Mathematical Modelling of Heat Transfer Properties for Perforated Ceramic Blocks

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Abstract

There exist many methods for estimation of heat transfer properties for building materials. It is impossible to replace the experimental methods for determination of heat conductivity for basic materials. Experiments carried out show that heat conductivity of each particular material is dependent on different factors and could not be easily calculated. One of the possible alternatives to measurements is the use of mathematical modelling in case when heat conductivity of base materials is experimentally measured and building structure is combined of such materials or in case when only geometry of already known material domains (such sizes, proportions etc.) is changed. The main advantage of this method is low cost, since no experimental equipment is needed, as well as ability to virtually modify the structure for maximizing its energy efficiency. Possibility to handle geometrically complex materials when no explicit analytical approach is applicable is also advantage of mathematical modelling approach. This research is developed to reveal dependences of heat conductivity of ceramic building materials from clay mineralogical composition, porosity, structure of geometrical cavities and influence of different heat transfer mechanisms for ceramic building materials with different macroscopic air domains and different filling materials.

Keywords - mathematical modelling; building materials; ceramics; heat transfer; thermal conductivity

1. Introduction

Applying of ceramic materials has key position in building industries. This is because of ceramics properties – hardness, building convenience and high resistance on environment influence and microorganisms. Thanks to their ability to control humidity, ceramic building materials provide a favorable microclimate in rooms. But traditional ceramic materials have high thermal conductivity. Thus decreasing thermal conductivity of ceramic material was always actual question.

Thermal conductivity of ceramic building products depends on thermal conductivity of main ceramic body and on number and configuration of perforation or cavities exist in the ceramic material. It is possible to experimentally measure the properties of different clays, but in order to estimate the total heat transfer properties for the whole construction including cavities, the best way is to develop mathematical model and to perform numerical calculation series varying geometry or filling properties. This significantly speeds up the development process and allows optimizing of the product properties before production.

2. Thermal Conductivity of Ceramic Body

To determine dependence of thermal conductivity from mineralogical content of ceramic clays of bigger Latvian deposits and heat conductivity properties of ceramic received from these clays were investigated. Experiments carried out in the laboratory showed that thermal conductivity of ceramic body depends on mineralogical content of clay. High quartz content, low carbonate content and low clay mineral content increases heat conductivity of ceramic body (Table 1 and Fig. 1).

Table 1. Properties of ceramic body for different clays fired at 1000°C

Deposit name	Heat conductivity λ, W/(m·K)	Density ρ, g/cm^3	Clay particles <5 µm, %	Sand >50 µm, %	SiO_2, %	CaO+ MgO, %
Progress	0.33	1.53	60.9	4	50.5	12.6
Apriķi	0.38	1.50	85.8	2.5	49.5	9.7
Līvāni	0.40	1.62	66.6	6.1	49.8	10.5
Kaiģi	0.41	1.50	34.7	4.3	54.6	14.9
Liepa	0.59	2.00	42.5	18.6	68.4	2.3

The main factor influencing thermal conductivity of ceramic body is mineralogical content of the clay and it could not be changed significantly. But it is possible to decrease thermal conductivity of ceramic by decreasing its density – to archive this different organic and inorganic pore forming additives are utilized.

Data summarized in Tables 2 and 3 shows influence of pore forming additives on thermal conductivity, density and compressive strength of ceramic. It is possible also to decrease thermal conductivity of ceramic body by adding pore forming additives. Quite big amount of additives should be added to achieve a considerable effect and appropriate thermal conductivity (λ<0,20 W/(m·K)) even in this case would not be achieved. Widely used solution is to use the main ceramic body with appropriate porosity and compressive strength with technological cavities. Thermal conductivity of ceramic building material would be influenced by quantity, shape, and filament of cavities.

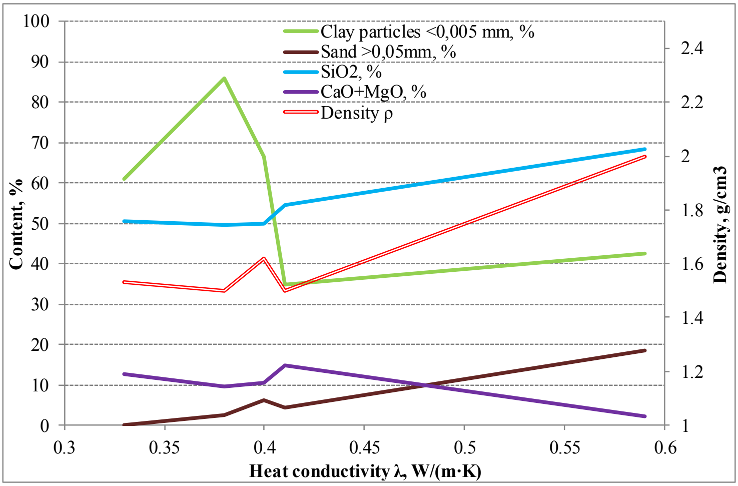

Fig.1. Factors influencing thermal conductivity of ceramic body

Table 2. Thermal conductivity of ceramic on base of clay from *Līvāni* from additive content

