# Modeling of Non-stationary Heating of Steel Plates with Fire- protective Coatings in Ansys under the Conditions of Hydrocarbon Fire Temperature Mode

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**Abstract.** The results of the experimental determination of temperature from a non-heating surface of steel plates with a fire-protective coating under conditions of fire exposure under the hydrocarbon fire temperature regime are presented. A calculated finite element model of the system “steel plate-flame retardant” was constructed to simulate the non-stationary heating of such a system in the ANSYS R17.1 software complex. The reliability of the numerical simulation results is estimated by real test, the adequacy of the developed model to the real processes occurring when heating the steel plates with fire-protective coating under the conditions of hydrocarbon fire temperature mode is made.

## 1 Introduction

The study of the fire resistance of steel structures and the fire-protective ability of coatings of such structures by experimental methods is a serious problem, because experiments are time-consuming and it is difficult to obtain a full range of information that reflects the behaviour of all elements of the structure under the influence of fire load. This makes the need to use numerical modeling techniques to obtain the necessary parameters as accurately and fairly as possible for all the elements of the test structure.

## 2 Actual scientific researches and issues analysis

A great number of works is devoted to the questions of computational evaluation of fire resistance of building structures [1–5]. In the work [1] experimental and calculated data for determining the temperature of steel plates with flame retardant under conditions of fire exposure according to the standard temperature of the fire are given. In the work [2] for assessing the fire resistance of metal structures, scenarios of possible real fires have been considered. The work [3] describes the calculation methods for evaluating the fire resistance of steel structures at a standard fire temperature. In the work [4] methods for increasing the limits of fire resistance of vessel and building structures using fireproof coatings at hydrocarbon temperature for metal structures are described, and [5] describes the combined effect on the steel column of the explosion, which causes deformation and subsequent fire. There is a series of works [6–10], in which an attempt was made to determine the fire resistance of steel structures under the conditions of the influence of the hydrocarbon fire temperature mode. However, in these works, the issues of developing a finite element model of the system “steel plate-flame retardant” to simulate the non-stationary heating of such a system in the ANSYS R17.1 software package have remained without the attention of the researchers.

## 3 Formulation of the problem and its solution

The purpose of the work was to evaluate the fire-retarding ability of coatings for steel structures under the hydrocarbon fire temperature conditions and the calculation of the non-stationary heating of a steel plate with a fire-protective coating system by means of ANSYS R17.1 software, and the calculation of the time to reach the critical temperature of heating of the steel plate (in this study 500 °C is accepted) of the determined thickness under the specified test conditions.

To achieve this goal, it was necessary to solve the following tasks:

– build adequate physical and computer models in the ANSYS R17.1 software environment, which would accurately and reliably reproduce the processes occurring in the system “steel plate-flame retardant” when heated under the conditions of the hydrocarbon fire temperature.

The computer model includes:

- the geometry of the investigated object;
- appropriate thermal effects;
- initial conditions;
- boundary conditions from the heating and non-heating surfaces (in our case, the boundary conditions of the third kind);
- loads, applied to the structure, if any;
- properties of system materials (thermal conductivity of coating and steel, heat capacity of coating and steel, humidity, temperature expansion coefficient for steel, etc.).

– determination of the error between the results of the experimental determination of the temperature of the steel plates with flame-retardant coating and modeling in the ANSYS R17.1 software environment.

Comparisons were made according to the data obtained from the non-stationary heating of the system “steel plate-flame retardant” in the conditions of their tests in the temperature regime of the hydrocarbon fire.

## 4 Main part

For this purpose, experiments were carried out to determine the temperature from a non-heated surface of a steel plate with a flame retardant under the conditions of a hydrocarbon fire temperature mode. The experiments were performed using steel plates 500 mm×500 mm×5 mm [11]. The flame retardant was applied in a mechanized manner, the average thickness of the coating was 0.42 mm. The experiments were performed at air temperature 20 °C, relative humidity 48 % and pressure 743 mm Hg.

