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DETERMINING THE EFFECT OF MODIFIED ADDITIVES ON THE FIRE-EXTINGUISHING PROPERTIES OF COMPRESSED AIR FOAM

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The object of this study is the fire extinguishing efficiency of compressed air foam with the use of modified additives.

The main hypothesis assumes that the use of modified additives in the composition of the compressed air foam will affect its fire extinguishing efficiency when extinguishing solid combustible materials.

The task addressed is to determine the effect of modified additives in compressed air foam with a concentration range of 1–5 % on its fire extinguishing properties. The results show that for all additives, when the concentration changes from 1 % to 5 %, characteristic is a slight decrease in the consumption of an aqueous solution of the foaming agent. On the contrary, an increase in the expansion ratio results in a significant decrease in the mass of the aqueous solution of the foaming agent consumed for extinguishing. An increase in the concentration of the additive in the range of 1 % to 3 % is characterized by a decrease in the extinguishing time, while a further increase from 3 % to 5 % is characterized by an increase in the extinguishing time. Also, the increase in the foam expansion ratio has a significant effect; with an increase from 5 to 20, a decrease in the extinguishing time is observed, and with a further increase to 25, an increase in time occurs.

For the compressed air foam with $NH_4H_2PO_4$, the highest efficiency index is $I_{e.e}$≈20.15 m^2/l·s, at a modified additive concentration of C≈3 % and a foam expansion ratio of K≈18; for the compressed air foam with $(NH_4)_2HPO_4$, the highest efficiency index is $I_{e.e}$=18.04 m^2/l·s, at a modified additive concentration of C≈3 % and a foam expansion ratio of K≈18; for a compression foam with $(NH_4)_2CO_3$, the highest efficiency index is $I_{e.e}$=14.99 m^2/l·s, at a modified additive concentration C≈3 % and a foam expansion ratio of K≈18.

Thus, based on the results of experimental studies, the most effective is the compressed air foam with $NH_4H_2PO_4$. The resulting extinguishing efficiency is 11 % higher than that of the compressed air foam with $(NH_4)_2HPO_4$, and 26 % higher than that of the compressed air foam with $(NH_4)_2CO_3$

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

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1. Introduction

Class A fires, which include burning of solid combustible substances and materials, are the most common class of fires that occur in the residential sector. Water is most often used to extinguish such fires [1]. Its advantages are cheapness and ease of use, but the main disadvantage is low fire extinguishing efficiency. Only 5–10 % of the total volume of water supplied for extinguishing reaches the fire site [2]. The rest remains excessively spilled and causes secondary damage.

Increasing the fire extinguishing efficiency of water is achieved by adding modified additives (MAs), foaming agents

(FAs), and flame retardants to its composition [3]. Various water extinguishing agents have become widespread in the field of fire extinguishing, including wetting agents, gel-forming compounds, aqueous solutions of inorganic salts, combined water and water-foam extinguishing agents. However, due to the high cost and complexity of application, the vast majority of water-based fire extinguishing agents remain in the form of experimental samples and have not been fully implemented in firefighting practice.

As an alternative to water, leading countries of the world, in particular the USA, Germany, China, etc., use compressed air foam (CAF), including for extinguishing class A fires. The CAF has increased penetrating properties and resistance, adhesion, high surface tension. It is characterized by greater fire extinguishing efficiency compared to water, which is achieved due to the technological process of generation.

Therefore, research aimed at increasing compressed air foam fire extinguishing efficiency when fighting class A fires is relevant.

2. Literature review and problem statement

When considering the scientific results of studies aimed at improving the fire extinguishing properties of CAF, the authors mainly focus on its conventional composition (water/FA/compressed gas). Ways to increase the fire extinguishing efficiency of compression foam are related to both class A and class B fires. In particular, the following approaches should be noted.

Study [4] was aimed at comparing the fire extinguishing efficiency of CAF of conventional composition with different foam expansion ratio with foaming agents of the AFFF and S type. It was found that at the same feed intensity, the highest fire extinguishing efficiency was recorded for foam with an expansion ratio of 7. In turn, the lowest fire extinguishing efficiency was observed at a foaming agent/air ratio of 1:10. It is also confirmed that the film-forming FA of the AFFF type has advantages over the synthetic FA of the S type. However, it should be noted that the conventional composition of CAF was used in this case and the authors did not consider the issue of the influence of CAF expansion ratio on its fire-extinguishing efficiency in the presence of MA in its composition.

The authors of work [5] compared the fire-extinguishing efficiency of CAF with the use of class A FA with different concentrations ranging from 0.4 % to 1 %. As a result, the shortest extinguishing time was recorded when using a solution with a FA concentration of 1 % for the "dry" CAF of the conventional composition within the foam expansion ratio from 10 to 20. The results are valuable specifically for the foaming agent of class A in the composition of the water/foaming agent/air foam. However, the issue of the presence and influence of MA on the fire-extinguishing properties in the CAF composition was not considered.

In [6] it is stated that compression foam of conventional composition with an expansion ratio of 10 has the highest fire extinguishing efficiency. It was also established that the consumption of an aqueous solution of FA for successful extinguishing should be at least 0.99 $l/(min \cdot m^2)$. These results are important from an economic point of view but do not cover the detection of the influence of MA in the conventional composition of CAF on both fire extinguishing efficiency and costs.

