometric length, m

Subscripts

e, E	east interface, east node
o	outside
nb	neighbors
n, N	north interface, north node
P	pole or central
r	room
s, S	south interface, south node
w, W	west interface, west node

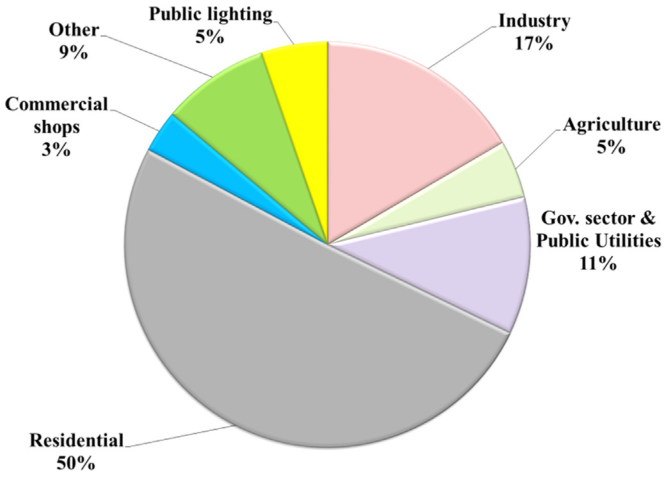


Fig. 1. Electrical energy distributed over purposes [1].

The thermal performance of nine types of clay bricks and two types of concrete blocks in Saudi Arabia was experimentally studied by Al-Hadhrami and Ahmad [6]. They reported that in general the addition of insulation increases the thermal resistance significantly. Moreover, the authors reported that from an economic point of view, the insulated clay brick showed the most effective as it has the lowest net present value.

Finding the optimum number and configuration of holes in hollow clay bricks (290 mm × 140 mm × 90 mm) was carried out by Li et al. [7] using the finite volume method. They mentioned that the optimum configuration has eight holes in length, four holes in width and one hole in height, whose equivalent thermal conductivity is the lowest (0.4 W/(m K)). They added that a temperature difference ranges from 50 °C to 20 °C between outdoor and indoor does not significantly affect the equivalent thermal conductivity for this configuration. In another study on multi-holed clay bricks, Li et al. [8] shows similar results as in [7]. They further concluded that depending on the relative importance of natural convection, surface radiation and heat conduction through the clay solid, the obtained equivalent thermal conductivity (0.419 W/(m K)) may decrease or increase with the hole number.

Svoboda and Kubrs [9] studied computationally the heat transfer in vertical cavities with small cross-sectional areas in hollow bricks heated from below to predict a ratio between the equivalent thermal conductivities in vertical and horizontal directions. The results showed that this ratio is smaller than 1.0 for downward heat flow and is between 1.0 and 1.5 for upward heat flow in bricks with a small number of large cavities. By contrast, bricks with a large number of small cavities showed almost the same ratio for both vertical directions of heat flow (from 2.2 to 2.7) depending on the holes structure.

A numerical analysis of vertically perforated bricks was carried out by Lacarriére et al. [10]. They reported that the vertically perforated bricks offered better mechanical properties than the horizontally perforated ones. In addition, walls can be constructed without any other materials than clay and mortar. They studied convection in ruptures and reported that it is a local phenomenon preferable to the thermal bridges caused by continuous mortar joints.

Lorente et al. [11] studied and developed an analytical model for heat transfer through a type of bricks full of large vertical cavities. They proved that heat exchange is two-dimensional. Finally, the authors extend their model to a whole hollow brick with lined-up cavities to calculate heat flux and thermal resistance. In another study, Lorente et al. [12] determined the thermal resistance of a wall built with vertical hollow bricks with different shapes under different boundary conditions. The authors tried to determine the most performing outline from a thermal point of view.

Zukowski and Haese [13] focused on the investigation of the effective thermal properties of a modern vertically perforated masonry unit filled with perlite insulation. The authors concluded that modern hollow bricks filled with perlite characterizes high thermal resistance and can be applied without any additional insulation layer.

