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Термінологію, яка використовується в самій назві журналу **«Eastern-European Journal of Enterprise Technologies»**, - «передові технології», слід розуміти як синонім «промислові технології», бо це всі ті кращі ідеї із науки, які можуть бути впроваджені в промисловість. Адже отримання конкурентоспроможної промислової продукції високої якості базується на впровадженні високих технологій з різних самостійних сфер наукових досліджень, але об'єднаних загальним кінцевим результатом - готовим високотехнологічним виробом. Серед цих наукових сфер: інформаційні технології і системи управління, інженерія, енергетика та енергозбереження. Публікація наукових статей саме за цими напрямками і є основними «векторами» розвитку «Eastern-European Journal of Enterprise Technologies».

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Проведеними дослідженнями зміни температури при пожежі у кабельному тунелі встановлено, що у зоні горіння зростання температури відбувається швидше у порівнянні із стандартним температурним режимом пожежі. Це свідчить про необхідність проведення випробувань на вогнестійкість будівельних конструкцій кабельних тунелів за температурним режимом, що відрізняється від стандартного.

Під час проведення досліджень створено послідовність процедур з детальним вибором обладнання та зразків для випробувань з метою забезпечення достовірних експериментальних даних при дослідженні температурного режиму пожежі у кабельному тунелі.

Таким чином, після проведення експериментальними досліджень визначено температурні режими пожежі у різних зонах кабельного тунелю за запропонованою методикою. Найвища температура спостерігається у безпосередній зоні горіння. У зоні осередку пожежі біля кабелів – 700–900 °С, між зоною осередку пожежі та отвором виходу продуктів горіння в межах 250–500 °С. У зоні між осередком пожежі та місцем підпору повітря температура сягає 80–150 °С. Швидкість розповсюдження полум'я у напрямку, що співпадає з напрямом руху повітря вдвічі швидша, ніж у протилежному.

Таким чином, є підстави стверджувати, що отримані результати досліджень є підставою для створення математичних моделей, які описують пожежі у кабельних тунелях та можуть бути використані для інженерної оцінки вогнестійкості будівельних конструкцій кабельних тунелів

Ключові слова: кабельний тунель, температурний режим пожежі, методика експериментальних досліджень, моделювання пожежі

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EXPERIMENTAL STUDY OF TEMPERATURE MODE OF A FIRE IN A CABLE TUNNEL

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1. Introduction

Cable tunnel is a closed facility (corridor) with supporting structures inside it, designed to hold cables and cable clutches. Cable tunnels should have a free passage along the entire length. This enables laying the cables, repairing and inspecting cable lines.

Cable tunnels and collectors with a rectangular cross-section are intended for a double-side and one-side cable laying [1].

Fig. 2 shows a standard cable arrangement in tunnels with a rectangular cross-section.

Fig. 1. Cable tunnel with a one-side cable laying: 1 — cable lines, 2 — armature for cable lines laying

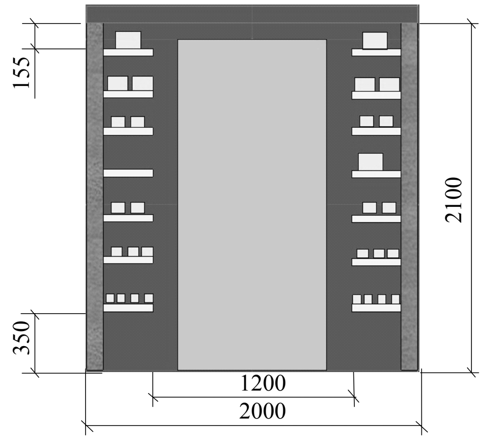


Fig. 2. Standard cable arrangment in tunnels and collectors with a rectangular cross-section [1]

The problem of fire safety of electric cables was escalated worldwide in the 1970s. This happened because of an increase in the number of fires at thermal power plants, nuclear power plants, and other large energy facilities. A significant increase in the number of fires in cable communications was due to an increase in the quantity of cables. Cables were laid in order to feed, control and manage electrical equipment at modern enterprises. In the case of laying general industrial cables in soil, no additional fire protection measures were taken. The branched cable communications are not only the carriers of a fire load, but also the guiding systems along which fire can propagate in buildings and structures.

