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STUDY OF FIRE TEMPERATURE MODES IN HORIZONTAL CABLE TUNNELS DEPENDING ON PARAMETERS AND FIRE LOAD

Based on the results of the work, the dependences describing the maximum temperature inside the cable tunnel during a fire, the duration of a fire in a certain local area of the cable tunnel, and the time to reach the maximum temperature inside the cable tunnel during a fire were obtained from the fire load, the cross-sectional area of the tunnel, and the speed of movement of air masses inside.

In one of the CFD software complexes, a mathematical model of the cable tunnel, similar to the real one, was created. A computational experiment was conducted. Modeling, as a method of scientific research, makes it possible to conduct all the necessary experiments on determining the temperature regimes of fire in cable tunnels without performing materially expensive and time-consuming field experiments on models.

Based on the results of the computational experiment and field tests, adequacy criteria were calculated (Student's t-test, Cochran's Q-test, Fisher's F-criterion). Based on the analysis, the adequacy of the used mathematical models was investigated.

A full factorial experiment was designed and conducted. According to its results, regressions of the maximum temperature inside the cable tunnel during a fire, the duration of a fire in a certain local area of the cable tunnel, and the time of reaching the maximum temperature inside the cable tunnel during a fire were obtained.

The temperature regime of the fire in cable tunnels with different sizes, aerodynamic parameters and fire load was determined, as well as the dependence on the specified parameters of the temperature regime of the fire.

Key words: *cable tunnel, electrical networks, power consumption, switching, computing experiment, fire resistance.*

Formulation of the problem. The development and improvement of public telecommunications networks of Ukraine is carried out in accordance with the Concept of Development of Telecommunications of Ukraine using the latest technologies in the field of telecommunications that meet international standards, taking into account the technological integrity of all networks and means of telecommunications, increasing the efficiency and sustainability of functioning. During the design and construction of cable networks, in particular, cable tunnels, it is necessary to comply with the requirements of building codes and regulations to ensure compliance with the limits of fire resistance of cable tunnel constructions in the event of a fire.

Cable products are constantly developing and improving. The standard fire temperature regime is used for fire resistance tests of cable tunnel building structures, which may not correspond to the fire regime in a real cable tunnel.

The study of the temperature regime of fire is an urgent issue, since 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 can differ both from the standard and among themselves. In this case, it is not possible to guarantee compliance of the fire resistance limits of the tested structures with the current regulations. In this case, the safety of people and material assets during fires in cable tunnels can be significantly reduced**.**

Analysis of recent achievements and publications. Many scientists have been and are engaged in the study of temperature conditions, especially in tunnels, particularly the temperature conditions of fire in vertical tunnels were offered in the study [1].

In [2-4] studies, the authors investigated the dynamics of fire development in cable structures and described the temperature dynamics in the combustion zone without and with inert gas supply.

In [5] study, the researchers checked the adequacy of mathematical models of heat and mass transfer during fires in vertical cable tunnels of nuclear power plants, which makes it possible to carry out similar calculations for horizontal tunnels.

The study [6] substantiated the methodology for conducting a full-scale experiment to determine the temperature regime of a fire in a cable tunnel. The data obtained are the basis for verifying computer models of fires in cable tunnels and determining the fire temperature regime for testing the fire resistance of building structures of cable tunnels.

Identification of previously unresolved parts of the general problem to which the article is devoted. According to previous studies [1-6], the variety of design features of cable tunnels, their fire load, inflow and outflow of gases, and other parameters causes significant differences in fire temperature conditions. In particular, modern insulation of cable products may differ in fire performance from that studied by scientists [1; 5].

This scientific paper investigates the temperature conditions of fire in horizontal cable tunnels depending on their parameters and fire load. To achieve this goal, we used field tests [6] as a basis and performed an analytical calculation in a similar tunnel configuration with the corresponding fire load, as well as a full factorial experiment.

The goal and objectives of the study.

The results of the study should be used to obtain dependencies describing the temperature regime in horizontal cable tunnels depending on their geometric parameters and fire load, which will be the basis for creating a mathematical model of the behavior of the enclosing building structures of cable tunnels and assessing their fire resistance limit at different fire temperature conditions.