The influence of cavity concentration in hollow bricks on static and dynamic thermal parameters was studied by Arendt et al. [14]. A semi-analytical method was proposed to enable calculations of thermal parameters of hollow bricks. They reported that hollow bricks made from materials with relatively high thermal conductivity required a cavity concentration of 45–65% which was impossible to obtain technologically.

Morales et al. [15] aimed to improve geometrical distributions of bricks in a wall to improve wall thermal conductivity. The authors concluded that with nonrectangular voids, the heat flux has to cross a higher number of voids, which improves its thermal properties. They also added that if the internal perforations are extended to the end of the tongue and groove, the direct thermal bridge in this type of brick is broken.

2. Problem formulation

In Egypt, masonry bricks with different configurations, Fig. 2a, are used in building construction. The red brick with circular holes aligned either in-line or staggered pattern along the brick length is commonly used. In summer, this type of brick transmits heat absorbed over a period of time to the occupied space. This increases

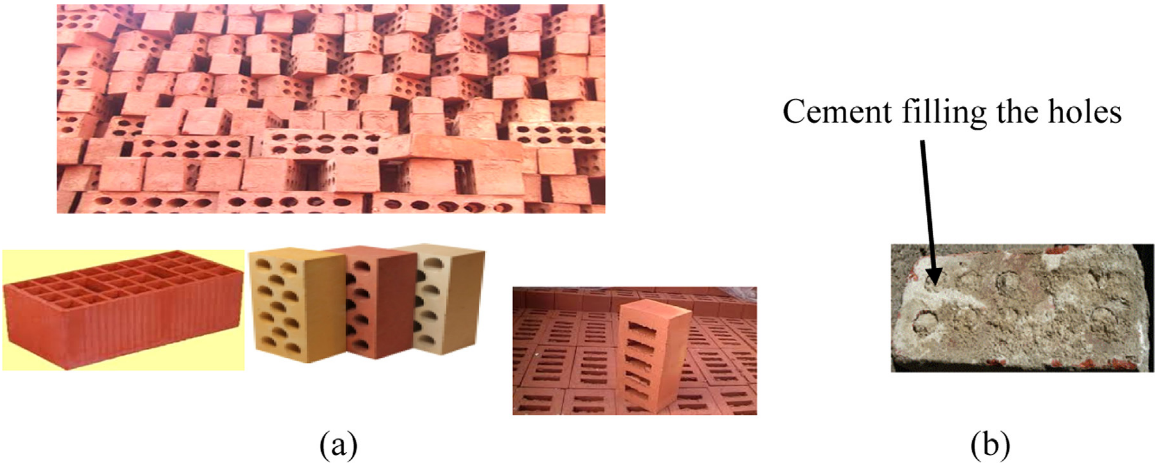


Fig. 2. Different configurations of masonry bricks used in Egypt (a) in addition to a brick filled with cement (b).

the internal thermal load and accordingly the space temperature. Accordingly, this entails the need to a mean to remove this thermal load, either by natural or forced ventilation. Hence, increasing the resistance against the transmitted heat would maintain a reasonable wall inner-surface temperature, and accordingly minimize the thermal load coming from the walls. In the present study, three different insulating materials are proposed to fill the holes in this type of brick, k=0.8 W/(m K). These materials are: polyurethane foam, k=0.017 W/(m K), rubber, k=0.163 W/(m K), and cork, k=0.04 W/(m K). In reality, using this type of brick allows mortar or cement, k=1.026 W/(m K) that bonds bricks altogether, to fill the holes, Fig. 2b; therefore this case is also studied in the present study.

3. The computational model

Heat transfer through perforated bricks can be governed by conduction through the brick body, conduction through the filler in the holes in addition to radiation and natural convection in the holes, if any. Fig. 3 shows an engineering drawing for a single perforated brick showing the computational domain of interest considering a similar or identical heat transfer for all holes along the brick length, L. The dimensions are 250 mm length, L, 120 mm width, W, and 60 mm height, H, with a 25-mm hole diameter. The void faction is almost 16%.

