

Theoretical Aspects of the Application of Compressed Air Foam Generated from a Sodium Polyacrylate-Based Fire Extinguishing Agent for High-Rise Firefighting

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Abstract. This article investigates the features of the generation and application of compressed air foam, obtained from an aqueous sodium polyacrylate-based fire extinguishing agent, for firefighting operations, particularly concerning the delivery of extinguishing agents to elevated heights. The relevance of this study is driven by the need to improve the efficiency of firefighting in high-rise buildings. The paper examines an experimental setup for producing compressed air foam, which ensures the formation of a foam stream using compressed air and an aqueous solution of a gelling agent. Experimental studies of the physical characteristics of the generated foam were conducted; specifically, its density, expansion ratio, stability, and formation parameters were determined depending on the concentration of the polymer component. It was established that introducing sodium polyacrylate into the fire extinguishing agent increases the solution's viscosity, promotes the formation of a more stable foam structure, and enhances its water retention capacity. Based on the obtained experimental data, the parameters for the vertical delivery of the generated compressed air foam were calculated. It is demonstrated that using the developed setup in combination with the modified aqueous fire extinguishing agent allows for the formation of stable compressed air foam with improved performance characteristics, thereby expanding its application capabilities for high-rise firefighting purposes.

1 Introduction

Today's security challenges cause a significant increase in the number of man-made and war-related fires resulting from missile and artillery strikes, the use of unmanned aerial vehicles, and attacks on critical infrastructure facilities, fuel and lubricant storage facilities, industrial enterprises, and natural ecosystems. Thus, a significant portion of the fire seats is located in high-hazard zones at elevated heights or in territories with restricted access for fire and rescue service units. This necessitates the search for new technological solutions aimed at increasing personnel safety and firefighting efficiency.

An urgent problem arises regarding the resolution of two main tasks: improving firefighting efficiency and ensuring personnel safety. Given the high level of danger, extinguishing such fires requires high promptness and the application of means capable of more effectively combating the combustion of hazardous substances and materials. Traditional firefighting methods often prove insufficiently effective or require excessive volumes of fire extinguishing agents (hereinafter referred to as FEA), which determines the acute scientific and practical relevance of implementing innovative technologies, particularly the use of compressed air foam with enhanced characteristics.

Compressed air foam is a promising firefighting medium formed by mixing an aqueous solution of a foam concentrate with compressed air. Thanks to this technology, a foam structure with a controlled expansion ratio and increased stability is formed [1]. Studies show that compressed air

foam can provide more effective suppression of Class A fires compared to water or traditional foams [2]. Furthermore, the use of compressed air foam allows for a significant reduction in FEA consumption and increases the efficiency of cooling combustible materials [3].

Of particular interest is the application of compressed air foam generated from an FEA based on sodium polyacrylate — a polymeric superabsorbent capable of forming gel-forming structures with a high content of bound water [4–6]. Sodium polyacrylate is characterized by its ability to accumulate water in volumes tens and hundreds of times exceeding its own mass, forming a viscous hydrogel system. In combination with compressed air foam technology, this allows for the creation of a stable foam-gel layer with increased adhesion to vertical and inclined surfaces, resistance to thermal exposure, and a reduced drainage rate [7].

Compared to traditional aqueous solutions and air-mechanical foam, sodium polyacrylate-based compressed air foam can provide:

- enhanced cooling efficiency due to the high content of bound water;
- prolonged retention on the surface of combustible materials;
- reduction of FEA losses due to evaporation or dispersion by air currents;
- the possibility of forming insulating and fire-preventive barriers.

An analysis of literature sources shows that despite a significant number of studies on compressed air foam, the issues of using polymeric gelling components in its composition and the possibilities of applying such systems for high-rise firefighting remain insufficiently studied.