1. To describe the process and results of a computational experiment using a mathematical model of a horizontal cable tunnel.
2. To check the adequacy of the results obtained on the basis of the data of the full-scale experiment.
3. Carry out a full factorial experiment to determine the temperature regime of a fire in a tunnel depending on significant options.
4. To figure out dependencies describing the temperature regime in horizontal cable tunnels depending on their geometric parameters and fire load.

Presentation of the main research material with full justification of the obtained results. To conduct a computational experiment using the created mathematical model of the cable tunnel for testing, the following sequence of calculation procedures was used.

1. Using a CAD program, a geometric configuration of the cable tunnel of the required dimensions is created. Inside, models of cables, steel corners, a hole for the exit of combustion products and a place for air supply are created. The geometric model is imported into the FDS calculation environment.

2. Initial parameters of modeling are entered, which cannot be changed during the calculation process: initial temperature of the environment, air pressure on one side of the tunnel, required fire time (30 minutes).

3. The combustion process is initiated in the middle part of the tunnel directly under the cables. For this purpose, a fire center of 0.6 $\times$ 0.6 m is modeled.

4. During the calculation, the temperature of the corresponding points in the tunnel and the temperature gradient are monitored online.

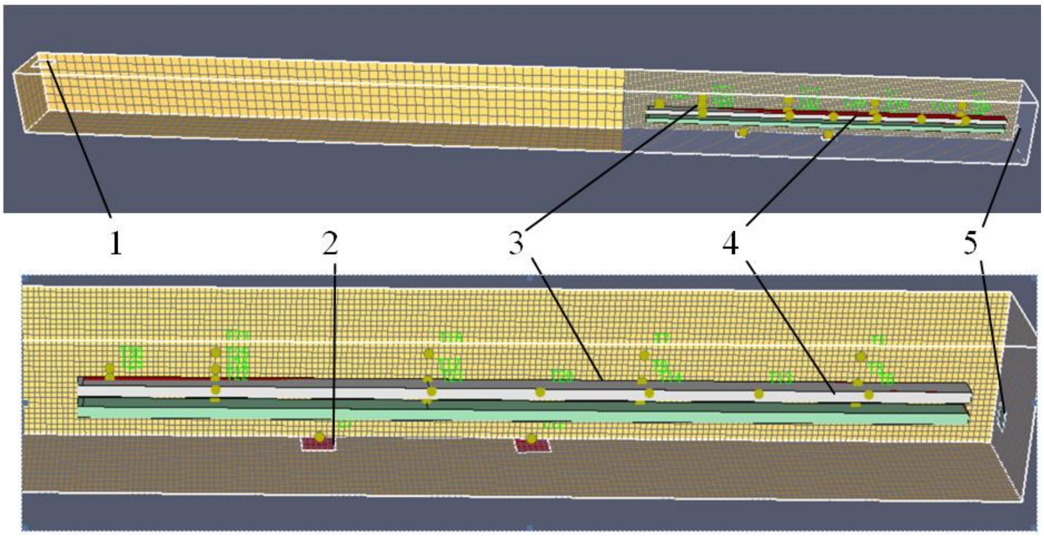


Figure 1 – The model of the cable tunnel used for the computational experiment: 1 - combustion product outlet; 2 - fire center; 3 - metal corner; 4 - cables; 5 - air supply zone

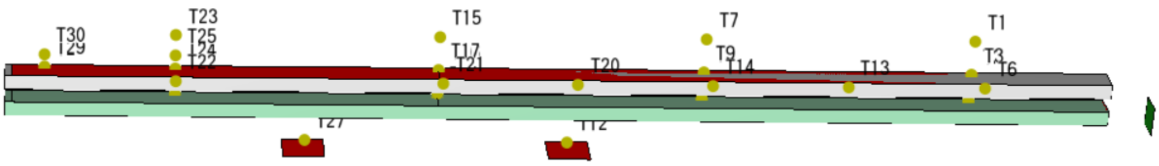


Figure 2 – Diagram of the location of temperature control points in the cable tunnel: T1 - T30 - control points (figure 1)

In order to control the temperature regime by means of the FDS computer complex, 30 temperature control points were created, which corresponded to the locations of thermocouples during the field experiment (figures 1; 2).

