Research of adequacy of mathematical model of heat-mass exchange in the furnace for fire resistance tests of bearing walls

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Abstract
The purpose of carrying out researches of this operation is the study of adequacy of mathematical models of fire furnaces for their further use in case of study of influence of constructive characteristics of fire furnaces on their metrological indices. For achievement of objective, fire resistance tests of bearing wall were carried out at test center and data on warming up of chamber of the furnace and of fragment under test are obtained.

Results. The mathematical model of the fire furnace, where the tests were carried out, was created in software environment of the computer system CFD FlowVision 2.5 by means of which computing experiment was conducted. Relying on results of computing experiment and fire tests, criteria of adequacy (Student criterion, Kokhren Q-criterion, F-ratio test) were calculated. On the basis of analysis, adequacy of the used mathematical models was investigated.

Scientific novelty. Application of computational experiments for design of new furnaces and enhancements of parameters of functional ones for tests according to fire resistance of bearing walls gained further development.

The **practical significance** consists in application of results of work for design and construction of new installations for test of bearing walls for the purpose of achievement of homogeneity of temperature field on the heated surfaces of constructions in the chamber of furnace, and as result, increase of efficiency of fire resistance tests as a basis for enhancement existing regulatory base and creation of new ones for tests of the specified constructions for fire resistance.

Key words: COMPUTER MODELLING, ADEQUACY OF MATHEMATICAL MODEL, BEARING WALL, FIRE RESISTANCE TESTS, COMPUTATIONAL FLUID DYNAMICS (CFD), FLOWVISION 2.5

Introduction

Enhancement of installations for fire resistance tests of building constructions is relevant problem, because in the existing laboratories, fire furnaces of such design differ significantly by geometrical configuration, type of fuel-injector system, layout diagram and design of measuring accessories. It can lead to the fact that different test facilities can give results which differ by 30% and more. In that case, it is impossible to guarantee correspondence of limits of fire resistance of constructions under test to valid standards. In this case, safety of people and material values in buildings and constructions can decrease significantly.

In order not to carry out expensive tests on study of the matter, there is an opportunity to perform such researches on the basis of results of computing experiments. The modern software on modelling of thermal processes by means of Computational Fluid Dynamics (CFD) allows considering all the necessary parameters of the researched processes and studying influence of geometrical and constructive characteristics of the furnace for tests of steel concrete constructions on quality of the obtained data.

The **purpose** of these researches is the study of adequacy of mathematical models of fire furnaces for their further use in case of study of influence of constructive characteristics of fire furnaces on their metrological indices.

Methods

For achievement of a goal, at test center of fire resistance the tests of bearing wall according to [1] were carried out and data on warming up of the chamber of furnace and fragment under test were obtained. The mathematical model of the fire furnace was created. In this model, tests in software environment of computer system CFD FlowVision 2.5, by means of which computing experiment was carried out, were conducted. Relying on results of computing experiment and fire tests, criteria of adequacy (Student criterion, Kokhren Q-criterion, F-ratio test) were calculated. On the basis of the carried-out analysis, adequacy of the used mathematical models is studied.

In papers [2, 3], advantages of application of methods of Computational Fluid Dynamics (CFD) for scientific researches in the sphere of modelling of fire resistance tests of building constructions were presented. Also in these papers, possibility of application of one of the program systems CFD FlowVision 2.5 of Tesis companies was described. Using the algorithm described in the specified papers, it was created geometrical and mathematical models of the vertical fire furnace on which tests were carried out.

