Comprehensive assessment of fire protective intumescent paint “terma”

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Abstract Fire protection of steel structures is aimed at increasing their fire resistance, the indicator of which is the fire resistance limit. The paper presents a calculation approach to solution of the problem of critical heating time determining for building structures with intumescent compositions. Methodological approach for assessment of heating layers of intumescent fire protective coating for different types of steel structures is developed. The applied approach allows taking into account the influence of the basic thermophysical parameters of the fire protection composition on its efficiency. The paper presents the calculations for a particular coating, which allow to determine the dependences of the thicknesses of dry layers on different reduced metal thicknesses and to obtain relevant correspondences between the calculation results and experimental data.

Fire protection of steel structures is carried out in order to increase their fire resistance, the indicator of which is the fire resistance limit. The actual fire resistance limit for unprotected structures and steel structures protected by cladding can be determined using the well-known in fire-technical practice method developed by Professor A.I. Yakovlev [1]. The number of intumescent fire protection paints by various manufacturers is growing, but unfortunately, there are no normative documents defining the methods of calculating the fire resistance limits taking into account their application to different standard sizes of steel structures. Let us remind that fire protection paints are a complex multiphase system that transforms from one state to another in the process of heating. In the initial stage, the intumescent composition is a dense substance (dry film with a thickness of 0.2 to 2.3 mm), when heated by internal gas release, which can be accompanied by the release or absorption of heat, the composition turns into a porous substance consisting of two phases - a homogeneous solid "skeleton" and gases that fill the pores [2-6]. While the methods of modeling heat transfer in conventional (non-intumescent) materials in case of fire have been developed in detail by now, for example [7-12], these problems have not been fully investigated yet with respect to intumescent fire protection materials. G.N. Isakov, A.Ya. Kuzin, V.L. Strakhov, A.N. Garashchenko and a number of other researchers made a great contribution to the development of models and modeling techniques of heat and mass transfer processes in intumescent materials [13-20].

In the present work the calculation approach is presented, designed to solve the problem of determining the time of heating of building structures to a critical temperature (500 °C) when using in-
tumescent compositions at the example of Therma fire protection paint. It is assumed that the protected steel structures have an elongated shape (I-beam, channel, pipe) and the process of heat and mass transfer in them can be considered in a two-dimensional statement. Heat transfer is described by the non-stationary equation of heat conductivity with achievement of intumescence temperature $T_{vsp}$.

$$c_r \rho \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \Phi, \quad (1)$$

where $T$ – temperature, C; $t$ – time, sec; $v_x, v_y$ - projections of the composition movement speed at the moment of foam formation, m/sec; $\rho$ - density, kg/m$^3$; $c_r$ – specific heat capacity coefficient, J/(kg K); $\lambda$ - heat conductivity coefficient, W/(mK); $\Phi$ - internal heat release W/m$^3$.

In this case, the composition expands several times in accordance with a given expansion ratio of the composition $k$ and starts to fill the surrounding space (empty cells). In our case, the composition expands into the free space without any counterpressure. Each cell $(i,j)$ was assigned a variable $k_{i,j}$ to store information about the degree of filling of this cell with substance. At the initial moment of time for all cells filled with the substance is set $k_{i,j} = 1$, and for empty cells, - $k_{i,j} = 0$. When the temperature in a cell filled with the substance in pre-foam forming condition reached the value, $T_{vsp}$, - it was supposed to be $k_{i,j} = k$ (k - expansion ratio).

The following algorithm was used to model the process of intumescent composition movement at each time step.

1. The cells with the condition $k_{i,j} > 1$ were searched for. This means that in such a cell the composition has gone into the foam state and it should be distributed among neighboring cells (and from these neighboring cells it may be necessary to redistribute the substance further until the condition is met in all cells).

2. The boundary condition on the heated surface of the calculation area was specified in the form:

$$\frac{\partial T}{\partial n} = \alpha_\delta (T_\delta - T), \quad (2)$$

where $\alpha_\delta$ – heat capacity coefficient during a fire, W/(m$^2$K); $n$ – external normal to the surface; $T_\delta$ – fire temperature.

For a cell where $k_{i,j} > 1$ all cells adjacent to it were considered successively. We checked the fulfillment of the condition: cell $(i+1,j)$ is either empty or contains the substance in the foam form and $k_{i,j} > k_{i+1,j}$.

The change in the external temperature of the fire with time was set by the dependence "standard fire":

$$T_\delta = 345 \log(0.133 t + 1) + 273, \quad (3)$$

where t - time, sec.