The temperature of the hydrocarbon fire was determined by the formula [12]:

$$\Theta_g=1080(1-0.325e^{-0.167t}-0.675e^{-2.5t})+20, \tag{1}$$

$\Theta_g$ – temperature of the gas environment near the structure, °C;

$t$ – time, minutes.

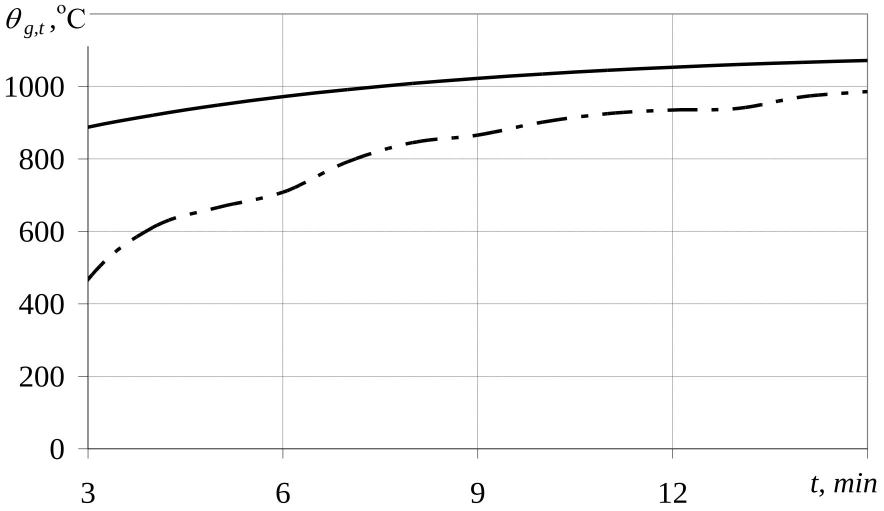

Fig 1. The dependence of the temperature in the furnace on the duration of fire exposure:
—– curve of the hydrocarbon fire temperature mode;
– · – temperature curve during the experiment in the furnace.

As can be seen from Fig. 1, after 3 min of fire exposure the temperature in the furnace approaches the temperature of the hydrocarbon fire and for 15 min reaches 986 ºC. The temperature from the unheated surface of the steel plate thus reached a critical temperature 536.4 ºC of steel for 16 min (Fig. 2).

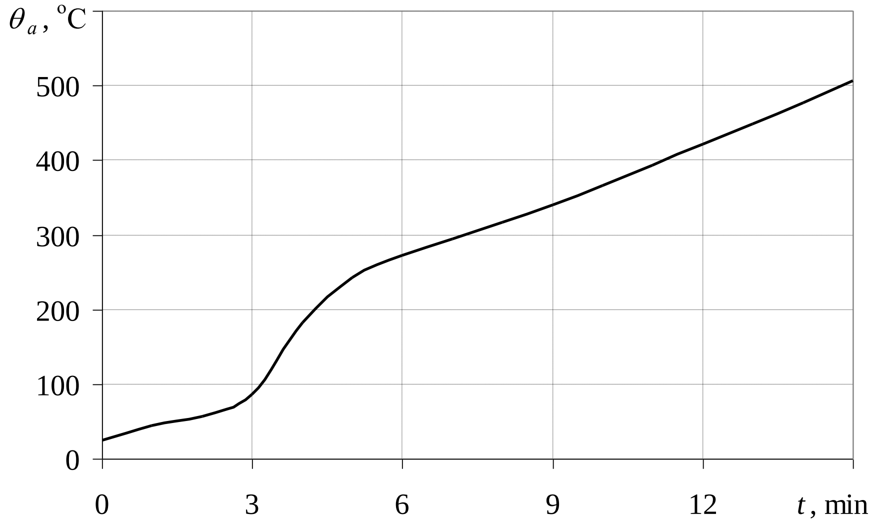

Fig. 2. The dependence of the average temperature on the unheated surface of a steel plate with a fireproof coating «Amotherm Steel Wb» from the time of fire exposure by the temperature mode of the hydrocarbon fire

With these temperatures, it is necessary to compare the results of computer simulation of non-stationary heating of a steel plate with a fireproof coating, made using ANSYS R17.1 software.

