The Impact of the Fourier Number on Calculation Accuracy of Transient Heat Transfer in Homogeneous Enclosures

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Transient heat transfer can be characterized by the concept of heat transfer when heated (cooled) material's temperature varies continuously in time. Usually, transient heat transfer is calculating according to finite element method. The great impact on the accuracy of calculation has a criteria of similarity, which is also known as Fourier number. This number shows the similarity of thermal variation in conditional layers of enclosures. Most scientists recommend to use 0.5 value of Fourier number and perform calculating of an transient heat transfer in all cases.

This paper introduces the results of experimental research of transient heat transfer in homogeneous building materials. Moreover, to compare the results of experimental research, transient heat transfer spreadsheet was created. Our research has shown that 0.5 value of Fourier number for calculations of transient heat transfer in homogeneous building materials is acceptable.

Keywords: transient heat transfer, transient heat exchanges, Fourier number, homogeneous enclosure.

INTRODUCTION

Fourier number in building physics is defined as dimensionless parameter, which characterizes the heat transfer. This number shows the similarity of thermal processes in conditional layers before and after of time step and is to be used for calculations of enclosures for transient heat transfer. Fourier number designated by symbol F_o and equation of this number is [1 – 3]:

$$F_o = \frac{a \cdot \Delta t}{\Delta x^2}, \tag{1}$$

here a is the thermal diffusivity (m^2/s), Δt is the time step (s), Δx is the thickness of conditional layer (m).

In the case of transient heat transfer, in any plane the temperature is determined by the following equation [1 – 3]:

$$\Theta_{n,t+1} = \Theta_{n,t} + F_o \cdot (\Theta_{n+1,t} - 2 \cdot \Theta_{n,t} + \Theta_{n-1,t}), \tag{2}$$

here $\Theta_{n,t+1}$ is the temperature in "n" interplane at the moment $t+\Delta t$ (°C), $\Theta_{n+1,t}$ is the temperature in "n+1" interplane at the moment t (°C), $\Theta_{n-1,t}$ is the temperature in "n–1" interplane at the moment t (°C), $\Theta_{n,t}$ is the temperature in "n" interplane at the moment t (°C).

By the individual case, if the values of Δt and Δx are chosen such that $F_o = 0.5$ [3 – 5], then equation (2) could be expressed as follows:

$$\Theta_{n,t+1} = \frac{(\Theta_{n+1,t} + \Theta_{n-1,t})}{2}, \tag{3}$$

According to [6 – 7] the value of the Fourier number equal to 0.5 is the most acceptable. Higher value of this number affects significant errors in the calculation of temperature [8].

According to the performed researches with multilayer enclosure, Fourier number value equal to 0.5 is a risky choice. In some cases, the temperature calculation average error increases significantly when the value of Fourier number reaches 0.47 [9].

It is unclear whether the same rule affects homogenous enclosure. So in this article we perform research with homogenous enclosures and determine the dependence of temperature calculation average error on Fourier number.

EXPERIMENTAL

In order to assess the accuracy of calculating transient heat transfer, the experimental research was carried out with the device "Lambda", which is designed for determining of thermal conductivity and isothermal heating oven (Fig. 3). This device was manufactured by scientists of Laboratory of Building physics of Kaunas University of Technology. "Lambda" device working principle is based on the stable heat flux method [3]. Isothermal heating oven – it's a simply heating oven, which maintains desirable temperature. In all cases of experiment, both of devices was used as temperature difference creators in the samples.

The experimental equipment consist of mentioned devices, samples, thermocouples, thermocouple data unit and personal computer (Fig. 1). A 500 mm × 500 mm sample composed of four expanded polystyrene foam (EPS) layers with 20 mm thickness has been selected for the experiment (Fig. 2). Manufacturer of the EPS is JSC "Kauno šilas", mark of material is EPS50, which declared

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thermal parameters are: thermal conductivity $\lambda_D = 0.043$ W/(mK), specific heat capacity $c = 1340$ J/(kgK), density $\rho = 12.41$ kg/m^3. The thermocouples have been placed between the layers and on both outside surfaces of the sample (Fig. 2). Surface thermocouples were covered by a thin sheet of porous polyethylene in order to avoid unexpected changes in surface temperature due to air movement, thermal radiation, and other factors [10].

