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INFLUENCE OF MODIFIED ADDITIVES ON THE PROPERTIES OF COMPRESSED AIR FOAM

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The object of this study is the properties of compressed air foam with the use of modified additives: its drainage time and expansion ratio.

The main properties of compressed air foam that affect the effectiveness of fire extinguishing are its drainage time and expansion ratio. At the same time, a number of authors have confirmed that the introduction of chemically modified additives into the composition of water fire extinguishing substances makes it possible to increase the effectiveness of fire extinguishing.

The problem to be solved was to determine the influence of five modified additives $(NH_4)_2HPO_4$, $NH_4H_2PO_4$, $(NH_4)_2CO_3$, K_2CO_3 and KCl in the concentration range of 1–5 % by mass on the expansion ratio and drainage time of the compressed air foam. The results showed that the content of additives $(NH_4)_2HPO_4$, $NH_4H_2PO_4$ and $(NH_4)_2CO_3$ in the aqueous solution of the foaming agent does not affect its expansion ratio within the given limits. On the other hand, with K_2CO_3 and KCl additives, it was not possible to obtain compressed air foam with a expansion ratio of 5–20, that is, their inefficiency in compressed air foam was noted.

The characteristic dependence of the effect of $(NH_4)_2HPO_4$, $NH_4H_2PO_4$ and $(NH_4)_2CO_3$ additives on drainage time has been determined. The greatest drainage time is characteristic of the K≈20 generation mode. The highest recorded drainage time index was established for $NH_4H_2PO_4$, namely 5.45 min; for $(NH_4)_2HPO_4$ the drainage time was lower by 8 %; for $(NH_4)_2CO_3$ the drainage time was lower by 20 %. At the same time, with the use of $(NH_4)_2HPO_4$, $NH_4H_2PO_4$ and $(NH_4)_2CO_3$, it is characteristic to obtain a foam with lower drainage time compared to foam of a conventional composition. Thus, for foam with a expansion ratio of K≈20, the drainage time of foam with $NH_4H_2PO_4$ is lower by 17 %, with $(NH_4)_2HPO_4$ by 23 %, and with $(NH_4)_2CO_3$ by 33 %.

The effect of reducing the drainage time of the foam can have a decisive role in reducing its effectiveness when used for extinguishing flammable liquids due to the extinguishing mechanism but is not decisive for extinguishing solid substances. Therefore, the fire-extinguishing effectiveness of compressed air foam with modified additives during the extinguishing of solid combustible materials in comparison with the conventional CAF composition requires further study

Keywords: compressed air foam, modified additives, drainage time, expansion ratio, properties, compressed air foam systems

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1. Introduction

Today, water is the most common extinguishing agent for extinguishing 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 center of the fire [2]. The rest remains excessively spilled and causes secondary damage. Increasing the fire-extinguishing efficiency of water is achieved by forming its solution with modified additives (hereinafter MAs), which are inorganic compounds of salts, foaming agents (hereinafter FAs), and flame inhibitors.

Compressed air foam (hereinafter CAF) has become widespread in the form of industrial samples of fire extinguishing systems among the leading countries of the world, in particular the USA, Germany, China, etc. It is used for extinguishing fires of both solid materials (class A) and flammable liquids (class B). CAF has increased penetrating property and drainage time, 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 in special systems (Compressed air foam systems). Typically, in terms of its content, CAF is formed from an aqueous solution of FA (water+surface-active substances) and compressed air.

The main properties of CAF are expansion ratio and drainage time. They depend, among other things, on the composition of the FA aqueous solution from which the foam is obtained [3]. The effectiveness of fire extinguishing depends on drainage time and expansion ratio, therefore, studying the influence of the composition of the aqueous solution of FA in CAF on its properties is an urgent task in the field of fire extinguishing.

2. Literature review and problem statement

When examining the scientific results of research on the properties of CAF, we have revealed the following.

In [4], the authors conducted a study on the analysis of the distribution of foam bubbles by diameters, formed using CAFS technology. The geometric dimensions of CAF were compared with the dimensions of the foam formed by the air-mechanical method. During the study, the parameters of the ratio of air/aqueous solution of the foaming agent were changed. The authors determined that with the help of CAFS technology, the bubbles formed are more homogeneous, and the foam is highly dispersed, compared to the parameters of air-mechanical foam bubbles. At the same time, the study did not consider the influence of the parameters of the foaming agent solution on the expansion ratio and drainage time of CAF.

In [5], the authors reported a study on varying the ratio of FA aqueous solution/air, pressure in the system (CAFS), and geometric parameters of 5 types of different nozzles for supplying CAF on its drainage time and expansion ratio. In it, the parameters of the geometric nozzles, their radius, diameter, depth, and hole design varied. The expansion ratio and drainage time of CAF with and without nozzles were also compared. In turn, the authors claim that the ratio of FA solution and compressed air has the primary influence on the specified parameters. System pressure was a secondary factor, and nozzle configuration had no significant effect. It was determined that for "dry foam" with a expansion ratio range of 10–20, the resistance is greater, relative to "wet" and "moist" types of foam. In the study, the authors used a class A foaming agent without extraneous impurities that can significantly affect the properties of the foam.

The authors of [6] in part of the research revealed the dependence of CAF drainage time on its expansion ratio from the use of film-forming FA AFFF with a concentration of 3 % in an aqueous solution. According to the results of research, it was established that the CAF with a expansion ratio of 4 has a drainage time of 1 min 50 s. A further increase in the expansion ratio to 7 is accompanied by a 2.4-fold increase in drainage time and is equal to 3 min 41 s. With an increase in the expansion ratio to 10, there is no significant increase in drainage time, but on the contrary, it decreases to 3 min 27 s. The reason for this may be the quality composition of the aqueous solution of the foaming agent from which this foam is obtained. However, this effect was not investigated in the work.

