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3D Numerical Analysis of Heat Exchange in Building Structures with Cavities

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Abstract

In this work the heat transfer inside the building block is analyzed. Brief overview of the physical problem is shown. The equations governing the heat exchange processes are given and numerical model is derived with the help of ANSYS software. The role of radiation and convection inside the cavities is emphasized throughout the work. Results show that radiation heat transfer mechanism is dominant for the cavities. Dependence on the properties of the clay material is examined. Several attempts are made to improve heat resistivity using given numerical model. In conclusion possibilities of practical application of the numerical modelling in the field of heat insulation material engineering are discussed.

Introduction

Empirical observations show that notable impact on the heat transfer in the walls of the buildings can be obtained by arranging gas inclusions inside the blocks. This impact can be analysed quantitative using experimental methods or by numerical modelling of the heat exchange processes inside the building structures. The efficiency of the second approach includes low costs for running the tests and ability to obtain the needed results promptly. Numerical modelling has proven it's applicability in works of other authors: for example [1], where this approach is realized in two-dimensional approximation.

The aim of this work is to develop the analysis methods, which would allow to describe their heat transfer properties by using numerical modelling and to describe the building structures with predicted thermal isolation characteristics. Usually when comparing heat transfer inside the building materials heat resistivity R ($m^2\times K/W$), coefficient of heat transmittance (or the heat transfer coefficient) U ($W/(m^2\times K)$) and effective heat conductivity λ_{eff} ($W/(m\times K)$) are examined. These quantities are determined by following formulae:

$$R = \frac{S\cdot\Delta T}{Q}, \quad U = \frac{1}{R} + h_{\text{out}} + h_{\text{in}}, \quad \lambda_{\text{eff}} = \frac{1}{R\cdot l}, \tag{1}$$

where Q is power (W), S is area of the wall, trough which heat transfer is realized, ΔT – temperature difference on the inner and outer surfaces of the wall, l – the thickness of the wall, h_{in} and h_{out} – heat exchange coefficients between the environment and outer or inner surfaces of the wall ($W/(m^2\times K)$). To examine the effect of inclusion of the cavities λ_{eff} is a convenient choice for monitoring, U and R are specifications of the whole structure.

1. Mathematical Description of the Discussed Processes

The heat transfer inside the solid materials is determined by Fourier law [2]:

$$\boldsymbol{q} = -\lambda \cdot \nabla T\,, \tag{2}$$

here $\boldsymbol{q}$ is the heat flux, λ is heat conductivity. Equation of thermodynamic balance for both fluids and solids can be derived from the following equation [2]:

$$\rho\, c_p \left(\frac{\partial T}{\partial t} + (\boldsymbol{v}\nabla)T\right) = \nabla(\lambda\, \nabla T)\,, \tag{3}$$

where T is temperature, λ - heat conductivity, ρ – density, c_p – heat capacity and $\boldsymbol{v}$ – velocity of the medium. Term $(\boldsymbol{v}\nabla)T$ stands for convection and therefore can be neglected for solids.

The motion of the fluid is given by the Navier-Stokes equation in the Boussinesque approximation [2]:

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\nabla)\boldsymbol{v} = -\frac{1}{\rho_{\mathrm{l}}}\nabla p + \nabla(\nu\, \nabla\boldsymbol{v}) + \boldsymbol{f} - \boldsymbol{g},\ \nabla\boldsymbol{v} = 0\,,\ \ \boldsymbol{f} = \beta(T - T_0)\boldsymbol{g}\,. \tag{4}$$

For these equation $\boldsymbol{v}$ is the velocity of liquid or gas, $\boldsymbol{g}$ is gravitational acceleration, p is pressure, ρ_{l} is density of incompressible gas or liquid, ν – kinematic viscosity, β – thermal expansion coefficient, T_0 – reference temperature. Since it was necessary to seek out only the steady state solutions, terms containing time derivatives were neglected.

