
G. V. Kuznetsov and V. P. Rudzinskii

Characteristics of the heat-transfer mechanism in a layer of intumescent heat- and fire-protection material are considered within the framework of a model that takes into account conductive, convective, and radiative transfers. It is established that radiative heat transfer plays a dominant role in the formation of a temperature field. The coke structure (the presence of perpendicular interlayers) exerts an insignificant influence on the rate and depth of heating of the material.

A reliable experimental evaluation of the effectiveness of intumescent heat- and fire-protection materials (IHFPMM) [1] for the protection of industrial and residential buildings from fires is extremely difficult. The reason lies in the continuous increase of the dimensions of the “char” formed upon severe heating of IHFPMM. The intumescence process results in a shift of thermocouples relative to the initial position. Therefore, it is practically impossible to record the distribution of temperature $T$ across the thickness of intumescent materials with required accuracy for analysis. In addition, thermocouples, embedded in a thin (usually not more than 1–2 mm) material layer directly and effectively inhibit intumescence of the IHFPMM in the cross section where the thermocouple is located (this has been experimentally observed by the authors of the present paper). This inhibition leads to cracking of the char and, hence, the operating conditions of such materials change radically as a result of the change of the heat transfer mechanism across the IHFPMM.

In the models of [1, 2], the radiative heat transfer in the char of IHFPMM is taken into account by introducing a “radiative” heat-transfer coefficient [2], or it is ignored altogether. In this case, the value of the “radiative” heat-transfer coefficient is determined from a comparison of experimental results with calculations using the model of [2].

The objective of the present paper is to numerically investigate the characteristics of the heat-transfer mechanism in a char layer of IHFPMM, taking into account the radiant heat flux component.

As is known, IHFPMM with a large intumescence coefficient (the ratio of the final to the initial dimensions of the material layer) are believed to be effective [1, 2]. In the final composition, a layer of completely charred IHFPMM should possess a porosity more than 0.9. Moreover, the most commonly encountered char structures have continuous cylindrical pores, stretched toward the heated surface with and without transverse interlayers. In the present investigation, we consider a IHFPMM model with a more complicated structure, namely with transverse interlayers (Fig. 1). It can be assumed that the transverse

1Institute of Applied Mathematics and Mechanics at the Tomsk State University, Tomsk 634050.
interlayers will inhibit the propagation of radiation into the depth of the IHFPM toward the structure protected from the fire, and such material will be more effective than a material with through pores.

The following assumptions were adopted in the formulation of the problem:

1. The problem is considered in a one-dimensional formulation. The possibility of re-emission by the pore walls is not taken into account. The radiation propagates only in one direction.

2. The thermal-decomposition products of the starting material, being filtered toward the heated surface, do not attenuate the radiation flux (they are absolutely transparent).

3. The thermomechanical intumescence processes proceed without energy absorption or release.

4. The temperatures of the gas and the skeleton are the identical.

5. The thermal characteristics of the gaseous and condensed products of the thermal decomposition of IHFPM are independent of the degree of deformation.

As in [2], we formulate a mathematical model for the heat transfer in the system of “intumescent heat- and fire-protection material-protected material layer” as follows:

\[ (cp)_{\Sigma} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_{T} \frac{\partial T}{\partial x} \right) + \dot{m}_{1} c_{1} \frac{\partial T}{\partial x} + WQ + \varphi \frac{\partial}{\partial x} (q_{r}), \]

\[ c_{m} \rho_{m} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_{m} T \right] + (cp)_{\Sigma} = c_{1} \rho_{1} \varphi + c_{2} \rho_{2} (1 - \varphi), \]

\[ \lambda_{T} = \lambda_{1} \varphi + \lambda_{2} (1 - \varphi), \]

\[ \dot{m} = \int_{x_{b,d}}^{x_{e,d}} W dz, \]

\[ W = \frac{\rho_{0} (1 - k) d \chi}{1 + \varepsilon} \frac{\partial \chi}{\partial t}, \]

\[ q_{r} = -\frac{4 \sigma}{3 \alpha_{a}} \frac{\partial T}{\partial x} T^{4}, \]

\[ \rho_{1} = \frac{p_{1} M}{RT}, \]

\[ \varphi = 1 - \rho_{0} [1 - \chi (1 - k)] \frac{1 - \varphi_{0}}{\rho_{1} (1 + \varepsilon)}, \]

\[ \delta = \delta_{0} \left( 1 + \int_{0}^{x} \varepsilon (T) dx, \right) \]

\[ T = T_{0}, \quad \delta = \delta_{0}. \]

Here \( \rho \) is the density, \( c \) is the specific heat, \( t \) is time, \( T \) is the temperature, \( x \) is the coordinate, \( \lambda \) is the thermal-conductivity coefficient, \( \dot{m} \) is the mass flow rate of the gaseous products of the thermal decomposition of the starting material, \( W \) and \( Q \) are the rate and thermal effect of the thermal-decomposition reaction, \( \varphi \) is the porosity, \( q_{r} \) is the radiant heat flux, \( \delta \) is the thickness of the IHFPM layer, \( d \) is the thickness of the metal layer, \( c_{m}, \rho_{m}, \) and \( \lambda_{m} \) are the thermal characteristics of the metal, \( \alpha \) is the heat-emission coefficient, \( k \) is the coke number, \( \chi \) is the degree of decomposition, \( \varepsilon \) is the coefficient of the relative deformation due to intumescence, \( \sigma \) is the Stefan–Boltzmann constant, \( \varepsilon_{0} \) is the normalized emissivity factor, \( \alpha_{a} \) is the absorption coefficient, \( p \) is the pressure, \( M \) is the molecular weight, and \( R \) is the universal gas constant. The subscript notation is as follows: 0 refers to the initial value, 1 to the gaseous products of the reaction, 2 to condensed products, \( \Sigma \) to the overall values, \( h \) to the heated material surface, \( b.d. \) to the beginning of decomposition, \( e.d. \) to the end of the decomposition, \( ext \) to the ambient medium.

To calculate \( \varepsilon \), we used the relations [2]

\[ \varepsilon = \begin{cases} 0, & T < T_{b}, \\ \varepsilon_{0} \frac{T - T_{b}}{T_{e} - T_{b}}, & T_{b} \leq T \leq T_{e}, \\ \varepsilon_{0}, & T > T_{e}. \end{cases} \]

The temperatures at the beginning and at the end of intumescence \( T_{b} \) and \( T_{e} \), respectively, were assumed, as in [2], to equal the temperature at the beginning of gas evolution and charring (the transition to a brittle state) of the skeleton of the charred layer.

The temperature of the external medium near the heated surface was specified using the known relation [3] for the compartment temperature during a fire:

\[ T_{ext} = 345 \log (8t/60 + 1) + T_{0}, \]

where \( T_{ext} \) and \( T_{0} \) are given in Kelvins and \( t \) in seconds.

The formulated mathematical model describes the heat transfer by conduction, convection, and radiation in the IHFPM layer and the heat conduction in the material layer protected from fire.

In the general case, the formation of chars of degraded materials is a complex of interrelated chemical and physical processes. A detailed analysis of these processes is possible only using extremely complicated models [4, 5], relying on numerous empirical constants, which are impossible to determine for in-