The authors of [7] claim that when using fluorocarbon surfactants, the foam has an increased film thickness and a lower diffusion coefficient than for protein foaming agents. The study is aimed at comparing the fire extinguishing properties of CAF of conventional composition with different types of foaming agents but the addition of MA to the foam composition is not covered in the study.

In [8], the fire extinguishing efficiency of CAF of conventional composition with photosynthetic foaming agents was compared. In this case, the authors added a chemical compound (2–bromo–3,3,3–trifluoro propene) to the composition of the CAF. As a result, it was found that the extinguishing time was 43 % shorter compared to the recorded extinguishing time of the CAF without adding the chemical compound. By adding the specified compound to the conventional composition of the CAF, the fire-extinguishing properties were increased; but it should be noted that it is organic. MAs are inorganic compounds, but the authors did not study their addition to the composition of CAF and their effect on its fire-extinguishing properties.

In work [9], 4 types of FA composition were used in the conventional composition of CAF. According to the results of extinguishing methanol, an assessment was given in the form of the advantages of foaming agents as follows:

FP/AR>AFFF>AFFF/AR>S>FP>S/AR.

For diesel fuel, the following dependence was observed:

S>S/AR>AFFF>AFFF/AR>FP>FP/AR.

These results are important specifically for extinguishing class B fires, but they do not answer the question of how the fire-extinguishing properties of the specified FA would change when MA is added to the foam composition.

In [10], the influence of FA concentration in the range of 1.2 % to 12 % in the conventional composition of compression foam was determined. As a result, it was found that with increasing FA concentration, the extinguishing time increases. At a FA concentration of 12 %, the extinguishing time is 2 times shorter than the time recorded at a FA concentration of 2.2 %. Thus, the authors managed to optimize the effective FA concentration in the conventional composition of CAF, but they did not consider the addition of MA.

Paper [11] reports studying the cooling effect of CAF of conventional composition during the extinguishing of model fires of class A with FA of their own production, part of which precipitates on the surface of the burning. As a result of the experiment, it was confirmed that the CAF with this type of FA effectively eliminates the flame and prevents re-ignition, due to the sediment on the surface of the solid combustible material. The authors chose the area of increasing the cooling properties of CAF with conventional composition, through the use of individual FA. In the work, the influence of MA in the composition of CAF on its fire extinguishing properties when extinguishing solid combustible substances was not assessed.

In [12, 13], nitrogen (N_2) was used instead of air to generate the CAF, and its fire extinguishing efficiency was assessed. It was confirmed that the CAF generated by nitrogen has increased fire extinguishing properties compared to foam of conventional composition, which can be explained by a change in the extinguishing mechanism. A chemical analysis of the generated foam was carried out and the relationship between the foam expansion ratio and its stability was determined. Using infrared analysis, it was determined that the dominant extinguishing mechanism is cooling. According to the authors, CAF with nitrogen has a higher extinguishing efficiency than that generated using compressed air. The indicated changes in the fire extinguishing efficiency of CAF with nitrogen can be explained by a change in the extinguishing mechanism, namely by the addition of an inhibitory and dispersing effect. The effect of MA on the properties of CAF theoretically has similar properties in terms of changing the quenching mechanism but was not evaluated by the authors.

Our review of the literature revealed that the following approaches are used to increase the fire-extinguishing efficiency of CAF: changing the foam expansion ratio and concentration of the aqueous solution of FA; using different types of FAs; changing the feed intensity; using nitrogen (N_2) instead of air.

But scientists did not pay attention to the issues aimed at determining the influence of certain MAs in the composition of CAF on its fire-extinguishing efficiency when extinguishing class A fires. This allows us to state that it is advisable to conduct a study aimed at determining the influence of MAs in the composition of CAF on its fire-extinguishing efficiency.

3. The aim and objectives of the study

The aim of our study is to identify the influence of modified additives on the fire extinguishing properties of compressed air foam when extinguishing a class A fire. From a practical point of view, the resulting dependences could make it possible to determine the feasibility of using modified additives in compressed air foam.

To achieve the goal, the following tasks were set:

– to experimentally determine the fire extinguishing efficiency of compressed air foam with modified additives in its composition;

– to compare the extinguishing efficiency indicators of compressed air foam with modified additives with each other.

4. The study materials and methods

The object of our study is the fire extinguishing efficiency of compressed air foam with the addition of modified additives.

The main hypothesis assumes that the use of modified additives in the composition of compressed air foam would affect its fire extinguishing efficiency when extinguishing solid combustible materials.

Based on the results of previous studies [14], the following MAs were selected: ammonium dihydrogen orthophosphate $NH_4H_2PO_4$ ammonium hydrogen phosphate $(NH_4)_2HPO_4$; ammonium carbonate $(NH_4)_2CO_3$. To generate foam, the general-purpose FA “Bars S” was used, with a concentration of 6 % in an aqueous solution according to the manufacturer’s recommendations.

