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RADIANT HEAT CONDUCTION IN THE HEAT INSULATING LIGHTWEIGHT MATERIALS

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ABSTRACT

An evaluation of scattering and absorbing abilities of light heat insulating materials in the IR spectrum range is given. The generalized form of Fourier equation application to such materials with taking into account radiant environment heat conduction is shown. Convection-less measurements of material specimen thermal resistance of different thickness are performed. Theoretical substantiations and ideas concerning heat-protective material properties are reliably confirmed. Exact values of total material heat conduction are obtained, and values of material radiant heat conduction, as well as of thermal radiation penetration depth into them are estimated.

Keywords: thermal radiation, environment scattering and absorption, Kirchhoff's law, radiant heat conduction, Fourier equation, radiation-conductive heat transport, material thermal resistance

Tasks of diffuse radiation scattering are met in optics relatively seldom and, therefore, are rather complex. Nevertheless, sometimes they should be solved when influence of diffuse radiation is significant. In this regard, this work is dedicated to distribution of thermal radiation in an incidentally scattering environment.

As it is known, there are three mechanisms of heat transfer: conduction, convection and thermal radiation. The latter only makes an essential contribution to heat transport in transparent environment, which under nature conditions is air only. The conductive component contribution is essential at a small air layer thickness, about several millimetres. In the case of the bigger air thickness, the radiation component dominates over the conductive.

Convection contribution to a significant extent depends on geometry of the system transferring heat and is extremely complex to be analysed. So, when measuring, we tried to make it insignificant.

Diffuse scattering occurs on environment random non-uniformities. If non-uniformity typical size is less than radiation wavelength, then scattering is frequency-dependent; the lower wavelength is, the scattering is more. For this reason namely, sunlight scattering on microscopic dust particles in atmosphere within the short-wave spectrum part is more intensive, and we see the blue sky.

And on the contrary, if non-uniformity size as in the case of drops or snowflakes in clouds is much more than radiation wavelength, scattering intensity does not depend on frequency, and we see white clouds respectively.

Modern light heat insulating materials have on the average almost isotropic structure, and for thermal radiation they can be considered a random scattering environment. There are two main types of such materials: foamed and fibrous. In the either case, bubble typical size (of about 100 µm) and fibre diameter (~ 20 µm) are more than the radiation wavelength (~ 10 µm). For our measurements, specimens were selected as follows:

- Foamed polyethylene of 2.2 mm thickness of 16.5 kg/m^3 density, of (0.1–0.3) mm bubble size and with the volume portion filled with polyethylene of 1.74 %;
- Foamed polystyrene (foamed plastics) of 5.0 mm thickness of 32 kg/m^3 density, 0.05–

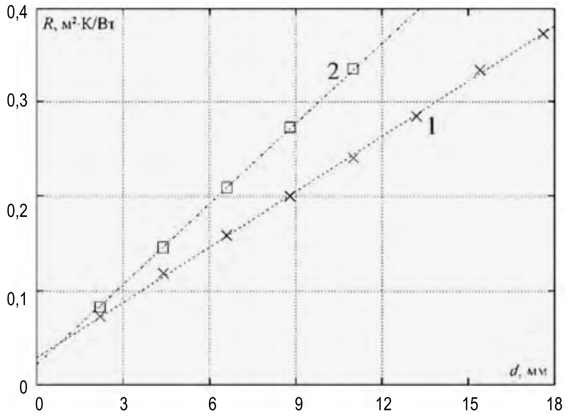

Fig.1. Thermal resistance dependences of foamed polyethylene specimen piles on thickness of the pile: 1 – without foil, 2 – for the pile interlaid from above, from below and between all layers with specula aluminium foil

0.15 mm bubble size and with the volume portion filled with polystyrene of 2.56 %;

- Nonwoven material manufactured under *Hollowfibre* brand of 6.0 mm thickness of 11.7 kg/m^3 density made of poliethylene terephtalate hollow fibres of 32 μ thickness and with the volume portion filled with it of 0.9 %.

