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DETERMINING THE DYNAMIC CHARACTERISTICS OF A CLASS B FIRE IN THE CASE OF EXTINGUISHING BY WATER SPRAY

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The object of this study is a class B fire, which is extinguished with sprayed water. The subject of the study is the characteristics of class B fires when they are extinguished with sprayed water. Diffusion burning of a flammable liquid is considered as such a fire, and its extinguishing is carried out by cooling the flame. Heat and oxygen balance equations are used to build a mathematical model describing the fire extinguishing process. The components of the heat balance equation are the power of heat during heat release due to the chemical reaction of liquid combustion and the power of heat dissipated to the environment. The second component takes into account heat removal due to radiation, convection, and evaporation. The component of removed heat due to evaporation takes into account the Sreznevsky constant. The mathematical model that describes the process of extinguishing a class B fire is built in the class of models belonging to differential equations with constant coefficients. Analytical expressions were obtained for these static and dynamic coefficients, which include thermophysical, kinematic, and geometric parameters of the flame and fire extinguishing agent. To determine these characteristics, the constructed mathematical fire model was transformed using the integral Laplace transform. The dynamic characteristics of the fire were obtained in the time domain – the transient function of the fire, and in the frequency domain – the amplitude-frequency and phase-frequency characteristics of the fire. It is shown that the parameters of these dynamic characteristics should be determined experimentally. Experimental methods for determining parameters of dynamic fire characteristics have been devised. The presence of dynamic characteristics of class B fire makes it possible to spread the proven methods of the theory of control systems to design effective fire extinguishing systems

Keywords: class B fire, sprayed water, dynamic characteristics, characteristics parameters

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1. Introduction

Sprayed water is a universal tool for localizing and eliminating fires of various types. It can be used to create water curtains [1] when protecting objects from the thermal effects of fire. Sprayed water is a very effective extinguishing agent, in particular, when extinguishing class B fires [2]. When water evaporates, its volume increases 1700 times, as a result of which the components of the combustible system are diluted with non-combustible water vapor. One of the ways to improve the effective use of water as a fire extinguishing agent is its application in mobile automatic or automated fire extinguishing systems. An example is the use of the mobile device "Colossus" by Shark Robotics (France) when extinguishing a fire in the Notre-Dame Cathedral (April 2019) [3]. The further development of mobile fire extinguishing means is the design of a new type of fire extinguishing system based on segways [4]. Such fire extinguishing systems include a human operator, as a result of which there is a need to match the characteristics of the human operator with the characteristics of the system itself [5]. This, in turn, requires the characteristics of the control object of such a system, which is a fire. In this regard, there is an urgent need to determine the dynamic characteristics of a fire as an object of fire extinguishing system management.

