Numerical Quantification of Thermal Properties of Insulation Coating

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Abstract: We are focused on numerical quantification of thermal properties of insulation coating applied to some building surfaces. The main objective is to determine the insulation coating impact on the heat flux transfer. This flux is modelled in terms of heat transfer coefficient at the surface of solid body. The heat transfer coefficient is obtained from the solution of the inverse heat conduction problem in 3D based on the temperature measurements. The determination procedure is a standard solution of inverse problem based on minimization of discrepancy between measured and computed temperature data. The practical validation is made for specimens of the KORUND® film applied to the concrete.

Key-Words: heat transfer coefficient, inverse problem, insulation coat, hollow microspheres

1 Introduction

The main motivation for this study is the fact, that the various coatings applied on the building surfaces can guarantee a great reduction of heating and cooling loads. A super effective coat based on rarefied air ceramic microspheres has been reported recently.

The special literature provides different technical details about these materials. For the review article you can see [1]. The thermodynamic details from different sources are extraordinary contradictory. Some sources say that their thermal conductivity is around 0.001-0.003 W/mK [2,3,4,5], but other publish much higher values (from 0.014 W/mK to 0.140 W/mK) [6,7]. Some sources indirectly determine the thermal conductivity of these coatings with heat transfer experiments of wall structures according to MSZ EN 1934:2000 and MSZ EN ISO 8990:2000 standards [2,3,7]. The reference [1] states that these methods are only suitable for determining the heat transfer coefficient of a global building structure. To measure the thermal conductivity of thermal insulation materials, it considers MSZ EN 12667:2001 as the only suitable standard. According to this standard, the thermal conductivity was measured in the Laboratory of Building Materials and Building Physics at Szechenyi Istvan University [8]. Based on these experiments, it was concluded that good thermal insulation quality of micro-ceramic thermal insulation coatings is not caused by very low thermal conductivity but rather by low convective heat transfer coefficient between the air and the surface of the building material. Further tests are required to determine it exactly [1].

The materials published by Russian company producing Korund® films [9] states that insulation properties of its product are caused by high reflectivity and low emissivity of spherical surfaces and by extremely low thermal diffusivity of the coating. According to them, the problem of measurement of thermal conductivity of such films lies in the fact that the lower the thermal conductivity causes the higher measurement error. Due to emissivity properties of ceramic rarefied micro-spheres they consider all non-contact temperature measurement methods as insufficient. We agree with such conclusion.

The fact that the thermal heat transfer dominates over the thermal conductivity in ceramic rarefied micro-spheres thin coatings is the starting point of our method, which allowing for the comparison of coats properties. When searching for heat transfer measurements using methods alternative to ours, you can refer to [10] as well.

Heat transfer through an interface of solid body and fluid is given by the Newton law

$$q = \alpha\left(T_0 - T_v\right), \quad (1)$$

where $\alpha\,[Wm^{-2}K^{-1}]$ is the heat transfer coefficient, T_0, T_v $[°C]$ stand for temperatures of the boundary surface and surrounding fluid, respectively and

q [$W.m^{-2}$] is the convective heat flux. Despite its simplicity, the equation (1) is very complicated due to the heat transfer coefficients' α dependency on the fluid thermal and mechanical properties inside the domain of the boundary layers.

The determination of the heat transfer coefficient α is possible for some simple arrangements in an analytical way, but for more complex cases more efficient methods are introduced in experimental studies of heat and mass transfer problems. The numerical modelling of boundary-value problems is used as well. Another approach to determine the heat transfer coefficient could be via inverse methods based on the minimization of discrepancy between measured and calculated temperatures at the selected locations of the measurement stand.

The subject of this study is the estimation of the heat transfer coefficients on the surface of concrete cubic sample with or without insulation coating. Knowledge of the heat transfer coefficient is essential for the calculation of the heat fluxes and for numerical quantification of the influence of insulation coating on the heating and cooling loads of a building.

2 Mathematical Model

The problem to be considered is shown in Fig.1.