Additives	Content in mass %							
Clay	100	90	80	75	85	80	80	95
Saw dust		5		5	5	5	6	
Coffee		5			5	5	5	
Wood gridding dust							4	
Dolomite			20	20	5	10		
Crushed expanded clay							1	
Crushed ceramic							4	
Milled glass								5
Heat conductivity λ, W/(m·K)	0.40	0.33	0.37	0.33	0.30	0.30	0.26	0.36
Density ρ, g/cm^3	1.62	1.30	1.50	1.33	1.24	1.24	1.15	1.46
Compressive strength, N/mm^2	22.0	15.0	20.0	17.9	7.0	12.3	4.7	18.2

Table 3. Ceramic produced from different clays with the same saw dust content properties

Name of deposit	*Spartaks*	*Apriķi*	*Līvāni*
Clay	95	95	95
Saw dust	5	5	5
Heat conductivity λ, W/(m·K)	0.32	0.36	0.34
Density ρ, g/cm^3	1.37	1.43	1.42
Compressive strength, N/mm^2	17.3	17	18

3. Numerical Calculation of Thermal Conductivity

One of the possible alternatives to experimental methods and empirical calculations for determination of the physical properties of the building materials is mathematical modelling approach. The main advantage of this method is low cost since no experimental equipment is needed to modify the geometry of the blocks and to change the filling and the properties of the cavities. The results obtained from these models demonstrate good agreement with experimental data [1, 2] and thus can be used in practice.

Two blocks with different cavity structure were compared in this research - *Keraterm 44* with experimentally determined equivalent thermal conductivity coefficient λ_e=0.129 W/(m·K) presently produced in *"Lode SIA"* and block structure with experimental cavity combination properties of which are calculated using mathematical modelling approach (Fig. 2).

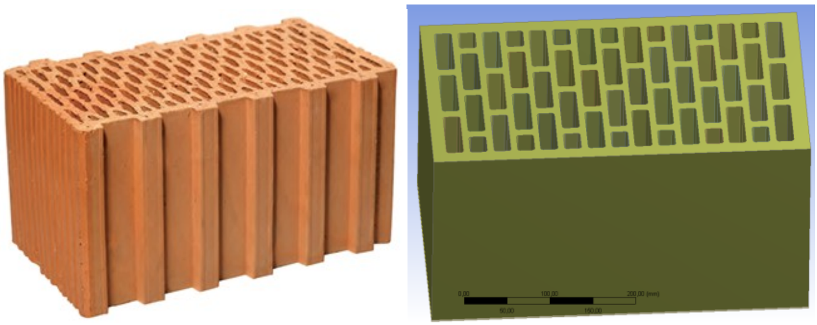

Fig. 2. Building blocks *Keraterm 44* produced presently by *„Lode SIA"* (left) and modelled block with experimental cavity combination (right).

Thermal resistance R for the whole structure can defined as the area S (m^2) and temperature difference ΔT (°C) on opposite surfaces (inner and outer walls) divided by the stationary heat flow Q (W) [3]:

$$R = \frac{S \cdot \Delta T}{Q}. \qquad (1)$$

Thermal resistance R characterizes the ability of a whole structure with fixed sizes to resist the flow of heat. Often it is needed to describe the heat transfer properties of known configuration of many components independent on the structure thickness. For this reason equivalent thermal conductivity coefficient $\lambda_{e.}$(W/(m·K)) is introduced, which describes the properties of the composite structure as for homogenous material; it can be calculated from heat resistance R of the construction with depth d (m):

$$\lambda_e = d/R \, . \qquad (2)$$

As it is seen from this equation, equivalent thermal conductivity is less for the structure with the same heat resistance but smaller thickness.

Mathematical modeling of the physical processed within the building blocks was made using commercial computational fluid dynamics software Ansys/CFX [4]. The main equations solved using finite volume method [5] are as follows [6]:

- The heat transfer in solid materials:

$$\vec{q} = -\lambda \nabla T \qquad (3)$$

where $\vec{q}$ is the heat flux density, λ is the heat conductivity and T is temperature.

