Journal of Quantitative Spectroscopy & Radiative Transfer 197 (2017) 166–172

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

A generalized analytical model for radiative transfer in vacuum thermal insulation of space vehicles

Irina V. Krainova [a,*], Leonid A. Dombrovsky [b,c], Aleksey V. Nenarokomov [a], Sergey A. Budnik [a], Dmitry M. Titov [a], Oleg M. Alifanov [a]

[a] Moscow Aviation Institute (Aerospace University), Volokolamskoe Shosse 4, Moscow 125993, Russia
[b] Joint Institute for High Temperatures, Krasnokazarmennaya Str. 17A, Moscow 111116, Russia
[c] Tyumen State University, Semakov 10, Tyumen 625003, Russia

ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form
6 January 2017
Accepted 31 January 2017
Available online 3 February 2017

Keywords:
Radiative transfer
Transport approximation
Thermal insulation
Fibrous spacer
Vacuum experiment

ABSTRACT

The previously developed spectral model for radiative transfer in vacuum thermal insulation of space vehicles is generalized to take into account possible thermal contact between a fibrous spacer and one of the neighboring aluminum foil layers. An approximate analytical solution based on slightly modified two-flux approximation for radiative transfer in a semi-transparent fibrous spacer is derived. It was shown that thermal contact between the spacer and adjacent foil may decrease significantly the quality of thermal insulation because of an increase in radiative flux to/from the opposite aluminum foil. Theoretical predictions are confirmed by comparison with new results of laboratory experiments.

1. Introduction

The paper is concerned with radiative heat transfer as applied to the Thermal Control Systems (TCS) of spacecrafts. The need in a TCS is dictated by the technological/functional limitations and reliability requirements of all equipment used onboard a spacecraft and, in the case of manned missions, by the need to provide the crew with a suitable living/working environment. Almost all sophisticated equipment has specified temperature ranges in which it will function correctly. The role of the TCS is therefore to maintain the temperature and temperature stability of every item onboard the spacecraft within those pre-defined limits during all mission phases and thereby using a minimum of spacecraft resources.

In previous papers of co-authors [1,2] the thermal properties of a multilayered thermal-insulating blanket (MLI), which is a screen-vacuum thermal insulation as a part of the TCS for perspective spacecrafts, have been estimated. Heat transfer in the MLI was analyzed on the basis of a theoretical model validated using the laboratory heat flux measurements and the inverse heat transfer problem technique. A transient nature and possible non-linearity of heat transfer can be referred to special features of thermal conditions of modern space structures and especially TCS. These factors considerably reduce the possibility of using some traditional theoretical and experimental methods. Therefore, it is important to develop new approaches to thermal engineering studies and carry out experimental studies under conditions similar to full-scale flight tests.

The particular objective of the present paper is two-fold: (1) to generalize the previously developed radiative transfer model and (2) to compare theoretical predictions with new laboratory experimental data. The methodology of the present paper is based on assumption of an isothermal thin spacer and continuous approach for the radiative transfer in a layered fibrous material of the spacer. The use of slightly modified two-flux approximation enables one to simplify the problem and obtain an analytical solution which is convenient for the engineering estimates. The previously developed vacuum thermal installation is used to measure the heat flux through the vacuum insulation at different conditions and validate the model suggested.

2. Theoretical model

The theoretical model suggested in the present paper is free from the main assumption of paper [2] on the absence of thermal contact between the spacer and the neighboring aluminum foil

* Corresponding author.
E-mail address: igrid@mail.ru (I.V. Krainova).

http://dx.doi.org/10.1016/j.jqsrt.2017.01.039
0022-4073/

Nomenclature

a	fiber radius
A, B	coefficients in solution (7a)
B_λ	Planck function
C	volumetric heat capacity
d	thickness of spacer
D	radiation diffusion coefficient
f	function introduced by Eq. (1).
F	function introduced by Eq. (16)
g	spectral irradiance
J	least-square residual of computational and measured temperatures
k	thermal conductivity
l	current number of the screen
N	the total number of nodes
p	coefficients in Eq. (16)
q	radiative flux
Q	efficiency factor of absorption, scattering or extinction
t	time
T	temperature
x, z	normal coordinate

