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Thermal stresses and heat–mass transfer in ablating composite materials

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Abstract—In designing a thermal protection made of ablating composite materials, constructors usually make calculations only for a heat field and a rate of material ablation; strength calculations are usually conducted only for determining thermoelastic stresses. However, there are known cases when thermal protection constructions designed this way and made of glass-plastics have destructed due to the action of the following effects that are usually not considered: pore pressure of gaseous pyrolise products generated in heating a composite, and shrinkage of a composite in heating up to the pyrolise temperature. To take account of these effects and conduct heat and strength calculations of thermal protection, in this paper a new mechanical–mathematical model is developed wherein ablating composites are considered to be porous multiphase media with phase transformations and chemical reactions of components in heating. The distinctive peculiarity of the model is that it allows description of the effect of physical–chemical transformations on a stress–strain state of the material.

INTRODUCTION

Ablating composite materials represent the unique case when a non-stable system, that is polymer composites at high temperatures, is used premeditatively in crucial elements of construction, for example in heat protection of vehicles, in determination of a glass-plastic construction resource in fire etc.

The reason for non-stability of composites lies in the fact that at high temperatures there are phase transformations, i.e. thermodestruction of polymer components with formation of a solid residue, usually a coke, and generation of a large quantity of gases in the pores.

At present, calculation methods for heat–mass transfer processes in ablating composites are well enough developed [1]: however, strength problems for their use in construction have been insufficiently studied. In the present paper the problem statement on determination of thermostresses in construction of ablating materials is given, an example of numerical solution of the problem for a cylindrical shell is presented, and peculiarities due to the presence of heat–mass transfer in the material are shown.

MATHEMATICAL MODEL

An ablating composite material is considered to be a multiphase system consisting of four phases: the first phase is a thermo-stable filler (carbon glass fibers which are thermostable in the considered temperature interval in an inert medium); the second phase is a solid polymer binder (epoxy-phenol, phenol and other resins) which thermodestruct at high temperatures; the third phase consists of solid products of thermodestruction (usually a coke); and the fourth phase consists of gaseous thermodestruction products in pores. If strains of solid phases are considered to be small, gas filtration in the pores is assumed to be subject to Darcy's equation, and the heating process is so relatively slow that temperature equilibrium has time to reach steady state for all phases with the same temperature, θ, then the heat–mass transfer equation system for the porous multiphase medium described is written in the following form [2, 3]:

$$\rho 2\frac{\partial \varphi_2}{\partial t} = -J \quad (1)$$

$$\frac{\partial \rho_g \varphi_g}{\partial t} = \nabla_x \cdot (\mathrm{R}\underset{\sim}{K} \cdot \nabla_x \rho_g \theta) + J\Gamma \quad (2)$$

$$\rho c\frac{\partial \theta}{\partial t} = \nabla_x \cdot (\underset{\sim}{\hat{\lambda}} \cdot \nabla_x \theta) + \mathrm{R} c_g \varphi_g \nabla_x \theta \cdot \underset{\sim}{K} \cdot \nabla_x \rho_g \theta - J\Delta e^0 \quad (3)$$

$$\nabla_x \cdot \varphi_s \underset{\sim}{\sigma} - \nabla_x \varphi_g p = 0 \quad (4)$$

where φ_i, ρ_2 are volumetric concentrations and densities of solid phases ($i = 1, 2, 3$), ρ_g is the density of gas in pores, φ_g is porosity, $\underset{\sim}{\sigma}$ is the stress tensor of all solid phase collections, being a unified frame, c_i is the phase heat capacity, and R is the gas constant.

