IOP Conf. Series: Materials Science and Engineering **163** (2017) 012018 doi:10.1088/1757-899X/163/1/012018

Using the heat flow plate method for determining thermal conductivity of building materials

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Abstract. The heat flow plate method is used to determine thermal conductivity of a building material sample made of Rohacell (insulating foam). Experimental technique consists in placing the sample with a reference material on top (polystyrene sample) in a calorimetric chamber and heating from underside. Considering that the heat flux which passes through the two layers is constant and knowing thermal conductivity of the reference material, the sample thermal conductivity is determined. The temperature difference between the two opposite sample's sides is recorded only when the steady state is achieved (constant heat flux).

1. Introduction

The phenomenon by which heat is transported through a material, when a temperature difference is applied between two opposite sides, is called thermal conduction. Thermal conductivity is the property which indicates the ability of materials to conduct heat [1]. Knowing material thermal properties is important in many applications especially in thermal insulation where the heat exchange with surroundings is a particularly important issue [2].

Since conductive heat transfer phenomenon takes place in a thermal field with temperature differences, of interest is how thermal conductivity varies with temperature. So, for materials majority was established the following dependence of thermal conductivity with temperature [1]:

$$\lambda = \lambda_0[1 + C_1(T - T_0)] \quad W/(m \cdot K) \tag{1}$$

where: λ is thermal conductivity at temperature T, λ_0 is thermal conductivity at reference temperature T_0, C_1 is a constant characteristic of each material.

Thermal conductivity values for some classes of substances (gases, liquids and solids) at moderate pressure and temperature are given in Figure 1 [1].

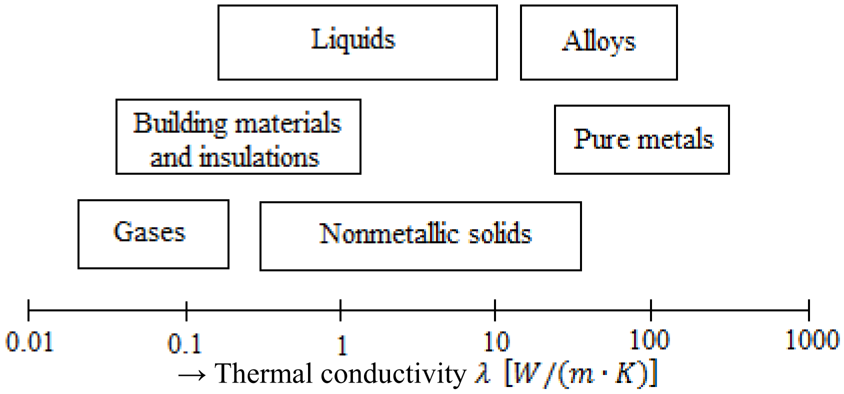

Figure 1. Thermal conductivity values for some categories of substances [1]

For building materials and insulations, λ has values in the range $(0.02 \div 3\ W/m \cdot K)$ and depends on material structure, porosity and humidity. These values increase with increasing temperature or with increasing density [1].

If the heat transfer process is stationary (steady-state condition), the heat flux which passes through each *n* layers of a flat wall is considered identical (Figure 2) [1]:

$$\dot{Q}_1 = \dot{Q}_2 = \cdots = \dot{Q}_n = \dot{Q}\ [W] \tag{2}$$

where: subscript *1…n* denotes layer number.

So, according to Fourier's Law of Heat Conduction, the heat flux passing through the first layer of the wall is [1], [2]:

$$\dot{Q}_1 = \frac{\lambda_1}{d_1} A(T_1 - T_2)\quad [W] \tag{3}$$

where: $\lambda_1\ [w/(m \cdot K)]$ is thermal conductivity; $d_1 [m]$ is the wall thickness; $A[m^2]$ is the wall area normal to the heat flux direction; T_1 and T_2 in [K] are the temperatures on two sides of the layer.

