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Determining the Dependence of Fire Parameters in a Cable Tunnel on its Characteristics

Oleksandr Nuianzin[1,6], Stanislav Sidnei[2], Petro Zayika[3], Svitlana Fedchenko[4], Bogdan Alimov[5]

[1]Science department of Cherkasy Institute of Fire Safety named after Chernobyl Heroes, National University of Civil Defence of Ukraine, 94 Chernyshevska Str. Kharkiv 61023, Ukraine
[2]Department of Safety of Construction Facilities and Labor Protection of Cherkasy Institute of Fire Safety named after Chernobyl Heroes, National University of Civil Defence of Ukraine, 94 Chernyshevska Str. Kharkiv 61023, Ukraine
[3]Department of Fire Prevention Work of Cherkasy Institute of Fire Safety named after Chernobyl Heroes, National University of Civil Defence of Ukraine, 94 Chernyshevska Str. Kharkiv 61023, Ukraine
[4]Post-graduate department of Cherkasy Institute of Fire Safety named after Chernobyl Heroes, National University of Civil Defence of Ukraine, 94 Chernyshevska Str. Kharkiv 61023, Ukraine
[5] Department of Substances and Materials of the Scientific and Testing Center, Institute of Public Administration and Research on Civil Defence, 18 Rybalska Str. Kyiv, 01001, Ukraine

[6]alexandrnuyanzin@gmail.com

Abstract. In order to study the parameters of fires in cable tunnels both experimental methods and numerical simulations are used. The purpose of this article was to determine the dependences of the maximum temperature inside the cable tunnel during a fire, the duration of the fire in a local area of the cable tunnel and the time of reaching the maximum temperature inside the cable tunnel during a fire on its characteristics (cross-sectional area of the cable tunnel, fire load) inside the tunnel. In the course of the research a complete factorial experiment was developed and conducted. According to its results, the required regressions were obtained. Thus, there are reasons to believe that the obtained results of the study are the basis for the creation of mathematical models that describe fires in cable tunnels and can be used for engineering assessment of fire resistance of cable tunnel structures. In addition, computer simulation of heat and mass transfer in case of fire in cable tunnels was further developed.

1. Introduction

Despite significant progress in solving the problem of improving the fire safety of cable products, there are now many problematic issues in the field of safety of cable structures.

Combustion of electric cables is accompanied by the release of a significant amount of heat, which is determined by the specific heat of combustion of insulation materials, protective sheaths of cables and the mass of these materials contained in a unit length of cable. Experiments on combustion of cable streams in a cable tunnel have shown that the temperature in the combustion zone of cables with PE insulation or with paper impregnated insulation reaches 1000-1200 °C [1]. At the same time, there is a significant amount of black smoke and other gaseous products, which leads to reduced visibility and complicates the actions of fire fighters and evacuation personnel.

2. Analysis of recent achievements and publications

In order to study the parameters of fires in cable tunnels both experimental methods [1-4] and numerical simulations [5-10] are used.

In the work [2], changes in the temperature during the propagation of flue gases during a fire in a cable tunnel are considered. However, this paper describes only the initial stage of the fire. The temperature during the entire time of the fire was not determined. In the work [3], field tests were conducted in a communal tunnel. A fire during the spillage of flammable liquid was simulated. This work can be the basis for the study of violations of the modes of operation of cables with oil filling. The work [4] describes the temperature distributions in tunnels with different ventilation conditions during full-scale experiments. The conducted study enabled analyzing the influence of air velocity on the specifics of fire development.

In the work [5] the causes of fires in tunnels were analyzed by numerical simulation. However, computational experiments on fire simulation were not performed. The work [6] is devoted to the analysis of the parameters of the burnout rate of PVC cable insulation. The linear velocity of fire propagation for different cable laying types was mathematically calculated. In the work [7], the temperature regime of the fire in the cable tunnel was determined depending on its shape, size and fire load. This made it possible to determine the parameters that most significantly affect the temperature of the fire inside the tunnel. The study [8] shows that the temperature in the real fire reached 800-900 °C. Based on this information, the type of thermocouples was selected to measure temperatures during the experiment. In the work [9] it was found that the width of the tunnel has little effect on the rate of burnout of the fire load. The influence of two ventilation systems on the temperature distribution in a small cross-section tunnel model was investigated in the work [10]. This allows us to conclude that the aerodynamics in the space of the tunnel affects the temperature of the fire.

