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SOLUTION OF NONAUTOMODELED PROBLEMS OF BOUNDARY-LAYER THEORY TAKING INTO ACCOUNT NONSTATIONARY CONJUGATE HEAT EXCHANGE AND BLOWING

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The results of an investigation of conjugate heat exchange when a supersonic flow of gas flows around a spherical shell when gas blows from the surface of the material are presented.

Theoretical and experimental investigations [1] of the effect of blowing on heat flows to the surface of bodies lead to problems of the supersonic flow of a perfect gas around a porous or perforated spherical shell. Because of the need to take into account the inertia of the heat transfer in the shell material one must solve a combined heat and mass transfer problem, since when the blowing law of the contour of the body is assigned arbitrarily, the heat-transfer coefficient will be the required function of the process and it is difficult to use a separate formulation.

As in [2-4], which are devoted to calculating conjugate heat exchange in the boundary layer, we considered a system of nonautomodeled equations of the boundary layer, we used the nonstationary equation of heat conduction for the material of the body, taking porosity into account, and on the boundary of separation of the media we used the condition of conservation of energy.

Consider the system of equations of the laminar boundary layer [4]

$$\frac{\partial}{\partial\eta}\left(l\frac{\partial^2 f}{\partial\eta^2}\right)+f\frac{\partial^2 f}{\partial\eta^2}+\beta\left[\frac{\Theta}{\Theta_e}-\left(\frac{\partial f}{\partial\eta}\right)^2\right]=\alpha\left(\frac{\partial f}{\partial\eta}\frac{\partial^2 f}{\partial\eta\partial s}-\frac{\partial^2 f}{\partial\eta^2}\frac{\partial f}{\partial s}\right), \tag{1}$$

$$\frac{\partial}{\partial\eta}\left(\frac{l}{\mathrm{Pr}}\frac{\partial\Theta}{\partial\eta}\right)+f\frac{\partial\Theta}{\partial\eta}=\beta\gamma\frac{\Theta}{\Theta_e}\frac{\partial f}{\partial\eta}-l\gamma\left(\frac{\partial^2 f}{\partial\eta^2}\right)^2+\alpha\left(\frac{\partial f}{\partial\eta}\frac{\partial\Theta}{\partial s}-\frac{\partial f}{\partial s}\frac{\partial\Theta}{\partial\eta}\right). \tag{2}$$

The equation of conservation of energy in a solid porous body, assuming the process to be one-dimensional, and that the medium is at the same temperature, has the form

$$\pi_\rho\frac{\partial\Theta_1}{\partial\tau}=\frac{\partial}{\partial y_1}\left(\pi\frac{\partial\Theta_1}{\partial y_1}\right)+\frac{\partial\Theta_1}{\partial y_1}\left[\sqrt{\mathrm{Re}}\,\mathrm{Pr}\frac{\lambda_{e0}}{\lambda_{1*}}(\overline{\rho v})_w\frac{1}{(1-y_1)^2}-\pi\frac{2}{(1-y_1)}\right]. \tag{3}$$

We used a natural system of coordinates when writing Eqs. (1)-(3). The coordinate y_1 for the body is directed into the material normal to the surface. We assumed that $(1-y_1)^2(\rho v)_g\varphi=(\rho v)_{gw}\varphi_w$ within the pores of the material because of our assumption of the quasistationary nature of the equation of continuity [5].

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We assumed that the gas which is blown has the same composition as the gas of the incoming flow, and that the porosity remains unchanged during the process. In addition, we used the law of conservation of mass $(\rho v)_{gw} \cdot \varphi_w = -(\rho v)_w$.

The boundary and initial conditions can be written as follows:

$$\frac{\partial f}{\partial \eta}(\infty, s) = 1, \ \Theta(\infty, s) = \Theta_e, \tag{4}$$

$$\frac{\partial f}{\partial \eta}(0, s) = 0, \ f(0, s) = f_w = -\int_0^s (\overline{\rho v})_w \sin s ds \left[2\int_0^s \frac{\rho_e}{\rho_{e0}} \frac{\mu_e}{\mu_{e0}} \frac{u_e}{v_m} \sin^2 s ds\right]^{-0.5},$$

$$q_w(0, s)\sqrt{\mathrm{Re}}\,\mathrm{Pr}\,\frac{\lambda_{e0}}{\lambda_{1*}} - \pi_\sigma \Theta_w^4 = -\pi(\Theta_w)\frac{\partial \Theta_1}{\partial y_1}(\tau, 0), \tag{5}$$

