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Combined radiation and conduction heat transfer in high temperature fiber thermal insulation

VADIM A. PETROV

Institute for High Temperatures, Russian Academy of Sciences, Moscow 127412, Russia

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Abstract—Three different approaches for describing combined radiation and conduction heat transfer in fiber thermal insulation at high temperatures are analyzed and compared. The considered approaches include the radiation transfer equation or its approximations, approximation of radiation thermal conductivity and the radiation diffusion approximation for radiation transfer. The first causes difficulties due to the need for experimental measurement of optical properties, while calculations based on the Mie theory may give inexact results. The second takes into account the radiation transfer inaccurately and the experimentally measured total thermal conductivity may depend on temperature drop, thickness of sample, properties of boundaries and time parameters at transient conditions. It is shown that the most preferable approach is the radiation diffusion approximation for radiation transfer. The comparison of the radiation thermal conductivity approximation and the radiation diffusion approximation is carried out for the example of modeling the working conditions of the fibrous thermal insulation of the Space Shuttle when the vehicle enters the Earth's atmosphere.

1. INTRODUCTION

Light weight fiber materials are widely used in various spheres of high temperature applications including thermal insulation of furnaces and heat exchangers, and reusable thermal protection systems of space vehicles entering dense layers of atmosphere at aerodynamic braking.

Considering energy transfer, fiber thermal insulation is a semitransparent disperse medium consisting of a fiber skeleton and air or another gas filling the volume between fibers. The energy transfer in this medium may be proceeded by various mechanisms: fiber skeleton conduction, gas conduction or convection and thermal radiation. Several excellent reviews on radiation and combined radiation and conduction energy transfer in dispersed media are available [1–4]. There are many papers that consider problems of heat transfer in glass fiber thermal insulation (Refs. [5–15] for example).

In several references [7, 10, 16, 17] the contribution of natural convection in total energy transfer is analyzed. The analyses show that for air at a pressure of 10^5 $\mathrm{Nm^{-2}}$ and a temperature drop of 1000K on the plane layer of fiber material with porosity $\Pi = 0.95-0.96$ and thickness 5 cm it is possible to neglect the contribution of natural convection. At high pressures (10^7 $\mathrm{Nm^{-2}}$ or more) the contribution of natural convection may be considerable, but fiber insulation is seldomly used in these conditions.

Thus, three mechanisms of heat transfer need to be considered: thermal conductivity of the solid skeleton, thermal conductivity of the gas and thermal radiation. By combining the first two it is possible to consider just two mechanisms: thermal conductivity and thermal radiation. These mechanisms are the subject of the investigation in most of the papers on the heat transfer in a fiber thermal insulation.

2. USE OF RADIATION TRANSFER EQUATION

It is accepted that the calculations of combined radiation and conduction heat transfer in rarefied dispersed media may be carried out on the basis of using the radiation transfer equation (or some of its approximations) in common with the energy conservation equation. However in practice the application of this method requires the knowledge of spectral and temperature dependencies of the absorption coefficient k_λ, the scattering coefficient β, and bidirectional phase function of scattering γ_λ. Calculation is possible using the Mie theory, if the spectral and temperature dependencies of the absorption coefficient and refractive index of the fiber material are known [5, 8, 18, 19] together with the diameter distribution of fibers.

In general the strict form of the radiation transfer equation is not used, and for simplification of calculation approximations are used. The most often used approximation is the two-flux Schuster–Schwarzchild approximation for the first time formulated in spectral form as applicable to fiber insulations in ref. [5] and used in refs. [8, 12, 18]. The application of this approach for solid materials is possible for the cases

NOMENCLATURE

C_p	heat capacity at constant pressure
D	radiation diffusion coefficient
I	intensity of radiation
k	absorption coefficient
$\bar{k}$	effective absorption coefficient
L	thickness of layer
n	refractive index
$\bar{n}$	effective refractive index
q	energy flux
T	temperature
t	time
U	radiation energy density
x	coordinate.