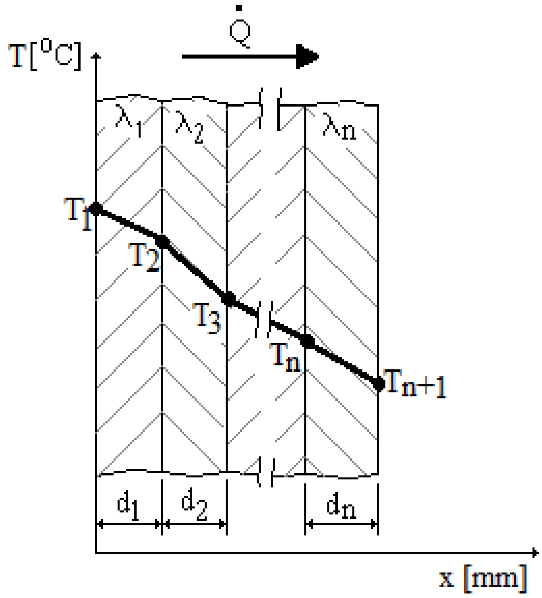

Figure 2. Temperature distribution in a flat wall with *n* layers crossed by a constant heat flux $\dot{Q}$ (steady state condition) [1]

Temperature difference in the first layer of d_1 thickness may be written as:

$$T_1 - T_2 = \frac{d_1}{\lambda_1 \cdot A} \dot{Q}_1 \tag{4}$$

in similar way, for the other layers results:

$$T_2 - T_3 = \frac{d_2}{\lambda_2 \cdot A}\dot{Q}_2 \quad (5)$$

....

$$T_n - T_{n+1} = \frac{d_n}{\lambda_n \cdot A}\dot{Q}_n \quad (6)$$

By adding equations (4) to (6), and taking into account equation (2) results the heat flow through the wall:

$$\dot{Q} = \frac{T_1 - T_{n+1}}{\sum_{i=1}^{n}\frac{d_i}{\lambda_i \cdot A}} \quad [W] \quad (7)$$

If the wall has one layer, relation (3) may be used for the heat flux determination.

Several experimental methods have been developed for thermal conductivity measurement, e.g.: steady-state techniques (heat flow plate [4-6], guarded hot plate [6], [7] and guarded hot box [8], [9]) or transient techniques (line heat source, plane heat source and disc heat source [6]).

The steady-state techniques require experimental conditions in which the temperature gradient does not change with time (i.e. constant heat flux as shown above in Figure 2), while the transient ones permits determinations when material's temperature varies in time.

This study is focused on the steady-state techniques which consists in measuring the temperature difference between two opposite sides of sample with certain thickness, knowing the heat flux value which passes through it. Therefore, thermal conductivity in a single layer wall may be deduced from relation 3 which represents the Fourier's Law of Heat Conduction for steady-state conditions [1], [2]:

$$\lambda = \dot{Q} \cdot d / A \cdot \Delta T \quad [W/m \cdot K] \quad (8)$$

where: $\Delta T = T_1 - T_2 \ [K]$ is the temperature difference between wall's two sides.

By the heat flow plate method it may be determined thermal conductivity of an unknown material plate (λ_x) with the aid of a reference material plate ("heat flow plate") with known thermal conductivity (λ_R) [2], [3].

The plates are placed one on top of another and crossed from underside by a constant heat flux (steady state condition):

$$\dot{Q}_x = \dot{Q}_R \rightarrow \lambda_x \cdot \Delta T_x \frac{A_x}{d_x} = \lambda_R \cdot \Delta T_R \frac{A_R}{d_R} \quad (9)$$

where subscript *x* denotes "unknown" and *R* denotes "reference".

As the two plates have same size ($A_x = A_R \ and \ d_x = d_R$), when the reference plate is placed on the bottom, results [1], [2]:

$$\lambda_x = \lambda_R \cdot \frac{\Delta T_R}{\Delta T_x} \quad [W/m \cdot K] \quad (10)$$

and when the reference plate is on top:

$$\lambda_x = \lambda_R \cdot \frac{\Delta T_x}{\Delta T_R} \quad [W/m \cdot K] \quad (11)$$

where: $\Delta T_R = (T_u - T_m)$ and $\Delta T_x = (T_m - T_o)$ are the temperature differences, with T_u – temperature on the underside (heated side); T_m – temperature in the middle, between the plates; T_o – temperature on the outside.

The aim of this paper is determining the thermal conductivity of Rohacell foam sample using the heat flow plate method, with polystyrene sample as the reference material. Two series of experiments were done: the first one using single layer wall of polystyrene, and the second one using a two-layer wall made of Rohacell foam (inside) and polystyrene (outside). So, the first experiment aims determining the thermal conductivity of the reference sample (polystyrene) by means of which the thermal conductivity of Rohacell sample is determined through the second experiment.