Enclosure structures of cable tunnels are typically made of reinforced concrete [1]. To determine their limit of fire resistance, a standard temperature mode of fire is used [2].

The fire in cable tunnels creates a special temperature mode, which differs from the standard one. This is explained by that the cable tunnels differ in design, fire load, aerodynamic and other parameters. A result of incorrect determining the limit of fire resistance for the building structures of cable tunnels might be their collapse at fire. Thus, studying the temperature mode of the fire is an important task.

2. Literature review and problem statement

In recent years, both experimental tests and numerical simulation have been widely used [3–16]. Particularly, these methods are applied to study the parameters of fires in cable tunnels.

Paper [3] proposed a temperature mode of fire in tunnels. However, the temperature dependence on the fire load and the geometrical dimensions of the tunnel is not considered; while the aerodynamic indicators are averaged.

Paper [4] considered the propagation of flue gases and changes in their temperature during fire in a cable tunnel. However, it should be noted that a given paper investigated only the initial stage of the fire. This means that the temperature regime over the whole period of fire is not defined.

In work [5], field tests were conducted in a municipal tunnel. The authors modeled a fire when a combustible liquid was spilt. This paper made it possible to determine the required amount of fuel, which was used during this experiment.

Study [6] shows that the temperature in the center of an actual fire reached 800–900 °C. Based on this information, the type of thermocouples was selected in order to measure temperature during the experiment.

In paper [7], it was established that the width of the tunnel has little effect on the rate of burning out a fire load. Study [8] describes a series of full-scale experiments. The temperature distribution in tunnels with different ventilation conditions was measured. The research conducted has made it possible to determine the required air support for experimental studies.

Numerical simulation [9] analyzed the causes of fires in tunnels. Thus, the source of the fire start was determined.

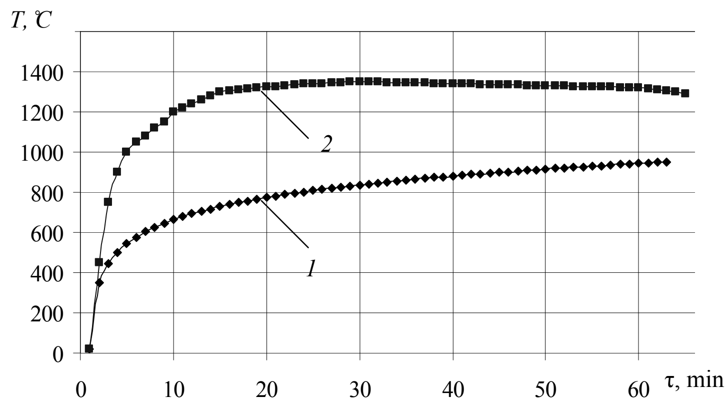


Fig. 3. Fire temperature modes: 1 – standard fire temperature mode [2]; 2 – fire mode in tunnels according to [3]

Work [10] reports analysis of parameters of the burning rate of insulation in a PVC-cable. The linear propagation speed of fire at different types of cable laying was considered. Despite the practical significance of such results, the methods of cable laying in tunnels with a rectangular cross-section were not considered in detail.

The influence of two systems of ventilation on the temperature distribution in the model of a tunnel with a small cross-section was investigated in paper [11]. That makes it possible to conclude that the aerodynamics in the tunnel space affects the temperature regime of fire.

Research [12] addresses effect of the mechanism of generating the flow of bifurcation of smoke on temperature distribution in the smoke layer for height. Only the influence of the horizontal component of the air exchange rate was analyzed in the paper.

Experimental studies were often conducted at model tunnels at a smaller scale; they are made of refractory glass [13] or galvanized steel [14].

The conclusion that the researchers drew in [15] suggests that the computational gas hydrodynamics (CFD) could be an addition to the experiments. The Fire Dynamic Simulator (FDS) is offered as one of the CFD tools, which provides reliable and accurate results when modeling fires in tunnels. However, any numerical experiments need to be verified based on actual experiments.

