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The empirical definition of total emissivity of modern super-thin liquid composite thermal insulators

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Abstract. Modern world trends in the field of energy and mineral resources preservation policy involves the need for a more cost-efficient use of the Earth's natural resources, including in the field of construction industry. Using insulation modern materials would largely solve this problem. The acceptability appraisal of various advanced heat-insulating blankets is a crucial task, which requires experimental verification of total emissivity empirical definition of modern super-thin liquid composite thermal insulators and their real value definition. Method of investigation is as follows: an empirical definition of blankets emissivity using the proposed laboratory equipment, which comprises a system of "gray" bodies, thermocouple probe and a source of continuous heat flux. Total emissivity of modern super-thin liquid composite thermal insulators is experimentally determined. It amounted $\varepsilon = 0.89$ for sample # 1, and $\varepsilon = 0.87$ for sample # 2 at a temperature of 35-65 °C. It was found that the actual emissivity of the samples was higher than it had been declared.

1. Introduction

The current global trends in policy of energy saving and resource economy demand different material-intensive productions (including construction industry) to use resources in efficient way. The use of modern heat insulating materials allows to solve the problem of sustainable use of the Earth's natural resources.

The ultrathin liquid composite insulating coatings (hereinafter insulating paints) of new generation have recently appeared on the market. They are presented by mascoat, tsmceramic, thermalcoat, Isollat, Astratek, Alfatek, Teplokott, Corund, etc. designed for thermal insulation of building faces and building structures as well as heat transfer pipes.

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The manufacturers of these paints assure they possess exceptional heat insulating properties. One layer of such paint with thickness of 1 to 3 mm spread on engineering pipes can successfully replace well-known mineral wool heat insulators with thickness of few centimeters [1, 2]. At the same time, some authors proved in their works [3, 4] that the real values of the thermal conductivity and emissivity factor of these materials differ greatly from published data of manufactures. Studies undertaken in 2015 [5, 6] had shown that the stated thermal conductivity ratio of two selected liquid insulating paints of known brands was not confirmed.

Also manufacturers often provide data on special heat-insulating properties of paints. They claim the capacity covered with the specified coatings takes on the properties of "thermos".

In the present context the urgent objective is to determine experimentally the total emissivity as a key indicator of the body's ability to reflect heat radiation for modern liquid insulating coatings. In this connection, we decided to carry out the experiment on determination of the total emissivity of some liquid insulating coatings to find their true value.

2. Review of existing methods

While planning an experiment to determine the total emissivity of liquid insulating coatings, the review of existing methods on the stated research topic was carried out [7-10]. We also considered the works of foreign [11-18] and Russian authors [19, 20], who conducted research on similar topics. The analysis of the existing methods of experimental determination of the total emissivity of various materials allows to make the following conclusions:

1. Typically, the stated methods are complicated and require a large amount of expensive equipment, or the presence of vacuum in the system.

2. A number of methods are not designed to conduct research ε for ultrathin liquid composite insulating coatings.

3. In some methods heat condition can cause internal deformation or heat damage of insulating paints, as they are not designed to work at temperatures above 200 °C. Furthermore, the change of heat condition can result in changes of coatings' thermal properties.

4. There are restrictions on the samples geometry.

5. The amount of heat consumed for test samples heating requires accurate records.

3. Theory of measurement

Based on the results of the analysis of the existing research methods, we decided to develop our own algorithm for calculation of ε for the stated insulating coatings. It would allow to perform measurement with satisfactory accuracy taking into account the physical properties of the samples.

Stefan-Boltzmann law proposes the expression for the calculation of gray body self-radiation flux density (emissivity):

$$E = \varepsilon \cdot E_0 = \varepsilon \cdot \sigma_0 \cdot T^4 = \varepsilon \cdot c_0 \cdot \left(\frac{T}{100}\right)^2 = c \cdot \left(\frac{T}{100}\right)^4 \tag{1}$$

where $c = \varepsilon \cdot c_0$ is the coefficient of gray body emissivity, W/(m$^2\cdot K^4$); T – temperature of body, K.

