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HEAT TRANSFER IN INTUMESCENT HEAT- AND FIRE-INSULATING COATINGS

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The physicochemical and thermophysical processes that jointly occur in intumescent heat- and fire-insulating coatings are studied numerically with the use of a model based on the hypothesis that the gaseous products of thermal expansion of an initial material are transparent. It is found that with the radiative mechanism of heat transfer in a layer of intumescent-coating coke taken into account, the temperature at the surface of a structure to be protected is almost equal to a temperature reached at this surface if a nonintumescent coating is used.

Intumescent heat- and fire-insulating coatings (IHFIC) are considered to be promising coatings for fire protection of various industrial and social objects [1, 2]. A model whose equations contain the coefficient of "radiative thermal conductivity" is used to analyze the effectiveness of these coatings [1]. Generally, this coefficient is written using Rosseland's approximation [3] in terms of the constant γ. This constant cannot be obtained only experimentally [1] and is found by comparing calculation results obtained with the use of model and experimental data. In this procedure of γ determination, the model [1] is not closed, and the parameter γ serves to match theoretical and experimental data.

In the present work, the basic specific features of the heat transfer in IHFIC are analyzed numerically with the use of the model of IHFIC with open pores and a transparent medium in them.

The problem of mixed heat transfer in a layer of IHFIC coke with open pores is considered. Materials with this porosity are widespread [1]. Figure 1 shows the scheme of the process considered. The problem is formulated under the following basic assumptions:

— the pores are open;

— the depth of radiation penetration is determined by the porosity;

— the possible superradiation of the wall pores is ignored;

— the radiative properties of the skeleton material of the pores do not depend on the degree of strain (intumescence) of IHFIC;

— the thermal-expansion products of the initial material, which are filtered to the surface, do not weaken the radiation flux;

— thermomechanical processes of intumescence occur without energy release or energy absorption;

— the intumescence rate and the strain coefficient for IHFIC are known;

— the gas and skeleton temperatures are equal;

— the problem is considered within the framework of Rosseland's approximation for media with high optical density.

The adopted assumptions do not impose strict restrictions on the range of variation of the parameters which determine the intensity of heat transfer in a layer of IHFIC coke with high porosity (up to 0. 95). In this formulation, the consideration omits minor factors allowance for which requires experimental data which cannot be obtained for the majority of IHFIC.

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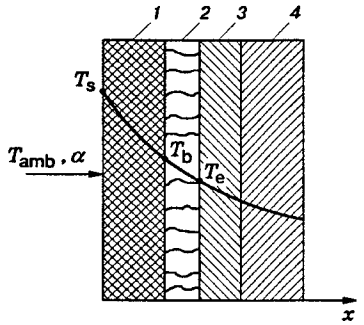

Fig. 1. Scheme of heating for an IHFIC: 1) coke; 2) layer of softened material; 3) IHFIC in the initial state; 4) metal layer (the structure to be insulated).

By analogy with [1, 2, 4–6], the energy equation which describes the process of heat transfer in an intumescent heat- and fire-insulating material of thickness δ is written in the form

$$(c\rho)_\Sigma \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_\Sigma \frac{\partial T}{\partial x}\right] + \dot{m}_1 c_1 \frac{\partial T}{\partial x} + WQ + \varphi \frac{\partial}{\partial x}(q_r), \tag{1}$$

where ρ is the density, c is the specific heat, t is the time, T is the temperature, x is the coordinate, λ is the coefficient of thermal conductivity, $\dot{m}$ is the mass rate of the gaseous products of the thermal expansion of the initial material, W and Q are the rate of thermal-expansion reaction and the thermal effect of this reaction, respectively, φ is the porosity, and q_r is the radiant thermal flux.

