

Estimation of the wall thermal properties through comparison of experimental and simulated heat flux

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Abstract – The aim of the paper is to estimate thermal properties (thermal conductivity and thermal diffusivity) of the concrete wall with unknown insulation. Short theoretical background of diffusive heat transfer and numerical solution of unsteady one-dimensional heat conduction equation is presented first. System of discretized equations is solved using MATLAB. Boundary conditions (i.e. temperatures on edges of the wall) required for solving parabolic partial differential equation are obtained from experimental measurements on the wall. One heat flux sensor and one temperature sensor is mounted on both sides of the wall. Temperature inside room is maintained on approximately constant value by air conditioner while outdoor temperature is varying through the day. Measured signals are collected using NI cDAQ and then analyzed, processed and displayed using LabVIEW. Measured heat flux and numerically calculated heat flux from room to wall are then compared and initially chosen thermal conductivity and thermal diffusivity of the wall are iteratively adjusted until difference between measured and simulated heat flux is minimized.

Keywords – heat flux, in situ measurement, thermal diffusivity, thermal conductivity, direct problem

I. INTRODUCTION

Energy efficiency is one of the fastest growing interests and most important issues in today's world. Different scientists and engineers are concerned with environmental and economic effect of reduced energy consumption in everyday life, from electrical and mechanical engineers to the experts in field of physics,

chemical and civil engineering and traffic. With growing technology development and improved living standard one of the major energy consumers has become heating and cooling systems so the problem of heat loss through the building envelope has to be addressed. Thermal properties of the walls are important factors in evaluating quality of thermal insulation which can degrade over time so identification of these parameters can be quite challenging.

The objective of our study was to estimate thermal conductivity and thermal diffusivity of the wall with unknown insulation and concrete characteristics through comparison of experimentally measured and numerically calculated heat flux using direct method. Experiment was held in situ, in real life conditions, with unsteady outdoor and steady indoor temperature. Results are presented in following sections.

II. RELATED RESULTS IN THE LITERATURE

Three key thermal parameters that characterize thermal behaviour of building materials are thermal conductivity, thermal diffusivity and specific heat capacity. Thermal conductivity is a measure of a material ability to conduct heat and it is inverse proportional to other important thermal property, thermal resistance (*R-value*), and proportional to overall heat transfer coefficient (*U-value*). Since material doesn't just conduct heat, it also has capacity to store heat so specific heat capacity can be defined as material ability to absorb and store heat. Thermal diffusivity links these two parameters and it measures the ability of material to conduct heat relative to its ability to store heat. It is the measure of thermal inertia of material.

There are two approaches for measuring thermal

properties of materials: steady state measurements and transient state measurements. Steady state tests are used for thermal conductivity measurement and are based on one-dimensional heat model where thermal conductivity is calculated after temperature gradients is established and heat flux is measured over known thickness of a sample. Hot-ball method [1], heat flow meter method [2, 3] and guarded hot plate method [4] are one of steady state methods. Transient state methods are based on analysis of temperature response caused by dynamic temperature field generated inside material. Main advantages of transient state tests are shorter measurement time and simultaneously measuring all three thermal properties. Thus it is used for rapid measurements of nonhomogeneous, damp, porous materials. We differ non-destructive (transient plane source [5] method) and destructive transient methods (step-wise method [6] and two linear and parallel probe method [7]). Different experimental methods have been developed for in situ measuring of *U-value* [2] and *R-value* [8]. Also lag time and decrement factor of different wall structures were experimentally obtained and numerically verified by finite volume method [9] and finite difference method [10].

In heat transfer analysis there are two kinds of problems, direct and inverse problems. When boundary and initial conditions, and thermophysical properties are all specified, the direct problem is only concerned with determination of temperature distribution inside material. In contrary, with inverse problem temperature distribution inside material is known, but either one of boundary conditions or thermophysical properties are to be estimated. Refer to [11-13] for complete review of specialized literature concerning heat transfer, modelling of the heat problems and use of numerical methods in solving heat equation.