According to the experimental data, the measurement of the temperature of the steel plates (Fig. 2) and the temperature in the furnace (Fig. 1) by solving of the inverse problems of thermal conductivity determined thermophysical characteristics of the investigated flame retardant coating. In this case, such a mathematical model, which is built for the accepted physical model of thermal state in the system “fireproof coating - steel plate - thermal insulation” is used (Fig. 3).

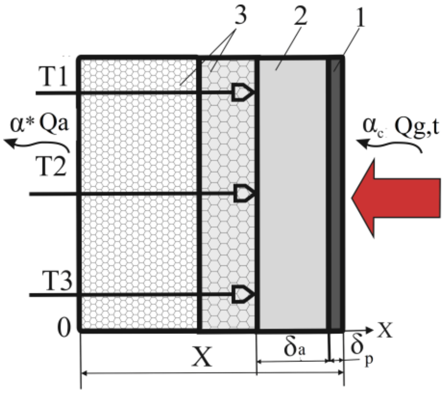

Fig. 3. Physical model of the thermal state in the system “fireproof coating - steel plate - thermal insulation”: 1 – fireproof coating; 2 – steel plate; 3 – 2 layers of insulation material

When solving a thermal problem, we determined the dependence of the temperature of the steel on the time of fire exposure by the temperature regime of the hydrocarbon fire and used a mathematical model of the thermal conductivity process in a one-dimensional nonlinear formulation, which contains the following equations [12]:

$$c_p \rho_p \frac{\partial \theta_p}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_p \frac{\partial \theta_p}{\partial x}\right), \tag{2}$$

$$0 < \mathrm{x} < \mathrm{d_p}; \;\; \theta_\mathrm{p} = \theta_\mathrm{p}(x, \mathrm{t}); \;\; 0 < \mathrm{t} < \mathrm{t_{fi,requ}},$$

– the initial condition: $\theta_p(x, 0) = \theta_0$, (3)

– boundary condition on the heating surface of the coating, at $x = d_p$:

$$\lambda_\mathrm{p} \frac{\partial \theta_\mathrm{p}}{\partial \mathrm{x}} = \alpha^* \left(\theta_\mathrm{g,t} - \theta_\mathrm{m}\right), \tag{4}$$

at $\alpha^* = \alpha_c + \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma[(\theta_{g,t} + 273)^4 - (\theta_m + 273)^4] / (\theta_{g,t} - \theta_m)$, (5)

– boundary condition on the inner surface of the coating, at $x = 0$:

$$\lambda_p \frac{\partial Q_p}{\partial x} = \mathrm{C_a} \cdot \rho_a \frac{V}{A_p} \cdot \frac{\partial Q_p}{\partial t}, \tag{6}$$

$$\theta_a(t) = \theta_p(0, t), \tag{7}$$

where $x$ – coordinate in coverage ($x = 0$ corresponds to the point of contact of the coating with the steel surface), m;

$t$ – time, sec;

$t_{fi,requ}$ – time corresponding to the normalized limit of fire resistance, $t_{fi,requ}$ = 15 minutes;

$\alpha_c$ – coefficient of heat transfer by convection on the heating surface of the coating, $\alpha_c$ = 50 W/(m·K);

$\alpha^*$ – the total coefficient of heat transfer by convection and thermal radiation on the heating surface of the coating, $\alpha^*$=18 W/(m·K);

$\Phi$ – angular coefficient, $\Phi$ = 1.0;