Volumetric coke concentration, and also porosity and concentration of a solid frame φ_s, can be expressed in terms of φ_2:

$$\varphi_3 = (\varphi_2(0) - \varphi_2)(1 - \Gamma)\frac{\rho_2}{\rho_3}$$

NOMENCLATURE

$b_{i\kappa}$	material constants describing a change of strength and elastic features of composites with temperature
c_g, c_i	specific heat capacities of phases $[\mathrm{m}^2(\mathrm{s}^2\,\mathrm{K}^{-1})]$
D_W	rate of a surface ablation $[\mathrm{m\,s}^{-1}]$
E_i	elasticity modules of phases $[\mathrm{kg\,m}^{-1}\,\mathrm{s}^{-2}]$
$f(\mathbf{x}, t)$	shape of phase separation surface
J	intensity of mass transfer from polymer phase to gas $[\mathrm{kg}\,(\mathrm{m}^3\,\mathrm{s})^{-1}]$
J_0	material constant characterizing a mass transfer from polymer phase to gas $[\mathrm{kg}\,(\mathrm{m}^3\,\mathrm{s})^{-1}]$
p_e	gas pressure on an external composite surface $[\mathrm{kg}\,(\mathrm{m\,s}^2)^{-1}]$
p	pore gas pressure $[\mathrm{kg}\,(\mathrm{m\,s}^2)^{-1}]$
t	time [s].

Greek symbols

$\alpha_i, \alpha_{\kappa i}$	coefficients of heat phase expansion $[\mathrm{K}^{-1}]$
α^T	coefficient of heat transfer $[\mathrm{kg}\,(\mathrm{s}^3\,\mathrm{K})^{-1}]$
β_κ, β_{sh}	shrinkage coefficients
Γ	gasification coefficient
$\Delta e^0, \Delta e^*$	heat of volumetric (thermodestruction) and surface ablation
$\underset{\sim}{\varepsilon}, \varepsilon_{ij}$	strain tensor and its components
θ	temperature
λ_{ij}	components of a heat-conduction tensor $[\mathrm{kg\,m}\,(\mathrm{s}^3\,\mathrm{K})^{-1}]$
ν_{ij}	Poisson coefficients
ρ_g, ρ_i	phase density $[\mathrm{kg\,m}^{-3}]$
σ_{ij}	stress tensor's components.

Subscripts

bl	(blow) indicator of parameters of outflowing gas into the surroundings
e	(external) parameters related to the surroundings with respect to the considered domain
g	(gas) parameters of a gas phase
i	number of a composite phase $(i = 1, \ldots, 3)$
i, j	indicator of a tensor component $(i, j = 1, 2, 3)$
s	(solid) parameters of a solid framework
V	occupied by a composite
W	parameters on an external composite surface
$\sim$	indicator of a tensor.

$$\varphi_s = \varphi_1 + \varphi_2\left(1 - (1-\Gamma)\frac{\rho_2}{\rho_3}\right) + \varphi_2(0)(1-\Gamma)\frac{\rho_2}{\rho_3}$$

$$\varphi_g = 1 - \varphi_s, \quad \varphi_1 = \text{const.} \tag{5}$$

Function J describes heat–mass transfer intensity in thermodestruction in accordance with Arrhenius's law:

$$J = J_0\varphi_2 \exp\left(-\frac{E_a}{\mathrm{R}\theta}\right). \tag{6}$$

Γ is the gasification coefficient of the composite in thermodestruction, and λ and $\underset{\sim}{K}$ are heat-conduction and gas-permeability tensors, respectively, that depend on the porosity φ_g:

$$\underset{\sim}{\lambda} = \underset{\sim}{\lambda}^0 f(\varphi_g); \quad \underset{\sim}{K} = \underset{\sim}{K}^0 f(\varphi_g) \quad f(\varphi_g) = \exp(S\varphi_g). \tag{7}$$

Here $\underset{\sim}{\lambda}^0$, $\underset{\sim}{K}^0$ are constant tensors and S is the material constant.

Gas in pores is assumed to be ideal and perfect:

$$p = \mathrm{R}\rho_g\theta \tag{8}$$

where p is pore gas pressure.

If we introduce a stress-tensor function $\underset{\sim}{F}$ so that

$$\underset{\sim}{\sigma} = \frac{\varphi_g}{\varphi_s} p\underset{\sim}{\delta} + \frac{1}{\varphi_s}\,\mathrm{Ink}\,\underset{\sim}{F} \tag{9}$$

where $\mathrm{Ink}\,\underset{\sim}{F}$ is the differential operator of incompatibility [4], then equilibrium equation (4) is satisfied identically. To determine a stress–strain state in an ablating composite, the compatibility equation for strains ε [4] should be considered:

$$\mathrm{Ink}\,\underset{\sim}{\varepsilon} = 0. \tag{10}$$

Constitutive relations

The thermodestruction process of composites can be considered as a phase transformation of the polymer phase into a collection of a new solid phase and a gas phase. For media with internal phase transformations of such type, constitutive relations of their solid frame correspond to the model of viscoelastic unstable medium, even if all the phases are elastic media.

