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SIMULATION OF THERMAL IMPACT OF FLAMES COMING FROM CLASS "B" TEST FIRE ON THE ELEMENTS OF THE ADJACENT FACILITIES

Summary. *Mathematical modelling of the processes of thermal impact of flames coming from fire on the elements of the adjacent facilities by gas dynamics methods was conducted. An algorithm of application was proposed for the heat exchange between the facilities during a fire by methods of gas dynamics in order to substantiate fire separations and appropriate model was developed. Using the mathematical model having been developed proper computation of the processes of thermal impact of flames coming from fire on the elements of the adjacent facilities was conducted. Comparative curves of temperature changes were plotted for the specimens under study when performing full-scale tests and those for the computation results. Check of adequacy was conducted against criteria of absolute deviations, relative deviations, root-men-square deviations and deviations by Fisher criterion.*

Key words: *fire separations, FDS software complex, fire safety, temperature distribution, FDS simulation.*

Problem definition. Statistical data on fires and their consequences show that each 30th fire involving buildings and structures is accompanied with flame spreading to the adjacent buildings (structures). Due to this material loss and consequences of similar fires enlarge and can be classified as emergencies [1; 2]. One of the causes of spreading fire from one building to another one can be mistake when determining fire separations between such buildings (structures). This situation makes it necessary to revise or improve available approaches to the determination of fire separations between buildings and structures. This lies in particular in the transition from the administrative specification of fire separations which does not allow managing risks of fire spread by way of taking into account construction, climatic, relief and other peculiarities of the development affecting much on the processes of heat exchange between the adjacent facilities at fire to parametric specification. One of the ways of realization of the parametric specification of fire separations on account of study of heat exchange processes is application of mathematical modelling methods. Processes of heat efficiency of buildings, heat and mass exchange during a fire, heat transfer within building constructions etc. were studied in papers [3–10] using mathematical modelling methods. However, heat transfer processes were not considered from the view-point of solving the problem related to substantiation of safe fire separations between buildings at that. Advantages of application of mathematical modelling methods when studying heat impact of flame coming from fire on the elements of the adjacent facilities lie in the possible realization of any fire development scenarios involving each of adjacent buildings taking into account their essential characteristics. Hence, creation of proper mathematical model used for the substantiation of fire separation between buildings and its check is an actual scientific problem.

Purpose of the work is the development of proper mathematical model of thermal impact of flames coming from fire on the elements of the adjacent facilities by gas dynamics method and its check. The following tasks were defined and solved for the achievement of the mentioned purpose:

– Mathematical model of the processes of thermal impact of flames coming from fire on the elements of the adjacent facilities by gas dynamics methods was developed;
– Mathematical modelling of thermal impact of flames coming from class B test fire on the elements of the adjacent facilities was conducted;
– Experimental studies of impact of flames coming from class B test fire on the elements of the adjacent facilities was conducted; and
– Check of the mathematical model having been developed was done.

Objects of the study are processes of heat exchange between the flames coming from fire and facilities.

Subject of the study is changing temperature of the elements of the facilities versus distance to the fire bed.

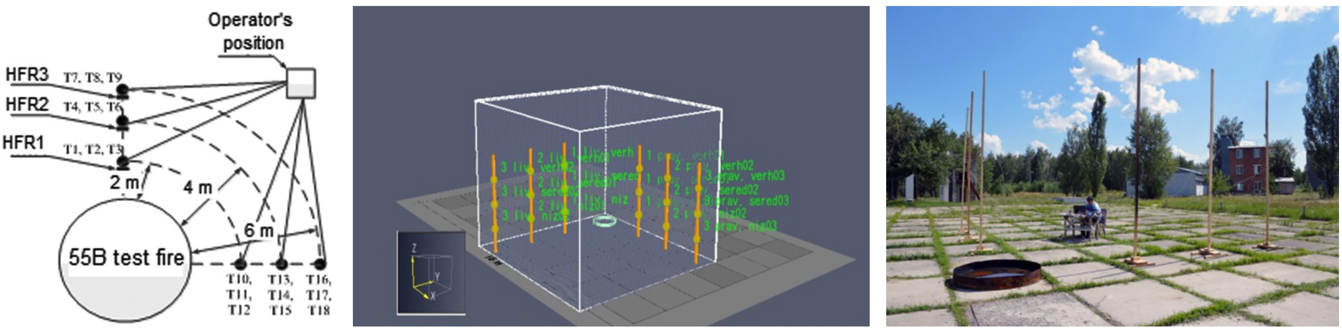
Mathematical modelling of the processes of thermal impact of flames coming from fire and elements of the adjacent facilities by gas dynamics as well as experimental studies was conducted as specified by methods expounded in [11]. Layout of the object of the study, appropriate mathematical model and photo of the experimental equipment are shown on Figure 1.