2. Experimental details

2.1. The experimental setup

Figure 3 shows a photograph of the experimental ensemble containing: transformer 2-12 V (1), calorimetric chamber with insulated housing (2), digital thermometer with 4 inputs (3) and laptop for data acquisition (4).

The calorimeter housing (2) is insulated but permits through several channels in the exterior walls, insertion of the thermocouple sensors. Inside it is placed a heater having a $80 \times 100\ mm$ surface, working by Joule effect. The heat flux magnitude may be adjusted by modifying the applied current and tension with the transformer (1). So, the heat flux is proportional with the electric power consumed by the heater and may be determined with relation:

$$\dot{Q} = U \cdot I \ [W] \tag{12}$$

where: $U[V]$ is tension and $I[A]$ is current applied to the heater.

For the first experiment, using a single layer wall of polystyrene, the parameters were: $U_1 = 10\,V$ and $I_1 = 1.44\,A$, giving a heat flux of $\dot{Q}_1 = 14.4\,W$. For the second experiment, using a two-layered wall of polystyrene and Rohacell foam, the parameters were: $U_2 = 6\,V$ and $I_2 = 0.87\,A$, giving a heat flux of $\dot{Q}_2 = 5.22\,W$.

A digital temperature indicator with 4 inputs (3) permits simultaneous displaying of temperature values which were recorded with the aid of a data acquisition system (4).

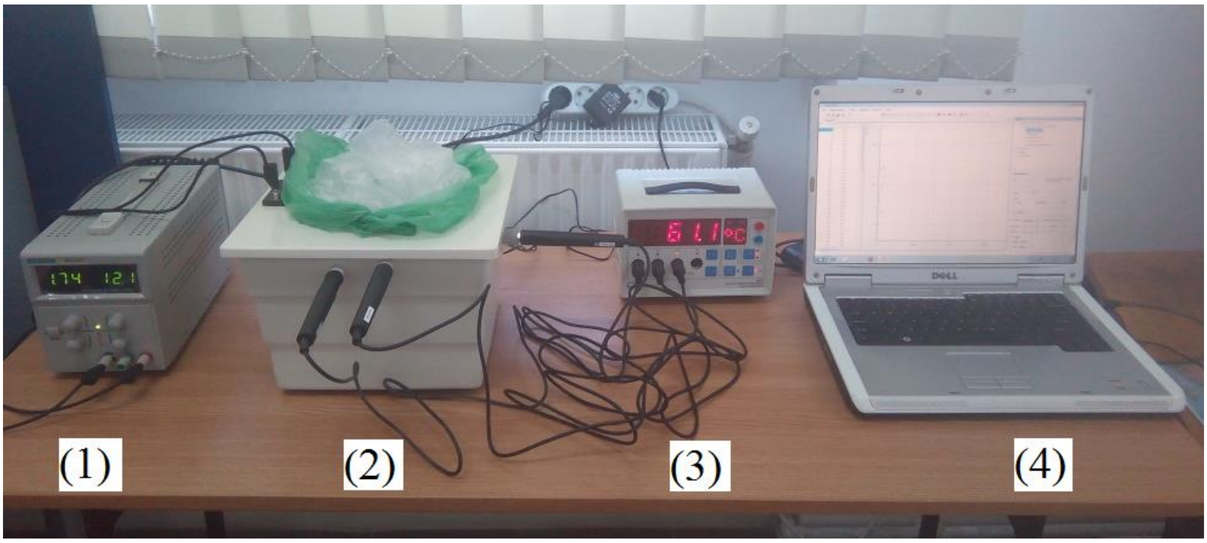

Figure 3. Photograph of experimental setup:
(1) Transformer; (2) Calorimetric chamber; (3) Digital temperature indicator; (4) Laptop

2.2. Temperature measurements

Thermocouples arrangement through the calorimetric chamber walls is shown in Figure 4, a) and b).

Three NiCr-Ni thermocouple sensors were used for temperature measurements as follows: $\mathbf{T_u}$ – on the underside, toward the interior of the calorimetric chamber (heated side); $\mathbf{T_m}$ – in the middle, between the two samples; $\mathbf{T_o}$ – outside sample surface, toward the exterior of the calorimetric chamber (Figure 4). When single sample was used, T_u represented the inside air temperature and T_m, underside sample temperature.

All samples have square surface of $150 \times 150\ mm$ and $10\ mm$ thickness and fit perfectly inside the calorimetric chamber in horizontal position (see Figure 4, b). Also, on both sides each sample has semi-circular grooves of $2\ mm$ diameter for inserting the thermocouples, so when a multilayered structure is formed, a perfect contact is permitted between samples (see Figure 4, b).