Study [16] describes a series of experimental tests in a tunnel of limited scale. The results showed that the temperature of a wall inside the tunnel varies depending on the rate of fire propagation and the maximum temperature in the fire center. According to [17], the temperature variance during fire affects the limit of fire resistance of building structures. Paper [18] reported analysis of the metrological toolset for field experiments. Given this, it is possible to correctly choose proper measuring instruments.

Therefore, there are reasons to believe that research in this field needs new insights. Additional studies should be conducted. At present, there is no a unified approved methodology for experiments related to cable tunnels in EU countries. Such a technique must be substantiated and verified.

3. The aim and objectives of the study

The purpose of this study is to substantiate a procedure and a set of techniques for investigating the temperature regime of a fire in the cable tunnel with a rectangular cross section.

To accomplish the aim, the following tasks have been set:

– to form a sequence of procedures with a detailed selection of equipment and test samples in order to provide reliable experimental data when studying the temperature regime of a fire in a cable tunnel;

– to substantiate a set of techniques for conducting research, as well as methods of subsequent processing of experimental results;

– to analyze the results of the experiment, conducted to determine the temperature mode of a fire in different zones of the cable tunnel, to make use of them in future for the verification of mathematical models.

4. Procedure and tools of the experimental research to determine the temperature mode of a fire in different zones of the cable tunnel

4. 1. Tools for conducting the experiment

According to the proposed scheme, a fragment of the fixed section of a cable tunnel that covers the source of ignition is considered. It is taken into consideration that the air support displaces the flame to the open part of the cable tunnel fragment.

The physical-chemical properties of materials of the fire load samples in the cable tunnel were set in order to perform a computing experiment according to the characteristics of the cable being tested. The proposed parameters of the fire load, consisting of an electric cable of A category [1] in a cable tunnel, are given in Table 1.

Table 1

Cable parameters for a fire load in the cable tunnel

No. of entry	Non-metallic material	Cable section length, mm	Material weight, g	Material density, g/cm^3	Volume of a non-metallic material per 1 m of cable, dm^3
1	Casing	1,000	40.02	1.43	0.0280
2	Thread insulation	1,000	18.90	1.43	0.0132
Total volume of non-metallic materials per 1 m of cable					0.0412

Fig. 4 shows the physical appearance of cables in a special frame to form a bundle of A category based on [1].

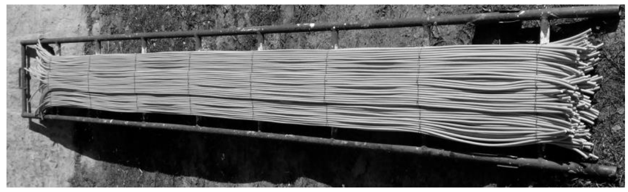


Fig. 4. Cable physical appearance in a special frame to form a bundle of A category based on [1]

The burning material of the electric cable is polyvinyl chloride (PVC). Material of the steel frame is the construction steel, grade St. 3.

To study the temperature regimes of a fire in a cable tunnel, a fragment of the cable tunnel is modeled. The inner space is 2,150×1,900×28,000 mm. The thickness of the enclosure of the cable tunnel is: side walls – 250 mm; top cover – 150 mm. In the space of a fragment of the cable tunnel, the brackets are used, in order to establish a fire load. Fig. 4 shows physical appearance of frames with a category A cable bundles in accordance with [1]. From one side, the cable tunnel is closed by a 1,900 mm reinforced concrete wall. From the other side, the cable tunnel is open. The side of the closed end of the cable tunnel has a special opening. It is used to receive the air that is pumped to create the head [7, 8]. Fig. 5 shows a structural diagram of the fragment of a cable tunnel.