$$\pi(\Theta_{1K})\frac{\partial \Theta_1}{\partial y_1}(\tau, L/R) = \sqrt{\mathrm{Re}}\,\mathrm{Pr}\,\frac{\lambda_{e0}}{\lambda_{1*}}(\overline{\rho v})_w(\Theta_{-\infty} - \Theta_{1K}), \tag{6}$$

$$\Theta_1(0, y_1) = \Theta_{1H}. \tag{7}$$

When writing the boundary-value problem (1)-(7), besides the notation used previously [4] and indicated at the end of this article, we introduced the following notation: $q_w = \lambda_w \left.\frac{\partial T}{\partial y}\right|_w \frac{\sqrt{\mathrm{Re}}}{v_m h_{e0} \rho_{e0}}$, dimensionless heat flow; $(\overline{\rho v})_w = (\rho v)_w \sqrt{\mathrm{Re}}\frac{1}{v_m \rho_{e0}}$, dimensionless rate of flow of gas when blowing through the porous shell; $\tau = \frac{t}{t_*}$, $t_* = \frac{R^2 \rho_{1*} c_{1*}}{\lambda_{1*}}$, $\pi = \frac{\lambda_1}{\lambda_{1*}}\varphi_1 + \frac{\lambda_g}{\lambda_{1*}}\varphi$, $\pi_\rho = \frac{\rho_1 c_1}{\rho_{1*} c_{1*}}\varphi_1 + \frac{\rho_g c_{pg}}{\rho_{1*} c_{1*}}\varphi$, $\pi_\sigma = \frac{\varepsilon \sigma R T_{e0}^3}{\lambda_{1*}}$.

The use of the quasistationary formulation of the problem implies the instantaneous matching of the fields in the gas phase with the change in the characteristics of the solid body, which corresponds to estimates of the relaxation time of the processes in the gaseous and solid phases.

The Prandtl number was taken as 0.7 in the numerical integration, and we used Sutherland's law for the coefficient of viscosity. Besides the assumption that c_p is constant, when carrying out the numerical integration the class of materials with specified porosity was limited in such a way that the second terms in the expressions for π and π_ρ could be neglected. In addition, in view of the relatively small temperature drop across the shell the thermal characteristics of the material were assumed to be constant quantities.

The boundary-value problem (1)-(7) was integrated using a difference scheme, obtained by an iterational-interpolational method [6]. The error of the approximation of the initial system of differential equations and boundary conditions was $O(\Delta\eta)^2 + O(\Delta s)$, $O(\Delta y_1)^2 + O(\Delta\tau)$. The difference scheme obtained ensured a stable calculation for different laws of blowing, and a number of calculations were carried out up to large time values τ, when, within the framework of the specified formulation, quasistationary flow occurs in the porous body. This enabled us to compare the numerical and analytical solutions.

The initial boundary-value problem includes the following parameters: M_∞, κ, adiabatic index; Pr, $\Theta_{-\infty}$, Θ_{1H}, $\sqrt{\mathrm{Re}}\,\mathrm{Pr}\,\lambda_{e0}/\lambda_{1*} = A$, conjugation parameter, characteristic for problems of conjugate heat exchange; L/R, relative thickness of the porous wall; the blowing law $(\overline{\rho v})_w(s)$; and also π_σ and φ_1.

For the numerical integration we varied the parameters M_∞, the temperature Θ_{1H}, which was taken equal to $\Theta_{-\infty}$, A, and L_R. We used two forms of the relation $(\overline{\rho v})_w(s)$: $(\overline{\rho v})_w = \text{const}$, $(\overline{\rho v})_w = -f_{w0}(\rho_e \mu_e u_e / \rho_{e0}\mu_{e0} v_m \alpha)^{0.5}$. The latter corresponds to the case $f_w = \text{const} = f_{w0}$.

We varied the step $\Delta\tau$ in the calculations, and in a number of versions we varied the step Δs. The method of numerical integration employed is the same as in [4].

We will consider the results of a calculation of the boundary-value problem (1)-(7). Figure 1 shows the change in the dimensionless heat flows q_w and the temperatures Θ_w and Θ_{1K} as a function of the longitudinal coordinate s for different instants of time and different blowing laws. Curves 1, 3, and 6 correspond to the initial instant of time $\tau = 0$, and curves 2, 4, 5, and 7-9 were obtained for $\tau = 0.07$ and correspond to the quasistationary temperature distribution in the solid porous body. When making the calculations for both blowing laws in the neighborhood of the front critical points, the dimensionless flow rate $(\overline{\rho v})_{w0}$ was taken to be the same.

