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Mathematical Modeling of Heat and Mass Transfer in a Thermal Protection Coating with Gas Flow Fluctuations

E. V. Stepanova and A. S. Yakimov
Tomsk State University, pr. Lenina 36, Tomsk, 634050 Russia
e-mail: yakimovas@mail.ru

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Abstract—The thermochemical destruction of a carbon fiber-reinforced polymer when affected by a high-enthalpy fluctuating gas flow is simulated numerically. The possibility of controlling the heat transfer process in the composite material is studied.

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INTRODUCTION

Technological processes in chemical reactors, heat-and-power plants, and flying vehicles (wherever polymer composites are used as thermal protective coatings) are always accompanied by small disturbances generated by external sources (wall vibrations, fluctuations, turbulent noises) and by the process of destruction of thermal-protective material in a gas flow with an oxidizing agent [1, 2]. The characteristics of thermochemical destruction in such systems can be substantially different.

The problem of intensification of heat and mass transfer processes in continuum and permeable media was considered in [2–4]. The limiting conditions for the binder concentration and intensity of oscillations when it becomes possible to reduce wall heat loads and to control the heat and mass transfer were found in [2]. In [3], the efficiency of a catalytic process in the regime of forced external effects was studied and the unsteady methods of implementation of catalytic processes with the purpose of heat and mass transfer intensification were used. An increase in the thermal conductivity coefficient of a porous body in the presence of pressure fluctuations on its boundary was obtained in [4].

In the present study, the effect of periodic disturbances and wall vibrations on the process of thermochemical destruction of a carbon fiber-reinforced polymer (CFRP) is investigated. The results obtained are compared with the known data.

FORMULATION OF THE PROBLEM

The physical nature of the arising oscillations is the wall vibration in the incoming flow direction. The wall vibrations were implemented by the harmonic law using a special vibration exciter [2, 5].

A varying convective heat flux q_w [6] with a modification for the boundary-layer fluctuating flow is considered to be prescribed as follows:

$$q_w = \frac{\alpha}{c_p}\left[1 - \frac{k(\rho v)_w}{\alpha/c_p}\right](h_e - h_w),$$
$$\frac{\alpha}{c_p} = \left(\frac{\alpha}{c_p}\right)_{\text{in}}\left[1 + \frac{A\cos(2\pi\nu t)}{(\alpha/c_p)_{\text{in}}}\right], \quad (1)$$

where $(\alpha/c_p)_{\text{in}}$ is the heat transfer coefficient without fluctuations; A and ν are the amplitude and frequency of gas flow fluctuations; t is time; h is enthalpy; $(\rho v)_w$ is the thermal-protection-material total mass ablation; k is the attenuation coefficient for the boundary-layer turbulent flow regime.

Comparison of the results of studying the filtration and thermal characteristics of porous materials in the presence of fluctuating and vibrational disturbances [5] points to the similarity of dependences of the viscous term in the filtration law and of the heat transfer relative function on the intensities of oscillations, as well as to the hydrodynamic nature of the process of heat transfer intensification. The following expression for an additional heat transfer q' in a porous body at periodic fluctuations of a gas-coolant was obtained in [5], namely,

$$q' = -\frac{\pi c_{p5}\varphi_5\rho_5 B^2\nu}{\sqrt{2}}\frac{\partial T}{\partial y}, \quad (2)$$

where T is the temperature of a (one-temperature) porous medium; c_{p5}, ρ_5, and φ_5 are the specific heat at constant pressure, the real density of the gas phase, and the density of thermal protective material, respectively; B is the amplitude of periodic fluctuations; y is the space coordinate.

The expression for effective viscosity μ_{ef} in the Darcy law is taken in the form of the Einstein modification [7], namely,

$$\mu_{\text{ef}} = \mu[1 + C\cos(2\pi\nu t)], \tag{3}$$

where C is the dimensionless coefficient, μ is the viscosity of gaseous products of filtration in the absence of periodic disturbances ($0 < C \le 0.25$).

The increase or decrease in the viscosity is associated with additional energy dissipation owing to the redistribution of the gradients of temperature, pressure, etc., in the flow for the case of fluctuating flow.

