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DETERMINING THE FIRE EXTINGUISHING EFFICIENCY OF COMPRESSED AIR FOAM WITH MODIFIED ADDITIVE $NH_4H_2PO_4$

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This study examines the fire extinguishing efficiency of aqueous fire extinguishing agents such as compressed air foam with a modified $NH_4H_2PO_4$ additive, compressed air foam of standard composition, water, and gel-forming composition.

The principal hypothesis assumes that compressed air foam with a modified $NH_4H_2PO_4$ additive has more effective fire extinguishing properties when extinguishing class A fires in comparison with compressed air foam of standard composition, water, and gel-forming compositions.

The task addressed was predetermined by the lack of scientifically substantiated comparative data on the fire extinguishing efficiency of aqueous fire extinguishing agents when extinguishing standardized model fires of class 1A: compressed air foam with a modified $NH_4H_2PO_4$ additive, compressed air foam of standard composition, water, and gel-forming composition.

When using all of the above fire extinguishing agents, successful elimination of combustion was observed. However, the lowest time and mass spent on extinguishing were established precisely for CAF with MA $NH_4H_2PO_4$. The mass spent on extinguishing the fire by the CAF with $NH_4H_2PO_4$ is 7% less than the mass of the CAF of standard composition and 52% less than the mass of water. For compressed air foam with MA $NH_4H_2PO_4$, the extinguishing time was recorded to be 10% less than the time required to extinguish the fire by the CAF of standard composition and 51% less than the time of extinguishing with water.

The extinguishing efficiency indicators of the CAF with MA $NH_4H_2PO_4$, CAF of standard composition, GFC, and water were compared with each other. As a result, the indicator for CAF with MA $NH_4H_2PO_4$ is $I_{e.e} = 16.5$ m²/kg·s; for CAF of standard composition, $I_{e.e} = 14.03$ m²/kg·s; for GFC, $I_{e.e} = 11.9$ m²/kg·s; for water, $I_{e.e} = 3.94$ m²/kg·s.

The results emphasize that the use of MA in the composition of CAF, in particular $NH_4H_2PO_4$, increases its fire-extinguishing properties when extinguishing class A fires. It has been proven that the fire-extinguishing efficiency of CAF with MA content is 15% higher compared to CAF of standard composition. Compared to GFC, the efficiency is 28% higher; compared to water, 77% higher

Keywords: compressed air foam, modified additives, fire-extinguishing properties, class A fires, water

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1. Introduction

Class A fires (burning of solid combustible materials) are the most common in the residential sector. Despite the development of the firefighting industry, water, as a fire extinguishing agent, remains the main one for extinguishing such fires.

This is due to a number of its advantages, namely, availability, low cost, and ease of use [1]. Notwithstanding, the disadvantage of water is its low fire extinguishing efficiency. Only 5–10% [2] of the total volume of water reaches the fire source directly, and the rest remains excessively spilled, causing significant secondary damage.

An alternative to water is a number of aqueous fire extinguishing agents (AFAs) to which chemical compounds are added; modified additives (MAs) and foaming agents (FAs) should be particularly noted. Due to this, its fire extinguishing efficiency is enhanced. Gel-forming compositions (GFCs), which are categorized as AFAs, have also become widespread.

But along with this, in the practice of fire extinguishing in the world's leading countries, compressed air foam (CAF) is used for extinguishing class A fires in the residential sector.

Its advantage over other water-based fire extinguishing agents has been repeatedly emphasized by scientific research in the field of fire safety. Due to the technology of generating CAF, a reduction in secondary damage, time for localization and liquidation of the fire is achieved.

Therefore, improving the fire-extinguishing efficiency of CAF for extinguishing class A fires in the fire science field is an urgent task.