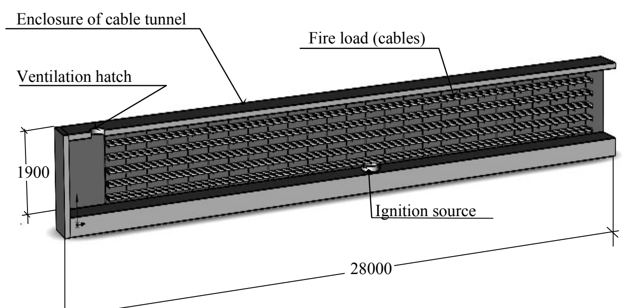


Fig. 5. Structural scheme of a cable tunnel fragment

Fig. 6 shows schematic of cables arrangement on the shelves, which are used as a fire load.

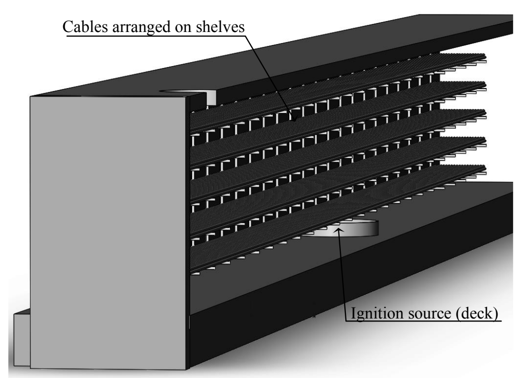


Fig. 6. Schematic of cables arrangement on shelves

According to the scheme in Fig. 6, cables are placed on the shelves. The shelves are made from a steel corner, 30×30 mm, based on [1].

A model fire of grade B [9] is used as the ignition source for cables. Fig. 7 shows the scheme of placement of the ignition source under the cables.

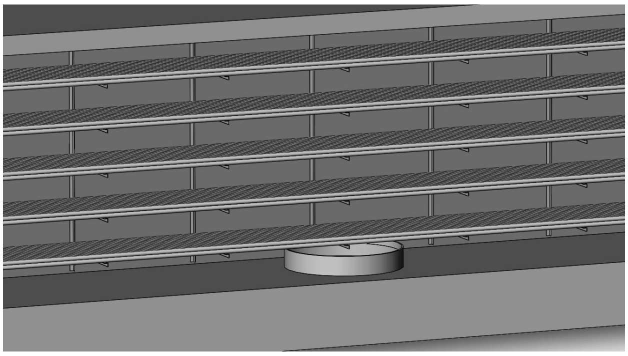


Fig. 7. Scheme of placement of ignition source under cables

Dimensions and main parameters of the ignition source are given in Table 2.

Table 2

Main technical parameters of the ignition source

Volume of liquid, l		Deck size for modeling the flame of fire
Water	Fuel	Burning area (approximate), m^2
7	14	0.36

Diesel fuel is used as fuel [5, 9].

The total volume of non-metallic materials per 1 m of cable (V) is calculated from formula:

$$V=\sum_{j=1}^{N}\frac{m_j}{\rho_j\cdot L}, \qquad (1)$$

where m_j is the mass of the j-th non-metallic material of the cable segment of length (L) not less than 300 mm, g; ρ_j is the density of the j-th non-metallic material of the cable segment, g/cm^3; L is the length of cable segment to determine the volume of non-metallic cable materials, mm; N is the number of non-metallic cable materials.

The number of segments of the electric cable in a bundle of A grade cables, based on [1], is calculated from formula:

$$n=\frac{V_A}{V}=\frac{7{,}0}{0{,}0412}\approx 169{,}89=170, \qquad (2)$$

where V_A is the normalized volume of non-metallic materials for a bundle of A grade, dm^3/m.

Thus, the experimental equipment includes:

– an actual segment of the cable tunnel;

– ventilation equipment for creating the air head in the interior space;

– fire load in the form of cables in a special frame to form a bundle of grade A based on [1];

– a cable ignition source in the form of a model fire of grade B;