An ablating composite is assumed to be an orthotropic material with orthotropy axes Ox_i, $i = 1, 2, 3$, having a laminated structure, and the Ox_1 axis being perpendicular to the layers.

The constitutive relations can be written in the following form:

CYLINDRICAL SHELL

Let us consider now a solution of the problem stated above for a cylindrical shell subjected both to intensive internal convective heating and internal pressure p_{e1} distributed uniformly at the inner surface $r = r_D$. Introduce a cylindrical coordinate system $Or\vartheta z$ and assume the composite material of the cylinder is cylindrically orthotropic; then the constitutive relations (11)–(18) keep their validity if, in place of Descartes's components σ_{ij}, ε_{ij}, their physical components, are substituted. One end of the cylinder, $z = 0$, is rigidly fastened and at the other end the pressure p_{e3} is given; the ends are assumed to be hermetic and heat-isolated. The exterior cylinder surface, $r = r_2$, is fastened together with a load-bearing shell. Due to thermomechanical ablation, the surface $r = r_D(t)$ will be mobile.

Within the scope of these assumptions, the problem (1)–(4), (13) solution is sought in terms of functions φ_2, ρ_g, θ, $F_1 \equiv F$ and W_1, depending only on r and t. Equations (9) can be rewritten in the case as follows:

$$\sigma_{11} = \frac{\varphi_g p}{\varphi_s} + \frac{F}{\varphi_s r} \quad \sigma_{22} = \frac{\varphi_g p}{\varphi_s} + \frac{F'}{\varphi_s}. \tag{21}$$

The rest of the stresses are equal to zero except σ_z, which can be expressed by the formula

$$\sigma_{33} = \beta_{10}\sigma_{11} + \beta_{20}\sigma_{22} - p(1-\beta_{10}-\beta_{20}) + \tilde{a}_1^0 E_3(C-\mathring{\varepsilon}_{33}) \tag{22}$$

$$\beta_{10} = -\frac{\nu_{13}\tilde{a}_1^0}{\tilde{a}_2} \quad \beta_{20} = -\nu_{23}$$

where $C(t) = \varepsilon_{33}$ is a function of time which can be determined by the following approximate formula (when Poisson effects at the cylinder end are neglected):

$$C = \mathring{\varepsilon}_{33} - \frac{p_{e3}(r_2^2 - r_1^2)}{2E_3\int_{R_1}^{R_2} \tilde{a}_1^0 r\,\mathrm{d}r}. \tag{23}$$

Here the designation $F' \equiv \partial F/\partial r$ is introduced.

Constitutive relations (11) and (13) are reduced to the form:

$$\varepsilon_{11} = \mathring{\tilde{\varepsilon}}_{11} + \beta_{10}C + \beta_{11}\sigma_{11} + \beta_{12}\sigma_{22}$$

$$\varepsilon_{22} = \mathring{\tilde{\varepsilon}}_{22} + \beta_{20}C + \beta_{12}\sigma_{11} + \beta_{22}\sigma_{22}$$

$$\dot{W}_1 + \dot{\varphi}_3 W_1 Q_1 = \frac{\dot{\varphi}_3}{\varphi_s}\left(\frac{F}{r} + \varphi_g p\right) \tag{24}$$

where

$$\beta_{11} = \frac{1}{E_i\tilde{a}_1^0} - \frac{\nu_{3i}^2}{E_3\tilde{a}_2^0}$$

$$\beta_{12} = -\frac{\nu_{12}\theta}{E_1\tilde{a}_1^0} - \frac{\nu_{31}\nu_{32}}{E_3\tilde{a}_2^0} \quad i = 1, 2$$

$$\mathring{\tilde{\varepsilon}}_{11} = \mathring{\varepsilon}_{11} + \beta_{10}(C - \mathring{\varepsilon}_{33}) + W_3 p_3$$

$$\mathring{\tilde{\varepsilon}}_{22} = \mathring{\varepsilon}_{11} + \beta_{20}(C - \mathring{\varepsilon}_{33}) \tag{25}$$

and heat deformations $\mathring{\varepsilon}_r$, $\mathring{\varepsilon}_\theta$, $\mathring{\varepsilon}_z$ are expressed by formulae (15) with indexes $\kappa = 1, 2, 3$, respectively.