$\varepsilon_m$ – coefficient of thermal radiation of the heating surface of the coating, $\varepsilon_m$ = 0.8;

$\varepsilon_f$ – the coefficient of thermal radiation of the flame, $\varepsilon_f$ = 1.0;

$\sigma$ – Stefan Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ W/(m$^2$ K$^4$);
$\theta_a$ – steel temperature, °C;
$\theta_{g,t}$ – the temperature of the gas environment at time t, which varies with the temperature of the hydrocarbon fire (1), °C;
$\theta_m$ – temperature of the heating surface of the coating, °C;
$\theta_0$ – initial temperature, $\theta_0 = 20$ °C;
$\theta_p$ – temperature of the surface, °C;
$\lambda_p$ – thermal conductivity of the coating, W/(m·K);
$c_a$ – specific heat of the steel, J/(kg·K);
$c_p$ – specific heat of the coating, J/(kg·K);
$\rho_p$ – the density of the coating, $\rho_p$=1420 kg/m$^3$ (manufacturer's data);
$\rho_a$ – density of the steel, $\rho_a$ = 7850 kg/m$^3$;
$A_p / V$ – section coefficient of the protected steel beam, m$^{-1}$.

Calculations of the temperature of steel according to this mathematical model were performed using the numerical method of solving using the implicit finite-difference approximation scheme.

Thermophysical properties of the specified coating is determined by the method described in Annex L [13] (with the help of the method of solving the inverse heat conduction problem). The dependence of the thermal conductivity of the coating on the temperature is shown in Fig. 4, and its volumetric capacity is $c_p \cdot \rho_p = 6 \cdot 10^4$ J/m$^3$·K.

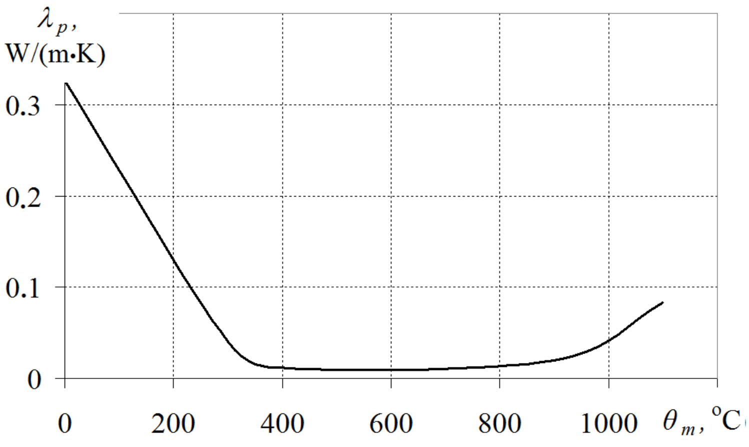

Fig. 4. The dependence of the effective coefficient of thermal conductivity of the coating “Amotherm Steel Wb” on the temperature found by the solution of the inverse problems of thermal conductivity

Table 1.The value of the coefficient of thermal conductivity of the flame retardant “Amotherm Steel Wb” found by solving the inverse problems of thermal conductivity

| Temperature, [°C] | The coefficient of thermal conductivity of the coating $\lambda_p$, [W/(m·K)] |
|---|---|
| 0 | 0.326 |
| 300 | 0.0399 |
| 414 | 0.0112 |
| 900 | 0.0194 |
| 1100 | 0.0831 |

Specific heat of steel $c_a$ (J/(kg·K)) was determined by the formulas [12]:
– for 20 °C ≤ $\theta_a$ ≤ 600 °C:

$$c_a = 425 + 7.73 \times 10^{-1}\,\theta_a - 1.69 \times 10^{-3}\,\theta_a^2 + 2.22 \times 10^{-6}\,\theta_a^3, \tag{8}$$

– for 600 °C ≤ $\theta_a$ ≤ 735 °C:

$$c_a = 666 + \frac{13002}{738 - \theta_a}, \tag{9}$$

– for 735 °C ≤ $\theta_a$ < 900 °C:

$$c_a = 545 + \frac{17820}{\theta_a - 731}, \tag{10}$$

– for 900 °C ≤ $\theta_a$ ≤ 1200 °C:

$$c_a = 650, \tag{11}$$

where $\theta_a$ – steel temperature, °C.

