Steady-state heat flow through hollow clay bricks

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Abstract. Clay bricks are commonly used for building wall. One of the functions of a wall is to create a habitable internal environment, such as enabling internal temperature to be controlled at a human comfort level (~24°C) which is lower than the outside temperature for hot and humid climate countries. Thus, it is important for clay bricks to minimize heat flow into the building to reduce the energy consumption by air-conditioning system. The aim of this paper is to investigate the reduction of heat flow through hollow clay bricks relative to solid bricks. Finite element method was used to simulate steady-state heat transfer through solid and hollow clay bricks. Several arrangements of cavities filled with air, wool and expanded foam were simulated. It was found that the effective thermal conductivity reached almost a constant when the void volume and reduction in cross-sectional area exceeds 10%. Generally, heat transfer through hollow clay brick is expected to be significantly lower than the solid clay brick. It can be concluded that building wall made from hollow clay bricks could reduce the energy consumption by its air conditioning system. Future work is on the transient heat flow analysis and evaluation of mechanical properties of hollow clay bricks.

1. Introduction

Buildings consume almost 40% of the world total energy consumption and emits more than 36% of total carbon dioxide [1]. One of the factors that leads to a high energy consumption in buildings is the cooling effect requirement for building in hot countries. For buildings in cold climate countries, energy for heating is significant. It can be concluded that heat flow through building’s wall contribute to the huge energy consumption in buildings [2]. Thus, this paper presents one method that could reduce heat flow through building’s wall by using hollow bricks filled with air, wool and expanded foam.

Since the heating and cooling systems in buildings consume huge amount of energy, a solution that can reduce energy consumption while maintaining a comfortable internal environment in tropical and cold climate countries is required. It is reported that 60 to 80% of heat loss occurs through building envelopes [3], a higher thermal resistance is required by building envelopes. It is also reported that almost 30% of the energy loss in building during winter is through wall [4]. Nowadays, the common method to improve wall insulation is to incorporate insulating layers in building’s envelope. A proper selection method of properties of building’s wall contribute to the reduction in energy consumption in buildings [5]. Well-insulated building walls can reduce cooling energy up to 23% [6].

Lately, clay hollow bricks have been widely used for the construction of single and double walls. Hollow bricks have different widths according to their cavity distribution. Such bricks are characterized...
by significant differences in thermal insulation properties depending on the model, the number and the distribution of holes. Several studies have been conducted to determine the correlation between the bricks’ holes and its properties. Walls made of hollow bricks are characterized by their thermal resistance which decreases when the size of the hole increases and its row decreases [7] [8] [9]. In another study, it has been concluded that as long as thermal bridges are avoided and hole rows are increased, a better thermal performance is guaranteed [10] [11]. A brick with a smaller diameter hole also has lower thermal conductivity [12].

Beside the choice of the appropriate building material, building insulation is an essential technology for energy saving. Incorporating insulating materials in hollow bricks cavities minimizes the thermal transfer from the outer to the inner space to reduce heat loss or gain [2]. Many researches advised to fill in the cavities of hollow bricks with different types of insulating materials. Polystyrene filled cavities decreased the heat transfer by 36% [13]. The study that used compressed straw filling cavities can lower heat transfer within a brick [14]. EPS filling showed that thermal improvement was noticed with the increase of EPS filling ratio [15].

To understand the properties of materials, several numerical methods and types of simulations have been elaborated. Advanced software was used to simulate different materials and display the distribution and behavior of their properties through a sequence of computer-generated experiments. Microstructure-Based Simulation has been adopted by many researchers. Kikuchi et al predicted the properties of Mo fiber-Cu composites through a finite element method of microstructure modelling [16]. Zbynek and Marek used CFD analyses to investigate the heat transfer of hollow bricks in vertical direction [17]. Mahmouda et al developed a CFD model for a thermal analysis of hollow autoclaved aerated concrete blocks used for hot climate buildings [18].

Thus, this paper presents work on further investigation of effect of void volume and reduction in cross-sectional area for heat transfer within hollow bricks. Effective thermal conductivity of bricks with various number of holes, different hole diameters and filling materials are presented.

2. Methodology

This section presents the preparation of models of bricks followed by method of steady-state heat flow simulation based on finite element model.

2.1. Preparation of models of bricks

The size of the brick models is conformed to the Malaysian Standard MS 1064-Part 08 [19], where the dimensions are 190 mm x 90 mm x 90 mm. Typical arrangement of holes in the brick is as in Figure 1. A total of 11 geometries of brick models were constructed as in Table 1. The holes were filled with air, wool or expanded form (Table 2).

![Figure 1. One of the brick models (10 holes).](image-url)
Table 1. Number and diameter of holes in bricks.

| Brick geometry | Number of holes | Diameter of hole (mm) |
|----------------|-----------------|-----------------------|
| 1              | 3               | 40                    |
| 2              | 3               | 35                    |
| 3              | 3               | 30                    |
| 4              | 6               | 30                    |
| 5              | 6               | 25                    |
| 6              | 6               | 20                    |
| 7              | 8               | 30                    |
| 8              | 8               | 25                    |
| 9              | 8               | 20                    |
| 10             | 10              | 25                    |
| 11             | 10              | 20                    |

Table 2. Thermal conductivity of materials used in the simulation.

| Material            | Thermal Conductivity (W/m.K) |
|---------------------|-----------------------------|
| Brick               | 1.1                         |
| Air                 | 0.0246                      |
| Wool                | 0.04                        |
| Expanded foam       | 0.03                        |

2.2. Steady-state heat flow simulation

The brick model was constructed and imported to ANSYS 19.2 (Student version). The thermal properties of brick were set according to Table 2. Then, the mesh (Figure 2) is generated by using hexahedral element (Hex 20 type). The minimum length of the hexahedral edge was set to 0.98175 mm to minimize errors. The skewness of the mesh was mainly between 0 and 0.13 which showed the closeness of the meshing to the ideal condition.