2. Literature review and problem statement

According to the results reported in [3], it was found that several approaches are used to increase the fire-extinguishing efficiency of CAF. Among them, changing the multiplicity and concentration of the aqueous solution of FAs, using different types of FAs, changing the feed rate, using nitrogen (N_2) instead of air in the CAF composition. At the same time, the work determined that to date there are no studies aimed at increasing the efficiency of compressed air foam by adding modified additives to its composition. The work did not determine the properties of MA or CAF with MA in its composition, and the extinguishing efficiency of CAF with MA in its composition was not determined. The cited work became the basis for the hypothesis that the use of MA in the composition of compressed air foam could increase its efficiency during fire extinguishing.

In [4], an analysis of MDs that can be used in compressed air foam to increase its efficiency was carried out. Studies by various authors were analyzed and based on them, five MDs were identified that are advisable to use to increase the efficiency of CAF. The disadvantage of the work is that the determination of these MDs was based on the method of analysis and search, and not on their own experimental studies. A logical continuation of work [4] was study [5], in which the authors experimentally determined the properties of compressed air foam with these five MDs in its composition. It was determined that CAF is formed in a mixture with the MDs $NH_4H_2PO_4$, $(NH_4)_2HPO_4$ and $(NH_4)_2CO_3$. For these MDs in the composition of CAF, its multiplicity and stability were determined. The authors did not determine the fire-extinguishing efficiency of CAF with the specified MDs in the work, which is justified by the scope of the study and preparation for the studies reported in [6]. In that paper, the authors experimentally determined the fire-extinguishing efficiency of compressed air foam with the $NH_4H_2PO_4$, $(NH_4)_2HPO_4$ and $(NH_4)_2CO_3$ MDs in its composition. At the same time, the CAF with MA $NH_4H_2PO_4$ demonstrated the highest extinguishing efficiency. But the results of study [6] have a number of shortcomings. First, the experiment was conducted on laboratory fires of class A and the results obtained need to be confirmed on standardized fires, which are regulated by DSTU EN 3-7:2014. Second, the experiment did not include a comparison of the fire extinguishing efficiency of the CAF with MA in its composition with other aqueous fire extinguishing agents. This is due to the objectives of the work, which are essentially a preliminary stage to the studies reported in our paper.

Regarding the comparison of CAF with other AFAs when extinguishing solid combustible materials, the authors are mainly limited to its standard composition (water / FA / compressed gas).

Thus, study [7] compared the fire extinguishing efficiency of CAF of standard composition when extinguishing model fires of class A with water and an aqueous solution of FA. The results showed that under test conditions CAF had the highest fire extinguishing efficiency. But the authors did not compare the fire extinguishing efficiency of CAF with water and an aqueous solution of FA with the addition of MA to its composition, including $NH_4H_2PO_4$, which is due to the purpose of their research.

Work [8] compared the efficiency of the cooling capacity of water and water with FA with the cooling capacity of the jet of wet, liquid, and dry CAF. The tests were carried out using standard model fires of class 5A. The results show that CAF has the highest fire extinguishing efficiency. At the same time, the authors did not add MA to the composition of the CAF, in particular $NH_4H_2PO_4$ but limited themselves only to changing the multiplicity when comparing with other AFAs.

Study [9] is aimed at comparing the fire-extinguishing efficiency of CAF, GFC, and water when extinguishing standardized model fires of class A. It was determined that CAF with a multiplicity of 25 at a working solution concentration of FA 6% more effectively eliminates fires, by 15% and 80%, compared to GFC and water, respectively. However, in the experiments during the comparison, the authors used CAF of standard composition, without adding MA $NH_4H_2PO_4$, which is explained by the scope of those studies.

In work [10], a comparative analysis of the extinguishing efficiency of wood piles by GFC and CAF was carried out with a study of the cooling effect on the internal temperature of wood piles. The test results showed that both GFC and CAF are capable of effectively extinguishing fires in wood piles. It was found that extinguishing by GFC is more effective in terms of time and costs. However, the authors did not consider the addition of $NH_4H_2PO_4$ MA in CAF with a comparison of the cooling effect with GFC.