As the analysis of thermogravimetric measurements shows [8], the process of pyrolysis of a CFRP based on a thermoset polymer binder is a multistage process. It includes the stage of polymer degradation that proceeds with heat absorption and the stages of generation of an intermediate condensed product (pyrosol) and a final condensed product (coke). The stage of coke generation can be interpreted as a fusion reaction that has an exothermal character [8].

The physics of the process in the condensed phase (c-phase) is as follows [9, 10]: when CFRP is affected by a high-temperature flow, the CFRP temperature increases up to the temperature of binder (resin) degradation; after that, the thermoset binder pyrolysis starts with generation of a pyrosol and a carbon residue (coke) that is contained in the matrix of carbon reinforcing fibers:

$$\begin{aligned} &\nu_1 A_1 + \nu_4 A_4 \to \nu_2' A_2 + \nu_4' A_4 + \nu_5' A_5 \\ &\to \nu_3'' A_3 + \nu_4'' A_4 + \nu_5'' A_5, \end{aligned} \tag{4}$$

where ν_1, ν_4, ν_2', ν_4', ν_3'', ν_4'', ν_5', and ν_5'' are the stoichiometric coefficients; A_i, $i = 1, \ldots, 5$ are the symbols of the original substance of the binder, the intermediate condensed product of the reaction (pyrosol), the final condensed product (coke), carbon reinforced fiber, and the gaseous product of the pyrolysis reaction, respectively. At $T_w > 800$ K, the carbon surface is destroyed owing to the interaction with dissociated air components [10, 11]. Gaseous products of the pyrolysis reaction can be filtered to the interface $y = 0$, be blown into the boundary layer, and reduce the convective heat flux to the body together with the carbon oxidation products.

The following assumptions are made in the formulation of the problem [9, 10]:

(1) The Reynolds number in the incoming hypersonic air flow is sufficiently high $(\mathrm{Re}_\infty \gg 1)$, and the boundary layer is generated in the vicinity of the body surface;

(2) The air on the boundary layer edge is in thermochemical equilibrium and is a five-component mixture, namely, a mixture of O, O_2, N, N_2, and NO;

(3) The following heterogeneous reactions proceed on the external surface of the thermal protection material at $T_w < 2000$ K:

$$\begin{gathered} \mathrm{C} + \mathrm{O}_2 \to \mathrm{CO}_2, \quad 2\mathrm{C} + \mathrm{O}_2 \to 2\mathrm{CO}, \quad \mathrm{C} + \mathrm{O} \to \mathrm{CO}, \\ \mathrm{C} + \mathrm{CO}_2 \to 2\mathrm{CO}, \quad \mathrm{O} + \mathrm{O} + \mathrm{C} \to \mathrm{O}_2 + \mathrm{C}, \\ \mathrm{N} + \mathrm{N} + \mathrm{C} \to \mathrm{N}_2 + \mathrm{C}. \end{gathered} \tag{5}$$

For higher temperatures $T > 2000$, it is possible to use the results of [11], where the main features were found which were included in the process of carbon material mass ablation by the use of its complete thermochemical model.

In order to calculate the composition at the interface of gaseous and c-phases, we will use the analogy of the processes of heat and mass transfer [6] on the assumption of "frozen" chemical reactions inside the boundary layer [10]. With the increase in the stagnation pressure, the model of a chemically equilibrium boundary layer is more consistent with real conditions. However, for high catalycity composites with respect to the dissociated air components, the heat fluxes in both cases do not differ very significantly, and, as the numerical computations of the surface destruction have shown [12], this approach can be applied to estimate the mass ablation.