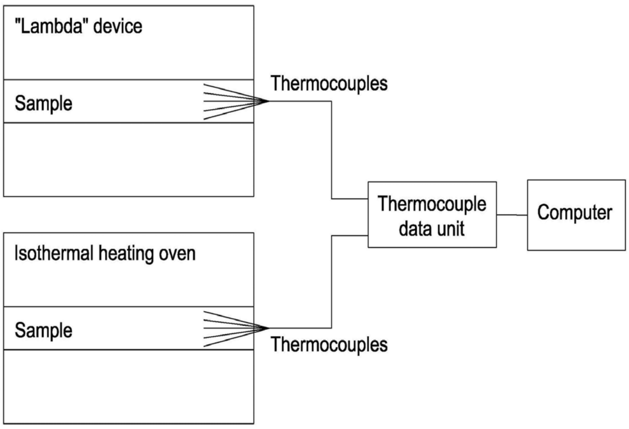

Fig. 1. Principal scheme of the experimental equipment

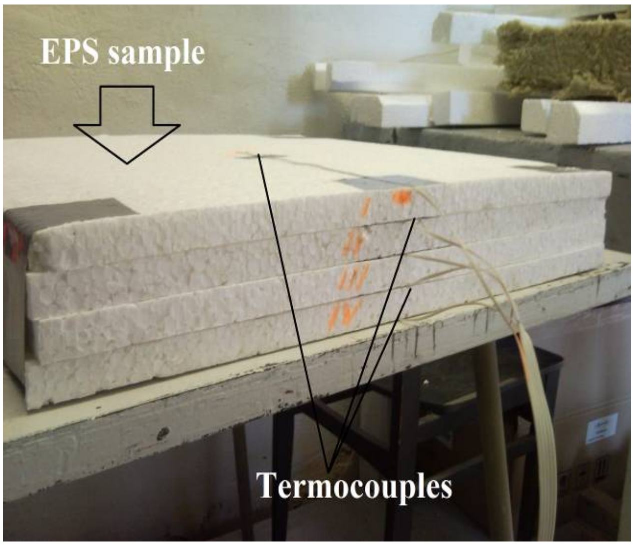

Fig. 2. The sample with installed thermocouples

The experimental research was started by heating the sample up to 40 °C and maintaining this temperature until it is steady in the entire sample. The heated sample was placed into the device "Lambda" (Fig. 3), which keeps temperature difference of 20 °C between both sides of the sample. Steady temperatures were kept on both sides of the sample: 20 °C in one side and 0 °C on the other side. The change of temperature in the entire cross-section of the sample takes place until steady state heat transfer is reached in the entire sample.

The change of temperature in the interplanes and surfaces of the sample was measured by thermocouples. The readings of thermocouples were recorded by the data acquisition unit, where they were converted to temperature values and forwarded to the programme "MS Excel". The standard deviation of mentioned data unit is ±0.075 K.

The measurements were taken at the intervals allowing to record each significant change of temperature of each interplane. After the thermal characteristics of the sample were chosen, the measurements were taken at the intervals of 90 seconds. The experiment was carried on until the steady state heat transfer condition (approximately 25 – 30 minutes for polystyrene foam).

After the experiment was carried out with the "Lambda" device expedient to perform a similar experiment under different temperature conditions. The isothermal heating oven was selected for this experiment. This device was manufactured by SC "Utenos elektrotechnika", mark of this device is "SNOL 200/200". The isothermal heating oven heats the entire surface area of the sample from ~28 °C to ~50 °C. The same sample of four 20 mm thickness polystyrene foam layers (Fig. 2) was used for this experiment.