- The thermodynamic balance for fluids:

$$\rho c_p \left(\frac{\partial T}{\partial t} + (\vec{v}\nabla)T \right) = \lambda \nabla^2 T \qquad (4)$$

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

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

$$\begin{cases} \dfrac{\partial \vec{v}}{\partial t} + (\vec{v}\nabla)\vec{v} = -\dfrac{1}{\rho}\nabla p + \nu\left(\nabla^2 \vec{v}\right) + \vec{f} - \vec{g} \\ \nabla \vec{v} = 0 \end{cases} \qquad (5)$$

with the buoyancy force $\vec{f}$ to be derived from the equation:

$$\vec{f} = \beta(T - T_0)\vec{g} \tag{6}$$

In these equations $\vec{g}$ is the gravitational acceleration, p – the pressure, ν – kinematic viscosity, β – thermal expansion coefficient, T_0 – reference temperature. Only steady state solutions are found, the terms containing time derivatives could be neglected.

Discrete heat transfer radiation model [7] is selected for the radiation heat transfer calculations, and the equation for the change of radiant intensity dI along path ds can be written as:

$$\frac{dI}{ds} + \alpha I = \frac{a\sigma T^4}{\pi} \tag{7}$$

where a is gas absorption coefficient and σ - Stefan-Boltzmann constant 5.672×10^{-8} W/(m^2·K^4). If a is constant along the ray, then $I(s)$ can be estimated as

$$I(s) = \frac{\sigma T^4}{\pi}\left(1 - e^{-as}\right) + I_0 \cdot e^{-as} \tag{8}$$

here I_0 is the radiant intensity at the start of the incremental path.

One geometry (Fig. 2, right) of the experimental block with different cavity filling is modeled to analyze the influence of the potential possible filling on the thermal resistance properties of a whole block. Dimensions of a block is set 440×245×240mm. Fixed surface temperatures of 0°C and +20°C are set as boundary conditions on block's surfaces according to the construction inner and outer walls, adiabatic boundary conditions are set on all other surfaces excluding heat exchange between similar blocks in the wall. Properties of the ceramic, air and filling materials are shown in the Table 4, discretisation mesh in the middle cross-section is shown on Fig. 3.

Table 4. Material properties used for mathematical modelling

Material	Density ρ, kg/m^3	Specific heat capacity c_p, J/(kg·K)	Thermal conductivity λ, W/(m·K)
Ceramic	1460	920	0.28
Air	1.185	1000	0.026
Mineral wool	220	2100	0.038
Polyurethane foam	40	1500	0.026

Fig. 3. Discretisation mesh in the middle cross-section of a modelled experimental block

4. Results

Due to structure of the block, which consists of ceramic material and cavities, different heat transfer mechanisms are included in the model – conduction, convection and radiation. Heat conduction is the only one heat transfer process for non-transparent solid ceramic part, convection and radiation are important only in case of gas filled cavities. In case when block has bigger cavities convection, transfer starts to play more important role in thermal conduction. This is confirmed by difference between equivalent thermal conductivity (Table 5) of real *Keraterm 44* block (Fig. 2, left) and experimental one (Fig. 2, right).

Table 5. Experimental data (*Keraterm 44*) and modelling results (A, W, P, A0.3)

Model	Cavities filling	Surface emission	Heat flux Q, W	$1/R$, W/(m^2·K)	λ_e, W/(m·K)
Keraterm 44	Air	*Experimental measurements*			0.129
A	Air	0.9	0.452	0.384	0.169
W	Mineral wool	-	0.295	0.250	0.110
P	Polyurethane	-	0.258	0.220	0.097
A0.3	Air	0.3	0.316	0.268	0.118

Modelling results for experimental block with different cavity fillings are summarized in Table 5. As one can see, the equivalent thermal conductivity λ_e=0.169 W/(m·K) is estimated for the block model without any special filling (model A), it is higher value than for experimental *Keraterm*

44 block with smaller cavities. The main reason for this difference is bigger size of internal air filled cavities which means more intensive convection.

Two different improvement of heat resistance for modelled block are investigated – cavity filling with the heat insulation materials (mineral wool – model W, polyurethane foam – model P) and the reducing of radiation heat transfer by decreasing of cavity surface emissions (model A0.3). The last one can be changed by coating the cavity surface with special low emission material. As it is seen from results (Table 5), mineral wool filling reduces the equivalent thermal conductivity of the block to 0.110 W/(m·K), but with the polyurethane filling λ_e decreases to 0.097 W/(m·K).

Mechanical filling of cavities is very complicated process in terms of technical implementation, the easiest way is to spray the special low emission coating into the cavities, in this case (model A0.3) reduction of radiation heat transfer causes the reduction of equivalent thermal conductivity down to 0.118 W/(m·K), which is very close to the effect of mineral wool filling.

Figures 4 and 5 show the temperature contours on the top of the block and in the middle cross-section for variants with air and polyurethane filling. Due to convection, heat transfer of air filled cavities is more intensive than in cavities with solid polyurethane filling.