In study [7], the authors evaluated the dependence of the flow rate of an aqueous solution of FA in the range of 0.1–3 l/min with a concentration of FA of 1 %, and the influence of the flow rate of compressed air in the range of 12–14 l/min on the expansion ratio of CAF. The authors found that an increase in the consumption of compressed air and aqueous FA solution is accompanied by a decrease in the expansion ratio of the foam. Thus, the lowest expansion ratio of foam 4 was obtained with the consumption ratio of FA aqueous solution and compressed air of 3/14 l/min. A decrease in the flow rate of an aqueous FA solution to 1.5 l/min with a compressed air flow rate of 13 l/min is accompanied by an increase in the expansion ratio to 10. The highest expansion ratio of 14 was recorded with a flow rate of an aqueous FA solution below 0.5 l/min to ensure a compressed air supply of 12 l/min. The authors also established the relationship between expansion ratio and foam drainage time. As a result of increasing the expansion ratio of foam from 4 to 20, resistance increases from 100 to 950 seconds. Such results are correlated with the studies of many authors, but do not answer the question of the influence of modified additives on the properties of compressed air foam.

The authors of [8] determined the interrelationship of the influence of the ratio of consumption of an aqueous solution of FA/air on the expansion ratio of CAF with a further assessment of its drainage time. It was determined that increasing the expansion ratio of the foam from 20 to 26 leads to a decrease in the drainage time of the foam by 1.6 times. At the same time, it is not clear from the work whether the composition of the aqueous solution of the foaming agent affects the indicated indicators.

In work [9], the viscosity and drainage time of CAF with FA AFFF were studied, adding chemical compounds to its composition. Carboxymethylcellulose, xanthan copper, triethanolamine and lauryl alcohol were added to the composition of FA. The mass concentration in AFFF was varied in the range of 0–2 %, 0–0.4 %, 0–4 %, and 0–3 %, respectively. As a result, it was established that the drainage time of the foam increases with the addition of carboxymethyl cellulose and xanthan but decreases with the addition of triethanolamine and lauryl alcohol. The highest foam drainage time was established for AFFF FA foam containing 0.4 % xanthan copper. It is worth noting that the additives that were added to the aqueous FA solution were chosen by the authors among organic compounds and do not include inorganic modified additives that can have a different effect on the properties of the CP.

The authors of [10] evaluated the properties of CAF, in particular expansion ratio, drainage time and viscosity using film-forming FA, with the addition of different concentrations of xanthan copper in the range of 0.1–0.5 %. According to the results, it was determined that the content of the additive has a slight effect on the surface tension of the solutions but has an effect on the viscosity. Also, the additive did not have a negative effect on the expansion ratio of the generated foam but increased its drainage time. The optimal content of xanthan copper, which was observed to increase the drainage time and decrease the viscosity of CAF, was 0.3 %.

In study [11], the influence of three sizes of nozzles of the CAFS system for supplying CAF, 200 mm long with holes with a diameter of 5 mm, 10 mm, and 20 mm, was studied on the size of the bubbles of the foam formed. Thus, the average diameter of the foam bubbles for a nozzle with an opening of 5 mm was 1.6 mm. An increase in the average bubble diameter to 1.68 mm was observed when the nozzle diameter increased to 10 mm. When using a nozzle with a diameter of 20 mm, the largest diameter of the bubbles was recorded, which is 1.78 mm. Thus, the authors claim a linear correlation between the size of the nozzle and the size of the bubble. It is also noted that when the diameter of the nozzle is reduced, highly dispersed foam is generated, which is characterized by increased drainage time. At the same time, the work did not evaluate the composition of the aqueous solution of the foaming agent on the properties of the foam.

One of the tasks in study [12] determined the relationship between the expansion ratio and drainage time of the foam using a 3 % concentration of FA AFFF. In the study, foam expansion ratio 7, 10, 16, 24 were compared. The shortest time was recorded for foam with expansion ratio 7, which was 176 seconds. A further increase in the expansion ratio to 10 was accompanied by an almost 2-fold increase in drainage time and amounted to 316 s. When increasing the expansion ratio to 16, no significant change in foam drainage time was recorded, the difference was 37 s. The highest drainage time of the foam, namely 446 s, is characteristic of the foam with a expansion ratio of 24. The authors emphasize that the drainage time of the foam increases as the expansion ratio increases. The authors also did not evaluate the influence of modified additives on the properties of compressed air foam.

The authors of [13] investigated the influence of the geometric parameters of static mixers in CAFS on the formation of CAF with a conventional composition. The relationship between the ratio of the sides of the elements, the angle of transition and the number of elements on the expansion ratio of the generated foam was established. In particular, the drainage time of the generated foam was evaluated. The optimal structure, which ensures the formation of highly dispersed stable foam, was substantiated. The influence of modified additives on the properties of compressed air foam was not evaluated by the authors, as well as the change of these properties when adding modified additives in each static mixer.

According to the results of our review, it was found that in the above studies on the properties of CAF, it is usually used in the conventional composition (aqueous FA solution/compressed air). However, research aimed at studying the properties of CAF by adding MA to its composition remained neglected by most authors. According to the results of the review [14], it was found that the use of modified additives in aqueous solutions significantly changes their properties, including those that affect fire-extinguishing efficiency, which was confirmed experimentally when extinguishing fires of various classes.

This allows us to state that it is appropriate to conduct a study on the influence of MA in an aqueous solution of FA CAF on its expansion ratio and drainage time.

3. The aim and objectives of the study

The purpose of our study is to identify the features of the effect of modified additives on the properties of CAF. From a practical point of view, the obtained dependences make it possible to further determine the fire extinguishing efficiency of compressed air foam with modified additives in its composition.

To achieve the goal, the following tasks were set:

– to experimentally determine the properties of compressed air foam with modified additives in its composition and the expediency of their use;

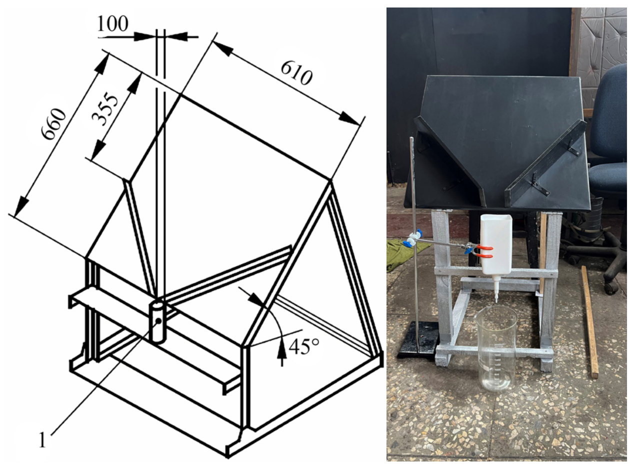
– to compare the properties of compressed air foam with modified additives with compressed air foam of conventional composition.

