Journal of Engineering Physics and Thermophysics, Vol. 71, No. 1, 1998

MODELING OF RADIATIVE HEAT TRANSFER AND MASS TRANSFER PROCESSES IN DROP-FLOW-BASED HEAT EXCHANGERS FOR SPACECRAFT

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UDC 62-714:629.7.018.3

Modeling of radiative heat transfer and mass transfer in drop-flow-based heat exchangers for spacecraft is considered. A Monte Carlo-based numerical model is presented. Results obtained with the aid of the model are analyzed and compared with existing data.

A cooling system should be organized on board a spacecraft to provide dissipation of heat into open space in the operation of energy sources and consumers. As applied to rather powerful energy installations ($N_{el} > 50$ kW), use of systems with direct contact of the coolant with space (in particular, drop coolers/radiators) is appropriate. Drop coolers/radiators have substantially smaller weight and dimensions than heat exchangers fabricated using standard technologies, since they have a better developed heat-exchange surface, which, in addition, need not be armored (armoring is used to protect channels filled with the coolant from possible destruction by micrometeorites).

To provide a practical solution to the problem of the development of the new type of cooler/radiator, reliable data are required that would make it possible to predict heat transfer processes, generation, motion, and accumulation of drops under conditions of zero gravity and high vacuum.

In simulation of radiative heat transfer, the model based on a discrete presentation of the drop layer is closest to a realistic description of the processes. This makes it possible to evaluate the temperature of any drop located at an arbitrary point of the drop layer. The use of methods of geometrical optics and the scalar Mie theory combined with Monte Carlo simulation makes it possible to make the most comprehensive allowance for absorption and scattering phenomena taking place in the drop layer. In addition, this approach is acceptable in modeling heat transfer and evaluating mass losses of the coolant due to evaporation.

In this work, we present results of developing mathematical models of heat and mass transfer processes and choosing the main parameters of a drop cooler/radiator unit.

1. An approximate analysis of the radiative cooling of a drop layer has been presented in [1]. A homogeneous distribution of the temperature over the layer thickness was assumed. The main advantage of this method consists in the fact that results can be obtained analytically. However, this method can be applied only to optically thin layers ($\tau \le 1$, where $\tau = C_e \pi r^2 nD$), when the radiation emitted by the drops leaves the layer almost entirely. It should be noted that C_e, as well as τ, is a dimensionless quantity. When the optical thickness of the layers increases, calculations based on the method of [1] lead to underestimated layer cooling times.

In the case of an optically thick layer ($\tau >> 1$) the temperature distribution and the intensity of the radiation source become inhomogeneous and time-dependent due to substantial screening. To take into account the temperature inhomogeneity, a method of two-dimensional calculation of the parameters of a flat drop layer has been proposed in [2]. In this case a homogeneous model of the drop layer is considered, which is a drawback of this method. This precludes the possibility of evaluating the actual temperature of drops located at the very edges of the layer, especially at peripheral corner zones.

Scientific-Research Institute of Thermal Processes, Moscow, Russia; Scientific-Research Institute of Applied Mechanics and Electrodynamics at the Moscow Aviation Institute, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 1, pp. 92-96, January-February, 1998. Original article submitted May 23, 1997.

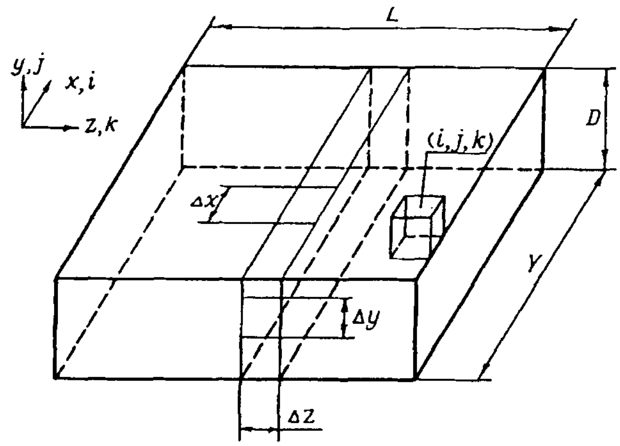

Fig. 1. Basic geometric model of a drop layer.

In [3, 4], methods making it possible to calculate the temperature of individual drops located at an arbitrary point of the drop layer have been presented. In these cases, geometrical models of the drop layer that consist of cells bounded by mutually perpendicular planes each of which contains a fixed number of drops are used. Thus, in [3] drops are situated on a straight line, and in [4] drops can be arranged arbitrarily, which makes it possible to evaluate the temperature of drops located at the periphery of a layer by setting corresponding boundary conditions on the bounding planes. Here complications arise when evaluating angular coefficients of radiative transfer between drops. The use of conventional methods is connected with explicit or inexplicit integration over surface areas, which is rather difficult.