Use of computing gas dynamics model of heat and mass transfer at the time of burning which solves Navier-Stokes equation numerically was proposed for the computation of heat impact of flames coming from fire on the elements of the adjacent buildings. The mentioned model itself is system of differential equations to describe preservation of mass, impulse and energy with partial derivatives; it describes special and time transition of temperature and velocities of gas medium (oxygen, burning products etc.), pressures and densities.

Principal task when developing any mathematical model is maximum approximation of the model's parameters to the conditions specified by the procedure of studies described in [10] as well as interrelations of the facilities, in particular: distances to the adjacent facilities, observation of the facilities' scale, materials of which they consist including multilayer ones, environmental parameters, fire load at the facilities and their burning reactions, and selection of appropriate scenario of occurrence and continuation of the combustion processes. Characteristics of the mathematical model are submitted in Table 1.

The following conditions and assumptions were adopted when arranging calculation mathematical model:

– Thermal impact caused by the fire is evaluated by modelling of heat transfer due to thermal radiation only because of the fact that heat transfer due to convection is insignificant under these conditions;
– Heat source at the thermal impact of fire are flames coming from it which have stable geometry and constant temperature equal to that of burning of diesel fuel;
– Centre of the tray is selected as initial burning point with further flame spread at a rate of 0.3 m/s. Nature and causes of occurrence of burning process are not considered;



a) b) c)

Fig. 1. a) arrangement of the object of the study (T1–T8 are thermocouples, HFR1 to HFR3 are heat flux receivers); b) mathematical model; c) photo of experimental equipment

Table 1

Characteristics of the mathematical model having been developed

No.	Characteristic	Data on the characteristic
1.	General mathematical model	Principal regulations of Navier-Stokes equation for low speed temperature dependent flows.
2.	Model of burning process	Equations to describe burning process within two-phase flow of air and particles of liquid fuel. Burning process is represented by generalized hydrocarbon formula of $C_xH_yO_z$ (C_6H_6O). In this case of model we consider burning of individual substance, namely diesel fuel.
3.	Chemical reaction	$C_xH_yO_z + (x + 0.25y - 0.5z)O_2 \xrightarrow{W} CO_2 + 0.5yH_2O$
4.	Solution	Solution of the basic equations of heat exchange between the facilities at the time of fire lies in the approximation of the calculation area using adaptive locally mince grid. We are to derive values of the functions being analyzed for some moment of time as consequence of conduction of a number of consecutive iterations.
5.	Turbulence model	Turbulence is being simulated using Smahorinskyi model of “Scaled eddies simulation” (LES).
6.	Radiation heat exchange	We used diffusion model of gas emanation in order to record radiation heat exchange within the gas medium between the medium and particles as well as solid material. This model is built assuming the medium isotropic.
7.	Simulation of flows and particles	We used Lagrange method of particles in order to take into account heat and mass exchange.
8.	Dimensions of the calculation grid	We used dichotomy method for the substantiation of the grid of the calculation of the mathematical model. Substantiated cells’ dimension was adopted as 10 cm × 10 cm.
9.	Objects of modelling	1) Model 55B test fire which is metal tray (1,480 ± 15) mm in diameter, height of its board is (150 ± 5) mm and thickness of the wall of the board is (2.5 ± 0.5) mm; 18 l of water and 37 l of diesel fuel were poured into it; 2) Wood specimen to be studied fabricated of solid pinewood bar; dimensions are 50 mm × 50 mm × 4,000 mm; 3) diesel fuel.
10.	Rate of loss of mass of fuel	$m_n^n(t) = m_{f,0}^n(t)e^{-\int k(t)dt}$
11.	Temperature measurement	For measuring temperature of the surface of the wood specimen under study a number of sensors (thermocouples) were installed.

