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DETERMINATION OF HEAT TRANSFER PROCESS IN VERTICAL CABLE TUNNELS OF NUCLEAR POWER PLANTS UNDER REAL FIRE CONDITIONS

The object of the study was heat and mass transfer processes occurring in vertical cable tunnels. The problem to be solved was the definition of process mechanisms in the inner space of the tunnel. For this, field tests were conducted, mathematical models were created, and computational experiments were conducted to establish specific parameters that affect the temperature regime of a fire in a vertical cable tunnel of a nuclear power plant. The dynamics of temperature changes with known geometric parameters and fire load were determined, and the adequacy of mathematical models built in the Fire Dynamics Simulator software was investigated and computational experiments were carried out. It has been proven that they consist in determining the temperature regime in a vertical cable tunnel of a nuclear power plant with known technical and geometric parameters. Such studies have practical applications in the field of safety of nuclear power plants and the development of new technologies in this field. An important conclusion of these studies is the possibility of determining the fire resistance of building structures of vertical cable tunnels of nuclear power plants with the selection of the most severe temperature regime, according to the conducted field test. This means that research results can be used in practice in designing and evaluating the safety of such objects.

The conducted research established that the temperature in the inner space of the tunnel can reach values from 1200 to 1400 °C. The following factors influence the maximum temperature value and the maximum time to reach the maximum temperature in the fire cell: fire load, height and area of the tunnel. With a lower fire load, the maximum temperature in the vertical cable tunnel of the nuclear power plant was 75 % lower. Therefore, the results of these studies have a direct practical application in the field of safety of nuclear power plants and can be used to improve and develop new technologies in this field

Keywords: full-scale fire tests, nuclear power plant, vertical cable tunnel, fire temperature regime

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1. Introduction

Four nuclear power plants in Ukraine operate 15 power units with a total installed capacity of 13,835 MW, which is 55.2 % of the total installed capacity of all power plants in the country. At nuclear power plants there are a large number of special rooms, corridors and chambers with different temperature regimes and pressure. This is provided for the need to lay cable lines. Cable lines are located both in channels, cable mezzanines, double floors, mines, open boxes and in vertical cable tunnels. The latter are located in the arrangement of the reactor compartment and connect important communication elements of the reactor control with the containment along its entire height. The cable tunnel is divided into fire-fighting compartments with a height of no more than 6 meters, the length of the cable tunnel is 25 meters starting from the +20,000 meter mark of the reactor compartment of the water-water power reactor unit (Fig. 1).

The study of the fire temperature regime is an urgent issue, since vertical cable tunnels differ in their geometric configuration, the type of cables laid in them, fire load and aerodynamic characteristics. This can lead to the fact that the temperature regime of the fire in such tunnels may differ both from the standard temperature regime of the fire and from each other. A well-known example of the difference from the standard is the study of TNO with the resulting RWS temperature fire curve (Fig. 2).

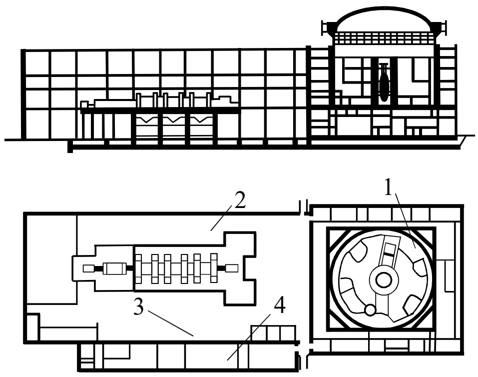


Fig. 1. Water-water power reactor: 1 – containment; 2 – turbine compartment; 3 – deaerator department; 4 – shelf of electrical appliances

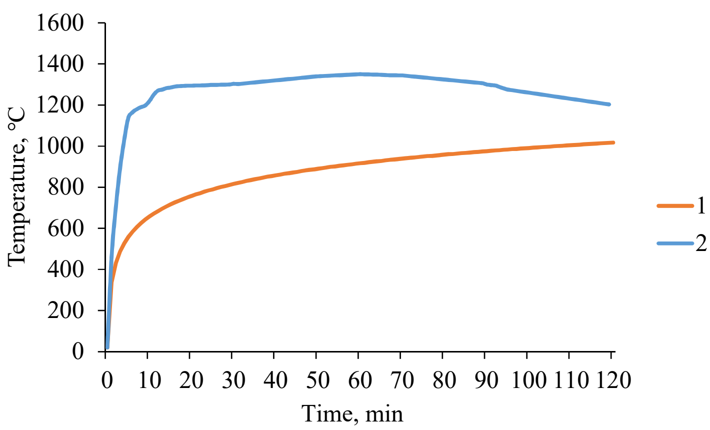


Fig. 2. Fire temperature regimes: 1 – standard fire temperature regime; 2 – RWS temperature fire curve

The standard fire temperature regime (Fig. 2) is determined in accordance with DSTU B B.1.1-4 in the form of the dependence of the temperature of the environment on time (1):

$$\theta_g = T_0 + 345 \cdot \log_{10}(8t+1), \quad (1)$$

where t – time, min.; T_0 – the initial temperature of the environment, °C.

