ECOLOGY

Підтверджено, що добавка азоту до вогнегасного аерозолю значно підвищує вогнегасну ефективність отриманої бінарної аерозольно-азотної суміші, та приводить до зменшення концентрацій компонентів суміші до 30 %. Визначено оптимальні співвідношення компонентів суміші аерозолю – 10 г/м³ та азоту – 12,1 %, при яких суміш є вогнегасною для дифузійного полум'я гептану та життєпридатною для людей

Ключові слова: азот, гази флегматизатори, інгібітори горіння, аерозольне пожежогасіння

Подтверждено, что добавка азота к огнетушащему аэрозолю значительно повышает огнетушащую эффективность полученной бинарной аэрозольно-азотной смеси и приводит к уменьшению концентраций компонентов смеси до 30 %. Определены оптимальные соотношения компонентов смеси аэрозоля – 10 г/м³ и азота – 12,1 %, при которых смесь является огнетушащей для диффузионного пламени гептана и жизнепригодной для людей

Ключевые слова: азот, газы флегматизаторы, ингибиторы горения, аэрозольное пожаротушение

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STUDY OF FIRE-EXTINGUISHING EFFICIENCY OF ENVIRONMENTALLY FRIENDLY BINARY AEROSOL-NITROGEN MIXTURES

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1. Introduction

In the practice of fire-extinguishing indoors, one of the most efficient ways to suppress the fire is the one in which such a medium inside the protected volume is created that does not support the process of combustion. Up to now, gas inert diluents or chemically active halogen hydrocarbons – halons – have been widely used with this aim as fire extinguishing agents. However, inert diluents have low fire extinguishing capacity, and the halons contribute to the destruction of the ozone layer of Earth. Fire-extinguishing powder formulations are inefficient at a volumetric method of extinguishing fires due to the large size of the particles and uneven distribution in the protected volume. In this regard, a new kind of volumetric extinguishing fire tools appears promising – pyrotechnic aerosol-forming fire-suppression mixtures (AFM) and fire-extinguishing aerosol generators on their basis. Modern aerosol tools by their main technical and economic indicators (high fire-extinguishing capacity, autonomy, automatic activation, ease of operation, minimal loss in the application) technologically exceed all the tools that are used to extinguish a fire. In this case, the gas phase in a two-phase system of aerosol is usually a mixture of inert gases that does not support combustion, and the solid phase is newly-formed highly-dispersed solid particles of inorganic salts, which possess high fire-suppression capacity. In addition, with regard to the climate changes on the planet, an acute problem now is the limitation of CO_2 emission as well as that of halons and other greenhouse gases into the atmosphere. Replacement of CO_2 and halons, which are currently used for extinguishing the A, B, C, E grades of fire, is an urgent task in need of the fastest solution because of their harmful effect on the planet's climate and ecology, as well as on the ozone layer.

Thus, the relevance of this work is explained by the fact that the fire-fighting tools are lacking at present with high fire suppression efficiency, eco-friendly, cheap, easy to manufacture and operate, which can be used even for fire extinguishing in the areas of temporary presence of people and living organisms without apparent damage to them as a result of filling up the areas with the mentioned fire suppression substances.

2. Analysis of scientific literature and the problem statement

A fire extinguishing aerosol is obtained by burning AFM, which consist of an oxidant, as a rule KNO_3, $KClO_4$

or their mixture and a reducing agent of fuel – epoxy, iditol, rubber, etc. High efficiency of these mixtures is attributed to the formation of highly dispersed condensed phase with the size of particles of 1 µm or less. As the condensed phase is the salts of K_2CO_3, KOH, KCl and others, some researchers tend to assume that the aerosol action mechanism is similar to the mechanism of action of fire suppression powders [1, 2], and an increase in the efficiency of aerosol can be achieved by increasing gasification of the output components of the formulations of AFM with maximum possible content of inert gas diluents (nitrogen, CO_2, water vapour) and the increase of gasification of aerosol [3] assists their fire extinguishing efficiency.

A major general disadvantage for most of the aerosol forming mixtures is their relatively high fire extinguishing concentrations and fairly high combustion temperature. Most of these formulations represent multi-component mixtures, which increases the cost of the composition, and complicates their manufacturing and storage. For example, a known composition [4], containing in its basis potassium nitrate (38–80 %), potassium perchlorate (30–45 %), as the combustible – soot (10–19.5 %), iditol (0.5–1.5 %), gypsum (5–13 %), Portland cement (10.5 %), liquid glass (17–45 %), sodium butilnaftalin, CMC (0.1–0.6 %), copper oxide (2 %), zinc oxide (4 %), iron oxide (0.5–1 %). A fire extinguishing concentration of the aerosol derived from such AFM is 59–133 g/m^3, which is at the level of some fire suppression powders.