Let us consider the chemical kinetics of heterogeneous processes that proceed on the body surface. If the order number of a component corresponds to the following enumeration, O, O_2, N, N_2, CO, CO_2, then the molar velocities of reactions (5) have the following form [9, 10]:

$$\begin{gathered} U_1 = \frac{k_{1w}\rho_w c_{2w}}{m_2}\exp\left(-\frac{E_{1w}}{RT_w}\right), \quad U_2 = \frac{k_{2w}\rho_w c_{2w}}{m_2} \\ \times \exp\left(-\frac{E_{2w}}{RT_w}\right), \quad U_3 = \frac{k_{3w}\rho_w c_{1w}}{m_1}\exp\left(-\frac{E_{3w}}{RT_w}\right), \\ U_4 = \frac{k_{4w}\rho_w c_{6w}}{m_6}\exp\left(-\frac{E_{4w}}{RT_w}\right), \\ U_5 = \frac{k_{5w}\rho_w c_{1w}}{m_1}, \quad U_6 = \frac{k_{6w}\rho_w c_{3w}}{m_3}. \end{gathered} \tag{6}$$

By using Eqs. (6), we will find the mass rates of generation (disappearance) of components as a result of heterogeneous reactions, namely,

$$\begin{gathered} R_{1w} = -m_1(U_3 + U_5), \; R_{2w} = -m_2(U_1 + U_2 - U_5/2), \\ R_{3w} = -m_3 U_6, \\ R_{4w} = m_4 U_6/2, \; R_{5w} = m_5(2U_2 + U_3 + 2U_4), \\ R_{6w} = m_6(U_1 - U_4) \end{gathered}$$

and the expressions for the mass ablation rate, namely,

$$\begin{gathered} (\rho v)_{2w} = (\varphi_4\rho)_w\left[\left(\frac{m_6}{m_2} - 1\right)c_{2w}B_1 + \left(2\frac{m_5}{m_2} - 1\right)c_{2w}B_2\right. \\ \left. + \left(\frac{m_5}{m_1} - 1\right)c_{1w}B_3 + \left(2\frac{m_5}{m_6} - 1\right)c_{6w}B_4\right], \\ B_i = k_{iw}\exp\left(-\frac{E_{iw}}{RT_{\mathrm{w}}}\right), \\ i = \overline{1,4}, \quad \rho_w = \frac{P_e m_w}{RT_{\mathrm{w}}}, \quad m_w^{-1} = \sum_{\alpha=1}^{6}\frac{c_{\alpha w}}{m_\alpha}. \end{gathered} \tag{7}$$

Note that, in accordance with the experimental data [2], a turbulent regime of the flow in the boundary layer over the thermal protective material was observed. For this case, attenuation coefficient (k) in the heat flux (Eq. (1)) was taken in the form of the Mugalev modification [6].

The balance relationships for the component mass concentrations (c_{iw}) are written using the Fick law for diffusion fluxes and the analogy of the processes of heat and mass transfer [6, 9]:

$$J_{iw} + (\rho v)_w c_{iw} = R_{iw}, \quad i = \overline{1,6},$$
$$J_{iw} = \beta(c_{iw} - c_{ie}), \quad \beta = \alpha/c_p,$$

where the total mass ablation rate $(\rho v)_w = (\rho v)_{1w} + (\rho v)_{2w}$, $(\rho v)_{1w}$ is the mass ablation rate due to pyrolysis, $(\rho v)_{2w}$ is the mass ablation rate due to heterogeneous reactions (5), $k = 0.19(m_e/m_w)^{0.35}$ [6], $m_e^{-1} = \sum_{i=1}^{5} c_{ie}/m_{ie}$.

It is assumed that the destruction products at $T_w <$ 2000 weakly dilute the air mixture in the boundary layer. This makes it possible to use the assumptions considered in the boundary layer.

The following assumptions are taken in the mathematical formulation of the problem in the c-phase:

(1) The CFRP thermochemcial destruction process is one-dimensional;

(2) The filterable gas is uniform with the molecular mass being close to the air mixture molecular mass;

(3) The porous medium in the process of heat transfer is considered to be one-temperature;

(4) The gas flow inside the flared pores is laminar and is described by the linear Darcy law [6, 9].

The first assumption is sufficiently exact, because the size of the recreation zone is on the order of 2.5×10^{-3} m at $T \geq 600$ K and the heated layer thickness is less than 4×10^{-3} m and considerably less than the original thickness of the thermal protection material, $L_{\text{in}} = 10^{-2}$ m.

The second assumption is taken for the simplicity of the model, because the chemical composition of the products of the filtering gas during thermochemical destruction is not known for the used carbon-phenol material (P5-13N) [2].