Taking into account the above, it is not possible to guarantee the compliance of the fire resistance limits of the tested structures with the current standards of GBN V.2.2-34620942-002:2015 "Line and cable structures of telecommunications. Design", NAPB 03.005-2002 "Fire safety standards for the design of nuclear power plants with water-water power reactors", DSTU B B.1.1-18:2007 "Buildings and fragments of buildings. The method of natural fire tests. General requirements", DSTU B B.1.1-4-98 "Fire protection. Building structures. Fire resistance test methods. General requirements" and [1–3]. In this case, the safety of people and material assets during fires in vertical cable tunnels of nuclear power plants can be significantly reduced. Therefore, studies devoted to improving the limits of fire resistance of structures of vertical cable tunnels of nuclear power plants are relevant and establish optimal parameters of structures that provide maximum fire resistance and efficiency in fire conditions. Research can help to develop new materials and technologies that will provide increased fire resistance of the enclosing structures of vertical cable tunnels of nuclear power plants.

2. Literature review and problem statement

The work [4] presented the results of studies related to the temperature effect of the fire in the Runehamr tunnel in Norway. It is noted that the TNO research confirmed previous results obtained in 1979 in the Netherlands. From the works of section VII.3 "Fire reaction of materials" of the 1999 05.05.B report "Fire and smoke control in tunnels" discusses the characteristics of rock tunnel linings compared to reinforced concrete. The intensity of heat generated during a large fire can cause the tunnel's enclosing structure to lose its load-bearing function. But after comparing the temperature-time dependences of fires (Fig. 2), objective difficulties arise in determining the fire resistance of reinforced concrete building structures of cable tunnels of nuclear power plants. Since the main method of determining the fire resistance of building structures is the method of tests according to the standard fire temperature regime (1). In works [5, 6], the issues related to the dynamics of fire development in cable structures and the temperature dynamics in the combustion zone with and without the supply of inert gases were solved. These studies are important for understanding fire processes. In [7], it was established that the width of the tunnel has little effect on the rate of burnout of the fire load, and temperature distributions were measured in tunnels with different ventilation conditions. This is important information for tunnel design. In work [8], the causes of fires in tunnels were analyzed with the help of numerical simulation. The work [9] is devoted to the analysis of the parameters of the burning speed of polyvinyl chloride insulation and the linear speed of fire propagation with different types of cable laying. These studies are important for determining the fire safety of materials and structures.

The work [9] is devoted to the analysis of the parameters of the burning speed of polyvinyl chloride insulation and the linear speed of fire propagation with different types of cable laying. The linear speed of fire propagation with different types of cable laying is considered. These studies are important for determining the fire safety of materials and structures. Despite the practical significance of such results, methods of laying cables in rectangular tunnels have not been sufficiently considered. Experimental studies are often conducted in reduced-scale model tunnels, which were made of fire-resistant glass [10] or galvanized steel [11].

An option to overcome the relevant difficulties may be to conduct research on a full-scale model dedicated to the verification of mathematical models of fires in vertical cable tunnels of nuclear power plants based on experimental data. This is the approach used in the work [12], the authors confirm the effectiveness of using mathematical models of fire dynamics of premises with the help of the Fire Dynamics Simulator software complex [13]. However, at present there is a question of compliance of fire resistance of the tested structures of vertical cable tunnels with excellent characteristics to the standard fire temperature regime (1) from geometrical, aerodynamic parameters and fire load. All this gives reason to assert that it is expedient to conduct a study devoted to the determination of heat and mass transfer processes during real fires in vertical cable tunnels of nuclear power plants.

3. The aim and objectives of the study

The aim of the study is to determine the characteristics of heat and mass transfer processes during a real fire in vertical cable tunnels of nuclear power plants. This will make it possible to determine the fire resistance of the enclosing structures of vertical cable tunnels of nuclear power plants for the stage of design and construction of new vertical cable tunnels. Improvement of recommendations for taking into account the maximum possible fire load that can be used in already built tunnels. The practical component of the conducted research contains the basis for improving the current and creating a new regulatory framework regarding the fire safety of cable structures. The proposed innovations will make it possible to ensure the necessary limit of fire resistance of the enclosing structures of vertical cable tunnels (cable shafts) of the enterprises of the Ministry of Energy of Ukraine.

To achieve the set aim, the following objectives were formed:

– to conduct a full-scale experiment on simulating a fire in a tunnel designed as an analogue of the tunnel at the Zaporizhzhia NPP with a sequence of procedures with a detailed selection of equipment and samples in order to provide reliable experimental data;

– conduct a simulation of a fire in a vertical cable tunnel of a nuclear power plant with parameters similar to a real-life experiment by means of mathematical gas-hydrodynamics with determination of the temperature regime of a fire in different zones of the tunnel;

– determine the adequacy of the created mathematical model with parameters similar to the natural experiment by means of mathematical gas-hydrodynamics with reproduction of the temperature regime of the fire in different zones of the tunnel by means of mathematical gas-hydrodynamics;

– conduct computational experiments with various geometric, aerodynamic parameters and fire load, as well as determine the dependence of the temperature regime of the fire on the specified parameters.