- Each of the sides of the calculation grid except for floor is specified as open space with free oxygen income and free evacuation of burning products;
- Total modelling time interval equals to 600 seconds; appropriate data are measured and recorded once per second; and
- Environmental conditions are equal to actual conditions of full-scale tests: temperature is 27 °C, pressure is 745 mm (Hg), relative humidity is 67% and crosswind speed is 5 to 7 m/s.

Thermal and physical properties of the material being constituent parts of the modelling objects are represented in Table 2.

Results of the mathematical modelling and experimental studies are shown as temperature distribution versus time during the process of the study as shown on Figures 2, 3.

Check of adequacy was conducted against the following criteria: absolute deviations, relative deviations, root-mean-square deviations and Fisher criterion.

Table 2

Thermal and physical properties of the materials

No.	Parameter	Parameter value
1.	Density: – steel – diesel fuel – wood	 7,850 kg/m³ 850 kg/m³ 520 kg/m³
2.	Steel thermal conductivity	45.8 W/(m·K)
3.	Emissivity factor: – old oxidized steel – diesel fuel – wood	 0.82 0.9 0.9
4.	Specific heat productivity of diesel fuel	5,800 kW/m²

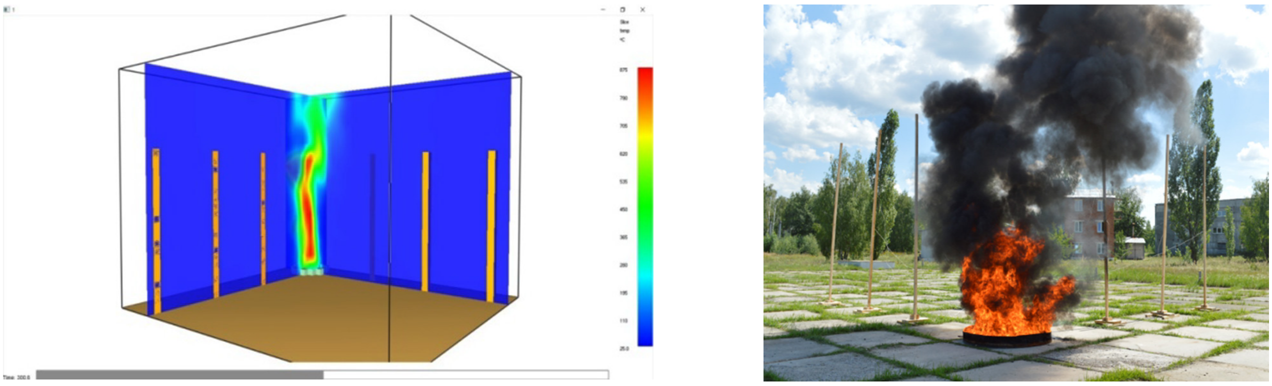


Fig. 2. Visualization of class B test fire burning at the 300[th] second while performing mathematical modelling and fire test studies