The method of calculation of radiative heat transfer from a drop layer in vacuum considered in what follows describes heat transfer in a three-dimensional formulation and modeling of scattering of thermal energy within the layer with account for the indicatrix of scattering on spherical particles.

2. Let us consider the thermal radiation of a rectangular drop layer in vacuum (Fig. 1). The layer consists of identical moving spherical drops of radius r and concentration n. The layer dimensions along the x, y, and z axes are Y, D, and L, respectively. The drops move along the z axis at a velocity u and are assumed to be distributed in a uniform manner within the layer. To carry out the numerical modeling, the layer is divided into rectangular cells with dimensions Δx, Δy, and Δz.

Due to the small size of the cells, the drops within a cell are considered to have the same temperature. Their initial temperature in the first layer along the z axis (at the exit of the drop generator) equals T_0. External heat supply (from the sun or other sources) is absent; however, if necessary, it can be taken into account by introducing corresponding source terms into the heat balance equation. The drops are assumed to emit monochromatic radiation. The wavelength at which the surface density of the monochromatic radiation flow reaches its maximum will be taken as the wavelength for which all optical parameters are evaluated. In the case of a blackbody it can be calculated by Wien's displacement law:

$$(\lambda T)_{\max q} = 2897.6 \quad [\mu\text{m}\cdot\text{K}] \quad \text{or} \quad \lambda = 2897.6/T \quad [\mu\text{m}].$$

Here T is the temperature of the drops for which the wavelength is evaluated. It can be assumed that $T = T_0$.

Knowning the drop radius r, the drop material, and the radiation wavelength λ, one can find the quantities C_s, C_a, and $C_e = C_a + C_s$ for a single drop. These cross sections are determined by means of the scalar Mie diffraction theory [5], which permits consideration of both transparent and opaque drops, which makes it possible to take scattering and absorption into account more completely. In evaluating the cross sections, the complex-valued refractive index of the droplet material $R = R_r + R_i i$ is used, where R_r is the real part of the refractive index, which determines the refraction itself (Snell's law), and R_i is the imaginary part of the refractive index, reflecting the degree of attenuation of the incident electromagnetic radiation (degree of absorption). Among possible droplet materials we considered Sn, Li, VM-1 and VM-4 grade vacuum oils, and PMS-type silicone liquids.

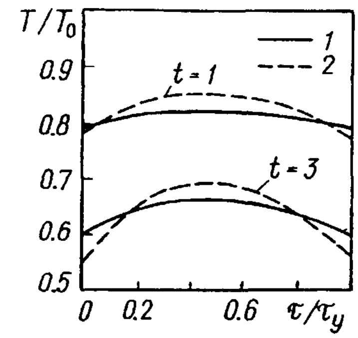

Fig. 2. Temperature field in a drop layer: 1) data from the present work, 2) [2].

For metals, in the case of long wavelengths (in particular, infrared radiation) one can obtain [6] $R_r = R_i = \lambda\sigma_0/c$, where σ_0 is the conductivity of the metal and c is the speed of light. This formula has been verified for infrared radiation and yielded rather accurate results for $\lambda > 5\ \mu$m. The energy balance in the cell with indices i, j, k, where k is the number of the cell layer along z, j is the number of the cell row along y, and i is the number of the cell row along x, is determined in the following manner. During the time interval $\Delta t = \Delta z/u$ all drops from the cell i, j, k move to the cell i, k, $k+1$ (see Fig. 1). It should be noted here that all cells are assumed to have the same dimensions. During the same time interval Δt the drops from the cell i, j, k emit the energy

$$E_{ijk} = n\Delta z\Delta y\Delta x\ 4\pi r^2 \varepsilon_\lambda\ \sigma T_{ijk}^4 \Delta t\,,$$

where ε_λ is the degree of blackness of the drop surface, which can be defined as $\varepsilon_\lambda = \ C_a\,\pi r^2$ or, in terms of the efficiency coefficients $Q_a = C_a/\pi r^2$, $Q_e = C_e/\pi r^2$, and $Q_s = C_s/\pi r^2$, as $\varepsilon_\lambda = Q_a$, σ is the Stefan–Boltzmann constant, and T_{ijk} is the temperature of the drops in the cell ijk. It is also assumed that the energy of all cells in the k-th layer is scattered only within this k-th layer and exits to the environment (vacuum), and the faces of the k-th layer separating this the layer from the $k-1$-th and $k+1$-th cell layers are specularly reflecting. This assumption is substantiated because the temperature gradient along the z direction is substantially smaller than those along x and y. Thus, one can assume that the layers k and $k-1$ or k and $k+1$ exchange approximately equal portions of energy during the time interval Δt. At the same time, a rather substantial portion of energy is transferred through boundaries of the k-th cell layer to the surrounding space without compensation from outside.

