Simulation of the propagation of heat waves in a radiation-cooled dispersed stream of liquid droplet radiators

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Abstract. The problem of radiation cooling of a moving dispers stream is solved taking into account the heat transfer along the movement of the stream due to the action of the radiation heat conduction mechanism. Taking this phenomenon into account leads to the formation of a heat wave region in the solution of model equations. The characteristic parameters of this heat wave are calculated, the influence of heat waves on the stability of the process of forming the equilibrium flow temperature profile is discussed.

1. Introduction

New scientific, technical, and information and telecommunication challenges related to the use of outer space imply a significant increase in the power supply of spacecraft. The most problematic part of their power plants is the low-potential heat removal system, the radiating element in which, as a rule, are radiator panels. With an increase in the output power, the surface area rapidly grows, and with it the mass and micrometeorite vulnerability of such systems. Calculations show that the use of panel radiators is effective in the case when the power installation of a long-term functioning spacecraft does not exceed ~ 100 kW. At high capacities, it becomes reasonable to use a liquid droplet radiator (LDR).

The schematic diagram of the LDR is shown in Fig. 1. The droplet generator creates a dispersed stream. Droplets in this stream freely move through outer space and collected by the droplet trap. As they propagate, the droplets cool by radiation.

The problem of radiative cooling of a drop sheet has been repeatedly considered in [1]. Using the model of isotropically scattering gray medium, cooling of an extended sheet of droplets moving along the x axis with velocity \( u \) was studied (Fig. 2). The initial temperature of the droplets was considered equal to \( T_0 \). The following approximate equation was used for the cooling of the medium:

\[
\rho_m c_m \frac{\partial T}{\partial x} = -C \frac{\partial q}{\partial y},
\]

(1)

\[
T(x = 0) = T_0,
\]

(2)

where \( q \) is the radiative heat flow per unit area and time, \( C \) is a constant depending on the optical properties of the medium and the flow velocity \( u \), \( c_m \) is the heat capacity of the medium, and \( \rho_m \) is the density of the medium.
The separation of variables shows that the cooling process occurs in two stages. Initially, an equilibrium flow temperature profile is formed, and then cooling occurs while maintaining this profile. The establishment process is numerically and analytically studied, and a method for calculating the optimal characteristics of a dispersed flow is proposed.

In the model setting, the problem was considered in [2]. It was believed that the dispersed LDR flow consists of uniformly distributed liquid aluminum droplets with a size of about 20 μm and a temperature close to 1000 K. In contrast to [1], a model of non-isotropically scattering gray medium was used. In this case, the approximate cooling equation (1) was also used. The effect of the optical properties of the flow on its cooling was studied; a method for calculating the optimal optical flow thickness is proposed.

The paper [3] presents the results of numerical simulation of radiation cooling of a dispersed stream of LDR, the material of the drops of which is aluminum.

In the work [4], the laws of radiation cooling of a dispersed LDR flow with technically feasible characteristics were studied: material and droplet size, their temperature, optical flow thickness, etc. It was shown that the approximation used by [1] of a negligible time to establish an equilibrium temperature profile applicable to high-temperature emitters \(T \sim 1000\) K is not true in the case of low-potential emitters \(T \sim 400\) K. It is also shown that the process of establishing the temperature profile is nonmonotonic, and at sufficiently high temperature the droplets can completely lose stability. The results were obtained in the approximation of a discrete medium, taking into account long-range radiation interactions in the stream. However, it follows from general reasoning that analogues of these results can also be obtained using the model of a continuous medium.

2. Statement of the problem

We studied the cooling of an extended droplet stream of thickness \(h\) (see Fig. 2). It was believed that particles in the flow are distributed isotropically with a concentration \(n\) equal to

\[
n = \frac{1}{\alpha r^3},
\]

where \(r\) is the radius of the droplets, and \(\alpha r\) is the average distance between adjacent drops.

It was considered that the working fluid is an organosilicon oil with a working temperature not exceeding \(T \sim 600\) K. It is technically possible to create a stable dispersed flow with droplets with a...
radius of more than 150 microns. Such particles effectively absorb their own thermal radiation: the integral degree of blackness of the droplets is close to 1 [5]. Thus, the average path length of thermal radiation in the stream will be \( l \)

\[
l = \frac{\alpha^3}{\pi r}
\]

Figure 2. Cooling of an extended flat dispersed stream.

Given this ratio, the thermal diffusivity of the medium \( \chi \) can be calculated using the formula [6]:

\[
\chi = \frac{1}{\rho c_m c_p} \frac{16\sigma T^3}{3} l = \left( \frac{\alpha}{\pi} \right)^2 \frac{\sigma r}{\rho c} T^3,
\]

where \( c \) and \( \rho \) are the heat capacity and density of the working fluid.