The finite volume method is used for modeling the studied problem under a steady-state condition. Some assumptions were adopted to make the analysis possible: neglect radiation effect, all holes are considered circular with equal diameter; holes are equidistance distributed along the length and width; brick material is homogenous, filler completely fills the holes, neglect contact resistance, outside temperature is uniform along the brick face, and heat transfer along brick height, H, is negligible if compared to other directions. All these assumptions lead to get benefit of symmetric boundary conditions to study and discretize the computational domain as shown in Fig. 4.

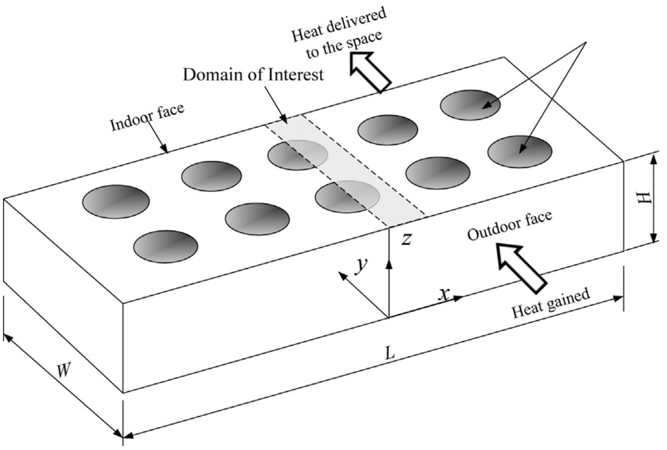


Fig. 3. An engineering drawing of a single Egyptian perforated brick.

The governing equation is the 2D Laplace equation as given below [16]:

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

along with the following boundary conditions:
$T(x, 0) = To$, $q''(x, W) = qconv$, and $\frac{\partial T}{\partial x}(0, y) = \frac{\partial T}{\partial x}(\ell, y) = 0$

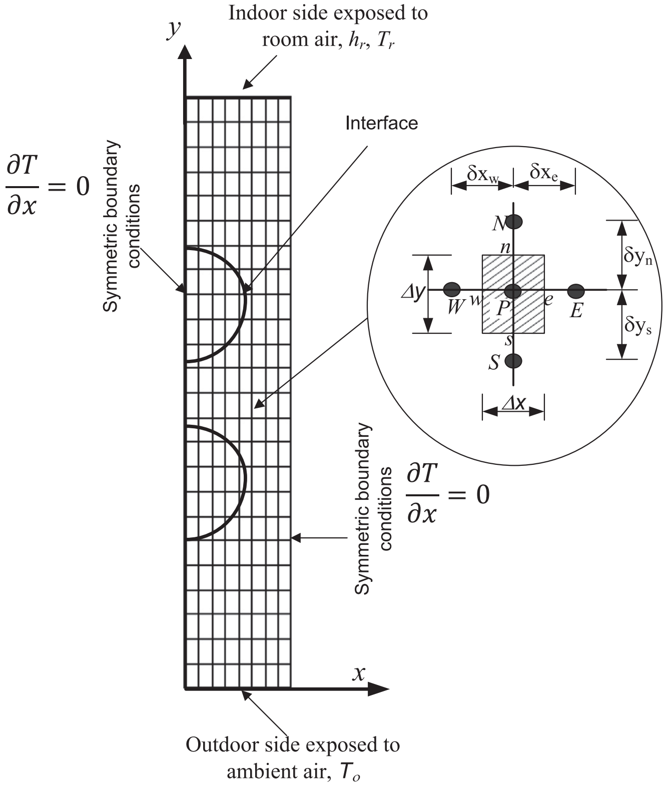


Fig. 4. A Schematic of domain mesh configuration.