Paper [11] reports the development of a method for assessing the adhesive properties and thermal protection efficiency of AFAs on the surface of solid combustible material. The study used GFC and CAF. The extinguishing efficiency, adhesive properties, costs, and thermal protection index were compared. However, the authors did not pay attention to the use of CAF with $NH_4H_2PO_4$ MA to determine the extinguishing efficiency, assess thermal protection and adhesive properties.

In [12], the effectiveness of CAF, air-mechanical foam, and water in extinguishing a fire of solid combustible materials in a modular fire container was compared. During the experiment, fire extinguishing agents were directed not to the fire center but to the outer walls of the container. The authors note the advantages of foams over water, while the greatest cooling effect was established for CAF itself. In this case, CAF was used with a standard composition, without adding modified additives to its composition, including $NH_4H_2PO_4$.

In [13], the effectiveness of CAF was investigated, depending on the multiplicity when extinguishing a model fire of class A, and was also compared with the effectiveness of water. Foam with a multiplicity of 13 had the greatest fire extinguishing effect. As a result, it was determined that water is more effective than CAF with a multiplicity of up to 13. In this case, both CAF and water were used with a standard composition, without adding modified additives, including $NH_4H_2PO_4$.

In [14], the heat-shielding properties of CAF and water when applied to horizontal surfaces of sandwich panels from the thermal radiation of a model fire of class A were investigated and compared. The experimental results showed that CAF effectively forms a stable insulating barrier, maintaining the temperature significantly below critical thresholds, compared to panels treated with water. The use of CAF demonstrated better thermal protection, reducing internal temperatures by up to 67.5% compared to the conditions of water treatment. The authors used CAF of standard composition, while the use and influence of modified additives, in particular $NH_4H_2PO_4$ in the CAF composition was not investigated.

In experimental studies [15], a comparison of the fire-extinguishing properties of CAF and water for extinguishing fires in residential premises was carried out. According to the results, it was found that the cooling capacity of both CAF and water was similar, and under testing conditions it was possible to achieve successful elimination of the fire. However, CAF was used of standard composition, without the addition of $NH_4H_2PO_4$.

In [16], the efficiency of extinguishing solid combustible materials in a model of a residential building was compared with dry and wet foam, including CAF with different types of FA (AR, Class A, Class B). As a result, the shortest extinguishing time was recorded for wet foam with a FA concentration of 0.3% Class A. At the same time, the fire-extinguishing properties of CAF with the use of MA in its compositions, in particular $NH_4H_2PO_4$, were not compared in the considered work.

So, based on the results of our review of the literature [7–16], all authors considered a comparison of the fire extinguishing efficiency of CAF of standard composition when extinguishing class A fires and a further comparison with such AFAs as water, an aqueous solution of FA, and GFC.

However, studies aimed at comparing the fire extinguishing efficiency of the CAF in its composition with the $NH_4H_2PO_4$ MA when extinguishing class A fires, in particular on standardized model fires, remained outside the attention of researchers. This allows us to argue that it is advisable to conduct a study aimed at comparing the fire extinguishing efficiency of CAF with the $NH_4H_2PO_4$ MA with other AFAs when extinguishing class A fires.

3. The aim and objectives of the study

The purpose of our study is to determine the fire extinguishing efficiency of compressed air foam with a modified $NH_4H_2PO_4$ additive when extinguishing standardized model fires of class 1A. This will make it possible to obtain scientifically confirmed data for their further implementation in the formulation of foaming agents for CAF.

To achieve the goal, the following tasks were set:

– to experimentally determine the quantitative indicator of the fire extinguishing efficiency of water-based fire extinguishing agents using standardized fires regulated by DSTU EN 3-7:2014;

– to compare the extinguishing efficiency indicators of the specified water-based fire extinguishing agents with each other.

4. The study materials and methods

The object of our study is the fire extinguishing efficiency of aqueous fire extinguishing agents: compressed air foam with a modified $NH_4H_2PO_4$ additive, compressed air foam of standard composition, water, and gel-forming composition.