4. Materials and methods of research

4. 1. Object and hypothesis of research

The object of research is vertical cable tunnels used at nuclear power plants. Thermal processes that occur in these tunnels during a fire and their impact on station safety were studied.

The main hypothesis of the study was the assumption that the temperature regime of fire in vertical cable tunnels can be adequately described by mathematical models and numerical methods. The mathematical model makes it possible to determine the temperature fields, as well as the temperatures of combustion products and gas, depending on the change of various mode parameters.

Simplifications related to models of heat conduction and stress-strain state, which were necessary for the numerical solution of the problem in real time.

4. 2. Methods of studying the process of heat and mass transfer in vertical cable tunnels of nuclear power plants

Theoretical studies have been carried out on the basis of systems of differential equations of continuous media, such as the Navier-Stokes equations to describe fluid motion. The equation of thermal conductivity for heat transfer, as well as the equation of the stress-strain state of reinforced concrete structures under conditions of heating during a fire. In our research, let's also use the Fourier equation to model the thermal regime of vertical cable tunnels of nuclear power plants.

For the numerical analysis of these equations and mathematical modeling, let's use various methods, such as the finite or boundary element method, non-reciprocal methods, Galerkin method, and optimization methods. This allowed to accurately approximate and analyze the complex physical processes that occurred during a fire in vertical cable tunnels. Natural fire tests were conducted in the model of the vertical cable tunnel TSK 1-DPRZ of the Main Directorate of the State Emergency Service of Ukraine in the Zaporizhzhia region for the protection of objects. Which was developed by analogy with real tunnels used for reactors of the VVER-1000 type. This allowed to create conditions as close as possible to real ones and to study the development of fire in such conditions.

4. 3. Investigated materials and equipment used in conducting full-scale fire tests

Fig. 3 shows the view of the cables in the corresponding section of the vertical cable tunnel for the formation of the maximum permissible fire load according to the standards for conducting research of DSTU B B.1.1-18.

a *b*

Fig. 3. View of vertically installed cables fixed in special cable brackets to form the existing fire load: *a* – photofixation of cables fixed on metal cable brackets; *b* – photofixation of cables fixed along the entire height of the vertical cable tunnel

The proposed parameters of the fire load, consisting of the insulation of electric cables of various diameters, starting from 20 mm and ending with 65 mm with polyvinyl chloride insulation, are given in the Table 1.

Table 1

Parameters of cables for the fire load of the cable tunnel

No.	Non-metal-lic material	Cable di-ameter, mm	Cable length, mm	Weight, kg	Density, kg/m^3	Volume of non-metallic material in 1 m of cable, kg
1	The outer cable sheath	75	18000	13.985	1430	3.3331
2		60	6000	6.7122		1.5997
3		30	48000	5.9683		1.4224
4		25	12000	1.2434		0.2963
5		20	24000	0.9946		0.2370
6	Insulation of veins	10	42000	0.8698		0.2072
7		10	3000	0.0620		0.0148
The total volume of non-metallic materials in 1 m of cable						7.1000
Fire load, MJ/m^2						3266.00

A model hearth of fire class 32B in the form of a pallet is used as an ignition source (Table 2).

Diesel fuel brand DP-3-Euro5-VO, gasoline brand A-92-Euro5-E0 are used as fuel.

Table 2

The main technical parameters of the ignition source

Rank	Volume of used liquid, l	Mass of used combustible materials, l		Burning area (approximate), m^2
		Diesel	Gasoline	
32B	32	30	2	1.0

According to the proposed scheme, the cable floor of the reactor compartment of the main building of the nuclear power station, 6 meters high, at the mark +33,200 m of the arrangement of the VVER-1000 reactor is considered.

An existing full-scale structure with an internal space of 2600×1800×6000 mm is selected for field tests in the vertical cable tunnel of the nuclear power plant. On one side, the vertical cable tunnel of the nuclear power plant is closed by a 2200 mm end reinforced concrete wall. On the other side, there is a slot measuring 900×2000 mm. On the side of the closed end, in the lower left corner, there is a special hole where air should be injected to create support. The cables are located in a vertical position by fixed metal wires of 1.5 mm diameter to the brackets.