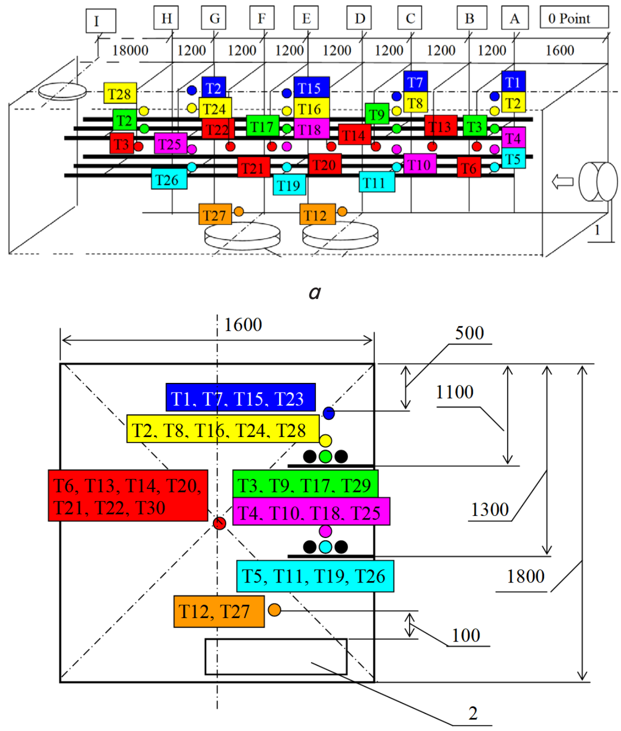
– control and measurement instruments;

– communication-control system for reading data from the sensors of control over parameters, which are measured in the process of experiments;

– means for activating the source of ignition;

– means for extinguishing a flame in the internal space of the fragment of a cable tunnel.

Control and measurement instruments are located in the zone of the developed fire (Fig. 6). We use, as temperature sensors, chromel-alumel thermocouples of type TXA. Using the control infrastructure and a personal computer, we identify temperature data from the thermocouples. The measurement error of thermocouples is ±1 °C (Fig. 8) [6].



a

b

- Thermocouples T1, T7, T15, T23 at a distance of 500 mm from the ceiling in the planes A, C, E, G
- Thermocouples T2, T8, T16, T24, T28 near the surface of the upper row of cables in planes A, C, E, G, H
- Thermocouples T3, T9, T17, T29 inside the upper row of cables in planes A, C, E, G, H
- Thermocouples T4, T10, T18, T25 near the surface of low cable row in planes A, C, E, G
- Thermocouples T5, T11, T19, T26 inside the surface of low cable row in planes A, C, E, G
- Thermocouples T6, T13, T14, T20, T21, T22, T30 in geometric center of a tunnel in planes A, B, C, D, E, F, G, H
- Thermocouples T12, T27 above the ignition sources at a distance of 100 mm in planes D, F

c

Fig. 8. Schematic of thermocouples arrangement in a cable tunnel. Row 1 of cable bundles less than 796 kg – above 791 kg; row 2 of cable bundles less than 864 kg – above 861 kg: *a* – view along the length of the tunnel, *b* – view of the cross section of the tunnel, *c* – thermocouple identification

In order to study the development of a fire in the cable tunnel in detail, we used video recording and photography. Photography is for registering the initial state of the cable tunnel, a fire load, the source of ignition, and the state of these objects after the experiment. Video recording is performed throughout the duration of the experiment.

Actual photographs of the fire load are shown in Fig. 9.

Table 3

Measurement tools

No. of entry	Name of equipment or device	Batch number	Measure-ment range	Error of measure-ment
1	Measuring ruler	–	from 0 mm to 1,000 mm	±1 mm
2	Stopwatch COC pr-2b-2-000	3401	from 0 sec to 60 sec, from 0 sec to 60 min	$\pm\left(\frac{0,4}{60}\cdot\tau\right)$ $\pm\left(0,4+\frac{1,5}{3540}\cdot(\tau-60)\right)$
3	Aspiration psychrome-ter MV-4M	14689	from 10 % to 100 % from – 10 °C to 50 °C	±4 % ±0.2 °C
4	Calipers SchC-1	3339340	from 0 mm to 125 mm	±0.1 mm
5	Barome-ter-aneroid M67	797	from 600 mm Hg to 800 mm Hg	±1 mm Hg
7	Anemome-ter ASO-3	12952	from 0.3 m/sec to 5 m/sec	±(0.1+0.05V) m/sec
8	Scale MW-1200	990208057	from 0 kg to 1.2 kg	±0.05 g

a

b

Fig. 9. Photographs of cables in the tunnel before the start of the experiment: *a* — at a distance of 3 m from the place of the air head, *b* — at a distance of 10 m from the place of air head

Fig. 9 clearly demonstrates that the cables were assembled into bundles. The length of the bundle was 11 m. The cables were laid on metal corners. The enclosure of the cable tunnel is made from the composite reinforced concrete structures.