As a rule, in the case of a two-temperature medium under destruction [13] (in contrast to the inert medium [6]), the volumetric heat transfer coefficient A_v is determined with a considerable error. The difference in temperatures of the solid and gas phases at the most real values of $A_v = 10^6$–10^8 W/(K m^3) does not exceed 323–373 K according to [13], if the coke residue temperature is 1273–2273 K.

Finally, in real conditions [2], transient and turbulent regimes of gas flow filtration in pores take place at the CFRP thermochemical destruction, which are described by the nonlinear Darcy law [6, 9]. However, the viscous and inertial coefficients for the material described below [2], in the case of a chemically reacting medium, were not found in the available literature.

The mathematical problem is reduced to the following system of equations written in the thermochemical-destruction-front coordinate system [9, 10]:

$$c_p\left(\frac{\partial T}{\partial t} - \omega\frac{\partial T}{\partial y}\right) + c_{p5}\rho_5\varphi_5 v\frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) - q_1R_1 + q_2R_2, \tag{8}$$

$$\frac{\partial\rho_5\varphi_5}{\partial t} - \omega\frac{\partial\rho_5\varphi_5}{\partial y} + \frac{\partial\rho_5\varphi_5 v}{\partial y} = (1-\alpha_1)R_1 + (1-\alpha_2)R_2, \tag{9}$$

$$\rho_1\left(\frac{\partial\varphi_1}{\partial t} - \omega\frac{\partial\varphi_1}{\partial y}\right) = -k_1\rho_1\varphi_1\exp\left(-\frac{E_1}{RT}\right), \tag{10}$$

$$\rho_2\left(\frac{\partial\varphi_2}{\partial t} - \omega\frac{\partial\varphi_2}{\partial y}\right) = \alpha_1k_1\rho_1\varphi_1\exp\left(-\frac{E_1}{RT}\right) - k_2\rho_2\varphi_2\exp\left(-\frac{E_2}{RT}\right), \tag{11}$$

$$\rho_3\left(\frac{\partial\varphi_3}{\partial t} - \omega\frac{\partial\varphi_3}{\partial y}\right) = \alpha_2k_2\rho_2\varphi_2\exp\left(-\frac{E_2}{RT}\right), \tag{12}$$

$$\rho_4\left(\frac{\partial\varphi_4}{\partial t} - \omega\frac{\partial\varphi_4}{\partial y}\right) = 0, \tag{13}$$

$$v = -\frac{z}{\mu_{\text{ef}}}\frac{\partial P}{\partial y}, \quad z = \frac{z_*\varphi_5^3}{(1-\varphi_5)^2}, \quad \varphi_5 = 1 - \sum_{i=1}^{4}\varphi_i, \quad P = \frac{\rho_5RT}{M_5}, \tag{14}$$

$$\lambda = \sum_{i=1}^{5}\lambda_i\varphi_i, \quad c_p = \sum_{i=1}^{4}c_{pi}\rho_i\varphi_i, \quad \lambda_5 = \lambda_{5*}\sqrt{\frac{T}{T_*}},$$

$$\mu = \mu_*\sqrt{\frac{T}{T_*}}, \quad \alpha_1 = \frac{\nu_2'M_{2s}}{\nu_1M_{1s}}, \quad R_1 = k_1\rho_1\varphi_1\exp\left(-\frac{E_1}{RT}\right),$$

$$R_2 = k_2\rho_2\varphi_2\exp\left(-\frac{E_2}{RT}\right), \quad \alpha_2 = \frac{\nu_3''M_{3s}}{\nu_2'M_{2s}}, \tag{15}$$

$$\omega = \frac{(\rho v)_{2w}}{(\rho_1\varphi_1 + \rho_2\varphi_2 + \rho_3\varphi_3 + \rho_4\varphi_4)_w},$$

$$(\rho v)_{1w} = -(\rho_5 v\varphi_5)_w, \quad c_{p5} = b_1 + 2b_2T,$$

$$\lambda_4 = \lambda_{4y} + \lambda_4', \quad \lambda_4' = \frac{\pi c_{p5}\varphi_5\rho_5B^2\nu}{\sqrt{2}}.$$