As the heat source is positioned under the samples, the heat flux is transmitted from bottom to top (see Figure 4, a). Also the temperature difference over the samples cross-sections is needed to be kept constant during measurements (steady state conditions), and so a constant outside temperature was maintained with the aid of ice, placed in a plastic bag covering the entire sample surface (Figure 3).

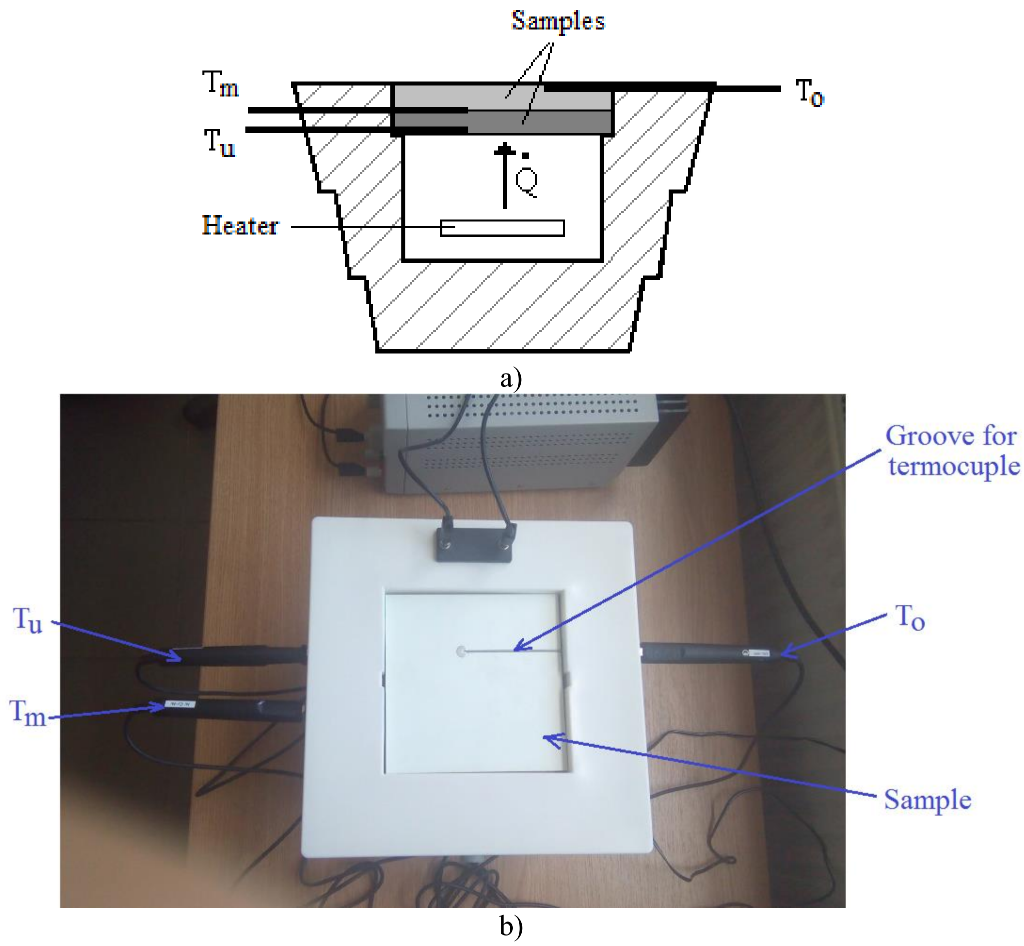

Figure 4. Thermocouples arrangement in the calorimetric chamber:
(a) schematic representation, side view and (b) photograph, top view

Temperature values were recorded only when the heating conditions achieved steady state. The procedure was as follows: the samples were positioned in the calorimetric chamber and the heat source was turned on. Further, both underside (T_u) and outside (T_o) temperatures were observed until the higher one started to rise and the lower one was maintained constant. It was recommended that the outside temperature (toward ice) T_o is kept constant in the range $-2°C$ and $+4°C$ [2].

3. Results and discussion

Temperature variations on both sides of polystyrene sample versus time, measured during the first experiment are presented in figure 5.