As can be seen from the graphs, because of the maximum heat flow in the neighborhood of the front critical point this part of the body becomes heated most strongly, and this is where the maximum temperature of the surface Θ_w is established. The nature of the variation of Θ_w and q_w over the contour at different instants of time depends on the blowing law used, and also on the value of the conjugation parameter. As might have been expected, it can be seen from Fig. 1 that when using the blowing law $f_w(S) = f_{w0}$ the relative change in the heat flux $q_w(s)$ and in the temperatures $\Theta_w(S)$, $\Theta_{1K}(S)$ over the contour decrease at different instants of time compared with the case when $(\overline{\rho v})_w = \text{const}$.

When the conjugation parameter is increased, other conditions being equal, the temperature of the surface Θ_w increases more strongly at the same physical instant of time, since the removal of heat within the depth of the shell is much less. The temperature gradient in the solid $(\partial\Theta_1/\partial y_1)(\tau, 0)$ in this case increases, while the value of the temperature on the inner wall of the shell Θ_{1K} falls. It will be shown below that for a conjugation parameter A = 69.1 the thermal wave does not in fact reach the inner wall of the shell and $\Theta_{1K} = \Theta_{-\infty}$ in the neighborhood of the front critical point and on the side surface of the sphere at all instants of time.

Since the calculations were carried out until the process ceased to be quasistationary it is interesting to obtain an analytical solution for q_w and Θ_w in this case and compare it with the numerical value. This solution can be found most simply in the neighborhood of the front critical point.

By using the equations for the heat flux, taking blowing into account [7], which, as calculations have shown, agrees well with the results of numerical integration with known Θ_{w0}, we can write the condition for conservation of energy at the boundary of separation of the media (5) in the above notation in the form

$$[0.764\mathrm{Pr}^{-0.6} l_{w0}^{0.1} + 0.945 f_{w0} l_{w0}^{0.5}(1 + 0.282 f_{w0})]\left[\frac{1}{v_m}\frac{du_e}{ds}(0)\right]^{0.5}(1-\Theta_{w0}) - \frac{\pi_\sigma}{A}\Theta_{w0}^4 = (\Theta_{w0} - \Theta_{-\infty})(\overline{\rho v})_{w0}\times$$

$$\times\left\{1 + \left[\left(1 - \frac{L}{R}\right)^{-2} - 1\right]\exp\left[\frac{A}{\varphi_1}(\overline{\rho v})_{w0}\left(1 - \frac{1}{1 - L/R}\right)\right]\right\}^{-1}. \qquad (8)$$

Equation (8) was obtained taking into account the temperature gradient $(\partial\Theta_1/\partial y_1)(0)$, obtained from the solution of the quasistationary equation of conservation of energy in a porous medium, with constant porosity of the shell.

By determining Θ_{w0} from (8), we obtain

$$\Theta_{w0} = \left[B\left\{1 + \left[\left(1 - \frac{L}{R}\right)^{-2} - 1\right]\exp\left[\frac{A}{\varphi_1}(\overline{\rho v})_{w0}\left(1 - \frac{1}{1 - L/R}\right)\right]\right\} + \right.$$

$$\left. + (\overline{\rho v})_{w0}\Theta_{-\infty}\right]\left\{1 + \left[\left(1 - \frac{L}{R}\right)^{-2} - 1\right]\exp\left[\frac{A}{\varphi_1}(\overline{\rho v})_{w0}\left(1 - \frac{1}{1 - L/R}\right)\right]\right\}\left(B + \frac{\pi_\sigma}{A}\Theta_{w0}^3\right) + (\overline{\rho v})_{w0}\Big|^{-1}, \qquad (9)$$

$$q_{w0} = B(1 - \Theta_{w0}),$$

where we have introduced the notation

$$B = \left[\frac{1}{v_m}\frac{du_e}{ds}(0)\right]^{0.5}[0.764\mathrm{Pr}^{-0.6} l_{w0}^{0.1} + 0.945 f_{w0} l_{w0}^{0.5}(1 + 0.282 f_{w0})],$$

$$(\overline{\rho v})_{w0} = -f_{w0}\left[\frac{2}{v_m}\frac{du_e}{ds}(0)\right]^{0.5}.$$

The accurate value of Θ_{w0} can easily be found using iterations of the algebraic equation (9), after which the dimensionless heat flux q_{w0} is obtained. The values of the blowing parameters used in the calculations corresponded to those values of f_{w0} for which the equation for the heat flux [7] holds. One can also use the equations in [8] as the equations for the heat flux q_{w0} from the gaseous phase taking blowing into account.