For delivering FEA to significant heights, one of the promising directions is the application of remote or high-rise firefighting technologies, which involve the delivery of FEA directly to the combustion zone without the need to deploy forces and equipment of the operational and rescue civil protection services. Such solutions may include specialized high-rise installations, robotic complexes, as well as unmanned aerial vehicles (UAVs), which are considered one of the modern tools for the prompt delivery of FEA. The application of such systems enables a rapid response, minimizes risks to personnel, ensures localized or barrier application of FEA in hard-to-reach places, and increases the efficiency of extinguishing fires in high-rise buildings. The relevance of such solutions particularly increases under martial law conditions, when fires can occur at high-hazard facilities, specifically ammunition depots, petroleum product reservoirs, energy infrastructure facilities, and in forest areas. Under such conditions, the use of remote FEA delivery systems, including those using UAVs, can significantly enhance the safety of fire and rescue operations.

In this regard, it is highly relevant to scientifically substantiate the possibility of using compressed air foam generated from a sodium polyacrylate-based FEA for high-rise firefighting systems, as well as to evaluate its technical, tactical, and operational efficiency.

2 Main Part

The aim of this work is to substantiate the possibility of using compressed air foam generated from a sodium polyacrylate-based FEA for high-rise firefighting. It should be noted that the upward delivery of foam through a vertical pipe is accompanied by its breakdown. Friction against the inner surface of the pipe increases the intensity of this breakdown.

The efficiency of firefighting, especially in challenging conditions (high-rise buildings, forest areas), significantly depends on the hydrodynamic parameters of the fire-extinguishing agent delivery [8].

As a result of the breakdown, water is released, which drains downward, gradually forming a water column (Fig. 1).

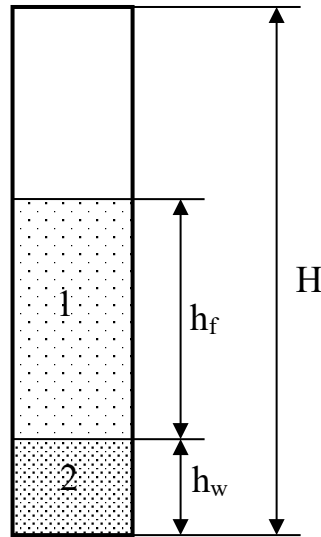


Fig. 1. Foam rise in a vertical pipe: 1 – foam; 2 – water.

Let, at a given time (t), the height of the water column be (h_w), and the height of the foam be (h_f). Then, the increment of the foam volume in the pipe, (dV_f), is determined by its volumetric delivery rate Q and the breakdown rate (1):

$$\frac{dV_f}{dt} = Q - \gamma V_f, \quad (1)$$

where, V_f - the volume of foam in the pipe; γ – the foam breakdown coefficient over time.

The increment of the water volume in the pipe is expressed as (2):

$$\frac{dV_w}{dt} = \frac{1}{K} \gamma V_f, \quad (2)$$

where, K – expansion ratio.

The volumes of water and foam in the pipe are related to their column heights, (h_w) and (h_f) (Fig. 1), by equations (3) and (4):

$$V_f = \frac{\pi d^2}{4} h_f, \quad (3)$$

$$V_w = \frac{\pi d^2}{4} h_w, \quad (4)$$

where, d – the pipe diameter.

Considering equations (3) and (4), we obtain:

$$\frac{dh_f}{dt} = \frac{4Q}{\pi d^2} - \gamma h_f, \quad (5)$$

$$\frac{dh_w}{dt} = \frac{1}{K} \gamma h_f. \quad (6)$$

The volumetric delivery rate of the foam decreases as the volumes of water and foam in the pipe increase:

$$Q = Q_{max} \left(1 - \frac{\Delta p}{p_{pump}} \right), \quad (7)$$

where, $Q_{\max}$ – the volumetric flow rate of foam into an empty pipe; p_{pump} – the pump outlet pressure; Δ_p – the total pressure drop.

