Thermal protective qualities of the combined material with reflective thermal insulation from aluminium foil

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Abstract. The article presents the results of experimental and theoretical studies of the thermal insulation qualities of foamed polyethylene with layers of reflective thermal insulation located in its thickness. Currently, the determination of the heat-protection properties of multilayer materials with reflective thermal insulation is carried out experimentally in laboratory conditions. Theoretical studies of the processes of heat transfer in the bulk of such multilayer materials and developed thermophysical model of the heat transfer process through this combined multilayer thermal insulation allowed to develop an engineering calculation method for determining the thermal resistance of multilayer polyethylene foam with reflective thermal insulation from aluminium foil, taking into account thermal conductivity and radiation. The obtained values of the thermal resistance of multilayer polyethylene of various thicknesses by calculation showed the convergence with experimental values. This indicates that reflective thermal insulation with a low emissivity of the surface, located in the thickness of the foamed polyethylene, increases its thermal performance qualities.

1. Introduction
The solution to the problem of energy conservation is impossible without effective heat-insulating materials. This group of insulation includes lightweight materials with density from 20 kg/m$^3$ to 40 kg/m$^3$. For them the porosity reaches 98%. Foamed polyethylene with a density of 26-32 kg/m$^3$ relates to these materials.

To increase its thermal protective properties, reflective thermal insulation, made of aluminum foil with a thickness of 10 microns, is placed between the layers of foamed polyethylene with a thickness of 3.5 - 4 mm. Foamed polyethylene layer and reflective thermal insulation are glued together with a thin layer of molten polyethylene. The result is multilayer material with a thickness of 8 mm to 32 mm. For evaluation its thermal insulation properties it is necessary to determine its thermal resistance taking into account that material has reflective insulation inside it.

It is known that the reflective thermal insulation increase heat-protection qualities of materials and constructions [1–6]. And decrease heat consumption of the buildings in cold and warm period of the year [7,8]. There are experimental investigation of heat protection properties of air gaps [1,9] and numerical estimation of air gaps [1,10–13] as well as experimental study of heat losses through constructions with reflective insulation [7,14–18]. Few theoretical studies have been conducted to evaluate the effectiveness of reflective thermal insulation from aluminum foil [19–23]. But, there no theoretical methods that allow us to estimate by calculations the heat-protection qualities of materials
using reflective thermal insulation like multilayer material made of foamed polyethylene with layers of reflective thermal insulation from aluminum foil located inside material.

Therefore, it is necessary to develop thermophysical model of heat transfer through material and work out the calculating method for theoretical determination of thermal resistance of the material, make experimental investigations of multilayer material with reflective insulation and establish the reliability of the developed calculation method.

2. Methods and results

2.1. Experimental investigations

To assess the heat-protective qualities of multilayer heat-insulating materials with reflective thermal insulation, a number of studies have been conducted. Samples with several layers of foamed polyethylene with reflective thermal insulation from aluminum foil located between them were used for this research. The thickness of the samples, depending on the number of layers, was 8, 16, 24, and 32 mm. The size of each sample was 250 × 250 mm. For each sample laboratory assistants determined dimensions, mass, and its density. Then, the samples were installed in a special device for determination heat protective properties and the thermal resistance of each sample and the equivalent thermal conductivity of the multilayer material were determined. All samples were tested at an average temperature of 25 °C and the temperature difference was 5 °C.

Table 1. Thermal performance indicators of samples of effective thermal insulation from foamed polyethylene and reflective thermal insulation from aluminium foil.

| Type of multilayer material                                                                 | Density, kg/m³ | Thermal resistance, m² °C/W | Equivalent thermal conductivity, W/ (m² °C) |
|--------------------------------------------------------------------------------------------|----------------|----------------------------|-------------------------------------------|
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminum foil located between them with total sample thickness 8 mm | 36.8           | 0.23                       | 0.035                                    |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminum foil located between them with total sample thickness 16 mm subsection | 37.2           | 0.41                       | 0.039                                    |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminum foil located between them with total sample thickness 24 mm | 35.5           | 0.66                       | 0.037                                    |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminum foil located between them with total sample thickness 32 mm | 37.2           | 0.91                       | 0.036                                    |

The results of determination of the thermal resistance and equivalent thermal conductivity of the samples of a multilayer material based on foamed polyethylene with thermal insulation from aluminum foil, located between layers of polyethylene, of different thicknesses are shown in table 1.