4. The study materials and methods

The object of research is the properties of compressed air foam with the use of modified additives: drainage time and expansion ratio.

The main hypothesis assumes that the use of modified additives in the composition of compressed air foam could affect its drainage time and expansion ratio.

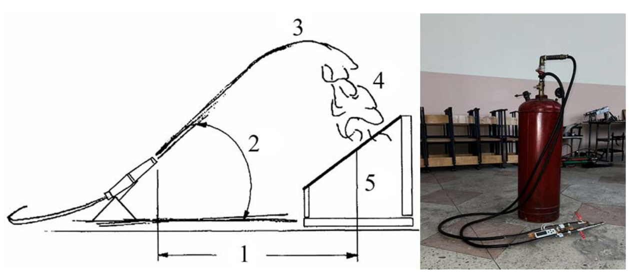
According to the DSTU EN 16327:2018 methodology, we used the equipment shown in Fig. 1.



a *b*

Fig. 1. Equipment for carrying out an experiment on measuring the drainage time and expansion ratio of foam: *a* – a foam collector: 1 – a foam collector with a draining device; *b* – a photograph of the designed bench

The arrangement of the barrel for supplying foam to the measuring bench (Fig. 2, *a*) met the requirements of DSTU EN 16327:20. During the research, an original designed sample of the CAF generation and supply system was used (Fig. 2, *b*) [15].



a *b*

Fig. 2. Research equipment and conditions: *a* – requirements for placement of the barrel and bench according to DSTU EN 16327:20; *b* – photograph of placement of the experimental sample and the bench; *c* – a photograph of the system of generation and supply of CAF of the original sample [15]

Evaluation of expansion ratio *K* and foam drainage time *S* in accordance with the recommendations outlined in DSTU EN 16327:2018. For each sample, the measurement of

S and K was repeated three times. The drainage time S was determined by the time interval during which 50 % of the liquid flows out of the generated foam by placing the foam collector on a scale, while recording its mass loss.

Foam K was calculated according to the formula:

$$E = \frac{V}{M_2 - M_1}, \quad (1)$$

where V is the volume of the foam collector, l;

M_1 – weight of the empty foam collector, kg;

M_2 is the mass of the foam collector filled with foam, kg.

MA for research was chosen according to [15]: ammonium hydrogen phosphate (hereinafter $(NH_4)_2HPO_4$); ammonium dihydrogen orthophosphate (hereinafter $NH_4H_2PO_4$); ammonium carbonate (hereinafter $(NH_4)_2CO_3$); potassium carbonate (hereinafter K_2CO_3); potassium chloride (hereinafter KCl). The concentration (hereinafter C) of MA in the composition of CAF varied from 1 % to 5 %, taking into account the analysis of the experience of predecessors reported in [15].

In the study, the general-purpose FA "Bars S" was used, with a concentration of P=6 % in an aqueous solution according to the manufacturer's recommendations.

5. Research results

5. 1. Results of experimental determination of properties of compressed air foam with modified additives

FA solution (94 % water and 6 % FA) from MA was prepared for each experiment in a volume of 1 l. According to the proportions of MA D in the range of 1–5 %, their required mass was determined, which was measured using electronic table scales. The calculated masses of MA are given in Table 1.

Table 1

Calculated mass of MAs

MA concentration, %	MA mass m, g				
	$NH_4H_2PO_4$	$(NH_4)_2HPO_4$	$(NH_4)_2CO_3$	K_2CO_3	KCl
1	10	10	10	10	10
2	20	20	20	20	20
3	30	30	30	30	30
4	40	40	40	40	40
5	50	50	50	50	50

The process of preparing the working solution from MA is shown in Fig. 3.

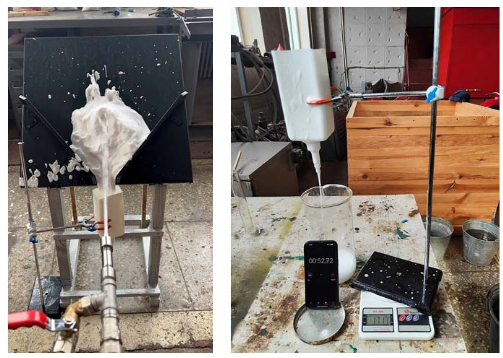
The Guide for the Use of Class A standard provides for three types of CAF according to K: "wet" with K from 1 to 5; "fluid", K from 5 to 10; "dry or stiff" from 10 to 20. CAF K is regulated by the ratio of the consumption of the water solution of FA and air and the pressure in the system. Taking into account the above, the pressure in the system was constant and equal to 6 bar. The valves of the barrel of the CAF generation and supply system were adjusted in such a way as to provide 4 modes (M1–M4) of the FA aqueous solution/air ratio, corresponding to K=5 for M1, K=10 for M2, K=15 for M3, and K=20 for M4 for compressed air foam without additives.

Fig. 4 shows a photograph of the research process.