In cases where we observe a radiation heat transfer in closed system consisting of two gray bodies separated by diathermancy environment (Figure 1), the resulting heat radiation flux should be calculated as follows:

$$Q_{w,1} = \varepsilon_c \cdot \sigma_0 \left(T_2^4 - T_1^4\right)\varphi_{21} \cdot F_2 \qquad \text{or} \qquad Q_{w,1} = c_c\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4\right] \cdot \varphi_{21} F_2$$
$$Q_{w,2} = \varepsilon_c \cdot \sigma_0 \left(T_1^4 - T_2^4\right)\varphi_{12} \cdot F_1 \qquad\qquad Q_{w,2} = c_c\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \cdot \varphi_{12} \cdot F_1 \quad (2)$$

where ε_c is the reduced degree of blackness in the system of two bodies; T_1 and T_2, F_1 and F_2 are absolute temperature and heat transfer area of the first and second body; φ_{12} and φ_{21} are radiation angular coefficients, which show the part of hemispherical radiation energy falling from one body to another.

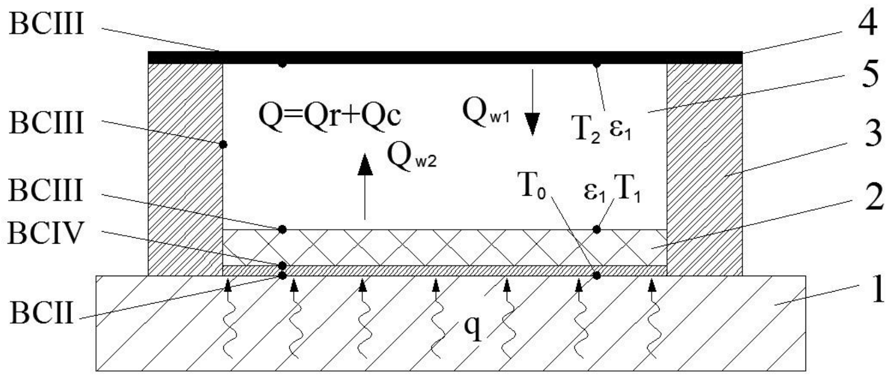


Figure 1. The proposed measurement scheme: 1 is the source of steady heat flow; 2 is the layer coating of the test applied on a copper plate with a known thickness and conductivity coefficient thermal conductivity; 3 is the insulator (polystyrene); 4 is the layer of material with a certain degree of blackness; 5 is the diathermancy environment (air)

For a closed system (figure 1) from the law of conservation of energy it follows the equality:

$$Q_{w,2} = -Q_{w,1}. \quad (4)$$

Taking into account that the heat source (1, figure 1) is in steady condition, we can calculate heat transfer rate in the present system by the law. The boundary conditions of the 2nd kind (BCII) between a layer of copper plate coated with insulated paint layer are formed.

$$q_u = \frac{\Delta Tu}{\dfrac{d_u}{\lambda_{effu}} - 2R_L}, \quad (5)$$

where d_u is the thickness of the sample during the test, m, ΔT_u is the temperature difference on the surface of copper plate and sample, °C ($\Delta T_u = T_0 - T_1$); R_L is the thermal resistance in copper plate coated with sample paint layer (m^2·°C)/W. Such change is correct and does not contradict the theory of thermal process study [20].

As the air layer is absent at the border of the copper plate and coated paint, we can accept the boundary conditions of the 4th kind (BC IV). We assume that all heat goes into the paint layer.

We can accept boundary conditions of the 3rd kind (BC III) at the boundaries of the coating surfaces of reference material and heat insulator. In this case, the heat flow from the coating to the reference sample is the sum of heat transferred by convection and radiation heat presented as $Q_{w,2} = Q_R + Q_C$. As the body system (figure 1) is closed, we consider there is no convection due to the "side" horizontal movements of air. In free convection the convective coefficient value (to calculate the appropriate amount of heat *Qc*) can be calculated by Nusselt number *Nu*.

Furthermore, we consider that the entire heat flow is transferred from the sample 2 to the reference material 4 (figure 1) and areas of the stated objects are equal.

Based on our assumptions, the reduced degree of blackness in the system of bodies shall be calculated by the law

$$\varepsilon_{\text{пр}} = \frac{q}{\sigma_0 (T_1^4 - T_2^4)} \tag{6}$$

Consequently, the total emissivity of insulating paint shall be calculated by the expression

$$\varepsilon_{\text{пр}} = \frac{1}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)} \quad \text{from here} \quad \varepsilon_1 = \frac{1}{\frac{1}{\varepsilon_{\text{пр}}} - \frac{1}{\varepsilon_2} + 1}. \tag{7}$$

where ε_1 and ε_2 are the total emissivity of the first and the second bodies.

The present method demands the heat conductivity coefficient of the layer of tested insulating paint to perform the experiment.

4. Description of the experiment

We considered a list of the most well-known manufacturers of liquid insulating coatings to perform the experiment.