The hypothesis of the study assumes that compressed air foam with a modified $NH_4H_2PO_4$ additive has more effective fire extinguishing properties when extinguishing class A fires in comparison with compressed air foam of standard composition, water, and gel-forming compositions.

To form compressed air foam, the general-purpose FA "Bars S" with a concentration of 6% in an aqueous solution was used in the work, in accordance with the manufacturer's recommendations. It was assumed that foaming agents from other manufacturers would have a similar effect on fire extinguishing efficiency, including with the addition of $NH_4H_2PO_4$.

In accordance with [9], the fire extinguishing efficiency of AFA is determined by calculating the fire extinguishing efficiency indicator $I_{e.e}$ from the following formula (1)

$$I_{e.e} = \frac{s_a}{m_s \tau}, \quad (1)$$

where s_a – area of the fire, m^2; m_s – mass of water/mass of the aqueous solution of FA from which the foam was obtained, kg; t – time of extinguishing the fire, s.

The experimental model of the CAF generation and supply system (Fig. 1, *a*), which was used during the research, corresponded to the parameters given in [9].

Experimental research was carried out in accordance with DSTU EN 3-7:2014: the temperature and climatic conditions of the research met the requirements of the standard and a standardized model fire source of class 1A was used (Fig. 1, *b*).

a *b*

Fig. 1. Equipment for comparing the fire extinguishing efficiency of water-based fire extinguishing agents: *a* – compressed air foam generation and supply system; *b* – photograph of a standardized model fire of class 1A

During the study, the following parameters were measured:

– mass m_s of water, aqueous solution of FA CAF of standard composition or aqueous solution of FA CAF with MA $NH_4H_2PO_4$, which was spent on extinguishing a standardized model fire of class 1A;

– extinguishing time t of a standardized model fire of class 1A with water, CAF of standard composition, or CAF with MA $NH_4H_2PO_4$.

To compare the results obtained during extinguishing a standardized model fire of class 1A with water, CAF of standard composition or CAF with MA $NH_4H_2PO_4$ with the results of extinguishing such a GFC fire, the known results from study [17] were used. It was simplified that, taking into account the identity of the conditions of the study, the following parameters of GFC extinguishing were used for comparison: time spent on extinguishing a standardized model fire of 1A $t = 60$ s, and the spent mass of GFC $m_s = 6.53$ kg.

5. Results of investigating the fire extinguishing efficiency of aqueous fire extinguishing substances and their comparison

5. 1. Results of determining the quantitative indicator of the fire extinguishing efficiency of aqueous fire extinguishing substances using standardized

When extinguishing a standardized model fire by CAF with MA, CAF of standard composition, and water, the pressure in the CAF generation and supply system was maintained constant and equal to 6 bar. The intensity of the supply of the FA CAF solution with MA $NH_4H_2PO_4$, CAF of standard composition, and water was the same.

CAF with MA $NH_4H_2PO_4$ was used with a multiplicity $K = 18$ and a concentration of $NH_4H_2PO_4$ $C = 3\%$, which is in line with results reported in [5], which confirmed the greatest efficiency of foam with this multiplicity and MA concentration when extinguishing a laboratory fire of class A.

CAF of standard composition was used with a multiplicity $K = 25$, which is in line with [9], which confirmed the greatest efficiency of foam with this multiplicity when extinguishing a standardized model fire of class 1A.

The mass of aqueous fire extinguishing agents m_s spent on extinguishing the fire was measured by weighing the container with the fire extinguishing agent before the start of extinguishing and after complete elimination of the flame. The extinguishing time t of the fire was measured from the beginning of directing the extinguishing jet into the fire center to the moment of complete extinguishing. One experiment was conducted with 3 series in each.

Fig. 2 shows a photograph of the process of extinguishing standardized model fires of class 1A with water-based fire extinguishing agents.