The MA concentration limits in the composition of CAF varied from 1 % to 5 %, taking into account the experience of predecessors reported in [14]. The compressed air foam expansion ratio varied according to the Guide for the Use of Class [15] A standard in the range from 5 to 25.

The fire-fighting efficiency of CAF with MA was estimated by calculating the extinguishing efficiency index $I_{e.e}$ [16] according to formula (1):

$$I_{e.e}=\frac{s_f}{m_p\tau}, \tag{1}$$

where s_f is the area of the fire, m^2; m_p – mass of the aqueous solution of FA from which the foam was obtained, kg; t – time of extinguishing the fire, s.

During the study, a designed prototype of the CAF generation and supply system was used [17], which is shown in Fig. 1, *a*. During the study, laboratory class A fire sources were used, which are widely used in determining the fire extinguishing ability of various fire extinguishing agents [18–20]. The laboratory fire source has the following parameters: a stack of 32 bars measuring (20×20×150) mm, laid in 8 layers of 4 bars each; the distance between the bars in a row is 20 mm; the total area of the bars is 0.41 m^2. The open burning surface of the fire source (after subtracting the overlap areas of the bars) is 0.32 m^2. Fig. 1 shows the equipment used in the experiment.

a

b

Fig. 1. Equipment for studying the fire extinguishing efficiency of compressed air foam: *a* – a laboratory sample of the compressed air foam generation and supply system; *b* – image of a laboratory fire

The experiment was planned according to the recommendations set out in [21]. The research was carried out according to the second-order plan, to obtain second-power equations. The parameters that were measured and the parameters that changed during the research are given below:

$y=m_p$ – mass of aqueous solution of FA CAF with MA, spent on extinguishing the model fire;

$z=t$ – time of extinguishing the model fire of CAF with MA;

$x_1=C$ – concentration of the modified additive in the aqueous solution of FA CAF;

$x_2=k$ – foam expansion ratio of CAF.

Table 1 gives code value of the factors for establishing variance intervals.

Based on the experimental plan, measurements were performed of such parameters as the mass of the aqueous solution of FA with MA spent on extinguishing and the duration of extinguishing the laboratory fire by CAF. These parameters are necessary to determine the indicator of the extinguishing efficiency of CAF.

Table 1

Factor coding

Interval of variance and level of factors	Concentration of MA (C, %)	CAF expansion ratio (k)
Level zero x_i=0	3	15
Interval of variance δ_i	2	10
Lower level x_i=–1	1	5
Upper level x_i=+1	5	25
Code designation	x_1	x_2

5. Results of detecting the influence of modified additives on the fire extinguishing properties of compressed air foam when extinguishing a class A fire

5. 1. Results of determining the fire extinguishing efficiency of compressed air foam with modified additives in its composition

During extinguishing, the pressure in the CAF generation and supply system was 6 bar and did not change. The system barrel valves were adjusted in such a way as to ensure the ratio of the FA/air aqueous solution, respectively, of 1:5; 1:15: 1:25, which corresponds to the foam expansion ratio of 5;15;25 according to the plan. The concentration of MA in the CAF composition was 1 %; 3 %; 5 %. The FA aqueous solution with the corresponding MA concentration was prepared in advance according to the method described in [22].

Using the adjusted barrel, the laboratory fire was extinguished. The CAF jet was initially directed to the front surface of the laboratory fire. Further, according to the procedure for conducting tests set out in DSTU EN 3–7:2014, extinguishing was continued, directing the jet to the upper, lower, and side surfaces (except for the back surface). We waited 10 minutes after the elimination of the flame in the laboratory fire source; it was considered extinguished if during that time there was no visible flame in it. The appearance of short-term flashes during the specified time after the end of extinguishing was not taken into account. Fig. 2 shows a photograph of the process of working moments during the experiment.

a *b*

Fig. 2. Photographs of the experiment: *a* – extinguishing process; *b* – measurement of the necessary parameters

Table 2 gives the results of measuring m_p spent on extinguishing, and the duration of extinguishing t by CAF with $NH_4H_2PO_4$, according to the second-order plan.

Table 2

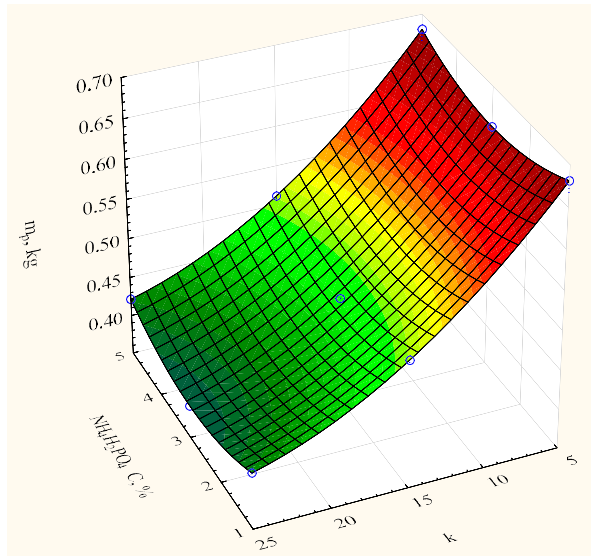
Results of experiments on extinguishing a model fire by CAF with $NH_4H_2PO_4$ according to the second-order plan