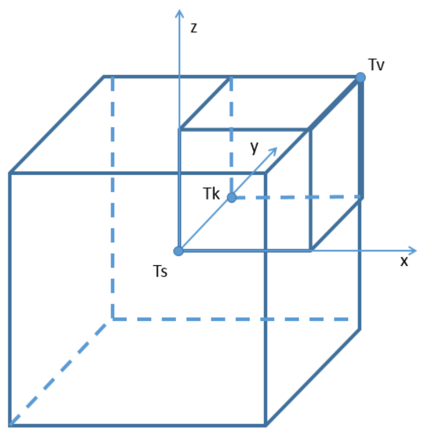

Fig.1 Cube-shaped sample with positions of measurement points.

A cube-shaped solid body is in the room with constant ambient air temperature. There is the heat exchange between the cube and the ambient air. Because of symmetry we consider just small cube K (1/8 volume of the original one). There is the heat exchange between ambient air and cube only through the tree boundary surfaces of cube K. The time evolution of temperature T in this cube is governed by the simple mathematical model

$$c.\rho.\partial_t T = \lambda.div(\nabla T) = div(-\mathbf{q}), \quad (2)$$

where λ is thermal conductivity coefficient,

$$\mathbf{q} = -\lambda.\nabla\mathbf{T} \quad (3)$$

is the heat flux and ρ, c are the density and specific heat capacity. The heat transfer boundary condition are expressed in the form

$$\mathbf{q}.\nu(\xi) = \alpha(\xi)(\mathbf{T}(\xi) - \mathbf{T_v})$$

$$\text{on boundary } \xi \in \partial_{\mathbf{K}}, \quad (4)$$

where ν is the outward unit normal to the boundary ∂_K of the cube K. The heat transfer coefficient is $\alpha(\xi) = \alpha_\Gamma$ for $\xi \in \Gamma_{4,5,6}$ and $\alpha(\xi) = 0_\Gamma$ for $\xi \in \Gamma_{1,2,3}$, where $\Gamma_{1,2,3,4,5,6}$ are the faces of the cube K. We assume that cube lies within the coordinates $K = (x,y,z) \in (0,V)^3$. We denote as Γ_1 the bottom $(z=0)$ surface and its opposite – top surface $(z=V)$ as Γ_4. Similarly, we denote the front surface $(y=0)$ as Γ_2 and opposite surface $(y=V)$ as Γ_5. Finally Γ_3, Γ_6 correspond to $x=0$, $x=V$, respectively.

3 Numerical Approximation

We have used the space discretization based on the finite volume method. We considered the uniformly distributed grid points (x_i, y_j, z_k) (for simplicity we assumed $(N+1)^3$ points). To generate approximation in a grid point we integrate (2) over the following control volume:

$$V_{i,j,k} = ((x_i - (\Delta x)/2, x_i + (\Delta x)/2) \times (y_j - (\Delta y)/2, y_j + (\Delta y)/2) \times (z_k - (\Delta z)/2, z_k + (\Delta z)/2)), \quad (5)$$

where $(\Delta x, \Delta y, \Delta z)$ is the corresponding space step.

To create a governing ODE for $T_{i,j,k}(t)$, we have used the following approximation:

$$\partial_t T_{i,j,k}(t) = \frac{\lambda}{c\rho} \times ((qx_{i+1/2,j,k} - qx_{i-1/2,j,k})/\Delta x + (qy_{i,j+1/2,k} - qy_{i,j-1/2,k})/\Delta y + (qz_{i,j,k+1/2} - qz_{i,k,j-1/2})/\Delta z), \quad (6)$$

where

$$\mathbf{q} = (qx, qy, qz) \quad (7)$$

and

$$qx_{i+1/2,j,k} = \frac{T_{i+1,j,k}(t) - T_{i,j,k}(t)}{\Delta x} \quad (8)$$

We have used the same approximation (with the corresponding reduction of control volume) in all inner grid points of sides $\Gamma_1 - \Gamma_6$. Analogously, we have constructed the ODE for inner points of 12 edges and finally for 8 grid points in the corners of the cube K. Due to physical reasons, we take into account the symmetries. The fluxes in the boundary points are given by (3). We solve the obtained ODE system by MATLAB ODE solver (for stiff systems). This system is rather large. We considered as sufficient to take N = 15 (15^3 grid points for the cube K) in our numerical experiments.