For radiation heat transfer in transparent medium, discrete model can be employed, which is determined by following equation:

$$I(s) = \frac{\sigma_{\mathrm{SB}}\, T^4}{\pi}\left(1 - e^{-\alpha s}\right) + I_0 e^{-\alpha s}\,, \tag{5}$$

where I is radiation intensity in certain direction, α is absorption coefficient, s is distance from the point with radiation, σ_{SB} is Stefan-Boltzmann constant.

2. Modeling and Meshing

2. 1. The Model

As an object for developing of our methods a building block out of perspective of manufacturer “LODE” was chosen [3]. This block has cavities of different sizes inside. A geometrical model of the block was produced (Fig. 1). The block was made of clay material, while air was inside the cavities and concavities on the side surfaces were intended to be filled with concrete gluing. It was assumed that there are no heat fluxes between the neighbour blocks therefore zero-heat flux condition on these boundaries were applied, while on the inside and outside surfaces of the block interference with the environment was modelled with help of an heat transfer coefficient. Symmetry conditions applied on the central plane. The sizes of the block and its material properties are given in the Tab. 1.

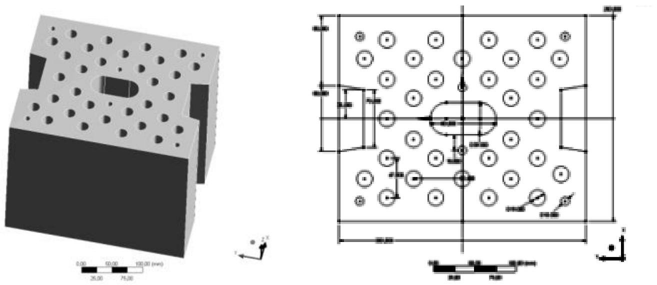

Fig. 1. Geometry of the modelled building block

Physical properties of air at 25°C from ANSYS CFX [4] material library were used in analysis. Since air is transparent discrete radiation heat transfer model could be applied. The fluid fluxes were assumed to be laminar. The blocks were separated from each other with a concrete gluing layer, and therefore no-slip wall conditions on the top and bottom boundaries of the cavities were applied.

Tab. 1. Sizes and material properties

Length/width/height, mm	300/250/249
Diameters of smaller cavities, mm	10/19
Sizes (length/width) of the larger cavity, mm	80/39
Heat conductivity λ, W/(m×K) for ceramics/concrete	0.3/0.9
Emissivity on the fluid-solid boundaries	0.9*
Heat transfer coefficient h, W/(m^2×K) on outside/inside surface	25/7.7
Temperature T (K) outside/inside	263*/293*

* - varied in numerical experiments

2. 2. The Model

To obtain the results a mesh was produced CFX meshing tools [4]. Because of the no-slip condition a fluid boundary layer was expected hence additional mesh grinding in proximity of the edges of cavities was required. The distances between nodes vary for solid domains from approximately 1 mm to 10 mm, and for fluid domains from 0.5 to 3 mm. The mesh is regular in vertical direction. For second mesh the spacing between the elements of fluid domain was decreased to 0.3 - 1.5 mm. The highest residuals appeared for the heat transfer inside the cavities. The time required for calculation varied from 30 to 90 minutes depending on the difficulty of the applied heat exchange model.

2. 3. Examination of Accuracy of the Mesh

To examine whether the results would be numerically correct additional calculations were made on more accurate mesh. The issues to inspect were the correctness of representation of the radiation processes and of the convective fluxes inside the cavities. Thus one calculation was made with increased mesh node number (Fig. 2) inside the cavities and the other with increased radiation ray number. The difference in the effective conductivity as well as in other quantities is less than 1%. The difference in maximum velocity is, however, in the region of 3%, yet the convective heat transfer does not have an appreciable effect on heat transfer, hence this difference can be neglected.