No.	C, % %	k	m, kg			t, s		
	x_1	x_2	1	2	$\bar{m}$	1	2	$\bar{t}$
			m_1	m_2		t_1	t_2	
1	1	5	0.67	0.73	0.7	69	67	68
2	5	5	0.66	0.73	0.695	72	77	74.5
3	1	25	0.4	0.45	0.425	54	55	54.5
4	5	25	0.38	0.43	0.405	55	57	56
5	1	15	0.49	0.51	0.5	41	39	40
6	5	15	0.52	0.49	0.505	38	37	37.5
7	3	5	0.63	0.62	0.625	64	65	64.5
8	3	25	0.39	0.41	0.4	46	47	46.5
9	3	15	0.51	0.49	0.5	32	34	33

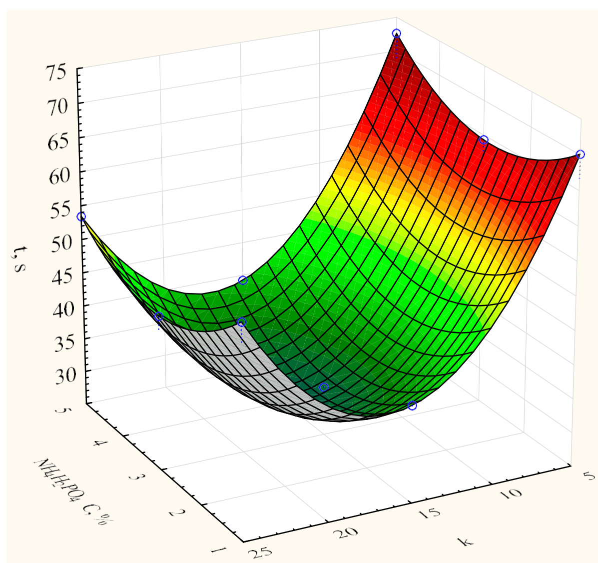
Based on the methodology from [21], after processing statistical data, the check was carried out according to the Fisher criterion:

$$F_y = 0.802 < F_{(0.05;3;4)} = 6.59; \quad F_z = 2.96 < F_{(0.05;3;4)} = 6.59.$$

Fig. 3 shows the dependence of the influence of $NH_4H_2PO_4$ on the fire-extinguishing properties of CAF.



a



b

Fig. 3. Dependence plots: *a* – consumption m_p of compressed air foam when extinguishing a model fire source on $NH_4H_2PO_4$ C and k; b – time of extinguishing a model fire source with compressed air foam on $NH_4H_2PO_4$ C and k

Table 3 gives the results of measuring m_p spent on extinguishing, and the duration of extinguishing t by CAF with $(NH_4)_2HPO_4$ according to the second-order plan.

Based on the methodology from [21], after processing statistical data, the check was carried out according to the Fisher criterion:

$$F_y = 0.669 < F_{(0.05;3;4)} = 6.59.$$

$$F_z = 2.99 < F_{(0.05;3;4)} = 6.59.$$

Fig. 4 shows the dependence of $(NH_4)_2HPO_4$ influence on the fire extinguishing properties of CAF.

Table 4 gives the results of measuring m_p spent on extinguishing, and the duration of extinguishing t by CAF with $(NH_4)_2CO_3$ according to the second-order plan.

Based on the methodology from [21], after processing statistical data, the check was carried out according to the Fisher criterion:

$$F_y = 0.787 < F_{(0.05;3;4)} = 6.59;$$

$$F_z = 2.97 < F_{(0.05;3;4)} = 6.59.$$

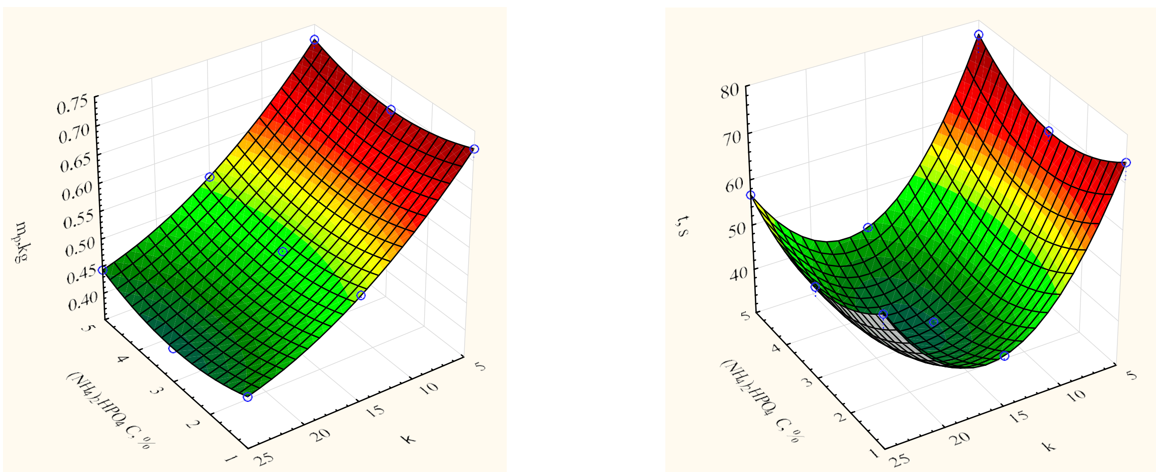
Fig. 5 shows the dependence of $(NH_4)_2CO_3$ influence on the fire extinguishing properties of CAF.