Table 1 give the results of measuring m_s spent on extinguishing a standardized model fire of class 1A with water/aqueous solution of FA CAF of standard composition/aqueous solution of FA CAF with $NH_4H_2PO_4$, and the duration of extinguishing t of a standardized model fire of class 1A with water/CAF of standard composition/CAF with $NH_4H_2PO_4$.

Fig. 3 shows a graphic representation of the obtained indicators, taking into account which the extinguishing of a standardized model fire of class 1A was carried out with water extinguishing agents (water, CAF, CAF of standard composition, CAF with $NH_4H_2PO_4$).

a

b

c

Fig. 2. Photograph of the experiment: *a* – water extinguishing process; *b* – extinguishing process with compressed air foam of standard composition; *c* – extinguishing process with compressed air foam with $NH_4H_2PO_4$

Table 1

Results of experiments on extinguishing a standardized model fire of class 1A with aqueous fire extinguishing agents (water, CAF, CAF of standard composition, CAF with $NH_4H_2PO_4$)

Indicator	m_s, kg				t, s			
Experiment No.	1	2	3	$\bar{m}$	1	2	3	$\bar{t}$
	m_1	m_2	m_3		t_1	t_2	t_3	
CAF with $NH_4H_2PO_4$	5.6	6.2	5.6	5.8	48	55	44	49 s
CAF of standard composition	5.8	6.8	5.9	6.2	51	64	49	54 s
Water	13.9	10.8	11	11.9	94	108	99	100 s

Taking into account our experimental results, the next step is to determine the calculated value of the extinguishing efficiency indicators of CAF with $NH_4H_2PO_4$, CAF of standard composition, water, and GFC.

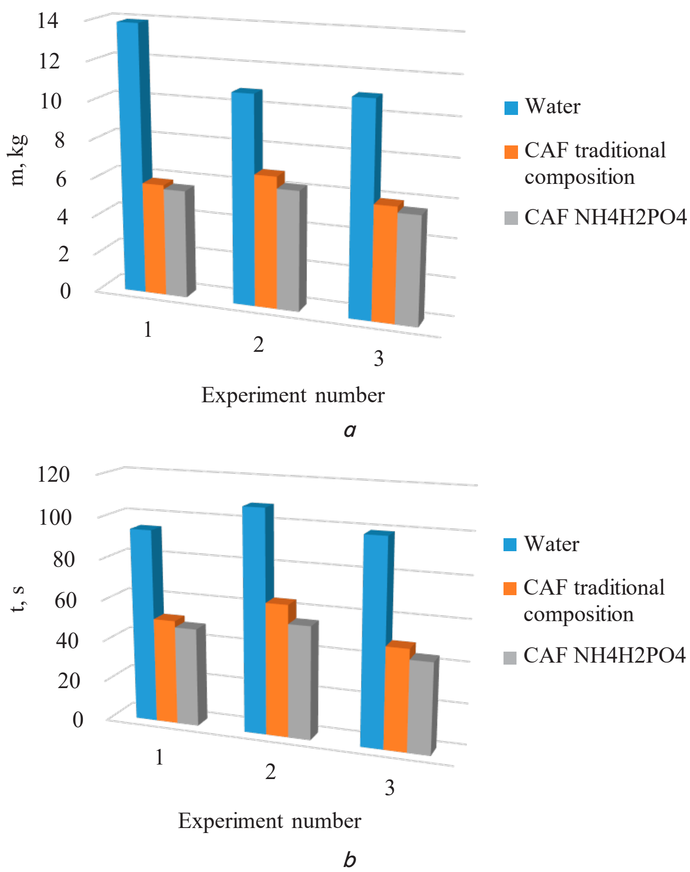

Fig. 3. Graphical representation of the resulting indicators: *a* — mass spent on extinguishing a standardized model fire of class 1A; *b* — extinguishing time of a standardized model fire of class 1A

5. 2. Results of comparing the fire extinguishing efficiency of aqueous fire extinguishing agents

The results of calculating $I_{e.e}$ from formula (1) for CAF with $NH_4H_2PO_4$, CAF of standard composition, water, and GFC are given in Table 2.