It is assumed that the energy E_{ijk} is emitted along N random directions, with the energy E_{ijk}/N emitted along each of the directions. This formulation makes it possible to use the Monte Carlo method. A model pseudoparticle whose motion in the drop layer takes place with scattering and absorption obeying the Mie law is assumed to be the energy carrier. It is known [5] that this law determines the coefficients of absorption and scattering of electromagnetic radiation by a sphere, as well as the scattering indicatrices for an arbitrary spherical particle. The pseudoparticles moving from the cell ijk can be scattered repeatedly on drops, followed by absorption in a cell of the k-th layer or exit to the surrounding space at the end of its trajectory. In the case of absorption, the energy carried by the pseudoparticle is added to the thermal energy of the absorbing cell. When the pseudoparticle exits into the surrounding space, the drop layer loses the corresponding energy.

The above-described operation is repeated for all N pseudoparticles of the cell ij and for all cells ij of the k-th layer. When this procedure is completed, the thermal balance of each cell ij is

$$4/3\ n\Delta x\Delta y\Delta z\,\pi r^3 \rho c_p\,(T_{ijk} - T_{ijk+1}) = E_{ij} - A_{ij}\,,$$

where ρ and c_p are the density and specific heat of the particle material, A_{ij} is the amount of energy introduced into the cell ij from neighboring cells due to absorption by pseudoparticles. As a result of solving this equation, the temperature T_{ijk+1} of the cell ij in the layer $k+1$ is determined. The calculation is repeated until the layer k_{max} (the layer in the vicinity of the drop collector) is reached. Thus, the distribution of temperatures T_{ij} is determined in the process of layer-to-layer motion. With the temperature distribution known, one can evaluate the energy emitted by the drop layer into the surrounding space per unit time:

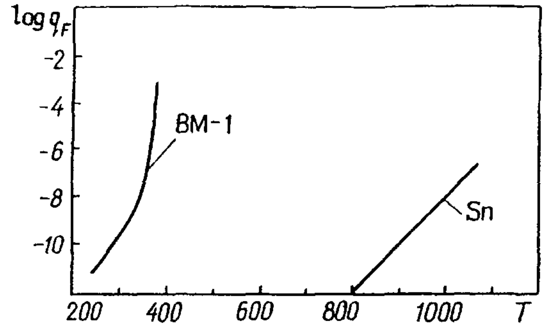

Fig. 3. Temperature dependence of the rate of removal of the coolant (tin and VM-1 grade vacuum oil) due to evaporation. T, K.

$$E = 4/3\,\pi r^3 \rho c_p un\Delta x\Delta y\, E_{ij}\,(T_0 - T_{ijk\,\max})\,.$$

Results of calculations by this method carried out for a layer of tin drops of size $d = 100$, 200, and 300 μm for $T_0 = 1000$ K and other conditions similar to those in [2] were compared with results of [2]. In the case of the model of an optically thin layer ($\tau = 1$) the results virtually coincided (Fig. 2), and for $\tau > 5$ satisfactory agreement was observed. In the method described, the three-dimensional nature of the layer is taken into account (in [2], a two-dimensional problem is considered), and more rigorous modeling of scattering of thermal energy within the layer is carried out with account for the indicatrix of scattering on spherical particles. Figure 2 presents results of calculations of temperature profiles for a layer with optical thickness $\tau = 5$ carried out by the two methods.

Results of calculations with the number of pseudoparticles $N = 100$, 200, 300, and 1000 agree rather well, which makes it possible to recommend, under the given conditions, use of $N = 100$. The temperature profile along the layer depth has a maximum that corresponds to the half-thickness of the layer and is explained by the inhomogeneity of the radiative heat transfer within the drop layer, since the optical thickness substantially exceeds unity. The number of cells along x, y, and z was specified as 10 to 20, 5 to 10, and 30 to 50, respectively.