Taking into account our experimental results, the next step is to determine the calculated value of the extinguishing efficiency indicators of compressed air foam with modified additives and compare them.

Table 3

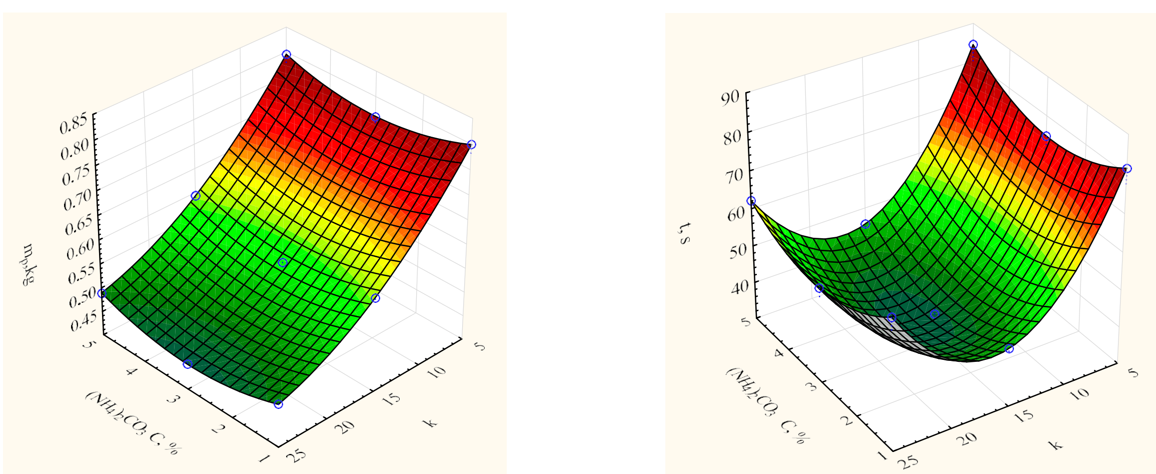
Results of experiments on extinguishing a model fire by CAF with $(NH_4)_2HPO_4$ according to the second-order plan

No.	C, % %	k	m_p, kg			t, s		
	x_1	x_2	1	2	$\bar{m}$	1	2	$\bar{t}$
			m_1	m_2		t_1	t_2	
1	1	5	0.71	0.77	0.74	73.01	70.90	71.96
2	5	5	0.70	0.77	0.735	76.19	81.48	78.84
3	1	25	0.42	0.48	0.45	57.14	58.20	57.67
4	5	25	0.40	0.46	0.43	58.20	60.31	59.26
5	1	15	0.52	0.54	0.53	43.38	41.27	42.33
6	5	15	0.55	0.52	0.535	40.21	39.15	39.68
7	3	5	0.67	0.66	0.665	67.72	68.78	68.25
8	3	25	0.41	0.43	0.42	48.67	49.73	49.2
9	3	15	0.54	0.52	0.53	33.86	35.98	34.92



a *b*

Fig. 4. Dependence plot:
a – consumption m_p of compressed air foam when extinguishing a model fire source on $(NH_4)_2HPO_4$ C and k;
b – time of extinguishing a model fire source with compressed air foam on $(NH_4)_2HPO_4$ C and k



a *b*

Fig. 5. Dependence plots:
a – consumption m_p of compressed air foam when extinguishing a model fire source on $(NH_4)_2HPO_4$ C and k;
b – time of extinguishing a model fire source with compressed air foam on $(NH_4)_2HPO_4$ C and k

Table 4

Results of experiments on extinguishing a model fire by CAF with $(NH_4)_2CO_3$ according to the second-order plan

No.	C, % %	k	m_p, kg			t, s		
	x_1	x_2	1	2	$\overline{m}$	1	2	$\overline{\tau}$
			m_1	m_2		τ_1	τ_2	
1	1	5	0.78	0.85	0.815	80.23	77.91	79.07
2	5	5	0.77	0.85	0.81	83.72	89.53	86.63
3	1	25	0.47	0.52	0.495	62.79	63.95	63.37
4	5	25	0.44	0.5	0.47	63.95	66.28	65.12
5	1	15	0.57	0.59	0.58	47.67	45.35	46.51
6	5	15	0.6	0.57	0.585	44.19	43.02	43.61
7	3	5	0.73	0.72	0.725	74.42	75.58	75
8	3	25	0.45	0.48	0.465	53.49	54.65	54.07
9	3	15	0.59	0.57	0.58	37.21	39.53	38.37

5. 2. Results of comparing fire extinguishing efficiency of compressed air foam with modified additives

Calculation of $I_{e.e}$ according to formula (1) for CAF with $NH_4H_2PO_4$, $(NH_4)_2HPO_4$ and $(NH_4)_2CO_3$ are given in Tables 5–7, respectively.