As one may observe, temperature T_o on the upper side of sample (outside, toward ice) was maintained in the range $+4.3°C$ and $+4.6°C$, so an average of $+4.45°C$ was considered for subsequent calculations. Temperature T_m on the underside of sample (toward the heater) rises from $19.5°C$ up to $34.2°C$ after heating during 50 minutes, when it's maintained constant. Also, temperature inside the calorimetric chamber T_u rises continuously from 35.5$°C$ up to about 84.5$°C$ after 50 minutes.

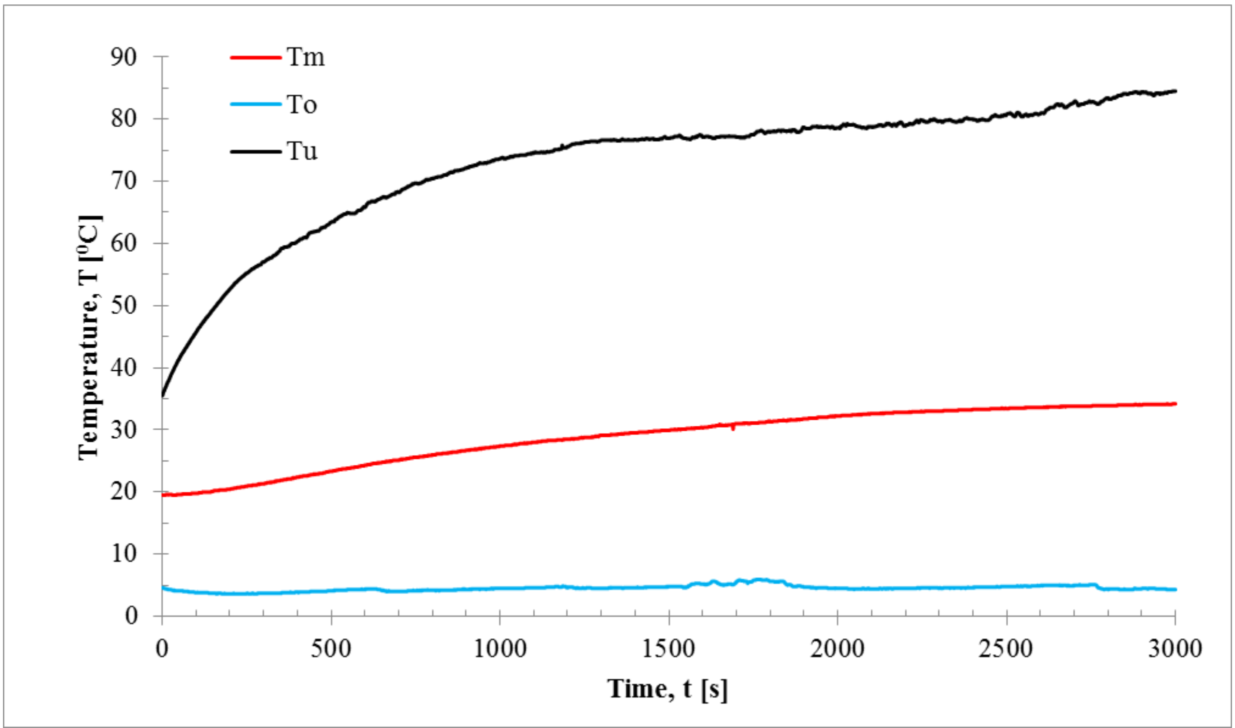

Figure 5. Temperature variation vs. time of polystyrene sample

For calculating the thermal conductivity of polystyrene sample is used formula (8) with the following quantities: $\dot{Q}_1 = 14.4\ W$, $d = 0.01\ m$, $A = 0.0225\ m^2$ and $\Delta T = T_m - T_o = 34.2 - 4.45 = 29.75°C$.

So, the calculated thermal conductivity of the reference material is: $\lambda_R = 0.2151\ \frac{W}{m \cdot K}$. This value is slightly bigger than that of $\lambda_R = 0.16 \div 0.18\ \frac{W}{m \cdot K}$ indicated by the polystyrene sample producer [2]. Also a bigger value is expected since the heat flux crossing the sample cross-section is not equal to the electric power consumption due to heat losses [2].

Temperature measurements during the second experiment when the polystyrene sample was placed on top of Rohacell sample are presented in Figure 6. Temperature T_o on the upper side of sample (outside, toward ice) was maintained in the range $+0.2°C$ and $+1.3°C$, so the average is of $+0.75°C$. After heating during 50 minutes the temperature between the samples is constant and is of $T_m = 10.7°C$, while temperature underside is $T_u = 41.7°C$.