Greek symbols

α	extinction coefficient
β	scattering coefficient
γ	phase function of scattering
Δr	distance
ΔT	temperature difference
ε	emittance
ζ	attenuation coefficient
Λ	thermal conductivity
λ	wavelength
$(\tilde{\lambda})$	wavelength range of semitransparency
$\bar{\mu}$	mean cosine of scattering angle
Π	porosity
ρ	density
ω	albedo of scattering.

Subscripts

1	left boundary
2	right boundary
C	conductive
R	radiation
t	total
λ	wavelength
Σ	total.

Superscript

P	equilibrium (Planckian).

when the distance between the cylindrical scatterers is more than the wavelength and the diameter. However ultralight weight fiber insulation with porosity about 95% does not quite correspond to these requirements because the fibers bend and cohere to one another at the junctions (there are three or four junctions per fiber). In any case there is no reason to assume that the scattering corresponds to the model of single independent scattering. Moreover, the presence of impurities and any specially introduced additions for sintering may change noticeably the value of the absorption coefficient or lead to the forming of the surface layers with unknown optical properties. Owing to the influence of these factors calculations based on the Mie theory may give inexact results. Then in a number of papers it was preferred to use optical properties of fiber insulation on the basis of measurement of unidirectional transmissivity [9], the directional-hemispherical reflectivity [13] or commonly the unidirectional and bidirectional transmissivity [20]. From the measurements of the unidirectional transmissivity it may be possible to obtain the extinction coefficient $\alpha = k+\beta$, but not values of k, β and γ.

In measurement of the spectral directional–hemispherical reflectivity of plane layers with different thickness [13], the data on k and β were obtained. The phase function of scattering is assumed to be known, although this cannot be justified at all. The most complete information on the optical properties of fiber thermal insulation is obtained using the method described in ref. [20]. From the results of measurements of the spectral bidirectional transmissivity of plane layers with different thickness at collimated normal incidence of radiation on the sample surface, three unknown parameters were determined: α, ω and the parameter g of the one parameter Henyey–Greenstein scattering phase function. The measurements covered the broad spectral region from 2 to 10 μm. Although the details of solving the inverse problem of radiation transfer in ref. [20] are not described, the published data on the obtained optical properties show a large discrepancy between values for samples having different thicknesses. In particular, it is considerable for the absorption coefficient, where the discrepancy reaches 50% or more. It is not clear if these discrepancies are due to inaccuracies of the measurements or if they are connected with the non-stable structure and properties of the testing samples of fiber thermal insulation.

It must be mentioned that in the measurement of the spectral transmissivity it is usually necessary to measure the low level signals, as the values of transmission radiation flux are often equal to tenths or even hundredths of a percent of incident ones. So even in the most complete study [20] the measured radiation took up the broad wavelength range of spectrum about 1 μm. In other works [9, 21, 22], large total radiation fluxes were used and the optical properties averaged in the spectrum range of incident radiation were obtained. The use of such characteristics is not quite sufficient and may give big errors. Most experimental data on the extinction coefficient exists for glass fiber thermal insulation of low density about 10 kg m^{-3}. Basically, this insulation is not really applicable at temperatures much above room temperature.

Little experimental data exists for the optical properties of more dense high temperature fiber thermal insulation due to the difficulties of measurement of low value transmitted radiation flux mentioned above.

3. USE OF RADIATION THERMAL CONDUCTIVITY APPROXIMATION

The most popular approach to the problem of combined radiation and conduction heat transfer in fiber thermal insulation at high temperatures is based on the use of radiation thermal conductivity approximation for describing the radiation transfer. In this approach the Fourier law may be applied for total energy flux

$$q = -(\Lambda_c + \Lambda_R)\nabla T \quad (1)$$

where ∇T is temperature gradient, Λ_c and Λ_R are conductive (true) and radiation thermal conductivity, accordingly. It is not necessary to known Λ_c and Λ_R separately or to measure their optical properties. The total value $\Lambda_\Sigma = \Lambda_c + \Lambda_R$ may be measured by usual methods based on the solution of inverse problems of thermal conductivity. The advantage of this approach lies also in the fact that it does not require the assumption on fulfilment of the radiation transfer equation, which is not always realized.