Table 5

Results of calculating $I_{e.e}$ for CAF with $NH_4H_2PO_4$

No.	k	C, %	m_p, kg	t, s	S_f, m²	$I_{e.e}$, m²/l·s
1	5	1	0.68	70.1	0.32	6.713
2	5	5	0.6813	72.603		6.469
3	25	1	0.4213	55.943		13.577
4	25	5	0.3813	53.44		15.704
5	15	1	0.5113	39.19		15.97
6	15	5	0.5113	39.193		15.9
7	5	3	0.6513	64.273		7.644
8	25	3	0.3913	47.613		17.176
9	15	3	0.4813	32.113		20.704

Table 6

Results of calculating $I_{e.e}$ for CAF with $(NH_4)_2HPO_4$

No.	k	C, %	m_p, kg	t, s	S_f, m²	$I_{e.e}$, m²/l·s
1	5	1	0.72	74.3	0.32	5.982
2	5	5	0.7234	76.937		5.75
3	25	1	0.4434	59.297		12.17
4	25	5	0.4434	56.66		12.74
5	15	1	0.5418	41.28		14.308
6	15	5	0.5418	41.277		14.31
7	5	3	0.6918	68.116		6.791
8	25	3	0.4118	50.477		15.396
9	15	3	0.5101	33.776		18.573

Fig. 6 shows the response surfaces of $I_{e.e}$ dependence on $NH_4H_2PO_4$, $(NH_4)_2HPO_4$ and $(NH_4)_2CO_3$ *C* and CAF *k*.

The regression equations that describe the resulting dependence are given by formulas (2) to (4):

– for $NH_4H_2PO_4$:

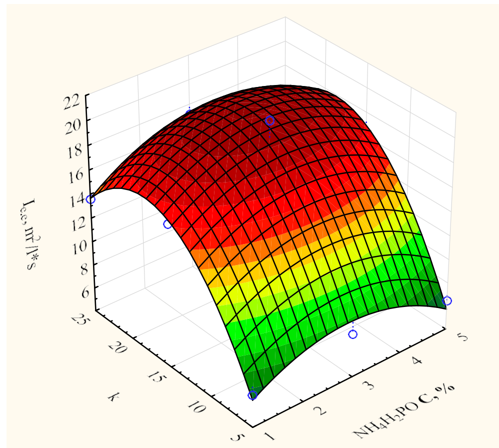
$$I_{e.e} = -6.63 + 3.87 \cdot C + 2.23 \cdot K - -0.69 \cdot C^2 - 0.063 \cdot K^2 + 0.0296 \cdot C \cdot K; \quad (2)$$

– for $(NH_4)_2HPO_4$:

$$I_{e.e} = -6.97 + 3.94 \cdot C + 2.11 \cdot K - -0.67 \cdot C^2 - 0.059 \cdot K^2 + 0.021 \cdot C \cdot K; \quad (3)$$

– for $(NH_4)_2CO_3$:

$$I_{e.e} = -5.84 + 3.3 \cdot C + 1.7 \cdot K - -0.56 \cdot C^2 - 0.004 \cdot K^2 + 0.0077 \cdot C \cdot K. \quad (4)$$



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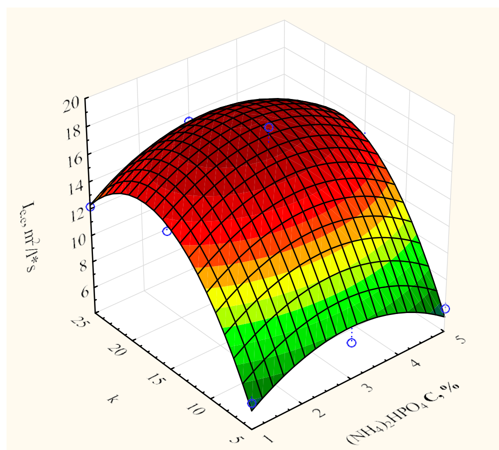

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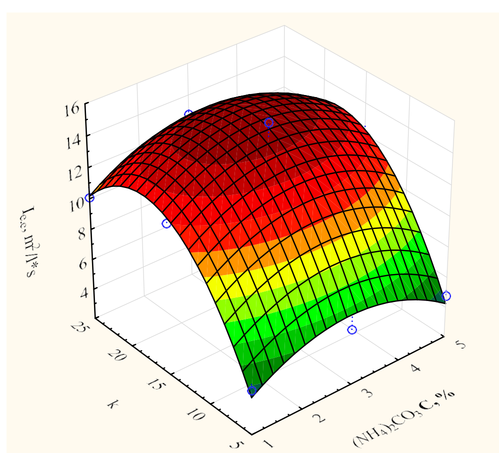

c

Fig. 6. Dependence of compressed air foam $I_{e.e}$ on *C* and *k* for: *a* – $NH_4H_2PO_4$; *b* – $(NH_4)_2HPO_4$; *c* – $(NH_4)_2CO_3$