Conducted thermal engineering tests and studies allowed to receive the following data. Thus, the thermal resistance of a multilayer sample based on foamed polyethylene with reflective thermal insulation of aluminum foil 8 mm thick ranged from 0.22 to 0.24 W / (m² °C), of a multilayer sample
16 mm thick from 0.4 to 0.44 W / (m$^2$ °C), of a multilayer sample 24 mm thick from 0.58 to 0.73 W/(m$^2$ °C) and a multilayer sample with a thickness of 32 mm from 0.8 to 1.3 W/(m$^2$ °C).

2.2. Theoretical research

Based on the research [24] that the heat transfer occurs in the pores of building materials the same way as in the air. Considering that, the density of foamed polyethylene, as already noted, is very low and porosity reaches 98%, with a sufficient degree of accuracy, it is possible to assume that the thickness of foamed polyethylene with a thickness of 3.5-4.0 mm is that this thickness will correspond to the thickness of the air gap. Then the heat transfer conditions in the material based on foamed polyethylene located between the reflective insulation of aluminum foil can be considered as an air gap with plane-parallel surfaces. Its surfaces will be foamed polyethylene from the outside and reflective thermal insulation of aluminum foil.

To determine the emissivity of the surface of foamed polyethylene, we use experimental data on its degree of transmission and absorption with transparency windows are given. Since the reflectivity is 5-10%, the emissivity of foamed polyethylene can be taken as $C_{\text{f.pol}} = 5.24 \, \text{W/(m}^2 \text{°C)}$.

The flat surface of reflective thermal insulation made of aluminum foil is adjacent to the pores by the skeleton of the foam material and the air therein. Therefore, when determining the emissivity of these surfaces, we take this quantity by analogy with highly oxidized and rough surfaces ($1.15-1.78 \, \text{W/(m}^2 \text{°C)}$) and $0.57-1.72 \, \text{W/(m}^2 \text{°C)}$ equal to $C_{\text{ref}} = 1.3 \, \text{W/(m}^2 \text{°C)}$.

Heat transfer through the air gap is characterized by the Prandtl criterion $Pr$ and by the Grashof criterion $Gr$

$$Gr = g \cdot \beta \cdot \Delta t \cdot \delta^3 / \nu^2,$$

where $g$ – the acceleration of gravity, m/s$^2$; $\beta$ – the temperature coefficient of volume expansion, °C$^{-1}$; $\nu$ – kinematic viscosity of air, m$^2$/s; $\lambda$ – thermal conductivity of air, W/(m$^2$ °C).

When calculating the criterion $Gr$, the thickness of the air gap $\delta$ is taken as the determining size and the temperature is the average temperature between two surfaces $t = 0.5 \, (\tau_1 - \tau_2)$. For small values of the argument $Gr \cdot Pr < 1000$, the heat transfer in the air gap is due only to thermal conductivity.

When determining the value of the Grashof criterion, we take the following components: the coefficient of volume expansion $\beta = 1/275.5 \, \text{°C}^{-1}$; the thickness of the air gap $\delta = 3.5-4.0 \, \text{mm}$; temperature difference of 2.5 °C, kinematic viscosity $\nu = 15.53 \cdot 10^{-6} \, \text{m}^2/\text{s}$ and Prandtl criterion value is 0.703. Then we calculate the multiplication of the Grashof and Prandtl criteria

$$Gr \cdot Pr = \frac{9.81 \cdot 3.75 \cdot 10^{-2} \cdot 2.5}{275.5 \cdot 15.53 \cdot 10^{-6}} \cdot 0.703 = 16.12.$$

As the value $Gr \cdot Pr = 16.12 < 1000$, the heat transfer in the air gap occurs due only to the process of heat conductivity.

Therefore, the process of heat transfer in an element of effective thermal insulation with reflective thermal insulation with a thickness of 0.35 – 4.0 mm can be written as follows:

$$Q = \frac{\lambda_{\text{air}}}{\delta_{\text{air,g}}} \cdot (\tau_1 - \tau_2),$$

where $\lambda_{\text{air}}$ – mean air conductivity, W/m °C; $\delta_{\text{air,g}}$ - average air gap, m;

As there is a temperature difference on the surfaces then between the surfaces of the foamed polyethylene and reflective heat insulation of aluminum foil, as well as a thin transparent glued surface, heat is transferred also by radiation.
Then the total amount of heat $Q_o$ passing through the structure consisting of elements of effective thermal insulation with reflective thermal insulation from aluminium foil occurs by thermal conductivity $Q_{con}$ and radiation $Q_{rad}$:

$$Q_o = Q_{con} + Q_{rad}. \quad (4)$$

For an element of effective thermal insulation with a thickness of $\delta = 8 \text{ mm}$, which consists of two air layers with a thickness of $\delta_1$ and $\delta_2$ each $4 \text{ mm}$ thick and one layer of reflective thermal insulation made of aluminium foil $10 \text{ microns}$ thick. The first layer has thermal conductivity $\lambda_1$ and the other one $\lambda_2$.