Table 2 gives the summarized results (average calculated values) from studying the influence of ammonium phosphates with C in the range of 1–5 % on the properties of CAF.

a *b* *c*

Fig. 3. The process of preparing the solution: *a* – control weighing of MA; *b* – preparation of FA solution from MA in given proportions; *c* – filling the capacity of the system for the generation and supply of CAF



a *b*

Fig. 4. Photograph of the research process: *a* – feeding CAF to the bench; *b* – measurements of K and S of CAF

Table 2

Effect of ammonium phosphates on K and S of CAF

MA	$(NH_4)_2HPO_4$					$NH_4H_2PO_4$				
M	1 (5)									
C, %	1	2	3	4	5	1	2	3	4	5
K	6	4	5	6	4	5	6	5	4	6
S, min	2.33	2.3	2.26	2.08	1.9	2.08	2.02	1.98	1.94	1.88
M	2 (10)									
K	9	11	10	9	10	11	10	10	11	10
S, min	2.84	2.67	2.58	2.81	2.98	2.18	2.33	2.47	2.59	2.75
M	3 (15)									
K	14	15	16	14	16	15	16	14	15	16
S, min	3.49	3.26	3.17	3.41	3.66	2.68	2.86	3.03	3.22	3.38
M	4 (20)									
K	21	19	21	20	19	21	20	21	19	20
S, min	5.20	4.90	4.72	5.11	5.45	3.99	4.23	4.51	4.78	5.03

Fig. 5 shows the dependence of the influence of ammonium phosphates in the range of C 1÷5 % in an aqueous solution of FA on the properties of CAF.

Fig. 6 shows the surface of the dependence of CAF properties on C of ammonium phosphates 1÷5 %.

Equations (1), (2) for planes reflecting the dependence of CAF properties on C $(NH_4)_2HPO_4$ and equations (3), (4) for planes reflecting the dependence of CAF properties on C $NH_4H_2PO_4$ are given below:

$$K = 0.05 - 0.05 \cdot C + 1.004 \cdot M, \quad (1)$$

$$S=3.2637-0.6402\cdot C-0.0903\cdot K+0.081\cdot C^2+ +0.0143\cdot C\cdot K+0.0091\cdot K^2, \quad (2)$$

$$K=0.525-0{,}075\cdot C+0.996\cdot M, \quad (3)$$

$$S=2.5393-0.0533\cdot C-0.1571\cdot K- -0.0169\cdot C^2+0.0241\cdot C\cdot K+0.0097\cdot K^2. \quad (4)$$

Table 3 gives the summarized results (average calculated values) from studying the influence of ammonium carbonates, potassium, and potassium chloride with *C* in the range of 1–5 % on the properties of CAF.

Fig. 7 shows the dependence of the effect of ammonium carbonate in the range of *C* 1÷5 % in an aqueous solution of FA on the properties of CAF.

Fig. 8 shows the surface of the dependence of CAF properties on *C* of ammonium carbonate 1÷5 %.

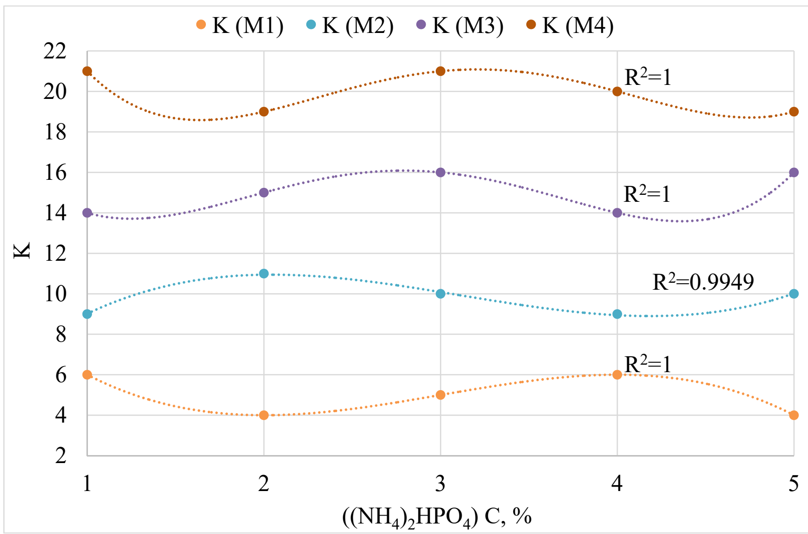
Equations (5), (6) for the planes, which reflect the dependence of CAF properties on $(NH_4)_2CO_3$ *C*, are given below:

$$K=0.1-0.2\cdot C+1.02\cdot M, \quad (5)$$

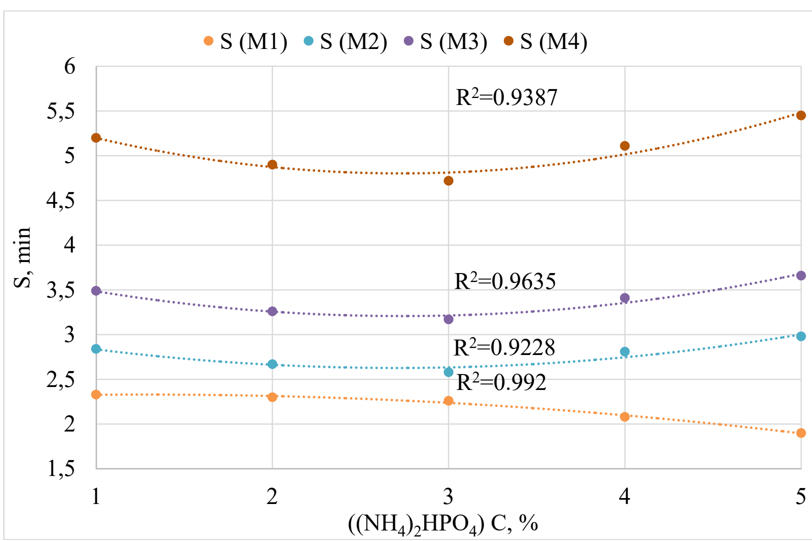
$$S=1.6505-0.1468\cdot C+0.0333\cdot K+ +0.0206*C^2-0.0002\cdot C\cdot K+0.0056\cdot K^2. \quad (6)$$

Thus, it was possible to obtain stable compressed air foam only with $(NH_4)_2HPO_4$, $NH_4H_2PO_4$ and $(NH_4)_2CO_3$ additives.

The next step was to determine the dependence of CAF *S* on its *K*, without adding MA in order to further compare the properties of the foam.