Fig. 4 shows a graphical representation of the resulting extinguishing efficiency index $I_{e.e}$ for CAF with $NH_4H_2PO_4$, CAF of standard composition, water, and GFC.

Therefore, based on our results, the values of extinguishing efficiency indicators were determined for CAF with $NH_4H_2PO_4$, CAF of standard composition, water, and GFC.

Table 2

Results of calculating $I_{e.e}$ for aqueous fire extinguishing agents

Water-based fire extinguishing agent	m_s, kg	*t*, s	*S*, m^2	$I_{e.e}$, m^2/kg·s
CAF with MA	5.8	49 c	4.7	16.5
CAF of standard composition	6.2	54 c		14.03
GFC	6.53	60 c		11.99
Water	11.9	100 c		3.94

6. Discussion of results of substantiating the effectiveness of using modified additives in compressed air foam

When analyzing our results of determining and comparing the fire extinguishing efficiency of CAF with MA $NH_4H_2PO_4$ with CAF of standard composition, water, and GFC when extinguishing standardized model fires of class 1A, the following was established.

The results (Table 1, Fig. 3) indicate that the presence of MA $NH_4H_2PO_4$ has a positive effect on the extinguishing time of a standardized model fire of class 1A in the CAF composition. Under equal conditions, the mass (Fig. 3, *a*) spent on extinguishing the fire of CAF with $NH_4H_2PO_4$ is 7% less than the mass of CAF of standard composition and 52% less than the mass of water. The difference in mass between CAF of standard composition and CAF with $NH_4H_2PO_4$ is not significant. Regarding the extinguishing time (Fig. 3, *b*), for compressed air foam with $NH_4H_2PO_4$ MA, the recorded time is 10% less than the time required to extinguish a fire with a conventional composition of CAF, and 51% less than the extinguishing time with water.

The results (Table 2, Fig. 4), obtained on the basis of experimental and reference data, demonstrate the superiority of CAF with $NH_4H_2PO_4$ over CAF with a conventional composition, water, and GFC. Under the same conditions, the highest fire-extinguishing efficiency according to the estimated indicator is recorded for CAF with $NH_4H_2PO_4$, which is 15% more than CAF with a conventional composition, 28% for GFC, and 77% for water.

Such results can be explained precisely by the presence and influence of $NH_4H_2PO_4$ MA on the fire-extinguishing properties of CAF. When heated (decomposition temperature of $NH_4H_2PO_4$ ~200–210°C), the reaction occurs: $NH_4H_2PO_4 \rightarrow NH_3 + H_3PO_4$. Ammonia ($NH_3$) dilutes combustible gases in the combustion zone, reducing the concentration of oxygen and combustion products (dilution effect). Phosphoric acid (H_3PO_4) further polymerizes into metaphosphoric acid, forming a viscous film on the surface of the solid fuel. H_3PO_4 acts as an acid catalyst for the dehydration of cellulose (the main component of class A fires), contributing to the formation of a carbon layer instead of volatile combustible gases. This blocks the access of oxygen and heat to the fuel. The large difference in mass between water and CAF is explained by the gas phase present in CAF, as well as the low content of the liquid phase.

Note a combination of several mechanisms for combustion cessation, namely cooling, insulation, and inhibition, which synergistically affects the fire extinguishing efficiency.