The values of $(c\rho)_\Sigma$, λ_Σ, $\dot{m}$, W, q_r, φ, and δ are found from the following expressions:

$$(c\rho)_\Sigma = c_1\rho_1\varphi + c_2\rho_2(1-\varphi), \quad \lambda_\Sigma = \lambda_1\varphi_1 + \lambda_2(1-\varphi), \quad \dot{m} = \int_{x_{b.e.}}^{x_{t.r.}} W\,dx,$$
$$W = \frac{\rho_0(1-k)}{1+\varepsilon}\frac{\partial \chi}{\partial t}, \quad q_r = -\frac{4\sigma}{3\alpha_p}\frac{\partial}{\partial x}T^4, \quad \varphi = 1 - \rho_0[1-\chi(1-k)](1-\varphi_0)/[\rho_2(1+\varepsilon)]; \tag{2}$$

$$\delta = L + \int_0^t \varepsilon(t)[\dot{x}_e(t) - \dot{x}_b(t)]\,dt. \tag{3}$$

Here k is the coke number, χ is the degree of expansion [1], ε is the coefficient of relative strain, σ is the Stefan-Boltzmann constant, α_p is the absorption coefficient, $\dot{x}_b$ and $\dot{x}_e$ are the velocities of displacement of the isotherms at the beginning and at the end of intumescence, and L is the initial thickness of the coating; the subscript 0 refers to the initial value, the abbreviations b.e. and t.e. refer to the beginning and termination of the expansion, respectively, the subscripts 1 and 2 refer to the gaseous and condensed products of the reaction, and the subscript Σ refers to the total values.

For simplicity, we consider a single-layer coating whose initial thickness is L. This coating protects a metal structure of thickness d for which the heat-conduction equation is written in the form

$$c_m\rho_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_m \frac{\partial T}{\partial x}\right]. \tag{4}$$

The problem is solved under the following boundary and initial conditions:

$$-\lambda_m \frac{\partial T}{\partial x} = 0, \quad x = 0, \qquad -\lambda_\Sigma \frac{\partial T}{\partial x} = -\lambda_m \frac{\partial T}{\partial x}, \quad T_{L-0} = T_{L+0}, \quad x = d,$$
$$-\lambda_\Sigma \frac{\partial T}{\partial x} = \alpha(T_{amb} - T_s) + \sigma\varepsilon_{red}(T_{amb}^4 - T_s^4), \quad x = \delta, \qquad T = T_0, \quad \delta = L, \quad t = 0. \tag{5}$$

In (4) and (5), d is the thickness of the metal layer, c_m, ρ_m, and λ_m are the thermophysical characteristics of

the metal, α is the heat-release coefficient, ε_{red} is the reduced degree of emissivity; the subscripts s and amb refer to the heated surface of the IHFIC and the ambient temperature, respectively.

In this formulation, the problem is reduced to the solution of the problem of thermal conduction for a two-layer metal plate of IHFIC with one moving boundary (Fig. 1).

The mathematical model formulated above differs from known heat-transfer models in IHFIC [1, 2] by the physical interpretation of the heat-transfer process in a layer of IHFIC coke. It is assumed that the IHFIC is a rigid skeleton and has open pores filled with radiation-transparent gaseous products of thermal expansion of the initial material [4]. It was noticed in the experiments described in [1] that the pores are almost closed on the external (heated) surface. The porosity is equal to 0.9 in the layer of the material at a small distance from the heated surface and to 0.2–0.4 in a thin ($\delta = 0.5$ mm) layer of the coke skeleton which separates the external medium and the intumescent material. This structure of the material is characteristic of the majority of real IHFIC. The difference between this model and the model of [1] is that the total thermal-conductivity coefficient λ_Σ is calculated according to the standard dependences for porous materials [7], which were checked in the solution of many problems [4, 5].

