Solution of the energy equation of a two-phase medium taking into account heat transfer between phases

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Abstract: *In this paper, we consider the problem of supersonic flow around a gas with solid particles. When studying the flow of gas with particles in the snot, a near-wall region of the light phase was found. In a specific example, numerical calculations are made and, on the basis of the results obtained, the shape of the surface of a curvilinear angle, the distribution of pressure and temperature of the flow along the surface at various values of the diameter and concentration of particles are constructed.*

Key words: *two-phase medium, supersonic flow, rarefaction wave, dynamic sliding, heat transfer, barotropic medium.*

In this work, the problem is solved with the involvement of the energy equation of both a single-phase and a two-phase medium, taking into account heat transfer between the phases. Using the interpenetrating model of a multivelocity continuum [1] and equation [2], the problem of flow around a “curvilinear angle” greater than 180° by a gas flow with solid particles at supersonic speed is solved (Fig. 1). In a barotropic medium [3], in the case of a rarefaction flow over the body surface, two regions are obtained: I - between the characteristic and the separation line (dashed line) and II - between the separation line and the solid surface (solid curve). When studying the flow of gas with particles in nozzles, a near-wall region of the light phase was found [4–8]. Without taking into account the volume occupied by particles, the supersonic two-phase flow around a thin airfoil was considered [9] and, in particular, the structure of the rarefaction wave and the near-wall region under dynamic phase slip were studied.

The article [13] analyzes the transfer of matter in inhomogeneous porous media, taking into account the inhomogeneous distribution of the velocity field.

In [14], the problem under consideration is of great importance for aviation and rocket and space technology. In the article, a comparative testing of the Chen k-ε, Sekundov γ_t-92 models and the turbulence model based on the dynamics of two fluids for an axisymmetric subsonic jet is carried out.

In contrast to [3,9], the above problem is solved using the energy equations of both a single-phase and a two-phase medium, taking into account heat transfer between the phases; the kinematic parameters of the gas in region II are determined from the solution of the corresponding boundary value problem, and the temperature is determined from the gas energy equation in finite differences. In a particular example, numerical calculations were made and, based on the results obtained, the shape of the surface of a curvilinear angle, the distribution of pressure and temperature of the flow along the surface were constructed for various values of the diameter and concentration of particles.

Let us consider the flow around a concave corner by a plane supersonic flow of a two-phase medium with an initial velocity U_0 . In this case, a rarefaction wave occurs, which in a linear setting degenerates into the characteristics x-ωy=0, and for a plane stationary flow of a mixture of gas and particles in the absence of external and heat flows, we have the equations of motion, continuity and energy [2] :

$$\left.\begin{aligned} u_n\frac{\partial u_n}{dx}+v_n\frac{\partial u_n}{dy}=-\frac{1}{p_{ni}}\frac{\partial p}{\partial x}+\frac{K}{p_n}\sum_{j=1}^{2}(u_j-u_n) \\ u_n\frac{\partial v_n}{dx}+v_n\frac{\partial v_n}{dy}=-\frac{1}{p_{ni}}\frac{\partial p}{\partial y}+\frac{K}{p_n}\sum_{j=1}^{2}(v_j-v_n) \end{aligned}\right\}. \quad (1)$$

$$\frac{\partial}{\partial x}(p_n u_n)+\frac{\partial}{\partial y}(p_n u_n)=0 \quad (2)$$

$$\left.\begin{aligned} \overrightarrow{V_1}\nabla i_1-\frac{1}{p_{1i}}\overrightarrow{V_1}\nabla p+N=0,\overrightarrow{V_2}\nabla i_2-q=0 \\ N=\frac{p_2}{p_1}\left[q+\frac{K}{p_2}(V_2-V_1)^2\right],\ V_n^2=u_n^2+v_n^2, n=1,2 \end{aligned}\right\}. \quad (3)$$

Considering that here we consider a mixture of gas and solid incompressible particles, we supplement the system (1)-(3) with the equations of state of the phases [10]

$$p=R_1p_{1i}T_1\,,p_{2i}=const,i_1=c_1T_1,i_2=c_2T_2\,, \quad (4)$$

expression for the function q of interfacial heat transfer

$$q=\gamma(T_1-T_2) \quad (5)$$

and ratio

$$\frac{p_1}{p_{1i}}+\frac{p_2}{p_{2i}}=1; \quad (6)$$

Here p −pressure,u_n, v_n − speed, T_n − temperature, p_{ni}, p_n − true and reduced densities $n-phase$, к, γ − the coefficients of interaction and heat transfer between the phases, which in this case are taken constant, depending on the diameter $d0$ and density $p00$ particles, $R1$ is the gas constant, $c1c2$ are the heat capacity coefficients.