Taking into account the last relation, the equation of medium cooling can be represented as:

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = \left( \frac{\alpha}{\pi} \right)^2 \frac{\sigma r}{\rho c} \text{div}(T^3 \text{grad}(T)) + \tilde{q},
\]

where the term \( \tilde{q} \) describes the volumetric release or absorption of heat. The boundary condition for equation (6) for \( y = 0 \) and \( y = h \) has the form:

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = \frac{3(1-\tilde{\phi})\sigma T^4}{\rho c},
\]

where \( \tilde{\phi} \) - geometric coefficient describing the re-irradiation of droplets on the surface of the stream.

3. One-dimensional model of the cooling process

The aim of this work is a qualitative study of the dynamics of radiation cooling of a dispersed stream. The problem was solved in a one-dimensional formulation. It was believed that the temperature of the drops depends only on \( x \) and \( t \). After integrating the system of equations and passing to dimensionless variables, we obtained the following model equation:

\[
\frac{\partial \tau}{\partial t} + \frac{\partial \tau}{\partial z} = \nu \frac{\partial^2 (\tau^4)}{\partial z^2} - \tau^4,
\]
The approximate equation (8) is not applicable for calculating the cooling of the LDR on location. However, this equation allows one to analyze the laws of radiation cooling of dispersed flows, and can also be used to verify computer models designed to solve equation (6). Below we consider only stationary solutions to equation (8).

The initial condition for equation (8) has the form

$$\tau|_{z=0} = 1, \quad \frac{\partial \tau}{\partial z}|_{z=0} = \frac{3(1-\varphi)\sigma T_0^3}{2\rho c u} = \beta$$

and is determined by the conditions of re-irradiation of particles with a droplet stream, as well as with a droplet generator.

Calculations show that the characteristic value of \( \varepsilon \) is \( \varepsilon \sim 10^{-3} \). Thus, relation (8) is a differential equation with a small parameter for the highest derivative. Therefore, the solution of the problem can be divided into two areas: internal and external solutions.

In the field of the internal solution, the variables are replaced: \( z = \varepsilon \xi \). In the first order of expansion in \( \varepsilon \), equation (8) takes the form:

$$\frac{\partial \tau}{\partial z} = \frac{\partial^2 (\tau^4)}{\partial z^2}$$

The solution of equation (11) has the form:

$$\xi = A^4 \ln \left( \frac{\tau - A}{A - 1} \right) - 4A^2 (\tau - 1) - 2A (\tau^2 - 1) - \frac{4}{3},$$

**Figure 3.** The characteristic form of the solution of the one-dimensional cooling equation. 1 - internal solution; 2 - external solution; \( \tau^* \) is the dimensionless temperature at the crosslinking point of the solutions; \( \phi \) - the characteristic length of the heat wave described by the internal solution.
\[ A = 1 - 4\varepsilon \beta \]  
\( \varphi = 4A^3 \ln \left( \frac{A}{A-1} \right) - 4A^2 - 2A - \frac{4}{3} \) \( \varphi = 4A^3 \ln \left( \frac{A}{A-1} \right) - 4A^2 - 2A - \frac{4}{3} \)

Near this point, the internal solution of equation (8) “stitches” with the external solution. The external solution is described by the equation

\[ \frac{\partial \tau}{\partial z} = -\tau^4 \]  
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The matching condition was the equality of the values of \( \tau \) of the external and internal solutions, as well as the equality of their derivatives with respect to the coordinate. The desired value of the dimensionless temperature \( \tau^* \) can be found from the equation

\[ \tau^* + 4\varepsilon \left( \tau^* \right)^7 = A, \]  
\[ \tau^* + 4\varepsilon \left( \tau^* \right)^7 = A, \]

whence, using equation (12), the coordinate of the crosslinking point \( z^* \) can be found. Using the values of these quantities, the solution of equation (15) can be easily calculated.

4. Discussion

Equation (6), obtained in the work for modeling the cooling of a dispersed LDR flow, differs from relation (1) used in other works in that it takes into account heat transfer along the flow due to the action of the radiation heat conduction mechanism. Taking this phenomenon into account leads to the fact that in the solution of model equations a heat wave region with a characteristic length \( \varphi \) is formed (see Fig. 3). In the region of the heat wave, the temperature of the particles slightly differs from the initial one. The presence of a heat wave significantly increases the power allocated to the LDR. A heat wave arises not only in solving model equation (8), but also in solving a complete system of equations (6). Numerical calculations show that the region of the heat wave has the shape of a tapering “tongue” in the coordinate system \( \{x, y\} \).

When the parameters of the droplet flow created by the droplet generator are changed, the value of parameter \( A \) changes. The disturbances inside the “tongue” of the heat wave propagate faster than the droplets [6]. Thus, changes in parameters lead to a change in the propagation length of the heat wave. This phenomenon is an analogue of the effect of oscillations of the phase trajectory of the system when establishing the equilibrium temperature profile of the dispersed flow described in [4].

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