Compatibility equations (10) in this case are reduced to the one, which after substituting relations (9) and (11) into it, has the form

$$\bar{\beta}_{22}F'' + \left(\bar{\beta}'_{22} + \frac{\bar{\beta}_{22}}{r}\right)F' + \left(\left(\frac{\bar{\beta}_{12}}{r}\right)' + \frac{\bar{\beta}_{12} - \bar{\beta}_{11}}{r}\right)F + (p(\bar{\beta}_{22} + \bar{\beta}_{12}))' + \frac{\varphi_g p}{r}(\bar{\beta}_{22} - \bar{\beta}_{11}) + \mathring{\tilde{\varepsilon}}'_{11} + \frac{\mathring{\tilde{\varepsilon}}_{22} - \mathring{\tilde{\varepsilon}}_{11}}{r} = 0 \tag{26}$$

where $\bar{\beta}_{ij} = \beta_{ij}/\varphi_s$.

Heat–mass transfer equations (1)–(3) for a cylindrical shell have the form:

$$\rho_2\dot{\varphi}_2 = -J$$

$$(\rho_g\varphi_g)^{\bullet} = \frac{1}{r}(\mathrm{R}K_{11}r(\rho_g\rho)')' + J\Gamma$$

$$\rho c\dot{\theta} = \frac{1}{r}(\lambda_{11}r\theta')' + c_g\mathrm{R}K_{11}\theta'(\rho_g\theta)' - J\Delta\mathrm{e}^0. \tag{27}$$

Boundary conditions for equation system (26), (27) have the form:

$$r = r_D(t): \quad \frac{F}{r_D} = -p_{e1} \quad \mathrm{R}\rho_g\theta = p_{e1}$$

$$-\lambda_{11}\theta' = \alpha_T(\theta_e - \theta) - \varphi_s\rho_s D_W\Delta e^* - \gamma_{bl}c_g\mathrm{R}K_{11}(\rho_g\theta)'(\theta_e - \theta) \tag{28}$$

$$r = r_2: \quad \varphi_s\left(\frac{F}{r_2} + \varphi_g p\right) = -p_{e2} - \frac{E_\Pi h_\Pi}{(1-\nu_\Pi^2)r_2} \times \left(\mathring{\tilde{\varepsilon}}_{22} + \bar{\beta}_{12}\left(\frac{F}{r_2} + \varphi_g p\right) + \bar{\beta}_{22}(F' + \varphi_g p)\right)$$

$$(\rho_g\theta)' = 0 \tag{29}$$

where E_Π, ν_Π and h_Π are the elasticity module, the Poisson coefficient and the substrate thickness, respectively.

The equation of the inner mobile surface has the form:

$$\dot{r}_D = D_W \quad r_D(0) = r_1. \tag{30}$$

Introducing now a new mobile coordinate y in place of r,

$$y = k(t)r + b(t)$$

$$k(t) = \frac{r_2 - r_1}{r_2 - r_D(t)} \quad b(t) = \frac{r_2(r_1 - r_D(t))}{r_2 - r_D(t)} \tag{31}$$

varying within the interval $r_1 \leqslant y \leqslant r_2$ for all $t \geqslant 0$ while $r_D(t) \leqslant r \leqslant r_2$.