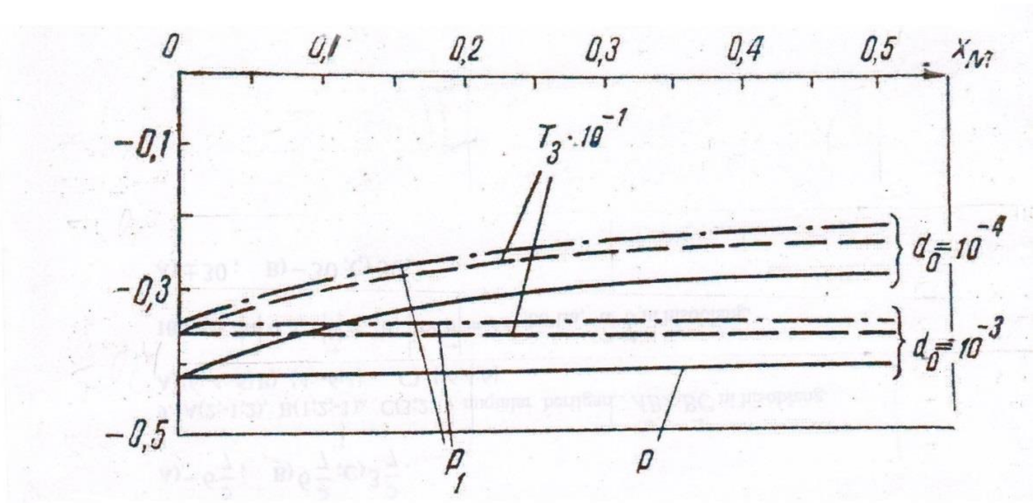

Fig.1. The contour of the flow around the angle is greater than 180° by the flow of gas with solid particles.

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$To\ system\ (1)-(6), which\ is\ valid\ in\ region\ I, the\ linearization\ method\ is\ applied\ for$

$$\left.\begin{matrix} u_n = u_0 + u_n^{`}\ ,\ \rho_n = \rho_{n0} + \delta_n\ , \rho_{1i} = \rho_0 + \varepsilon_1 \\ T_n = T_0 + T_n^{`}\ , p = p_0 + p^{`} \end{matrix}\right\}, \qquad (7)$$

where u_0, ρ_{n0}, p_0, ρ_0, T_0 are constants; $u_n^{`}$, $\varepsilon_n$, $\delta_n$, $T_n^{`}$, $p^{`}$-small values, indices 1 and 2 correspond to gas and particle parameters.

In the case of an irrotational potential flow (1)-(6), taking into account (7), they take the form

$$A_1\frac{\partial^3\varphi_1}{\partial x^3} + A_2\frac{\partial^3\varphi_1}{\partial x\partial y^2} + A_3\left(\frac{\partial^3\varphi_2}{\partial x^3} + \frac{\partial^3\varphi_2}{\partial x\partial y^2}\right) - A_4\frac{\partial^2\varphi_1}{\partial x^2} + A_5\frac{\partial^2\varphi_1}{\partial y^2} + A_6\frac{\partial^2\varphi_2}{\partial x^2} + A_7\frac{\partial^2\varphi_2}{\partial y^2} + A_8\left(\frac{\partial\varphi_2}{\partial x} - \frac{d\varphi_1}{dx}\right) = 0\ , \qquad (8)$$

$$B_1\frac{\partial\varphi_1}{\partial x} - B_2\frac{\partial\varphi_2}{\partial x} = -B_3(\varphi_1 - \varphi_2)\ ; \qquad (9)$$

φ_1, φ_2 − speed potentials, $A_i(i = \overline{1,8}), B_j(j = \overline{1,3})$ − known constant coefficients depending on the Mach number in the gas, concentration and phase interaction coefficient. Since the near-wall region II is occupied by a gaseous medium, then for the velocity potential φ_3 of the perturbed flow

$\varphi_{3yy} = \mu^2\varphi_{3xx}(\mu^2 = M_1^2 - 1).$ (10)

The pressure and temperature of the flow on a solid surface are found by the Bernoulli and energy equations [11] in a finite difference. Such an approximation of the energy equation will be the more accurate, the smaller the thickness of the near-wall region II.