To visualize the processes of heating the space of the cable tunnel during the computational experiment, planes were created in the computer model where the temperature value is visualized using colors.

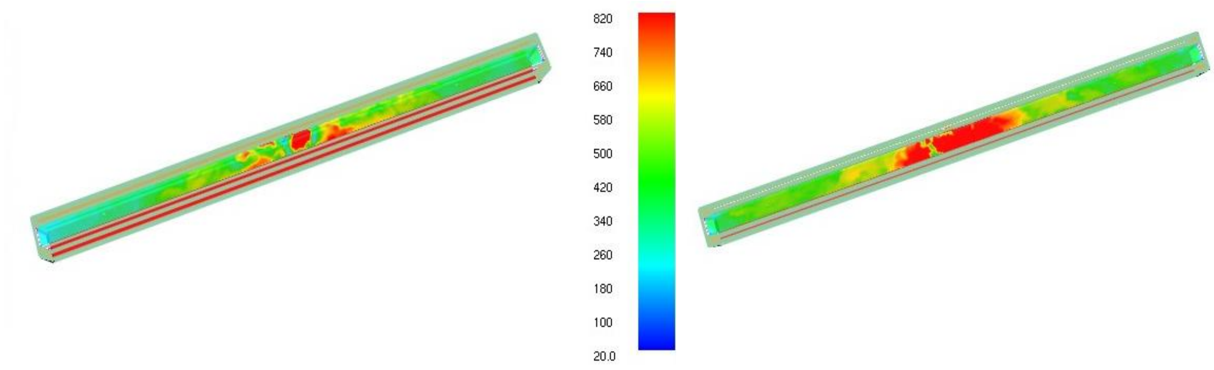
The study of the fire temperature regime was divided into several stages in order to be most effective:

1. Determination of the parameters of the cable tunnel on which the temperature regime depends and the limits of their variations.

2. Determination of the most significant parameters.

3. Planning experiments with the variation of the most significant parameters.

4. Conducting computational experiments and determining the dependence of fire temperature conditions on significant parameters.



a b

Figure 3 – Temperature gradient in the space of the cable tunnel model: a - 5 minutes, b - 30 minutes

Table 1 summarizes the parameters of the cable tunnel on which the temperature regime depends and the limits of their variations.

Table 1 – The parameters of the cable tunnel on which the temperature regime depends and the limits of their variations

Parameter					
Hole spacing	Cross-sectional area of the cable tunnel		Fire burden of one cable line	The number of cable lines	Number (n) and area (S) of ventilation and inspection hatches
L, m	Y, m	Z, m	Q, MJ/m^2	N	$n \cdot S$, m^2
5-10	1,6-2	1,8-2,15	688-2000	2-10	1-3 · 0,3

In order to determine the most significant parameters of the cable tunnel on which the temperature regime of the fire depends and the limits of their variations, a number of computational experiments were carried out to determine to what extent a certain parameter (geometric dimensions, fire load, etc.) affects the temperature regime of the fire in the cable tunnel. To determine the significance of a particular parameter, a mathematical modeling of the fire was first carried out at average parameters, and then the parameter was increased and decreased to extreme values. Having received 2 new samples and comparing them with the first one, the relative deviation of the temperature-time curves of the fire regime in the cable tunnel was calculated.

According to the temperature distribution shown in Fig. 3, the cable tunnel can be divided into 3 zones: the fire center, between the fire center and the combustion product outlet, and between the fire center and the air supply.

After finishing the computational experiment, temperature data were obtained for each control point for verification.

Figure 4 shows graphs of the average temperature in different parts of the cable tunnel during the computational experiment.