The total pressure drop (Δ_p) consists of the hydrostatic pressure of the water column (p_w), calculated by Equation (9), the hydrostatic pressure of the foam column calculated by Equation (10), and the pressure loss due to the friction of the foam against the pipe wall (p_{fr}), calculated by Equation (11), and is expressed as Equation (8):

$$\Delta_p = p_w + p_f + p_{fr}, \quad (8)$$

$$p_w = \rho g h_w, \quad (9)$$

where, g – the acceleration due to gravity; ρ – the density of water.

$$p_f = \frac{\rho}{K} g h_f, \quad (10)$$

$$p_{fr} = \mu \frac{h_f \rho v^2}{d \cdot 2K}, \quad (11)$$

where, μ – the friction coefficient of the foam against the pipe wall; v – the average velocity of the foam, calculated by Equation (12):

$$v = \frac{4Q}{\pi d^2}. \quad (12)$$

Considering Equations (9)–(12), the total pressure drop is given by Equation (13):

$$\Delta_p = \rho g h_w + \frac{\rho}{K} \rho g h_f + \mu \frac{h_f \rho}{d \cdot 2K} \left(\frac{4Q}{\pi d^2} \right)^2, \quad (13)$$

$$\Delta_p = \rho g \left(h_w + \frac{1}{K} h_f \right) + \mu \frac{h_f 8 \rho Q^2}{d^5 \pi^2 K}.$$

The system of differential equations (5) and (6), where the quantity Q is determined by equations (7) and (13), describes the change in the heights of the foam and water columns in the pipe over time. The initial conditions are given by (14) and (15):

$$h_f(0) = 0, \quad (14)$$

$$h_w(0) = 0. \quad (15)$$

Moreover, the following conditions must be satisfied:

$$h_w \leq H, \quad (16)$$

$$h_f \leq H - h_w. \quad (17)$$

Once the foam reaches the top of the pipe, its volumetric flow rate can be calculated from equations (7) and (13). In this case, the delivery pressure at the top of the pipe is given by Equation (18):

$$p = p_{\text{pump}} - \Delta_p. \quad (18)$$

To determine the initial data, according to the conducted analysis [9], a system for producing compressed air foam [10, 11] was utilized. The advantages of this foam generator include its high capacity and a novel technology for generating compressed air foam in a confined space. This technology involves the formation of compressed air foam in an enclosed volume through the following sequence of main stages:

- foam generation;
- foam refinement within a confined space..

The dispersion of the foam structure is carried out through the application of a specific technology—the surface layer effect. Through this refinement, it allows for the generation of compressed air foam with a homogeneous monodisperse structure, maintaining stability throughout the entire volume, which is its main advantage over currently available models.

The proposed technology has a rather wide range of practical applications and can be utilized in automated and stationary fire extinguishing systems integrated into technological complexes and facilities, as well as in stationary, mobile, and modular firefighting installations.

The schematic of the setup is presented in Figure 2.

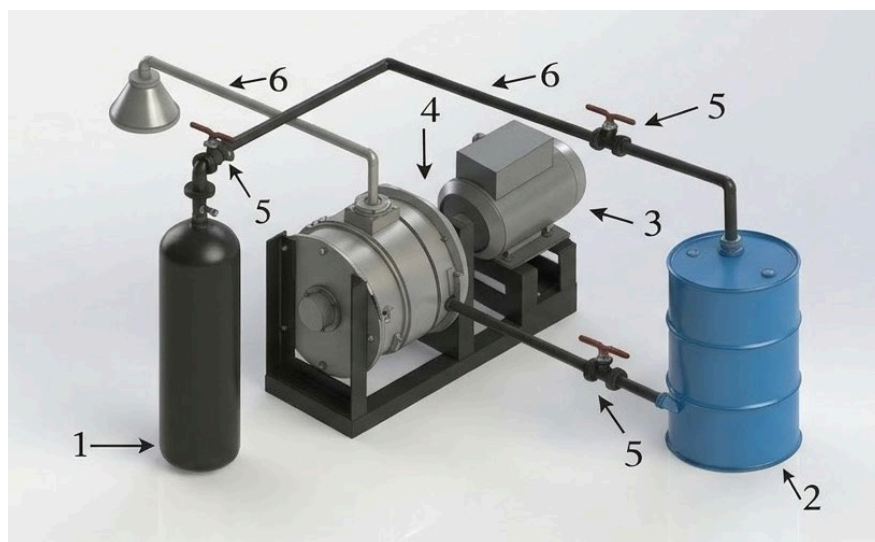


Fig. 2. Schematic diagram of the setup for generating compressed air foam.