To calculate the relative volumetric strain of intumescence ε, the dependence [1]

$$\varepsilon = \begin{cases} 0, & T < T_{\text{b}}, \\ \varepsilon_0 \dfrac{T - T_{\text{b}}}{T_{\text{e}} - T_{\text{b}}}, & T_{\text{b}} \leqslant T \leqslant T_{\text{e}}, \\ \varepsilon_0, & T > T_{\text{e}} \end{cases} \tag{6}$$

was used. As in [1], the temperatures at the beginning T_{b} and at the end T_{e} of intumescence are taken to be equal to the temperature at the beginning of gas release and coking (the transition to a brittle state) of the skeleton of the charred layer. In the calculations, the coefficient ε_0 and the thermophysical and thermokinetic constants of the problem are the same as those in [1].

The formulated system of nonlinear differential equations and boundary and initial conditions is solved by the finite-difference method [8]. The iteration method with marching on each iteration [8] is applied to its solution. The parameters of the implicit iterative four-point scheme used [8] are chosen so as to ensure an approximation not lower than h^2 (h is the step of the difference grid on the coordinate x) for all calculation regimes.

In connection with the deformation of the solution domain, an irregular and nonuniform difference grid whose parameters are chosen to ensure the convergence and stability of the solution is used during numerical analysis [8]. On each temporal layer, the difference grid is rearranged. The values of the temperature and of the auxiliary parameters in the nodes of the new grid are determined by interpolating over the values of the desired function and the parameters in the nodes of the old grid.

For numerical studies, an algorithm and a Fortran program for solving the problem were developed. Calculations were carried out for several variants which are the most important for analysis: the radiative heat transfer in the IHFIC coke is described within the framework of the model (1)–(6); this transfer is absent in the IHFIC coke within the framework of the model of [1] for $\gamma = 10^{-9}$ and $\gamma = 10^{-10}$ ($\gamma = 0$), and intumescence does not occur ($\varepsilon = 0$).

The empirical parameter γ enters into the expression for the total coefficient of thermal conductivity of the coke [1]:

$$\lambda_\Sigma = \lambda_1 \varphi + \lambda_2 (1 - \varphi) + \gamma \sigma T^3.$$

Figures 2 and 3 show the typical results of a numerical solution. The temperature distribution over the thickness of the material (Fig. 2) shows that radiation plays a basic role in heat transfer through IHFIC. For the typical regimes of fires in premises, the relative portion of the heat due to the thermal conduction does not exceed 10% of the total flux [9]. The results in Fig. 2 show that the proposed model of thermophysical processes in intumescent heat- and fire-insulating materials ensures the assessment of the contribution from each mechanism of heat transfer with allowance for actual conditions. For example, in a layer of IHFIC coke

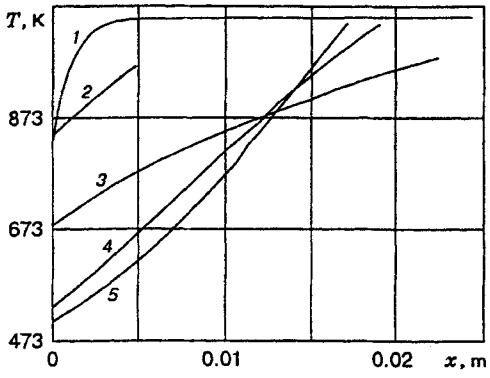

Fig. 2

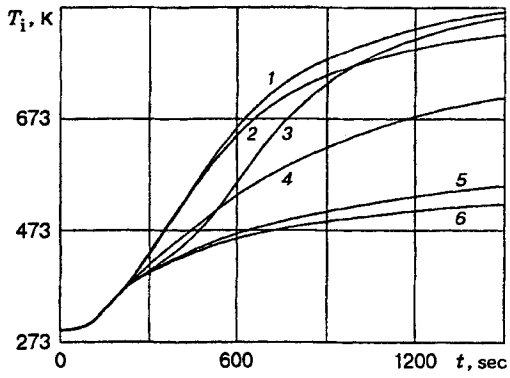

Fig. 3

Fig. 2. Calculation results for the temperature distribution over the coordinate x for $t = 10^3$ sec: calculation with allowance for the radiative heat flux and the intumescence of the coating (the basic variant) (curve 1), ignoring intumescence ($\varepsilon = 0$) (curve 2), and 5 with allowance for radiative transfer according to the model of "radiative thermal conduction" [1] for $\gamma = 10^{-9}$, 10^{-10}, and 0 (curves 3, 4, and 5, respectively).