The dynamics of the formation of the quasistationary values of q_w, Θ_w and Θ_{1K} for the blowing law $(\overline{\rho v})_w = \text{const} = 0.53$ are shown in Fig. 2. The broken curves in this figure represent the quasistationary solutions, which are obtained for Θ_{w0}, q_{w0} from (9) and agree well with the results of numerical integration of the boundary-value problem.

Graphs of the variation of q_w and Θ_w with time for a conjugation parameter A = 69.1 for different blowing laws are shown in Fig. 3. Curves 1 and 3 were obtained in the neighborhood of the critical point, and curves 2, 4-6 correspond to s = 60°. As follows from an analysis of the curves in Figs. 2 and 3, when the conjugation parameter increases due to a reduction in λ_{1*} the physical time taken to emerge from the quasistationary flow mode decreases.

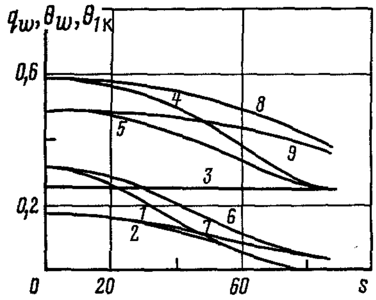

Fig. 1

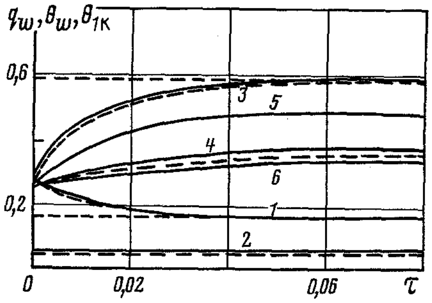

Fig. 2

Fig. 1. Dimensionless heat fluxes q_W (curves 1, 2, 6, 7), the temperatures Θ_W (curves 3, 4, 8) and Θ_{1K} (curves 3, 5, 9) as a function of the longitudinal coordinate s (in degrees) at different instants of time: $M_\infty = 4$, $T_\infty = 288°K$, $A = 6.91$; $L/R = 0.1$; $T_{1H} = 300°K$. Curves 1-5 correspond to the blowing law $(\overline{\rho v})_W = \text{const} = 0.53$, and curves 6-9 correspond to $f_W = f_{W0} = -0.5$.

Fig. 2. Dynamics of the variation of the heat flux q_W (curves 1, 2), the temperature Θ_W (curves 3, 4) and the temperature Θ_{1K} (curves 5, 6) with time at different points of the surface of the body. The calculated parameters of the curves (1-6) are indicated for Fig. 1. Curves 1, 3, 5 correspond to the neighborhood of the critical point, and curves 2, 4, 6 are drawn for $s = 60°$.

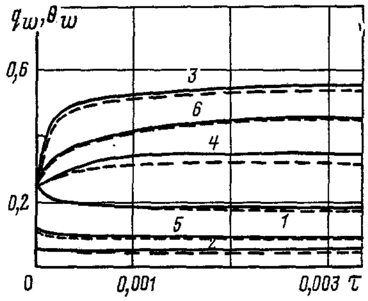

Fig. 3. Dimensionless heat fluxes q_1 (curves 1, 2, 5) and the surface temperature Θ_W (curves 3, 4, 6) as a function of time for different blowing laws at different points of the surface of the body. The calculated parameters are indicated in Fig. 1 with the exception of the parameter $A = 69.1$. Curves 1-4 are drawn for $(\overline{\rho v})_W = 0.53$, and curves 5, 6 correspond to $f_W = -0.5$.