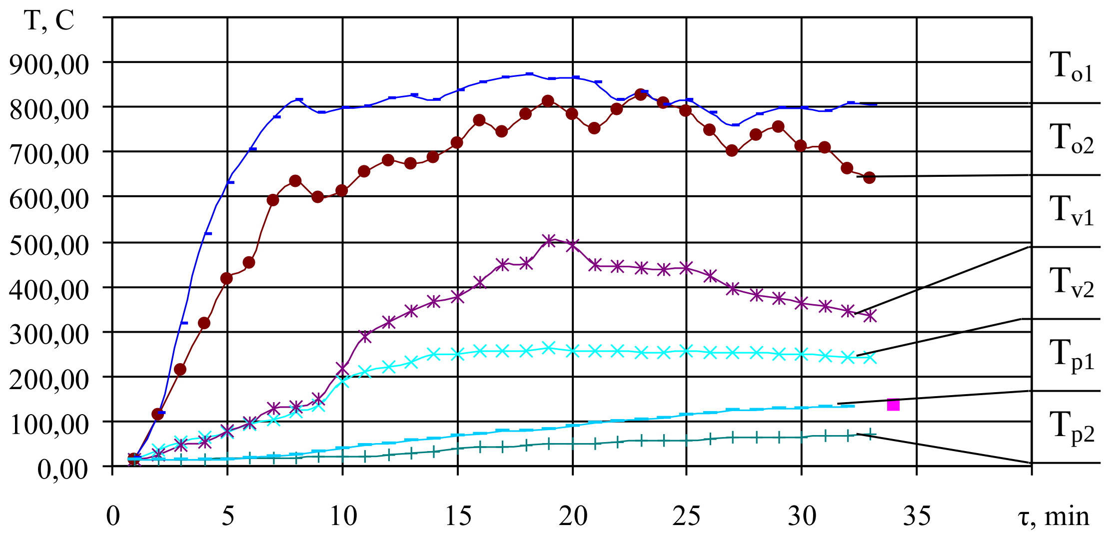


Figure 4 – Average temperature in 3 zones of the cable tunnel: T_{o1} - in the upper part of the tunnel of the fire zone; T_{o2} - in the lower part of the tunnel of the fire zone; T_{v1} - in the upper part of the tunnel of the zone between the fire zone and the hole for the exit of combustion products; T_{v2} - in the lower part of the tunnel of the zone between the fire center and the hole for the exit of combustion products; T_{p1} - in the upper part of the tunnel of the zone between the fire center and the place of air supply; T_{p2} - in the lower part of the tunnel of the zone between the fire center and the place of air supply

Checking the adequacy is carried out on the basis of experimental information obtained as a result of tests [6].

The following adequacy criteria were used to verify the adequacy of the modeling results:

- Fisher's F- criterion . Using the Fisher's criterion, it is possible to test the hypothesis of equality of the general variances, the temperature spread at each minute of the test.

$$F = \frac{S_{xy}^2}{S_y^2}, \tag{1}$$

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

The adequacy variance was calculated as the deviation between the calculated and experimental data for each of the thermocouples installed during the field experiment and the corresponding temperature measurement point in the mathematical model.

There are 30 temperature measurement points in the model, and 30 thermocouples in the experiment. The data from each of the thermocouples were compared in turn with the thermocouples of the experiment. Thus, 30 values of the adequacy variance were obtained.

$$S_{xy}^2 = \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}, \qquad (2)$$

n – quantity of temperature measurements, y_i - the value of the criterion in the modelling, x_i - criterion value during testing.

The variance of reproducibility was calculated as the deviation between the results of two full-scale experiments, taking into account the experimental error [7].

$$S_y^2 = \frac{1}{n}\sum_{i=1}^{n}(\left|y_i - \overline{y}\right| + 15)^2, \qquad (3)$$

n – quantity of temperature measurements, $\overline{y}$ – temperature of the second full-scale experiment, y_i - temperature of the first full-scale experiment.

Thus, we take 30 values of the adequacy variance alternately, compare them with the reproducibility variance, and calculate the Fisher's criterion.

All the results are summarized in Table 2.

- Student's t-test is used to compare the results of real and computational experiments:

$$t = \frac{\overline{y_1} - \overline{y_2}}{\sqrt{(n_1 - 1)\cdot S_1^2 + (n_2 - 1)\cdot S_2^2}} \cdot \sqrt{\frac{n_1 \cdot n_2 \cdot (n_1 + n_2 - 2)}{n_1 + n_2}}, \qquad (4)$$

$$\overline{y}_{1,2} = \frac{1}{n}\sum_{i=1}^{n} y_i, \qquad (5)$$

S_1^2, S_2^2 – estimates of the variances of the natural and computational experiments were calculated similarly to the calculation of Fisher's criterion.