The system of equations (8)–(13) should be solved taking into account the following initial and boundary conditions:

$$T\big|_{t=0} = T_{\text{in}}, \quad \rho_5\big|_{t=0} = \rho_{5\text{in}}, \quad \varphi_i\big|_{t=0} = \varphi_{i\text{in}}, \quad i = 1,\ldots,4; \tag{16}$$

$$q_w - (\rho v)_{1w}(h_w - h_g) - (\rho v)_{2w}(h_w - h_c) - \varphi_4\varepsilon\sigma T_w^4 = -\lambda\frac{\partial T}{\partial y}\Big|_{y=0-s(t)}, \tag{17}$$

$$l = L_{\text{in}} - s(t), \quad s(t) = \int_0^t \omega(\tau) d\tau, \quad h_w = \sum_{\alpha=1}^{6} h_\alpha c_{\alpha w},$$
$$h_g = \int_0^T c_{p5} dT, \quad P_e = P_w\big|_{y=0-s(t)}, \quad P_e = \rho_e T_e R \sum_{i=1}^{5} \frac{c_{ie}}{m_{ie}}, \tag{18}$$

$$T\big|_{y=l} = T_{\text{in}}, \quad v\big|_{y=l} = 0, \quad \varphi_i\big|_{y=l} = \varphi_{i\text{in}}, \quad i = 1,\ldots,4. \tag{19}$$

Hereinafter, b_i, $i = 1, 2$ are constants; c_p is the specific heat at constant pressure; $c_{\alpha w}$ are the mass concentrations of components on the interface between the gas phase and the c-phase [9]; E_i is the activation energy; k_i, $i = 1, 2$ is the pre-exponential factor; l is the CFRP variable thickness; $L_{\text{н}}$ is the CFRP initial thickness; m is the molecular weight; M_5 is the molecular weight of gaseous products of the pyrolysis reaction; P is the gas pressure in pores; q_i, $i = 1, 2$ are the heat effects of the decomposition reaction of a binder and a pyrosol; R is the universal gas constant; $s(t)$ is the burn-up fraction; v is the velocity of gaseous products of binder decomposition reaction; z is the CFRP permeability coefficient; α_1 and α_2 are the reduced stoichiometric coefficients [9] from pyrolysis chemical scheme (4); β is the mass transfer coefficient; ε is the integral coefficient of radiation; $(\rho v)_w$ is the total mass ablation; $\varphi_i, i = \overline{1,4}$ are the volume fractions; $\lambda_i, i = \overline{1,5}$, are the thermal conductivity coefficients; μ is the dynamic viscosity coefficient; ρ is density; σ is the Stefan-Boltzmann constant; ω is the linear rate of CFRP thermochemical destruction. The subscripts denote the following: e is the boundary layer edge; w is the surface of the body in flow; * is the characteristic value; in means the initial conditions; s is the c-phase; g is the gas phase; ∞ means the parameter at infinity; c is the carbon surface; 1–5 correspond to the binder, pyrosol, coke, filler, and the gas in the c-phase; the prime corresponds to the fluctuations; y is the effective value.

TECHNIQUE OF THE COMPUTATIONS, VERIFICATION, INITIAL DATA

System of equations (8)–(13) with initial and boundary conditions (16)–(19) was solved numerically using an implicit, absolutely stable monotonic difference scheme [14]. In order to check the code of computations, the results found in [10] were repeated. In addition, the procedure of testing the numerical method was performed for the basic variant (combined regime of heat and mass transfer). All other initial parameters being equal, the computations were performed for different spatial steps: $h_1 = 10^{-4}$, $h_2 = h_1/2$, $h_3 = h_1/4$, $h_4 = h_1/8$. The temperature of the thermal protective material and gas density ρ_5 were fixed for the body depth at different time moments. In all variants, the problem was solved with a variable time step, which was chosen from the condition of a prescribed accuracy similar for all spatial steps. The difference in the errors of body temperature and gas density in the thermal protection material ($\delta = \max\,[\delta_T, \delta_{\rho_5}]$) decreased: $\delta_1 = 10.8\%$, $\delta_2 = 5.1\%$, and $\delta_3 = 1.9\,\%$. The results of the computation for spatial step $h_1 = 0.25 \times 10^{-4}$ m are given below.