As non-uniformity dimensions of all specimens are much more than the wavelength, thermal radiation scattering in them should be frequency-independent.

Though polyethylene, polystyrene and poliethylene terephtalate have a number of absorption lines, their transparency in the IR range is comparatively high (average penetration depth is about 1 mm) [1]. As portion of porous materials space filled with solid substance is (1–2)% only, their thickness equivalent by absorption should be (5–10) cm. From the visual evaluation of porous materials characteristics, it is easy to understand that radiation scattering occurs at a "thickness" of about 5 mm, i.e. much lesser than 5 cm. In the case of a simultaneous presence of absorption and scattering, penetration depth of radiation is determined by two parameters: scattering factor v and absorption factor χ [2]:

$$a = (v + \chi)^{-1}.$$

The scattering factor v of the selected materials is obviously much more than the absorption factor χ, and respectively, one should consider that a does not practically depend on the wavelength within the IR range, and each material can be considered as a diffuse grey environment.

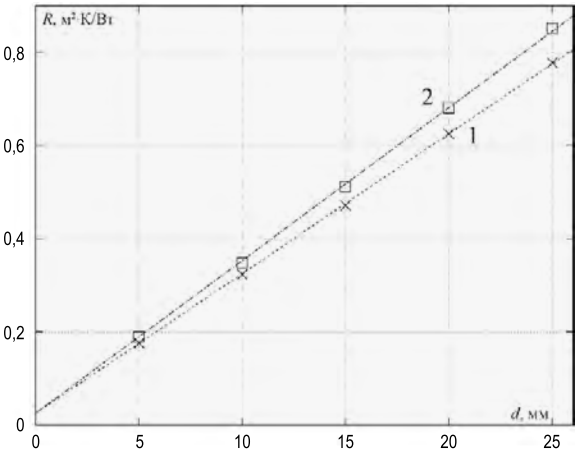

Fig.2. Thermal resistance dependences of foamed polystyrene specimen piles on thickness of the pile: 1 – without foil, 2 – for the pile interlaid from above, from below and between all layers with specula aluminium foil

Dynamics of radiant heat distribution in a diffuse grey environment is considered according to the Kirchhoff's law for thermal radiation. The radiation component of heat transport within such environment is characterised by its radiant heat conduction [3]

$$L = 16 \cdot \sigma \cdot T^{3} \cdot a/3, \tag{1}$$

where σ is the Stefan-Boltzmann constant and T is the absolute temperature. If to consider that optical environment thickness is big at the distances from the boundaries significantly greater than thermal radiation penetration depths, radiant flux density Φ is directly proportional to temperature gradient ∇T, similar to the Fourier equation for conductive heat transfer. Therefore, in case of radiation-and-conductive heat transport in such materials, Fourier equation in a generalised configuration should be met

$$\Phi = -(L + D)\nabla T, \tag{2}$$

where D is the environment conductive heat transfer.

Respectively thermal resistance R of a material layer should be proportional to its thickness d:

$$R = \Delta T/\Phi = d/(L + D). \tag{3}$$

Using an installation developed for convectionless measurements of thermal permeability [4] "in plane-parallel geometry", dependences of specimen pile thermal resistance on material layer number (thickness) have been determined. The results are presented in Figs. 1–3 (dependence #1). At the same place, to demonstrate presence of radiant heat conduction, thermal resistance dependences of the same specimen piles are given with the difference that between the layers, the thin aluminium foil (10 µ) is laid from above and from below the piles and between all layers (dependence #2).

A feature of this installation is that operation plain elements, between which a temperature difference is created, are manufactured of the transparent within the IR spectrum range single-crystal silicon. This significantly weakens surface effects, because of which environment boundaries influence is almost imperceptible.

The fact that thermal resistance dependence on environment thickness for all materials is close to a straight line with a high precision (of about 1 %), confirms our ideas about properties of the studied materials with a high reliability (3). Approximation of radiant heat conduction (2) is quite applicable to such environments. A value reciprocal of inclination coefficient of straight lines, is equal to environment total heat conduction $L + D$. Its correspondent values for foamed polyethylene, polystyrene and for Hollowfiber are as follows: – 0.0514 ± 0.0003, 0.0333 ± 0.0005 and 0.0610 ± 0.0005 W / m · K.