Table 7

Results of calculating $I_{e.e}$ for CAF with $(NH_4)_2CO_3$

No.	k	C, %	m_p, kg	t, s	S_f, m²	$I_{e.e}$, m²/l·s
1	5	1	0.8	81.52	0.32	4.907
2	5	5	0.7953	84.429		4.766
3	25	1	0.4886	65.049		10.068
4	25	5	0.4886	62.14		10.54
5	15	1	0.5936	45.57		11.83
6	15	5	0.5936	45.574		11.83
7	5	3	0.7594	74.741		5.64
8	25	3	0.4527	55.361		12.768
9	15	3	0.5578	37.337		15.366

Considering the resulting response surfaces in Fig. 6, the next step was to study them and search for a conditional extremum. Thus, the following was obtained:

– for $NH_4H_2PO_4$ at C=3.18 % and k=18.44, an extremum point was established. In this case, the value of $I_{e.e}$=20.15 m²/l·s;

– for $(NH_4)_2HPO_4$ at C=3.04 % and k=18.05, an extremum point was established. In this case, the value of $I_{e.e}$=18.04 m²/l·s;

– for $(NH_4)_2CO_3$ at C=3.04 % and k=18.09, an extremum point was established. In this case, the value of $I_{e.e}$=14.99 m²/l·s.

6. Discussion of results regarding the substantiation of effectiveness of the use of modified additives in the composition of compressed air foam

From the analysis of the response surface (Fig. 3, *a*) it is clear that the foam expansion ratio has a significant effect on the reduction of the mass of the aqueous solution of the foaming agent with the modified $NH_4H_2PO_4$ additive. An increase or decrease in the concentration of the modified $NH_4H_2PO_4$ additive has a minor effect. Thus, the smallest mass of the foaming agent required to extinguish a laboratory fire is observed at a foam expansion ratio of 25 and a MA concentration of 3 % and is 0.318 kg, as evidenced by the results in Table 2. This is 54 % less than the mass of the FA aqueous solution, at a foam expansion ratio of 5 and a MA concentration of 1 %. This effect can be explained precisely by the amount of air in the generated foam, since with an increase in the foam expansion ratio, the amount of air increases. When analyzing the response surface (Fig. 3, *b*), which reflects the dependence of extinguishing time on the concentration of the modified $NH_4H_2PO_4$ additive and the foam expansion ratio, a significant effect of both the MA concentration and the foam expansion ratio was found. In contrast to the results obtained during the analysis of the influence of MA concentration on the mass of an aqueous foaming agent solution, the shortest extinguishing time was established precisely at an additive concentration of approximately 3 % and a foam expansion ratio within 15. From the lowest extinguishing time indicator, which is 72.6 seconds, with the specified foam parameters (K=5; C=1 %), the extinguishing time decreases by 56 %, as evidenced by the results in Table 2. This effect can be explained precisely by the presence of an inhibitory effect in the compressed air foam, which was obtained by adding a modified additive to its composition in a certain concentration.

The presence and effect of $(NH_4)_2HPO_4$ is similar in nature to the effect of NH_4HPO_4 on the flow rate of the aqueous foaming agent solution, as evidenced by the obtained response surface in Fig. 4, *a*. When increasing or decreasing the concentration of $(NH_4)_2HPO_4$, there is a slight effect on the flow rate of the aqueous solution. The smallest mass of foaming agent that was consumed to extinguish the laboratory fire is also observed at a foam expansion ratio of 25 and a MA concentration of 3 % and was 0.41 kg. This is 44 % less than the mass of the aqueous FA solution, at a foam expansion ratio of 5 and a MA concentration of 1 %, as evidenced by the results in Table 3. This effect can also be explained by the amount of air in the foam generated. When the foam expansion ratio increases, the gas phase increases. The use of $(NH_4)_2HPO_4$ in an aqueous solution of FA compressed air foam has a similar nature to the effect of NH_4HPO_4 on the extinguishing time of a laboratory fire, as evidenced by Fig. 4, *b*. Therefore, the concentration of $(NH_4)_2HPO_4$ along with the foam expansion ratio has a significant effect on the time. The shortest extinguishing time was also recorded at an additive concentration of 3 % and a foam expansion ratio of 15. The longest extinguishing time was established at a foam expansion ratio of 5 with an additive concentration of 1 %. The difference between the obtained experimental values is 52 %, as evidenced by the results in Table 3. This effect confirms the previously put forward hypothesis regarding the increase in the fire extinguishing ability of compressed air foam due to the use of modified additives. At the same time, the most effective concentration of MA was found.

When using the $(NH_4)_2CO_3$ additive in the composition of compressed air foam, a similar pattern is observed in the consumption of the aqueous solution of the foaming agent, as when using NH_4HPO_4 and $(NH_4)_2HPO_4$, which is shown in Fig. 5, *a*. At a foam expansion ratio of 25 and an additive concentration of 1 %, the mass of the foaming agent solution consumed for extinguishing is 0.81 kg, which is 46 % more than the mass of the aqueous FA solution consumed for extinguishing, at a foam expansion ratio of 25 and an additive concentration of 3 %, as evidenced by the results in Table 3. This is also a previously confirmed dependence, namely that increasing the foam expansion ratio has a direct effect on the amount of air in the solution. And the presence of a low content of the additive does not significantly affect the consumption of the solution. The $(NH_4)_2CO_3$ additive, as in the case of NH_4HPO_4 and $(NH_4)_2HPO_4$ together with the foam expansion ratio has a positive synergistic effect on the extinguishing time, which is shown in Fig. 5, *b*. The shortest extinguishing time was established at an additive concentration of approximately 3 % and a foam expansion ratio within 20. With the specified parameters, the extinguishing time is 38.3 seconds, which is 48 % less compared to the extinguishing time with foam with a foam expansion ratio of 5 with an additive concentration of 1 %, which is confirmed by the data presented in Table 3. Therefore, the obtained results also give grounds to assert that changing the concentration of modified additives has a positive effect on the fire extinguishing ability of compressed air foam. This is explained by the peculiarity of the chemical composition of such MAs.