Thus, 30 values of the criterion were obtained when calculating the variance of reproducibility as the deviation of the calculated temperature of the space directly near the modeled thermocouple and the readings of the modeled thermocouple, taking into account the experimental error [7].

- Cochrane's Q- criterion (determination of emissions and quasi-emissions):

$$Q = \frac{S_{max}^2}{\sum_{i=1}^{p} S_i^2}, \qquad (6)$$

S_{max} –the largest standard deviation of the test results.

The Q-test is used when comparing three or more samples of the same amount. The variances between the two full-scale experiments and the computational one were compared, and 30 values of the criterion were obtained at the location of each thermocouple.

All the results are summarised in Table 2.

Table 2 – Parameters of variance of the results of mathematical modeling of the heat transfer process during a fire in a cable tunnel from experimental data [6-8]

Thermocouple's zone (p. 2, figure 4)	Maximum deviation, °C	Average deviation, °C	Relative deviation %	F-criterion	Critical value F-criterion[7]	t-test	Critical value t-test[7]	Q-test	Critical value Q-test [7]
T_1	54,3	14,1	10,4	2,42	4,00	1,81	2,75	0,42	0,88
T_2	52,1	10,3	9,9	2,27		1,68		0,32	
T_3	45,5	17,8	9,8	2,08		1,80		0,43	
T_4	45,6	17,9	11,6	2,43		1,93		0,50	
T_5	20,2	6,1	7,3	1,84		1,23		0,24	
T_6	39,7	19,0	11,5	2,53		2,14		0,53	
T_7	49,4	17,2	11,7	2,77		1,95		0,44	
T_8	46,3	14,9	9,8	2,17		1,69		0,37	
T_9	50,2	13,1	8,1	1,98		1,21		0,23	
T_{10}	59,5	20,2	10,1	2,06		1,78		0,38	
T_{11}	51,1	21,0	10,0	2,04		1,78		0,37	
T_{12}	81,9	19,7	6,8	1,44		1,01		0,14	
T_{13}	45,8	18,4	7,9	1,42		1,20		0,19	
T_{14}	74,1	25,9	7,3	1,45		1,18		0,17	
T_{15}	131,2	50,3	6,4	1,42		1,18		0,17	
T_{16}	139,7	48,1	6,4	1,35		1,17		0,17	
T_{17}	132,8	48,0	6,5	1,41		1,14		0,15	
T_{18}	109,2	46,4	5,7	1,32		1,15		0,15	
T_{19}	122,5	57,8	7,9	1,48		1,19		0,20	
T_{20}	92,9	45,4	8,2	1,54		1,21		0,23	
T_{21}	91,0	36,1	6,7	1,50		1,17		0,19	
T_{22}	98,8	36,8	7,0	1,56		1,18		0,21	
T_{23}	82,3	36,0	8,6	1,69		1,24		0,23	
T_{24}	72,1	32,8	6,6	1,47		1,20		0,21	
T_{25}	75,4	43,7	8,7	1,66		1,23		0,21	
T_{26}	70,6	40,2	8,4	1,62		1,22		0,22	
T_{27}	100,7	61,4	7,0	1,58		1,24		0,20	
T_{28}	28,9	15,6	8,6	1,69		1,11		0,13	
T_{29}	24,9	13,9	13,5	3,45		2,53		0,66	
T_{30}	28,0	10,2	8,8	1,70		1,09		0,13	
Average value	70,6	28,61	8,58	1,84		1,84		0,27	

Analysing the comparison of the variance of the results of mathematical modelling of the heat transfer process during a fire in a cable tunnel and experimental data (Table 2), it can be stated that none of the values of the adequacy criteria exceeds the permissible values, with a relative deviation of 8.58 %, which shows the effectiveness of modelling thermal processes for further studies of temperature conditions of fires in cable tunnels.