Table 3

Means of measuring technology

No.	Equipment name	Measuring range	Measurement error
1	Measuring tape STANLEY	from 0 mm to 3000 mm	1± mm
2	SOS stopwatch pr-2b-2-000	from 0 s to 60 s, from 0 s to 60 min	$\pm\left(\frac{0.4}{60}\tau\right)$, $\pm\left(0.4+\frac{1.5}{3540}(\tau-60)\right)$
3	MV-4M aspiration psychrometer	from 10 % to 100 %, from – 10 °C to 50 °C	±4 %, ±0.2 °C
4	Vernier caliper Shts-1	from 0 mm to 125 mm	±0.1 mm
5	M67 aneroid barometer	from 600 mm Hg to 800 mm Hg	±1 mm Hg
6	Anemometer ASO-3	from 0.3 m/s to 5 m/s	±(0.1+0.05 V) m/s
7	Scales MW-1200	from 0 kg to 1.2 kg	±0.05 g
8	Xiaomi Fimi X8 Mini quadcopter	Working time 30 minutes	±0.05 min
9	Thermocouples TXA Kronos*	from –50 °C to 1300 °C	±0.1 °C
10	Measuring device Kronos TM-902S**	from –50 °C to 1300 °C	±0.8 °C

Chromel-alumel thermocouples are used as temperature sensors, complete with a control infrastructure for identifying temperature data from temperature sensors. The measurement error of thermocouples is ±1 °C. The location of control and measuring fittings in the form of temperature sensors is regulated by the requirements of DSTU B B.1.1-18 norms, it was chosen taking into account geometric parameters (Fig. 4).

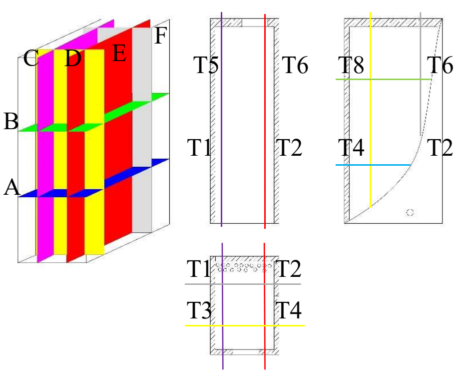


Fig. 4. Diagram of the location of thermocouples along the measuring planes on the floor of the vertical cable tunnel of the nuclear power plant (mark +33,200 m)

4. 4. The method of determining the process of heat and mass transfer under the conditions of creating a mathematical model in the Fire Dynamics Simulator

The Fire Dynamics Simulator program was developed by the National Institute of Standards and Technology of the US Department of Commerce with the assistance of the VTT Technical Research Center (Finland). Fire Dynamics Simulator is free software. Under US Code Chapter 17 Part 105 the developers' copyrights are not protected, the program is public software. The Fire Dynamics Simulator program can be used to solve a wide range of scientific and applied problems of heat and mass transfer during a fire [13]. The Fire Dynamics Simulator program can be used to solve a wide range of scientific and applied problems of heat and mass transfer during a fire [13]. Fire Dynamics Simulator numerically solves the Navier-Stokes equation for low-speed temperature-dependent flows. With the help of the abstract object "SURF" it is possible to set the boundary conditions of solid bodies (walls, ceilings, obstacles, etc.). The surface is flexible and has many parameters. A specialized software tool of a personal computer is chosen for building mathematical models and performing calculations.

Using the initial data, a combustion model was created using the Fire Dynamics Simulator computer environment in the following stages:

– I stage "Creating a grid". The tunnel model must be created according to standard dimensions, that is, indicate the grid boundaries: length 2.67 m, width 1.86 m and height 5.9 m and indicate the number of cells in X, Y, and Z. In this model, the total number is one hundred thousand eight hundred cells;

– II stage "Creation of initial data". "MISC" was chosen to write the initial data, the initial temperature, relative air humidity, the duration of the calculation was indicated by "TIME". The initial combustion reaction was set, "REAC" was added;

– III stage "Formation of ventilation holes". For this model, it was necessary to create 3 technological ventilation holes. To do this, it is possible to write "VENT" and set its border according to the coordinates in meters and indicate "SURF", that is, an open hole "OPEN". The first – with an area of 25 cm^2, the second – with an area of 150 cm^2, the third – with an area of 1.8 m^2;

– IV stage "Formation of measuring planes". To create planes, write "SLCF": coordinate, plane position, gas phase value and set vector. The planes were set according to the diagram of the arrangement of thermocouples (Fig. 4);

– V stage "Installation of temperature sensors". To visualize the fire using colors, the temperature sensors were indicated – for this, "DEVC" was written, the thermocouple "QUANTITY='THERMOCOUPLE'" was selected, a constant value was set, and the coordinates of the installed sensors were indicated;

– VI stage "Installation of ignition source". Before installing the ignition source, it is necessary to add exactly what kind of surface is needed – diesel fuel, gasoline. To set the ignition source, write the code "VENT" and note "SURF_ID='Diesel fuel; gasoline", which was chosen before that. Place the ignition source between the first and second openings of the vertical cable tunnel;

– VII "Installation of cable lines". For the installation of cable lines, the "MATL" material of cable insulation and other fire load was chosen, the surface of the fire load was chosen from the "SURF" library, namely "AVVG cable".