2. Literature review and problem statement

In [6], the transient mass rates of combustion are studied experimentally on the examples of diesel fuel and heptane for different modes of supply of sprayed water. The research was conducted with a vertical supply of sprayed water to the combustion chamber. At the same time, the properties of this type of fire were not determined but only one of the quality indicators of the extinguishing process was defined – fire extinguishing time. In [7], the characteristics of sprayed water were experimentally investigated when using solid-cone simplex nozzles with an X-type vortex insert. The distribution of the number of water droplets – Rosin-Ramler distribution, their average diameter (SMD), the average spraying speed, as well as the mass or volume density of the sprayed water flow (supply intensity) were determined. The research was carried out with a vertical supply of sprayed water for heights of (0.55÷1.75) m. The injection pressure was (6÷10) bar. Research, as in [6], was conducted under conditions that are typical for stationary fire extinguishing systems. At the same time, attention was focused on obtaining estimates of local indicators of the quality of the process of extinguishing burning liquids. Similar results are given in [8]. In addition, in [8] such indicators of the process of extinguishing a class B fire as extinguishing time, the presence of wind, its speed, and the amount of water consumed were determined. There is no information on determining the dynamic properties of fire. In [9], the influence of the temperature of sprayed water on the process of extinguishing diesel and heptane fires was determined. Fire extinguishing efficiency was evaluated using such an indicator as extinguishing time. Time estimates for extinguishing class B fires with sprayed water were determined experimentally. The reduction in the extinguishing time of sprayed water fires from 40 s to 10 s at a water temperature of 80 °C compared to the extinguishing time of sprayed water at a temperature of 20 °C is explained on a qualitative level. It should also be noted that the extinguishing time does not fully characterize the fire extinguishing process but is an indicator of the speed of this process. Sometimes, in addition to the extinguishing time, the consumption of extinguishing agent is used to evaluate the effectiveness of fire extinguishing [10]. In the conducted experiments, the extinguishing time was 262 seconds with a water consumption of 5.3 liters. But such studies are conducted only experimentally. In [11], data are given regarding the created experimental base for conducting research on extinguishing the flame of a class B fire with sprayed water. At this experimental base, studies were conducted on the qualitative analysis of the interaction between sprayed water and fire and received recommendations for the rationalization of its use. Despite the powerful capabilities of the experimental setup, the dynamic characteristics of fires when they are extinguished with sprayed water remained outside the scope of research. The presence of such dynamic characteristics of fires opens up opportunities for obtaining a priori estimates of their quality indicators, in particular, the extinguishing time, the critical value of the intensity of the supply of sprayed water, etc. In [12], a series of experiments was conducted, the results of which were used to build a theoretical model. Such a theoretical model was built after a quantitative study of the change in the flame structure of a class B fire during its expansion. But this model belongs to the class of local models, which describes only one of the properties of this type of fire. In [13] it is noted that some additives added to sprayed water can increase the effectiveness of fire extinguishing by breaking the flame reaction chains. Such additives include CO_2-based additives, which help reduce the height of the flame when burning gasoline. As in most cases of extinguishing class B fires with water spray, these studies are experimental and local in nature. An example of the same approach is research, the results of which are given in [14], where the influence of the slope on the nature of oil combustion was studied. In contrast to [13], in [14] empirical analytical dependences were obtained, which in the first approximation describe this process. But these analytical dependences can be used only for burning oil. In this connection, there is a need to conduct research for a wide range of fuel types. Such studies were conducted by the joint efforts of FM Global and Sandia National Laboratories [15]. Research was conducted for hydrocarbons, alcohols, and their mixtures in pools with a diameter of (0.1÷2.0) m. The research determined a correlation that can be applied to a wide range of fuel types and fire sizes. However, the parameters of the proposed correlations are not universal as they mostly depend on the fuel and require a priori knowledge of the burning rate of the liquid. One of the directions related to the improvement of efficiency in the study of fires is the use of CFD computational fluid dynamics [16]. CFD can provide more detailed simulation of both single (SPF) and multiple (MPF) fire scenarios. In [16], the corresponding coding and simulation were performed using Fire Dynamic Simulator (FDS) using Pyrosium (preprocessor) and Smokeview (postprocessor). The effect of water spray droplet size (DSD) on fire extinguishing efficiency has been thoroughly investigated. The research is of a local nature and essentially aimed at forming recommendations when choosing the type and characteristics of sprinklers of the fire extinguishing system. It should be noted that the complexity of these computational approaches prevents their use in practice. As a rule, computational procedures of this type are used under laboratory conditions, and when solving engineering problems, empirical correlations are used. Such computational procedures are aimed at detecting physical phenomena that occur when extinguishing fires and are not aimed at creating samples of automatic fire extinguishing systems. This is confirmed by the example given in [17], which presents studies of the effect of wind on the coefficient of mass loss per unit area (MLRPUA) during a heptane fire. For different scales of heptane fires, simulations were carried out using FDS in a wide range of Froude numbers – from 0 to 2.5. The range of wind speed change was (0÷5) m/s. It is shown that MLRPUA varies within ±30 % in a wide range of wind speeds. With the use of CFD simulations, the physics of scaling effects in class B fires was determined. The research results do not contain data on their use for solving engineering problems. In [18], a physical phenomenon related to the behavior of water droplets collected in local areas of the flame before their complete evaporation is investigated. It should be noted that the coordinates of such local areas depend significantly on the flame parameters. The obtained results refer to the quality indicators of class B fires when they are extinguished with sprayed water and are aimed at improving the quality of CFD simulation. An example of the use of analytical methods for obtaining a mathematical description of the process of extinguishing a class B fire with sprayed water is given in [2]. The method is based on the use of a non-stationary heat conduction equation, which is matched by an operator equation using the integral Laplace transform. This approach makes it possible to obtain a dynamic fire characteristic in the time domain, but the use of the fire transfer function obtained in this way is problematic in the construction of automatic fire extinguishing systems. This problem is related to the irrationality of the transfer function of fire. One of the ways out of this situation is the transition to a small-rational form of representation of the transfer function. In [19], this approach was implemented using the minimax approximation using the Remez algorithm. This made it possible to obtain the dynamic characteristics of a class B fire in the time domain in the form of a superposition of several transient functions of inertial links. But it should be noted that in both cases, the models and dynamic characteristics of class B fires when extinguished with sprayed water were obtained for combustible liquids, which are extinguished by cooling the burning surface. Such mathematical models and dynamic characteristics do not apply to fire extinguishing processes that occur when flammable liquids are burning.

