HEAT TRANSFER IN BLOCK WALLS

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ABSTRACT

Combined conduction-convection-radiation heat transfer in concrete block walls with one or two cavities is simulated using the CFD code "FIDAP". It is shown that the resistance of the block itself depends on the temperature difference between the external and internal parts. The heat flux is shown to vary appreciably, approximately 30 %, between the upper and the lower parts of the block. Assuming spatially cyclic boundary conditions, ie heat transfer to the lower part of the block equal to heat transfer from its upper part, results in a vertical heat flux upwards which can be of the order of 20-30 % of the heat flux across the block.

INTRODUCTION

In many Mediterranean countries, walls are made of hollow concrete block walls. Resistance of heat flow in such walls is mainly due to the cavities, in which the main mechanisms of heat transfer are convection and radiation.Traditionally, heat transfer in such blocks is modeled using a film resistance coefficient to describe the combined radiation and convection heat transfer in the cavities, which depends on the thickness of the cavity and makes it possible to make a simple unidirectional heat flux and surface temperature calculation. The block was then characterised using an overall heat transfer coefficient U, to be calculated either by the parallel path method, or by the isothermal plane method (See Burch et al, 1979).

These calculations have been extended to carry three-dimensional heat transfer calculations in concrete block walls, but even in most of these calculations, the radiative-convective heat transfer is modeled by using the concept of an equivalent material which would give the same assumed resistance as an air-gap of the same thickness.

The nature of heat-transfer by convection and radiation is essentially different than heat transfer by conduction and thus trying to find an equivalence between these two modes of heat transfer may lead in misinterpreting some of the features of heat transfer. For example it can lead one to ignore the effect of stratifications within the air gap and of the variation of surface temperatures across the surface of a concrete block wall.

In this work, the combined heat transfer by conduction, convection and radiation in a concrete block wall will be analyzed using a known CFD program - with particular emphasis on the influence of the boundary conditions. On the basis of this analysis, the heat flux and temperature variation in the internal and external surface of the block, as well as other particularities of concrete block heat transfer, will be documented.

HEAT TRANSFER EQUATIONS

The time independent 2-D equations describing natural convection in a rectangular cavity are: the Navier-Stokes equations, the continuity equation and the convective heat transfer equation:

$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + \frac{\partial P}{\rho\,\partial x} = \nu\left(\frac{\partial^2 U}{\partial y^2}+\frac{\partial^2 U}{\partial x^2}\right) \quad (1)$$

$$U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + \frac{\partial P}{\rho\,\partial y} = \nu\left(\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial x^2}\right) - \beta g(T-T_o) \quad (2)$$

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (3)$$

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} = \frac{\lambda}{\rho\, c}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

In the above equations, y is the vertical direction, To is a reference temperature, β is the volumetric expansion coefficient of air ν is the kinematic viscosity and c is the constant-pressure specific heat. The Boussinesq approximation is assumed, ie air is considered an incompressible fluid, except for the influence of compressibility on the gravitational terms.

Heat transfer in the solid walls is described by the Laplace equation, which results from the conduction equation when time-dependence is eliminated and constant heat transfer properties are assumed:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad (5)$$

Heat transfer by long-wave radiation between the internal surfaces of the internal cavity of the block wall is described using the gray body approximation:

$$\frac{Q_i}{\varepsilon_i} - \sum_{j=1}^{n} F_{i\to j} Q_j \frac{1-\varepsilon_j}{\varepsilon_j} = \sigma T_i^4 - \sum_{j=1}^{n} F_{i\to j}\sigma T_j^4 \quad (6)$$

where Q_i is the net radiative heat flux from surface i, ε_i is the emissivity of the surface,$F_{i\text{->}j}$ is the view factor of surface i relative to surface j, T_i is the absolute temperature and σ is the Stefan-Boltzmann constant. At the boundary between the wall and the internal cavity, continuity of temperature and heat flux (conductive on the wall side, convective and radiative at the cavity side) has been assumed.