Based on the above, conducting additional study is required to establish the mathematical dependences of the temperature of the fire in the tunnel on its parameters.

3. Purpose

To determine the dependence of the maximum temperature inside the cable tunnel during a fire, the duration of the fire in a local area of the cable tunnel and the time of reaching the maximum temperature inside the cable tunnel during a fire on its characteristics (cross-sectional area of the cable tunnel, fire load) inside the tunnel.

4. Method

The scheme of the tunnel with geometric parameters that have changed is shown in figure 1.

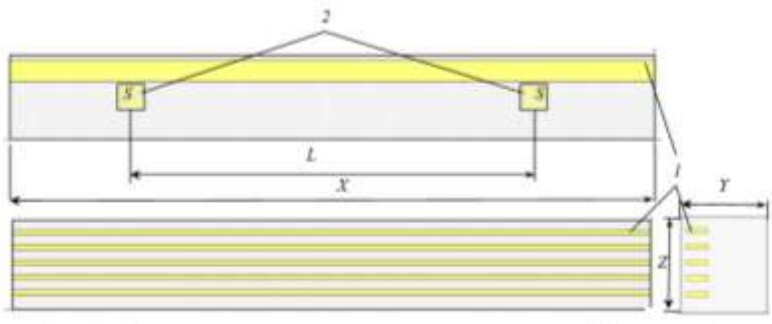

Figure 1. The scheme of the tunnel with geometric parameters that have changed: 1 – Model of cable lines; 2 – Model of ventilation and inspection hatches area S, m^2; X, Y, Z, L – the distance between the holes.

Table 1. Thermophysical characteristics of materials and conditions of convection and radiation heat exchange.

Characteristic	Units of measurement	Value
Thermal conductivity coefficient	W / (m·K)	0.159
Specific heat capacity	J/(kg·K)	1320
Density	kg/m^3	1400
Degree of blackness	-	0.85
Thermal conductivity coefficient	W/(m·K)	390
Specific heat capacity	J/(kg·K)	420
Density	kg/m^3	8900
Degree of blackness	-	0.7
Stefan–Boltzmann constant	W/(m^2·K^4)	$5.67 \cdot 10^{-8}$

Theoretical studies were carried out on the basis of systems of differential equations of continuous media of the type of Navier-Stokes equations and Fourier thermal conductivity equations. To solve the equations in the work, the method of finite or boundary elements, non-relation methods, Galerkin method, and optimization methods are used. Computational experiments were carried out in the Fire Dynamics Simulator (FDS).

According to the calculation scheme of the mathematical model of the tunnel (fig. 1) in order to conduct a full analysis of the parameters that affect the temperature of the fire, the following parameters varied:

- Fire load: cable lines were modelled on two and one side; the number of cable lines was from 1 to 10; the insulation material of cables and wire cores changed. Due to this, the rate of heat output from 1 m^2 of cable lines varied (table 1).
- Geometric parameters of the cable tunnel: varied as the cross-sectional area, using a combination of parameters Y and Z, the general parameter – the cross-sectional area of the cable tunnel (table 1).
- Aerodynamic parameters: the horizontal component of air velocity was set as a parameter that characterizes the excess or lack of oxidant and affects the intensity of development and spread of fire.

To take into account the specific features of the heterogeneity of the material of which the cable lines are made, as well as the conditions of conductive heat transfer (thermal conductivity in the solid material), cable lines are given as a multi-component material.

5. Consideration on methods and results

To build a mathematical model of the temperature of a fire in a cable tunnel, a complete factor computational experiment should be conducted. There are three independent factors – the cross-sectional area of the cable tunnel, fire load, as well as the horizontal component of air movement inside the tunnel. In the table 2 shows the parameter intervals in the experiment, which are selected as factors.

Table 2. Intervals of variation of factors in a computational experiment.