In studies of measurements of Λ_Σ several methods are used, as for nontransparent materials. They include the guarded hot plate method, the cylindrical layer method and the method of monotonous heating [23–26], they were used during design and following improvement of the thermal protection system of a space shuttle [27]. However measurements of total effective thermal conductivity by different methods use different temperature gradients in the test specimens. These gradients differed from those existing in shuttle thermal protection material at its transient heating during entering the dense layers of the Earth's atmosphere. It was revealed [27] that the results of the calculation of temperature distribution in the thermal insulation during reentry using experimental data measured by the guarded hot plate method differed from temperature distribution measured experimentally. The predicted in-depth temperatures exceeded the measured ones by 100K and more. In this connection it was also noted [27] that the accuracy obtained by the steady state methods is limited in transient environments, where surface temperatures change rapidly. This is conditioned by the larger role of radiation transfer at high temperatures. It must be mentioned that the possible inaccuracy of inner temperature measurement of fiber thermal insulation by thermocouples for conditions [27] evaluated in accordance with [28, 29] is significantly less than 100K.

The role of radiation heat transfer in transient conditions has been considered in detail [30]. In this work the energy transfer in fiber thermal insulation was considered at temperatures slightly above room temperature. It was noted that serious problems were associated with transient measurements and significant errors can occur if the radiation plays an appreciable role in energy transfer. It was noted also that the transient measurements of thermal diffusivity of porous thermal insulation gave as much as 30% smaller values than those received on the base of steady-state measurement of thermal conductivity. It was also shown that the model of combined radiation and conduction heat transfer, based on the description of radiation transfer by the two-flux approximation, provides the temperature distribution under transient conditions more correctly. In this model the radiation transfer is considered for a gray medium and the results are more qualitative than quantitative. However, the analysis shows that it is necessary to take into account the radiation transfer more rigorously than on the basis of the radiation thermal conductivity model. Thus it can be said that the experimental data on total effective thermal conductivity depend on specific conditions of the experiments. The value of Λ_Σ may depend on the temperature difference, the thickness of the specimen, the emittance of its boundaries (in steady state experiments) and on time parameters (in transient experiments).

Sometimes it is supposed that to measure Λ_Σ under conditions of modeling of the real ones, for example entering dense layers of atmosphere, is a good way out of a situation [27]. However the advantages of this approach are very small. It is possible by using the results of modeling to choose such function of $\Lambda_\Sigma(T)$ that gives the dependence $T(t)$ that agrees well with the experimental data. However this function Λ_Σ will be suitable only for the analogous aerothermodynamic heating environment of thermal protection system. Other values of $\Lambda_\Sigma(T)$ will correspond to each condition of heating, and so such an approach comes to test modeling of the different real flight conditions.

It follows that for describing energy transfer in fiber thermal insulation, especially at high temperatures and transient conditions, it is necessary to consider combined radiation and conduction heat transfer. The most important question now is: how to better describe the radiation transfer? It is noted above that use of the radiation transfer equation or its approximations are not expedient. There is no way to base the radiation thermal conductivity approximation and experimental measurement of Λ_Σ.

4. USE OF THE DIFFUSION APPROXIMATION

The use of a diffusion model is preferable for describing radiation transfer [31–33]. Usually the diffusion approximation is considered as a particular case of describing the radiation transfer in optically thick layers of scattering media. According to this approximation the radiation transfer may be described by an equation that is analogous to the Fick law for the mass diffusion:

$$q_\lambda = -D_\lambda \nabla U_\lambda \tag{2}$$

where q_λ is spectral radiation flux, U_λ is the energy density, the average value over a physically infinitely small volume, and D_λ is the radiation diffusion coefficient. This approximation accurately describes the processes of radiation transfer in the diffusion limit:

$$k_\lambda D_\lambda \ll 1, \tag{3a}$$

$$\frac{D_\lambda}{\Delta r} \ll 1, \tag{3b}$$

where Δr is the medium distance from a point in the interior of medium to the boundary. The radiation diffusion coefficient is connected with usual parameters of radiation transfer equation by an expression

$$D_\lambda = \tfrac{1}{3}[k_\lambda + \beta_\lambda(1-\bar{\mu})]^{-1}, \tag{4}$$