Fig. 3. The temperature at the boundary of the structure to be protected versus time: no intumescence ($\varepsilon = 0$) (curve 1), no intumescence and radiative heat transfer ($\varepsilon = 0$ and $q_r = 0$) (curve 2), calculation with allowance for intumescence of the coating and the radiative heat transfer (the basic variant) (curve 3), and calculation of the radiative heat transfer according to the model of "radiative thermal conduction" [1] for $\gamma = 10^{-9}$, 10^{-10}, and 0 (curves 4, 5, and 6, respectively).

with a porosity not greater than 0.9, the temperature drop over the thickness reaches 600 K in the absence of radiative heat transfer in the pores of the layer, and the temperature at the IHFIC–structure-to-be protected boundary (T_i) does not exceed 500 K at the moment of time $t = 10^3$ sec (Fig. 3). At the same time, with account of the radiative heat flux, T falls off to 100 K, and T_i reaches 900 K, with other parameters being specified.

In addition, a numerical analysis shows (see Fig. 2) that with the radiative heat flux taken into account, the value of T_i differs slightly from the temperature in the nonintumescent coatings of the same initial thickness. The initial data allow one to conclude that the effectiveness of intumescent coatings can be adequately estimated only if the radiation heat transfer is taken into account correctly in the coke of these materials.

It is necessary to note that, in contrast to foam plastics whose porosity is also very high (up to 0.95) and the pores are closed in the whole volume, the IHFIC pores are not only elongated toward the heated surface, but are open, as in the majority of materials.

Figure 3 shows the dependences of T_i on time for the same heat-exchange conditions as those in Fig. 2. One can see that the above specifics of the mechanism of heat transfer in the coke layer of intumescent heat- and fire-insulating materials show up during the entire time interval considered. This interval is characterized by complete intumescence of the coating.

The results obtained allow one to assess the effectiveness of application of IHFIC for which the mechanism of intumescence is the most probable [1]. This mechanism is illustrated schematically in Fig. 4. As a result of the physicochemical processes occurring in the material upon heating to temperatures of the order of 400–600 K, the thin near-surface layer, which possesses a greater strength compared with the strength of the coke of typical IHFIC, separates. This layer can be fabricated, for example, with the use of reinforced filaments or even fibers. A gas interlayer with minor inserts of condensed reaction products (coke) is formed between this layer and the zone of physicochemical transformations. The thickness of this interlayer

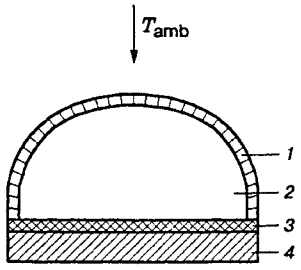

Fig. 4. Scheme of the mechanism of intumescence of an IHFIC with a reinforced near-surface layer: 1) reinforced skeleton of the screen; 2) gas interlayer; 3) IHFIC in the initial state; 4) metal layer (the structure to be insulated).

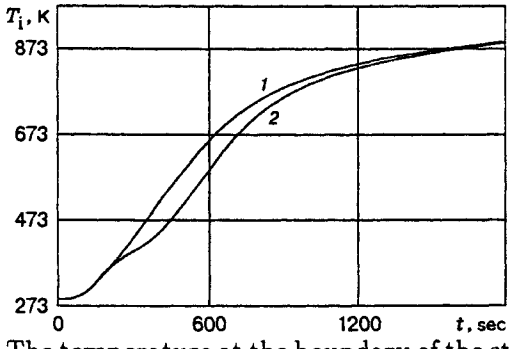

Fig. 5. The temperature at the boundary of the structure to be insulated versus the time when the intumescence is ignored (curve 1) and when the intumescence is allowed for in the presence of a screen (curve 2).