Introducing the auxiliary function $\zeta(y, t)$

$$\zeta(y,t)=\frac{D_{\mathrm{W}}}{r_2-r_{\mathrm{D}}(t)}\left(\frac{r_2-r_1}{(r_2-r_{\mathrm{D}}(t))^2}\right.$$

$$\left.\times\left(\frac{y-b(t)}{k(t)}+r_2\right)-r_2\right). \quad (32)$$

Then, passing to new variables (y, t), the equation system (26), (27) will be written in the form

$$\dot{\varphi}_2+\zeta\varphi_2' = -\frac{J}{\rho_2} \quad (33)$$

$$(\rho_g\varphi_g)^{\bullet}+\zeta(\rho_g\varphi_g)'$$

$$=\frac{k^2}{y-b}\left(\mathrm{R}K_{11}(y-b)(\rho_g\theta)'\right)'+J\Gamma \quad (34)$$

$$\rho c\dot{\theta}+\rho c\zeta\theta' = \frac{k^2}{y-b}\left(\lambda_{11}(y-b)\theta'\right)'$$

$$+c_g k^2\mathrm{R}K_{11}\theta'(\rho_g\theta)'-J\Delta e^0 \quad (35)$$

$$\bar{\beta}_{22}F''+\left(\bar{\beta}_{22}'+\frac{\bar{\beta}_{22}}{y-b}\right)F'$$

$$+\left(\left(\frac{\bar{\beta}_{12}}{y-b}\right)'+\frac{\bar{\beta}_{12}-\bar{\beta}_{11}}{y-b}\right)F$$

$$+\frac{1}{k}\left[\mathring{\tilde{\varepsilon}}_{11}'+\frac{\mathring{\tilde{\varepsilon}}_{22}-\mathring{\tilde{\varepsilon}}_{11}}{y-b}\right.$$

$$\left.+p(\bar{\beta}_{22}+\bar{\beta}_{12})'+\frac{p}{y-b}(\bar{\beta}_{22}-\bar{\beta}_{11})\right]=0 \quad (36)$$

$$\dot{W}_1+\zeta W_1'+\dot{\varphi}_3 Q_1 W_1 = \frac{\dot{\varphi}_3}{\varphi_s}\left(\frac{F}{y-b}+\varphi_g p\right) \quad (37)$$

where $F' \equiv \partial F/\partial y$.

Boundary conditions (28) in variables (y, t) are written in the form

$$r=r_1: \quad F=-r_{\mathrm{D}}p_{\mathrm{e1}} \quad \mathrm{R}\rho_g\theta=-p_{\mathrm{e1}} \quad (38)$$

$$-\lambda_{11}k\theta' = (\alpha_{\Gamma}-\lambda_{\mathrm{b1}}c_g\mathrm{R}K_{11}(\rho_g\theta)')$$

$$\times(\theta_e-\theta)-\rho_s\varphi_s D_w\Delta e^* \quad (39)$$

and the boundary condition (29) keeps its form. Adjoining initial conditions to the system (33)–(38), (29).

$$t=0: \quad \varphi_2=\varphi_2^0 \quad \rho_g=\rho_g^0 \quad \theta=\theta_0 \quad W_3=0$$

we get the complete problem statement to determine functions φ_2, ρ_g, θ, F and W_1, after showing that the stresses σ_{11}, σ_{22}, σ_{33} can be evaluated according to equations (21) and (22).

COMPUTED RESULTS

Solving the problem was performed numerically with the help of the step-by-step method using difference schemes and sweep procedures.

Computed results have been obtained for glass-plastic on epoxy-phenol binder and silica fabric. In computations the following values of the constants were given:

$$b_{11}=1.2\,\mathrm{K}^{-1}\,(\mathrm{s})^{b_{21}-1} \quad b_{21}=0.42 \quad b_{31}=5$$

$$b_{12}=0.5\,\mathrm{K}^{-1}\,(\mathrm{s})^{b_{22}-1} \quad b_{22}=0.22 \quad b_{32}=5$$

$$\alpha_{21}=20\cdot10^{-6}\,\mathrm{K}^{-1} \quad \alpha_{31}=2\cdot10^{-6}\,\mathrm{K}^{-1} \quad \beta_1=5$$

$$\alpha_{22}=4\cdot10^{-6}\,\mathrm{K}^{-1} \quad \alpha_{32}=2\cdot10^{-6}\,\mathrm{K}^{-1} \quad \beta_2=0.05$$

$$\alpha_{23}=4\cdot10^{-6}\,\mathrm{K}^{-1} \quad \alpha_{33}=2\cdot10^{-6}\,\mathrm{K}^{-1} \quad \beta_3=0.05$$