1 – compressed air cylinder or compressor; 2 – foam concentrate tank; 3 – electric motor; 4 – foam generator; 5 – foam concentrate flow control valves; 6 – pipelines for supplying the foam solution and compressed air.

To generate the compressed air foam, a 1.5% aqueous solution of a fire-extinguishing agent (FEA) based on sodium polyacrylate was used, consisting of a gel-forming sodium polyacrylate (28 wt.%), refined rapeseed oil (24 wt.%), a general-purpose foam concentrate (6 wt.%), and water (42 wt.%).

One of the determining factors in the effectiveness of FEAs in firefighting, particularly on vertical and inclined surfaces, is their adhesive capacity and resistance to runoff. In this context, compressed air foam formed on the basis of a gel-forming polymeric substance fundamentally differs in its surface interaction mechanism from compressed air foam produced from a conventional foam concentrate.

Traditional compressed air foam is formed by surfactants that stabilize the bubble structure by reducing surface tension. Such foam is characterized by thin liquid films between gas cells and a relatively low viscosity of the liquid phase. After application to a surface, gradual drainage occurs—the outflow of the liquid phase under gravity. This leads to a decrease in the layer thickness, loss of the mechanical integrity of the foam structure, and a reduction in the duration of the insulating effect. On vertical surfaces, conventional compressed air foam is retained for a

limited time and undergoes rapid breakdown under the influence of thermal radiation and convective heat fluxes.

In contrast, when using a gel-forming substance based on sodium polyacrylate, the liquid phase acquires viscoelastic properties due to the formation of a three-dimensional polymer network that binds a significant volume of water. Within the compressed air foam, such a system creates a stabilized foam-gel structure with enhanced cohesion and mechanical strength. Upon application to a surface, not only does wetting occur, which is typical for traditional foam, but there is also a mechanical interlocking of the gel mass with the micro-irregularities of the material. This ensures significantly higher adhesion and a much lower tendency to drain.

According to [7], the relative adhesion capacity of a hydrogel based on a polymer gel-forming agent can reach significant values (7 to 8 times higher compared to water). The protective hydrogel layer contains a large amount of water, which can protect surfaces from heating.

While investigating the feasibility of generating compressed air foam from a 1.5% aqueous solution of the sodium polyacrylate-based FEA using the aforementioned setup, the following quality indicators of the produced compressed air foam were determined:

- expansion ratio and stability;
- density.

Additionally, the flow rate of the FEA provided by the installation for generating compressed air foam was determined. The aforementioned parameters were also determined for compressed air foam produced from a 6% aqueous solution of a domestically produced general-purpose foam concentrate.

The expansion ratio of the produced foam was determined in accordance with the requirements of [12, 13] as the ratio of the volume of the produced foam to the volume of the FEA solution consumed to generate the foam, using Equation (19):

$$K = \frac{V_{\pi}}{V_p}; \quad (19)$$

where, K – expansion ratio; V_{π} – об'єм the volume of the produced foam; V_p – he volume of the solution consumed to generate the foam.

Foam stability was determined as the time required for half of the solution used for its generation to drain from the produced foam.

The density of the produced foam was calculated using Equation (20):

$$\rho = \frac{m_{\pi}}{V_{\pi}}, kg/m^3 \quad (20)$$

where, ρ – the density of the produced foam; m_{π} – the mass of the produced foam; V_{π} – he volume of the produced foam.

The study of the expansion ratio, stability, density, and flow rate of the generated foam was conducted under normal conditions, and the averaged research results are presented in Table 1.