The geometrical configuration of the fire furnace for fire resistance tests of bearing walls is presented in Figure 1

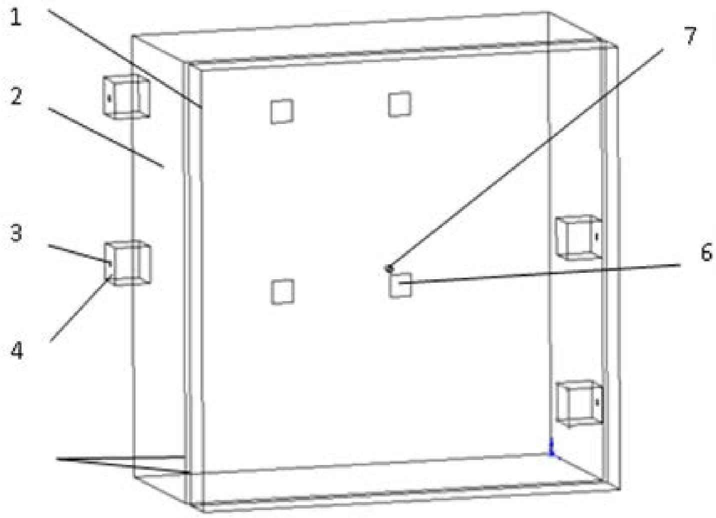
The created geometrical models import to the environment of program complex FlowVision for creation of analytical model. The basic principles of its creation are the following:

1) as the main instrument of model creation and carrying out computing experiment the program com-

plex “FlowVision 2.5” is used;

2) in the course of computing experiment, convective and radiation heat exchange of surface of constructions under test and space of chamber of the furnace is considered;

3) the thermocouple model in the form of the rod of 100 mm long and with diameter of 6 mm is provided in chambers considering convective and radiation heat exchange.



Dimensions of chamber of the fire furnace, mm			Source
Width	Height	Depth	
3000	3000	1500	[4]

Figure 1. Geometrical configuration of the furnace of installation for fire resistance tests of bearing walls: 1 – bearing wall; 2 - furnace skin; 3 - region of blow-in; 4 - region of injector; 5 - surfaces which interface; 6 - region of output of burning products, 7 – thermocouple model

After input of model parameters, the subarea of furnace chamber is interfaced to construction and thermocouple. Besides, general parameters such as gravitation axis, Courant-Friedrichs-Levy stability criterion [5], etc. are inserted.

The following stage consisted in creation of network model of the furnace. The method of control volumes applied in a program complex has certain features (Figure 2).

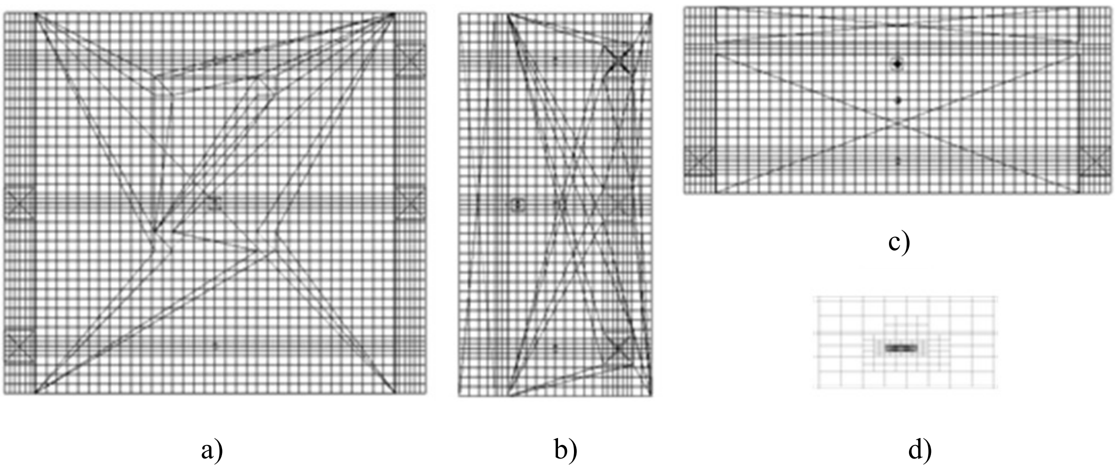


Figure 2. Grid model of area of the vertical furnace: a – view along the axis Y; b – view along the axis X; c – view along the axis Z; d – adaptive grid for the thermocouple (a view of lateral surface of the thermocouple)

Numerical integration of the equations on spatial coordinates is carried out with use of rectangular, adaptive and locally refined grid. On the one hand, this approach allows using of simple uniform non-adaptive grid in case of tasks execution on rather simple geometry. On the other hand, in the course of solution of tasks with complex geometry there is opportunity to carry out adaptation of grid to features of geometry close to boundary conditions, and in case of solution of tasks with noncontinuous flows, adaptation on values of analyzable functions, their gradients, etc. can be carried out.