4 Solution of Inverse Problem

To determine model parameters $param = (\alpha, \lambda)$ we have used the measurements of temperature in the centre of the original cube (x = V/2; y = V/2; z = V/2). Additional measurements were available at the point (x = V/2; y = V; z = V/2) and (x = V; y = V; z = V). We realized these measurements in the prescribed time moments included in the vector *t*. Thus, we obtain

$$M(t) = \{T_{0,0,0}(t), T_{0,N+1,0}(t), T_{N+1,N+1,N+1}(t)\} \qquad (9)$$

We denote by $M_c(t, param)$ the computed temperatures at the same time moments *t* using some chosen starting values for *param*. Finally, we applied the minimization solver "fminsearch" from MATLAB toolbox to obtain „optimal“ *param* in an iterative way. We observed light dependence of calculated “*param*” on the chosen starting points for *param*. In this way we have tested the reliability of our solutions. This is the way we have proved the sufficiency of our measurements for the proposed determination procedure.

5 Results

In this study of quantification of the thermal-insulation properties of surface coat KORUND® we used the inverse method presented in the previous section.

The basic compositions of the composite coat KORUND® are acrylic substance and rarefied air ceramic microspheres [11]. The coat layer has thickness of approximately 1 mm.

To illustrate the validity of the presented inverse algorithm in identifying the heat transfer and thermal conductivity coefficients, we conducted some simple laboratory experiments.

We performed the measurements on the cubic samples with the edge length *0.1 m*. We carried out experiments for two types of concrete (hardened concrete and aerated concrete). The initial temperature of the entire cube was T_0. At the initial time of the experiment the cube was suddenly moved from the environment with constant temperature T_0 to the environment with a different constant temperature T_V.

We measured the temperature evolution during

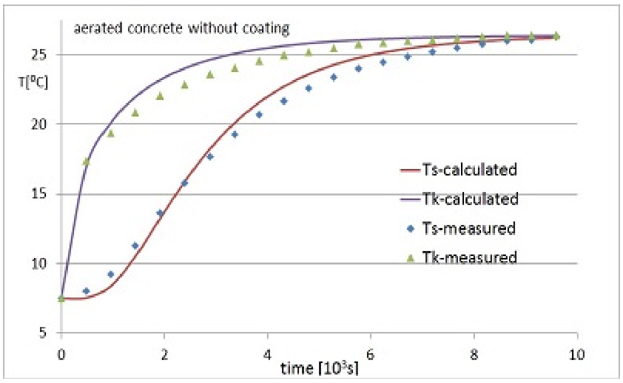

Fig. 1 Measured and calculated temperature evolution in selected points for aerated concrete without coating.

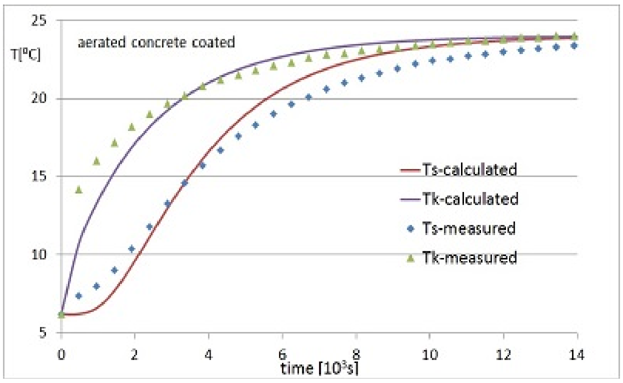

Fig. 2 Measured and calculated temperature evolution in selected points for aerated concrete coated by isolation film.