Several authors have demonstrated various experimental and/or numerical solutions of different inverse heat conduction problems, from boundary flux to thermal conductivity and thermal diffusivity determination [14-17]. One of the most interesting and progressive inverse method that has been developed recent is based on artificial neural networks using thermograms (thermal response diagrams) obtained by a non-destructive photothermal method [18].

There are also commercial software tools available on the market for modelling, simulation and analysis of heat transfer problems [4, 19].

Heat conduction problems had been also solved analytically. [20] has presented general lumped model for unsteady one-dimensional heat conduction problem. Temperature distribution inside simple geometries has been obtained using perturbation method. Method presented in the study [21] closely resembles our work where analytical model was used to obtain temperature distribution within asphalt concrete, after what thermal

properties were iteratively calculated until temperature distribution obtained in experiment matches temperature distribution calculated analytically.

III. RESULTS AND DISCUSSION

A. Theoretical background

Well-known differential equation that describes one-dimensional unsteady heat conduction in homogeneous and isotropic material without heat generation is:

$$c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}. \quad (1)$$

where $c = \rho C$, ρ is volumetric mass density, C is specific heat capacity, k is thermal conductivity of a material and $T(x, t)$ is temperature. Eq. (1) is solved numerically using finite element method and Crank-Nicolson finite difference method. Starting equation for implementation in MATLAB is obtained:

$$\left(\frac{1}{\Delta t} \mathbf{A} + 0.5 \mathbf{B}\right) \mathbf{T}^{n+1} = \left(\frac{1}{\Delta t} \mathbf{A} - 0.5 \mathbf{B}\right) \mathbf{T}^n + 0.5(\mathbf{Q}^{n+1} + \mathbf{Q}^n), \quad (2)$$

where matrices \mathbf{A} and \mathbf{B} depend on thermal parameters, is heat flux matrix, \mathbf{T}^n and \mathbf{T}^{n+1} are temperature matrices at $t = t_n$ and $t = t_n + \Delta t$ moments, respectively.

B. Measurement of the wall temperature and heat flux

Temperature and heat flux are measured on both sides of the wall. The goal of this experiment is to determine temperatures on the edges of the wall as a function of time which will then be used in MATLAB for numerical solution of heat equation. After that, measured and simulated heat fluxes at inside edge of the wall are compared and simulated heat flux is iteratively computed to obtain thermal parameters of the wall.

The wall studied in this experiment is at the west side of the building, protected all day from direct sunlight from neighbour building. The wall is 25 cm thick and made of reinforced concrete with unknown insulation thickness. Two heat flux sensors used in this experiment are HFP01 from Hukseflux. Temperature is measured with NTC thermistors EC95F103 located near heat flux sensor at surface of the wall. Temperature inside room is maintained on approximately constant temperature by air conditioner. The measurement was performed during few warm spring days from which period of three days of periodic temperature change was analyzed and displayed.

Heat flux and temperature measured data are acquired by NI 9211 and NI 9215 modules, respectively, which are installed on NI cDAQ 9188 chassis. The experimental setup is shown in Fig. 1.

Measured data are then processed, analyzed and

displayed in LabVIEW. Measured data will be displayed in next subsection so it can be compared with numerically computed data.

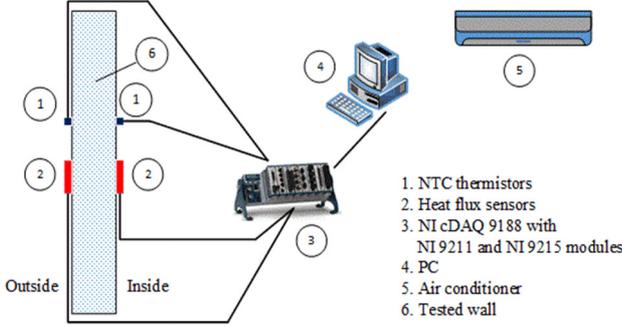


Fig. 1. Schema of experimental setup

C. Numerical model in MATLAB

As earlier said, Eq. (2) is starting equation for numerically solving heat equation. Solving Eq. (2) requires defining two boundary conditions and initial conditions. Two boundary conditions are taken as:

$$T(0, t) = T_1(t), \quad (3)$$

$$T(L, t) = T_n(t), \quad (4)$$

where L is thickness of the wall, $T_1(t)$ and $T_n(t)$ are temperatures as a function of time which are determined in LabVIEW from measurement of temperatures on edges of the wall. Temperatures are filtered using first order low-pass filter. Filtered boundary temperatures can be seen in Fig. 2.

