Experimental study of thermophysical properties of thin-film coatings based on hollow microspheres

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Abstract. The paper describes results of an experimental study of thermal properties of energy-efficient thin-film coatings based on hollow glass microspheres MS-V2L in a styrene acrylic dispersion binder «Akrilan 101». A value of energy-efficient paint thermal conductivity depending on its composition and temperature and a value of the thermal diffusivity of the paint were experimentally determined. Data on the energy saving paint density and specific heat capacity were also obtained.

1. Introduction

Reduction of heat loss is an urgent task to improve energy efficiency of heat energy generating, transmission and consumption facilities. To reduce heat loss various insulating materials are used, which must have a number of positive characteristics, i.e. low thermal conductivity, low moisture absorption, low corrosive activity and mechanical strength [1,2,3]. At present, in order to save energy thin film coatings consisting of hollow microspheres arranged in a binder material are widely used, which have physical properties of a paint, but with a lower thermal conductivity [4,5]. The data known in the literature on the thermal properties of energy-efficient thin-film coatings are highly contradictory and differ by at least an order of magnitude [6,7]. Therefore, the study of the thermal properties of energy-efficient thin-film coatings (energy saving paints) is a vital task, the solution of which will improve the accuracy of the thermal calculations.

2. Investigation of thermophysical properties of energy-saving paint

2.1. Determination of the thermal conductivity coefficient

An estimate of the thermal conductivity coefficient was made experimentally for energy-saving paint samples with a mass content of microspheres of 8%, 25% and 32.6% in acrylic binder and for a sample of acrylic coating with no added microspheres. The thickness of the test samples was as follows: 1.5 mm for a binder with added microspheres and 1 mm for pure acrylic. The thermal conductivity coefficient of the samples was determined on a laboratory bench by the method of a cylindrical layer in the regular regime of thermal conductivity [8,9].

Laboratory bench is a thick-walled steel cylinder with an outer diameter of 245 mm and 630 mm in length, inside which there are the two electrical heaters connected to the electrical network via an autotransformer. To ensure uniform heat transfer on the surface of the working zone and exclude convective currents near electric heaters, the inner cavity of the steel cylinder was filled with claydite. To reduce heat losses, the side and end surfaces of the cylinder were covered with thermal insulation.
The surface temperature of the cylinder was measured by thermocouples located at 8 points along the circumference of the laboratory bench working zone. Energy-saving paint was applied to a thin plate of mild steel with a width of 50 mm and a thickness of 0.2 mm. The steel plate with the applied energy-saving paint was placed on the working zone of the laboratory bench. The temperature of the inner surface of the layer of the test sample is equal to the average surface temperature of the cylinder, which was found from the thermocouples readings of the working zone. The temperature of the outer layer of the test sample was determined by means of 4 contact thermocouples applied to the test sample. The density of the heat flow passing through the layer of energy-saving paint was determined by the ITP-MG4.03/X(I) "Potok" instrument with a relative error of measurement of ±6% and automatic data fixation function. The temperature of the internal and external surfaces of the energy-saving paint was determined using type "T" thermocouples and a secondary device ADAM-4000 with an error of measurement of ±1°C. The power of the electric heaters was regulated by an autotransformer in the range from 5V to 65V in steps of 15 volts. The stationary mode of thermal conductivity was established in 24 hours after the heating start. The readings of the measuring instruments were recorded in automatic mode with an interval of 1 hour.

A series of experiments was performed at different values of the heat flux passing through the samples under study. The average value of the thermal conductivity coefficient in the temperature range of 20 to 100°C was as follows: ~0.028 W/(m·K) for the binder (acrylic); ~0.025 W/(m·K) at 8% content of microspheres in energy-saving paint by weight; ~0.022 W/(m·K) at 25% microsphere content; ~0.019 W/(m·K) at 32.6% content of microspheres. The thermal conductivity coefficient of the energy-saving paint in the temperature range of 20 to 100°C with accuracy better than 12% can be approximated by the formula, W/(m·K):

\[
\lambda = \frac{2.24}{10^4} T - \left( \frac{2.44}{10^6} T + \frac{1.27}{10^5} \right) C + \frac{1.61}{10^5}
\]  

(1)

where C is the mass concentration of microspheres,%; T is the temperature, °C.