5. Results of studies of indicators of the heat and mass transfer process

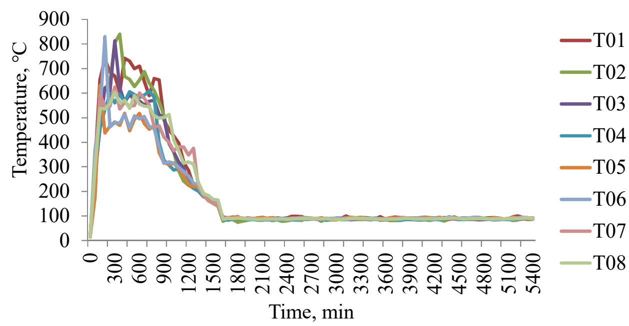
5. 1. Obtained experimental data of full-scale fire tests in a vertical cable tunnel of a nuclear power plant

3 experiments were conducted on the sections of the vertical cable tunnel of the nuclear power plant, similar to the designed building structures at the Zaporizhzhia NPP, at different points (Fig. 5).

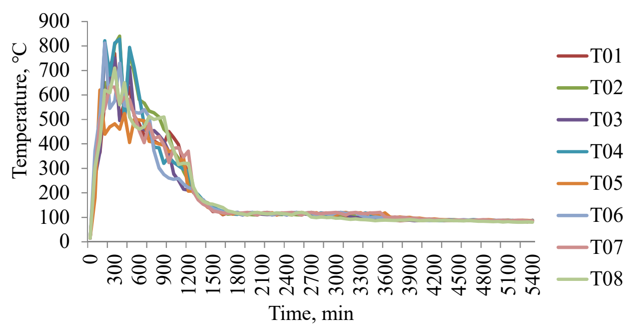
The duration of each of them was 90 minutes. The test was conducted at a temperature of +16 °C and a relative humidity of 48 %, which meets the requirements of DSTU B B.1.1-4 and [1–3]. Every minute, temperature sensors were checked (Fig. 6) in accordance with DSTU B B.1.1-18.

Analyzing the temperature-time dependences based on the results of three experimental studies in a vertical cable tunnel (Fig. 6), it can be stated that the highest temperature is observed in the zone of plane D in the range of 800–900 °C. Thermal energy spreads more intensively in the direction of filling the space opposite to the filling of the outlet of combustion products and ventilation holes. The temperature in the zone of the C plane is in the range of 500–800 °C.

Fig. 5. Photo of the cable tunnel during the experiment



a



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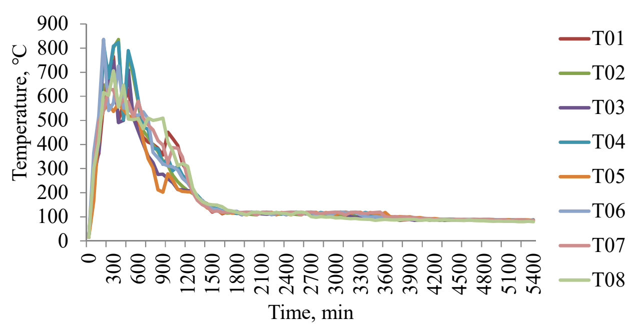

c

Fig. 6. Temperature-time dependence according to the results of: *a* – the first experimental study; *b* – the second experimental study; *c* – the third experimental study; for each of the 8 installed thermocouples (Fig. 4)

5. 2. Obtained data of the mathematical model of the heat and mass transfer process in the Fire Dynamics Simulator software

Considering the complexity of the processes that take place during fires in vertical cable tunnels, it is most appropriate to use field models based on the full system of Navier-Stokes equations in calculations. In vector form for an incompressible fluid, they are written as follows:

$$\frac{\partial\vec{\upsilon}}{\partial t}=-\left(\vec{\upsilon}\cdot\nabla\right)\vec{\upsilon}+\upsilon\Delta\vec{\upsilon}-\frac{1}{P}\nabla P+\vec{f}. \quad (2)$$

The combustion model is determined by the speed of light and consumption of fuel, oxidizer, and combustion products [14, 15]. Quantitative ratios are determined by the generalized chemical equation:

$$C_xH_yO_z+\left(x+0.25y-0.5z\right)O_2\xrightarrow{W}CO_2+0.5H_2O. \quad (3)$$

Magnussen's combustion model can be used as a combustion model, according to recommendations for premixed fuel and oxidizer [15]. The rate of mixing and the chemical reaction of combustion in the Magnussen model is determined by formula:

$$W_{mix}=23.6\left(\frac{\mu\varepsilon}{\rho k^2}\right)^{0.25}\rho\times$$
$$\times\frac{\varepsilon}{k}\min\left(Y_{C_xH_yO_z},\frac{Y_O}{i_{chem}}\right). \quad (4)$$

Equations are used that take into account radiation heat exchange in the gaseous medium and mutual heat exchange between the medium and particles, as well as solid material. The model is built on the assumption that the optical medium is isotropic, the process of radiative heat transfer is described by equation:

$$\nabla\left(\frac{1}{\alpha+\beta}\nabla E_r\right)+3\left(\alpha E_b-\alpha E_r\right)=0. \quad (5)$$

In general, the available mathematical models and their numerical implementation make it possible to accurately and effectively simulate the process of heat and mass transfer in the vertical cable tunnel of a nuclear power plant.