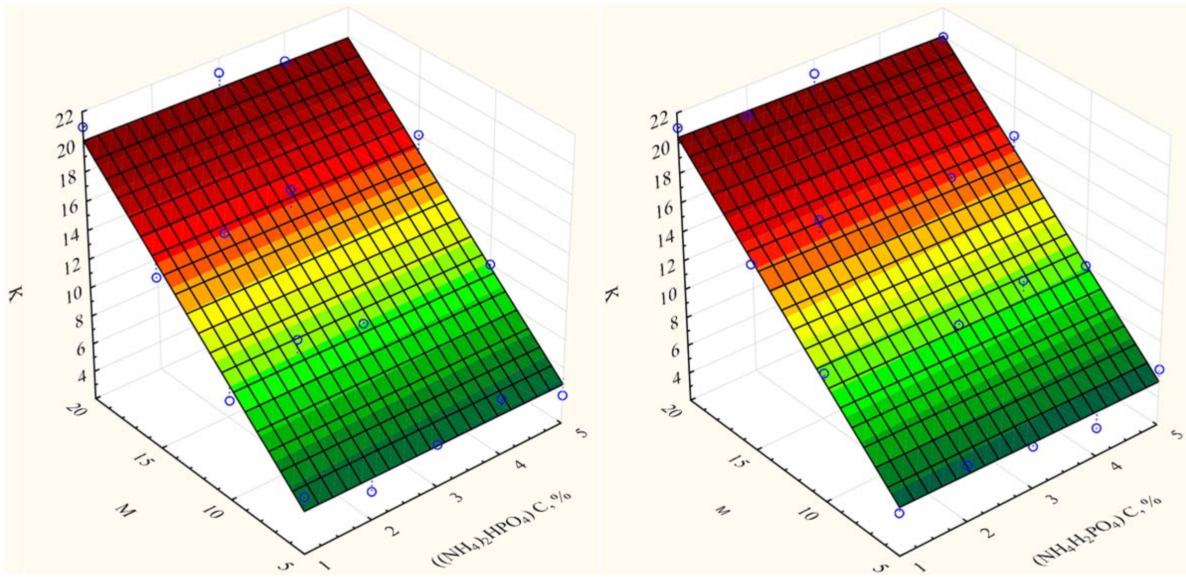


a



b

Fig. 5. The effect of ammonium phosphates C in an aqueous solution of FA on the properties of CAF:
a – *K* under modes M1–M4 with $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$;
b – *S* taking into account *K* obtained under the M1–M4 regimes with $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$



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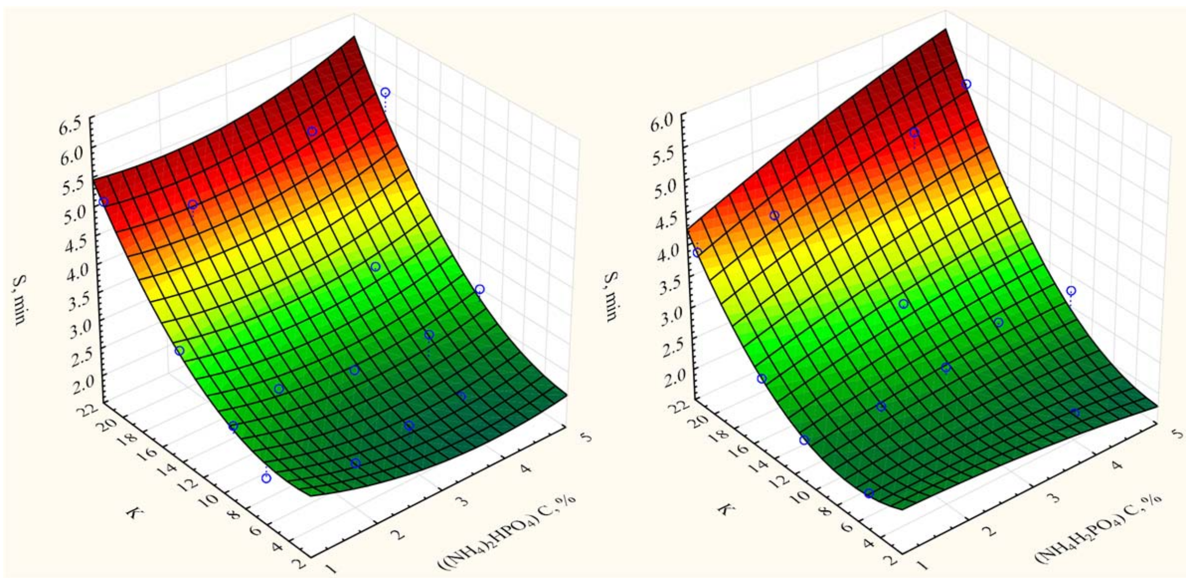


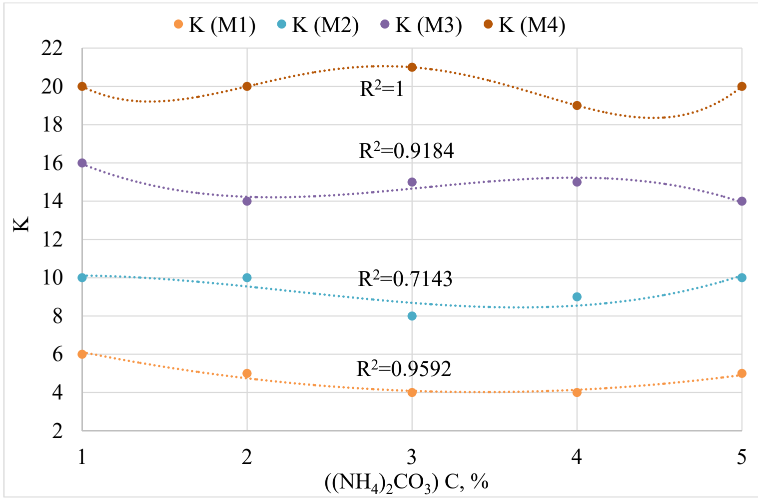
b

Fig. 6. Dependences of CAF properties for: *a* – *K* taking into account modes M1–M4 with $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$; *b* – *S* taking into account *K* obtained under the M1–M4 regimes with $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$

Table 3

Effect of potassium, ammonium carbonates and potassium chloride on CAF *K* and *S*