The experimental values of the thermal conductivity coefficient of energy-saving paint depending on the temperature and the composition are shown in figure 1 and figure 2.

**Figure 1.** Dependence of the thermal conductivity coefficient of energy-saving paint (\(\lambda\), W/m·K) on temperature (\(T\), °C) at mass concentration of microspheres in the binder: 1 - 0%; 2 - 8%; 3 - 25%; 4 - 32.6%; Solid lines - calculation by formula (1).
2.2. Determination of thermal diffusivity

The coefficient of thermal diffusivity of energy-saving paint was found by the regular regime method [10,11] using a modified air "a-calorimeter", in which the test sample was asymmetrically heated longitudinally by the flow of hot air around it. The air flow velocity was chosen so that the condition of the thermally thick body Bi> 100 was satisfied for the heated sample. The test sample was a parallelepiped with dimensions of 45x60x75 mm, made of energy-saving paint with a mass content of microspheres of ~ 32.6% in an acrylic binder. The sample, insulated with mineral wool on all sides except the working surface, was blown by a stream of hot air from a blower with a built-in heater. Using the blower control unit, it was possible to change the velocity and temperature of the air flow in the interval of 0 to 20 m/s and 20 to 120°C, respectively. During the experiments, the velocity and temperature of the air flow were measured using a MES-200A meteorological meter with a velocity measurement error of ± 1.5 m/s and a temperature measurement error of ±0.5°C. The temperature of the sample at three points (in the center, on the upper and lower faces) was determined using type "T" thermocouples and a secondary device ADAM-4000 with an error of measurement of ±1°C. A series of experiments was performed at different air temperatures. It was found that the thermal diffusivity of the energy-saving paint was in the range of 2.7·10⁻⁸ to 3.1·10⁻⁸ m²/s.

2.3. Determination of density

The density of the energy-saving paint was determined by weighing the test sample on an electronic scale SHIMADZU UW-420H with a mass measurement error of 0.001 g. The test sample was made by successively applying layers of paint ~ 2 mm thick in a cylindrical form with a volume of 383.5 ml. After applying each layer of paint, the sample was dried during the day. Also, the form was weighed with energy-saving paint without drying it. The density of the energy-saving paint was determined by the well-known expression, kg/m³:

\[ \rho = \frac{m}{V} \]  

(2)

where m is the mass of the sample, kg; V is the sample volume, m³.

The dry energy-saving paint density is 245.23 kg/m³, and the same of wet paint is 525.76 kg/m³.
2.4. Calculation of the specific heat capacity

Knowing the experimental data on the thermal conductivity, thermal diffusivity and density of the energy-saving paint, the mean specific mass heat capacity can be found by formula (3), J/(kg·K):

\[ c = \frac{\lambda}{a \cdot \rho} \]  

(3)

where \( \lambda \) is the coefficient of thermal conductivity of energy-saving paint, W/(m·K); \( a \) is the coefficient of thermal diffusivity, m\(^2\)/s; \( \rho \) is the energy-saving paint density, kg/m\(^3\).

The specific mass heat capacity of energy-saving paint with a mass content of microspheres of 32.6% is \(- 2670\) J/(kg·K).

3. Conclusions

New data on the value of the thermal conductivity coefficient of energy-saving paint, depending on its composition and temperature were obtained, also the value of the coefficient of thermal diffusivity was estimated. The density of energy-saving paint and its specific heat capacity were determined. The new data on the thermophysical properties of thin-film coatings (energy-saving paints) will increase the accuracy of heat transfer analysis of multi-layer enclosing structures.

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