To conduct a computational experiment using the created mathematical model for testing, the above sequence of calculation procedures was used. In order to control the temperature regime by means of the Fire Dynamics Simulator computer complex, 8 places of its control were created, which corresponded to the places of placement of thermocouples during the field experiment (Fig. 4). After the completion of the computational experiment, temperature data were obtained for each control location to test the adequacy of the mathematical model (Fig. 7).

In the first 4 minutes, the temperature-time dependence of the fire (Fig. 7) in the vertical cable tunnel coincides with the temperature regime reflected in the work of RWS [4] and with the natural fire test (Fig. 6). Then the combustion zone shifts, the maximum temperature is observed and then decreases, due to the combustion of oxygen in the interior space and the fire load.

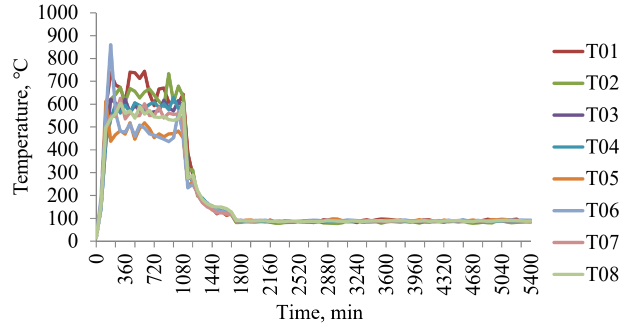

Fig. 7. Temperature-time dependence in the vertical cable tunnel of the nuclear power plant based on the results of the calculated experiment for each of the 8 installed thermocouples

5. 3. Determining the adequacy of the mathematical model for reproducing the process of heat and mass transfer during a real fire

The following adequacy criteria (6)–(11) were used to check the adequacy of the modeling results: Fisher's F-test, Student's t-test, and Cochran's Q-test:

– Fisher's F-test:

$$F=\frac{S_{xy}^2}{S_y^2}, \quad (6)$$

where S_{xy}^2 – the variance of adequacy, S_y^2 – the variance of reproducibility.

Adequacy variance was calculated (7) as the deviation between calculated and experimental data for each of the thermocouples installed during the field experiment and the corresponding temperature measurement location in the mathematical model:

$$S_{xy}^2=\frac{\sum_{i=1}^{n}\left(x_i+y_i\right)^2}{n}, \quad (7)$$

where n – the number of temperature measurements, y_i – the criterion value during simulation, x_i – the criterion value during testing.

The dispersion of reproducibility was calculated (8) as a deviation between the results of two full-scale experiments, taking into account the experimental error [16]:

$$S_y^2=\frac{1}{n}\sum_{i=1}^{n}\left(\left|y_i-\bar{y}\right|-16\right)^2, \quad (8)$$

where n – the number of temperature measurements, $\bar{y}$ – the temperature of the second full-scale experiment, y_i – the temperature of the first full-scale experiment;

– Student's t-test, used to compare the results of real and computational experiments (9), (10):

$$t=\frac{\bar{y}_1-\bar{y}_2}{\sqrt{\left(n_1-1\right)\cdot S_1^2+\left(n_2-1\right)\cdot S_2^2}}\cdot\sqrt{\frac{n_1\cdot n_2\cdot\left(n_1+n_2-2\right)}{n_1+n_2}}, \quad (9)$$

$$\bar{y}_{1,2}=\frac{1}{n}\sum_{i=1}^{n}y_i; \quad (10)$$

– Cochran's Q-criterion:

$$Q = \frac{S^2_{max}}{\sum_{i=1}^{p} S_i^2}, \quad (11)$$

where S^2_{max} – the largest root mean square deviation of test results.

Analyzing the comparison of the dispersion of the results of the mathematical modeling of the heat exchange process during a fire in the tunnel (Table 4), it can be stated that none of the values of the adequacy criteria exceed the permissible values.

The relative deviation is 7.85 %, which shows the effectiveness of modeling thermal processes for conducting further studies of fire temperature regimes in vertical cable tunnels of nuclear power plants.

Table 4

Dispersion parameters of the results of the heat and mass transfer process during a fire

Adequacy criteria	Thermocouple zone (Fig. 4)								Critical value
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	
F-criterion	0.94	0.98	1.26	1.47	2.12	1.77	1.42	1.40	2.28
t-test	0.58	0.11	0.68	1.13	0.73	1.38	0.43	0.13	1.65
Q-criterion	0.338	0.337	0.336	0.337	0.345	0.34	0.338	0.34	0.43

5. 4. Computational experiment of the temperature regime during a real fire in a vertical cable tunnel

To determine the most significant parameters of the vertical cable tunnel of the nuclear power plant, which affect the temperature regime of the fire and the limits of their change, 15 computational experiments were conducted. The purpose of the research was to establish how much a specific parameter affects the temperature regime of a fire in a vertical cable tunnel of a nuclear power plant. In order to determine the importance of a specific parameter, mathematical modeling of a fire was first carried out with average parameters, and then a certain parameter was increased and decreased to extreme values (Table 5).