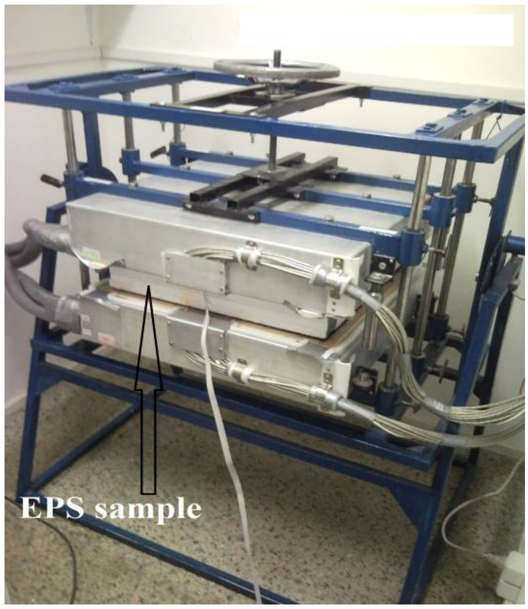

Fig. 3. Experimental set-up of „Lambda" device

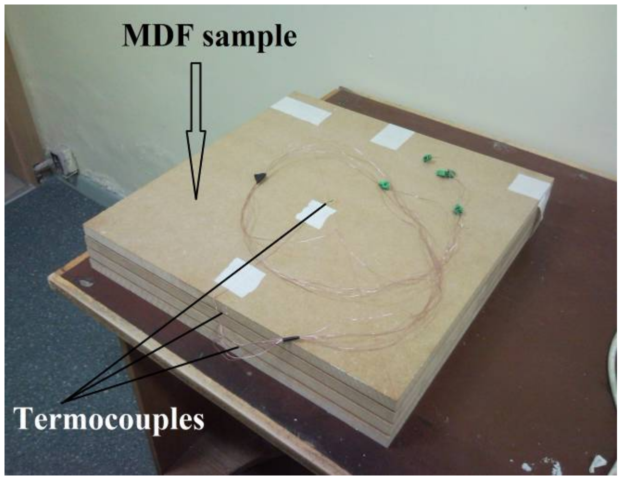

Fig. 4. Sample of wood fibreboard panel (MDF)

Based on the laws of transient heat transfer the greatest influence on the change of temperature in the sample makes the volumetric heat capacity c_V of the material

[1, 11 – 13]. Therefore, the wood fibreboard (MDF) sample of higher volumetric heat capacity and thermal inertia was selected for the next experiment. This sample consisted of four wood fibreboards of 18 mm thickness, which had the thermocouples installed in the interplanes and surfaces (Fig. 4). Manufacturer of the MDF is JSC “Girių bizonas”, which declared thermal parameters are: thermal conductivity $\lambda_D = 0.116$ W/(mK), specific heat capacity $c = 1460$ J/(kgK), density $\rho = 770.5$ kg/m^3.

This experiment was carried out by the setting fixed temperature in the isothermal heating oven (about 27 °C) and waiting for steady state temperature is reached through the sample. After the temperature stabilization, it was suddenly increased up to 50 °C and the experiment was started, i. e. the readings of temperature variation in the entire sample are measured at each time step.

EXPERIMENTAL RESULTS

The results of the experimental research with EPS in “Lambda” device are presented in Fig. 5; vertical lines represent interplanes of the sample and horizontal lines – the temperature curves through cross-section of sample.

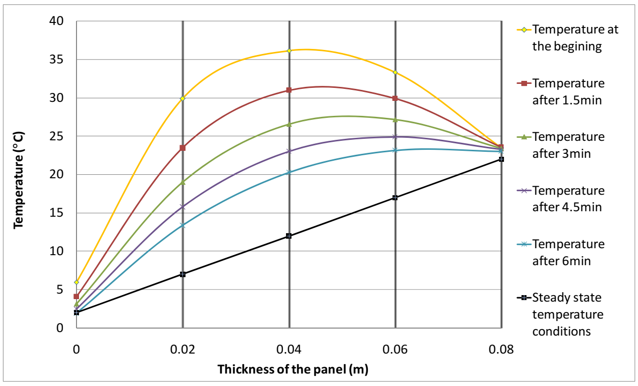

Fig. 5. Temperature distribution in time at the cross-section of tested sample of EPS in „Lambda“ device

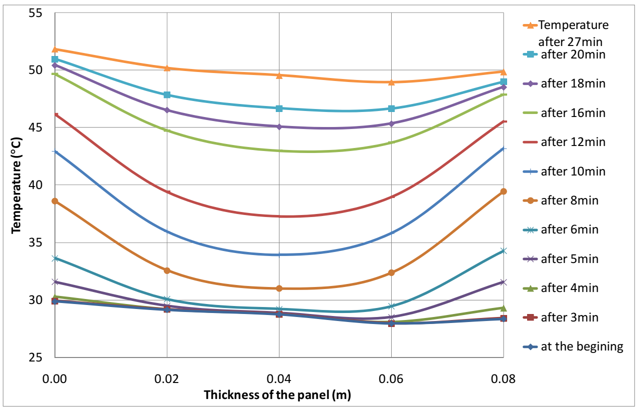

Fig. 6. Temperature distribution in time at the cross-section of tested sample of EPS in isothermal heating oven

The upper line represents the distribution of temperature through the sample at the beginning of the experiment; the lower line represents the distribution of temperature through the sample as the steady state transfer is reached, i. e. the end of the experiment; intermediate curves represent the distribution of temperature through the sample after 90 s, 180 s, 270 s and 360 s from the beginning of the experiment.

The results of the experiment with EPS in isothermal heating oven are presented in Fig. 6. The diagram depicts 12 curves; each of them represents the temperature distribution in the sample and its layers after 3 min, 4 min, 5 min, 6 min, 8 min, etc. up to 27 min.