4. 2. Procedure for conducting the experiment in a cable tunnel

The experiment on the development of a fire in a cable tunnel is conducted based on the following procedures:

1. Installation of thermocouples in the space of the control section of the fragment of the cable tunnel [7, 8].
2. Installation of a cable fire load in special frames according to Fig. 7. The test sample is as follows: cable bundles of grade A in line with GOST 12176-89. Row 1 from the deck of the ignition source is formed from the cable segments of brand AVBbSHb, 3×150+95 mm^2 [1].
3. Installation of the cable segments in a section of the cable tunnel.
4. Installation of the ignition source according to the scheme in Fig. 8.

Parameters of the ignition sources:
– height of the side is 200 mm;
– diameter of the deck is 750 mm;
– diesel fuel: 30 l per each;
– duration of flame application to samples – 30 min. [5, 9].

5. Photographic registration of the tunnel, ready for the experiment.
6. Initiation of fuel combustion in the source of ignition and the beginning of the experiment with a video recording and temperature control per every 1 min.
7. Creating the air head [7, 8] with the help of a smoke pump. The rate of air flow in planes (Fig. 8):
– in the plane of point 0 is equal to 9.42 m/s;
– in plane *A* is equal to 2.84 m/s;
– in plane *D* is equal to 0.26 m/s;
– in plane *G* is equal to 0.15 m/s;
– in the opening of the tunnel in plane *I* is equal to 0.59 m/s.
8. End of the experiment by using the means of fire extinguishing.
9. Photographic registration of the results of the experiment in a zone of the fire load damaged by the fire.
10. Conducting necessary measurements of the damaged zones.

5. Results of full-time experiment to model a fire in a cable tunnel

We conducted experimental research at the testing ground of the Ukrainian Research Institute of Civil Protection (Kyiv), in line with the procedure described above. To correlate the results, 2 experiments were performed. Duration of each of them was 30 minutes. In the course of the field experiment, we observed a heavy smoke due to the combustion of polymeric insulation materials of the cables.

Fig. 10 shows physical appearance of the cable tunnel in the process of experimental study.

Fig. 10. Photograph of the cable tunnel in the course of the experiment

Fig. 11 shows physical appearance of cables in the tunnel after finishing the experiment.

Fig. 11. Photographs of cables in the tunnel after finishing the experiment

Approximated results of thermocouple readings (Fig. 8) are shown in Fig. 12.

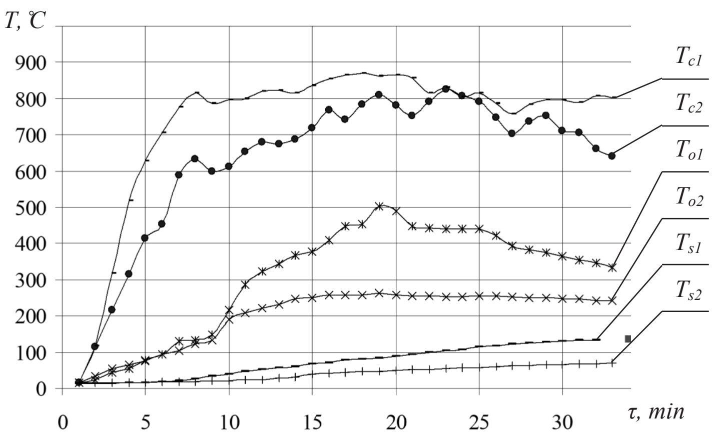


Fig. 12. The mean temperature in the 3 zones of the cable tunnel: T_{c1} – in the upper part of the tunnel in the zone of a fire center; T_{c2} – in the lower part of the tunnel in the zone of a fire center; T_{o1} – in the upper part of a tunnel in the zone between a fire center and the opening for the discharge of combustion products; T_{o2} – in the lower part of the tunnel in the zone between a fire center and the opening for the discharge of combustion products; T_{s1} – in the upper part of the tunnel in the zone between a fire center and the place of air head; T_{s2} – in the lower part of the tunnel in the zone between a fire center and the place of air head