The change in the specific heat depending on the temperature is shown in Fig. 5.

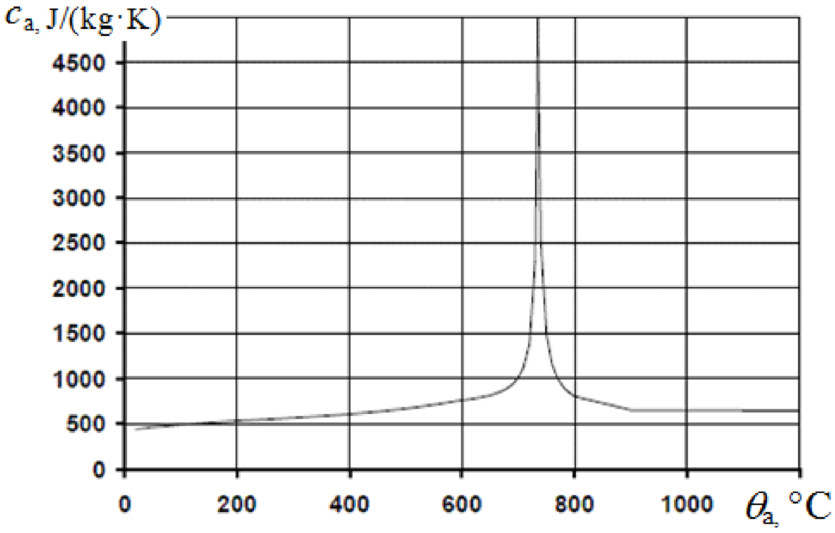

Fig. 5. Change of specific heat of steel depending on temperature

Thermal conductivity of the steel $\lambda_a$ (W/(m·K)) was determined by the formulas [12]:
– for 20 °C ≤ $\theta_a$ ≤ 800 °C:

$$\lambda_a = 54 - 3.33 \times 10^{-2}\,\theta_a, \tag{12}$$

– for 800 °C ≤ $\theta_a$ ≤ 1200 °C:

$$\lambda_a = 27.3, \tag{13}$$

where $\theta_a$ – steel temperature, °C.

The change in thermal conductivity depending on the temperature is shown in Fig. 6.

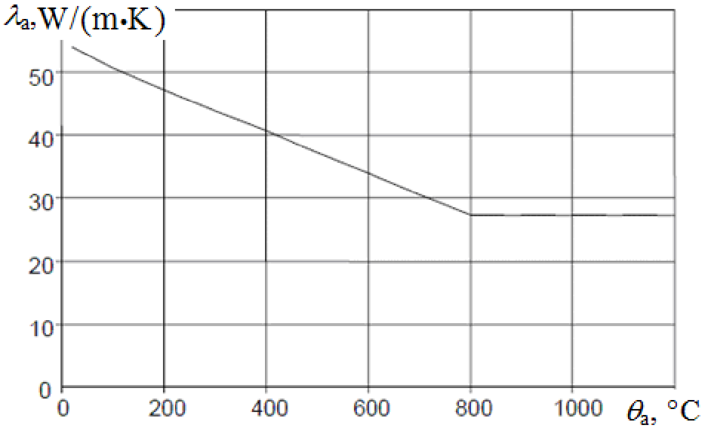

Fig. 6. Carbon steel thermal conductivity depending on the temperature

The Poisson coefficient of steel was set $\nu$ = 0.3, modulus of elasticity of the steel – $E_s$=2.1·$10^5$ MPa.