Employing the finite volume method to discretize the governing equation, Eq. (1), considering half-thickness control volumes at the boundaries, as follows:

$$\int_{CV} \left(\frac{\partial}{\partial x}\left(k_x A \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k_y A \frac{\partial T}{\partial y} \right) \right) dV = 0 \tag{2}$$

The integration of Eq. (2) over a control volume, $V = \Delta x \times \Delta y \times 1$, as shown in Fig. 4 can be written as:

$$\int_s^n \int_w^e \left(\frac{\partial}{\partial x}\left(k_x A \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k_y A \frac{\partial T}{\partial y} \right) \right) dx.\, dy = 0 \tag{3}$$

Carrying the double integration of Eq. (3) results in the final model equation as:

$$a_P T_P = a_E T_E + a_W T_W + a_S T_S + a_N T_N + S_c \tag{4}$$

where the coefficients are as follows:

$a_E = \frac{k_e \Delta y}{\delta x_e}$, $a_W = \frac{k_w \Delta y}{\delta x_w}$, $a_S = \frac{k_s \Delta x}{\delta y_s}$, $a_N = \frac{k_n \Delta x}{\delta y_n}$, $and a_P = \sum a_{nb} - S_P$

Eq. (4) is then applied to all control volumes, knowing that for control volumes located at the interface, the thermal conductivity is calculated based on the harmonic mean: $k_m = \frac{2 k_f k_b}{(k_f + k_b)}$; where k_f and k_b are the filler and brick thermal conductivities, respectively.

For control volumes adjacent to the outdoor boundary, Eq. (4) is written as:

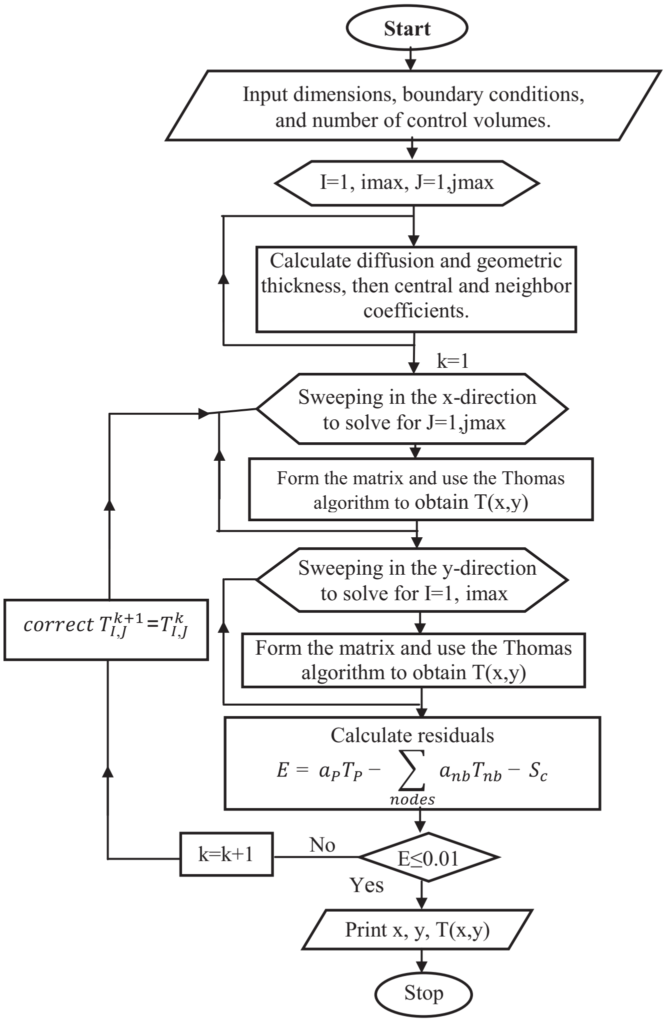


Fig. 5. A flow chart for the developed Fortran program.

$$(a_E + a_N + S_P) T_P = a_E T_E + a_N T_N + S_c \tag{5}$$

rature T_o enters Eq.(5) via the source term, S, which is written as $S = S_c + S_p\, T_P$, where;

$$S_c = \frac{k_s \Delta x}{2.\delta y_s} T_o and S_P = -\frac{k_s \Delta x}{2.\delta y_s} \tag{6}$$