Thermokinetic constants k_{iw}, E_{iw} in Eqs. (6), (7) for reactions (5) were given in [9], and those for reactions (4) were given in [2, 8]. Enthalpy h_c of the carbon material in the condensed state was calculated by formulas from [15]. For the carbon-phenol composite, the thermophysical coefficients (c_{p4}, λ_{4y}, and density ρ_4) were taken from [16]. The air specific heat at constant pressure c_{p5} from Eq. (15) was found by the interpolation formula of study [17]. Permeability (z) of the ideal porous medium in the Darcy law in Eq. (14) was determined by the well-known Kozeny formula [9].

The results given below were found at $T_{\text{in}} = 293$ K, $(\alpha/c_p)_{\text{in}} = 0.2$ kg/cm^2, $A = 0.01$ kg/cm^2, $\nu = 10$–30 s^{-1}, $\mu_* = 4.2 \times 10^{-5}$ kg/(m s), $B = 2 \times 10^{-3}$ m, $T_* = 1500$ K, $\lambda_{5*} = 0.067$ W/(m K), $T_e = 3600$ K, $h_e = 1.449 \times 10^7$ J/kg, $\rho_e = 0.088$ kg/m^3, $c_{p1} = c_{p2} = 1700$ J/(kg K), $c_{p3} = 1020$ J/(kg K), $\rho_1 = 1200$ kg/m^3, $\rho_2 = 1100$ kg/m^3, $\rho_3 = 1300$ kg/m^3, $\lambda_1 = \lambda_2 = 0.21$ W/(m K), $\lambda_3 = 0.041$ W/(m K), $R = 8.314$ J/(mole K), $L_{\text{in}} = 10^{-2}$ m, $E_1/R = 3462$ K, $E_2/R = 11305$ K, $k_1 = 9.6 \times 10^4$ s^{-1}, $k_2 = 1.2 \times 10^5$ s^{-1}, $q_1 = 2 \times 10^5$ J/kg, $q_2 = 10^5$ J/kg, $z_* = 5 \times 10^{-11}$ m^2, $M_5 = 29$ kg/kmole, $\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4), $\alpha_1 = 0.5$, $\alpha_2 = 0.5$, $\varepsilon = 0.9$, $\varphi_{1\text{in}} = 0.3$, $\varphi_{2\text{in}} = 0.01$, $\varphi_{3\text{in}} = 0.01$, $\varphi_{4\text{in}} = 0.6$, $b_1 = 965.5$, $b_2 = 0.0735$.

NUMERICAL SOLUTION RESULTS AND ANALYSIS

Figure 1 shows time dependences of the surface temperature T_w and the total mass ablation velocity $(\rho v)_w$ from the surface of thermal protective material. Curves *1–3* in Fig. 1 correspond to the frequency $\nu = 10$, 20, and 30 s^{-1}, respectively. The mass ablation velocity $(\rho v)_w$ has a maximum at a time moment close to the initial moment ($t < 0.5$ s) due to an abrupt increase in T_w. Then, owing to the generation of a coke layer and the increase in its drag on the motion of the filtering gas, $(\rho v)_w$ can decrease. However, as long as the thermal protective material becomes more and more heated by the convective heat flux q_w and as long as the heat wave penetrates deeper into the body, the CFRP pyrolysis continues with generation of gaseous and condensed products of the reaction of decomposition of binder (resin). Because the maximum of pressure of gaseous products of filtration is inside the thermal protective material [10], the gaseous products of filtration can move into the body. Owing to exothermal reaction (4) of coke generation from pyrosol, they can heat coke and the next cold layers of the thermal pro-