We selected two samples of liquid insulators for our study. These are «Izolatt» and «Teplomett» (hereinafter Sample #1 and Sample #2).

We determined in advance the heat conductivity coefficient values of samples of insulating coatings [5, 6]. The heat conductivity of copper plate with thickness δ = 0.5 mm, equals to λ = 384 W / (m·°C). The ambient room temperature during the experiment was equal to t = 24 °C, the relative humidity is equal to φ = 48%.

Check measurements were made to regulate meter readings during its "warming up" and heat flow transfer into steady condition (heat flow flattening). However, we recorded the dynamics of meter readings of 3 thermocouple sensors for half an hour with 5 minutes' intervals of measurement.

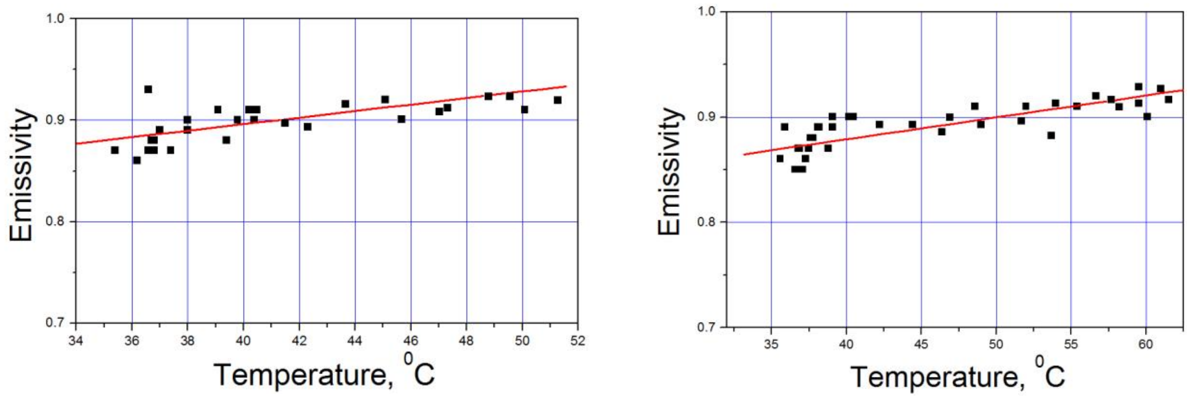
Calibration works were performed to test the adequacy of the developed device measuring total emissivity of insulating paints. The radiometer sensor was placed on the surface of tested coating to show the heat flow. The discrepancy does not exceed 5%.

The obtained data suggest that the error of this method is within tolerable limits. It proves the chosen scheme is correct.

5. Analysis of the results of the experiment

Sample #1 and sample #2 were tested in various temperature conditions at various heat flow to analyze the dynamics of the total emissivity, depending on the temperature of the paint sample. The obtained results are shown in figure 2. As can be seen from figure 2, the average value of the blackness degree increases as paint sample temperature also increases. This observation corresponds satisfactorily with similar results presented in [19, 20].

The experiment shows that the sample #1 has average emissivity ε = 0.89, the sample #2 has average emissivity ε = 0.87 within the temperature range from 35÷65 °C. A further increase of temperature is inappropriate, since test samples were used for painting pipelines of heating systems where the temperature conditions are limited to 100 °C. The obtained results correspond satisfactorily with experimental data obtained by other authors [6].



a) b)

Figure 2. Experimental results on determination of paint sample emissivity: a) sample #1; b) sample #2

6. Conclusion

As a result, we experimentally determined the total emissivity (ε) of ultrathin liquid composite insulating coatings. It makes ε = 0.89 for the "Sample #1» and ε = 0.87 for the "Sample #2» within the temperature range from 35÷65 °C. Comparing the results with the available data we can conclude that the degree of blackness of the tested materials is comparable by its properties to asbestos paper (ε = 0.93) or gypsum (ε = 0.9). Also the obtained emissivity is very close to white enamel varnish spread on metal sheet (ε = 0.906). At the same time, the statements of manufactures of insulating paints, assuring they possess high reflectance, are overdone.

The authors of the present article assume the discrepancy between experimental and stated characteristics is possible due to the fact, that as the selected paint samples are filled with gas but not bubble microspheres. Some manufacturers indicate this difference in microspheres, because their thermal properties are not the same.

Despite this, such liquid insulating coatings are of great interest to builders. They allow to warm objects of complex geometric shapes (valves, complex nodes, etc.), that in some cases makes them irreplaceable.

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