3. Evaporation of the coolant in the drop layer during operation of the radiator is an important factor that determines whether the drop cooler/radiator can be used under the conditions of open space. The flow density of the matter evaporating from unit surface in unit time (vapor mass rate) can be determined in the following manner:

$$q_F = G_v/F = \gamma_v u_v K^v\,,$$

where $\gamma_v = P_{sat}/(RT)^{1/2}$ is the density of the vapor formed, $u_v = (8kT)^{1/2}/\pi m_v$ is the average thermal velocity of the vapor molecules at the surface, K^v is a coefficient that takes into account the fraction of vapor molecules formed, G_v is the mass flow rate of the vapor, F is the area of the evaporation surface, T is the temperature of the evaporating drop surface, k is the Boltzmann constant, P_{sat} is the temperature-dependent pressure of the saturated vapor, and m_v is the mass of a vapor molecule.

Taking into account that $R = k/m_v$ and $K^v = 0.25$, one can write

$$q_F = \gamma_v u_v K^v = P_{sat}\,(T)/(2\pi RT)^{1/2}\,.$$

The expression obtained is known as the Langmuir–Knudsen formula. Other, more rigorous approaches to the evaluation of the mass rate of evaporation of the material that also take into account the condensation rate of the vapor in the boundary layer of the evaporation surface are known. Figure 3 presents results of calculations of the rate of removal of the coolant (tin and VM-1 grade vacuum oil) due to evaporation, expressed in kg per m^2 of the surface of the material being evaporated per second. The results indicate that the mass losses of these materials allow their use as the working body of drop coolers/radiators within the considered range of the parameters.

4. A drop cooler/radiator should operate under conditions of open space, i.e., under conditions of microgravity and high vacuum. At the same time, one should provide for the process of generation of a flow of drops moving at a predetermined velocity and their collection. A decision on the practical use of a cooler of the type under

consideration in cooling systems of power installations will be possible only after experiments in space (under the actual conditions of the simultaneous action of microgravity and high vacuum and the special features of the generation and collection of drops). Without dwelling in detail on how to arrange such an experiment, we should note that, in order to provide the necessary accuracy of the experiment and better conditions for visual observation of the motion of a single drop, use of the following two drop generators is proposed: 1) the spinneret of the generator has one hole, and drops move along a straight line perpendicular to the spinneret surface; 2) the spinneret has several holes whose axes lie in a plane perpendicular to the spinneret surface. Under these conditions, one can observe the formation and motion of single drops and convergence/divergence of single-drop flows. As regards an on-board power installation based on the Brighton cycle in which the temperature of the coolant in the cooler/radiator changes from 400 to 300 K, drops of VM-1-type vacuum oil or silicone liquid can be used as the working body [7]. Spinnerets with a diameter of the holes of 100–200 μm (produced at the Moscow Power Engineering Institute, the Scientific-Research Institute of Applied Mechanics and Electrodynamics at the Moscow Aviation Institute, and the M. V. Keldysh Research Center) allow obtaining drop diameters of the same order. For these initial data, calculations were carried out that made it possible to determine the thickness of a flat drop layer within which a temperature variation along the thickness is admissible. In the future, to obtain optimum relationships among the geometric parameters of the drop cooler/radiator and decrease in temperature inhomogeneities, it is appropriate to consider profiling the layer by changing the drop diameter along its thickness. Based on the performed numerical analysis of the parameters of the drop cooler/radiator with account for results of laboratory experiments [4, 7] and the possibilities of the technology of fabrication of spinnerets, we can recommend the following ranges of variation of the main parameters of the generator: the drop diameter 100 to 200 μm, the drop velocity 5 to 10 m/sec, and the distance between the axes of the flows (i.e., between the centers of the spinneret channels) 2 to 5 mm.

The developed model and method for calculation of radiation heat transfer in a drop layer in a three-dimensional formulation with account for the scattering indicatrix of the thermal energy within the layer made it possible to model transfer processes in drop layers. The main parameters of a drop cooler/radiator were determined as a result of the numerical investigation carried out in the present work.

NOTATION

N_{el}, power of the energy installation; τ, optical thickness; $\tau_y = yr/D$, its current value across the drop layer; n, concentration of the drops; r, drop radius; x, y, and z, Cartesian coordinates; Y, D, and L, width, thickness, and length of the drop layer; u, velocity of motion of the drops; Δx, Δy, and Δz, cell dimensions along the corresponding axes; T_0, initial temperature of the drops; λ, wavelength; T, temperature of the drops; t, time; C_s, C_e, and C_a, scattering, extinction, and absorption cross sections of a single drop.

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