Similarly, for control volumes at the indoor side exposed to convection, Eq. (4) is written as:

$$(a_E + a_W + a_S + S_P) T_P = a_E T_E + a_W T_W + a_S T_S + S_c \tag{7}$$

where; the indoor temperature T_r enters the equation via the source term, S, also as:

$S_c = h \Delta x T_r and S_P = -h \Delta x$

A Fortran computer program was built according to the flow chart shown in Fig. 5 that iteratively solves the whole matrix using the line-by-line successive over relaxation, SOR, method. The indoor temperature and convective heat transfer coefficient are considered 25 °C and 10 W/(m^2 K), respectively; while the outdoor temperature was assumed 35 °C. The convergence is declared when an insignificant difference in the temperature residual of almost 0.01 is achieved.

4. Results and discussions

Since the study is a numerical analysis, it is important to prove that the solution is grid independent. Fig. 6 shows the temperature variation along the domain width at $x=0$ in case of foam filler for a gradual mesh refinement from a coarse grid of (2 × 6) to a fine grid of (10 × 45). The figure illustrates the slope variation due to the different thermal conductivities, particularly for mesh beyond 2 × 6 grids. The figure indicates that a grid increase beyond the 8 × 24 has insignificant effect on temperature variation but only increases the computational time, so the grid adopted in the present study is 8 × 24.

Fig. 7 shows a temperature contour plot (a) as well as a quantitative temperature distribution through the brick width at $x=0$ (b). A comparison is held between results predicted for different fillers. The contour plot shows uniform heat diffusion in