Factor 1. Fire load in terms of 1 m^2 of cable tunnel, mJ/m^2 (hereinafter – x_1)	Factor 2. Cross-sectional area of the cable tunnel, m^2 (hereinafter – x_2)	Factor 3. The horizontal component of air velocity, m/s (hereinafter – x_3)
224.7–2247	2.88–4.4	0–5

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

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_1x_3 + b_6x_2x_3 + b_7x_1x_2x_3 \quad (1)$$

where b_0, b_1, b_2, b_3, b_4, b_5, b_6, b_7 – regression coefficients.

To construct a regression according to formula (1) it is necessary to conduct 8 numerical experiments according to the accepted planning matrix, which is written in the form of the tab. 3.

Table 3. Typical matrix for planning a complete factorial experiment to determine the temperature of a fire in a tunnel.

No.	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	+	+	+	+	+	+	+
2	-	+	+	-	-	+	-
3	+	-	+	-	+	-	-
4	-	-	+	+	-	-	+
5	+	+	-	+	-	-	-
6	-	+	-	-	+	-	+
7	+	-	-	-	-	+	+
8	-	-	-	-	-	-	-

To determine the initial data of the complete factorial experiment, 8 computer models were calculated [7] in which the parameters of the maximum and minimum intervals in different combinations were laid down. The results of experiments are shown in figure 2.

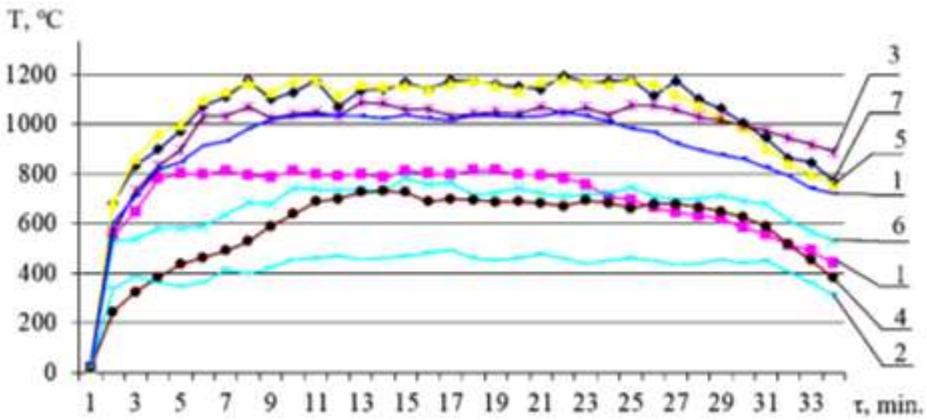

Figure 2. Summary graph of calculation of 8 computer models, the data of which are the input for a complete factorial experiment: 1–8 – experiment number according to Table 3.

The graphs in figure 2 show that the temperature regime of the fire in cable tunnels with different sizes, aerodynamic parameters and fire load, as well as the dependence of the temperature regime of the fire on these parameters are determined. With 10 laid cable lines and fire load 2247 MJ/m^2 the maximum temperature exceeded 1200℃, when there is 1 line and fire load 224.7 MJ/m^2 – 500℃.

With the smallest cross-sectional area of the tunnel and a decrease in air flow velocities, the temperature inside increases 50% faster than the average parameters. In addition, excess fresh air reduces the combustion temperature by 50–70℃, although it contributes to the faster spread of fire along the cable lines.

Further, in figures 3 – 5 the results of a complete factorial experiment to determine the temperature of the fire in the tunnel are presented.

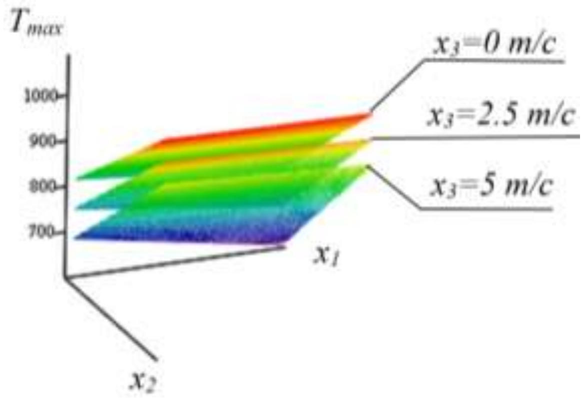

Figure 3. Maximum temperature inside the cable tunnel during a fire (T_{max}).

