FIRE AND INDUSTRIAL SAFETY (CIVIL ENGINEERING)

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METHOD OF CALCULATION OF FIRE RESISTANCE OF HEAT-INSULATED METAL CONSTRUCTIONS

On the basis of analytical solution of problem of non-stationary thermal conductivity the correlaton for estimation of fire resistance of metal constructions has been obtained using indicators of metal warming up to critical temperature. Suffered method has high accuracy, doesn’t demand application of computer and can be used in engineering practice.

Keywords: fire safety, building materials, fire resistance.

The actual limit of fire resistance of metal structures is determined by the time of heating of a metal to critical temperature. As a result, collapse of structures occurs or irreversible deformations appear, and further operation is impracticable. It is possible to determine the limit of fire resistance using experiment or calculation. Calculation requires less material costs and time, and, according to [1], is 0.01 of the cost of experiment.

Considering importance of computational methods from both theoretical and practical point of view, consider the problem of determination of the actual limits of fire resistance of metal structures of the column of a square or round section type, with fire-retardant surface which doesn't change its aggregative state during fire exposure. From a physical point of view, such structures can be viewed simplistically as a two-layer wall with different physical characteristics. In this case heating occurs from side of surface, and heat loss from the surface of the metal layer can be neglected.

It is well known [2] that the temperature difference in heat-insulated metal constructions in terms of fire exposure occurs in a layer of heat insulation, and temperature over thickness of metal layer is practically uniform. This model of physical process of heating of the heat insulated metal plate allows to use mathematical solution of differential equation of non-stationary heat conductivity for the layer with the boundary conditions that take into account the volumetric heat capacity of the metal layer.

Consequently, it is necessary to find a solution of the system of equations

$$\partial t / \partial \tau = a\,(\partial^2 / \partial \chi^2), \quad (1)$$

$$t_{(\chi,0)} = t_0, \quad (2)$$

$$c_м \gamma_м \delta_м\,(\partial t / \partial \tau)\Big|_{\chi=0} = -\lambda(\partial t/\partial \chi)\Big|_{\chi=0}, \quad (3)$$

$$t_{(\chi,\tau)}\Big|_{\chi=\delta} = f(\tau), \quad (4)$$

where $f(\tau)$ is the temperature of heated surface of heat insulation; symbol "*м*" means "metal".

Equation (1) describes the change in temperature in the layer of heat insulation. The boundary condition (3) indicates that heat flux from the layer of insulation is equal to change in heat content in the metal layer.

Temperature of the metal is equal to the temperature of heat insulation in the plane of layers contact ($x = 0$).

Solution of the system of equations (1)—(4) for a case when temperature o heat insulation surface is equal ($f(\tau) = t_c = \text{const}$), according to [3], can be written as follows:

$$(t_{(\chi,\tau)} - t_0)/(t_c - t_0) = 1 - \sum_{n=1}^{\infty} A_n \{\cos\mu_n\xi - (\mu_n/N)\sin\mu_n\xi\} \exp(-\mu_n^2 F_0), \quad (5)$$

where

$$A_n = (2\sin\mu_n) / (\mu_n + \sin\mu_n\cos\mu_n);$$

$$\xi = \chi / \delta;\ F_0 = a\tau/\delta^2;\ N = (c\gamma^\delta) / (c_м\gamma_м\delta_м)$$

is the non-dimentional parameter, describing interrelation between accumulation capacity of heat insulation layer and accumulation capacity of metal layer; μ_n are roots of characteristic equation $\mathrm{ctg}\mu = \mu/N$.

Tabulated values A_n and μ_n for different values N are described in [4]. Setting in (5) $\xi = 0$ obtain a time dependence of metal temperature:

$$(t_м(\tau) - t_0) / (t_c - t_0) = 1 - \sum_{n=1}^{\infty} A_n \exp(-\mu_n^2 F_0). \tag{6}$$

To obtain a solution of problem (1)—(4), use **Duhamel's theorem** which can be written as

$$t_{(\chi,\tau)} = \int_0^{\tau} f'(\tau - \nu)\, t_1(\chi, \nu)\, d\nu + f(0)\, t_1(\chi, \tau), \tag{7}$$

where $t_1(\chi,\tau)$ is ratio (6) at $t_c = 1$ and $t_0 = 0$.

Considering (6), obtain from (7)

$$\begin{gathered} t_м(\tau) = f(0)\,[1 - \sum_{n=1}^{\infty} A_n exp(-\mu_n^2 F_0)] + \\ + \sum_{n=1}^{\infty} A_n exp(-\mu_n^2 (a\nu/\delta^2))]d\nu. \end{gathered} \tag{8}$$

Equation (8) is a general formula for determining heating of a metal layer with an arbitrary function of the temperature of insulation surface. It is easy to determine the function of heating of the metal for specific conditions of heating.

