Contribution of radiant component to thermal conductivity of the medium

E Yu Shamparov, A L Bugrimov, S V Rode and I N Jagrina

Physics Department, A N Kosygin RSU, 117997, Moscow, Sadovnicheskaya st., h. 33, Russia

e-mail: shamparov@bk.ru, jagrina@mail.ru

Abstract. Radiation-conductive heat transfer in a semi-transparent medium has been studied. Two methods for measuring thermal conductivity components are described. Thermal resistance of a remote reflecting surface, the thickness of radiation-conductive relaxation, the depth of penetration of thermal radiation, as well as radiant and conductive components of thermal conductivity of foamed polyethylene were measured using an aluminum foil radiation screen. The dependences of the total thermal conductivity of simple and aluminum-metalized polyester bulk non-woven canvases on the thickness to which it is compressed were measured. Radiant and conductive components of the thermal conductivity of non-woven material are calculated. It is shown how metal nanocoating of fibers reduces radiant thermal conductivity of the material.

1. Introduction

Unfairly much less attention is given to the role of the medium in radiation heat transfer than to the role of the surface. Often, when considering, radiation heat transfer in the medium is not separated from the conductive one. In the fundamental domestic work on Thermophysics [1], description of the phenomenon of thermal radiation diffusion and the determination of the radiant thermal conductivity of the medium were found only in the last Chapter. Moreover, conditions for the applicability of such an approximation are not considered there. Radiation permeability of the medium is unjustifiably neglected. There is an extremely erroneous opinion that the best thermal insulator is a vacuum, whereas it should be perceived by a medium with an infinitely large radiant thermal conductivity. In the world scientific literature, there are a number of analytical works on radiation-conductive heat transfer [2, 3], but simple and clear solutions have not been obtained there either. Currently, most of the work on this topic is related to attempts to solve emerging problems numerically [4]. But in this case, the laws of propagation of diffuse radiation are not applied. This is surprising, because there is a whole class of technically important materials for which this approximation works perfectly. This work is devoted to practical measurements of heat transfer components in fibrous and foamed lightweight insulation materials.

2. Materials and methods

In one of our recent papers [5] it was shown that far from the borders of the medium (at a large optical thickness, when distance to border is much more than penetration depth of thermal radiation $\alpha$), in accordance with Einstein's diffusion law, process of heat propagation is linear, when temperature gradient is small enough.
\[ \nabla T \ll T / a . \]  

(1)

Radiation heat flux density \( \Phi_r \) is directly proportional to the temperature gradient

\[ \Phi_r = -L \nabla T. \]  

(2)

Proportionality coefficient \( L \) [1-3] is called the radiant thermal conductivity of the medium

\[ L = 16 \sigma T^3 a / 3, \]  

(3)

where \( \sigma \) is the Stefan-Boltzmann constant.

Main parameter of the medium is penetration depth of thermal radiation \( a \). Studied materials have random inhomogeneous structure that not only absorbs, but also effectively scatters radiation. Because the size of non-homogeneities is much larger than the radiation wavelength, penetration depth for all wavelengths is approximately the same. Under ambient conditions temperature of the sample \( T \) is usually significantly higher than the temperature difference applied to it. Because typical penetration depth for the materials under study is \( a \approx 1 \) mm, condition (1) is usually fulfilled exactly.

It should be noted that penetration depth of radiation plays the same role for radiation heat transfer as free path length of molecules for conductive one. These two types of transfer are described by similar equations. In both cases random inhomogeneous medium can be characterized by average value of thermal conductivity, when sample size is much larger than the size of the non-homogeneities. In such far from the borders medium the Fourier equation is valid in a generalized form for radiation-conductive heat transfer

\[ \Phi = -\lambda \nabla T_w \ . \]  

(4)

With a stationary parallel heat flow in the medium far from the borders a temperature field with the same temperature gradient \( \nabla T_w \) is established. The total thermal conductivity of the medium \( \lambda \) consists of radiant \( L \) and conductive \( D \) components

\[ \lambda = L + D. \]  

(5)

In [5] the problem of stationary radiation-conductive heat transfer in a gray medium near a flat opaque surface was solved analytically. For a constant perpendicular surface heat flux density \( \Phi \) the dependence of the medium temperature on the distance \( x \) to the opaque border is

\[ T = T_b + x \nabla T_w + \tau \exp(-x / b), \]  

(6)

where \( b \) is thickness of the radiation-conductive relaxation and \( \tau \) is near-surface temperature jump,

\[ b = a / \gamma , \]  

(7)

\[ \gamma^2 = \lambda / D \]  

(8)

For fully reflective surface

\[ \tau = -a \Phi (\gamma^2 - 1) / (\lambda \gamma) \]  

(9)

Remote surface is characterized by its additional thermal resistance

\[ R_e = \tau / \Phi. \]  

(10)

For measurements a layer of 0.75 mm thick foamed polyethylene was taken, from which samples were cut according to the dimensions (85×85 mm²) of the working part of the unit [6]. Weight of each sample is 177 mg. Density is 32.6 kg/m³. Share of occupied by polyethylene volume is 3.3%.