MA	$(NH_4)_2CO_3$					K_2CO_3; KCL				
M	1 (5)									
C, %	1	2	3	4	5	1	2	3	4	5
K	6	5	4	4	5	Foam does not form				
S, min	1.78	1.71	1.63	1.58	1.55					
M	2(10)									
K	10	10	8	9	10	Foam does not form				
S, min	2.57	2.44	2.31	2.36	2.4					
M	3(15)									
K	16	14	15	15	14	Foam does not form				
S, min	3.16	2.97	2.84	2.91	2.95					
M	4(20)									
K	20	20	21	19	20	Foam does not form				
S, min	4.71	4.49	4.23	4.33	4.39					



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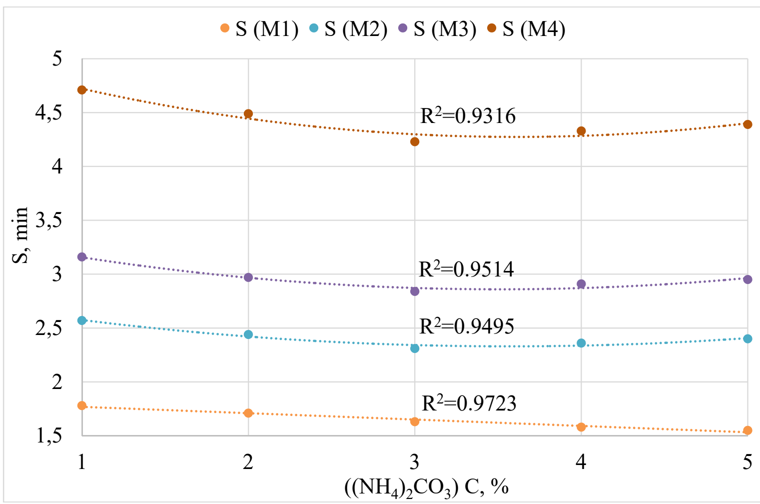
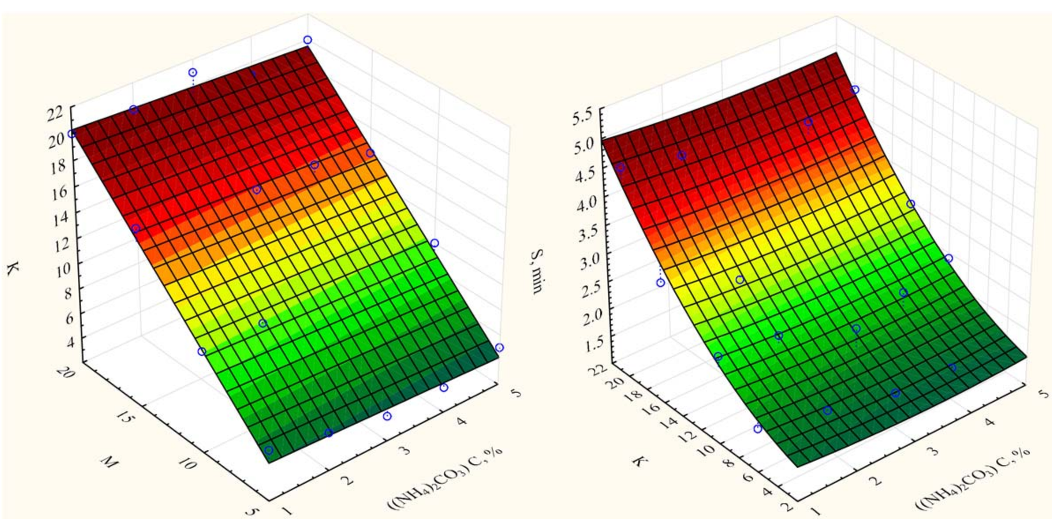


b

Fig. 7. The influence of ammonium carbonate C in the aqueous solution of foaming agent on the properties of compressed air foam: *a* – *K*, taking into account the regimes M1–M4 with $(NH_4)_2CO_3$;
b – *S*, taking into account *K* obtained under the M1–M4 regimes with $(NH_4)_2CO_3$



a *b*

Fig. 8. Dependences of CAF properties for: *a* – *K*, taking into account modes M1–M4 with $(NH_4)_2CO_3$;
b – *S*, taking into account *K* obtained under the M1–M4 regimes with $(NH_4)_2CO_3$

5. 2. Results of comparing the properties of compressed air foam with modified additives and compressed air foam of conventional composition

In order to compare the influence of types and *C* of MA and CAF of conventional composition, the relationship between *S* and *K* of CAF for regimes M1–M4 was determined. Table 4 gives the results of determining *K* and *S* of the generated CAF without adding MA.

Comparison of the properties of CAF foam with MA was carried out separately for each *C* (1; 2; 3; 4; 5). The resulting graphical dependences are shown in Fig. 9.