At present, along with the fire extinguishing aerosols, the inert diluents are applied for volumetric suppression. Inert diluents are a group of gas fire-suppression substances that are, in particular, carbon dioxide, nitrogen, argon and their mixtures – non-toxic, which do not produce toxic thermal decomposition products, do not deplete the ozone layer and are readily available and cheaper than the halons and some combustion inhibitors. Since in the framework of the Montreal Protocol [5] the production of halons was discontinued in all developed countries, the issue of replacing them emerged in many research centers and institutes of the world. One of the first gas fire suppression substances that were suggested as an alternative to halons was carbon dioxide (CO_2).

But according to the Montreal and Kyoto Protocols [5, 6], CO_2 refers to greenhouse gases, the emission of which are regulated, and the research on innovative environmentally-safe technologies is a priority, corresponding to paragraph 4 of Article 2 of the Protocol. Therefore, in order to reduce the emission of this gas into atmosphere, to ensure stabilizing efficiency of gas-aerosols, nitrogen N_2 is expedient to use, which is widely applied as an eco-friendly stabilizing and fire-extinguishing agent. It should be noted that at present quite a large number of alternative to the halons tools of fire extinguishing are created [3, 7, 8]. However, most of them are not absolutely simple in operation, cheap or, in particular, environmentally clean as yet. Nitrogen as a fire-extinguishing agent possesses "valuable" characteristics – chemically neutral to most substances, inexpensive, not deficient, molar density – 28.01 g/mol, providing for even fill-up of the volume, while fire extinguishing concentration of N_2 for n-heptane (C_7H_{16}) is 33 % [9]. Nitrogen is widely used for various fire-fighting systems. In particular, there are installations on the territory of Ukraine and abroad in which this gas is used as the base by the principle of oxygen displacement. In the paper [9] the authors suggest using nitrogen mixed with chladone, to extinguish fires during aircraft accidents, and in [10] – to purge internal technological volumes. Developers in [11] used a joint supply of nitrogen with the dispersed water for fire extinguishing, as well as in the work [12], in which the authors propose a joint supply of nitrogen with water in sprinkler systems or, in the paper [13], also a joint supply of nitrogen and water, but in the form of water mist. In all the cases nitrogen was used to reduce the concentration of oxygen, which led to an increase of efficiency of the fire extinguishing by another component, usually inhibitor.

Analysis of common patterns of the processes of inhibition shows that the increase in the efficiency of inhibiting agents can be achieved by reducing the contents of an oxidant in the combustible mixture. It is sufficient to reduce the concentration of an oxidant not on the whole premises but in the area of combustion. Thus, non-flammable gaseous components further dilute the burning system, reduce the concentration of oxygen and thus dramatically increase the efficiency of the fire extinguishing action of an inhibitor. For example, dilution of the mixture "natural gas+air" with 10 % of nitrogen reduces the fire suppression concentration of chladone by 2 times, and at dilution by 20 %, fire extinguishing concentration of chladone is only 0.5–0.6 % [14].

Besides, with addition of thermal phlegmatizers to chemical inhibitors, fire extinguishing efficiency of the latter increases sharply, as stated by the authors of the paper [15]. Similar effect is observed when using CO_2 [16], in which the authors explain that with the decrease of the concentration of oxygen in the air, the efficiency of inhibitors dramatically increases, and as a result, stabilizing concentration of CO_2 is reduced to 8 % at the concentrations of aerosol of 15 g/m^3. Therefore, the mechanism of volumetric fire suppression by aerosol with gas addition is expedient to consider by the principle of combined action of fire suppression tools, which combine the effects of cooling and inhibition that leads to significant resulting fire-extinguishing effect.

The conducted analysis regarding joint action of gas diluents and solid dispersed inhibitors that form aerosol confirms total synergetic action of the components of a binary gas-aerosol system. Thus, the effect of nitrogen on the fire suppression efficiency of aerosols is an open question, which requires theoretical analysis of the characteristics of aerosol and experimental determining of fire-extinguishing efficiency of binary mixtures of aerosol and nitrogen.

Nitrogen as a fire extinguishing component has been explored by many researchers, including the authors of the paper [17]. They tested the efficiency of fire suppression by gaseous nitrogen by using different full-scale fire tests. The volume of the test chamber was 102 m^3. The tests were carried out at the concentration of nitrogen $C_{firefighting}$ =33,6 vol. % and the minimum concentration of oxygen of 13.9 %. None of the 10 tests demonstrated re-combustion of the sample. The tests were performed on the samples – representatives of each grade of fires. Table 1 presents the data from the fire extinguishing of C grade – on the cables with polyethylene insulation.