After obtaining 2 new samples and comparing them with the first, the relative deviation of the temperature-time curves of the fire regime in the vertical cable tunnel of the nuclear power plant was calculated (Fig. 8).

According to the conducted computational experiment (Fig. 8), the longitudinal cross-sectional area of the vertical cable tunnel of the nuclear power plant affects the rate of temperature increase. Reaching the maximum temperature was observed in 2–8 minutes in various mathematical models. At a lower height, the fire load burned out faster and a decrease in temperature was observed at 18 minutes of the experiment, and at the highest simulated height at 36 minutes.

According to the obtained experimental data (Fig. 8) and comparing with the temperature-time dependence of temperature (Fig. 9), it can be stated that the highest temperature in the center of the fire reaches temperature values from 1200 to 1400 °C.

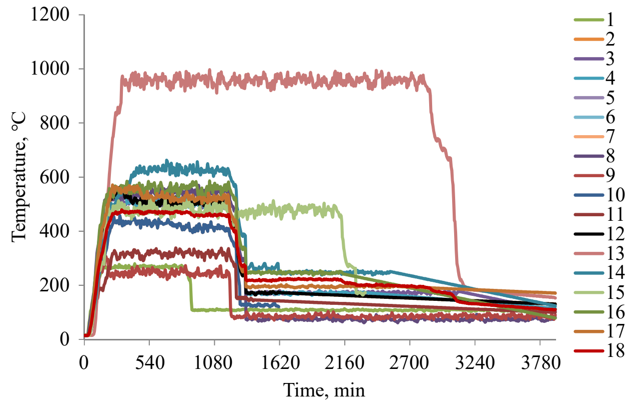

Fig. 8. Average fire temperature regimes in the mathematical model of a vertical cable tunnel of a nuclear power plant with parameters (Table 5): 1 – fire load: minimum volume of non-metallic materials in 1 meter of cable; 2 – fire load: cable insulation material – polyvinyl chloride; 3 – fire load: cable insulation material – polychloride; 4 – fire load: cable insulation material – cross-linked polyethylene; 5 – fire load: cable insulation material – rubber; 6 – fire load: cable insulation material – silicone; 7 – fire load: cable insulation material – oil-filled; 8 – geometric dimensions: the minimum size of the area of the longitudinal section; 9 – geometric dimensions: height; 10 – geometric dimensions: the minimum area of the ventilation and inspection passage; 11 – air flow: minimum air flow; 12 – basic experiment; 13 – fire load: the maximum volume of non-metallic materials in one meter of cable; 14 – geometric dimensions: the maximum size of the area of the longitudinal section; 15 – geometric dimensions: maximum height; 16 – geometric dimensions: the maximum area of the ventilation and inspection passage; 17 – air: maximum air flow; 18 is the average temperature between graphs 1–17

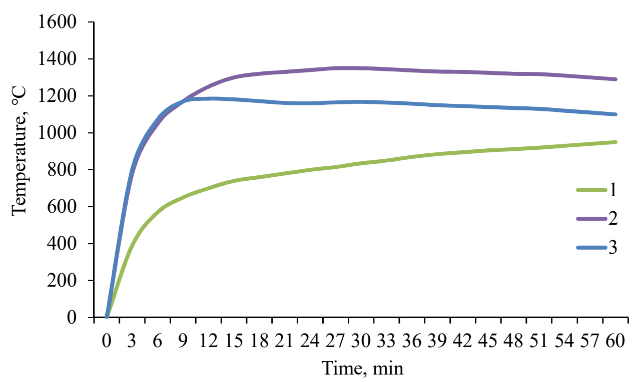

Fig. 9. Fire temperature regimes: 1 – standard fire temperature regime in accordance with DSTU B B.1.1-4; 2 – fire mode in tunnels according to [4]; 3 – the average temperature of the calculated experiments in the vertical cable tunnels of the nuclear power plant (Fig. 8)

Table 5

The parameters of the tunnel on which the temperature regime depends and the range of their variations

Insulation material	Height	Cross-sectional area		The total volume of materials in 1 meter of cable	The area of the ventilation and inspection passage	Air movement
	Z, m	Y, m	X, m	V, kg	S, m^2	V, m/s
Polyvinyl chloride, polyvinyl chloride, cross-linked polyethylene, rubber, silicone, oil-filled	2–10	1.0–3.0	1.0–3.0	1–10	1.26–3.75	0.1–0.6

This temperature was reached in the 9^{th} minute. The maximum time of intensive burning was 39 minutes, after which a gradual decrease in the temperature in the cell was observed due to the burnout of the fire load.

6. Discussion of the results of the process of heat and mass transfer of vertical cable tunnels of a nuclear power plant under the conditions of real fires

The conducted research is aimed at analyzing the process of heat and mass transfer during real fires in vertical cable tunnels of a nuclear power plant. To analyze the process of heat and mass transfer during fires in the vertical cable tunnels of the nuclear power plant, mathematical models were created in the Fire Dynamics Simulator software. The results of the study indicate the effectiveness of modeling thermal processes in such conditions and have an important application in the field of safety of nuclear power plants. Geometric, aerodynamic parameters and fire load were taken into account for the study.