Figure 2. Mesh of 12 holes (3x4) hollow brick.

Figure 3. Distribution of the mesh skewness.
After the mesh was generated, two boundary conditions were defined for steady-state thermal analysis. One of the faces on the long edge of the brick was set to 32°C while another face was set to 24°C. This was to mimic internal and external temperature of building walls.

Besides the boundary conditions, commands “OUTRES,ERASE” and “OUTRES,ALL,ALL” have been inserted using the command object to obtain the gradient temperature and the thermal flux in the x-direction, which are necessary to obtain the thermal conductivity since by default, ANSYS did not display those results. Simulation was performed and 6 results are displayed: temperature distribution total thermal flux, directional thermal flux, gradient temperature in x-direction, thermal flux in x-direction, and the thermal conductivity after applying Fourier’s Law of heat conduction.

3. Results

3.1. Temperature and heat flux distribution within brick

Figure 4 shows typical temperature distribution within the bricks. The temperature distribution is slightly distorted by the holes. This indicates the heat flux is not uniform for bricks with holes as in Figure 5. Heat flow is restricted by the hole, and to compensate for smaller cross-sectional area, the heat flux in this region is higher than other regions within the brick. For the solid brick, the heat flux is uniform.

Figure 4. Temperature distribution in (a) 6 holes with 25mm diameter (b) 8 holes with 25mm diameter and (c) 6 holes with 30mm diameter.
3.2. Effect of void volume on effective thermal conductivity

The effective thermal conductivity (Figures 6 through 8) of bricks was reduced to almost half of the solid brick when the percentage of volume of holes reach 10%. At higher percentage, the effective thermal conductivity was reduced to its lowest at 0.4 W/mK, regardless of the filling materials. This may indicate that once the thermal conductivity of filling material is below a specific value, there are no significant differences can be observed in the effective thermal conductivity of brick.

Figure 5. Variation of heat flux in (a) solid clay brick and (b) hollow brick with 3 holes.

Figure 6. Thermal conductivity at various percentage of void volume for hollow bricks filled with air.
Figure 7. Thermal conductivity at various percentage of void volume for hollow bricks filled with wool.

Figure 8. Thermal conductivity at various percentage of void volume for hollow bricks filled with expanded foam.

3.3. Effect of reduction in cross-sectional area on effective thermal conductivity

Figures 9 through 11 show the effective thermal conductivity of brick was reduced by almost 50% relative to a solid brick thermal conductivity when the cross-sectional area is reduced by 10%. This effect is similar to the trend shows by the effect of void volume on effective thermal conductivity of bricks. This finding shows that a higher reduction in cross-sectional area of bricks is not beneficial to its thermal properties. However, excessive reduction in cross-sectional area may compromise the mechanical properties of bricks.
Figure 9. Thermal conductivity at various percentage of reduction in cross sectional area for heat conduction for hollow bricks filled with air.

Figure 10. Thermal conductivity at various percentage of reduction in cross sectional area for heat conduction for hollow bricks filled with wool.
4. Discussion
The results of this study show that the presence of holes in clay bricks can reduce its effective thermal conductivity by 50%. It is worth to note that this is based on steady state heat conduction analysis where other properties such as specific heat capacity and density is not considered. Thus, cautions should be taken in predicting the corresponding reduction in cooling load because the time lag for heat transmission through wall may altered the variation of cooling requirement. For instance, the highest cooling load may occur six hours after the external temperature of a wall reached its peak value [20]. The time lag between external peak temperature and highest cooling load is also influenced by the thermal mass and density of wall.

The pessimistic estimation of accuracy of effective thermal conductivity for clay bricks with its cavity filled with air obtained from the simulations is within 10% of its actual value. This is because there is no effect of heat convection included in the simulation. The assumption that there is no bulk movement of air is true for the cavity with a smaller diameter. For a cavity with a larger diameter, the effect of heat convection is more significant. For building’s wall, heat transfer due to transport of moisture is expected to be more dominant and will alters the effective thermal conductivity of a wall. Thus, this may make the effect of heat convection is negligible. Further investigation on the effect of heat convection within the cavity filled with air is required in future work.

The effective thermal conductivity of hollow bricks was reduced by almost 50% when the void volume and reduction in cross-sectional area for heat transfer is more than 10%. This indicate that higher percentage of void volume and small cross-sectional area would not further reduce the effective thermal conductivity. This information is very useful to limit our intuitive desire in minimizing the percentage of solid clay since mechanical properties may be significantly affected if less solid is available to withstand compressive force.

5. Conclusion
The steady-state thermal performance of hollow bricks filled with air, wool and expanded foam was investigated. It can be concluded that the effective thermal conductivity is almost constant if the percentage of void volume and reduction in cross-sectional area was 10% or higher. It was found that the heat flux was non-uniform for hollow bricks, which lead to higher heat flux at several regions within the bricks. The findings presented in this paper is useful to construction industry where some reduction in energy consumption is feasible through usage of hollow brick as building wall. Further analysis is
required to determine the effect of diameter of hole on the effective thermal conductivity of bricks. In future, it is worth to evaluate the transient thermal analysis to determine the effect of time lag on heat transmission, which is important to the evaluation of timewise cooling load of buildings. The mechanical properties of the bricks also need to be evaluated.

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