$$\rho_1=2.5\cdot10^3\,\mathrm{kg\,m^{-3}} \quad \rho_2=1.2\cdot10^3\,\mathrm{kg\,m^{-3}}$$

$$\rho_3=2.2\cdot10^3\,\mathrm{kg\,m^{-3}} \quad c_1=0.89\,\mathrm{kJ\,kg^{-1}\,K^{-1}},$$

$$c_2=0.6\,\mathrm{kJ\,kg^{-1}\,K^{-1}} \quad c_3=1.5\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$$

$$c_g=3.1\,\mathrm{kJ\,kg^{-1}\,K^{-1}} \quad \lambda_{13}=0.51\,\mathrm{Wt\,m^{-3}\,K^{-1}}$$

$$\lambda_{23}=0.27\,\mathrm{Wt\,m^{-3}\,K^{-1}} \quad \lambda_{33}=0.5\,\mathrm{Wt\,m^{-3}\,K^{-1}}$$

$$\lambda_{g3}=0.1\,\mathrm{Wt\,m^{-3}\,K^{-1}} \quad J_0=3.2\cdot10^6\,\mathrm{kg\,m^{-3}\,s^{-1}}$$

$$E_a/\mathrm{R}=5.5\cdot10^3\,\mathrm{K} \quad \Gamma=0.78$$

$$K^0=1.8\cdot10^{-19}\,\mathrm{s} \quad S=100 \quad \sigma_b=200\,\mathrm{MPa}$$

$$n=5 \quad E_1=20\,\mathrm{GPa} \quad E_2=20\,\mathrm{GPa}$$

$$E_3=2\,\mathrm{GPa} \quad \nu_{12}=0.27 \quad \nu_{23}=0.021$$

$$\nu_{13}=0.021 \quad G_{12}=8\,\mathrm{GPa}$$

$$G_{23}=0.72\,\mathrm{GPa} \quad G_{13}=0.72\,\mathrm{GPa}.$$

Geometric parameters and characteristics of the load-bearing shell were chosen as follows:

$$r_1/r_2=0.97 \quad h_{\Pi}=2\cdot10^{-3}\,\mathrm{m}$$

$$\nu_{\Pi}=0.3 \quad E_{\Pi}=6\cdot10^4\,\mathrm{MPa}.$$

Conditions of thermo-force loading the cylinder are shown in Fig. 1: for time $t = 0.2$ s the temperature θ_e and the pressure p_e of gas flowing along the inside

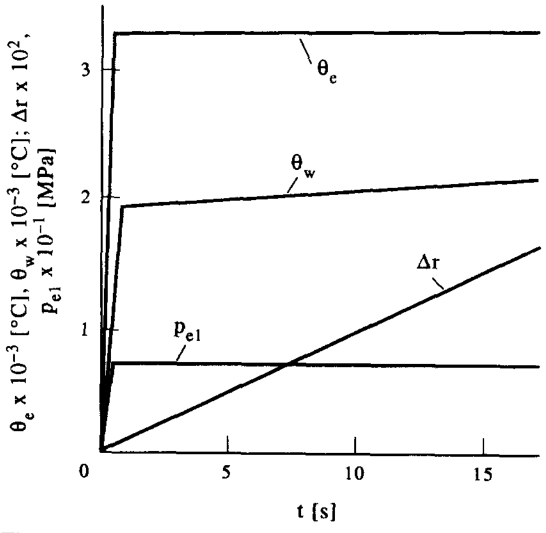

Fig. 1. Dependence of temperature θ_e and pressure p_{e1} of external gas medium, temperature θ_W of the cylinder surface heated and relative thickness Δr of material, moved away in time, where t is time [s].