The scientific work [5] investigated the temperature regimes of fire in cable tunnels at their various parameters. To build a mathematical model of the temperature regime of a fire in a cable tunnel, it is necessary to conduct a full factorial computational experiment. In this case, three independent factors are established - the cross-sectional area of the cable tunnel, the fire load, and the horizontal component of air movement inside the tunnel [6]. Table 3 shows the intervals of the parameters in the experiment that were selected as factors.

Table 3 – Intervals for varying factors in a computational experiment

Factor 1. Fire load per 1 m^2 of cable tunnel, MJ/m^2 (Next – x1)	Factor 2. Cross-sectional area of the cable tunnel, m^2 (Next– x2)	Factor 3.Horizontal component of the air velocity, m/s (Next–x3)
224,7-2247	2,88-4,4	0-5

The chosen mathematical model is a linear dependence of the maximum temperature inside the cable tunnel on the selected factors, which has the form.

$$y = b0 + b1x1 + b2x2 + b3x3 + b4x1x2 + b5x1x3 + b6x2x3 + b7x1x2x3, \quad (7)$$

b0, b1, b2, b3, b4, b5, b6, b7 – regression coefficients.

To determine the initial data of the full factorial experiment, 8 computer models were calculated, in which the parameters of the maximum and minimum intervals in various combinations were included.

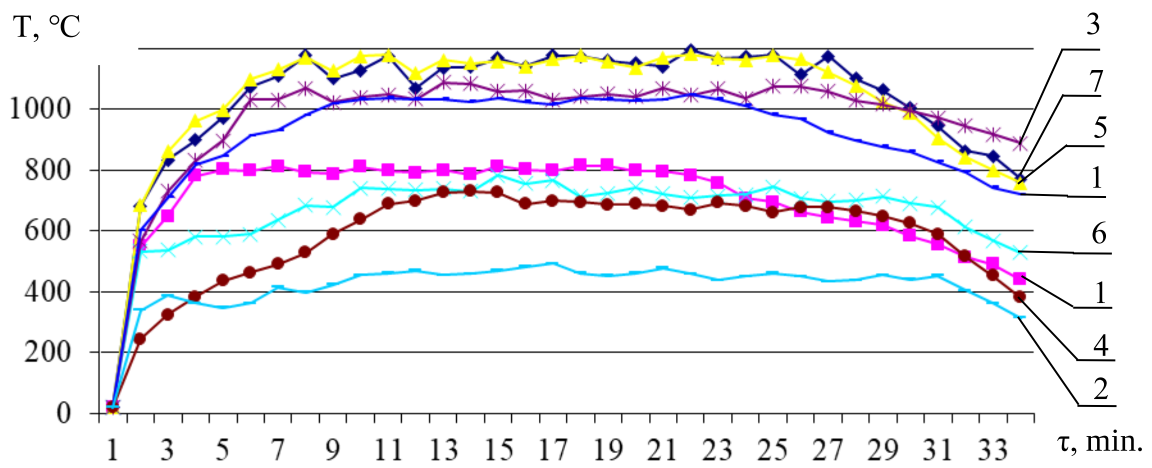


Figure 5 – A summary graph of the calculation of 8 computer models, the data of which are used as input for a full factorial experiment: 1-8 - experiment number

Next, [Fig. 6 - Fig. 8], the results of the full factorial experiment for determining the temperature regime of the fire in the tunnel are presented.

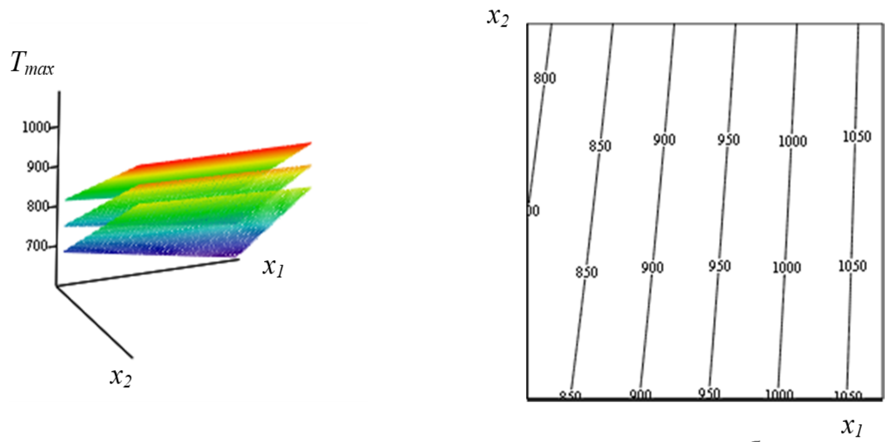


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Figure 6 – Maximum temperature inside the cable tunnel during a fire (T_{max}): a - in the form of graphs; b - in the form of nomograms