increases as the zone of physicochemical transformations extends to the depth of the material. Generally, this quantity depends not only on the characteristics of the material, but also on the parameters of the ambient medium (the temperature, pressure, and velocity of the gas, the intensity of mechanical actions, etc.), i.e., one can create a special "screen" above the surface of the structure to be insulated. This variant is a certain idealization of the common mechanism of work of any intumescent coating; nevertheless, it can be realized in practice, since this screen is more stable to external mechanical actions than any intumescent material with a porosity greater than 0.85.

The effectiveness of application of this IHFIC was analyzed numerically using the mathematical model of thermophysical processes in a coating formulated at the beginning of the paper [Eqs. (1) and (4), relation (2), and the boundary and initial conditions (5)]. The coordinates of the position of a "screen" and the thickness of the gas gap were calculated using the values of ε obtained from a calculation of the standard IHFIC according to the approximate model described above. At each moment of time, the total thickness of the coating with a "screen" was taken to be equal to the thickness of a screen-free IHFIC in the problem considered above.

It was found that coatings of this type decrease the level of heating of the structure to be protected, but this effect is insignificant (15–20%) compared with the variant when the standard coatings of a small thickness equal to the initial thickness is used (Fig. 5). The radiative heat transfer between the screen and

the surface of the protected body leads to an abrupt temperature rise at the structure–gas interlayer interface compared with a variant where the radiative energy transfer is absent. One can conclude that coatings of this type also exert a weak (15–20%) effect on the temperature drop at the surface of the object to be insulated.

One can assume that the effectiveness of IHFIC is affected by the optical characteristics of the medium between their external and internal surfaces. It is difficult to estimate the scales of this effect for the time being, because we cannot determine the characteristics, in particular, the absorption coefficient of radiation for the IHFIC coke.

In known studies dealing with analysis of thermophysical processes in heat- and fire-insulating materials, in calculations of the heat flux to the heated surface of the coke, the gaseous products of physical and chemical processes occurring upon heating of these materials to high temperatures are generally assumed to be transparent [1, 2, 4, 5]. This assumption does not lead to a marked discrepancy between the theoretical and experimental data [1, 2, 4, 5], which points to their validity.

It is noteworthy that the contribution of the radiative heat transfer to the coke layer of heat-insulating materials (HIM) has not yet been estimated. In the models of [4, 5], the assumption that the total effect of the molecular and radiative heat transfer (over the porous skeleton and inside it) can be taken into account only in the thermal-conductivity coefficient λ_Σ was used. This assumption holds, because the size of the pores in the typical HIM was small compared with the depth of heating. In [4, 5], this assumption is justified owing to not only the small sizes of the pores and the low porosity of the typical HIM. The typical heat-insulating materials are fabricated with the use of reinforced filaments or granules if the filler is located in the layers in the plane perpendicular to the vector of the heat flux in HIM. For this reason, the pores formed during thermal expansion of the initial polymer are not open. The pores of nonintumescent HIM have the characteristic size along the coordinate whose direction coincides with the direction of the heat-flux vector in HIM, and is not thicker than the reinforcing filaments or granules.

However, for intumescent materials with a finite porosity not greater than 0.8, this assumption does not hold, because the pores are open in the typical IHFIC and the size of the pores differs little from the depth of heating. Our results go beyond the range of application of the well-known models [4, 5], but support the validity of these boundaries.

Thus, our numerical studies of the complex thermophysical processes that occur in the IHFIC layer have shown that the radiative heat transfer dominates in them, and the effectiveness of the process should be assessed with allowance for the radiation-induced energy transfer in a layer of IHFIC coke. The results permit us to conclude that the models of [1, 2] are not sufficient to show the effectiveness of IHFIC.

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