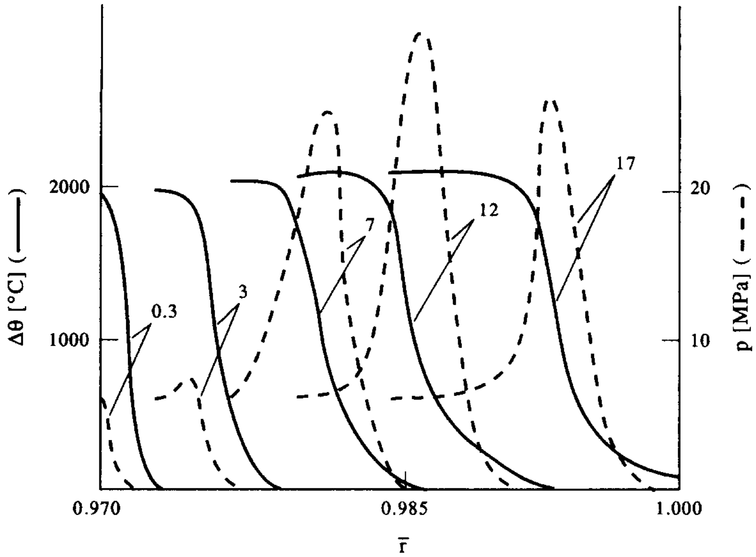

Fig. 2. Distribution of temperature θ and pore pressure p vs the cylinder thickness, taking account of surface ablation. Symbols on curves are time t [s].

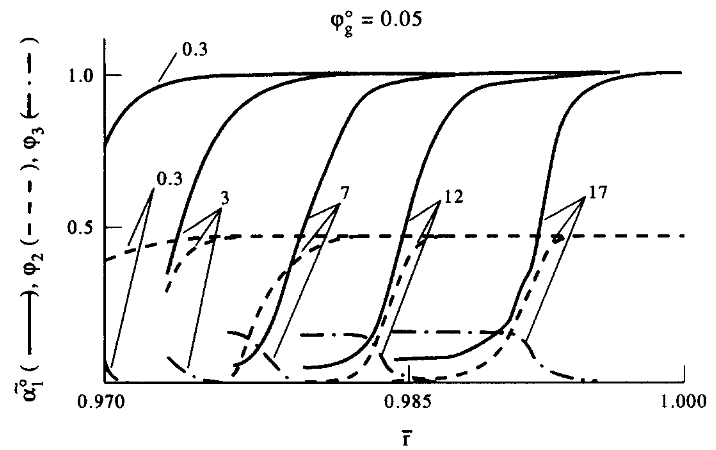

Fig. 3. Distribution of volumetric phase concentrations φ_2, φ_3 and coefficient of change of elastic properties $\tilde{\alpha}_1^0$ vs the ablating cylinder thickness for different times. Symbols on curves are time t [s].

of the cylinder rapidly reach a stationary state. In a stationary interval of heating, the material surface temperature θ_w slowly increases, and simultaneously the composite surface ablation occurs practically by linear law [see Fig. 1, the curve $\Delta r(t)$, where $\Delta r = (r_D(t) - r_1)/r_2$].

Due to the presence of a surface ablation, there exists a solution only in the interval $\bar{r}_D(t) \leqslant \bar{r} \leqslant 1$; therefore on the left from the point $r = r_D(t)$ all the functions terminate (Figs. 2–5).

As seen from Fig. 2, the pore pressure p is localized in a comparatively narrow zone corresponding to the interval where the temperature falls off. It is connected to the fact that, in a colder zone where the composite is not heated to thermodestruction temperatures, the material gas-permeability is very small, but in a zone coked, with porosity $\varphi_g \approx 0.26$, on the contrary, great rates of gas filtration to the internal surface arise, leading to equalization of p with the inner pressure p_{e1}.

In the computations the value of the initial material porosity was varied, $\varphi_g^0 = 0.05$ and 0.1. A considerable value of the inner pressure p_{e1}, which is characteristic for problems of this type, leads to an increase in the compressing radial stress σ_r (Fig. 4), having at initial time $t < 3$ s practically a linear distribution through the thickness. Peaks of stresses σ_r which appear when $t > 3$ s are connected to a local growth of pore pressure p in a composite thermodestruction zone. For a material with initial porosity $\varphi_g = 0.05$, the value of these peaks is substantially more than for $\varphi_g = 0.1$, and when $t > 12$ s, local tensile stresses arise in the composite.