The derived temperature-time curves have an extremum (Fig. 12). According to experimental studies, the time of fire is divided into 3 stages. The first stage is the growth of temperature (to minute 8). The second stage is the burning of a fire load at the highest temperature (minutes 8–33). The third stage is the tendency to burn out in a specific fire zone (after minute 33). A decrease in temperature occurs after burning out a fire load in the zone of the thermocouple arrangement. This agrees with the theoretical data known from papers [3–4, 6]. Two identical experiments were conducted and verified to validate their adequacy. None of the calculated adequacy criteria exceeded the critical (tabular) values.

6. Discussion of results of the study into determining the temperature mode of a fire in a cable tunnel

When analyzing the obtained temperature charts in a cable tunnel, it becomes possible to state that the highest temperature is observed in the zone of the fire center near the cables, 700–900 °C, this a temperature range, it depends on the location of the place of control. Thermal energy propagates more intensively towards the opening for the discharge of combustion products. The temperature in this zone is within the range of 250–500 °C. In a zone between the fire center and the place of the air head, the temperature is within the range of 80–150 °C (Fig. 10).

Thus, to test construction structures for fire resistance, it is necessary to choose the most severe temperature mode. The maximum temperature in the combustion zone is achieved at the eighth minute of the actual experiment. This temperature, in accordance with the standard temperature mode [1], is achieved not earlier than in 40 minutes. One can state that the standard temperature regime of a fire is not adequate for testing the fire resistance of construction structures of cable tunnels. This does not differ from practical data known from papers [5, 8, 10].

The conducted research is original. At present, in Ukraine and around the world, the preference is given to mathematical modeling. In contrast, the experiment reported in this paper makes it possible to verify the estimated data.

The benefits of this study imply that the obtained data are the basis for the verification of computer models of fire in cable tunnels and determining the temperature mode of a fire for testing construction structures of cable tunnels for fire resistance. Further work could address creating a computer model of the cable tunnel in which the experiment was conducted. Initial data and boundary conditions must match the actual experiment. Computer simulation is chosen as a tool that has advantages over the field research in terms of environmental friendliness, efficiency, and effectiveness. In case the adequacy of computer simulation results is confirmed by verification data, it would be possible to investigate the temperature regimes of fires in cable tunnels with different dimensions at different fire loads.

7. Conclusions

1. This paper substantiates the procedure for studying experimentally the temperature mode of a fire in a cable tunnel with a rectangular cross-section with the predefined fire load and structural features. The length of the tunnel was 28 m, the cross-sectional area was 2.88 m. The fire load was created using the bundles of electric cables of A grade [1].

2. Experimental studies have determined the temperature regimes of a fire in different zones of the cable tunnel according to the proposed procedure. The highest temperature is observed directly in the combustion zone. The direction of air flow in a tunnel significantly influences the change in the combustion zone. In the zone of the fire center near the cables, it is 700–900 °C; between the zone of a fire center and the opening for the discharge of combustion

products, it is within 250–500 °C. In the zone between a fire center and the place of the air head, the temperature reaches 80–150 °C (Fig. 10).

3. We analyzed results of the conducted experiment for determining the temperature mode of a fire in different zones of the cable tunnel according to the proposed procedure. The temperature in the combustion zone increases by 150 % faster compared to the standard temperature regime of a fire. This testifies to the necessity of making tests of construction structures of cable tunnels for fire resistance under the temperature mode, which differs from the standard one. The data obtained are the basis for the verification of computer models of fires in cable tunnels and for determining the temperature mode of a fire when testing construction structures of cable tunnels for fire resistance.

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