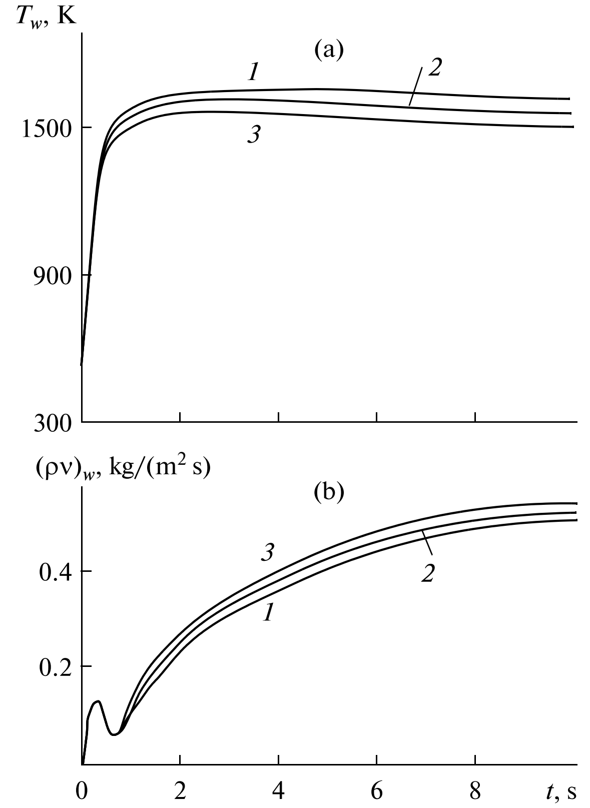

Fig. 1. (a) Surface temperature and (b) total mass ablation rate versus time: (*1*) $\nu = 10\ \text{s}^{-1}$, (*2*) $\nu = 20\ \text{s}^{-1}$, and (*3*) $\nu = 30\ \text{s}^{-1}$.

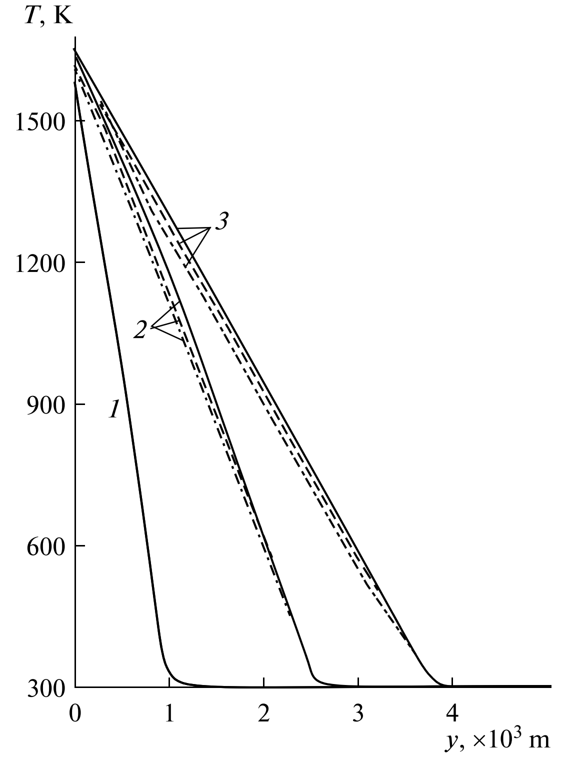

Fig. 2. Temperature distribution over the layer depth at different time moments for $\nu = 10\ \text{s}^{-1}$: solid curves correspond to $\lambda_4' = 0$, $C = 0$; dashed curves correspond to $\lambda_4' \neq 0$, $C = 0$; and dash-and-dot curves correspond to $\lambda_4' \neq 0$, $C \neq 0$; (1) $t = 1$ s, (2) $t = 5$ s, and (3) $t = 10$ s.

tection material. This leads to a further increase in $(\rho v)_w$. In addition, at $T_w > 800$ K, the mass ablation from the surface of the thermal protection material is continuous because of the carbon surface destruction at kinetic ($T_w < 1500$ K) and diffusion ($T_w > 1500$ K) regimes of heterogeneous chemical reactions (5).

