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Short communication

Conjugate conduction-natural convection heat transfer in a hollow building block

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ABSTRACT

Conjugate heat transfer across a hollow block is investigated numerically. Conduction heat transfer in the block material and natural convection in the cavity are considered. Results show that increasing the number of cavities while keeping the block width constant decreases the heat loss (increases the *R*-value) significantly. A maximum number of six cavities can fit the building block without compromising the strength. With this number of cavities, no insulation would be needed to fill the cavities as a result of the reduced effect of natural convection. This study may provide guidelines for engineers toward better design and selection of building materials for higher thermal resistance.

1. Introduction

A substantial amount of energy is consumed to compensate for the heat leak through building walls and ceilings. The cooling/heating load calculations specify the amount of heat that need to be removed/added from buildings to achieve internal thermal comfort conditions. Therefore, climate control units require a significant amount of the total consumed electricity in residential as well as commercial buildings. Electric energy reduction as a means of energy conservation received considerable attention in the past decades. Heat transfer through building walls and ceilings contributes significantly to the heat leak from the hot outside climate to the colder air-conditioned space during summer (or vice versa during winter). An accurate estimate of the heat leak through multi-layered walls accompanied by practical low cost methods for reducing the heat leaks -or increasing thermal resistances- may significantly reduce energy consumption. Typical wall arrangements include hollow blocks where heat transfers by conduction through solid material and by natural convection through the cavities. Previous investigations in the open literature that analyze such problems considered isothermal vertical surfaces and adiabatic horizontal surfaces as boundary conditions within cavities.

Experimental and numerical studies of Nishimura et al. [2] and Turkoglu and Yucel [1], indicate that *Nu* decreases as the number of partitions increases whereas Aviram et al. [3] reported that increasing aspect ratio, decreases flow magnitude, and increases the cavity thermal resistance.

Del_Coz_Diaz et al. [4] investigated experimentally and numerically the thermal transmittance coefficient, *U*, of Arliblock bricks indicating that wall insulation decreases by increasing mortar and material conductivities. Soria et al. [5] investigated numerically the behavior of differentially heated cavities for both 2-dimensional and 3-dimensional cases. It was concluded that 2-D simulations are sufficient to capture the main features of natural convection flows, such as the local and overall *Nu* numbers.

Al-Hazmy [6] investigated three different configurations for heat transfer through a common hollow building brick. He reported that the insertion of polystyrene bars reduced the heat rate by a maximum of 36%. His main target was to eliminate convection heat transfer within the cavities by filling them with insulating materials. Tong and Gerner [7] reported that locating a partition midway of the cavity resulted in maximum heat leak reduction compared to other locations of the partition.

Other models were also developed by Soylemez [8], Kangni et. al. [9], Manz [11] and Ho and Yih [10] to analyze conduction and convection heat transfer in composite walls. Antar and Thomas [12,13] showed the significance of convection and radiation resistances through a simplified model for a single cavity block. Then, Antar [14] showed cases where simple one-dimensional convection/radiation model may be accepted.

This work is aimed at developing a 2-dimensional convection/conduction heat transfer analysis for a hollow block of different layouts to obtain an effective and economical means of reducing heat leaks. Therefore, the benefit of alternative layouts is justified quantitatively.

2. Formulation

2.1. Conduction heat transfer

Steady 2-dimensional conduction in solid material

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Nomenclature

C	specific heat at constant pressure
g	gravitational acceleration
k	thermal conductivity
L	block width
Nu	nusselt number, $Nu = \frac{Q_{actual}}{Q_{conduction\ in\ air\text{-}filled\ non\text{-}partial\ enclosure}}$
q''	heat flux
Pr	prandtl number
p	pressure
Ra	rayleigh number, $Ra = \frac{g\beta(T_{left} - T_{right})L^3}{\nu\alpha}$
T	temperature
u	velocity component in the x-direction
v	velocity component in the y-direction
w	height