Table 1

Results of fire extinguishing test [17]

Agent	$C_{firefighting}$, % vol.	Time, s	Re-combustion occurrence	Time of after-combustion, s
Nitrogen IG-100	39.1	11	Yes	3
IG-541	40.2	13	Yes	6
m-200	1.6	6	Yes	Several seconds
HFC-23	15.9	6	Yes	Several seconds

It should be noted that in the case of supply of the inert diluent to a closed tight room, the air medium can remain fit for breathing and saving people's lives up to the extinguishing of the fire. The use of combined aerosol-gas systems with concentration of gas and aerosol by the order of magnitude less than required for fire suppression can provide life-safe concentration of oxygen.

It is known [18] that during AFM burning each gram forms 0.3–0.5 l of aerosol, which is made up of dispersed particles of inorganic salts of potassium, sodium, calcium and others, and a mixture of inert gases – phlegmatizers – CO_2, N_2, steam, etc. The interaction of these particles forms a complex system, the structure and composition of which are constantly changing in time. So, at the moment of formation of the gas-aerosol system it consists of ultra-dispersed particles of salts of potassium, which can form structures containing water and CO_2. Such structures will cause much more efficient fire-extinguishing effect due to the combined action of the inhibitors and phlegmatizers [18].

In the paper [19] research results showed that the efficiency of fire extinguishing of aerosols does not depend on the order of introduction of the inert gases, and depends only on their concentration, and even a small amount of inert gas entered in the volume of solid-phase aerosol significantly reduces the concentration of the latter.

The advantage of the combined nature of fire extinguishing, as an example, is also stressed by the data in the paper [20] about the presence of inert gas diluents significantly increasing the efficiency of the aerosol. The results of experiments [19, 20] showed another rather significant effect of additional use of inert diluents jointly with aerosol, namely, the presence of CO_2 or N_2 increases optical permeability of aerosol, i.e. increased visibility. This is especially noticeable in the concentrations of CO_2 or N_2 of 2 % or higher. From a practical point of view it is very important. When addressing the issue, which inert gas is better to use, it becomes apparent that nitrogen, due to its low toxicity, has an absolute advantage over CO_2, though its secondary effect is slightly less than from CO_2. But if there is a question about fire extinguishing in uninhabited areas, then the use of CO_2 is by all means superior to N_2.

Therefore, not taking into account the concentration of the solid-phase, adding such gases as CO_2, N_2 or H_2O to it should slightly increase the heat absorption capacity of the binary mixture of aerosol and gas-phlegmatizers. It is confirmed in the paper [21], which indicates that the aerosol displays increased heat absorption effect at the concentrations higher than 50 g/m^3, and at aerosol concentration of about 80–100 g/m^3, it leads to a decrease in temperature from 2100K to 1700–1400K with the aerosols and also acting with the addition of gases, in this case adding CO_2 led to a larger decrease in temperature. The authors of the work [22] also confirmed a significant increase of fire-extinguishing efficiency of the binary mixture of combustion inhibitors and gas-phlegmatizers, due to thermalphysic qualities of gases-phlegmatizers.

The issue of finding new fire suppression substances and synergies between chemical and physical fire suppression agents was also examined by the authors [23] who were looking for a new eco-friendly fire suppression substance, in which they wanted to keep all useful properties of Halon-1301, but this search was not successful, as the resulting fire extinguishing agent 1-bromo-3,3,3-tryftorpropen did not correspond to the stated requirements – it had a low fire suppression concentration, low boiling temperature, high price etc. According to the research results of the same authors [23], only a mixture of 1-bromo-3,3,3-tryftorpropen with nitrogen possessed high fire suppression efficiency through the synergy of its components. In order to obtain "environmentally" friendly fire suppression agents, the researchers suggest using liquefied nitrogen [24, 25] which, as they point out, can be used to extinguish fires in the buildings and the reservoirs. But the question arises as to the technological implementation of this method, which of course will be more expensive than standard storage of compressed nitrogen in cylinders. As to the fire-extinguishing efficiency of nitrogen, it is necessary to use as the gas that reduces the concentration of oxygen, and it can be supplied in different ways, but in general it is necessary that the gas reaches the combustion zone. Thus, the authors [26] carried out a study of the efficiency of fire extinguishing by soap bubbles – capsules, which they believed would lead to a decrease in the consumption of gas for fire extinguishing. Therefore, as can be seen from the conducted analysis, the researchers have been working on the task of reducing the fire-extinguishing concentration of the gas supplied to the fire extinguishing, and they engage different methods and techniques that have their shortcomings mentioned above.