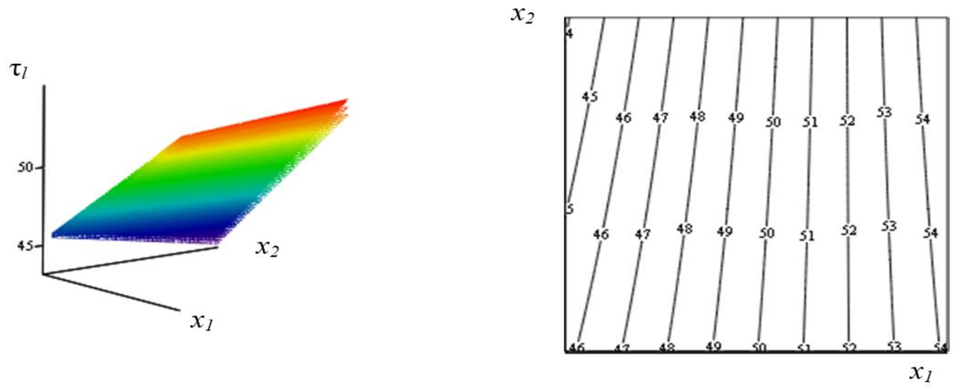

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Figure 7 – Fire duration in a certain zone of the cable tunnel (τ_l): a - in the form of graphs; b - in the form of nomograms

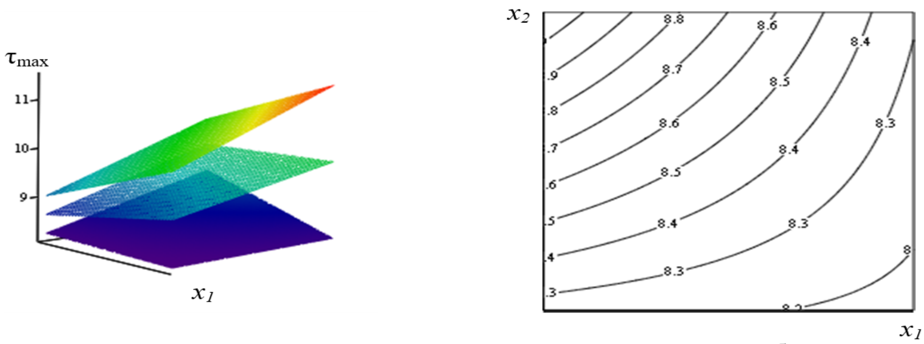

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Figure 8 – Time to reach the maximum temperature inside the cable tunnel during a fire (τ_{max}): a - in the form of graphs; b - in the form of nomograms

According to the results of the full factorial experiment, we obtained regressions of the maximum temperature inside the cable tunnel during the fire (T_{max}), the duration of the fire in a certain local zone of the cable tunnel (τ_l), and the time of reaching the maximum temperature inside the cable tunnel during the fire (τ_{max}), represented by the expressions:

$$T_{max}=0.097\cdot x_1-27.92\cdot x_2-11.391\cdot x_3+0.01\cdot x_1\cdot x_2-0.001\cdot x_1\cdot x_3-5.279\cdot x_2\cdot x_3+0.001\cdot x_1\cdot x_2\cdot x_3+870.594 \quad (8)$$

$$\tau_l = 0{,}002\cdot x_1-1{,}439\cdot x_2+0{,}0125\cdot x_3+0.001\cdot x_1\cdot x2-0{,}016\cdot x_2\cdot x_3+48{,}969 \quad (9)$$

$$\tau_{\max} = 0{,}001\cdot x_1+0{,}596\cdot x_2+0{,}05625\cdot x3+0{,}025\cdot x_2\cdot x_3+6{,}55 \quad (10)$$

The obtained regression dependencies make it possible to create a mathematical model of the behaviour of cable tunnel enclosing structures and to assess their fire resistance limit under different fire temperature conditions.