where $\bar{\mu}$ is the mean cosine of the scattering angle. However equation (2) can be given a broader interpretation that is not connected with the radiation transfer equation. It can be considered as a phenomenological law holding in a depth of highly scattering poorly absorbing medium when the conditions given in equation (3) are applied. This is despite whether it deals with rarefied media for which the transfer equation holds, or with dense packed structures for which the transfer equation is not applicable. In the latter case the radiation diffusion coefficient is not expressed by equation (4). It must be understood as a phenomenological parameter measured experimentally and equal, in its order of magnitude, to the mean free path of the radiation. With this approach the combined radiation and conduction heat transfer in a plane layer of thermal insulation is described by the combination of the energy conservation equation with fitted initial and boundary conditions and radiation diffusion equation with fitted boundary conditions.

5. COMPARISON OF THE RADIATION THERMAL CONDUCTIVITY APPROXIMATION AND THE RADIATION DIFFUSION APPROXIMATION

It may be shown that the condition of the applicability of the radiation thermal conductivity approximation to fibrous thermal insulation is defined by an inequality

$$\zeta_\lambda \Delta r \gg 1 \tag{5}$$

where $\zeta_\lambda = (\bar{k}_\lambda / D_\lambda)^{1/2}$ is the attenuation coefficient and $\bar{k}$ is the effective absorption coefficient. The $\bar{k}$ and the effective refractive index $\bar{n}$ are defined in refs. [34, 35]. In the presence of large temperature gradients and in the absence of the external directional radiation sources the condition (5) may be written in the form:

$$\left(\frac{\partial T}{\partial X}\right) \Big/ T \ll \zeta_\lambda. \tag{6}$$

The conditions (5) or (6) must be fulfilled in the wavelength range important for thermal radiation. So, expression (6) is the necessary condition of the applicability of the radiation thermal conductivity approximation and corresponding use of the Fourier law in form (1) with total thermal conductivity Λ_Σ. If it is not fulfilled in the real conditions of the functioning of thermal insulation or in the conditions of the measurement of total thermal conductivity, then the calculations of temperature distribution based on the solution of transient thermal conductivity equations may lead to errors. The diffusion approximation has a broader field of applicability than the radiation thermal conductivity approximation. It provides the possibility to take into account the nonlocal character of energy transfer and may be applied at considerably greater temperature gradients.

The comparison of the realizations of the radiation diffusion approximation and the radiation thermal conductivity approximation, considered in ref. [36], can be established from the confrontation of conditions (3) and (5). As considered in the present fiber materials $\zeta_\lambda^{-1} = (\bar{k}_\lambda/D_\lambda)^{-1/2} = (\bar{k}_\lambda D_\lambda)^{-1/2} D_\lambda$, the product $\bar{k}_\lambda D_\lambda$ in the region of transparency of fiber material is always much less than 1, then $\zeta_\lambda^{-1} \gg D_\lambda$. Comparing this with equation (5) one may see that the radiation thermal conductivity approximation begins to be fulfilled at the distance from the boundary $\Delta r \gg 1/\zeta$. This limitation is more than the limitation (3b) $\Delta r \gg D_\lambda$, which must be fulfilled for the diffusion approximation.

Thus traveling from the boundary along the normal to the surface into the insulation, first, at distances appreciably greater than D_λ, the diffusion approximation begins to be fulfilled, and after that, at distances appreciably greater than $1/\zeta_\lambda$, the radiation thermal conductivity approximation is fulfilled. This is one of the reasons whereby the experimental results for Λ_Σ obtained by transient methods differ from values of Λ_Σ obtained by steady-state methods.

In order to illustrate this conclusion, regarding the errors that can be obtained, consider a plane layer of space shuttle thermal insulation with thickness L = 5 cm manufactured from silica fibers and having a density ρ = 144 kg m^{-3} (the porosity $\Pi = 0.934$). The left boundary of the layer has a thin nontransparent coating with the total hemispherical emittance $\varepsilon_t = 1$. The right boundary is adiabatically insulated and its total emittance is zero. The boundary conditions on the left boundary correspond approximately with conditions of the Shuttle entering the Earth atmosphere. Changing this boundary temperature $T_1(t)$ with time has the character shown in Fig. 1. The total time durations when T_1 is above room temperature is equal to 20 min, and the heating and cooling periods are 5 min each.