Figure 4 shows the temperature field in the boundary layer of the body at different instants of time for different values of s in the case when $(\overline{\rho} v)_W = 0.53$. The analytical solutions for Θ_1 agree with sufficient accuracy with curves 2 and 5 (Fig. 4), which were drawn for values of τ corresponding to the quasistationary solution. As follows from the behavior of curve 5, for large conjugation parameters (small coefficients λ_{1*}) the depth of heating decreases rapidly, and in this case boundary conditions of the first kind can be specified on the rear wall of the shell. In addition, as calculated data and the analysis (8) show, the effects of taking into account the curvature of the body can be neglected and we can consider the problem of the heating of the shell in the plane approximation. In this case, under quasistationary conditions $\Theta_W(s)$ and $q_W(s)$ will not depend on the conductivity of the material of the body.

To confirm this the table shows quasistationary values of q_W and Θ_W in the neighborhood of the front critical point for different values of A. As follows from the data in the table obtained with the theoretical parameters of Fig. 1, when the conjugation parameter is increased the heat flux and the surface temperature

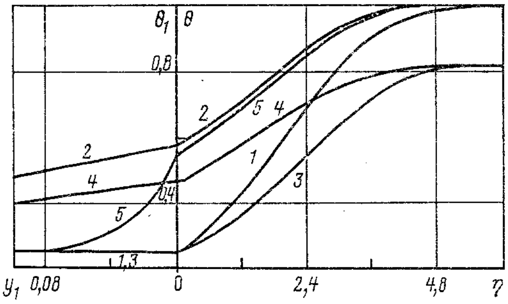

Fig. 4. Temperature field in the boundary layer and the body at different instants of time 1, 3) $\tau = 0$; 2, 4) $\tau = 0.07$ for different values of s. The calculated parameters for curves 1-4 agree with the data in Fig. 1; curves 1 and 2 correspond to s = 0°, and curves 3 and 4 correspond to s = 60°. For curve 5, A = 69.1, s = 0°, and $\tau = 0.07$.

TABLE 1. Dependence of the Quasistationary Values of the Heat Flux q_w and the Surface Temperature Θ_w on the Conjugation Parameter A

A	3,455	6,910	13,820	27,620	34,550	69,100	92,130
q_w	0,164	0,166	0,169	0,172	0,173	0,174	0,174
Θ_w	0,573	0,568	0,560	0,551	0,548	0,545	0,545

are practically the same as the corresponding values of these quantities obtained for the case when the shell is heated in the plane approximation and are $q_w = 0.175$ and $\Theta_w = 0.545$.

After numerical calculations for M_∞ from 3 to 6 and varying the decisive parameters of the problem for a very practical range of values, it is established that the results of integration can conveniently be represented in the form of the ratio of Stanton numbers – an extremely conservative function of the process. Using the following expressions for the St numbers:

$$\mathrm{St} = q_w v_m h_{e0} \rho_{e0} / \sqrt{\mathrm{Re}}\, \rho_\infty v_\infty c_p (T_{e0} - T_w), \tag{10}$$

we obtain the following ratio of the St number at the current point of the surface to St_0 determined at the front critical point:

$$\frac{\mathrm{St}}{\mathrm{St}_0} = \frac{q_w}{q_{w0}} \frac{(1-\Theta_{w0})}{(1-\Theta_w)}. \tag{11}$$

As calculations show the ratio of the Stanton numbers changes only slightly with time over a large part of the side surface of a spherical body, despite the considerable variation in the heat flux and the surface temperature as a function of τ. Hence, the ratio of the heat fluxes for a nonisothermal surface at any instant of time can be expressed with sufficient accuracy for practical purposes in terms of the ratio of the fluxes at the initial instant of time, for which $\Theta_w = \mathrm{const}$:

$$\frac{q_w}{q_{w0}} = \left(\frac{q_w}{q_{w0}}\right)^0 \frac{(1-\Theta_w)}{(1-\Theta_{w0})}. \tag{12}$$

In (12) the superscript 0 corresponds to the ratio of the heat fluxes for an isothermal surface. Hence, using the equation for the heat flux taking the blowing q_{w0} into account, one can obtain the heat flux q_w at any instant of time τ, when the analytical or approximation dependence for $(q_w/q_{w0})^0$ is specified.