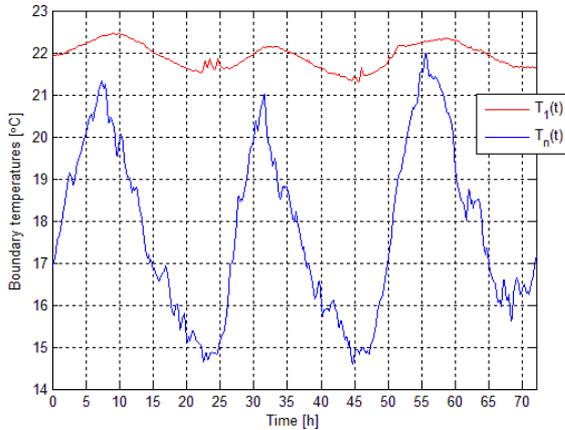


Fig. 2. Filtered boundary temperatures

The initial condition corresponds to those of temperature distribution in steady state:

$$T(x, 0) = \frac{T_n(0) - T_1(0)}{L} \cdot x + T_1(0). \quad (5)$$

Heat flux that enters the wall at $x = 0$ is computed after the temperature distribution inside the wall is known according to Eq. (6)

$$q(0, t) = q_0(t) = -k \cdot \frac{T_2(t) - T_1(t)}{\Delta x}, \quad (6)$$

where $T_2(t)$ is temperature function at second node ($x = x_2$) and $\Delta x = L/(n - 1)$. Eq. (6) represents well-known Fourier heat conduction law for first finite element.

Thermal properties of the wall are obtained by comparing measured and calculated heat flux at $x = 0$ (at the inside edge of the wall) because outside changeable weather conditions have a significant effect on a heat flux measured at the outside edge of the wall ($x = L$). We have also made valid assumption that heat flux measured by the heat flux sensor at the inside edge of the wall is equal to the heat flux entering the wall.

Thermal conductivity (k) and thermal diffusivity (K) had been iteratively estimated by changing initially assumed values in MATLAB program until difference between simulated heat flux and measured heat flux is minimized. It is shown from above equations that once the boundary and initial conditions are known, temperature distribution and heat flux depends only on this two thermal parameters. Simulated and measured heat fluxes are shown in Fig.3.

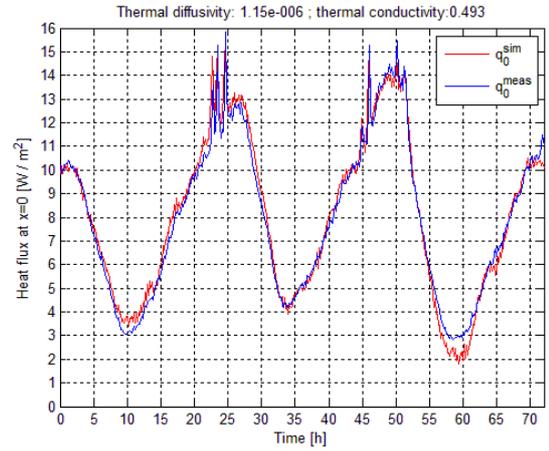


Fig. 3. Measured and simulated heat fluxes

Thermal conductivity and thermal diffusivity values obtained from this test are $k = 0.493 [Wm^{-1}K^{-1}]$ and $= 1.15 \cdot 10^{-6} [m^2s^{-1}]$. Peaks in heat flux which can be seen in Fig.3. are consequences of fast and sudden, but small changes in inside temperature (red line, Fig. 2.), probably caused by someone working near temperature sensor.