The heat flow $Q_{con}$ through this element is equal to

$$Q_{con} = \frac{\tau_1 - \tau_2}{\delta_1 + \delta_2} \frac{1}{\lambda_1 + \frac{1}{\lambda_2}}, \quad (5)$$

where $\tau_1, \tau_2$ - temperature on the outer surfaces of the effective thermal insulation element, $^0\text{C}$.

The value of the heat flow passing by radiation $Q_{rad}$ through the layers of effective thermal insulation element with two air layers from and one reflective thermal insulation layer is equal

$$Q_{rad} = \left(\frac{T_1}{C_f pol} - \frac{T_2}{C_0}\right) + \left(\frac{T_1}{C_f pol} - \frac{T_2}{C_0}\right), \quad (6)$$

where $T_1, T_2$ – absolute value of temperature on the outer surfaces of the effective thermal insulation element, $^{0}\text{K}$.

As a result, the thermal resistance of the effective thermal insulation element can be calculated by the formula

$$R = \frac{\tau_1 - \tau_2}{Q_{con} + Q_{rad}}. \quad (7)$$

3. Results and Discussion

For an element of effective thermal insulation with reflective thermal insulation of aluminium foil with a thickness of $8 \text{ mm}$, we will calculate the thermal resistance at a temperature difference $\tau_1 = 27.5 \ ^\circ\text{C}$ and $\tau_2 = 22.5 \ ^\circ\text{C}$. Heat transfer by thermal conductivity will be found by the formula (5):

$$Q_{con} = \frac{27.5 - 22.5}{0.00375 + 0.00375} = 17.42 \frac{W}{m^2} \quad (8)$$

Heat transfer by radiation is calculated by the formula (6):
The thermal resistance of an effective thermal insulation element with reflective thermal insulation of aluminum foil 8 mm thick is:

\[ R = \frac{27.5 - 22.5}{17.42 + 3.36} = 0.24 \text{ m}^2 \cdot \text{°C}/\text{W} \]  

(10)

In a similar way, using the proposed calculation method, we calculate the thermal resistance of samples consisting of:
- two elements of effective thermal insulation with reflective thermal insulation of aluminium foil 16 mm thick;
- three elements of effective thermal insulation with reflective thermal insulation of aluminium foil 24 mm thick;
- four elements of effective thermal insulation with reflective thermal insulation of aluminium foil 32 mm thick.

The calculation results are presented in table 2.

**Table 2.** Thermal resistance of samples obtained by calculation using the proposed method

| Type of multilayer material | Thermal resistance, m²·°C/W |
|-----------------------------|-----------------------------|
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminium foil located between them with total sample thickness 8 mm | 0.24 |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminium foil located between them with total sample thickness 16 mm | 0.47 |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminium foil located between them with total sample thickness 24 mm | 0.71 |
| Multilayer material made of foamed polyethylene with reflective thermal insulation from aluminium foil located between them with total sample thickness 32 mm | 0.96 |

4. Conclusion

Thus, according to the results of the studies, the following conclusions can be made:

1. The calculation method has been developed for determining the thermal conductivity of multilayer material – foamed polyethylene with reflective thermal insulation from aluminum foil – taking into account the transfer of heat by conductivity and radiation.

2. It is scientifically substantiated in the study that calculations of the thermal resistance of multilayer polyethylene foam with layers of reflective insulation from aluminum foil, can be done regardless of the convective component of heat transfer.

3. Comparison of the results of calculating the thermal resistance of multilayer polyethylene foam with reflective layers of aluminum foil according to a new developed method with the results of laboratory experimental studies showed good convergence. This allows to recommend this method for use in the practice of designing building envelope.
The studies and calculations showed that multilayer polyethylene foam with layers of reflective thermal insulation is an effective thermal insulation material.

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