Conclusions. Based on the results of the study, dependencies (7) - (9) were obtained that describe the maximum temperature inside a cable tunnel during a fire, the duration of the fire in a certain local area of the cable tunnel, and the time to reach the maximum temperature inside the cable tunnel during a fire as a function of the fire load, the cross-sectional area of the tunnel, and the speed of air masses inside. This is the basis for creating a mathematical model of the behaviour of cable tunnel enclosing building structures and assessing their fire resistance limit under different fire temperature conditions.

1. A computer model of a fire in a cable tunnel, similar to the natural one, was created. The calculation data of the computer model and the full-scale model were obtained: the temperature observed in the fire zone near the cables was in the range of 700-900℃, depending on the location of the control point. Thermal energy spreads more intensively towards the combustion product outlet. The temperature in the area of the combustion product outlet ranges from 250-500 °C. In the area between the air supply and the fire centre, the temperature is in the range of 80-150 °C.

2. The adequacy of the constructed mathematical models and experimental data was checked. The calculated adequacy criteria (Cochran's Q-test, Student's t-test, Fisher's F-criterion) do not exceed the permissible values [8] (Table 2), which indicates the effectiveness of modelling thermal processes for their use in the study of fire resistance of cable tunnel enclosing structures.

3. A full factorial experiment was performed. Based on its results, we obtained regressions of the maximum temperature inside the cable tunnel during a fire, the duration of the fire in a certain local zone of the cable tunnel, and the time of reaching the maximum temperature inside the cable tunnel during a fire, represented by expressions (7) - (9).

4. The temperature regime of fire in cable tunnels with different sizes, aerodynamic parameters and fire load, as well as the dependence of the fire temperature regime on these parameters, were determined. In the case of 10 laid cable lines and a fire load of 2247 MJ/m^2, the maximum temperature exceeded 1200℃, and in the case of 1 line and a fire load of 224.7 MJ/m^2 - 500℃.

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ДОСЛІДЖЕННЯ ТЕМПЕРАТУРНИХ РЕЖИМІВ ПОЖЕЖІ У ГОРИЗОНТАЛЬНИХ КАБЕЛЬНИХ ТУНЕЛЯХ В ЗАЛЕЖНОСТІ ВІД ЇХНІХ ПАРАМЕТРІВ ТА ПОЖЕЖНОГО НАВАНТАЖЕННЯ

За результатами роботи отримано залежності, що описують максимальну температури всередині кабельного тунелю під час пожежі, тривалість пожежі в певній локальній зоні кабельного тунелю та часу досягнення максимальної температури всередині кабельного тунелю під час пожежі від пожежного навантаження, площі поперечного перерізу тунелю та швидкості руху повітряних мас всередині.

У одному з програмних комплексів CFD була створена математична модель кабельного тунелю, аналогічна до натурного. Проведено обчислювальний експеримент. Моделювання, як метод наукового дослідження дає можливість, не виконуючи матеріально затратних та трудомістких натурних експериментів на моделях проводити всі необхідні досліди щодо визначення температурних режимів пожежі у кабельних тунелях.

Спираючись на результати обчислювального експерименту і натурних випробувань, були розраховані критерії адекватності (Т-критерій Стьюдента, Q-

критерій Кохрена, F-критерій Фішера). На основі проведеного аналізу досліджена адекватність використовуваних математичних моделей.

Розроблено та проведено повний факторний експеримент. За його результатами отримано регресі максимальної температури всередині кабельного тунелю під час пожежі, тривалості пожежі в певній локальній зоні кабельного тунелю та часу досягнення максимальної температури всередині кабельного тунелю під час пожежі.

Визначено температурний режим пожежі в кабельних тунелях із різними розмірами, аеродинамічними показниками й пожежним навантаженням, а також залежність від зазначених параметрів температурного режиму пожежі.

Ключові слова: *кабельний тунель, електричні мережі, потужність споживання, комутація, обчислювальний експеримент, вогнестійкість.*