Aluminium foil almost completely (for 99 %) reflects thermal radiation. And with such a small thickness, its contribution to heat conductive transport is negligible. Respectively a result of foil addition between material layer should only be reduction of the heat transport radiation component. Differences of the dependences for specimens with foil and without foil (Fig. 1–3) show that contribution of the radiation component is comparable with contribution of the conductive. As well as in the event with specimens without foil, in the second case several specimens with identical thermal resistance were installed sequentially. Therefore diagrammes of thermal resistance dependences on pile thickness with foil were straight lines too. In this case, the diagramme inclination increased, and “heat conduction” decreased. Total heat conduction of materials with foil is 0.0353 ± 0.0003 for foamed polyethylene, 0.0305 ± 0.0005 for foamed polystyrene and 0.0490 ± 0.0005 W/m · K for Hollofiber. The less distance between the foil screens is, the more essential reduction of heat transport radiation component should be. Therefore for foamed polyethylene of 2.2 mm thickness, relative “heat conduction” change (31.3 %) was significantly greater than for 5 mm thickness foamed polystyrene (8.4 %) and for 6 mm thickness Hollofiber (19.7 %).

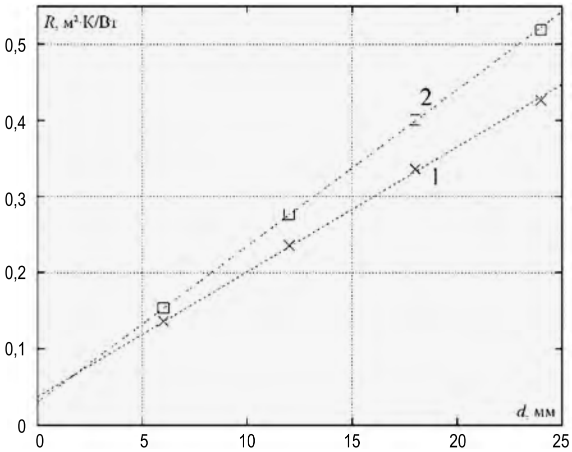

Fig.3. Thermal resistance dependences of foamed *Hollowfibre* specimen piles on thickness of the pile: 1 – without foil, 2 – for the pile interlaid from above, from below and between all layers with specula aluminium foil

Conductive heat transfer of polymers is comparatevely low. Therefore among the studied materials, the main role in conductive heat transfer is played by air occupying 99 % of the total volume. Air heat conduction at average temperature measurements is 0.0272 W/(m·K) [5]. Radiant heat conduction of foamed polyethylene and of the *Hollowfibre* is approximately equal to conductive. According to formula (1), it is easy to estimate depth of thermal radiation penetration into these materials: $a \approx 3.5$mm. This rather good coincides both with visually observed material transparency and with the measurement results for specimen piles with foil. A more dense and finely-divided foamed polystyrene is significantly less transparent for thermal radiation. Its radiant heat conduction is (3–5) times less than of two other materials, and, respectively, $a \approx 1$ mm. So, despite a lesser thickness (5 mm) than of the *Hollowfibre* (6 mm), its “heat conduction” relative change (8.4 %) (for specimens with foil) was considerably lesser than of the *Hollowfibre* (19.7 %).

Thus our measurement results demonstrate a role of radiant heat conduction in light heat insulating materials. The formed concepts and correct measurements allow finding characteristics of heat-protective material properties exactly enough. At what it is possible to do by using visual material characteristics. In the attempts to make heat insulating materials as light as possible, the manufacturers have already reached such a level when the radiation component contribution to the thermal transport is comparable with the conductive component contribution. Material upgrade in respect of reducing their heat conduction radiation component is a significant reserve of improving their heat-protective properties and an important direction of development of the correspondent production in the near future.

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