The usual model based on the Fourier law and

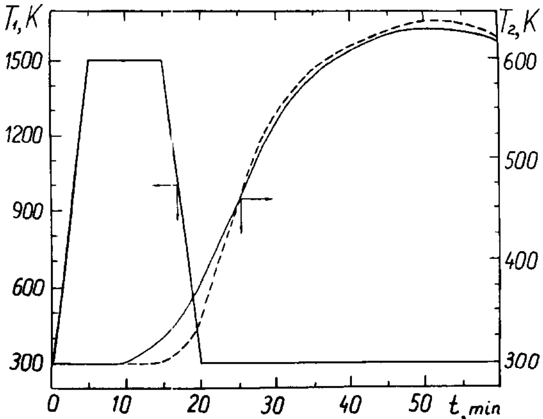

Fig. 1. Calculated time dependence of internal boundary temperature T_2 of thermal insulation (solid line—the diffusion approximation; dashed line—the radiation thermal conductivity approximation) at the prescribed time dependence of external boundary temperature T_1 modeling space shuttle entering Earth's atmosphere.

the radiation thermal conductivity approximation is described by the following:

$$C_p\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\Lambda_\Sigma\frac{\partial T}{\partial X} \tag{7}$$

$$T(x,0) = T_0;\quad T(0,t) = T_1(t);\quad \left.\frac{\partial T}{\partial X}\right|_{x=L} = 0 \tag{8}$$

where x is distance from left heated boundary.

The radiation diffusion model is described by two equations with corresponding conditions. The equation of energy conservation:

$$C_p\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\Lambda_c\frac{\partial T}{\partial X} - \int_{(\bar\lambda)} \bar{k}_\lambda(\bar{n}_\lambda^2\, U_\lambda^p - U_\lambda)\,\mathrm{d}\lambda \tag{9}$$

$$T(x,0) = T_0;\quad T(0,t) = T_1(t);\quad \left.\frac{\partial T}{\partial X}\right|_{x=L} = 0. \tag{10}$$

The radiation diffusion equation:

$$-\frac{\partial}{\partial X}D_\lambda\frac{\partial U_\lambda}{\partial X} + \bar{k}_\lambda U_\lambda = \bar{k}_\lambda\bar{n}_\lambda^2\, U_\lambda^p, \tag{11}$$

$$-D\left.\frac{\partial U_\lambda}{\partial X}\right|_{x=0} + \tfrac{1}{2}U_\lambda(0) = 2\pi\overline{n^2}I_\lambda^p(T_1);$$

$$-\left.\frac{\partial U_\lambda}{\partial X}\right|_{x=L} = 0. \tag{12}$$

In these equations $U_\lambda^p = 4\pi I_\lambda^p$ is the equilibrium (Planckian) energy density, I_λ^p is the Planckian intensity of radiation, $(\tilde\lambda)$ is the spectral range of semitransparency, $T_0 = 300$K.

The necessary data for the optical and thermophysical properties were obtained in the following way. The heat capacity of silica glass (fiber material) was calculated from the formula given in ref. [37]:

$$C_p = 931.3 + 0.256T - 2.4\cdot 10^7/T^2,\quad \mathrm{J\,kg^{-1}\,K^{-1}}. \tag{13}$$

The value of true thermal conductivity Λ_c was determined using the supposition that the thermal conductivity due to the presence of gas in the pores is negligible (it corresponds to vacuum environment). Then

$$\Lambda_c = \varphi(\Pi)\Lambda_0 \tag{14}$$

where Λ_0 is the true (lattice) thermal conductivity of silica glass (data were taken from ref. [38]), and $\varphi(\Pi)$ is a function dependent on material structure and porosity. This was determined from data [39] on thermal conductivity of the fiber insulation at room temperature, where the influence of radiation transfer is disregarded (for $\Pi = 0.934$ the value $\varphi(\Pi) = 1.25\cdot 10^{-2}$).