With the heat capacity coefficient given by [1]:

$$\alpha_\delta = 29 + 3.9 \cdot 10^{-8} \frac{(T_\delta + 273)^4 - (T + 273)^4}{T_\delta - T}. \quad (4)$$
When this condition was met we transferred part of the excessive mass from cell \((i,j)\) to cell \((i+1,j)\), to meet either the condition \(k_{i,j} = k_{i+1,j}\), or \(k_{i,j} = 1\) and \(k_{i+1,j} < 1\) conditions. When this condition was not met we went back to point 1.

Note also that the size of the difference grid at the beginning of time should be taken "with a margin", i.e. such that the grid includes, in addition to the calculated structure, also a sufficient number of surrounding empty cells, which will then be filled with intumescent composition.

To calculate the fire protection properties of the composition, it is necessary to specify, among other things, \(T_v - T\). For the numerical solution of equations (1)-(4), the finite volume method was used, implemented on an uneven orthogonal difference grid (see, for example). At the initial moment of time, parts of grid cells were assigned characteristics of either metal (in the case of unprotected metal surface by composition) or composition before foam forming, in accordance with the geometry of the calculated structure. The rest of the grid cells initially remained empty. As the temperature in the grid cells occupied by the composition begins to warm up, it starts to reach the value of the heat conductivity coefficient of the composition after foam forming (of the foam coke formed), the determination of which is an additional task. At temperatures lower than the foam forming temperature \(T_{vsp}\), heat conductivity of the composition can be determined either from reference data or by standard measurements of this parameter. However, the main thermophysical characteristic of the composition, which influences its flame retardant properties, is the thermal conductivity coefficient of foam coke \(\lambda_2\). Conducting direct experimental measurement of \(\lambda_2\) value is associated with great difficulty: in addition to high temperatures, the composition in the foamed state is a porous viscous and very fragile substance. A number of works are devoted to this subject. Thus, the publication describes a method that combines mathematical modeling and laboratory bench tests for numerical calculations of material characteristics. In the porous medium is considered as a structure that can be represented as a periodically recurring set of one or more characteristic elementary cells of space. The cell is an air cavity surrounded by solid walls. Numerical modeling of heat transfer through such a cell first determines the effective coefficient of thermal conductivity of the elementary cell at various combinations of thermophysical and geometric parameters, and then calculates the coefficient of effective thermal conductivity of the entire porous medium.

Numerous experimental data on the heating of steel columns were used to determine the thermophysical properties of the Terma fire protection intumescent paint. On the basis of the described technique by comparison of the calculation results with the experimental data, it was possible to determine the thermophysical characteristics of the composition - \(T_{vsp}\), \(\lambda_1\) and \(\lambda_2\). The experimental dependence of temperature on time also enabled us to determine these characteristics consistently. (Otherwise, it would be impossible to exclude the possibility of several solutions to this problem). At the initial stage of heating the first part of the experimental curve was used, located in the time interval from 0 to 4 minutes from the beginning of the experiment. Comparison of the results of the calculation and the experiment on this part of the curve allowed us to determine the \(\lambda_1\) value. After that the \(\lambda_2\) value providing the greatest coincidence of calculation and experiment on the remaining (second) part of the curve was selected. The temperature value \(T_{bcp}\) was determined from the condition of providing the best smooth joining of the first and second parts of the curve, which were: \(T_{vsp}= 210^\circ C\), \(\lambda_1 = 0,1 W/(mK)\), \(\lambda_2 = 0,08 + 0,00015T\), \(W/(mK)\). The results of comparison of the experiment, for example, according to the data from the reports on certification tests № № 4407 - 45 min, № 4984 - 60 min
and the calculation of the composition at the specified characteristics are presented in Fig. 1 (a, b), respectively.

![Comparison of the results of the experiment and calculation for Therma composition: a) average temperature curves of two samples of columns - 45 min; b) average temperature curves of two samples of columns - 60 min.](image)

**Figure 1.** Comparison of the results of the experiment and calculation for Therma composition: a) average temperature curves of two samples of columns - 45 min; b) average temperature curves of two samples of columns - 60 min.

The coincidence of the results of the calculation (in such a statement already having good reason to be called a forecast) and the experiment (Fig. 1), show that although the available limited experimental material was limited, it was still possible to determine the thermophysical characteristics of the composition with sufficient accuracy. Other thermophysical characteristics were accepted as follows: for carbon steel $\rho = 7800 \text{ kg/m}^3$; $c_p = 500 \text{ J/(kg*K)}$; $\lambda = 35...25 \text{ W/(m*K)}$ at $T = 20...500^\circ\text{C}$ [12]; for Therma composition were determined experimentally in laboratory conditions and set the following: $\rho_1 = 1800 \text{ kg/m}^3$; $c_p = 1000 \text{ J/(kg*K)}$; $k = 40$.