Greek symbols

α	absorption coefficient
β	extinction coefficient
δ_f	integral error of measurements
ε	emittance
ζ	spline functions in Eq. (18).
λ	radiation wavelength
σ	scattering coefficient
τ	optical thickness
ξ	eigenvalue
φ, ψ	correction parameters
ω	albedo

Subscripts and superscripts

0	initial
1, 2	screen numbers
a	absorption
exp	experimental
f	foil
gl	glass
min	minimum
max	maximum
s	scattering
sp	spacer
theor	theoretical
tr	transport
λ	spectral

layers. At the same time, the assumptions of a small optical thickness of a fibrous spacer and random orientation of fibers in planes remain without changes. The latter is sufficient to neglect the temperature difference across the spacer. Of course, the maximum estimate of an effect of thermal contact between the foil and spacer can be obtained by ignoring possible local gaps between them. It means that the temperature of the fibrous spacer is assumed equal to the temperature of the adjacent aluminum foil. Strictly speaking, one can take into account a temperature difference across the spacer. This can be done using the approaches developed in papers [3–7]. At the same time, the maximum estimate is considered in the model suggested when this temperature difference is expected to be negligible because of a very small geometrical thickness of ordinary spacers. This is the main simplification which will be evaluated by comparison with the experimental data. Note that the effect of an isothermal spacer is in an increase of spectral emissivity of the foil-spacer system and the solution to the problem under consideration does not depend on which foil (relatively cold or hot) is in the thermal contact with the spacer.

A representative fragment of the vacuum insulation is considered. This fragment consists of two parallel aluminum foils and a flat fibrous spacer between the foils. The spacer is made of several layers of quartz fibers, and the fibers are randomly positioned and oriented in every layer. So, the fibrous medium of a single spacer is the only participating medium between the foils. For brevity, the following designation is used in subsequent analysis:

$$f_j = \pi B_\lambda(T_j) \quad j = 1, 2 \tag{1}$$

where j is the foil number ($T_1 > T_2$) and $B_\lambda(T)$ is the Planck function. The spectral radiative flux in a plane-parallel single layer of the vacuum insulation is determined as follows (hereafter the subscript λ for spectral quantities is omitted for brevity):

$$q = (f_1 - f_2)/(1/\varepsilon_1 + 1/\varepsilon_2 - 1) \tag{2}$$

Assume for definiteness that the spacer contacts with the hotter foil ($T_s = T_1$, subscript "s" refers to the spacer). In this case $\varepsilon_2 = \varepsilon_f$ (subscript "f" refers to the foil), whereas the value of ε_1 taking into account the spacer effect should be obtained.

The principal assumption of the present paper is that a continuous approach is applicable to radiative transfer in a thin semi-transparent fibrous spacer. This assumption may lead to quantitative errors in the limit of a spacer containing only few flat layers of fibers, but the obvious advantage of the continuous approach, which enables one to use a simple differential approximation for the radiative transfer, is too attractive to be ignored. In addition, the limiting case of a very thin and almost transparent spacer is not so interesting because of a small overall effect. This effect increases and it deserves special consideration in the case of multiple scattering of infrared radiation in a spacer. The latter circumstance explains the methodological choice made in the present study.

The schematic of the problem under consideration is shown in Fig. 1. In many cases, the 1-D problem for radiative transfer in the isothermal spacer can be rather accurately solved using the transport approximation for the scattering phase function and the traditional two-flux method [8–10]. Perhaps, the most detailed study of errors of the two-flux (or Schuster–Schwarzschild) approximation for the radiative transfer problems of this type is presented in the first chapter of the monograph [8] (see also chapter 15 of the excellent textbook [10]). It was shown that this approach enables one to determine the radiative flux very accurately because of the integral nature (over the angles) of this quantity. This statement appears to be true for an arbitrary thickness of the medium layer. The typical error in the radiative flux is less that about 5%. At the same time, it will be shown below that some corrections of the boundary condition should be made in the optically thin limit and low emissivity of the boundary surface. The mathematical problem statement for the uniform