It follows from the above review:

– the vast majority of research into the processes of extinguishing class B fires with sprayed water is of an experimental nature;

– these studies are aimed at obtaining empirical functional dependences for quality indicators of the fire extinguishing process, which are usually used as fire extinguishing time, water consumption or the size of water droplets;

– the use of computational procedures is mainly reduced to the detection of physical phenomena that occur during fire extinguishing, as well as to improve the quality of CFD simulations;

– analytical methods are used least of all to construct a mathematical description of the processes of extinguishing class B fires with sprayed water.

All this gives reason to assert that it is expedient to conduct research aimed at determining the dynamic characteristics of class B fires when they are extinguished with sprayed water, which fully characterize the dynamic properties of such fires.

3. The aim and objectives of the study

The purpose of this study is to determine the dynamic characteristics in the time and frequency domains for a class B fire extinguished by sprayed water. In practice, the presence of such characteristics opens up opportunities for the use of proven methods of automatic control theory when creating automatic fire extinguishing systems of increased efficiency.

To achieve this goal, the following tasks must be solved:

– to build a mathematical model in the class of differential equations, which describes the process of extinguishing a class B fire using sprayed water and is fundamental for determining the dynamic characteristics of a fire of this type;

– to provide a mathematical description for the dynamic characteristics of class B fires when they are extinguished with sprayed water in the time and frequency domains, devise methods for determining their integral parameters and provide recommendations for their selection.

4. The study materials and methods

The object of our study is a class B fire, which is extinguished with sprayed water. The subject of the study is the characteristics of a class B fire when it is extinguished with sprayed water. The main research hypothesis assumes that extinguishing a class B fire with sprayed water is carried out due to the cooling of the flame.

The main assumptions are:

– a class B fire is caused by the burning of a flammable liquid;

– the combustion mode is diffusion;

– sprayed water, which is supplied to the flame, completely evaporates in it.

Flammable liquids were considered as materials. Such liquids include, for example, acetone, gasoline, hexane, benzene, toluene, propanol, etc. A test signal in the form of the Heaviside function is used to determine the dynamic characteristics of a class B fire in the time domain. When determining the dynamic characteristics of a class B fire, a test signal in the form of a harmonic function of time is used. When building a mathematical model that describes the process of extinguishing a class B fire with sprayed water, thermodynamic methods, in particular the heat balance equation, were used. To construct a mathematical description of the dynamic characteristics of fires of this type, the properties of the integral Laplace transform and the methods of the theory of the function of a complex variable were used. The substantiation of experimental methods for determining the parameters of dynamic fire characteristics is carried out in the time and frequency domains using similar expressions for such fire characteristics.

5. Results of determining the dynamic characteristics of a class B fire when it is extinguished with sprayed water

5. 1. Construction of a mathematical model of the B class fire extinguishing process

The process of extinguishing flammable liquids with sprayed water is determined by the cooling of the flame due to the evaporation of water droplets. For a cylindrical flame with volume V, area S, and height H, there is a thermal balance formalized by the differential equation:

$$\frac{dT}{dt}=\frac{q_p-q_v}{\rho c_p V}, \tag{1}$$

where T is the flame temperature; ρ, c_p – flame density and heat capacity, respectively; q_p – heat power during heat release due to the chemical reaction of liquid combustion; q_v – power of heat that is dissipated to the environment.

For q_p, the following expression holds:

$$q_p=VQw, \tag{2}$$

where Q is the thermal effect of combustion; w is the rate of chemical reaction.

To determine the speed w, the oxygen balance is used, which is formalized by the expression:

$$kC_0SH=\beta\left(C-C_0\right)S, \tag{3}$$

where C_0, C – oxygen concentration in the volume of the flame and in the environment, respectively; β – mass transfer coefficient;

$$k=k_0\exp\left(-\frac{E}{RT}\right); \tag{4}$$

k_0 is the chemical reaction rate constant; E – activation energy; R is a universal gas constant.