For the horizontal boundary between two consecutive blocks, it is usually assumed that the heat flux is zero. (Purch et al, 1981). This need not be the case, however. We have considered here a heat distribution cyclic in space, ie that the temperature and heat flux distribution across the lower and the upper block boundary are equal, ensuring that the amount of heat flowing into the cavity from below is equal to the amount of heat exiting from above. Thus, referring to the single cavity block:

$$T_{AD} = T_{BC} \tag{7}$$

$$Q_r + \lambda_{air}\frac{\partial T}{\partial y}\Big|_{bc} = \lambda_{con}\frac{\partial T}{\partial y}\Big|_{ad} \tag{8}$$

Q_r being the net radiative heat flux from surface bc. Eq. (8) is valid for the solid-fluid boundary, ad, the suffix con referring to concrete and the suffix air to the air. For the solid-solid boundary in the vicinity of the internal and external walls of the block, Eq. (7) remains valid whereas Eq. (8) is replaced by continuity in the temperature gradient:

$$\frac{\partial T}{\partial y}\Big|_{Aa} = \frac{\partial T}{\partial y}\Big|_{Bb} \tag{9}$$

with a similar condition between Dd and Cc.

Similar equations valid for the two-cavity block along lines AD and BC (Fig 1ii).

For the external and internal surfaces of the wall (AB and CD respectively) two sorts of boundary conditions were considered:

a. Constant temperature boundary conditions at the wall surfaces AB and CD:

$$T_{AB} = T_{so} \text{ and } T_{CD} = T_{si} \tag{10}$$

b. “Radiation” conditions at AB and CD, the external heat transfer coefficient h_o being assumed equal to 25 $W/m^2.K$ and the internal one h_i being assumed equal to 8.33 $W/m^2.K$:

Along AB,

$$-\lambda_{con}\frac{\partial T}{\partial x} = h_o(T_o - T) \tag{11}$$

Along CD,

$$-\lambda_{con}\frac{\partial T}{\partial x} = h_i(T - T_i) \tag{12}$$

RESULTS

Two blocks were considered, one with a single internal cavity and a second one with two cavities (Fig. 1). The thickness and the height of the block was assumed to be 20 cm, the thickness of the concrete being assumed equal to 2 cm and its thermal conductivity equal to 2 W/m.K. Between two blocks lying one over the other, a layer of connecting material (BCFE), 2cm thick with properties equal to those of concrete was assumed. The 2-D case was solved at this stage, 3-D effects being considered secondary, consistently with the results of Mallinson and de Vahl Davis (1977), who claim that 3-D heat transfer coefficients are very close to their 2-D values.The internal temperature was assumed to be 22^{o}C, the difference between the internal and the external temperature varying between 1 and 16 K.The equations were solved using the FIDAP CFD package. The grid used is uniform inside the wall but inside the cavity is more dense in the vicinity of walls.In Figures 2 and 3, the variation of the heat flux along the hot wall and the lower end of the cavity is shown. It can be seen that there is a very appreciable variation of heat flux along the wall, reaching a maximum at the vicinity of the “seam” between the two concrete block walls. The minimum value is reached in the vicinity of the upper part of the wall (correspondingly, the lower part for the case of the cold wall), reflecting the stratification inside the cavity, in which the temperature is higher in the upper part, in comparison to the lower part.

Most important, though, it can be seen that the assumed "cyclic" boundary condition results in a mostly upward heat flux at the lower edge of the cavity, whose average magnitude is approximately 15 % of the horizontal heat flux for one-cavity blocks and 20 % for two cavity blocks, these figures being almost independent of temperature difference. Such a flux is due to the natural convection of the air, hotter air being concentrated in upper layers and colder air in lower layers and cannot be described using the concepts of equivalent thermal resistance of the gap, which are pertinent to conductive heat transfer.