Using Eq. (12) it is easy to find an analytical solution for the heat flux and the surface temperature on the side surface of the sphere in the quasistationary case. In fact, in this case we have

$$\Theta_w = \left[B\left(\frac{q_w}{q_{w0}}\right)^0 \left\{1 + \left[\left(1 - \frac{L}{R}\right)^{-2} - 1\right] \exp\left[\frac{A(\overline{\rho v})_w}{\varphi_1} \times \right.\right.\right.$$
$$\left.\left.\left. \times \left(1 - \frac{1}{1 - L/R}\right)\right]\right\} + (\overline{\rho v})_w \Theta_{-\infty}\right] \left[\left(B + \frac{\pi_\sigma}{A} \Theta_w^3\right)\left(\frac{q_w}{q_{w0}}\right)^0 \times \right. \quad (13)$$
$$\left. \times \left\{1 + \left[\left(1 - \frac{L}{R}\right)^{-2} - 1\right] \exp\left[\frac{A(\overline{\rho v})_w}{\varphi_1}\left(1 - \frac{1}{1 - L/R}\right)\right]\right\} + (\overline{\rho v})_w\right]^{-1},$$
$$q_w = B\left(\frac{q_w}{q_{w0}}\right)^0 (1 - \Theta_w).$$

In Figs. 2 and 3 we compare the results of calculations of the boundary value problem (1)-(7) with the results of a numerical integration (the broken curves) of the equation of conservation of energy (3) taking the boundary and initial conditions (5)-(7) into account for a specified value of the heat flux from the gas phase (13). It is easy to see that in this case the required characteristics, such as $\Theta_w(s, \tau)$ and $q_w(s, \tau)$, obtained by solving the problem in the conjugate and separate formulation, agree fairly well for the instantaneous instants of time. When the flow process ceases to be quasistationary the surface temperature, found from (13), on the side surface of the sphere up to 70° differs from the accurate numerical solution by not more than 10-15% for a blowing law $(\overline{\rho v})_w$ = const. When using the blowing law f_w = const, as can be seen from Fig. 3, the agreement between the solutions is much better.

Hence, relation (12) for the heat fluxes can be used to solve problems on the heating of porous bodies with a specified blowing distribution over the sphere.

NOTATION

$\xi, \eta = \frac{u_e r}{\sqrt{2\xi}} \int_0^y \rho dy$, Dorodnitsyn–Liz variables; $s = x/R$, angle in radians measured from the critical point; x and y, axes in the system of coordinates connected with the body; f, dimensionless current function; $f' = u/u_e$, dimensionless velocity; $l = \rho\mu/\rho_e\mu_e$, a dimensionless parameter; Pr, Re $= v_m\rho_{e0}R/\mu_{e0}$, Prandtl and Reynolds numbers, respectively; $\alpha = 2\int_0^s \rho_e\mu_e u_e (r/R)^2 ds / \rho_e\mu_e u_e (r/R)^2$, $\beta = \alpha \frac{1}{u_e}\frac{du_e}{ds}$, $\gamma = u_e^2/c_p T_{e0}$, dimensionless parameters; $y_1 = -y/R$; $\tau = t/t_*$, dimensionless coordinate in the solid and time; $\Theta = T/T_{e0}$, dimensionless temperature; h, ρ, and c_p, enthalpy, density, and specific heat, respectively; μ, λ, viscosity and thermal conductivity, respectively; t, physical time; $(\overline{\rho v})_w$, flow of gas when blowing through the porous shell; $v_m = \sqrt{2h_{e0}}$, maximum velocity; φ, porosity; $\varphi_1 = 1 - \varphi$; R, radius of the sphere; L, thickness of the porous shell; $t_* = R^2\rho_{1*}c_{1*}/\lambda_{1*}$, characteristic time; σ, Stefan–Boltzmann constant; ε, emissivity; St $= q_w v_m h_{e0}\rho_{e0}/\sqrt{Re}\rho_\infty v_\infty c_p(T_{e0} - T_w)$, Stanton number; $B = \left[\frac{1}{v_m}\frac{du_e}{ds}(0)\right]^{0.5}[0.764 Pr^{-0.6} l_{w0}^{0.1} + 0.945 f_{w0} l_{w0}^{0.5}(1 + 0.282 f_{w0})]$, $A = \sqrt{Re}\,Pr \cdot (\lambda_{e0}/\lambda_{1*})(1/\varphi_1)$, notation used. The indices e, e0, w, and K are quantities on the external boundary of the boundary layer, on the external boundary at the slowing-down point, on the surface of the body, and on the inner wall of the shell for $y_1 = L/R$, respectively, 1 corresponds to characteristics of the solid component of the porous shell, and also the temperature of the porous material, g is the gaseous component in the porous body, 1H is the temperature at the initial instant of time, $-\infty$ is the temperature of the gas in a cavity of the shell, and * represents characteristic quantities.

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