Tab. 2. Calculation on different meshes

		Coarse mesh	Accurate mesh	Difference, %
Convection	v_{max}, cm/s	6.03	5.86	2.8
	λ_{eff}	0.2486	0.2480	0.2
Radiation	Number of rays	8	30	-
	λ_{eff}	0.2704	0.2709	0.2

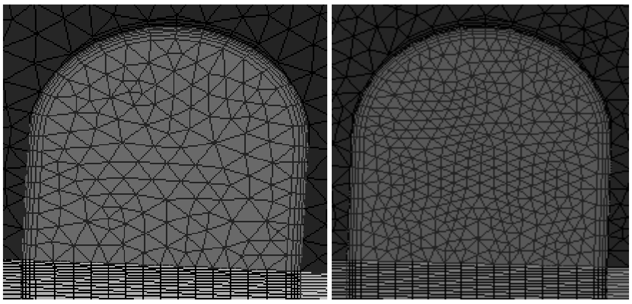

Fig. 2. Standard mesh (left) and a mesh used for accuracy examination (right)

3. Results

3. 1. Influence of Different Heat Transfer Mechanisms on the Heat Resistivity

Three different heat exchange mechanisms were examined: heat conduction, convection and thermal radiation. It was shown in work [1] that the thermal radiation is dominant in transferring the thermal energy across air domains.

To obtain the quantitative criteria for the significance of the processes involved four different physical models were analyzed: including only conduction mechanisms in all domains, then adding separately convection and radiation models inside the fluid domains and, in conclusion, involving all three mechanisms into the heat transfer. For each analysis type here and from now on calculation were made for three air temperature differences inside and outside: 10° C, 20° C and 30° C. The results are shown on Fig. 3. Since Re<2000 it is assumed that the flow is laminar in all calculations.

It can be shown that it is theoretically possible to reduce the effective conductivity up to 19%, if the radiation and convective mechanisms are suppressed. For comparison the effective conductivity is reduced only by 9% for model with all heat transfer mechanisms.

As expected, radiation has the major influence on the heat transfer inside the cavities while the convection does not lead to changes that exceed 4% in heat resistivity. In similar manner the dependence on temperature difference by fixed inside air temperature is observed. This dependence is weakly expressed for this type of building blocks (Fig. 3).

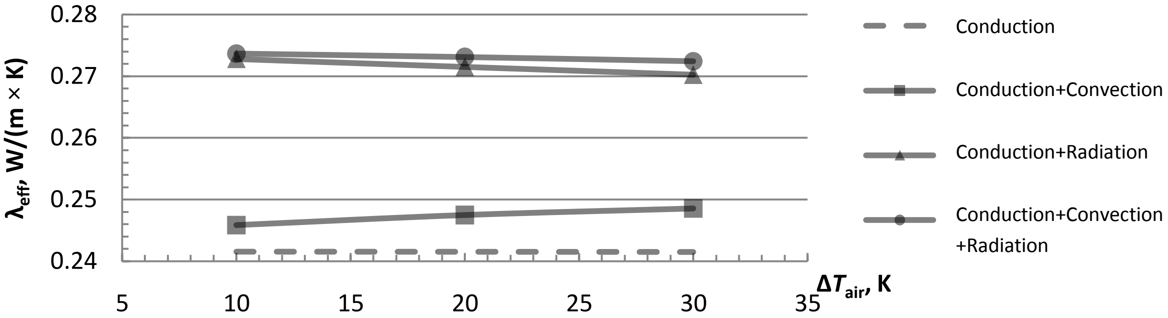

Fig. 3. The dependence of effective heat conductivity on different processes involved

3. 2. The Dependence of the Heat Resistivity on the Properties of the Clay Material

It is generally known that due to technological difficulties manufacturers can't guarantee for all ceramic blocks to have constant and homogeneous heat conductivity distribution. On the other hand it is generally useful for the manufacturer to know the effective heat conductivity dependence on the clay material properties to calibrate the production cycle to maximum efficiency. To examine this dependence calculations were made changing λ value in the range from 0.2 W/(m×K) to 0.4 W/(m×K) - see Fig. 4.