Finally, in Figures 4 and 5, the variation of the characteristic heat ransfer coefficient, based on the temperature difference between the internal and the external wall surface temperature, with temperature difference between the two surfaces, is shown and compared with the corresponding quantity, calculated using the parallel path method and an equivalent thermal resistance of 0.16 $m^2.K/W$ for the air gap. In the parallel path method, the heat transfer coefficient is equal to the width-weighted average value of the conductance across the seams and across the walls with the cavities. It is shown that there is an appreciable variation for low temperature differences, but the simplified calculation based on the parallel path method becomes more accurate for high temperature differences.

DISCUSSION and CONCLUSIONS

The heat transfer processes in a concrete block wall are simulated using a CFD package. The heat transfer processes include conductive heat transfer in the solid concrete, convective heat transfer in the air of the cavities and radiative heat transfer between the internal surfaces of the cavity.

The overall heat conductance as calculated using the parallel path method and a constant air gap resistance re equal to 0.16 $m^2.K/W$ is shown to be a relatively accurate approximation for temperature differences of the order of 10 K, but for lower temperature differences, the use of that temperature difference independent resistance results in overestimating the overall conductance.

However, there are other features of heat transfer in a wall made of concrete blocks that cannot be adequately described when using an equivalent resistance for the air-gap: these include the variation of heat flux over the surface of the block and the existence of a vertical upward heat flux, whose order of magnitude may be

15-20 % of the horizontal heat flux through a single block. This flux, which results in heat transfer from lower blocks to higher blocks, means that the upper parts of a block wall will be hotter than the lower parts and temperatures near the ceiling being higher than near the floor.

There are, of course, several limitations to this work, the main one being that laminar heat transfer was assumed. This assumption is correct for low temperature differences, but for high temperature differences turbulent heat transfer would be possible. The problem would then require the use of a low Reynolds number eddy viscosity energy-dissipation model, as opposed to the high Reynolds number one used in FIDAP. The two-dimensionality and stationarity assumed introduce further errors. However, it is thought that the analysis used here helps unveil some of the characteristics of heat transfer in concrete block walls which are not well represented in the usual methodologies, which are based on the equivalent conductivity concepts.

ACKNOWLEDGEMENT

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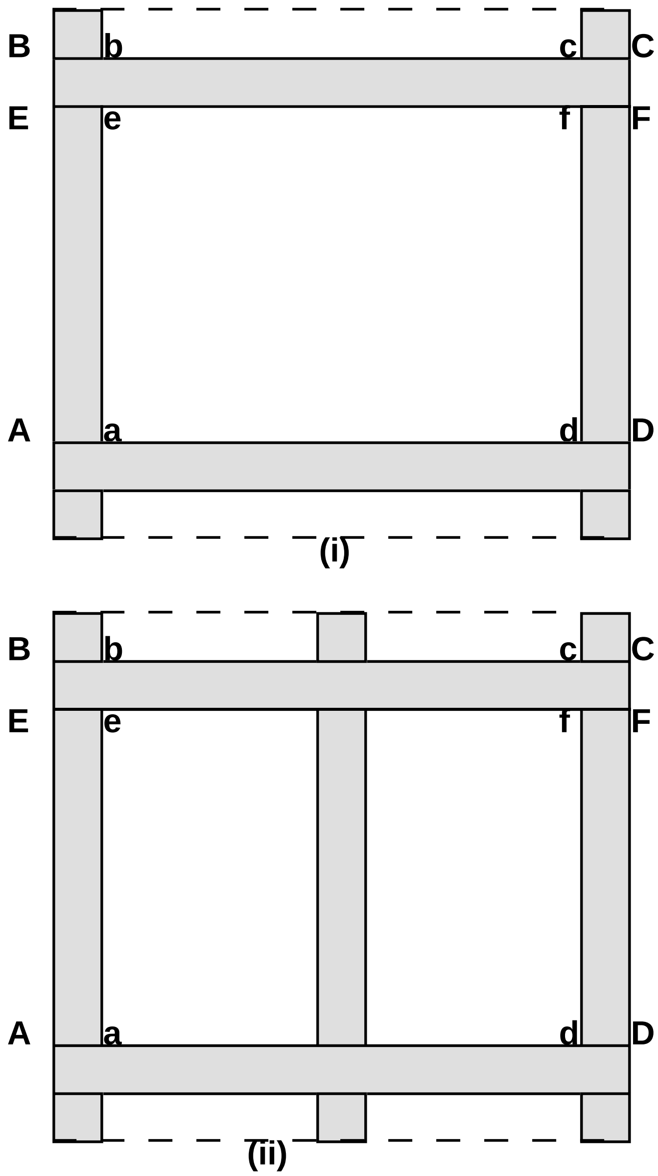