Fig. 2 shows how the thickness of the composition layer changes in the process of calculation by the example of I-beam B120 GOST 26020-83 at certain moments of time under the influence of a standard fire (taking into account the double symmetry of the temperature field in this case, Fig. 2 shows 1/4 of the calculated area).
As the calculation (Fig. 2) has shown, under these conditions, foam forming began at 1.5 minutes on the sharp edges of the I-beam. Further the front of foam forming starts spreading along the I-beam surface (time interval from 1.5 to 2.0 minutes) and finally, at 3.7 minutes, the whole composition is covered with foam.

After checking the model for adequacy using the regression analysis method (Fisher's criterion was more than 20%), a compact program interface was created to calculate the thickness of the composition necessary to achieve the required heating time (15, 30, 45, 60, 75, 90, 120 min) for I-beams, channels and pipes of different cross-sections.

**Table 1.** Program start sequence for calculation, output structure of the DVYTAVR.txt file

| Type | h, mm | b, mm | s, mm | t, mm | A/P, mm | t(H=0), min | H(15min), mm | H(30min), mm |
|------|-------|-------|-------|-------|---------|-------------|--------------|--------------|
| 20B  | 200   | 100   | 5.6   | 8.5   | 3.45    | 8.16        | 0.15         | 0.49         |
| 10   |       |       |       |       |         |             |              |              |
| H(45min), mm | H(60min), mm | H(75min), mm | H(90min), mm | H(105min), mm | H(120min), mm |
| 1.05 | 1.77  | 2.68  | 3.90  | 5.61  | 7.49    |              |              |              |
Diagram of the dependence of the dry layer of Therma fire protection paint on reduced thickness of the steel structure.

![Diagram of the dependence of the dry layer of Therma fire protection paint on reduced thickness of the steel structure.](image)

**Figure 3.** Dependence of the composition thickness on reduced steel thickness for different fire protection efficiency groups according to NPB 236-97.

To calculate the thickness of the composition, which provides a given fire resistance of typical steel structures, the following data are entered into the source file `AutoRun2Tavr.dat` in the form: 10B1, 100, 50, 3.6, 4.2, etc.

Each line contains all the necessary information for the calculation of each structure (e.g. I-beam No. 20B1 GOST 26020-83). In the first column the type of the structure is placed, in the columns from the second to the last there are geometrical characteristics of the given I-beam ("h" - height of the I-beam, "b" - width of the shelf, "s" - thickness of the wall, "t" - thickness of the shelf) according to the normative-technical documentation for this type of structures. For calculation of the time of heating of structures of channel type it is necessary to enter the initial data in the `AutoRunShveller.dat` file, for pipes of rectangular section - in the `AutoRunRectangle.dat` file, for pipes of round section - in the `AutoRunTryba.dat` file, etc. These source files are located in the same directory as the executable file and can include an unlimited number of lines. The program reads the next line from the source file, uses the data from this line to calculate, outputs the results to the output file and then reads the next line from the source file. The program stops when the last line is read and the corresponding construction is done.

To work with the program run the `teplo.exe` file. On the dialogue panel which appears it is necessary to choose a structure for the calculation of from the options given - T-beam, channel, pipe (round section or rectangular). It is also necessary to select the heating mode "From all sides" or "3 sides".

Column 7 shows the time of reaching the critical temperature of the unprotected structure, columns 8 to 15 show the results of the calculation of Therma composition thickness necessary to
achieve the required heating time of the structure - 15, 30, 45, 60, 75, 90, 105 and 120 minutes respectively.

According to the calculation data for practical purposes of designing fire protection of steel building structures it is possible to construct graphs showing the dependence of composition thicknesses on the reduced thickness of steel profiles of structures (Fig.3). Calculation can be performed for both four and three-side heating, taking into account the shape of the protected structure and all the basic thermophysical parameters of the composition.

Thus, in the considered model and method of calculation of time of achievement of critical temperature for the steel structures covered with an intumescent fire protection composition layer the moment when the critical value $= 500^\circ$C is achieved is taken as a condition of loss of the carrying capacity for a sample. This model takes into account the influence of the basic thermophysical parameters of the fire protection composition on its fire retardant efficiency. Calculations made for a particular coating allowed us to determine the dependences of dry layer thicknesses on different reduced metal thicknesses and to obtain satisfactory correspondence between the results of calculations and experimental data. The above enables us to use the developed method for calculations to design fire protection of steel structures with a thin layer of intumescent coating.

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