Passing on to a joint application of aerosol and nitrogen, it is necessary to consider thermotechnical characteristics of aerosol. Thus, in paper [27] they compared obtained calculated values of thermal capacity of AFM to the thermal capacity of gas-phlegmatizers CO_2 and N_2 at the flame temperature of 1400 °C, which amounted, accordingly, to $Q=3241$ kJ/m^3 and $Q=2012{,}5$ kJ/m^3. The results of the paper show that thermal capacity of aerosol considerably exceeds the thermal capacity of these gases, especially so in the cases of formation of K_2CO_3 or $K_2CO_3{\cdot}2H_2O$. Thus, for example, for the charges with excess fuel that meets stoichiometric coefficient of fuel n=1.5, the thermal capacity of 1 m^3 of the aerosol in the AFM based on iditol, lactose, carbon (assuming creation of K_2CO_3) is several times higher than the thermal capacity of 1m^3 of CO_2, N_2 (Table 2) [26].

Table 2

Ratio of the value of aerosol thermal capacity to inert gases [26]

Gas \ AFM	Iditol – 20 % KNO_3 – 80 %	Lactose – 28 % KNO_3 – 72 %	Carbon – 20 % KNO_3 – 80 %
CO_2	<2,85	<2,11	<3,42
N_2	<4,59	<3,40	<5,51

As can be seen from Table 2, the estimated heat absorption capacity of aerosol is at least 2.11 times higher than the heat absorption capacity of CO_2, and by 3 times higher than the thermal capacity of nitrogen, which coincides with the results of the authors [21], who point to high heat absorption capacity of aerosols at high concentrations. Received characteristics of aerosols create prerequisites for their use in the binary fire suppression systems by strengthening their fire suppression characteristics by adding gas thermal phlegmatizers, particularly nitrogen.

Therefore, the effect of nitrogen additives on the efficiency of fire suppression of the aerosols based on inorganic salts of potassium, especially fire suppression and characteristics of binary aerosol nitrogen mixtures, has not been sufficiently studied, and it confirms the need for research in the indicated direction.

3. The purpose and objectives of the study

The purpose of the work is to identify fire-extinguishing efficiency and peciliarities of the fire extinguishing of the heptane diffusion flame by the binary aerosol nitrogen mixture under conditions of experimental chamber.

To achieve the set goal, the following tasks are to be solved:

– to design experimental installation and a method for determining fire-extinguishing efficiency of the binary aerosol nitrogen mixture;

– to define fire suppression efficiency and the ratio of components of the binary aerosol nitrogen mixture;

– to identify the features of the process of fire extinguishing at different concentrations and ratios of components of the binary aerosol nitrogen mixture;

– to determine intensity and the features of cooling kinetic and diffusion flames of heptane at its presence in the binary aerosol nitrogen mixture.

4. Materials and methods of the study of the peculiarities of the process of fire extinguishing and of fire-extinguishing efficiency of the binary aerosol nitrogen mixture

For determining the fire-extinguishing efficiency and the peculiarities of the fire extinguishing by the proposed binary aerosol nitrogen mixture (BANM) we used the following materials and devices. Aerosol forming mixture consists of iditol ($C_{13}H_{12}O_2$) – 20 % and potassium nitrate (KNO_3) – 80 %. AFM is prepared by preliminary grinding, stirring and pressing of the corresponding weight of the charge. Nitrogen, N_2, chemically pure by 99.96 %. To determine the features of fire extinguishing, we conducted video fixation by the Nikon camera 1 J4, with capacity of shooting 3-second video clips with frame rate from 60 to 1200 per second at 144×416 at the resolution 416×144 P [28]. With this camera when analyzing the shot sequence we determined the frequency of pulsations of the flame. The change in temperature was determined using a chromel-alumel thermocouple with the thickness of the conductor 0.3 mm and the regulator of the converter RT-0102. The data were received in the form of digital indicators in the interface of the software program RP-8 by the developer PAT NVO "Lvivtermoprilad" on the Windows OS (Fig. 1).

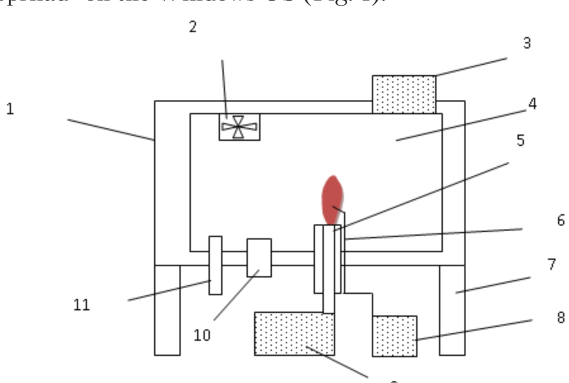

Fig. 1. Experimental installation for determining fire-extinguishing efficiency of BANM: 1 — chamber body; 2 — fan; 3 — opening for the purging of the vessel; 4 — viewing window; 5 — heptane burner; 6 — chromel-alumel thermocouple; 7 — racks; 8 — regulator — converter 01–02; 9 — heated reservoir with heptane; 10 — AFM ignition source; 11 — gas supply pipe

Determining the efficiency of fire suppression was performed in the following way. The appropriate sample of AFM was burnt in the chamber, then the appropriate amount of nitrogen was added, the mixture was stirred and the heptane burner was led into the opening followed by registering the result of "fire extinguishing", "no fire extinguishing", "flame termination". The cooling efficiency of the fire-extinguishing mixture was determined by using a heptane burner with attached thermocouple, the signal of which was transmitted to the regulator-meter 0102 (Fig. 1) and from it – to the software program RP-8, in which we received the digital value of the intensity in the decrease of temperature.