Greek symbols

α	thermal diffusivity
β	coefficient of thermal expansion
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Subscripts

o	outer
i	inner

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \tag{1}$$

$$T = T_i \quad \text{at } x = 0, \quad T = T_o \quad \text{at } x = L \tag{2}$$

$$\frac{\partial T}{\partial y} = 0 \quad \text{at } y = 0, \quad \frac{\partial T}{\partial y} = 0 \quad \text{at } y = w \tag{3}$$

$$-k\frac{\partial T}{\partial x} = q''_{s,x} \quad \text{at } x = L_1 \text{ and at } x = L_1 + L_2$$
$$\text{for } w_1 \le y \le w_1 + w_2 \tag{4}$$

$$-k\frac{\partial T}{\partial y} = q''_{s,y} \quad \text{at } y = w_1 \text{ and at } y = w_1 + w_2$$
$$\text{for } L_1 \le x \le L_1 + L_2 \tag{5}$$

where $L = (L_1 + L_2 + L_1)$, $w = (w_1 + w_2 + w_1)$.

$q''_{s,x}$ and $q''_{s,y}$ are the convection heat transfer flux at the interface in both x and y directions (Fig. 1a).

2.2. Convection heat transfer

Consider free convection within each of the enclosures with constant properties, no heat dissipation, applying Boussinesq approximation as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{6}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{7}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - g\beta(T - T_\infty) \tag{8}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho C}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{9}$$

No slip condition applies at interior surfaces

$$u = v = 0 \tag{10}$$

Continuity of temperature and heat flux is considered at inner surfaces. However, temperatures are unknown and found through the iterative solution

$$q''_{conduction} = q''_{convection} \tag{11}$$

These boundary conditions will be applied for all the air gaps in the material.

3. Numerical solution and grid independence

Mesh points were concentrated at the walls and corners where higher gradients exist [15]. Grid independent tests are conducted. A sample grid is shown in Fig. 2a whereas a sample of grid independence study is shown in Fig. 2b.

4. Results and discussions

The thermophysical properties of the blocks used in this study are listed in Table 1. Since the current geometry and the associated boundary conditions were not reported in the open literature, the code was tested for some of the cases published by various researchers [1,9,10]. They investigated natural convection in enclosures with conducting multi partitions and side walls. They used standard boundary conditions of vertical isothermal surfaces and adiabatic horizontal ones within the cavity. Using the same definition of Nu as given in [9], the current model was adjusted to match these conditions. Table 2 shows an excellent agreement between the current work and these calculations.

Conjugate convection/conduction heat transfer analysis is performed across a hollow block to investigate the parameters that result in an increase in the block thermal resistance. Several configurations were considered keeping the total width of the block constant. Due to space limitation, a sample of these results will be shown. A typical block with single cavity, Fig. 1a, is considered as the base or reference case. Further modifications are compared to the base case to illustrate the percentage benefit in terms of increasing the R-value. It should be noted, however, that one third of the block is considered due to symmetry (see Fig. 1a). It is known that the heat transfer coefficient is dependent on the width of the cavity, fluid properties as well as the temperature difference between the inner vertical surfaces. This heat transfer rate (given in terms of Rayliegh number, Ra) can be decreased either by reducing the width of the cavity or by decreasing the temperature difference between cavity vertical walls. Both are achieved by replacing the single cavity with two or more cavities separated by solid material (partition) as shown in Fig. 1b that shows a sample case with five partitions (six cavities), keeping the total block width unchanged.

Results show that increasing the number of cavities to two, and then three cavities keeping the total width constant, resulted in a decrease of the maximum air velocity within the cavities by 30.34% and 40.56%, respectively, indicating a significant decrease in the convective heat transfer coefficient. Increasing the number of cavities to more than 3 leads to a further reduction of the values of the air velocity values within the cavities, and the heat transfer coefficient is reduced.