Given:

$$w=kC_0, \tag{5}$$

then after combining expressions (3) and (5), the following will take place:

$$w = k\beta C\left(kH+\beta\right)^{-1}. \quad (6)$$

If we take into account that in the diffusion mode of combustion:

$$\beta\left(kH\right)^{-1} << 1, \quad (7)$$

then expression (6) given (4) will be transformed to the form:

$$w = \beta CH^{-1}\left[1-\beta\left(k_0 H\right)^{-1}\exp\left(\frac{E}{RT}\right)\right]. \quad (8)$$

For q_v:

$$q_v = \sum_{i=1}^{3} q_i, \quad (9)$$

where i=1, 2, 3 corresponds to the removal of heat to the environment by radiation, convection, and evaporation of water droplets, respectively.

The power q_1 is determined by the expression:

$$q_1 = \alpha_1 S\left(T-T_0\right), \quad (10)$$

where T_0 is the ambient temperature; α_1 is the heat transfer coefficient, which has the following expression:

$$\alpha_1 = \varepsilon\sigma\left(T_N+T_0\right)\left(T_N^2+T_0^2\right); \quad (11)$$

ε is the degree of blackness; σ is the Stefan-Boltzmann constant; T_N is the initial flame temperature.

The power q_2 has the expression:

$$q_2 = \alpha_2 S\left(T-T_0\right), \quad (12)$$

where α_2 – heat transfer coefficient, which is determined by:

$$\alpha_2 = Nu\lambda D^{-1}; \quad (13)$$

λ is the thermal conductivity coefficient of the flame; D is the diameter of the water drop; Nu is the Nusselt number, which is determined by the criterion equation:

$$Nu = 2+0.03\mathrm{Re}^{0.54}\mathrm{Pr}^{0.33}+0.35\mathrm{Re}^{0.53}\mathrm{Pr}^{0.36}; \quad (14)$$

Re, Pr are the Reynolds and Prandtl numbers, respectively.

For power q_3 we can write:

$$q_3 = rS\left[1-\left(DD_0^{-1}\right)^3\right]\gamma I, \quad (15)$$

where r is the heat of vaporization; D_0 is the initial diameter of the water drop; γ is the coefficient of water use; I is the intensity of flame irrigation with sprayed water.

According to Sreznevsky's law:

$$\frac{dD^2}{dt} = A = \mathrm{const}, \quad (16)$$

where A is the water evaporation constant, and also taking into account that the total evaporation time t_v of the sprayed water is related to the movement speed u of water droplets in the flame through the expression:

$$t_v = Hu^{-1}, \quad (17)$$

expression (15) will be transformed as follows:

$$q_3 = rS\left[1-\left[1-AH\left(uD_0^2\right)^{-1}\right]^{1.5}\right]\gamma I. \quad (18)$$

The Sreznevsky constant A is determined under the condition of heat balance for a drop of water that evaporates in a flame. For such a heat balance, the following holds:

$$S_v\alpha_2\left(T-T_v\right) = -S_v\rho_v r\frac{dD}{dt}, \quad (19)$$

where S_v is the surface area of the water drop; T_v, ρ_v are the temperature and density of the water drop.

If we set $Nu\approx2$, then after substituting (13) into (19), we can write:

$$\int_0^{t_v}\mathrm{d}t = \int_0^{D_0}\rho_v r\left[2\lambda\left(T-T_v\right)\right]^{-1}D\mathrm{d}D. \quad (20)$$

From the comparison of (16) and (20) at D=0, which corresponds to the complete evaporation of a drop of water, the expression for the constant A follows:

$$A = 4\lambda\left(T-T_v\right)\left(\rho_v r\right)^{-1}. \quad (21)$$

For hydrocarbon liquids, the flame temperature is $(1.5\div1.6)\cdot10^3$ K. Even at such temperatures, the temperature T_v of a drop of water does not reach its boiling point. This makes it possible to rewrite expression (21) in the form:

$$A = 4\lambda T_N\left(\rho_v r\right)^{-1}. \quad (22)$$

At $\lambda=2.2\cdot10^{-2}$ W·(m·K)$^{-1}$; $\rho_v=10^3$ kg·m^{-3}; $r=2.3\cdot10^6$ J·kg^{-1} we have:

$$A = 3.8\cdot10^{-11}T_N,\ \mathrm{m^2s^{-1}}.$$

Given the fact that for water:

$$AH\left(uD_0^2\right)^{-1} << 1, \quad (23)$$

then, after decomposition into a power series, expression (18) will take the form:

$$q_3 = 1.5AHrS\left(uD_0^2\right)^{-1}\gamma I. \quad (24)$$

The combination of expressions (1), (2), (8) to (10), (12), (24) taking into account condition (7) leads to a differential equation that describes the process of extinguishing the flame of a flammable liquid – class fire B with sprayed water:

$$\frac{dT}{dt} = \left[\beta QC-\alpha\left(T-T_0\right)\right]\left(\rho c_p H\right)^{-1} - -1.5Ar\left(uD_0^2\rho c_p\right)^{-1}\gamma I, \quad (25)$$

where $\alpha=\alpha_1+\alpha_2$ is the generalized heat transfer coefficient.