Let the phase separation line be given as a straight line and form an angle β_0 with the x-axis. It is obvious that this line is represented as a boundary streamline of particles through which the gas passes freely into region II. Therefore, for (8)-(10) we have boundary conditions at $y = 0$, $\varphi_{2y} = -u_0\beta_0$, $\varphi_{1y} = \varphi_{3y}$, $\varphi_{1x} = \varphi_{3x}$. (11)

We add that the speeds of a two-phase system at infinity are limited and on the characteristic

$\varphi_1 = \varphi_2 = 0$ (12)

On the solid boundary, the condition of flow around the gaseous medium is satisfied, at

$y = f(x), \varphi_{3y} = -u_0\beta(x), \left[\beta(x) = \frac{df(x)}{dx}\right]$; (13)

here β(x) is the angle of inclination of the tangents to the elements of the curvilinear side of the angle, which depends on the shape of the dividing line, the structure of the flow, is an unknown function and must be determined in the process of solving the problem.

Applying the Laplace transform [12] to (8), (9), it is easy to obtain solutions (8), (9) for X that satisfy the boundary conditions (11) и (12):

$$\varphi_1(x,y) = u_0\beta_0 e^{-a_0 y}\frac{\rho_{00}}{\rho_0}\sum_{v=0}^{\infty} b_v\left\{\frac{t^{*v+1}}{(v+1)!} + \sum_{x=1}^{\infty} c_x^0\frac{t^{*v+x+1}}{(v+x+1)!} - \frac{k}{\rho_{10}}\frac{\rho_0}{\rho_{20}}\left(\frac{\rho_{00}}{\rho_0} - 1\right)\left[\int_0^{t^*} f_1(t^*-\tau)f_3(\tau)d\tau + \sum_{x=1}^{\infty} c_x^0\int_0^{t^*} f_2(t^*-\tau)f_3(\tau)d\tau\right]\right\},$$

$$\varphi_2(x,y) = u_0\beta_0 e^{-a_0 y}\sum_{v=0}^{\infty} b_v\left[\frac{t^{*v+1}}{(v+1)!} + \sum_{x=1}^{\infty} c_x^0\frac{t^{*v+x+1}}{(v+x+1)!}\right], \qquad (14)$$

где

$$t^* = x - wy, w^2 = -\frac{A_1B_2 + A_3B_1}{A_2B_2 + A_3B_1},$$

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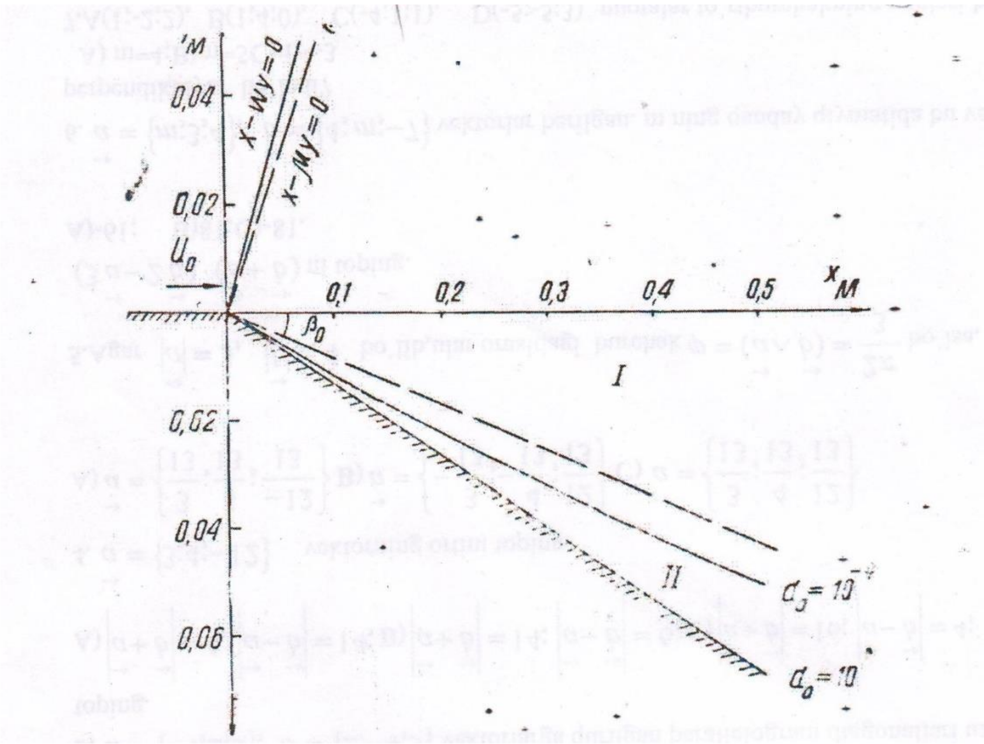
$$f_1(t^*) = \frac{t^{*v+1}}{(v+1)!},$$