The obtained results make it possible to understand the influence of various factors on the temperature regime of fire in vertical cable tunnels. The results of the obtained data determine the effectiveness of modeling thermal processes in the vertical cable tunnels of the nuclear power plant. None of the values of the adequacy criteria exceed the permissible values (Table 4). At the critical values of Fisher's F-criterion (2) – 2.28, Student's t-criterion (5), (6) – 1.65, Cochran's Q-criterion (7) – 0.43 [16], their average values were: 1.42; 0.65 and 0.33, respectively, and the maximum value did not exceed the critical value (Table 4). The results of the research show the effectiveness of modeling thermal processes for conducting further studies of fire temperature regimes in vertical cable tunnels of a nuclear power plant.

The obtained results determine important factors affecting the temperature regime of fire in vertical cable tunnels, in particular, fire load, tunnel height and longitudinal cross-sectional area (Table 4). According to the results of computational experiments (Fig. 8), the fire load has a directly proportional effect on the maximum temperature generated during a fire in a vertical cable tunnel. The temperature regime of the fire (Fig. 2) in the vertical cable tunnel with the maximum simulated fire load in the first 8 minutes coincides with the temperature regime reflected in the RWS operation [4] within an error of 3 %. Then the combustion zone shifts and a decrease in temperature is observed due to the combustion of oxygen in the interior space and the fire load. However, with a lower fire load, the maximum temperature in the vertical cable tunnel was 20–75 % lower.

It is noted that the standard fire temperature regime (1) does not correspond to real conditions and cannot serve as an adequate criterion for testing the fire resistance of building structures in accordance with the requirements of DSTU B B.1.1-4. Instead, it is proposed to use the temperature regime (Fig. 9), obtained by computational experiment. For greater confidence in the validity of our results, let's compare them with the data of other known studies [4–12], in particular from the works of section VII.3 "Fire reaction of materials" of the 1999 05.05.B report "Fire and smoke control in tunnels", which discuss the characteristics of rock tunnel linings compared to reinforced concrete. The intensity of heat generated during a large fire can cause the tunnel's enclosing structure to lose its load-bearing function. The comparison showed that our results follow the general trend and are consistent with known data.

The obtained results of the study of the process of heat and mass transfer in the vertical cable tunnels of the nuclear power plant are of practical significance for improving the safety of the stations and developing new technologies in the field of safety. To test the fire resistance of building structures of tunnels, it is recommended to use the temperature regime obtained by the computational experiment (Fig. 9), since the standard temperature regime (1) is not adequate for testing the fire resistance of building structures. The proposed innovations will make it possible to ensure the necessary limit of fire resistance of the enclosing structures of vertical cable tunnels (cable shafts) of the enterprises of the Ministry of Energy of Ukraine.

Further work will be directed to the study of the fire resistance of the building structures of the vertical cable tunnels of the nuclear power plant with the identified main factors affecting the temperature regime of the fire with a full factorial experiment.

7. Conclusions

1. At the training and sports complex of the 1st State Fire and Rescue Squad of the Main Directorate of the State Emergency Service of Ukraine in the Zaporizhzhia region, field experimental studies were conducted on object protection. According to the developed methodology, cables were laid in a model of a 25-m-high vertical cable tunnel at the rate of 7 liters per meter of tunnel height, and the process of burning the cables was initiated. To correlate the results, 3 experiments were conducted. Temperature-time dependences were obtained for each installed thermocouple in the corresponding planes of the inner space of the cable tunnel. The highest temperature is observed in the zone of plane D in the range of 800–900 °C.

2. Mathematical modeling of a fire in a vertical cable tunnel with parameters similar to a natural experiment using mathematical gas-hydrodynamics was carried out. The temperature-time dependences of the temperatures in the vertical cable tunnel were obtained, which indicate the zone of plane D as the highest temperature observed in the 3 conducted experiments. Thermal energy spreads most intensively in the direction of the exit of combustion products through the hole. Mathematical simulation of fire in comparison with field test data is 7.85 %, which shows the effectiveness of simulation of thermal processes.

3. Adequacy of constructed mathematical models and experimental data was verified. The calculated adequacy criteria (Student's t-criterion, Cochran's Q-criterion, Fisher's F-criterion) do not exceed the permissible values, which proves the effectiveness of modeling thermal processes for their use in the study of the fire resistance of the enclosing structures of the vertical cable tunnels of the nuclear power plant.

4. A computational experiment was carried out with the appropriate frameworks of parameter variations on which the temperature regime of the fire depends. The area of the longitudinal section of the vertical cable tunnel has a significant influence on the rate of temperature increase, the larger it was, the slower the maximum temperature value was reached. According to the data of computational experiments, reaching the maximum temperature was observed in

2–8 minutes in various computer models, which coincides with the data displayed in the works of various computer models. The height of the vertical cable tunnel affected the burnout rate of the fire load. At a lower height, the fire load burned out faster and a decrease in temperature was observed at 18 minutes of the experiment, and at the highest simulated height at 36 minutes.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

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