The results of the experiment with MDF in isothermal heating oven are presented in Fig. 7. The diagram depicts 9 curves; each of them represents the temperature distribution in the sample and its layers after 10 min, 30 min, 70 min, etc. up to 800 min.

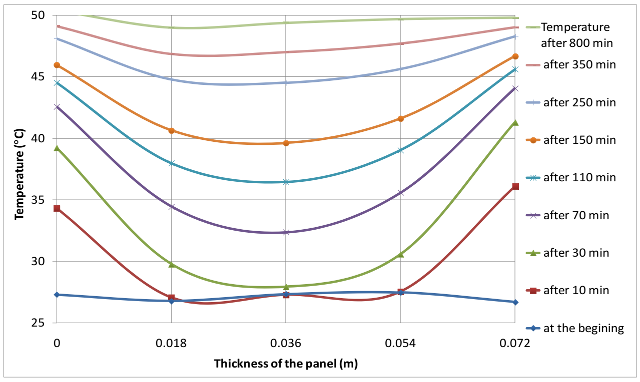

Fig. 7. Temperature distribution in time at the cross-section of tested sample of MDF in isothermal heating oven

CALCULATIONS

In order to compare the results of experimental research with homogeneous enclosures, the transient heat transfer spreadsheet was created. This spreadsheet is programmable in “MS Excel”, where the columns represent the temperatures of the surfaces and interplanes and the rows represent time intervals.

The calculation is performed by changing the time step, recording the value of Fourier number and analysing the graph, which presents calculated and measured temperature values. If the time step Δt is changed, the programme recalculates all cells and selects necessary temperature in the characteristic points according to the results of the experimental research.

The accuracy of calculation and relevant choice of calculation parameters are estimated by comparing the results of experimental measurements with calculated ones. To achieve this purpose, results of the experimental measurements were loaded into the spreadsheet and compared with calculated values of temperature. The result of comparison is expressed as the temperature’s calculation average error M. This is a comparison of the results of experimental measurements and calculated temperature values, by summing the modulus of these temperature differences and calculating the average of them:

$$M = \frac{\sum_{i=1}^{n} \left| \Theta_{\exp} - \Theta_{cal} \right|}{n}, (°C), \tag{4}$$

here Θ_{exp} is the measured value of the temperature (°C), Θ_{cal} is the calculated value of the temperature (°C).

DISCUSSION

The dependence of temperature's calculation average error M on Fourier number F_o according to experimental researches in "Lambda" device and isothermal heating oven is shown in Fig. 8.

It can be seen that if the Fourier number value exceeds 0.63 when calculating according to the experimental research with the EPS panel in "Lambda" device, the temperature's calculation average error M begins to increase rapidly. Similar results are observed when calculating according to the experiment with EPS panel in the isothermal heating oven, although the breakpoint here is at the value of 0.76. In the calculations with material of higher thermal inertia (MDF) – higher stability is observed with regard to the temperature's calculation average error.

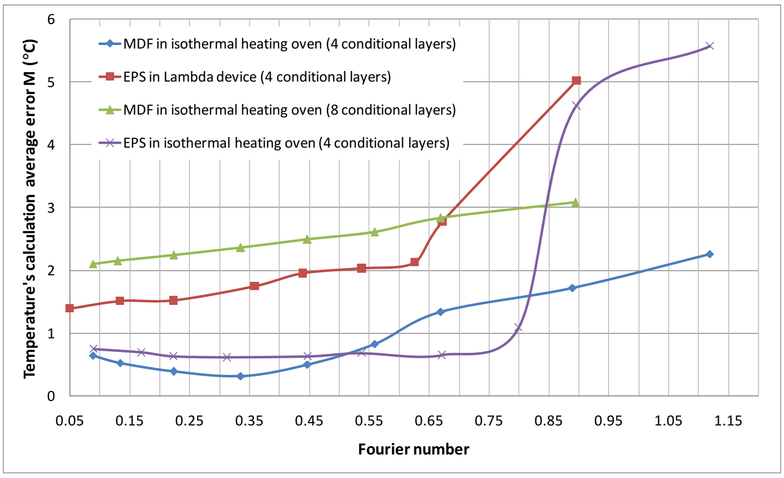

Fig. 8. The dependence of temperature's calculation average error M on Fourier number F_o

CONCLUSIONS

1. Our research has shown that 0.5 value of Fourier number to calculations of an transient heat transfer in homogeneous building materials is acceptable.
2. Our research has shown, that greater number of conditional layers have negative impact to calculation accuracy.

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