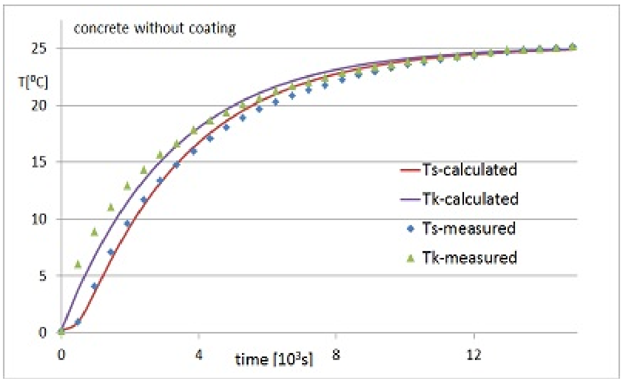

Fig. 3 Measured and calculated temperature evolution in selected points for hardened concrete without coating.

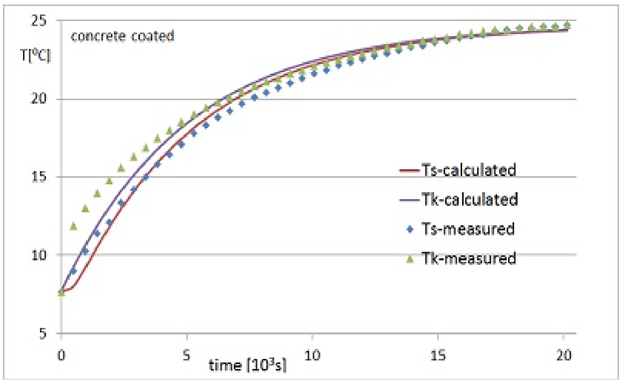

Fig. 4 Measured and calculated temperature evolution in selected points for hardened concrete coated by isolation film.

heat transfer at the cube's centre and at the centre of one of the cube's vertical surfaces for cubes with coating and without coating.

The calculated values of thermal conductivity coefficients λ and heat transfer coefficients α from inverse analysis are given in Table 1 for several runs that differ in the starting parameters

	aerated concrete (ρ=490 kg.m^{-3}, c=850 J.kg^{-1}.K^{-1})	
	without coating	with coating
λ [W.m^{-1}.K^{-1}]	1.4	1.3
α [W.K^{-1}]	1.8	0.9
	hardened concrete (ρ=2200 kg.m^{-3}, c=850 J.kg^{-1}.K^{-1})	
	without coating	with coating
λ [W.m^{-1}.K^{-1}]	1.8	1.8
α [W.K^{-1}]	1.3	0.9

Table 1 Calculated heat transfer coefficients and thermal conductivity coefficients for two kinds of concrete with coating and without coating.

Since we were not able to obtain reliable measurements in cube corner, we have removed them from the measurement vector *M*.

We note that measurements in the centre of the cube are more important for the determination of λ, while boundary measurements are more important for the determination of α. Based on these facts we can assign different weights for different measurements.

In the cube without coating we can emphasise the measurements in the centre while in the coated cube we can emphasise the measurements at the surface.

The ratio of parameters α for coated and uncoated cube can express the thermal isolation effectiveness of coating material.

Uneven conditions at which we performed our measurements led to uncertainties in calculated results. There was a time shift between the moment when we moved the cube from the colder environment to the hot environment and the moment when we started the measurement. We estimate its duration to 2-3 minutes. We were not able to establish uniform thickness of coating over the whole cube surface as well.

We believe that the presented mathematical method is principally correct. However, we need to perform and process our measurements more appropriately. We will aim our future effort in this direction. Our measurements prove that coating serve as thermo-isolation, as is illustrated by the graphs Fig. 1 - Fig. 4. The same can be seen from the fact that the ratio of heat transfer coefficients with coat and without coat is smaller than 1.

6 Conclusion

The results of our calculation support acceptance of presented approach for quantification of the thermal-insulation properties of a surface coat applied to some building materials. We highlight the potential of our method to serve as a standard for quantification of thermal properties of thin insulation coats in all cases where the thermal properties of material under investigation are dominated by process of heat transfer between the film and the surrounding fluid. There are some possibilities how to expand our model. The effort should be focus on the cases in which the coat thickness contribution to thermal transfer process plays more significant role. We see the possibility of improving the fit of theoretical temperature dependencies to measured ones by involving the temperature detector response properties into the mathematical model.

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