The temperature distribution in the cross section of a steel plate with a flame retardant finite element method during the hydrocarbon fire mode was calculated (Fig. 7).

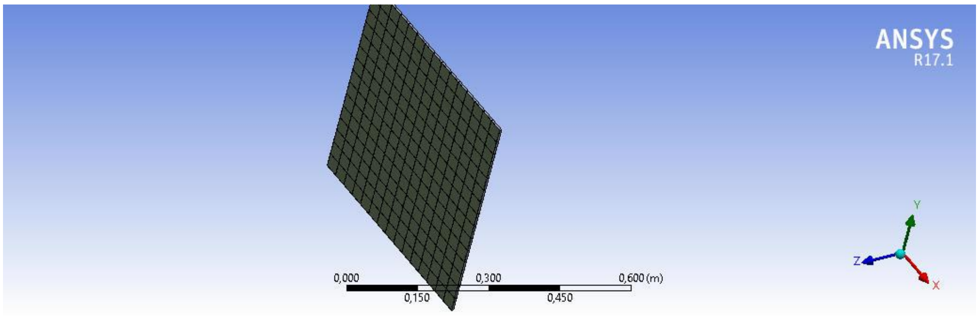

Fig. 7. Estimated finite element model of the system "steel plate-flame retardant coating"

Using the calculated finite element model of the system "steel plate-flame retardant", the non-stationary heating of such a system was calculated in the ANSYS R17.1 software complex. The results of which are shown in Fig. 8, 9.

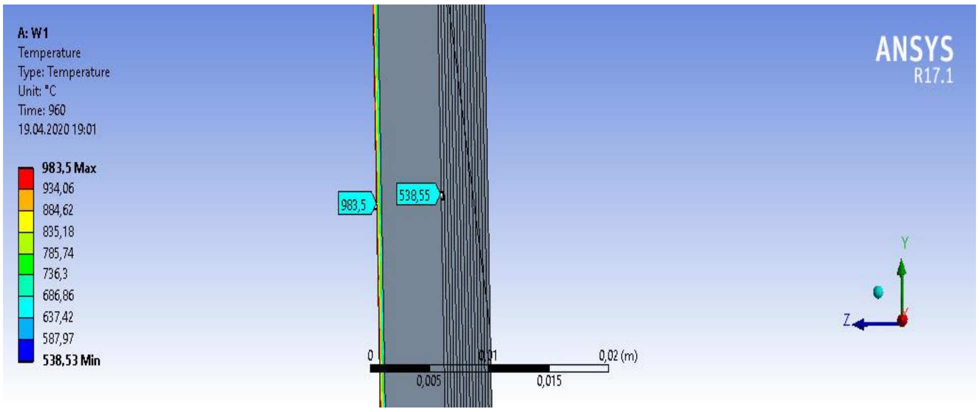

Fig. 8. The temperature distribution in the model "steel plate-flame retardant" after 16 minutes tests under conditions of hydrocarbon fire temperature (side view)