Table 4

K and *S* of generated foam without adding MA

M	*K*	*S*, min
1	5	2.68
2	10	3.55
3	15	4.36
4	20	6.5

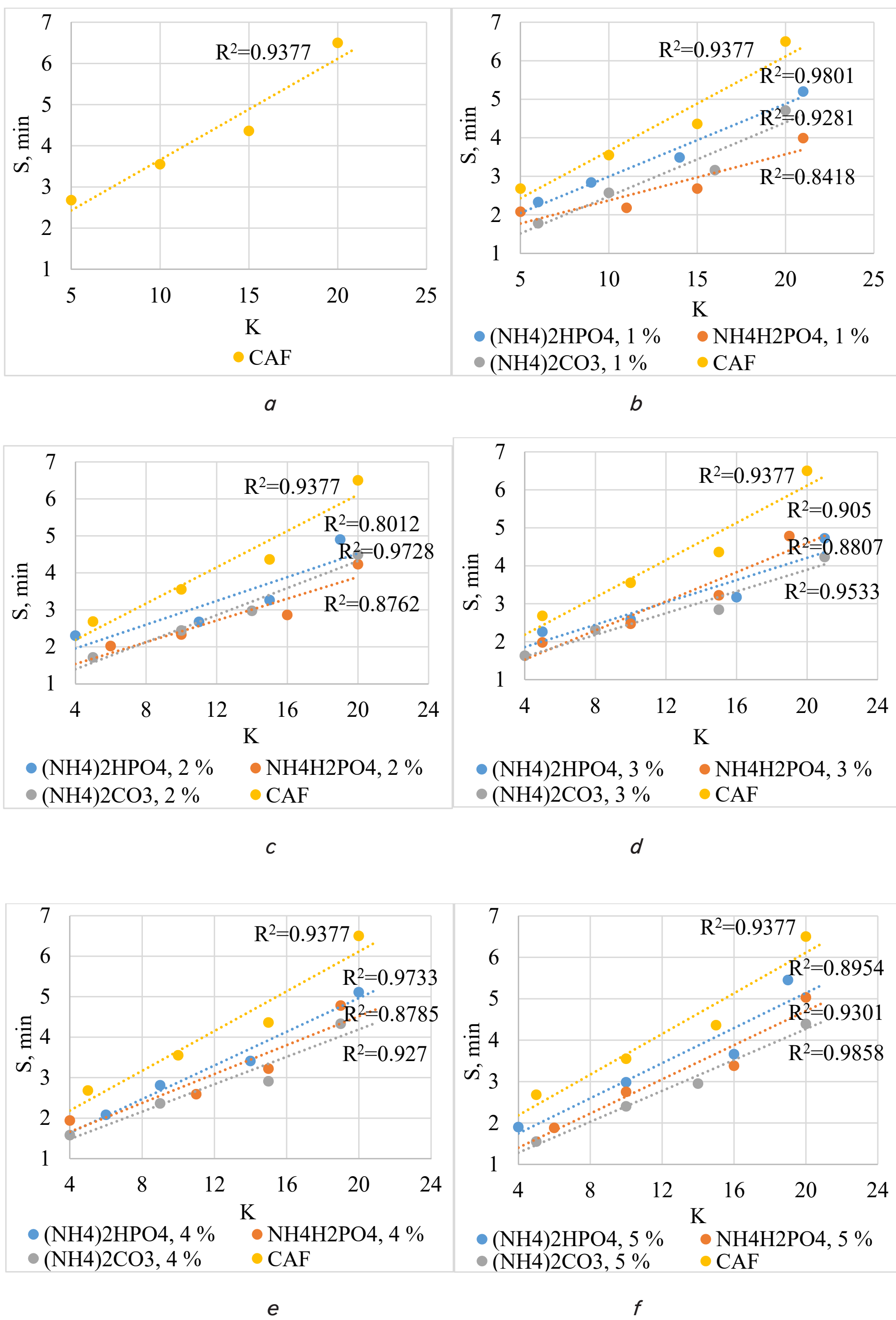


Fig. 9. Comparison of the properties of CAF with MA and with CAF of conventional composition: *a* – CAF without MA; *b* – C MA 1 %; *c* – C MA 2 %; *d* – C MA 3 %; *e* – C MA 4 %; *f* – C MA 5 %

The plots in Fig. 9 clearly demonstrate that the drainage time of the compressed air foam is reduced when modified additives are used in comparison with the conventional compressed air foam.

6. Discussion of results based on the research into the properties of compressed air foam with modified additives

When analyzing our results of the influence of modified additives on the drainage time and expansion ratio of compressed air foam, the following was established.

The use of modified additives of ammonium dihydrogen orthophosphate $NH_4H_2PO_4$, ammonium hydrogen phosphate $(NH_4)_2HPO_4$ and ammonium carbonate $(NH_4)_2CO_3$ in the composition of compressed air foam does not have a negative effect on its expansion ratio within 1–5 % (Tables 2, 3, Fig. 5–8, *a*). During the study of the influence of potassium carbonate K_2CO_3 and potassium chloride KCL, it was established (Table 3) that the use of modified additives in the concentration range of 1 % to 5 % has a negative effect on the possibility of obtaining compressed air foam. In particular, it was not possible to obtain foam with a expansion ratio ≥5 under any of the modes (M1–M4). The obtained water-foam solution did not have characteristic features of foam. This can be explained by the different properties of ammonium cations (NH_4^+) and potassium cations (K^+). Ammonium cations are a weak acid that lowers the pH of the aqueous solution, thus adsorbing ions on the surface of the foam bubbles, increases the viscosity of the solution, and lowers the surface tension, positively affecting the drainage time of the foam. At the same time, potassium cations are metal cations that do not form hydrogen bonds and do not significantly affect surface tension. In addition, carbonate $\left(CO_3^{2-}\right)$ and chloride (Cl^-) anions also do not have foaming properties.

Regarding the drainage time of the foam, it was determined that with the use of $NH_4H_2PO_4$:

– under mode M1, there is a decrease in foam drainage time by 19 % when the concentration of the additive is increased from 1 % to 5 % (Table 2, Fig. 5, *b*, 6, *b*);

– under modes M2–M4 with an increase in additive concentration from 1 % to 3 %, there is a characteristic decrease in foam drainage time by 10 %, with a further increase in additive concentration to 4–5 %, an increase in drainage time is observed. With the use of a concentration of 5 %, the drainage time of the foam is 5 % higher relative to the drainage time with a concentration of the additive of 1 % (Table 2, Fig. 5, *b*, 6, *b*).

Regarding the drainage time of the foam, it was determined that with the use of $(NH_4)_2HPO_4$:

– under mode M1, a decrease in foam drainage time by 10 % is observed when the concentration of the additive is increased from 1 % to 5 % (Table 2, Fig. 5, *b*, 6, *b*);

– under modes M2–M4, increasing the additive concentration from 1 % to 5 % results in a characteristic increase in foam drainage time by 26 % (Table 2, Fig. 5, *b*, 6, *b*).

For both additives, the increase in foam drainage time with increasing additive concentration can be explained by an increase in the amount of phosphate anions that can form complexes with metals and other ions that may be present in the foaming agent solution, thereby stabilizing the foam. The difference in the change in foam drainage time under mode M1 and modes M2–M4 requires additional theoretical and experimental research.