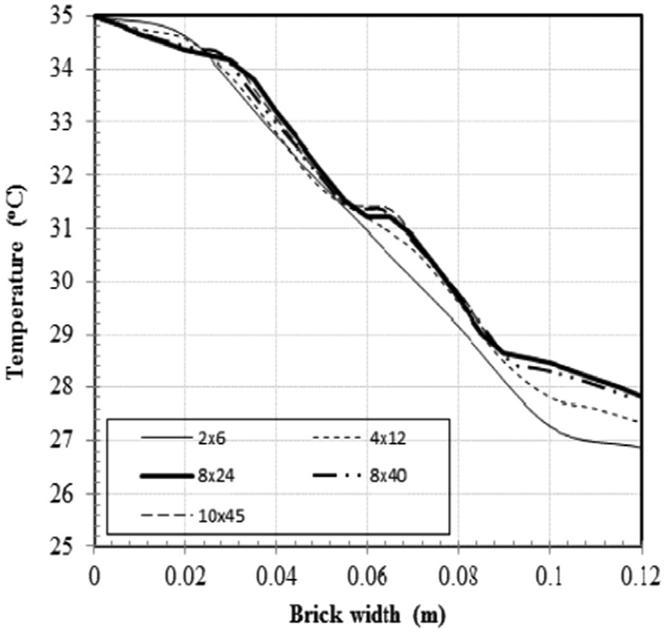
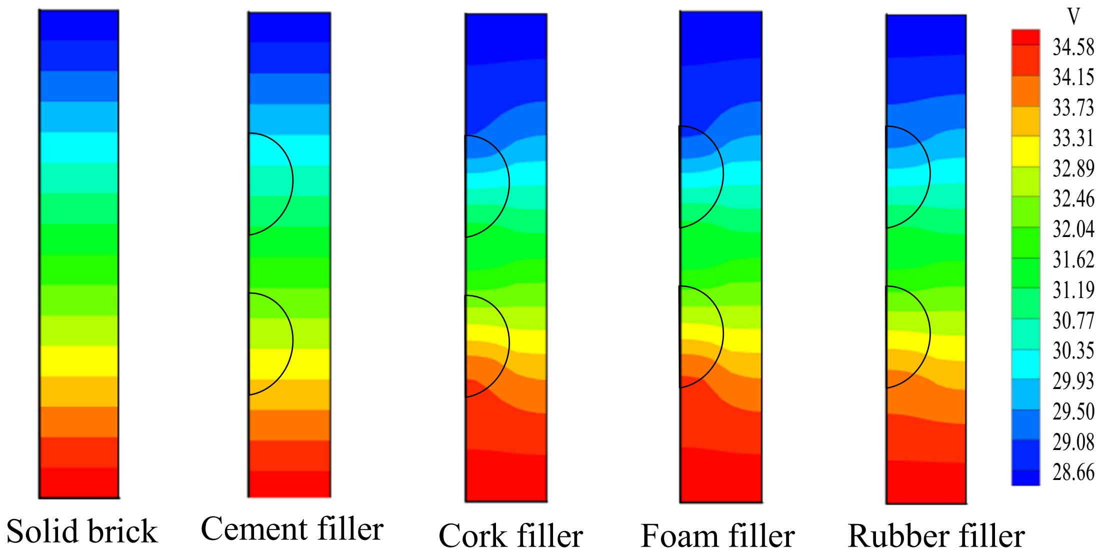
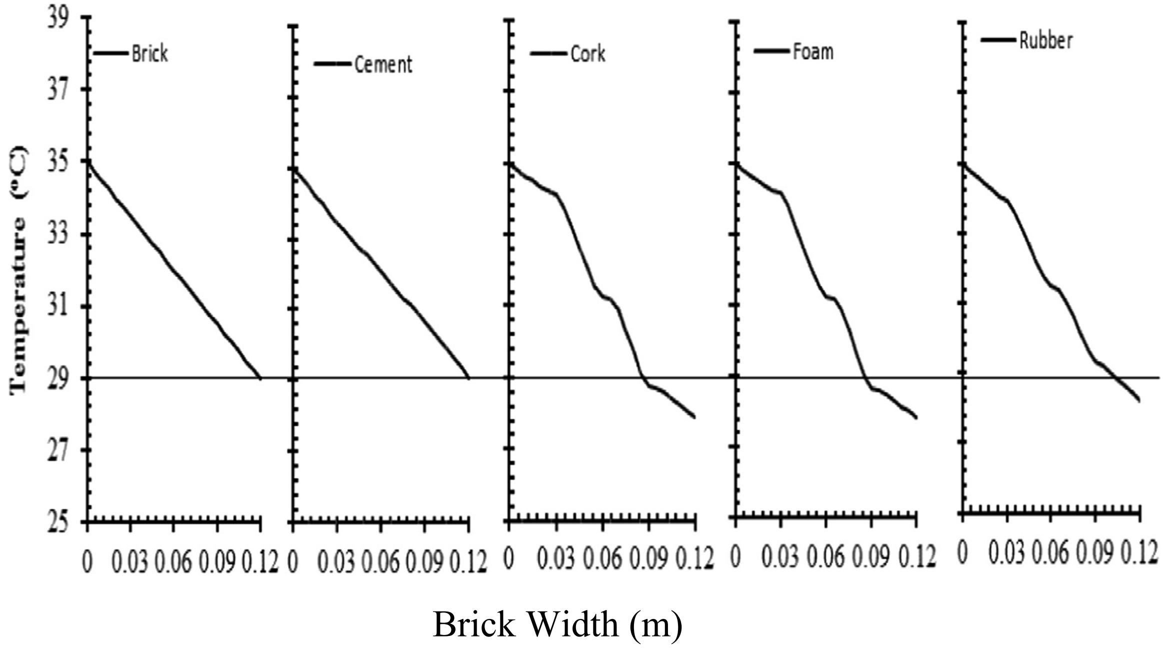


Fig. 6. Grid-independent solution for different meshes.



(a) Contour plot



(b) Temperature variation at $x = 0$

Fig. 7. Temperature distributions from outdoor to indoor along the brick width.

case of solid brick or perforated brick filled with cement; while heat faces a high resistance near the filler of low-thermal conductivity and accordingly deviates to regions of low thermal resistance. Fig. 7b shows the temperature gradient along domain width. It can be seen from the figure the temperature slope variation from outdoor to indoor in case of cork, foam, and rubber. Further, the results illustrate that using foam or cork as fillers resulted in a lower temperature at the wall inner-surface that significantly affects the heat delivered to the space.