As we didn't have data on optical properties of the space shuttle thermal insulation, we used the result of measurements [35] for practically isotropic silica thermal insulation. These measurements were carried out at three wavelengths 0.63, 1.15 and 3.39 μm. The data obtained were extrapolated over the whole semitransparent region. The effective refractive index was calculated from the data [40] for the refractive index of silica glass using the expression given in ref. [35]. Table 1 gives the data on optical properties used in the calculations, which were averaged in the indicated spectral ranges.

The temperature dependence of $\bar{k}_\lambda$ was calculated using data [40] and the assumption that $\bar{k}_\lambda$ of the thermal insulation is proportional to the absorption coefficient of silica glass.

The radiation thermal conductivity was calculated on the basis of the data on optical properties given in Table 1. For this calculation:

$$\Lambda_R = 4\pi\int_{(\bar\lambda)} D_\lambda\bar{n}_\lambda^2\frac{\partial I_\lambda^p}{\partial T}\mathrm{d}\lambda. \tag{15}$$

It must be noted that the calculated data on the total thermal conductivity Λ_Σ agree with data [39] for the total thermal conductivity of the shuttle thermal insulation. Figure 1 shows the results of calculations of time dependence of the temperature of the adiabatically insulated boundary $T_2 \equiv T(L)$. It may be seen from this figure that results of the calculations based on the diffusion model give the higher values during heating of this boundary up to 25 min and then at $t > 25$ min— the lower values. This is explained by the fact that the diffusion model takes into account the nonlocal radiation transfer. At $t = 18$ min there is the maximum difference, which equals 31K. It may be seen also that during the period of time after 18 min the discrepancy decreases and the difference of the highest possible temperatures of the adiabatic bound-

Table 1. Optical properties of silica fiber thermal insulation

Number of spectral range	Limits of spectral range (μm)	Effective refractive index $\bar{n}$	Radiation diffusion coefficient D (cm)	Effective absorption coefficient $\bar{k}$ (cm^{-1})
1	0.3–2.0	1.036	5.8×10^{-3}	7.0×10^{-3}
2	2.0–2.4	1.035	5.0×10^{-3}	2.5×10^{-3}
3	2.4–3.0	1.034	4.2×10^{-3}	7.5×10^{-2}
4	3.0–4.8	1.032	3.2×10^{-3}	1.0×10^{-1}

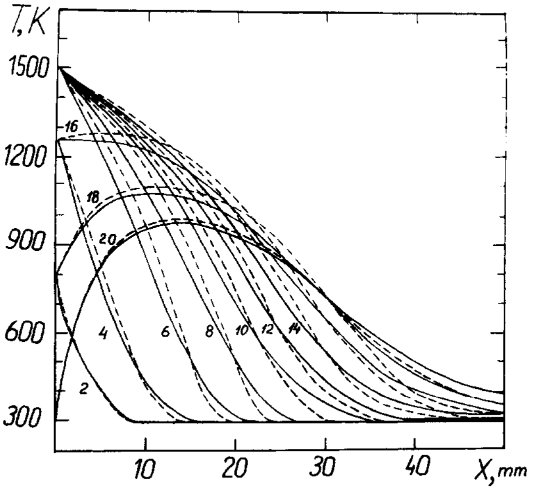

Fig. 2. Temperature distributions in the layer of thermal insulation at different moments from the start of heating marked by figures at the curves in minutes (solid line—the diffusion approximation; dashed line—the radiation thermal conductivity approximation).

ary, calculated according to the two models, is small, being approximately 4K. However, the differences of in-depth temperatures during heating are much greater. For example at $t = 6$ min for the distance from surface $x = 1$ cm the difference is equal to 120 K as shown in Fig. 2. This figure shows the temperature distributions inside the layer at 2 min intervals after the beginning of heating.

It may be seen that the discrepancy of results calculated by using the two considered models is large only during heating when the radiation of the left black boundary is important due to its high temperature. After 20 min the temperature of this boundary is small and discrepancy is also small.

6. CONCLUSIONS

The comparison of the results of calculation of temperature distribution in the layer of fiber thermal insulation under its transient heating, based on using the diffusion model and the model of the radiation thermal conductivity, shows that describing the radiation transfer on the base of the diffusion model gives the more exact data. However for fulfilment of the calculations in the frame of the diffusion model it is necessary to use a larger quantity of experimentally measured thermophysical and optical properties.

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