Regarding foam drainage time, it was determined that with the use of $(NH_4)_2CO_3$:

– under mode M1, there is a decrease in foam drainage time by 13 % when the concentration of the additive is increased from 1 % to 5 % (Table 3, Fig. 7, *b*, 8, *b*);

– under modes M2–M4 with an increase in additive concentration from 1 % to 5 %, there is a characteristic decrease in foam drainage time by 7 % (Table 3, Fig. 7, *b*, 8, *b*).

The decrease in foam drainage time when adding ($(NH_4)_2CO_3$ compared to $NH_4H_2PO_4$ and $(NH_4)_2HPO_4$ can be explained by the presence of carbonate anions, which are less effective in foaming compared to phosphates.

When comparing the properties (Fig. 8, *b*–*f*) of compressed air foam with modified additives and compressed air foam of conventional composition, the following was established:

– when comparing the modified additives $NH_4H_2PO_4$, $(NH_4)_2HPO_4$, $(NH_4)_2CO_3$, a characteristic dependence was revealed regarding the effect on the expansion ratio of foam, namely, the presence of a concentration from 1 % to 5 % has the same character. Under modes M1–M4, it is possible to provide the necessary foam expansion ratio in the range from 1 to 20. This also correlates with previous assumptions about the positive effect of ammonium cations on foam formation and the absence of destructive action of other ions;

– when comparing the modified additives $NH_4H_2PO_4$, $(NH_4)_2HPO_4$, $(NH_4)_2CO_3$, the peculiarities of the influence of the concentration and type of the modified additive in the compressed air foam on its drainage time were revealed. Thus, the greatest drainage time is characteristic of three types of additives using the M4 generation mode (*K* 20). The highest recorded drainage time index was established for $NH_4H_2PO_4$, namely 5.45 min, for $(NH_4)_2HPO_4$ the drainage time is lower by 8 %, for $(NH_4)_2CO_3$ the drainage time is lower by 20 %. This is explained by the stronger effect on foaming of the amount of phosphate anions that stabilize the foam and, on the other hand, the less significant effect of carbonate anions;

– when comparing the effect of $NH_4H_2PO_4$, $(NH_4)_2HPO_4$, $(NH_4)_2CO_3$ in the composition of compressed air foam with foam without the content of modified additives, it was found that the required expansion ratio range (*K*=5–20) can be provided. As for the drainage time of the foam, it is characteristic of the specified additives to obtain a foam with lower drainage time, relative to the foam of a conventional composition. Thus, for mode M4, the drainage time of foam with $NH_4H_2PO_4$ is lower by 17 %, with $(NH_4)_2HPO_4$ by 23 %, and with $NH_4)_2CO_3$ by 33 %. Although usually ammonium salts increase the stabilization of the foam and its drainage time, our results can be explained by an excessive effect on the viscosity, a significant increase of which leads to the formation of a non-uniform foam that quickly collapses. In addition, ammonium salts can interact with other components in the general-purpose foaming agent "Bars S", thereby inhibiting their action and reducing the efficiency of foaming. Therefore, it will be appropriate to conduct similar experiments with other foaming agents in the future.

A comparison of the properties of foam with K_2CO_3 and KCL was not carried out since the generation of compressed air foam is not possible, which is due to the negative effect of the specified additives on the foaming agent solution and foaming ability. It is not advisable to use them as part of compressed air foam.

Owing to our experimental results (Table 5, Fig. 7), in contrast to [5–14], the influence of modified additives in the aqueous solution of FA CAF on its expansion ratio and drainage time was revealed.

As a limitation of the conducted research, it should be taken into account that the influence of the types and concentrations of modified additives on the dispersion and homogeneity of compressed air foam bubbles was not determined. The specified properties also affect its fire-fighting effectiveness, in particular, durability.

The shortcomings of this study include the fact that the results of studying the influence of types and concentrations of modified additives were conducted 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 have a different effect.

Despite the negative effect of modified additives on foam drainage time, this property is dominant during the extinguishing of flammable liquids, as it depends on the ability to isolate the surface of the combustible liquid from the access of oxygen for a certain time. In turn, during the application of compressed air foam for extinguishing solid combustible substances and materials, cooling is the dominant property. In addition, modified additives have the ability to inhibit the combustion reaction and create a protective film on the surface of the material.

Therefore, the development of our research in the future is to determine the fire-extinguishing efficiency of compressed air foam with modified additives during the extinguishing of laboratory cells of solid combustible materials in comparison with the conventional composition of CAF.

7. Conclusions

1. The properties of the compressed air foam (drainage time and expansion ratio) with modified additives $(NH_4)_2HPO_4$, $NH_4H_2PO_4$, $(NH_4)_2CO_3$, K_2CO_3, KCl in the composition of the aqueous solution of the foaming agent with a concentration ranging from 1 % to 5 % have been determined experimentally. It was established that the presence of additives ($(NH_4)_2HPO_4$), ($NH_4H_2PO_4$), ($(NH_4)_2CO_3$) within the specified limits do not have a negative effect on the expansion ratio of the compressed air foam. When using (K_2CO_3) (KCl) with a concentration ranging from 1 % to 5 %, it was not possible to obtain foam. Quantitative indicators of the drainage time of the compressed air foam with $(NH_4)_2HPO_4$, $NH_4H_2PO_4$ and $(NH_4)_2CO_3$ additives in the aqueous solution of the foaming agent were determined.

2. The properties of the compressed air foam with modified additives $(NH_4)_2HPO_4$, ($NH_4H_2PO_4$), $(NH_4)_2CO_3$) with their concentration in the aqueous solution of the foaming agent in the range from 1 % to 5 % were compared with each other and with the compressed air foam of the conventional composition. It was determined that the presence of these additives in the compressed air foam does not affect its expansion ratio. For foam drainage time, $NH_4H_2PO_4$ foam has the highest drainage time recorded (5.45 min), $(NH_4)_2HPO_4$ foam has 8 % lower drainage time, and $(NH_4)_2CO_3$ foam has 20 % lower drainage time. Comparing the drainage time of foam with modified additives with foam of conventional composition, it was established that the presence of modified additives $NH_4H_2PO_4$, $(NH_4)_2HPO_4$ and $(NH_4)_2CO_3$ in the composition of compressed air foam reduces its drainage time index by 13 %, 23 %, and 33 %, respectively.

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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