Procedure of local refinement of grid in the field of adaptation assumes sequential distribution: from initial, each previous cell into 4 smaller-sized cells (in a three-dimensional case into 8) for fulfilment of condition of adaptation (for example, achievement of the specified accuracy of calculation of gradient of the considered function).

There is directly proportional dependence between the accuracy of calculation and quantity of computational cells, and inversely proportional dependence takes place between quantity of cells and time of calculation. Therefore, it is necessary to find balance between the necessary accuracy of calculation and time which will be spent for calculation.

For calculation of convective and radiation heat exchange of surface of the thermocouple and space of the furnace chamber, the adaptive grid for the thermocouple is considerably refined (Figure 2 d). Adaptation in the thermocouple is formed for this purpose.

For considering of feature which consists in availability of thermocouple models, two-stage adaptation is created at first of 1 level of space of the cylinder and 1 level of space of subarea thermocouple; it consists of the thermocouple with radius of 0.01 m and 0.12 m high.

Carrying out of computing experiment consists in initialization of burning process with temperature monitoring in thermocouple model in such a way that temperature condition of its heating precisely matches temperature standard curve of the fire [1]. For this purpose, control means of FlowVision system take off continuous data from the thermocouple in an interactive mode, and, in case of achievement of maximum temperature, for this step time parameters of burning process are changed. Then procedure of parameters change of burning process is repeated for the following time slot. At the same time, the data on temperature of surface, reinforcing layer and center of reinforced concrete products for this interval are recorded.

During experiment, temperature monitoring took place in such a way that temperature condition of thermocouple heating precisely matched temperature standard curve of the fire and did not exceed admissible limits of test [1]. For this purpose, control means of FlowVision 2.5 system took off continuous data from the thermocouple in an interactive mode, and, in case of achievement of maximum temperature, for this step time parameters of burning process were changed.

For carrying out computing experiment with use of the created mathematical models of fire furnaces, the sequences of calculation procedures described below are observed:

1) initialization of burning process with the minimum global step on time;

2) visualization value of temperature of the thermocouple and comparing control for time step of tests (the best selected value of 10 s);

3) establishment of coarser step after 0,05 s;

4) achievement of temperature corresponding to standard one of temperature condition of the fire for the current time slot, extinction of burning process by installation of the appropriate boundary conditions;

5) establishment of even more coarse step after burning-off of all particles of fuel (determined by flames temperature) to the following time slot;

6) repetition of estimated procedures for the following time slot;

7) temperature control in the construction and volume of the furnace when carrying out calculation is performed in the points of control (Figure 4 and Figure 5).

In Figure 3, the diagram of thermocouples arrangement for control of temperature condition in the furnace chamber is presented.

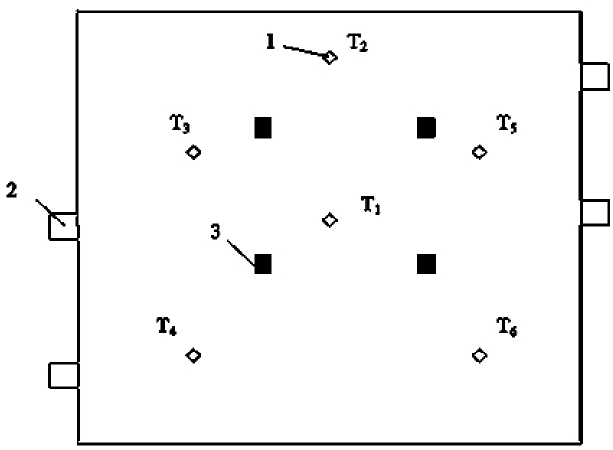


Figure 3. The diagram of thermocouples arrangement for control of temperature condition in the furnace chamber: $T_{1\text{-}6}$ – thermocouples; 1 –thermocouple; 2 – burner; 3 – hole for removal of burning products