A profile of the stress σ_θ at initial time $t \lesssim 10$ s is

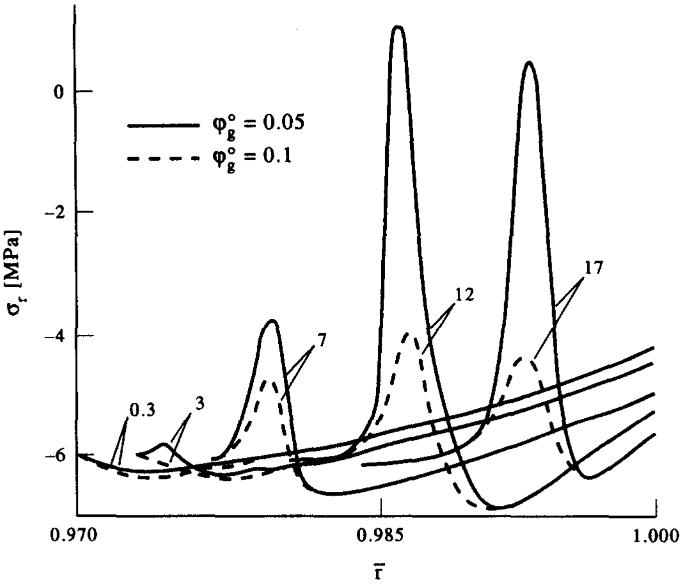

Fig. 4. Distribution of radial stress σ_r vs the ablating cylinder thickness. Symbols on curves are time t [s].

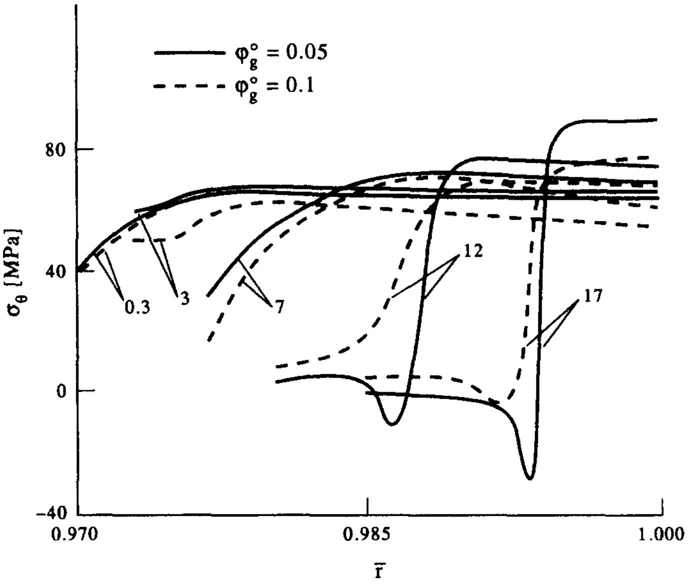

Fig. 5. Distribution of tangential stress σ_θ vs the ablating cylinder thickness for different times. Symbols on curves are time t [s].

determined, in the main, by the presence of the inner gas pressure p_{el} and by the temperature gradient. That is why there are tensile stresses through all the cylinder thickness and a minimum of σ_ϑ at the internal surface (Fig. 5). When $t \gtrsim 10$ s, a material thermodestruction becomes essential, leading to an increase in two additional factors having an effect on the stress σ_ϑ, a formation of local pore pressure and a composite shrinkage in coking. The local pore pressure causes local minimums of σ_ϑ to appear, but the shrinkage, on the contrary, leads to increasing the stresses σ_ϑ at the internal cylinder surface. Decreasing the glass-plastic thickness practically to half-thickness due to surface ablation leads to an increase in the maximum of stresses σ_ϑ from 60 to 85 MPa.

As follows from Fig. 5, it is tangential stresses σ_ϑ that are the most dangerous for similar types of glass-plastic constructions that are connected to the presence of the high inner pressure p_{e1}, displacing the stress σ_r into the domain of negative values.

CONCLUSIONS

The problem statement, to determine thermostresses in constructions made of ablating composite materials, is given. Evaluation of these stresses is very important in high temperature techniques, for example in designing thermal protection for spacecraft, ignition chambers for solid fuel engines, or construction resources made from composites for use in fires, etc. The example of numerical solution of the problem for non-stationary heating of a cylindrical shell shows that thermostresses have peculiarities for ablating composites that connect with internal gas generation in material and chemical shrinkage in coking.

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