5. The results of the study of indicators. Influence of the ratio of aerosol and nitrogen on the fire suppression efficiency of BANM during suppression of diffusion flame of heptane

To confirm that the joint action of aerosol with addition of nitrogen will result in a significant increase in the fire-extinguishing efficiency of the final binary aerosol-nitrogen mixture, we conducted a series of experiments and obtained corresponding dependencies shown in Fig. 2. The diagram of dependency of fire-extinguishing concentration was built under condition that the fire-extinguishing concentration of aerosol, formed of AFM on the basis of iditol, for heptane is 25 g/m^3, and of nitrogen for heptane – 33 % [9, 10, 12, 16].

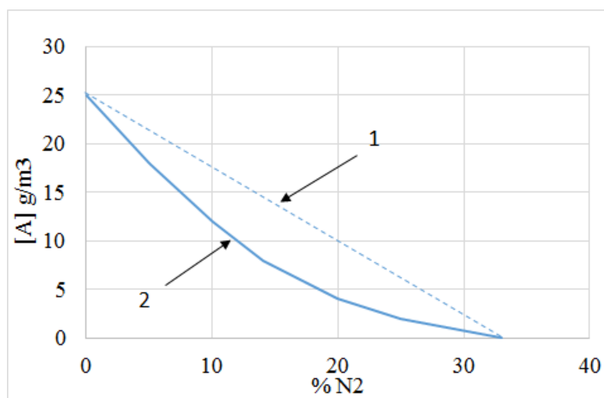

Fig. 2. Diagram of the change in the fire-extinguishing concentration of BANM for diffusion flame of heptane, depending on the concentration of aerosol — [A] g/m^3 and nitrogen — N_2 %: 1 — straight line of dependency (theoretical) with additions; 2 — curve of dependency according to experimental data

Fig. 2 shows the diagram of dependency of the change in the fire-extinguishing concentration for diffusion flame of heptane on the ratio of the fire-extinguishing aerosol content, and nitrogen with their joint supply to the test chamber.

As can be seen from the diagram, experimental values of the components of BANM are located below the values for the case with the additions, accordingly, the synergy was registered among the components of BANM.

To discover the peculiarities of the fire suppression, dependencies and fire-extinguishing efficiency of BANM on its nitrogen concentration change, the research was conducted of the change in the temperature when the kinetic flame was exposed to the BANM with the ratio of aerosol of 45 g/m^3 and addition of nitrogen of 5, 10, and 15 %. Kinetic flame was received upon advance mixing heptane steam with air on the corresponding burner.

Then we explored the fire suppression effect on the kinetic flame by BANM. When acting on the kinetic flame with BANM of the concentrations of up to 100 g/m^3 and adding nitrogen of up to 30 %, the fire extinguishing of this flame failed. The flame acquired blue color, its speed decreased, it was slightly terminated, but the combustion process went on.

Fig. 3 shows dynamics of decrease in temperature at adding specified volumes of nitrogen. In all cases, the temperature of the flame when taking it in BANM dramatically decreased. The temperature decreased minimally by 50 °C when taking the burner to pure aerosol, and maximally by almost 200 °C when taking the burner in BANM with the ratio of aerosol 45 g/m^3 and nitrogen of 15 %.

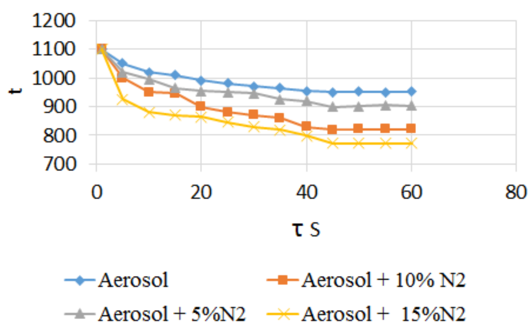

Fig. 3. Dependency of the change in temperature (t) of kinetic flame of heptane in time (τ s) depending on the concentration of nitrogen at stable concentration of aerosol in BANM – 45 g/m^3

Then the research was conducted to determine the influence of BANM on the temperature of heptane diffusion flame. The results are shown in Fig. 4.