In case of modelling of tests, the geometrical configuration of the furnace, which reproduces parameters of the chamber of real installation as accurately as possible, (Figure 1) was used. Temperature was controlled in 4 points of the furnace chamber, at distance of 100 mm from tested sample. Coordinates of temperature control area match coordinates of arrangement of thermocouples 1-6 (Figure 3) in the chamber of real installation. Temperature control is performed in such a way that the average temperature in the furnace chamber precisely matches a temperature of standard curve of the fire and did not exceed admissible limits of test [1]. In addition, the thermocouple model in the form of the rod with a diameter of 6 mm and length of 100 mm is provided in the chamber of the modeled installation for study of inertness of operation of the furnace thermocouples.

Results

Thermal process is combustion of the kerosene particles sprayed by nozzle in heating channels (Figure 1) and partially in the furnace chamber. Layout of channels causes circulation of hot air with combustion products in the chamber of the furnace and removal of the last via the smoke hole.

Indices of temperature were recorded every second for achievement of necessary accuracy during creation of diagrams.

In Figures 4 and 5, temperature curves of heating of chambers of the virtual and real furnaces are presented.

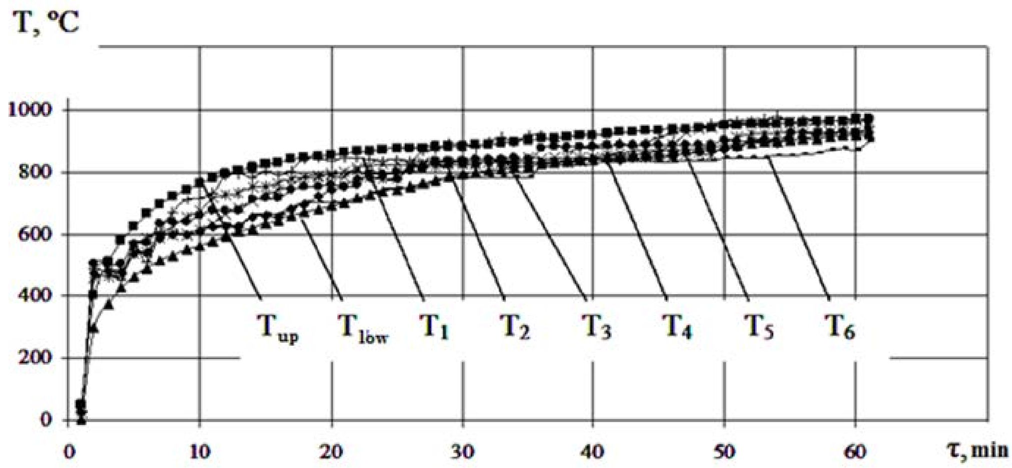


Figure 4. Temperature curves of heating of chamber area of the modeled furnace: $T_{1\text{-}6}$ – temperatures in locations of thermocouples with appropriate numbers; T_{up}, T_{low} – limit curves of deviations of indices of thermocouples from standard temperature curve of the fire [1]