Fig. 8 illustrates the conducted or transmitted heat along the brick width. It shows the significant heat decrease at the holes' locations in case of cork, foam, and rubber due to the increase in thermal resistance. This is totally different from the case of cement filler due to its higher thermal conductivity. The figure concludes that a smaller average amount of heat is transmitted in case of cork, foam, and rubber compared to solid brick or when holes are filled with mortar or cement.

Since filling the holes with the proposed material mainly affects the thermal resistance, it is helpful to quantitatively evaluate the thermal resistance to support the findings of Fig. 8. As can be seen in Fig. 9, the higher resistance is clear at filler place, particularly in case of filling material of low-thermal conductivity (foam, cork, and rubber) compared to the very low thermal resistance in case of solid brick or perforated brick filled with cement. The figure also shows a similar or identical behavior for both holes.

To depict the average heat transmission and its variation along a single row of five holes over brick length, Fig. 10 is presented. The figure clearly shows the similar trend of transmitted heat from outdoor to indoor along the brick width for two-rows, five holes

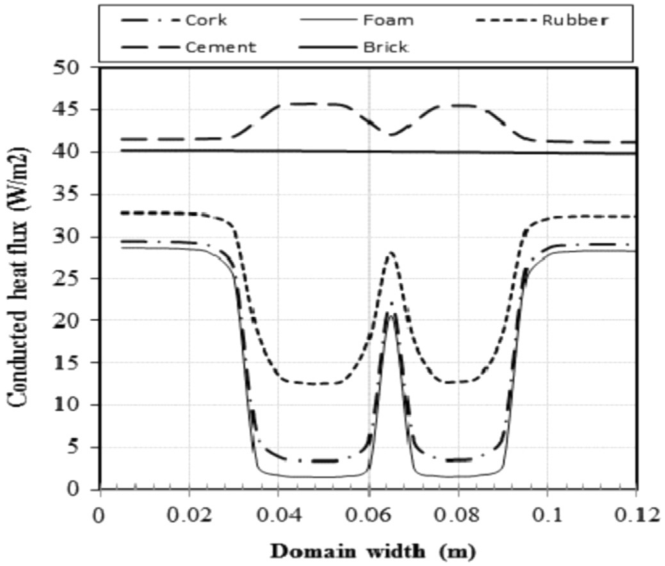


Fig. 8. Mid-plane transmitted heat along domain width for different fillers.

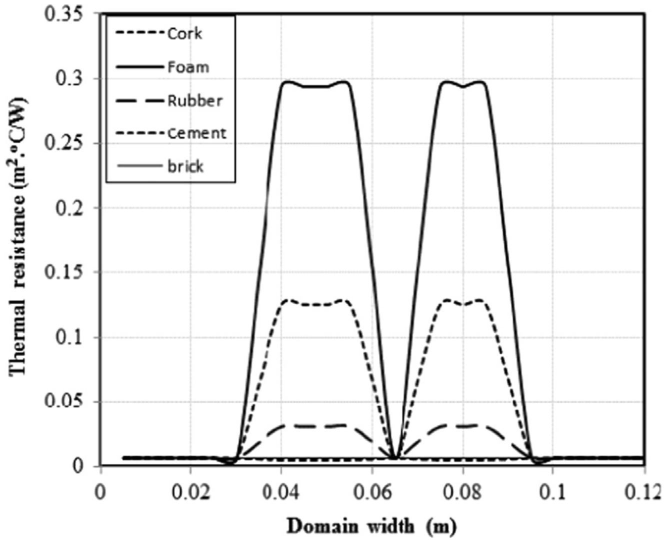


Fig. 9. Thermal resistance variation along domain width at $x=0$.