Fig. 1. Geometry of blocks. (i) Single-cavity block (ii) Double Cavity Block

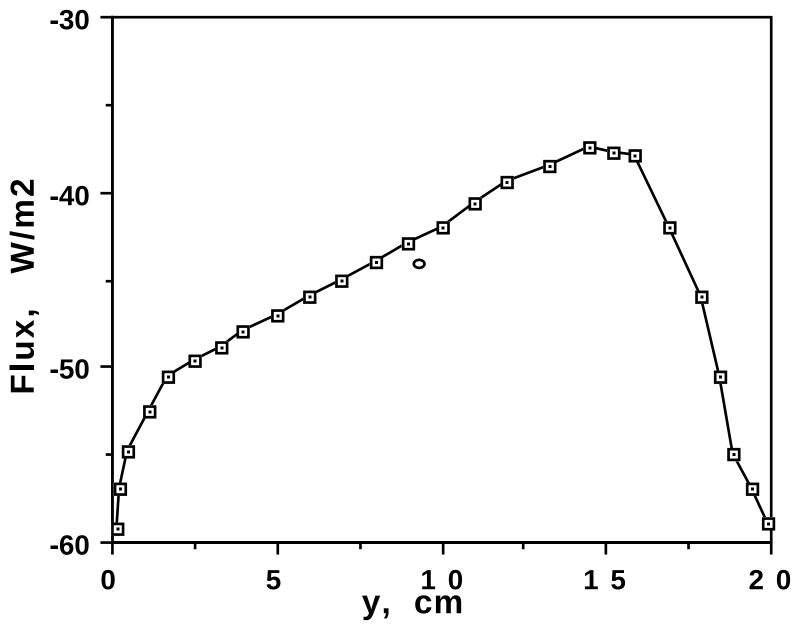

Fig. 2. Horizontal heat flux variation with height near the cold side of a hollow one-cavity concrete block wall. Temperature difference=10K.

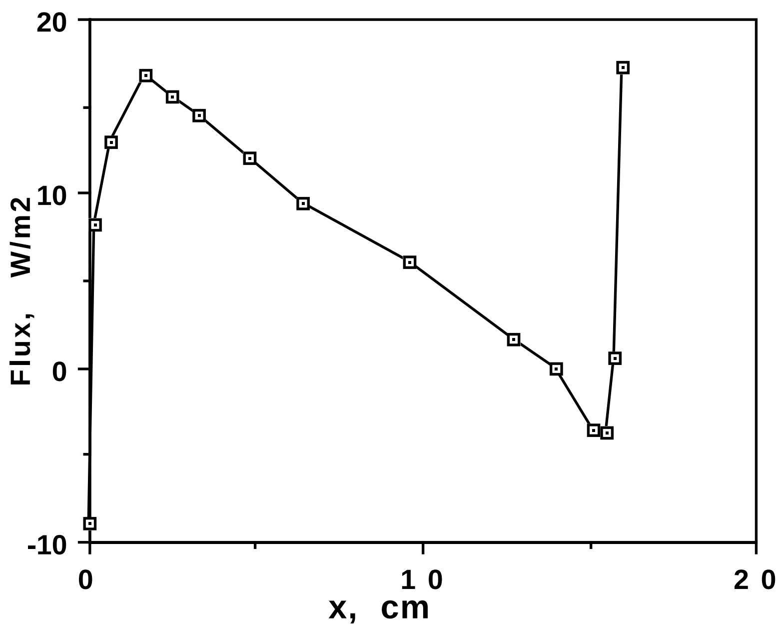

Fig. 3. Vertical heat flux variation across the lower side of a hollow one-cavity concrete block wall. Temperature difference=10K.