Suppose that the temperature of surface of insulation varies during the fire exposure according to the temperature regime of a standard fire, which according to [5] can be described by the relationship

$$t_в(\tau) = 925 + 150 \ln(\tau + \xi), \tag{9}$$

where τ is the time, hour; ξ is the parameter for specification of initial temperature of fire t_0. Substitution of (9) in (8) gives

$$\begin{gathered} t_м(\tau) = (925 + 150 ln\varepsilon)\,[1 - \sum_{n=1}^{\infty} A_n exp(-\mu_n^2 F_0) + 150(ln(\tau+\varepsilon) - ln\,\varepsilon)] + \\ + 150 \sum_{n=1}^{\infty} A_n \left\{ ln\varepsilon - ln(\tau+\varepsilon) - \sum_{n=1}^{\infty} A_n \left(\left[\mu_n^2 (a/\delta^2)(\tau+\varepsilon)\right]^m - \mu_n^2 \left[(a/\delta^2)\varepsilon\right]^m \right) / (m \cdot m!) \right\} \\ exp\left[-\mu_n^2 (a/\delta^2)(\tau+\varepsilon)\right]. \end{gathered} \tag{10}$$

Considering that initial temperature of structure is t_0, equality of relationships 150[ln $(\tau + \varepsilon)$ – lnε] and $t_b(\tau) - t_0$, also 925+1501nε and t_0, formula (10) can be written as

$$\theta = t_0 \; / \; t_0 - \; t_b \;\; \tau \;\; \left[1 - \sum_{n=1}^{\infty} A_n exp\,(-\mu_n{}^2 F_0)\right] +$$
$$+\sum_{n=1}^{\infty} A_n \left\{1 + \sum_{n=1}^{\infty} A_n \left[(\mu_n{}^2 F_0)^m\right] / \; ln(\tau+\varepsilon) \;\; - -ln\varepsilon \;\; m \cdot m! \right\} exp \;\; -\mu_n{}^2 F_0 \;\; . \qquad (11)$$

where
$$\Theta = \frac{t_b(\tau) - t_M(\tau)}{t_b(\tau) - t_0}.$$

The analysis shows that the first summand in the right side of equation can be neglected because this summand is three orders less than the second. Relationship (11) can be written as

$$\Theta = \sum_{n=1}^{\infty} A_n \left\{1 + \sum_{m=1}^{\infty} \frac{(\mu_n^2 F_0)^m}{\left[\ln \;\; \tau + \varepsilon \;\; - \ln \varepsilon\right] m \cdot m!}\right\} \exp\cdot \;\; -\mu_n^2 F_0 \;\; . \qquad (12)$$

Formula (12) shows that heating of the metal depends on the temperature of surface of insulation, initial temperature and thermophysical properties of metal and heat insulation, as well as on the relationship between heat accumulation ability of heat insulation layer and metal layer.

We have solved the problem with constant coefficients of heat transfer. It is impossible in actual practice so in practical calculations modifications of thermophysical properties of materials due to temperature and humidity of heat insulation should be considered using method [6].

In order to simplify practical implementation of the formula (12) the curves Θ (see Fig. 1) were made with the use of results of computer calculation of “M-220” for various values of N and P_o.

As the result, heating of the metal is calculated using formula

$$t_{м(\tau)} = t_{пов\,(\tau)} - \Theta(t_{пов\,(\tau)} - t_0)\;, \qquad (13)$$

where $t_{пов\,(\tau)}$ is the temperature of surface of heat insulation which can be calculated using method [6]; value Θ is determined from Fig. 1.

To compare accuracy of proposed method the curves of heating of steel plate with concrete heat insulation for different values of parameter N were made (Fig. 2). These curves were made with the use of numerical method [6] and formula (13) taking into account modifications of thermalphysic properties of materials.

Calculation using formula (13) were made with following thermalphysic properties of materials:

- for steel

t_{cp} = 250°C, γ = 7800 kg/m^3, c_{tcp} = 0.569 kJ/kg • degree,

- for concrete (considering humidity)

t_{cp} = 450°C; γ_c = 2350 kg/m^3; λ_{tcp} = 3.747 kJ/(m·h • degree);

c_{tcp} = 1.264 kJ/kg•degree, a_{np} = 0.00126 m^2/h.

Fig. 2 shows that curves of heating obtained using different methods are closely spaced or coincide. Maximum discrepancy or a wide range of values of N and F_o doesn't exceed 7 %.

This fact substantiates high accuracy of proposed method.