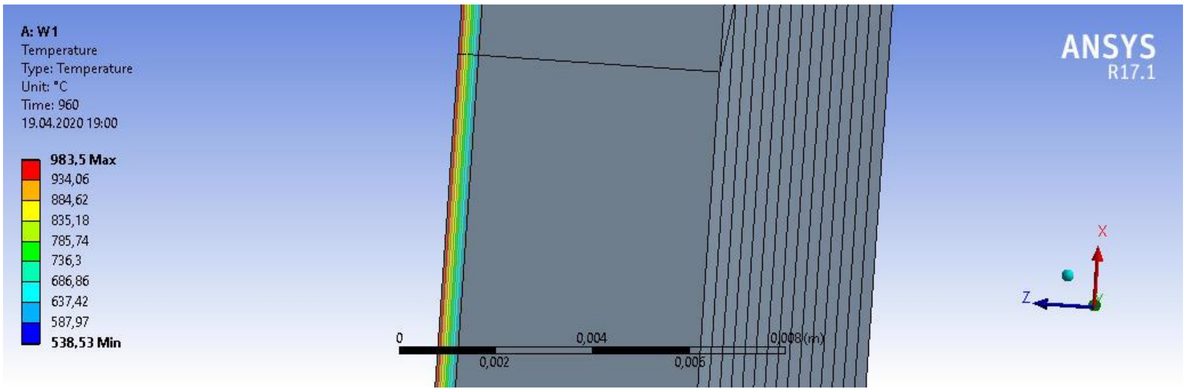

Fig. 9. The temperature distribution in the model "steel plate-flame retardant" after 16 minutes tests under conditions of hydrocarbon fire temperature

The obtained temperatures were compared with the data of the experimental determination of the temperature of steel plates with flame retardant under conditions of fire exposure under the hydrocarbon fire temperature mode (Fig. 10).

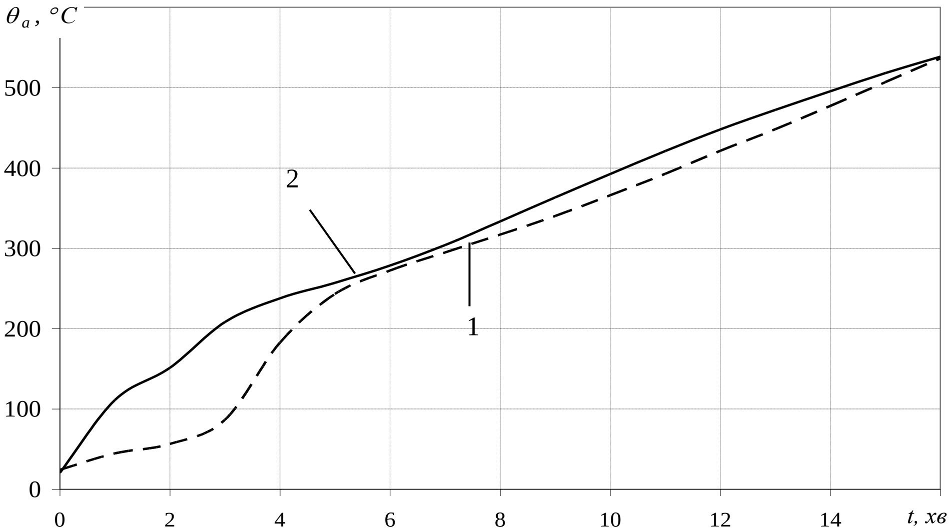

Fig. 10. The dependence of the average temperature on the unheated surface of a steel plate with a flame retardant on the time of fire exposure by the hydrocarbon fire temperature mode:

1 – obtained experimentally;

2 – obtained by simulation in ANSYS R17.1.

As can be seen from Fig. 10 in the initial stage in the first 5 minutes there is an unsatisfactory convergence of the calculated and experimental values. This is due to the impossibility and extreme complexity of creating a temperature mode of hydrocarbon fire in the furnace in the first minutes of the test [13].

Verification of the calculation model revealed that the results of experimental studies and numerical analysis in ANSYS R17.1 for the first 5 minutes differ significantly at all control points, but in the future this difference is stabilized, and up to the end of the experiment does not exceed 10%, and is 6.76%, which can be considered an acceptable result.

## 5 Conclusions

1. The reliability of the numerical simulation results was evaluated using a real test, and it was established that the results of the experimental studies and numerical analysis in the ANSYS R17.1 program correlate positively within the tolerable error, which is 6.76 %.

2. The conclusion is made about the adequacy of the developed model to the real processes that occur when heating steel plates with flame retardant under conditions of fire exposure under the hydrocarbon fire temperature mode.

3. A further direction of work based on the writing of programs for calculating steel structures for fire resistance and for solving the larger-scale problems of numerical simulation of fire effects on fire-resistant steel structures has been identified.

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