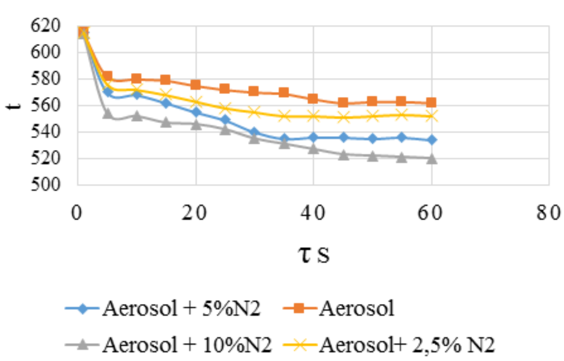

Fig. 4. Dependency of the change in temperature (t) of diffusion flame of heptane in time (τ S) depending on the concentration of nitrogen with stable concentration of aerosol in BANM – 10 g/m^3

As can be seen from the results of the experiment, the cooling efficiency of the aerosol with addition of nitrogen in different concentrations happens to be insignificant, but still, reduces the temperature of a diffusion heptane flame (Fig. 4). The aerosol itself reduces the temperature of the flame by also around 40 °C at the concentration of only 10 g/m^3. Adding 2.5 % of nitrogen to the aerosol, the temperature of the flame during first 5 seconds is reduced to about 50 °C in the beginning and to 70 °C later on. At the highest increase in the concentration of nitrogen up to 10 %, the flame temperature lowers more drastically by approximately 75 °C, and eventually the temperature decreases in general by 100 °C, to 565 °C. Thus, reduction of the temperature with the addition of nitrogen occurs, but not quite significantly, and in general the dynamics of decrease in the temperature of the flame is not very different from the temperature decrease at the lower concentrations of nitrogen. To confirm that the action of BANM produces combined effect on the kinetic and diffusion flame, the peculiarities of fire extinguishing with aerosol and aerosol-nitrogen mixture were determined.

The results of analysis of the video shot sequence are shown in Fig. 5. As can be seen from Fig. 5 pos. 1, when putting out kinetic flame, the change of the color of the flame occurs first, then the flame slightly terminates and returns to a stable state. The termination occurs in the 25–60th second. In this moment the flame temperature reduces by almost 150 °C.

Fig. 5. The process of fire extinguishing of the diffusion flame of heptane by BANM with the ratio of aerosol – 15 g/m^3, N_2 – 7.5 %: 1–4 pulsation of the flame with frequency of 24–35 Hz. 5 – pulsation, reducing the size and extinguishing of the flame due to pulsations

Below we show the video shot sequence of fire extinguishing by aerosol-nitrogen mixture. To determine the characteristics of the influence of BANM on the kinetic and diffusion flame, we captured on video a fire extinguishing by BANM by the camera NIKON 1 J4 with a frequency of 120 frames per second. The results of the video shot sequence of diffusion flame of heptane of the BANM with the ratio of aerosol – 15 g/m^3 and nitrogen – 7.5 % are shown in Fig. 5. Fig. 6 shows the effect on the kinetic flame by the BANM with the ratio of aerosol – 45 g/m^3 and nitrogen – from 10 % to 20 %.

At the suppression of a diffusion flame (Fig. 5), it was slightly colored, thereafter it began to pulsate, Fig. 5, pos. 1–4, grew less in size Fig. 5, pos. 5, and subsided. The burner cross-section is shown in Fig. 5 and 6 by horizontal lines and the size of the flame (Fig. 5) and its termination (Fig. 6) are shown by arrows.

In general, the performance of the diffusion and kinetic flame when exposed to BANM is different, given the fact that the kinetic flame cannot be put out by BANM even with known concentrations, and the diffusion flame is extinguished at low concentrations of the components of BANM. Probably the reason for this is that the air reaches the kinetic flame outside of the installation without BANM, and the diffusion – along with BANM from inside the installation, which leads to a difference in the temperature of combustion, which is about 1100 °C for the kinetic flame, and is two times lower for the diffusion one and it is 615 °C. In this case, when adding nitrogen to the aerosol, the suppression of the diffusion flame is caused not by its termination but as a result of the increase in the frequency of pulsations to 24–35 Hz, which was determined by the method of video recording. The flame in the process of pulsation reduces in size and goes off (Fig. 5, pos. 5).