The unit used for measurements is assembled in such a way that convective heat transfer is almost completely excluded. To do this, horizontal heater is placed directly above the cooler. A samples stack, controlled by the thickness, is placed to the gap between them. To direct all the heat generated by the electric current in the heater through the samples to the cooler, a heat shield is contained behind the heater. During measuring, we set and stabilize the screen temperature, find a voltage supplied to the heater at which the temperature of the heater does not change and is equal to the screen temperature. In this case the heat flow from the heater to the screen is small because of two reasons. First reason is the good thermal insulation between them, and second one is their small temperature difference. Heat flow from the heater to the cooler is almost constant. Flow density is almost the same throughout the entire working volume of the unit. Duration of each measurement is determined particularly by the relaxation time of the sample temperature. A separate measurement usually takes from 10 minutes to half an hour.
Having sufficient duration and professionalism of measurements, accuracy better than 1% can be achieved.

3. Results
At figure 1 two dependencies of the thermal resistance $R$ on the thickness of the medium $d$ (the number of layers of foamed polyethylene) are shown, differing in that in the second case an aluminum foil screen is placed in the middle of the stack.

![Figure 1](image)

**Figure 1.** Dependencies of thermal resistance on thickness of: 1 – stacks of samples of polyethylene foam and approximating straight line $R = d/\lambda$; 2 – the same stacks with aluminum foil in the middle. Inset (a): dependence $A(d)$ and approximating curve.

For the first dependency $R_1(d)$ data fell on the expected straight line accurately. From the slope of the straight line

$$\frac{dR_1}{dd} = \lambda^{-1}$$

(11)

total thermal conductivity of foamed polyethylene was calculated $\lambda = 0.0483$ W/(m·K).

Theoretically predicted type of second dependency

$$R_2 = d / \lambda + 2R_s \left(1 - \exp\left(-d/(2b)\right)\right).$$

(12)

Therefore, data of the second dependency was converted to the form

$$A = R_s - d / \lambda.$$  

(13)

By means of their approximation (figure 1(a)) of the curve of the form

$$A = 2R_s \left(1 - \exp\left(-d/(2b)\right)\right).$$

(14)
thermal resistance of remote surface $R_\infty = 0.0053$ m$^2$/K/W and thickness of radiation-conductive relaxation $b = 0.97$ mm are found. Because of

$$L / D = \gamma^2 - 1 = R_\infty \lambda / b,$$

obtained values allowed us to calculate radiant thermal conductivity $L = 0.0101$ and conductive thermal conductivity $D = 0.0382$ W/(m·K) for foamed polyethylene, as well as $\gamma = 1.124$ and penetration depth of thermal radiation $a = 1.09$ mm. Self-consistency of our measurements was verified by formula (3) at average temperature $T = 312$ K. Then $L'= 0.0100$ W/(m·K). Relatively low (~4%) accuracy of measuring thermal conductivity components is due to small depth of radiation penetration, only 1.5 times the thickness of the material layer. However, we were able to observe thermal resistance of remote surface and thickness of radiation-conductive relaxation directly and estimate contribution of each thermal conductivity component. Theoretical justifications and results of practical measurements showed good accordance.

Conductive thermal conductivity of massive polyethylene 0.4 W/(m·K) is many times greater than thermal conductivity of air, at measurement temperature equal to $D_\lambda = 0.026$ W/(m·K). Polyethylene occupies 1/30 of the volume, so we can assume that contribution to conductive thermal conductivity of material, due to the movement of heat through polyethylene, is near 30 times less than thermal conductivity of massive polyethylene. Accordingly, conductive component of thermal conductivity of the material $D = 0.038$ is composed of one part due to the movement of heat through air $D_\lambda = 0.026$ and the other one due to the movement through the polyethylene $D_8 = 0.012$ W/(m·K)

$$D = D_\lambda + D_8.$$

In the second part of the work, we studied how the contribution of each of thermal conductivity components changes depending on density of the medium. For measurements, we took a bulk non-woven canvas with surface density of 70 g/m$^2$, produced under brand "hollowfiber" (in the world its close analog, produced under brand "tinsulate", is better known). The canvas consists of hollow thermally molded polyester (polyethylene terephthalate) fibers with thickness near 30 microns. This is the thinnest version of currently produced canvases. For the second series of measurements, aluminum with front layer thickness near 100 nm was applied to the canvas on both sides by means of vacuum thermal evaporation. Our estimates have shown that depth of penetration of thermal radiation into such canvas is slightly more than half of its thickness. Sprayed metal should penetrate the canvas to about the same depth. Therefore, we can consider that the aluminum metallization is applied fairly evenly throughout the thickness of the material.