If I=0, then under the steady-state mode of the chemical reaction of combustion, the following relationship occurs:

$$\beta QC=\alpha(T_N-T_0), \qquad (26)$$

As a result, differential equation (25) takes the following form:

$$\tau\frac{d\theta}{dt}+\theta=BI; \qquad (27)$$

$$\theta=T_N-T; \qquad (28)$$

$$\tau=\rho c_p H\alpha^{-1}; \qquad (29)$$

$$B=1.5ArH\left(\alpha u D_0^2\right)^{-1}\gamma. \qquad (30)$$

For hydrocarbon liquids, the values of these parameters lie in the range τ=(20÷40) s; B=(0.05÷1.0) $m^2\cdot s\cdot K\cdot kg^{-1}$ (at u~1 m/s; D_0~10^{-3} m).

5. 2. Construction of a mathematical description for the dynamic characteristics of a class B fire

To determine the dynamic characteristics of class B fires when they are extinguished with sprayed water, we shall use the fire transfer function, which, according to differential equation (27), takes the form:

$$W(p)=B(\tau p+1)^{-1}, \qquad (31)$$

where p is a complex variable; B, τ are the transmission coefficient and the time constant, respectively.

Dynamic characteristics of fire in the time domain – the transition function is determined by:

$$I(t)=I\cdot 1(t), \qquad (32)$$

where I=const; $1(t)$ is the Heaviside function.

Under condition (32), the fire transition function has the description:

$$\theta(t)=L^{-1}\left[W(p)I(p)\right]=BI\left[1-\exp\left(-\frac{t}{\tau}\right)\right], \qquad (33)$$

where L^{-1} is the inverse Laplace transform operator; $I(p)=L[I(t)]$; L is the Laplace integral transform operator.

Dynamic fire characteristics in the frequency domain – amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics are determined by the expressions:

$$A(\omega)=\text{abs}\,W(j\omega)=B\left[1+(\omega\tau)^2\right]^{-0.5}; \qquad (34)$$

$$\phi(\omega)=\arg W(j\omega)=-\text{arctg}\,\omega\tau, \qquad (35)$$

where ω is the circular frequency; j is an imaginary unit.

Fig. 1 shows the relative time characteristics of a class B fire when it is extinguished with sprayed water for τ=20.0 s and τ=30.0 s; Fig. 2, 3 show the relative frequency characteristics of the fire for the same values of the time constant

The nature of change in these dynamic characteristics is determined by the value of the time constant τ, which hereafter is termed the dynamic parameter of the fire. Parameter B affects only the scale of dynamic characteristics, as a result of which it will be called a static fire parameter in the future. This parameter is a parameter of the static characteristic of fire, which is determined by the expression:

$$\theta=\lim_{t\to\infty}\theta(t)=\lim_{p\to 0}p\theta(p)=BI, \qquad (36)$$

where $\theta(p)=L[\theta(t)]$.