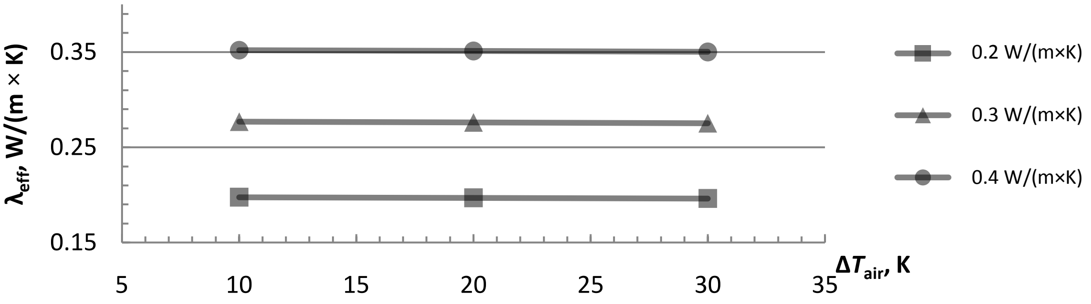

Fig. 4. The dependence of the heat resistivity on the properties of the clay material

The calculations were made involving all heat transfer mechanisms possible. By approximation of obtained λ_{eff} values as function of conductivity of the clay material we can conclude that this dependence can be treated as linear for this ceramics conductivity interval since R-squared values of this approximation are close to one.

The interpretation of this result can be given if we assume that $\lambda_{\text{eff}} = \lambda_{\text{ceramics}} + \Delta\lambda$, where $\Delta\lambda$ stands for the impact of the cavities on the heat exchange. Since the λ_{eff} can be expressed as a function of $\lambda_{\text{ceramics}}$, it is possible to write (Fig. 5):

$$\lambda_{\text{eff}} \approx 0.764\ \lambda_{\text{ceramics}} + 0.0425 = \lambda_{\text{ceramics}} + \Delta\lambda\,, \tag{6}$$
$$\Delta\lambda \approx 0.0425 - 0.236\,\lambda_{\text{ceramics}}\ . \tag{7}$$

This equation demonstrates that the effect of the cavities on the heat flux is notable only for larger conductivity values.

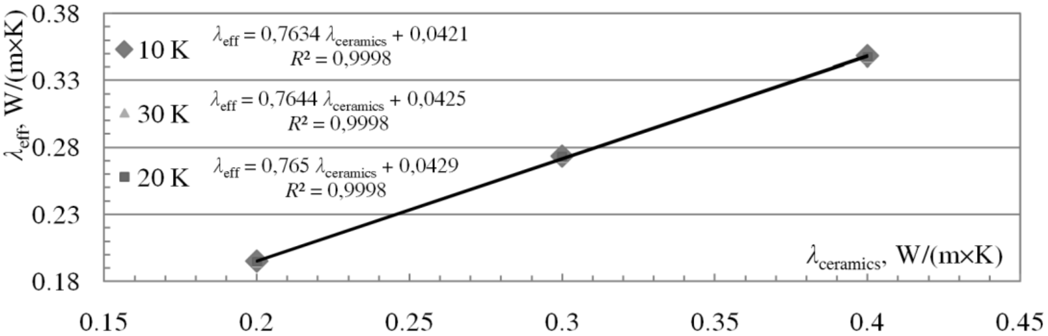

Fig. 5. The dependence of the effective heat conductivity on the properties of the clay material for various temperature difference and linear approximation

3. 3. Decreasing of the Heat Resistivity by Altering the Substances Inside the Cavities

To demonstrate the advantages of modelling approach in predicting of material properties several calculations were made as an attempt to solve the problem of minimizing radiation heat losses in this particular block.