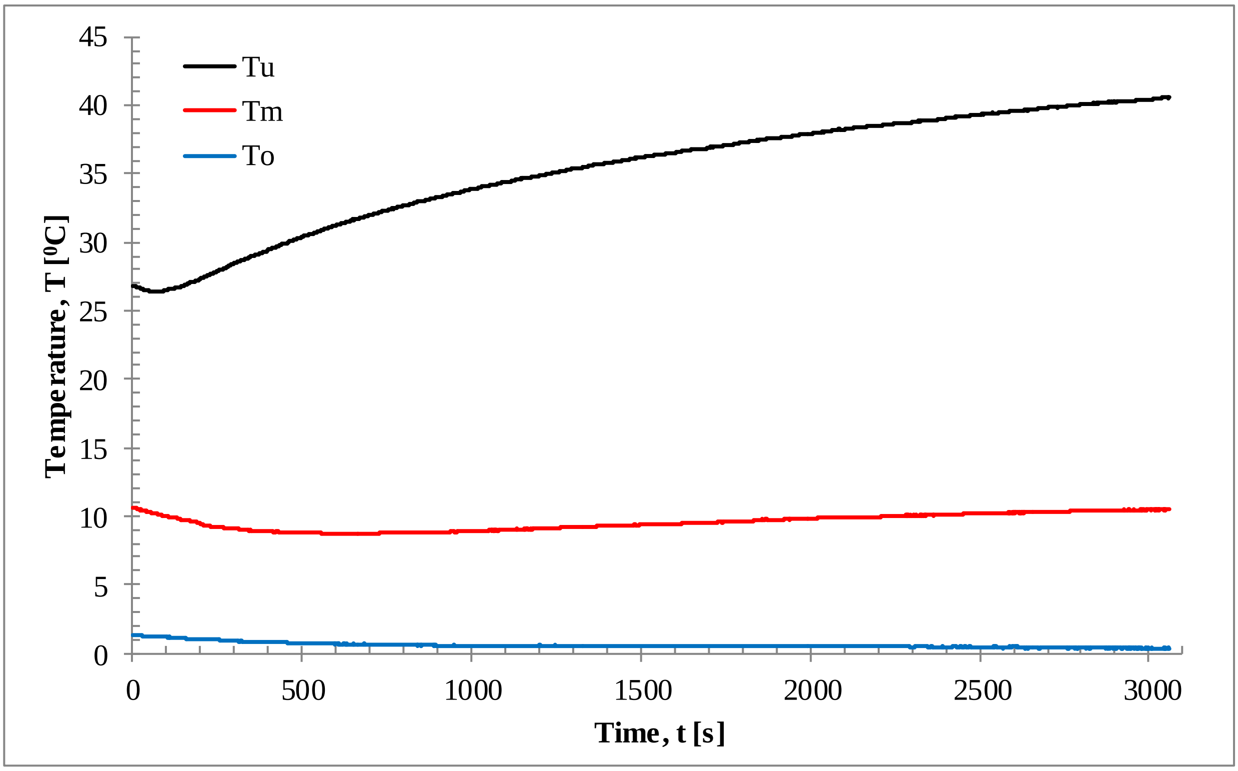

Figure 6. Temperature variation vs. time of polystirene and Rohacell samples

Thermal conductivity of Rohacell sample calculated with the formula (4) is: $\lambda_x = 0.2151\,\frac{10.7-0.75}{41.7-10.7} = 0.0690\ W/m\cdot K$. As attended and explained above, obtained value is slightly bigger than that recommended by the producer, i.e. $\lambda_x = 0.02 \div 0.05\ W/m\cdot K$ [2].

4. Conclusions

In order to determine thermal conductivity of Rohacell (insulating foam) sample by heat flow plate method, the polystyrene reference sample thermal conductivity was first established. So, from Fourier law of heat conduction thermal conductivity was determined knowing the heat flux which passes through the sample of certain dimensions and the experimentally determined temperature difference between the two opposite sides of the sample. Next, considering a two layered sample (polystyrene sample placed on the Rohacell one) and a constant heat flux which passes through both layers, thermal conductivity of Rohacell sample was determined in function of previous calculated polystyrene thermal conductivity (reference material). A small difference between determined values and the producer recommended ones is probably due to heat losses during experiments.

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