It should be noted that the intensity of heat transfer of the flow from the CFRP decreases (see Fig. 1a) and the intensity of mass transfer increases (see Fig. 1b) with the increase in frequency $\nu = 10$, 20, and 30 s^{-1}. The latter result is in qualitative agreement with the experimental data [2]. It is associated with the fact that the heat flux fluctuations lead to a more intensive thermal destruction of the binder and to an increase of blowing $(\rho v)_{1w}$. In this case, the temperature of the surface decreases due to the convective heat flux q_w reduction in formula (1) and the decrease in the total heat flux to the c-phase

$$Q_w = q_w - (\rho v)_{1w}(h_w - h_g) - (\rho v)_{2w}(h_w - h_c) - \varphi_4 \varepsilon \sigma T_w^4.$$

At the steady-state thermochemical destruction of CFRP ($8 \leq t \leq 10$ s) the discrepancy between the calculated and experimental surface temperatures (see Fig. 1 in [2]) at $\nu = 10$ s^{-1} and $\nu = 30$ s^{-1} does not exceed 22% and 30%, respectively. In the unsteady regime of the CFRP warmup ($t < 8$ s), transient and turbulent regimes of filtration with the temperature increase were observed in the physical experiment. In addition, a nonmonotonic variation of $(\rho v)_w$ with time was observed [2], the behavior and value of which were related to different rates of the decomposition of CFRP binder and filler. Note that, at the first stage of the investigation, these physical processes (turbulent flow regime in pores, peelings, and delamination) in the thermal protection material warmup were not taken into account in the mathematical model. This is related to the absence of reliable data on filtration, structural, and kinetic characteristics of the materials used [2, 16].

Figure 2 shows the CFRP temperature distribution over the layer length at different time moments for $\nu = 10$ s^{-1}. Solid curves in Fig. 2 correspond to the regime of destruction of thermal protective material without fluctuation components of heat transfer ($\lambda_4' = 0$) in Eqs. (2) and (15) and without viscosity ($C = 0$) in Eq. (3); dashed lines correspond to the variant with $\lambda_4' \neq 0$, $C = 0$; dash-and-dot lines correspond to the combined regime of the thermal protective material: $\lambda_4' \neq 0$, $C = 0.2$. Lines marked with numbers *1*–*3* correspond to the time moments t of 1, 5, and 10 s.

CFRP temperature versus fluctuation flow parameters at $t = 10$ s

	T, K		
y, m	0	2×10^{-3}	3×10^{-3}
$\lambda_4' = 0, C = 0$	1647	773	433
$\lambda_4' \neq 0, C = 0$	1615	758.3	406
$\lambda_4' \neq 0, C = 0.15$	1627	760	408
$\lambda_4' \neq 0, C = 0.2$	1614	758.6	413
$\lambda_4' \neq 0, C = 0.25$	1591	757.4	420

It follows from the analysis of the curves in Fig. 2 that the wave coefficient of thermal conductivity λ_4' that appears in the permeable material under the effect of fluctuations reduces the thermal protective material temperature owing to the increase in the intensity of the filtration flows. This effect is intensified in the thermal-protective-material combined regime: $\lambda_4' \neq 0, C \neq 0$ (see Fig. 2). The application of this way of heat removal seems to be reasonable when the reactions proceed with an exothermal effect in the thermal protective materials under destruction.

The table gives the values for the CFRP temperature on the surface and deep in the body at $t = 10$ s versus fluctuations components λ_4' and C that enter into Eqs. (15) and (3). It can be concluded from the analysis of the table that far from the surface, $y = 3 \times 10^{-3}$ m, the CFRP temperature varies monotonically with the increase in C, and the thermal wave weakly heats the material. However, the temperature of the surface and near it, $y = 2 \times 10^{-3}$ m, can be nonmonotonic: it can firstly increase and then it can decrease with the increase in C. The latter result seems to be associated with the additional dissipation of energy caused by the fluctuating flow.

CONCLUSIONS

The problem of the thermochemical destruction of a thermal protection material that takes into account the effect of fluctuations in a porous body was formulated. Under the effect of periodic disturbances, the heat and mass transfer process intensification reduces the CFRP temperature. As long as the frequency of fluctuations increases, the calculated temperature of the destruction surface of thermal protective material is in qualitative agreement with the experimental data [2]. According to the first formula in Eq. (14), in the case of a fluctuating flow in the thermal protective material, the surface temperature varies nonmonotonically with the increase in C (Eq. (3)) in the Darcy law.

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