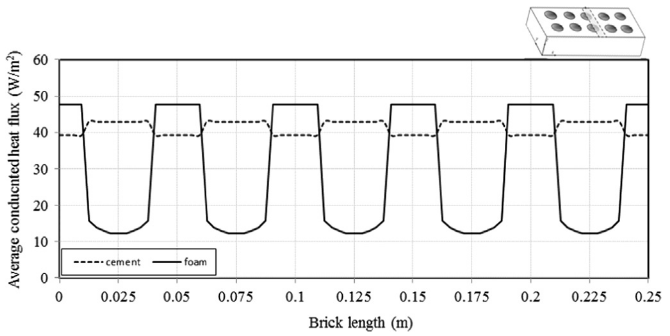


Fig. 10. A similar behavior of conducted heat through a perforated 2-five. holes rows single brick.

per row along the brick length for foam filler. The figure illustrates the decrease of heat at holes locations due to filler high thermal resistance. Then heat increases in the brick body or thermal bridge between holes. It is worthy to notice that almost a 30% reduction in the average transmitted heat is obtained if fillers of low thermal conductivity are used compared to the solid brick or when cement fills the holes.

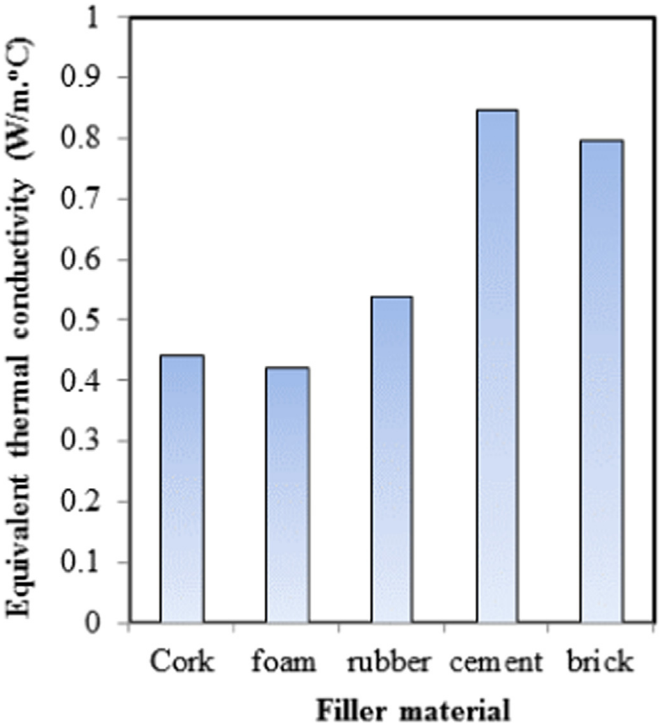


Fig. 11. Equivalent thermal conductivity for different fillers.

It is important for such analysis to estimate the equivalent thermal conductivity of the perforated brick having filling materials. Fig. 11 indicates the variation of the equivalent thermal conductivity and assures its lower value when using polyurethane foam or cork as fillers compared to the solid brick. The figure concludes that for the studied type of brick, almost a 45% reduction in the equivalent thermal conductivity when using foam or cork to fill the holes is achieved.

Considering a single wall of 3 m × 3 m is built of this type of brick with the proposed fillers, this can reduce the heat transmission from outdoor to indoor space by almost 30%. Indeed, a significant amount of heat can be prevented from crossing the building's envelope if a practical way to use proposed fillers is found and applied.

5. Conclusions

The present study numerically models the thermal analysis of masonry perforated red brick used in Egypt. The following conclusions can be drawn out of the results:

- Filling the holes with a low-thermal conductivity material such as the polyurethane foam or cork significantly increases the thermal resistance in the path of heat flow.
- A similar trend of the conducted heat along a single brick is obtained with noticeable low values at places of filling with low-conductivity materials.
- A reduction in the equivalent thermal conductivity by nearly 45% can be obtained in case of filling the holes with polyurethane foam.
- Almost a 30% reduction in transmitted heat through a wall of 3 m × 3 m made of perforated brick filled with materials of low thermal conductivity.

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