Fig. 6. Influence of the BANM on the kinetic flame of heptane: 1 – burning flame with the addition of BANM (aerosol – 45 g/m^3, nitrogen – 10 %); 2 – flame termination by 4 mm with the addition of BANM (aerosol – 45 g/m^3, nitrogen – 15 %); 3 – flame termination by 12 mm with the addition of BANM (aerosol – 45 g/m^3, nitrogen – 20 %)

As can be seen from Fig. 6, pos. 1, under the action of BANM on the kinetic flame, the change in the color of the flame occurs initially, sometimes it is slightly terminated and then returns to its original state and continues to burn. Moreover, with increasing volume of nitrogen to 15 % (Fig. 6, pos. 2), the termination is 4 mm maximum, and at 20 % (Fig. 6, pos. 3) it terminates to 12 mm, shown by the arrow (horizontal line marks the cross-section of the burner). A slight tilt of the flame to the left is due to the work of the fan.

Based on the research results, we can state interesting patterns, which are a small difference of the values, by which the temperature decreases of both the kinetic and diffusion flames under the influence of the BANM on them with significant differences in the concentrations of aerosol and nitrogen. The peculiarity lies in the fact that the BANM, when interacting with the kinetic flame, does not enter inside it in large quantities, but leads to lowering its temperature by flowing around the flame. Also interesting is the fact that it is impossible to extinguish the kinetic flame of heptane by BANM even at its high concentrations, at the same time the diffusion flame is extinguished much easier at that, and the difference in the concentrations of BANM is up to 4 times.

6. Discussion of the results of the study of the influence of nitrogen additives on the fire suppression efficiency and the peculiarities of extinguishing the kinetic and diffusion flame of heptane by BANM

In determining the efficacy of the influence of nitrogen on the fire suppression efficiency of a binary aerosol-nitrogen mixture, as derived from the obtained results (Fig. 3), logical is a joint reduction in the fire suppression concentrations of aerosol and nitrogen. This is due to synergetic activities among the components of BANM due to the dilution of combustible medium with gas phlegmatizer and significant growth in the inhibiting action of the aerosol. Taking the diffusion flame of heptane to the chamber with BANM, when the air is fed to the burning mixture from outside at stoichiometric ratio of the combustible and the oxidant, does not lead to its extinguishing, even with significant concentrations of BANM. In this case, as follows from the results of the experiment, to guarantee a fire extinguishing, gas-aerosol mixture must reach inside the flame in the specified volume along with air. Aerosol-nitrogen mixture's reaching inside the flame together with air leads to significant lowering of the temperature compared to taking the kinetic flame of heptane inside BANM when the air is supplied from outside at the concentration of the aerosol less by 4 times. Therefore, lowering the flame temperature is due to a complex inhibiting-cooling influence of the components of BANM on the flame.

Based on the results of measurements of the temperature of the kinetic flame (Fig. 3), one can say that the aerosol (Fig. 3) does not produce significant fire-suppression effect in low concentrations, and only by increasing the concentration of the aerosol, its fire extinguishing action significantly increases, which leads to possible greater cooling effect. And when taking a heptane burner with a kinetic flame to the aerosol, its temperature sharply decreased by about 120 °C, in 10th second, which can be seen from a diagram in Fig. 3, but it did not lead to its extinguishing. Then the temperature of a diffusion flame slightly decreased to stabilize at the level of approximately 950 °C. Adding nitrogen to the aerosol in the volume of 5 % led to the decrease in temperature in the beginning to 1000 °C, which can be seen from a diagram in Fig. 3, after which the temperature stabilized at around 905 °C. Further increase in the concentration of nitrogen up to 10 % led to a decrease in the temperature of the final result, to 887 °C, and adding 15 % led to a decrease in the temperature to 866 °C, in this case the decrease in temperature within first 10 seconds was even larger, to 849 °C, then the temperature stabilized at the level of 866 °C.

Temperature measurement of the diffusion flame showed similar results (Fig. 5) and by adding the aerosol at the concentrations of 10 % the temperature of the flame decreased from 620 °C to 580 in the 5th second and then the temperature was decreasing to approximately 560 °C to stabilize in the 40th second at the level of 564 °C. The flame at this decreased in size and pulsated with the frequency of 3–8 Hz. Adding 2.5 % of nitrogen to the aerosol led to greater reduction in the temperature at the time of taking the flame to BANM, then the lowering of the temperature went on and in the 35th second the temperature stabilized at around 553 °C. The increase in the concentration of nitrogen in BANM from 2.5 % to 5 % led to a sharper decrease in the temperature, when taking the burner inside the chamber in the 5th second, the temperature dropped to 568 °C, then a slight decrease in the temperature continued to stabilize at 540 °C. An increase in nitrogen concentration in BANM to 10 %, initial reduction in the temperature went on and amounted to 554 °C, after which the temperature stabilized at 522 °C. The flame at that significantly decreased in size and passed into unstable condition – it pulsed with the frequency of about 8–12 Hz, partially terminated and stabilized again. Therefore, the extinguishing of the flame occurred with its reducing in size and as a result of pulsation, not termination, while the temperature decreased by 250 °C maximum from the initial.