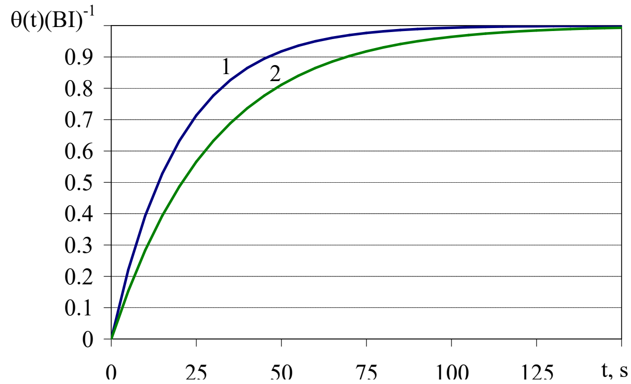

Fig. 1. Relative time characteristics of a fire: 1 – τ=20 s; 2 – τ=30 s

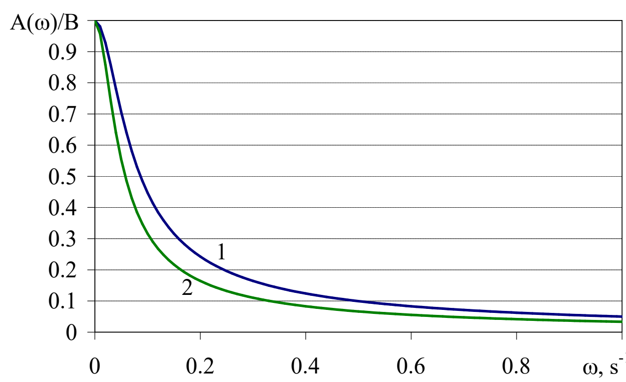

Fig. 2. Relative amplitude and frequency characteristics of a fire: 1 – τ=20 s; 2 – τ=30 s

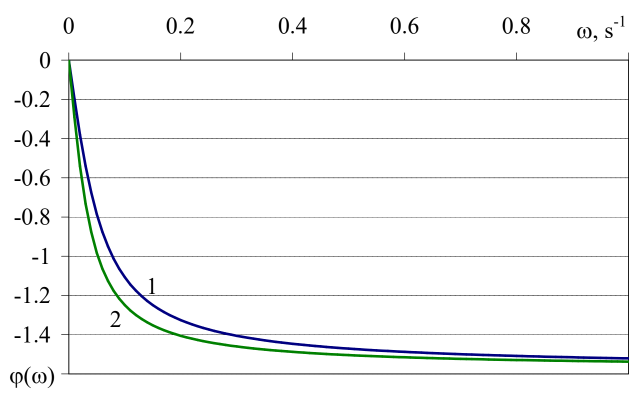

Fig. 3. Phase-frequency response of a fire: 1 – τ=20 s; 2 – τ=30 s

The theoretical values of parameters B and τ are determined by dependences (29) and (30), but their determination using these dependences has some difficulties. These difficulties are associated with obtaining information about such quantities as the heat transfer coefficient, flame height, speed of movement of water droplets, and especially about the value of the water utilization coefficient. Difficulties of this nature can be overcome in the presence of data on the dynamic characteristics of the fire, which are obtained experimentally. Let's consider examples of such an approach.

Example 1. For the time characteristic (33), there is an expression that defines the dynamic parameter τ in the form:

$$\tau = t\left[\ln\left[1-\theta(t)(BI)^{-1}\right]\right]^{-1}. \quad (37)$$

Since $\theta(t)(BI)^{-1}<1$, we can write:

$$\ln\left[1-\theta(t)(BI)^{-1}\right]= =-\theta(t)(BI)^{-1}\left[1+0.5\theta(t)(BI)^{-1}\right]. \quad (38)$$

When $\theta(t)(BI)^{-1}\leq 0.3$, the methodological error when using expression (38) does not exceed 0.9 %.

For two moments of time t_1 and t_2, at which the transition function $\theta_1=\theta(t_1)$ and $\theta_2=\theta(t_2)$ is measured, according to (37) and (38), the relation holds:

$$t_1\theta_2\left[1+0.5\theta_2(BI)^{-1}\right]=t_2\theta_1\left[1+0.5\theta_1(BI)^{-1}\right]. \quad (39)$$

The expression for the static fire parameter follows from this relation, which is:

$$B=\left(t_2\theta_1^2-t_1\theta_1^2\right)\left[2I\left(t_1\theta_2-t_2\theta_1\right)\right]^{-1}. \quad (40)$$

After combining (37) and (40), we have the expression for the dynamic fire parameter:

$$\tau=\left(t_2\theta_1^2-t_1\theta_2^2\right)^2\left[2\theta_1\theta_2\left(\theta_1-\theta_2\right)\left(t_1\theta_2-t_2\theta_1\right)\right]^{-1}. \quad (41)$$

The determination of parameters B and τ is reduced to obtaining information about the values of the transition function $\theta(t)$ of the fire at two a priori specified moments of time t_1 and t_2 at the a priori specified value of the intensity of the supply of sprayed water I=const.