This results indicates existence of insulation layer inside the wall beside reinforced concrete. The wall studied in this test is composite wall, consisting of concrete layer (cca. 20 cm thick) and insulation layer (cca. 5cm thick). Exact physical properties (e.g. thickness) of these two layers are unknown, but according to total width of the wall that we measured ($W = 25\text{cm}$) we can assume aforementioned width of layers.

Total thermal resistance of the composite wall is equal to thermal resistances of materials building the wall connected in series:

$$R_w^{th} = R_c^{th} + R_i^{th}, \quad (7)$$

$$\frac{L_w}{k \cdot A} = \frac{L_c}{k_c \cdot A} + \frac{L_i}{k_i \cdot A}, \quad (8)$$

where $L_w = 25\text{ cm}$, $L_c = 20\text{ cm}$ and $L_i = 5\text{ cm}$ are width of wall, concrete layer and insulation layer, respectively, $k = 0.493\text{ Wm}^{-1}\text{K}^{-1}$ is thermal conductivity of the wall obtained from tests, $k_c = 1\text{ Wm}^{-1}\text{K}^{-1}$ is thermal conductivity of concrete which can be found from literature (dense concrete for building walls), k_i is unknown thermal conductivity of insulation layer and A is the area of the wall.

Inserting all these value in Eq. (8) and multiplying equation with A we get $k_i = 0.163\text{ Wm}^{-1}\text{K}^{-1}$ which corresponds to gypsum board.

IV. NOVELTIES IN THE PAPER

As already said, many studies have been carried out to determine different thermal parameters [5-7, 14-18], where thermal conductivity and thermal diffusivity are one of the most important for characterization of thermal behaviour of materials. What is common to all this studies is that they conduct tests (mostly destructive) in controlled laboratory environment on previously prepared specimens and often use expensive and sophisticated apparatus.

Contribution of this work is in its simplicity regarding both measurement and simulation on computer, ability for in situ measurement under real life conditions, usage of inexpensive measurement equipment and non-destructive nature. All these advantages distinguish this method from before mentioned methods.

V. CONCLUSIONS

Numerical model of unsteady one-dimensional heat conduction equation was derived first using finite element method and θ time integration method. A MATLAB program was developed then for implementation and solving of heat problem. Measurements of temperatures

on both sides of the wall and heat flux on the inner side of the wall as a function of time were then conducted. Measured temperatures were then used in simulation to obtain heat flux at the inner side of the wall. Initially chosen thermal diffusivity and thermal conductivity that are required for finding numerical solution of direct heat conduction problem were then iteratively changed until difference between simulated and measured heat flux is minimized. Finally, estimated thermal parameters of the wall were obtained.