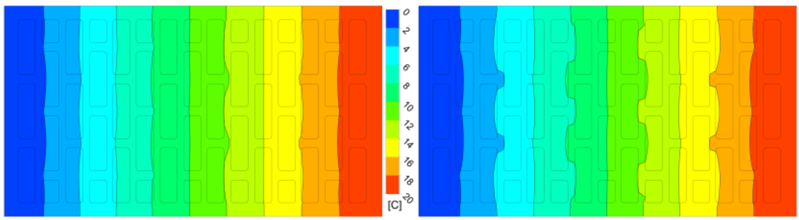

Fig. 4. Temperature field on top of the block for model A (left) and model P (right).

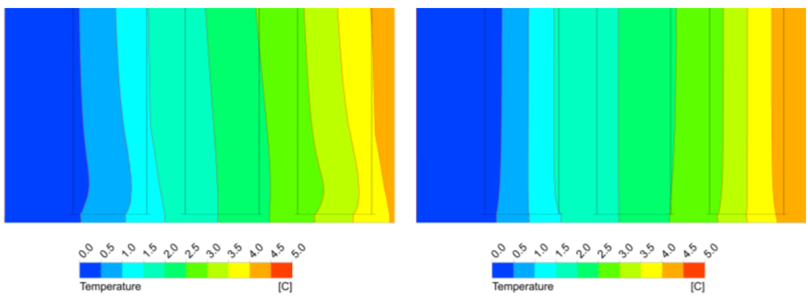

Fig. 5. Temperature field on bottom part of vertical cross-section in the middle of block for model A (left) and model P (right).

Non-symmetrical temperature distribution in the lower part of the cavities (Fig. 5) demonstrates the influence of convectional air transfer with air movement. In case of air-filled cavities (red line) the temperature distribution in more homogenous than for case of polyurethane filling with greater temperature gradients in all domains. On the pictures shown on Fig. 7 velocity vectors in the air filled cavities are visualized – in the middle vertical part they are symmetrical, but in the upper part situation changes resulting also shift in temperature field seen in Fig. 5 (left).

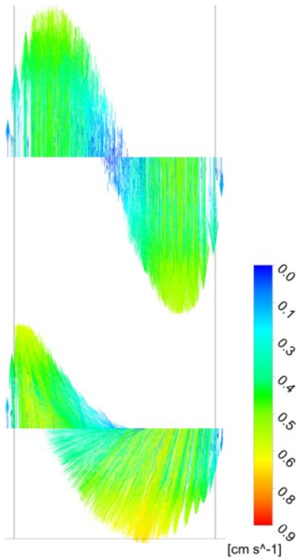

Fig. 7. Velocity vectors in the middle part (above) and in the upper part of the cavitiy (below).

Numerical calculation of heat transfer properties for ceramics blocks with cavities need accurate input data. Thermal properties of basic materials (ceramics, solid filling etc.) and geometrical properties can be easily found, but some other factors needs to be evaluated based on empirical data (e.g., real emissivity of the surfaces to correctly include the radiation heat transfer). Therefore it is very important to perform also the experimental research for some already modeled products to compare measured and calculated heat transport properties.

Other important mechanism for this kind of building structure is moisture transport due to low vapour resistance. It influences the heat conductivity of a ceramics, in this way increasing the heat transmittance for whole structure. Modelling for some observed ceramic blocks was carried out (e.g., [2]), but coupled heat and air moisture (HAM) transport modeling is needed to obtain more accurate results. Measurements carried out in the Laboratory for mathematical modelling of environmental and technological processes for such kind of ceramic blocks showed, that the difference in resulting *U* value can be more than 20% under different humidity conditions.

5. Conclusions

It is many possibilities to decrease thermal conductivity of ceramic material. Thermal conductivity of ceramic body could be decreased by modification clay mineralogical content and increasing porosity of ceramic body. This method could give some improvements but it is limited with compressive strength of material. The same limit has increasing amount of macro cavities in ceramic block.

Modelling pointed out that decreasing radiation inside cavities decreases thermal conductivity considerably. Additional improvement gives removing convection from heat transfer process. Previous researches showed a good agreement of mathematical modelling method with manufacturer data [2].

Therefore the method of mathematical modelling can be used to determine the heat transfer properties of the building materials in a quick and easy way. The usage of this method is both precise and cheap (especially considering the modern rate of the evolution of computers and computer software). The precision is achieved through inclusion of such physical processes as radiation heat transfer that cannot be introduced fully adequately by other methods. The obtained results provide ideas to the manufacturers how to improve thermal resistance of present materials by combining effects of physical and geometrical factors.

6. Acknowledgment

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7. References

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