$$f_2(t^*) = \frac{t^{*v+x+1}}{(v+x+1)!}$$

$$f_3(t^*) = e^{-\frac{B_3}{B_1}t^*},$$

$a_0, \alpha_1, \alpha_2, \beta_1, \beta_2, b_v, c_x^0$ – known constant coefficients. Now, taking into account (14) and the equations of motion and energy (1), (3), it is easy to obtain formulas for pressure and temperature at the phase separation line.



Rice. Fig. 2. Distribution of gas flow pressure and gas temperature (dashed line) in the flow region.

Equation (10) has a solution

$$\varphi_3(x,y) = f_1(x-\mu y) + f_2(x+\mu y) \quad ; \qquad (15)$$

the functions $f_1(x)$ and $f_2(x)$ taking into account (11), are known from the solution (14) in the flow region of a two-phase medium, are not given. Substituting (15) into (13), we obtain a first-order differential equation with respect to $f(x)$, which determines the shape of the solid surface.

The direct problem is solved similarly, i.e. for a given value of the angle β_{00} of the solid surface with the X axis, in the course of solving, the parameters of regions I, II and the shape of the surface of the phase separation line are found.

For a specific calculation, consider the case $v_0 = 0$, $x = 1$ and use the Stokes resistance law cd=24/Re to find the phase interaction coefficient. Then the results for the steam-water mixture [10] at $p_0 = 10$ atm, corresponding to the initial parameters

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$$T_0 = 481 \text{ град}, c_1 = 4{,}8 \cdot 10^3 \text{ м}^2/\text{сек}^2 \cdot \text{град},$$

$$c_2 = 4{,}4 \cdot 10^3 \text{ м}^2/\text{сек}^2 \cdot \text{град}, \beta_0 = 0{,}0875,$$

$$M_1 = 1{,}85\ ,\ \rho_{00}/\rho_0 = 1{,}8\ , \rho_0 = 0{,}5 \text{ кг} \cdot \text{сек}^2/\text{м}^4,$$

$$\rho_{00} = 0{,}9 \text{ кг} \cdot \text{сек}^2/\text{м}^4, \rho_{10} = 0{,}45 \text{ кг} \cdot \text{сек}^2/\text{м}^4$$

and coefficients K,γ for different values of the particle diameter d_0 are shown in Figs. 2. According to the calculations, the thickness of the near-wall region II depends on the concentration and diameter of the particles, i.e. the smaller the particle, the thinner the region II, and at $d_0 = 10^{-5} sm$ it almost disappears, then, apparently, the flow should be considered as single-velocity. The two-phase flow parameter is less than the pure gas parameter, therefore, the perturbed region I becomes wider than the perturbed region of pure gas.

The pressure increment curves of the mixture of gas and particles in fig. 2 is higher in absolute value than the corresponding single-phase flow curves p_1, and the gas temperature distribution curve $(T_3 = T_3^{`}/T_0)$ on a solid surface at $d_0 = 10^{-4} sm$ is concave relative to the x axis and is located above the corresponding direct line for $d_0 = 10^{-3} sm$ see

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