VI. ACKNOWLEDGMENT

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REFERENCES

- [1] Kubičár, L., Vretenár, V., Štofanič, V., Boháč, V., "Hot-Ball Method for Measuring Thermal Conductivity", International J. of Thermophysics 31(10), pp. 1904-1918. 2010. DOI: 10.1007/s10765-008-0544-4
- [2] Meng, X., Yan, B., Gao, Y., Wang, J., Zhang, W., Long, E., "Factors affecting the in situ measurement accuracy of the wall heat transfer coefficient using the heat flow meter method", Energy and Buildings 86, pp. 754-765. 2015. DOI: 10.1016/j.enbuild.2014.11.005
- [3] Yoon, S., Macphee, D. E., Imbabi, M. S., "Estimation of the thermal properties of hardened cement paste on the basis of guarded heat flow meter measurements", Thermochemica Acta 588, pp. 1-10. 2014. DOI: 10.1016/j.tca.2014.04.015
- [4] Nagy, B., Nehme, S. G., Szagri, D., "Thermal properties and modeling of fiber reinforced concretes", Energy Procedia 78, pp. 2742-2747. 2015. DOI: 10.1016/j.egypro.2015.11.616
- [5] Oktay, H., Yumrutas, R., Akpolat, A., "Mechanical and thermophysical properties of lightweight aggregate concretes", Construction and Building Materials 96, pp. 217-225. 2015. DOI: 10.1016/j.conbuildmat.2015.08.015
- [6] Kubičár, L., Boháč, V., "A step-wise method for measuring thermophysical parameters of materials", Measurement Science and Technology 11(3), pp. 252-258. 2000. DOI: 10.1088/0957-0233/11/3/312
- [7] Morabito, P., "Thermal conductivity and diffusivity measurements by the transient two linear and parallel probe method", Thermochemica Acta 148, pp. 513-520. 1989. DOI: 10.1016/0040-6031(89)85255-4
- [8] Peng, C., Wu, Z., "In situ measuring and evaluating the thermal resistance of building construction", En. and Buildings 40(11), pp. 2076-2082. 2008. DOI: 10.1016/j.enbuild.2008.05.012
- [9] Barrios, G., Huelsz, G., Rechtman, R., Rojas, J., "Wall/roof thermal performance differences between air-conditioned and non air-conditioned rooms", Energy and Buildings 43(1), pp. 219-223. 2011. DOI: 10.1016/j.enbuild.2010.09.015
- [10] Vijayalakshmi, M. M., Natarajan, E., Shanmuga- sundaram, V., "Thermal Behaviour of Building Wall Elements", J. of Applied Sciences 6(15), pp. 3128-3133. 2006. DOI: 10.3923/jas.2006.3128.3133
- [11] M. N. Ozisik, "Inverse Heat Transfer: Fundamentals and Applications", CRC Press, 2000
- [12] Zienkiewicz, O.C., Morgan, K., "Finite elements and approximation", Wiley, 1983

- [13] Lienhard IV, J. H., Lienhard V, J. H., "A heat transfer textbook", Phlogiston Press, 2015
- [14] Chaffar, K., Chauchois, A., Defer, D., Zalewski, L., "Thermal characterization of homogeneous walls using inverse method", *Energy and Buildings* 78, pp. 248-255. 2014. DOI: 10.1016/j.enbuild.2014.04.038
- [15] Chen, T.-C., Tuan, P.-C., "Input estimation method including finite-element scheme for solving inverse heat conduction problems", *An International J. of Computation and Methodology* 47(3), pp. 277-290. 2005. DOI: 10.1080/10407790590883487
- [16] Monde, M., Kosaka, M., Mitsutake, Y., "Simple measurement of thermal diffusivity and thermal conductivity using inverse solution for one-dimensional heat conduction", *International J. of Heat and Mass Transfer* 53(23-24), pp. 5343-5349. 2010. DOI: 10.1016/j.ijheatmasstransfer.2010.07.022
- [17] Woodfield, P. L., Monde, M., Mitsutake, Y., "On estimating thermal diffusivity using analytical inverse solution for unsteady one-dimensional heat conduction", *International J. of Heat and Mass Transfer* 50(5-6), pp. 1202-1205. 2007. DOI: 10.1016/j.ijheatmasstransfer.2006.08.031
- [18] Grieu, S., Faugeroux, O., Traore, A., Claudet, B., Bodnar, J.-L., "Artificial intelligence tools and inverse methods for estimating the thermal diffusivity of building materials", *Energy and Buildings* 43(2-3), pp. 543-554. 2011. DOI: 10.1016/j.enbuild.2010.10.020
- [19] Corlay, C., Advani, S. G., "Temperature distribution in a thin composite plate exposed to a concentrated heat source", *International J. of Heat and Mass Transfer* 50(15-16), pp. 2883-2894. 2007. DOI: 10.1016/j.ijheatmasstransfer.2007.01.014
- [20] Sadat, H., "A general lumped model for transient heat conduction in one-dimensional geometries", *Applied Thermal Engineering* 25(4), pp. 567-576. 2005. DOI: 10.1016/j.applthermaleng.2004.06.018
- [21] Xu, Q., Solaimanian, M., "Modeling temperature distribution and thermal property of asphalt concrete for laboratory testing applications", *Construction and Building Materials* 24(4), pp. 487-497. 2010. DOI: 10.1016/j.conbuildmat.2009.10.013