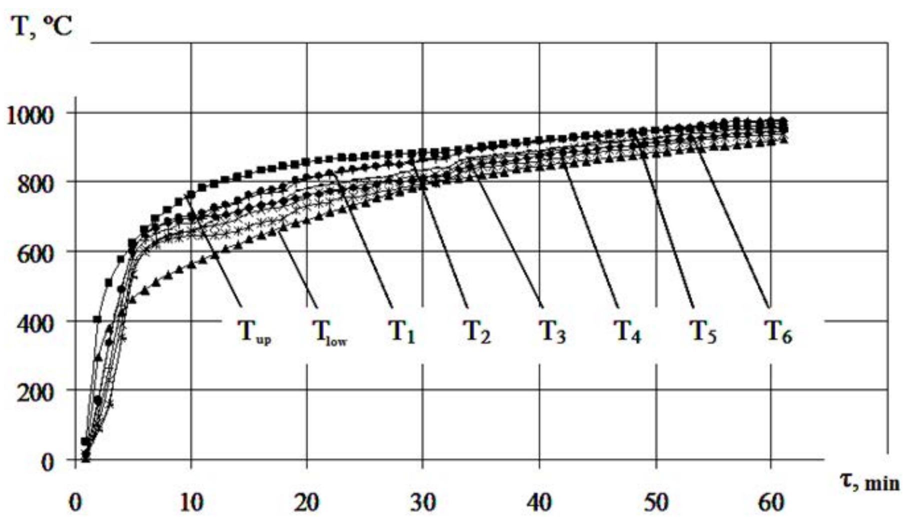


Figure 5. Temperature curves of heating of chamber area of the furnace according to the test protocol: 1-6 – temperatures of thermocouples with appropriate number; T_{up}, T_{low} – limit curves of deviations of indices of thermocouples from standard temperature curve of the fire [1]

A test of adequacy is carried out on the basis of the experimental information obtained as a result of fire tests of fragment of building construction; during this experiment, the interesting processes are observed [6].

For testing of adequacy of modelling results, such criteria of adequacy were used:

- F-ratio test. By means of Fischer's test, it is possible to check a hypothesis of equality of basic dispersions, dispersion of temperatures at every minute of tests.

Dispersion of adequacy was calculated as deviation between calculated and experimental data on each thermocouple of the experimental installation and corresponding place of temperature measurement in the model.

In the created model, 6 places of temperature control are equal as well as during experiment. Data of each thermocouple of calculation were compared with experiment thermocouples. Thus, 6 values of adequacy dispersion are obtained.

Dispersion of reproducibility was calculated as deviation of calculated temperature of area directly near the modeled thermocouple and indications of the modeled thermocouple considering experimental error [1].

Thus, we alternatively compare 6 values of adequacy dispersion, to reproducibility dispersion and calculate F-ratio test.

- Student criterion is applied to comparing of results of real and computing experiments.

6 values of criterion were obtained when calculating of reproducibility dispersion as deviation of calculated temperature of area directly near the modeled thermocouple and indications of the modeled thermocouple considering experimental error [1].

- Kokhren Q-criterion (determination of emissions and quasiemissions):

The Q-criterion is used when comparing three and more selections of identical volume. We have alternatively compared dispersions between experimental and computational data in location of each thermocouple to 2 dispersions between symmetric points in case of experiment (2 pairs of thermocouples in relation to longitudinal axis of symmetry). 6 values of criterion were obtained.

Results are summarized in the table.

Table. Parameters of dispersion of results of mathematical modelling of fire tests of bearing wall from the experimental data

Criterion		Maximum deviation, °C	Average deviation, °C	Rlative deviation, %	F-criterion	t-criterion	Q-criterion
Thermocouple zone	T_1	57,4	24,0	5,15	1,62	1,52	0,32
	T_2	64,3	22,4	4,81	3,84	1,77	0,35
	T_3	68,9	19,4	4,16	3,49	1,93	0,39
	T_4	108,1	25,0	5,37	3,77	1,82	0,32
	T_5	47,9	21,8	4,67	1,31	1,18	0,33
	T_6	42,8	21,7	4,66	4,03	1,45	0,32
Average value		64,9	22,4	4,81	3,01	1,61	0,34
Critical value		-	-	15 [1]	4,49 [6]	2,92 [6]	0,45 [6]

*author's development

Scientific novelty and practical significance. Application of computational experiments for design of new furnaces and enhancements of parameters of functional ones for tests according to fire resistance of bearing walls gained further development.

Conclusions

Relying on results of computing experiment in software environment of the computer system CFD FlowVision 2.5 and fire tests, criteria of adequacy (Student criterion, Kokhren Q-criterion, F-ratio test) were calculated. None of values of criteria exceed admissible values that shows efficiency of modelling of thermal processes for its further use in case of study of influence of constructive characteristics of fire furnaces on their metrological indices.

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