The resulting response surface in Fig. 6 indicates a significant change in the extinguishing efficiency index within certain limits when changing both the foam expansion ratio and the concentration of MA. The highest index was recorded at a foam expansion ratio of 15 and a concentration of $NH_4H_2PO_4$, which is equal to 20.7 m²/l·s. This is 68 % higher than the lowest value of the extinguishing efficiency index of 6.46 m²/l·s, which was established for foam with a foam expansion ratio of 5 with a concentration of MA of 5 %. A significant effect of both the foam expansion ratio and the concentration on the extinguishing efficiency index with $(NH_4)_2HPO_4$ MA is also observed, as for $NH_4H_2PO_4$. The highest index was recorded at a foam expansion ratio of 15 and a concentration of $(NH_4)_2HPO_4$, which is equal to 18.57 m^2/l·s. This is 69 % higher than the lowest value of the extinguishing efficiency index of 5.74 m^2/l·s, which was also established for foam with a foam expansion ratio of 5 with a concentration of MA of 5 %. Analyzing the response surface of the dependence of the change in the extinguishing efficiency index $I_{e.e}$ on the foam expansion ratio of foam K and the concentration of $(NH_4)_2CO_3$, the characteristics of the impact are similar both with $(NH_4)_2HPO_4$ and with $(NH_4)_2HPO_4$. The highest indicator was recorded at a foam expansion ratio of 15 and a concentration of $(NH_4)_2CO_3$, which is equal to 15.36 m^2/l·s. This is 69 % higher than the lowest value of the extinguishing efficiency index of 4.9 m^2/l·s, which was also established for foam with a foam expansion ratio of 5 with a concentration of MA of 5 %.

Given our experimental results (Tables 5–7, Fig. 6), in contrast to [4–13], the dependence of the fire-extinguishing efficiency of compressed air foam on the presence of modified additives in its composition has been revealed.

A limitation of the study is that the experiments were conducted on laboratory fire sources and therefore require further refinements on standardized larger fires.

The disadvantages of this study include the fact that the results of the study of the influence of types and concentrations of modified additives on the fire-extinguishing efficiency of foam relate to using one type of foaming agent "Bars–S". In the case of using other types of foaming agents, the effect of these modified additives may vary.

Therefore, the further development of the study involves comparing the fire-extinguishing efficiency of compressed air foam with the modified $NH_4H_2PO_4$ additive in its composition with compressed air foam of conventional composition and water.

7. Conclusions

1. When determining the fire extinguishing efficiency of compressed air foam with modified additives in its composition, their influence on the extinguishing time of a laboratory fire and the consumption of an aqueous solution of the foaming agent was established. All additives are characterized by a non-significant decrease in the consumption of an aqueous solution of FA when the concentration of the MA changes from 1 % to 5 %. The consequence of increasing the foam expansion ratio, on the contrary, is a significant decrease in the mass of the aqueous solution of the foaming agent consumed for extinguishing. Regarding the extinguishing time, with an increase in the concentration of the additive in the range from 1 to 3 %, a decrease in the extinguishing time is inherent, with a further increase from 3 % to 5 %, a characteristic increase in the extinguishing time. Also, an increase in the foam expansion ratio of the foam has a significant effect, in particular, with an increase from 5 to 20, a decrease in the extinguishing time is observed, and with a further increase to 25, an increase in the time occurs.

2. The results of comparing the fire extinguishing efficiency of compressed air foam with modified additives with each other have determined the following: for compressed air foam with modified $NH_4H_2PO_4$ additive, the highest efficiency index was $I_{e.e}\approx20.15$ m^2/l·s, at a concentration of MA C≈3 % and a foam expansion ratio $K\approx18$; for compressed air foam with modified $(NH_4)_2HPO_4$ additive, the highest efficiency index was $I_{e.e}=18.04$ m^2/l·s, at a concentration of MA C≈3 % and a foam expansion ratio $K\approx18$; for compressed air foam with modified $(NH_4)_2CO_3$ additive, the highest efficiency index was $I_{e.e}=14.99$ m^2/l·s, at a concentration of MA C≈3 % and a foam expansion ratio $K\approx18$. Thus, based on the results of experimental studies and their evaluation, the most effective is compressed air foam with $NH_4H_2PO_4$. The resulting extinguishing efficiency is 11 % higher than that of CAF with $(NH_4)_2HPO_4$ and 26 % higher than that of CAF with $(NH_4)_2CO_3$.

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.

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