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Radiative heat transfer from supersonic flow with suspended particles to a blunt body

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ABSTRACT

The spectral radiative transfer problem for a supersonic gas flow with suspended particles at the front surface of a blunt body is solved using the combined two-step model based on transport approximation for the scattering phase function. The particle laden flow is calculated taking into account both dynamic and temperature non-equilibrium of micron-sized particles suspended in the carrier gas. A computational study of the problem showed that the effect of collisions between polydisperse particles including those reflected from the body is significant for both the flow field of particles behind the shock wave and the radiative heat transfer. At the same time, one can use a monodisperse approximation instead of complete calculations to estimate both the radiation flux and equilibrium temperature of the body surface.

1. Introduction

The problem of thermal interaction of a supersonic flow of a gas or plasma with a blunt body is very important in some aerospace applications. This interaction is especially strong in two cases: at very high relative velocities of the flow and also in the case when solid or liquid particles are suspended in a gas. The latter case is characterized by specific difficulties because of a complex behavior of composite materials under the action of a gas flow with particles [1]. The solid particles can increase essentially the heat transfer near the stagnation point. In the case of large particles impinging on the body surface, a contribution to the heat flux is related to transformation of the particle kinetic energy [2–4]. For fine particles, an increase in the heat flux is explained by modification of the flow in the boundary layer [5]. This problem of fluid mechanics has been theoretically studied in detail for wide ranges of particle sizes and free stream particle volume fraction in the recent paper [6].

It is well-known that a contribution of thermal radiation to combined heat transfer in supersonic flow over the bodies may be significant. This problem is usually considered as applied to the re-entry stage of space missions [7,8]. Most recent studies are focused on plasma radiation at very high re-entry velocity [9–13]. The presence of micron-sized particles makes this problem rather different from that for gas or plasma flow without particles. On the one hand, the complex radiative properties of the host medium appears to be not so important and there is no need in extremely detailed spectral calculations because of a continuous emission spectrum of particles. On the other hand, one should take into account both the local dynamic and thermal nonequilibrium of particles [1,6,14–18] and the radiation scattering by particles of size comparable with the wavelength [19–24].

The computational modeling of supersonic flows of a gas with suspended particles is not a simple task, especially in the case when collisions of particles with each other and also with the body surface are important. The flow model appears to be especially complex in the realistic case of a wide size distribution of particles because of numerous collisions between the particles of different size. In papers [23,24], the monodisperse approximation has been used. Of course, this approach simplified radically the mathematics of both the flow field and the radiative transfer calculations. At the same time, it was not clear how to choose an appropriate average size of particles in this approach and to estimate the errors of the monodisperse approximation in the main parameters of the calculated flow field and radiative transfer. Moreover, it is not obvious that this approach is applicable to the problem under consideration. In addition, one should recall the real cases when monodisperse approximation gives too crude results even for integral (over the spectrum) radiative flux from an isothermal particle

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Nomenclature

a	particle radius
A, B	size-distribution parameters
$\vec{C}, \vec{F}, \vec{G}, \vec{N}, \vec{q}$	vectors in Eq. (6a)
D	radiation diffusion coefficient
E	internal energy
E_a, E_s	specific coefficients introduced by Eq. (22)
f_v	volume fraction of particles
$\vec{f}$	force
F	gamma-distribution
G	spectral incident radiation
H	enthalpy
I	radiation intensity
K	coefficient in Eq. (13)
l	the number of particle fractions
m	complex index of refraction or mass of particle
N_p	number of particles
q	radiative flux
Q	efficiency factor of absorption or scattering
R	radius of spherical body
s	coordinate along the body surface
S	emission term of the source function
x	diffraction parameter

Greek symbols

α	absorption coefficient
β	extinction coefficient
γ	specific heat ratio
ϵ	emissivity
κ	index of absorption
λ	wavelength
σ	scattering coefficient
σ_0	Stefan–Boltzmann constant
$\vec{\omega}$	angular velocity
$\vec{\Omega}$	unit vector of direction

Subscripts and superscripts

a	absorbed
b	blackbody
d	drag
m	maximum
M	Magnus
p	particle
r	radiative
s	scattered
t	total (integral)
tr	transport
w	wall
ω	rotational

cloud [19,22,25]. Note that this approximation is totally inapplicable for thermal radiation of some polydisperse systems when particles of different size have considerably different temperatures. The known examples are: thermal radiation of particles in plasma spraying [26–28], radiation from combustion products in exhaust plumes of aluminized-propellant rocket engines [19,21,22,29,30] and radiative cooling of core melt droplets in nuclear fuel–coolant interaction [31–33].

The objective of the present paper is twofold: (1) To summarize the methodological results for radiative transfer calculations presented in [24] for the case of numerous collisions between polydisperse particles [34] and (2) To examine the monodisperse approximation in the realistic case of equilibrium temperature of the body surface.

According to [34], the value of an average particle radius which gives good estimate of the radiative flux is different for relatively cold and hot surface of the blunt body. Therefore, the solution to the second task is not obvious. Note that possible use of the monodisperse approach is very promising to decrease the computational time. The latter is especially important for the conjugated problems with destruction of the body material under the combined thermal and mechanical action of the flow containing particles [1,18,35].

The results of recent analysis of different approximate methods in radiative transfer calculations reported by Dombrovsky and Reviznikov [24] are used in the present paper. According to these results, the traditional P_1 approximation is sufficiently accurate only in the case of a relatively cold body surface (see also papers [22,36–38]), whereas the combined method including the ray-tracing procedure [22,39] can be employed to solve the radiative transfer equation at the second step of numerical solution in the case of arbitrary temperature of the body surface.

The present study is motivated mainly by the interest to thermal conditions in the experimental testing of composite materials used in design of rocket engines. Therefore, we consider a model problem with parameters typical of engineering problems of this type. At the same time, the methods suggested are expected to be also applicable to some re-entry problems.

The present paper is focused mainly on elaboration of the advanced computational model and illustration of this model quality in the most important range of the problem parameters. Some specific features of the problem solution at various geometrical and thermal parameters have been already studied in recent publications by the authors [23,24,34].

2. Flow field model for gas with suspended particles

A general scheme of the problem under consideration is illustrated in Fig. 1 taken from recent paper [24]. The uniform supersonic flow of combustion products containing small alumina particles interacts with a blunt body. It is assumed that there are both dynamic and thermal equilibrium between the gas and small alumina particles in the exit cross section of the nozzle. In contrast to papers [23,24], the only variant of the geometrical parameters of the nozzle and spherical obstacle is considered: the radius 3 cm of the sphere, the radius 4.66 cm of the nozzle exit cross section and the distance 5.33 cm from the nozzle exit to the sphere center. This limitation is explained by the limiting length of the journal paper. The physical parameters of the model problem under consideration are similar to those reported in the above referred papers. At the nozzle exit, the specific heat ratio $\gamma = 1.25$, density $\rho = 0.6\ \mathrm{kg\ m^{-3}}$, pressure $p = 0.269$ MPa, temperature $T = 1558$ K, and Mach number M = 2 were taken. Note that the stagnation temperature is equal to $T_0 = 2336$ K at the above conditions. The initial volume fraction of particles is equal to $f_{v0} = 10^{-4}$. It was assumed that all particles, which reach the body surface, undergo specular reflection with the recovery factor equal to 0.9.

It is typical for the combustion problems that small volume elements contain a large number of particles, so that a representative local size distribution of particles can be introduced. For simplicity,