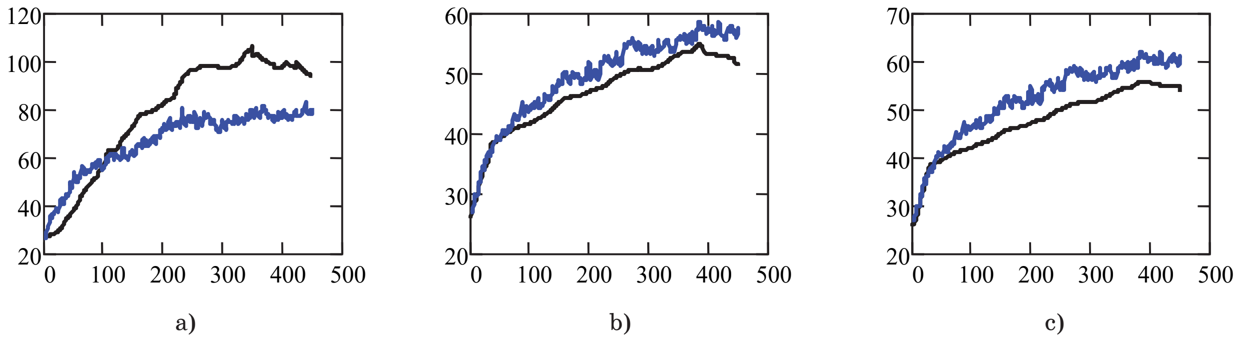


Fig. 3. Results of mathematical modelling (blue curve) and experimental studies (black curve): a) by T1 thermocouple; b) by T4 thermocouple; c) by T5 thermocouple

Table 3

Results of checking adequacy of the mathematical model having been developed

No.	Thermocouple No.	Absolute deviation	Relative deviation	Root-mean-square deviation	Fisher criterion value
1.	T1	15,2	19	17	1.9
2.	T2	6.027	9.755	6.626	3
3.	T3	5.566	10.183	6.24	4.63
4.	T4	3.09	6.592	3.497	2.14
5.	T5	4.868	10.154	5.175	1.69
6.	T6	4.619	10.688	5.02	1.42
7.	T7	7.908	18.046	8.572	1.596
8.	T8	6.097	14.083	6.59	1.306
9.	T9	5.802	13.91	6.065	1.18
10.	T10	10.1	15	11	1,4
11.	T11	13.244	14.966	15.815	1.2
12.	T12	6.984	10.874	7.51	1.1
13.	T13	9.188	15.597	9.583	1.66
14.	T14	5.34	9.685	6.219	2.66
15.	T15	4.145	7.432	5.197	2.97
16.	T16	4.84	11.683	5.128	2.29
17.	T17	1.64	5.094	1.95	2.34
18.	T18	1.482	4.16	1.903	1.57

Results of checking adequacy of the mathematical model having been developed are submitted in Table 3.

Thus, absolute deviations between the results of mathematical modelling and averaged results of the experimental studies do not exceed 16 °C which is not more than 20% in percent indices; root-mean-square deviations equal to 2 to 17 °C which indicates that the data derived in mathematical modelling are maximally close to the averaged experimental data. Maximum Fisher criterion value is 4.63. At that, tabulated Fisher criterion value for the statistical significance of 5% and number of degrees of freedom $k_1 = 4$ and $k_2 = 4$ is 9.15 [12]. Calculated Fisher criterion value being less than the tabulated one, the data do not contradict to nil hypothesis at 0.95 statistical probability i.e. difference between dispersion between the experimental data and those derived by mathematical modelling can be considered insignificant.

Conclusion. It was approved as result of the studies having been conducted that solution of the mathematical model of the processes of thermal impact of flame coming from class B test fire on the elements of the adjacent facilities could be realised in the FDS program complex with adequate reproducibility compared with appropriate experimental data. Based upon the studies having been carried out dependencies of spatial and time distribution of the temperature versus distance to the adjacent facilities positioning were determined. The data derived will be used in the substantiation of fire separations between buildings and structures due to mathematical model of heat exchange between the facilities during a fire by gas dynamics methods as well as in the substantiation of proper algorithm of arrangement of FDS mathematical model of heat transfer at the time of class B fire burning.

The next stage of the study can be realization of the solution of the mathematical model in FDS software complex as to spatial and time distribution of temperature and rates of gas medium at the time of burning of class A test fire and verification of the results if full-scale studies.

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