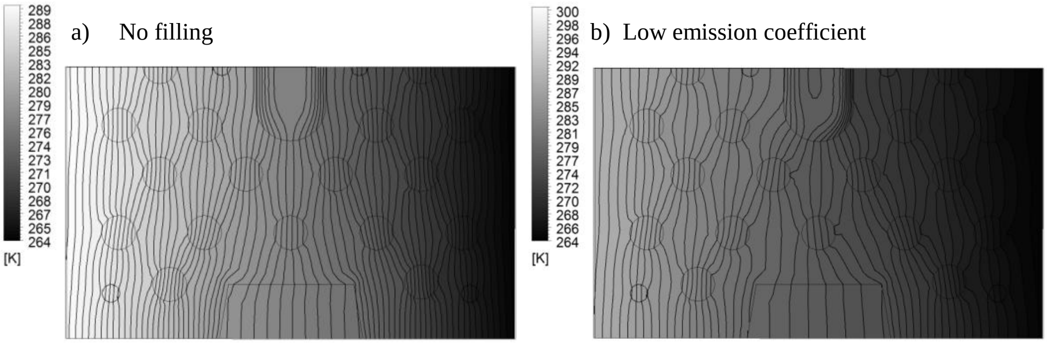

Fig. 6. Cross-section of the block in the middle at air temperature difference of 30° C: a) no filling (primarily radiation heat transfer) b) low emission coefficient spraying (primarily convection)

Different fillings were checked. The best results were obtained by using mineral wool as filling in all cavities or using a low-emission spraying on the walls of cavities. However, the best technical solution could be using mineral wool filling only in the largest cavity due to technical difficulties and economical costs of the solutions discussed above. The concrete filling is inefficient on account of its high thermal conductivity (it leads to decrease of the heat resistivity compared to block without filling in cavities). However, under certain circumstances it may necessary to use concrete to support the structural strength.

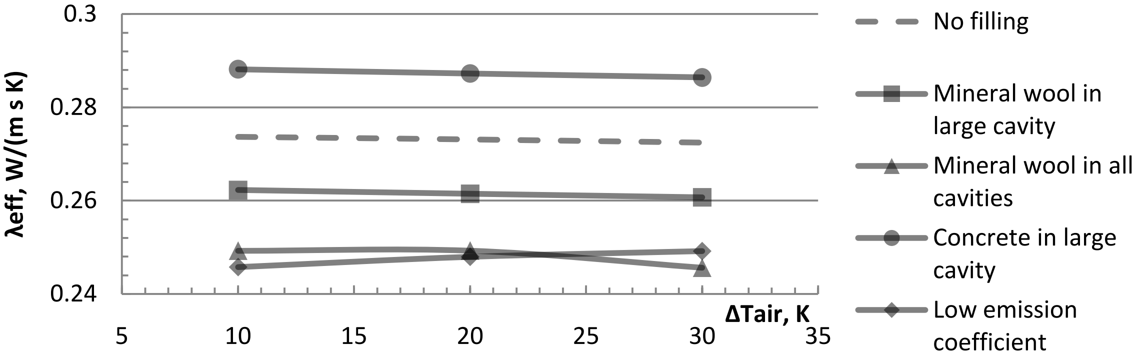

Fig. 7. The heat conductivity of the block with different fillings inside the cavities

Conclusions

Radiation and convection processes have important role in heat transfer inside building materials with gas cavities – the decrease in heat resistivity caused by these mechanisms reaches the level of 10%. In order to minimize the effect different engineering solutions can implemented returning heat resistivity on the level that is comparable with results obtained when only heat conduction is taken into account.

The methods of numerical modelling help to point out the best choice when no other testing tools but experimental are available due to complexity of the geometry and physical properties of the heat transferring media. By the use of computer modelling these tests can be carried out in a short period of time and with low financial expenses.

The results are in good agreement the effective heat conductivity values given by manufacturer “LODE” for the KERATEM type building blocks and with work [1] in terms of evaluating the significance of the different heat transfer mechanisms.

Concepts developed in this work include methodology for practical implementation of this kind of modelling for improvement of the thermal isolation of building materials (in form of an example with an existing building block.)

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