The results of the video shot sequence of the process of fire extinguishing by the aerosol and aerosol with the addition of nitrogen have shown that the aerosol without additions of nitrogen provides change of color of the diffusion flame followed by its suppression. Adding from 5 to 12 % of nitrogen to the aerosol leads to a change in the mechanism of suppression, which accelerates the moment of instability of the flame and increases the pulsation frequency to 24–35 Hz and a faster fire extinguishing after brief unstable state in the time by 30 % less than without the additive. And the flame, as was noted, was not suppressed, while the increase in the concentration of N_2 in BANM led to insignificant increase in termination and insignificant reduction in the size of the flame (Fig. 6, pos. 1–3).

As can be seen from the results of the experiment, the action of BANM on the kinetic and diffusion flame does not lead to its strong and sharp cooling and the maximum reduction in temperature was around 230 °C, but the flame was not suppressed. Thus, the action of BANM probably leads to a decrease in heat formation due to the dilution of the atmosphere with nitrogen and agrees well with the results of the authors [29], where they also indicated the reduction in temperature as a result of the influence of the mixture of chladone and carbon dioxide on the hydrocarbon flame. Further increase in the concentration of aerosol and nitrogen leads first to a sharp decrease in temperature, but it is reduced further for 30–40 seconds from taking the burner to the flame, then it stabilizes. This can be explained by a decrease in the efficiency of heat formation of the reaction, and possibly by a minor increase in the concentration of the products of combustion of heptane and cooling aerosol.

Comparison of the results of the temperature changes when taking the diffusion flame of heptane and aerosol with the addition of nitrogen to the aerosol leads to a decrease in temperature in the specified range, i. e. the temperature when the burner is taken in reduces by approximately 100 °C, after which the flame terminates and dies out. Thus, despite the fact that the action of BANM still needs to be explored and the dominant mechanism of suppression defined, it has significant fire suppression efficiency, which is significantly higher than the fire suppression efficiency of separately taken components of BANM aerosol and nitrogen.

Thus, the obtained data for the values of the fire-extinguishing efficiency and peculiarities of the extinguishing by BANM could form the base for creation of environmentally friendly fire suppression systems for extinguishing flammable homogeneous and heterogeneous media. Defined ratios of aerosol and nitrogen provide satisfactory conditions for the life of a human being during extinguishing fires in closed areas. When applying BANM for fire suppression the oxygen concentration on the protected premises does not decrease below 16 %, which allows for the people to stay temporarily inside this area. The aerosol itself does not produce strong toxic action [30] at the fire suppression concentrations of 40–50 g/m^3 and at a lesser concentration in the mixture with neutral eco-friendly nitrogen is suitable as an alternative of a fire-extinguishing component for the automatic fire-extinguishing systems, to ensure the fire suppression in the areas with people and living organisms inside.

7. Conclusions

1. Experimental methods were developed and the installation for determining fire-extinguishing efficiency of binary aerosol-nitrogen mixtures was designed, in which two types of flame – diffusion and kinetic were used to study the fire-extinguishing efficiency of binary aerosol-nitrogen mixtures.

2. The fire suppression efficiency of binary aerosol nitrogen mixture was defined and we found that nitrogen additive to the aerosol of inorganic salts of potassium leads to a significant increase in the fire-extinguishing efficiency of binary aerosol-gas mixture due to the synergy of its components. The result of adding nitrogen to the aerosol is the decrease in the fire-extinguishing concentration of the components of binary mixtures to 30 %. It was determined that the optimal ratio of the components in aerosol-nitrogen mixture is: aerosol – 10 g/m^3, nitrogen – 12.1 %, at which the mixture is capable of fire suppression, for the diffusion flames of heptane and maintains life-safe concentration of oxygen.

3. We found that the fire extinguishing of the diffusion flame of heptane occurs not through its termination but through its reduction in size and pulsation at the frequencies of 24–35 Hz. It was defined that taking a kinetic flame of heptane to BANM at the concentrations significantly exceeding fire extinguishing for the diffusion flame of heptane, did not lead to fire extinguishing.

4. The intensity and the values of decrease in temperature of the diffusion and kinetic flame at its stay in the binary aerosol-nitrogen mixture were determined. A temperature difference between the initial value of the temperature and under the action of BANM is 230 °C maximum. Decrease in the temperature occurs as a result of the fact that the addition of BANM probably leads to a reduction of the heat formation of the reaction of combustion and, consequently, reduces the temperature of the flame.

Received dependencies and specifications of aerosol-nitrogen mixtures can be the basis for the creation of ecologically clean, cheap, and simple in the production and operation fire-fighting tools with high fire suppression efficiency, which can be used for fire extinguishing in the areas of temporary stay of people and living organisms without apparent damage to them as a result of fire extinguishing by the described mixtures.

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