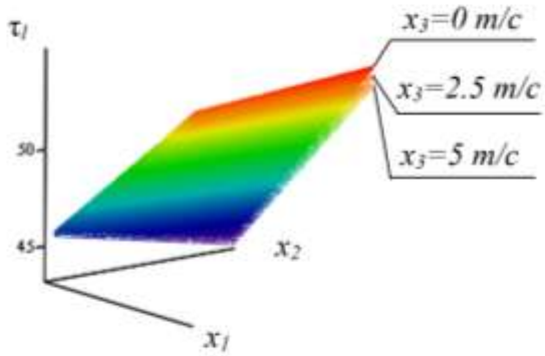

Figure 4. The duration of the fire in a certain area of the cable tunnel (τ_l).

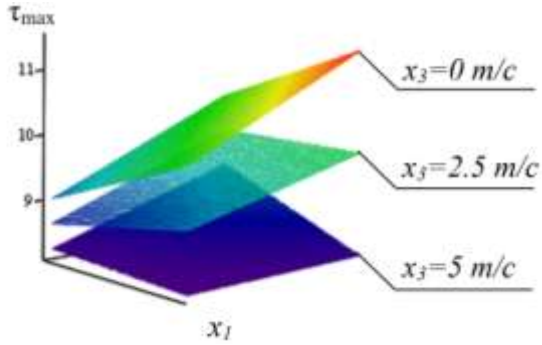

Figure 5. Time to reach maximum temperature inside the cable tunnel during a fire (τ_{max}).

According to the results of a complete factorial experiment, the regression of the maximum temperature inside the cable tunnel during a fire was obtained (T_{max}), duration of the fire in a certain local area of the cable tunnel (τ_l) and the time to reach the maximum temperature inside the cable tunnel during a fire (τ_{max}) are represented by expressions (2) – (4):

$$T_{max} = 0.097 \cdot x_1 - 27.92 \cdot x_2 - 11.391 \cdot x_3 + 0.01 \cdot x_1 \cdot x_2 - 0.001 \cdot x_1 \cdot x_3 - 5.279 \cdot x_2 \cdot x_3 + 0.001 \cdot x_1 \cdot x_2 \cdot x_3 + 870.594 \quad (2)$$

$$\tau_l = 0.002 \cdot x_1 - 1.439 \cdot x_2 + 0.0125 \cdot x_3 + 0.001 \cdot x_1 \cdot x_2 - 0.016 \cdot x_2 \cdot x_3 + 48.969 \quad (3)$$

$$\tau_{max} = 0.001 \cdot x_1 + 0.596 \cdot x_2 + 0.05625 \cdot x_3 + 0.025 \cdot x_2 \cdot x_3 + 6.55 \quad (4)$$

After obtaining regression dependences, it became possible to create a mathematical model of the behaviour of enclosing building structures of cable tunnels and to estimate their limit of fire resistance at different fire temperatures.

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6. Conclusions

1. A complete factorial experiment was developed and conducted. According to its results, the regression of the maximum temperature inside the 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 are represented by expressions (2) – (4).

2. The temperature regime of the fire in cable tunnels with different sizes, aerodynamic parameters and fire load, as well as the dependence of the temperature regime of the fire on these parameters are determined. With 10 laid cable lines and fire load 2247 MJ/m^2 the maximum temperature exceeded 1200℃, when there is 1 line and fire load 224.7 MJ/m^2 – 500℃.

3. With the smallest cross-sectional area of the tunnel and a decrease in air flow velocities, the temperature inside increases 50% faster than the average parameters. In addition, excess fresh air reduces the combustion temperature by 50–70℃, although it contributes to the faster spread of fire along the cable lines.

4. It is expedient to direct further work on research of fire resistance of enclosing building designs of cable tunnels at the temperature modes of fire defined in this section of work, using regression dependences (2) – (4).

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