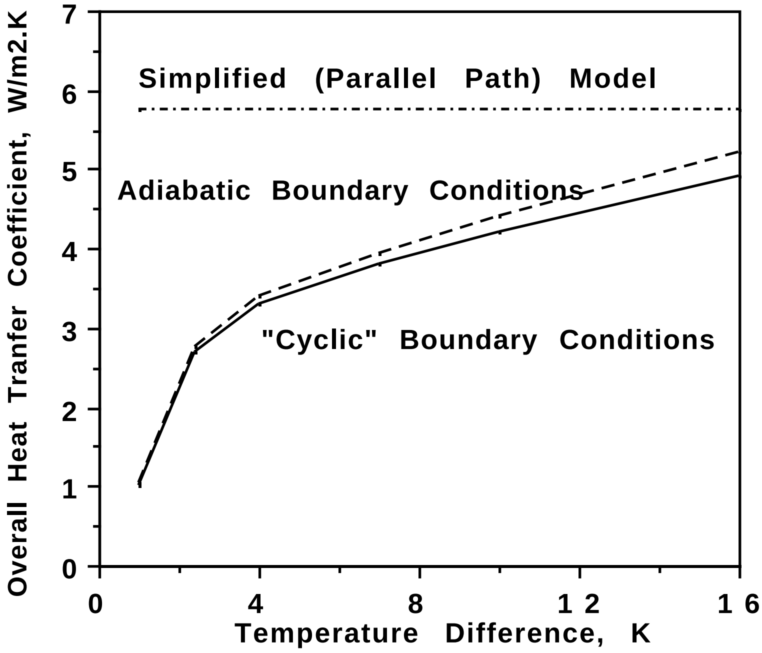

Fig. 4. Calculated variation of heat transfer coefficient with temperature difference between outside and inside wall for one-cavity hollow block wall

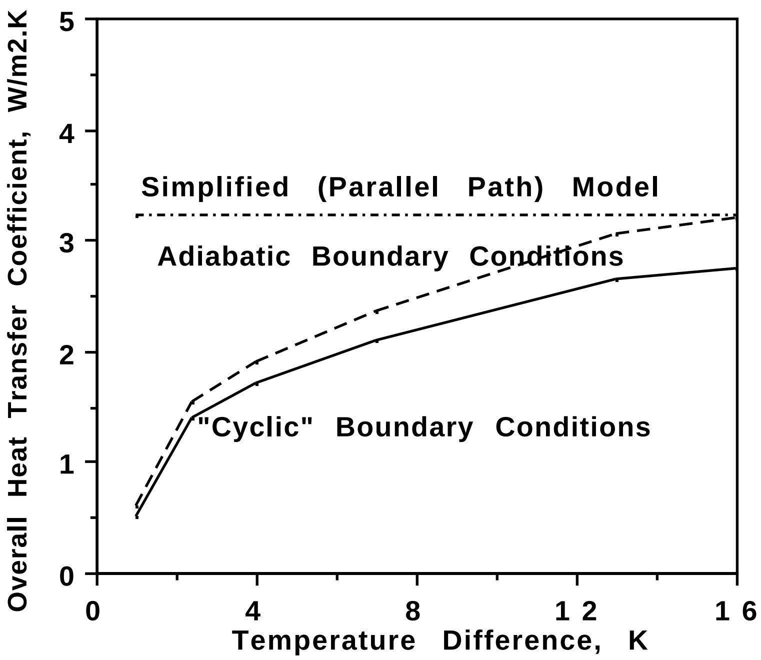

Fig. 5. Calculated variation of heat transfer coefficient with temperature difference between outside and inside wall for two-cavity hollow block wall.