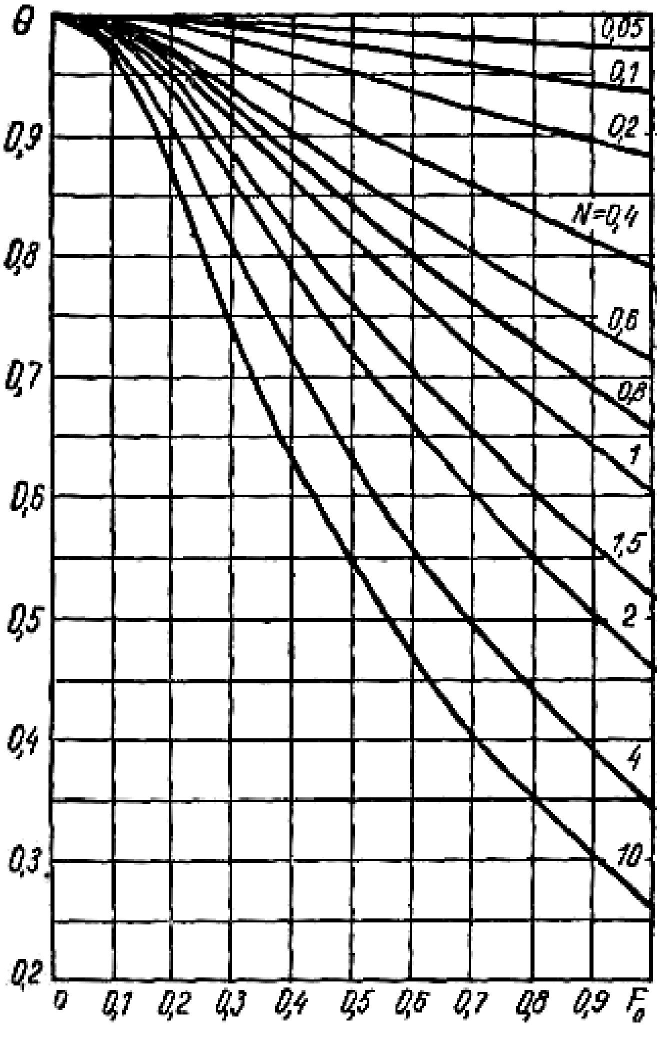

Fig. 1. Relative excess temperature Θ distribution curves in heat insulated metal structure

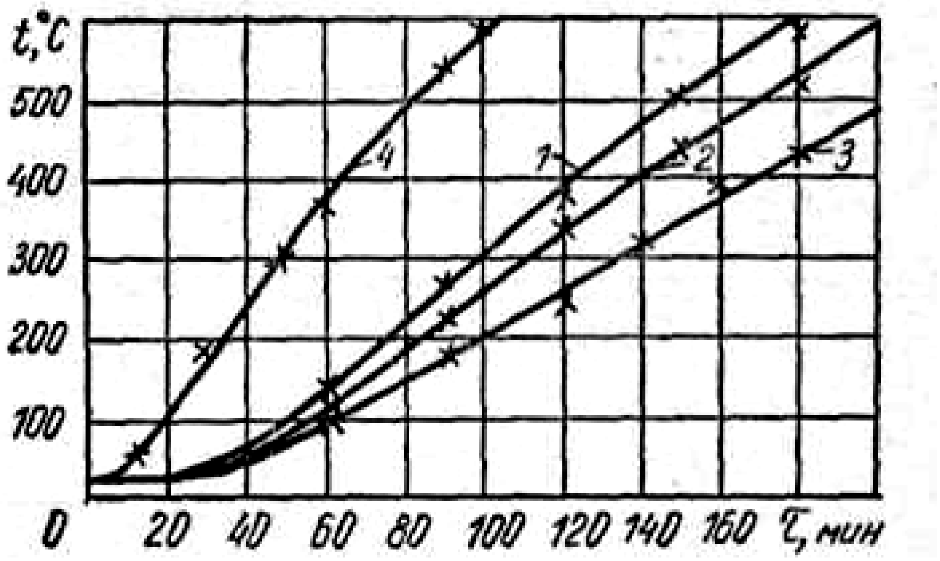

Fig. 2. Curves of heat insulated steel plates heating:
______ — obtained with the help of numerical method; x x x x — obtained with the help of formula (13); 1 — δ_M = 0.005, δ = 0.08, N = 10.7; 2 — δ_M = 0.01, δ = 0.08, N = 5.35; 3 — δ_M = 0.02, δ = 0.08, N = 2.675; 4 — δ_M = 0.0374, δ = 0.028, N = 0.5.
Thickness of a layer is given in metres

Conclusion

Calculation relationship for determination of fire resistance of heat insulated metal constructions according to heating of a metal up to critical temperature was obtained on the base of analytical solution of the problem of non-stationary heat conductivity.

Proposed method has high accuracy, doesn't require application of a computer and can be used in engineering practice.

References

1. Lay, T. T., Alen, D. E. Calculation of fire ferroconcrete columns resistance: transl. from Engl. Moscow, 1973. 128 pp.

2. Lay, T. T. Temperature distribution in buildings columns in a case of fire. Heat transfer: proceeding of American society of mechanical engineer. N 4. 1977. P. 25—29.

3. Mikhaylov, N. D. Non-stationary temperature fields in covers. Moscow, 1967. 220 pp.

4. Lykov, A. V. Theory of heat conductivity. Moscow, 1967. 176 pp.

5. Krikunov, G. N., Zaytsev, A. M. Calculation of metal constructions fire resistance. Fire resistance of building constructions. Iss. 5. 1977. P. 72—78.

6. Directions on calculation of actual limits of ferroconcrete building constructions fire resistance on the basis of computer applications. Moscow, 1975. 36 pp.