For both material types the dependence of total thermal conductivity $\lambda$ on thickness $d$, to which it is compressed, is measured (figure 2). The samples are stacked in two layers with total initial thickness of 20 mm and weight of 998 mg. Then portion of the volume, occupied by polyethylene terephthalate, is equal to 0.5%.

As the material expands, part of conductive component of its thermal conductivity due to movement of heat through air stays almost constant, and part of conductive component due to movement of heat through solid ($D_8$) decreases inversely proportional to thickness

$$D = D_\lambda + k_1 / d .$$

Under the same conditions, material transparency and radiant component of its thermal conductivity increases. Radiant component grows, firstly, in direct proportion to the thickness due to optical density of the medium decrease, but, secondly, there is an addition due to change of direction of fibers

$$L = k_2 d - k_2 d^{3/2} .$$

Both experimentally obtained dependencies were approximated by curves of the form

$$\lambda = 0.026 + k_1 / d + k_2 d - k_2 d^{3/2} .$$

The coefficients, found for the first dependence, are $k_{11} = 0.030, k_{31} = 0.00465, k_{31} = 0.00054$ and for the second dependence are $k_{12} = 0.025, k_{22} = 0.00438, k_{32} = 0.00054$. They allowed estimating contribution of each thermal conductivity component.
Figure 2. Dependencies of the total thermal conductivity on the thickness, to which it is compressed, and approximating curves for "hollowfiber": 1 – without metallization and 2 – with metallization.

Total thermal conductivity of both modifications is minimal: $\lambda_{1\text{min}} = 0.0474$ and $\lambda_{2\text{min}} = 0.0449$ W/(m·K) at $d \approx 3$ mm. At this thickness contribution due to movement of heat through the plastic in both cases is about $D_S = 0.009$ W/(m·K) and radiant thermal conductivity is $L_1 = 0.012$ and $L_2 = 0.010$ W/(m·K).

It should be noted that with this thickness, portion of volume occupied by solid substance in the "hollowfiber" is the same 3.3% as that in foamed polyethylene. It is not difficult to notice that contribution of each component to thermal conductivity of both materials is also approximately the same. The fact that two essentially different measurement methods produce similar results is significant confirmation of correctness of our ideas.

Metal layer of negligible thickness doesn’t lead to increase in conductive thermal conductivity of the material. However, despite the fact that average distance between fibers (250 microns at $d = 10$ mm) is quite large compared to wavelength of radiation, radiant thermal conductivity decreased significantly. At a thickness of 7.5 mm for simple and metalized "hollowfiber", it is 0.024 and 0.021 W/(m·K), respectively, at 20 mm – 0.045 and 0.040 W/(m·K). As material thickness increases, effect due to metallization increases in absolute value. But relative difference in radiant thermal conductivity decreases and is 15, 12 and 11% at $d = 3$, 7.5 and 20 mm.

4. Conclusion
Behavior of metalized material under compression is similar to behavior of radiation transmission by metal lattice, when the wavelength is much longer and approaches the size of the cell. When distance
between fibers approaches wavelength of radiation, radiant thermal conductivity of metalized material should decrease sharply.

Metalized bulk non-woven canvas is material of the future. At the same distance between the fibers and, respectively, at approximately the same radiant thermal conductivity, density of material is proportional to the square of the thickness of fibers. Metallization of materials with very thin fibers is a way to obtain ultra-light insulation materials. In mass production such materials are still too expensive, but in high-tech products – in cryo- or in space technology, it is time to use them.

Thus, two methods showing qualitative and quantitative accordance are presented and practical measurements of the thermal conductivity components of foamed and fibrous insulation materials are carried out. It is found how each of these components depends on density of the medium. Contribution of radiation component to heat transfer and ways to reduce it are described. A method for constructing ultra-light insulation materials is shown. Measurements of radiation-conductive heat transfer are unique in their information content and are extremely promising for the study and understanding of properties of materials with a complex structure that is close to chaotic.

References

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