Example 2. It follows from the expression for the fire transfer function (31) that:

$$W^{-1}(j\omega)=B^{-1}(1+j\omega\tau)^{0.5}=A^{-1}(\omega)\exp\left[-j\phi(\omega)\right]= =A^{-1}(\omega)\left[\cos\phi(\omega)-j\sin\phi(\omega)\right]. \quad (42)$$

Using Moivre's formula, we get:

$$B^{-2}(1+j\omega\tau)=A^{-2}(\omega)\left[\cos 2\phi(\omega)-j\sin 2\phi(\omega)\right], \quad (43)$$

which is equivalent to a system of equations with respect to parameters B and τ:

$$B^{-2}=A^{-2}(\omega)\cos 2\phi(\omega);$$

$$B^{-2}\omega\tau=A^{-2}(\omega)\sin 2\phi(\omega). \quad (44)$$

For the dynamic parameter τ, the expression follows from (44):

$$\tau=-\omega^{-1}\mathrm{tg}2\phi(\omega). \quad (45)$$

If we substitute this expression for (34) and take into account the relation:

$$\cos 2\phi(\omega)=\left[1+\mathrm{tg}^2 2\phi(\omega)\right]^{-0.5},$$

then the expression for the static parameter B of the fire will take the form:

$$B=A(\omega)\left[\cos 2\phi(\omega)\right]^{-1}. \quad (46)$$

Determination of parameters B and τ is reduced to obtaining information about the values of amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics of the fire at a priori given frequency ω.

From the comparison of these two methods, it follows:

– for the implementation of the frequency method of determining fire parameters, additional equipment is required, which ensures a change in the intensity of the supply of sprayed water according to the expression $I(t)=I\sin\omega t$. The implementation of the time method requires a change in the intensity of the sprayed water supply according to (32), which is possible by switching the water flow;

– when implementing the frequency method, it is necessary to convert the value of the intensity of the supply of sprayed water into an electrical signal. This is due to the need to measure the amplitude of the intensity of the sprayed water supply and the phase shift between such an electrical signal and a signal that carries information about the flame temperature. In the time method, only information about the flame temperature is used;

– for the implementation of the time method, a time is required, the value of which does not exceed the value of t_2 (when $t_1<t_2$), which, in turn, does not exceed the value of the time constant τ of the fire;

– the time of implementation of the frequency method is several values of the time constant τ of the fire.

Analysis of these features reveals that when choosing a method for determining parameters B and τ, preference should be given to the time method, which is simpler in its technical implementation and does not require a lot of time.

6. Discussion of results of determining the dynamic characteristics of a class B fire when it is extinguished with sprayed water

A fire, in particular, of class B, which occurs when a flammable liquid is burning, is the object of control of the automatic fire extinguishing system. The development of control algorithms in these systems, which ensure effective extinguishing of such fires, is based on information about the properties of the control object. The properties of the control object of the automatic fire extinguishing system – class B fires are determined in a formalized form by their mathematical models and characteristics. The basis of the construction of a mathematical model that describes the process of extinguishing a class B fire with sprayed water is the use of the heat balance equation. This equation includes two components for heat capacity, one of which is due to heat release due to the chemical reaction of liquid combustion, and the second due to its removal to the environment. Using the oxygen balance equation, an expression for the rate of the chemical reaction of burning a flammable liquid was obtained, which is used to determine the heat output. When determining the second component of the heat balance equation, the removal of heat to the environment due to radiation, convection, and evaporation is taken into account. For these three components, expressions were obtained for their capacities, and taking into account the Sreznevsky constant made it possible to simplify the expression for the power of heat transferred to the environment due to evaporation. The set of obtained expressions included in the heat balance equation formalizes the process of extinguishing class B fire using sprayed water in the form of a differential equation. The parameters of this differential equation are the dynamic parameter τ (29) and the static parameter B (30). With the use of the integral Laplace transform, a transition from a mathematical model belonging to the class of differential models to a mathematical model belonging to the class of algebraic models, in particular, to the fire transfer function, was performed. This made it possible to determine the dynamic characteristics of the fire as a control object of the automatic control system in the time and frequency domains. The dynamic characteristic of a fire in the time domain characterizes the nature of the change in the process of extinguishing it when spraying water is supplied to it, the intensity of which changes in accordance with the expression described by the Heaviside function. The dynamic characteristics of a fire in the frequency domain characterize the nature of the change in the process of extinguishing it depending on the frequency of the intensity of the supply of sprayed water, the value of which is a harmonic function. The amplitude-frequency $A(\omega)$ – expression (34) and phase-frequency $\varphi(\omega)$ – expression (35) characteristics are used as frequency characteristics of a fire when it is extinguished with sprayed water. Graphical dependences, which are shown in Fig. 1–3, demonstrate that the parameters B and τ fully characterize the process of extinguishing a fire with sprayed water. The presence of dynamic characteristics of fire as an object of control of the automatic fire extinguishing system makes it possible to spread the proven methods of analysis and synthesis of the automatic control system to class B fire extinguishing systems. In practice, the obtained results can be used both directly and in combination with the characteristics of fire extinguishing systems. In particular, the time characteristic of the fire (33) can be used to obtain the time of extinguishing the fire, provided that the intensity of the supply of sprayed water has the description of the form (32). Fire frequency characteristics (34), (35) can be used in the development of fire extinguishing systems for class B fires using frequency methods used in the synthesis of automatic control systems. It should be noted that the use of expressions for determining the parameters of dynamic fire characteristics in the form (29), (30) has some difficulties. These difficulties are connected with obtaining information in a theoretical way regarding such quantities as the heat transfer coefficient, flame height, speed of movement of water droplets and especially the value of the coefficient of water use. To overcome these difficulties, it is expedient to determine fire parameters using experiments that use time or frequency characteristics of fire. Examples of such an approach are developed methods for determining parameters B and τ, which are based on:

– obtaining information regarding the values of the time characteristic (33) of the fire at two a priori specified moments of time at the a priori specified value of the intensity of the supply of sprayed water;

– obtaining information about the values of frequency characteristics (34) and (35) at a priori set frequency.

The advantage of the first method is the small time spent on its implementation (less than the value of the constant fire time), as well as the simplicity of technical implementation.

The peculiarity of the developed method, in contrast to the methods discussed in [6, 9, 18], is that the characteristics of a class B fire are determined when it is extinguished with sprayed water, which fully determine the dynamic properties of this class of fires. In [6, 9, 18], not dynamic characteristics of fires are determined but their quality indicators, in particular, extinguishing time, consumption of fire extinguishing agent, etc.

By determining the dynamic characteristics of a class B fire when it is extinguished with sprayed water in the time and frequency domains, information about its dynamic properties is obtained. In contrast to known solutions, the presence of such dynamic fire characteristics fully determines the dynamic properties of class B fire.

The positive thing when determining the properties of a class B fire, which is extinguished with sprayed water, is that these properties are taken into account using two integral parameters.

Limitations in determining the dynamic characteristics of a class B fire are associated with the use of only sprayed water as a fire extinguishing agent.

A disadvantage of the procedure for determining the dynamic characteristics of a class B fire is the lack of research into the influence of variations in the form of intensity of spray water supply on the accuracy of obtaining estimates of fire parameters.

Further advancement of this direction of research may be related to the development of algorithms for assessing the impact of variations in the form of the intensity of the spray water supply when extinguishing class B fires.

7. Conclusions

1. A mathematical model was built for class B fire when extinguished with sprayed water, which belongs to the class of models in the form of differential equations. The parameters of such a mathematical model are two coefficients, one of which establishes a connection between the deviation of the temperature of the fire flame from its initial value and the intensity of the supply of sprayed water to it. The second parameter of the mathematical model characterizes the inertial properties of the fire flame when it is extinguished with sprayed water. Analytical expressions were obtained for these parameters of the mathematical model, which include thermophysical, kinematic, and geometric parameters of the flammable burning liquid and the fire-extinguishing substance – sprayed water. The values of these parameters for hydrocarbon liquids during their diffusion combustion lie in the range: τ=(20÷40) s, B=(0.05÷1.0) $m^2 \cdot s \cdot K \cdot kg^{-1}$. The mathematical model of class B fire, which is represented in the form of a differential equation, is the basis for determining the dynamic characteristics of this type of fire.

2. Mathematical descriptions were obtained for the dynamic characteristics of a class B fire when it is extinguished with sprayed water, for the construction of which the integral Laplace transformation was used. The dynamic characteristics of the fire are constructed both in the time domain – the transient function of the fire, and in the frequency domain – the amplitude-frequency and phase-frequency characteristics of the fire. To determine the dynamic and static parameters of these dynamic characteristics, experimental methods of their identification have been developed. When implementing these methods, information is obtained regarding:

– the values of the time dynamic characteristic of the fire at two a priori specified moments of time at the a priori specified value of the intensity of the supply of sprayed water;

– values of the amplitude-frequency and phase-frequency characteristics of the fire at the a priori set frequency.

It is noted that when choosing a method for determining the parameters of the dynamic characteristics of a fire, preference should be given to the method based on the use of time characteristics of the fire. The implementation of this method requires time that does not exceed the value of the dynamic parameter of the fire. For hydrocarbon liquids, this time is in the range (20÷40) s.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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