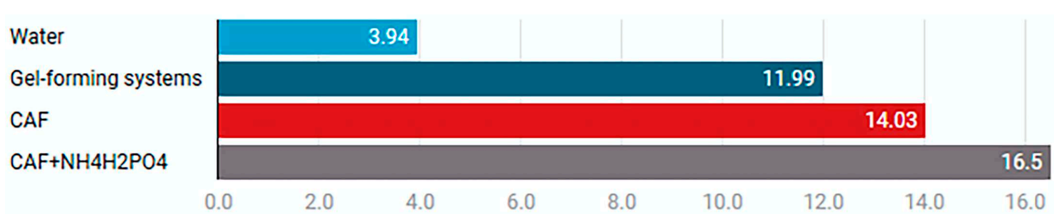

Fig. 4. Graphical representation of the resulting extinguishing efficiency indicator $I_{e.e}$ for aqueous fire extinguishing agents

Owning to our experimental results (Tables 2, 3, Fig. 3, 4), in contrast to [7–16], the fire extinguishing efficiency of compressed air foam with a modified $NH_4H_2PO_4$ additive was determined and compared with compressed air foam of standard composition, water, and gel-forming composition when extinguishing standardized model fires of class 1A.

As a limitation of the study, it should be noted that the comparison was not made with other aqueous fire extinguishing agents, in particular with wetting agents with different types of surfactants, thermally activated and finely atomized water. Also, the results regarding the fire extinguishing efficiency of the gel-forming composition are already 14 years old and today there are other compositions that were not taken into account in our study.

The disadvantage of the work is the use of one type of foaming agent, namely "Bars-S". When using other foaming agents, the fire extinguishing efficiency of compressed air foam with a modified $NH_4H_2PO_4$ additive may vary.

At this point, the study on the issue of compressed air foam with modifying additives in its composition and its use for extinguishing class A fires within certain limits is considered complete.

7. Conclusions

1. The quantitative indicator of fire extinguishing efficiency of compressed air foam with a modified $NH_4H_2PO_4$ additive, compressed air foam of standard composition, and water, when extinguishing standardized model fires of class 1A has been experimentally evaluated. When using all the specified fire extinguishing agents, successful elimination of combustion was observed. However, the lowest time and mass spent on extinguishing were established precisely for compressed air foam with $NH_4H_2PO_4$. The mass spent on extinguishing a fire with compressed air foam with $NH_4H_2PO_4$ is 7% less than the mass of compressed air foam of standard composition and 52% less than the mass of water. For compressed air foam with $NH_4H_2PO_4$, the extinguishing time was recorded to be 10% less than the time required for extinguishing a fire with compressed air foam of standard composition, and 51% less than the extinguishing time with water.

2. The extinguishing efficiency indicators of compressed air foam with a modified $NH_4H_2PO_4$ additive, compressed air foam of standard composition, gel-forming composition, and water were calculated and compared. As a result, the indicator for compressed air foam with a modified $NH_4H_2PO_4$ additive is $I_{e.e} = 16.5$ m^2/kg·s, for foam of standard composition $I_{e.e} = 14.03$ m^2/kg·s, for gel-forming composition $I_{e.e} = 11.9$ m^2/kg·s, for water $I_{e.e} = 3.94$ m^2/kg·s. Our results emphasize that the use of MA in the composition of CAF, in particular $NH_4H_2PO_4$, increases its fire-extinguishing properties when extinguishing class A fires. It has been proven that the fire-extinguishing efficiency of CAF with the MA content is 15% higher compared to the CAF of standard composition. Compared to GFC, the efficiency is 28% higher, and compared to water, it is 77% higher.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

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

Authors' contributions

Stanislav Shakhov: Conceptualization, Methodology, Writing – review & editing; **Stanislav Vynohradov:** Conceptualization, Supervision, Project administration; **Dmytry Hryschenko:** Methodology, Writing – original draft; **Andrii Melnychenko:** Resources, Writing – review & editing; **Evgen Grinchenko:** Methodology, Resources; **Liudmyla Knaub:** Validation, Writing – review & editing; **Nataliia Maslich:** Validation, Formal analysis; **Tetiana Mohylianets:** Validation, Formal analysis; **Volodymyr Pinder:** Formal Analysis, Resources, Visualization; **Yuriy Pavlyuk:** Formal analysis, Resources, Visualization.

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