The data in the table indicate that the stability of the foam generated from the sodium polyacrylate-based FEA is higher than that of the foam produced from the general-purpose foam concentrate.

The appearance of the foam generated from the sodium polyacrylate-based FEA applied to a vertical surface is shown in Figure 3.

Table 1. Results of studies on the expansion ratio, stability, density, and flow rate of the generated foam.

FEA	Expansion ratio	Stability of the produced foam, [s]	The density of the produced foam, [kg/m ³]	Flow rate of the produced foam, [L/s]
Sodium polyacrylate-based FEA	8.0	911	135	3.0
Foam concentrate-based FEA	8.0	826	125	3.0

**Fig. 3.** Appearance of the foam generated from the sodium polyacrylate-based FEA applied to a vertical surface.

The data obtained from the experimental studies allowed for the determination of the main physical characteristics of the generated compressed air foam, specifically its density, expansion ratio, and stability. These parameters are crucial in evaluating the feasibility of transporting the foam to the fire source, particularly in cases of firefighting at significant heights. In particular, foam density and expansion ratio directly affect the hydraulic parameters of its delivery, the pressure loss during transportation, and the efficiency of delivering the fire-extinguishing agent to the combustion zone. Given this, the next stage of the study involved calculating the parameters for delivering compressed air foam to a height, which allows for an assessment of its practical application in high-rise firefighting systems.

The value of the friction coefficient of the foam against the wall was taken as $\mu = 0.06$, and the foam destruction coefficient as $\gamma = 10^{-3} \text{ s}^{-1}$. The dynamics of the foam parameter changes in a vertical pipe with a height $H = 50 \text{ m}$ and a diameter $d = 77 \text{ mm}$ are shown in Fig. 4. The pump pressure was assumed to be $p_{\text{pump}} = 8 \text{ bar}$, and the volumetric flow rate of the foam into the empty pipe $Q_{\text{max}} = 3 \text{ L/s}$. Fig. 5 illustrates the situation where $\mu = 0.08$, $\gamma = 2 \cdot 10^{-3} \text{ s}^{-1}$.

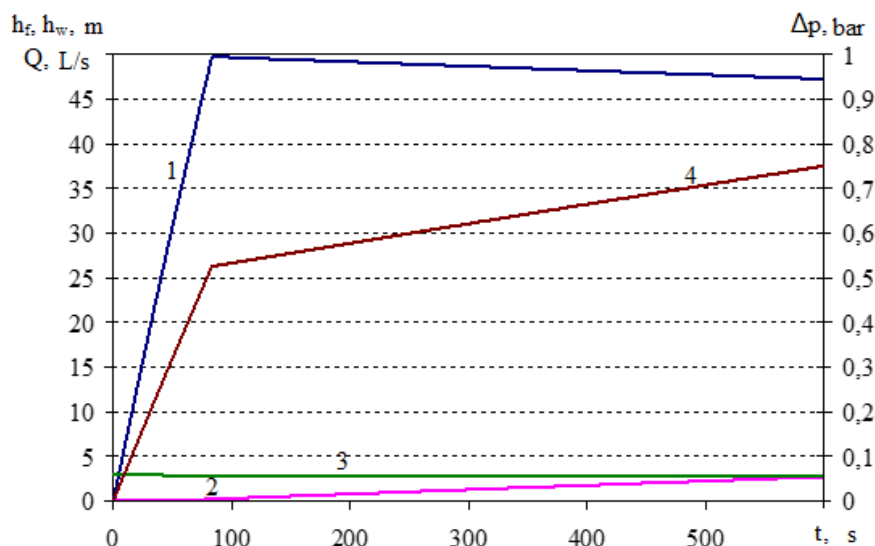


Fig. 4. Dynamics of the foam parameters in a vertical pipe with a height of 50 m: 1 – foam column height; 2 – water column height; 3 – volumetric foam flow rate; 4 – pressure losses (on the right axis).

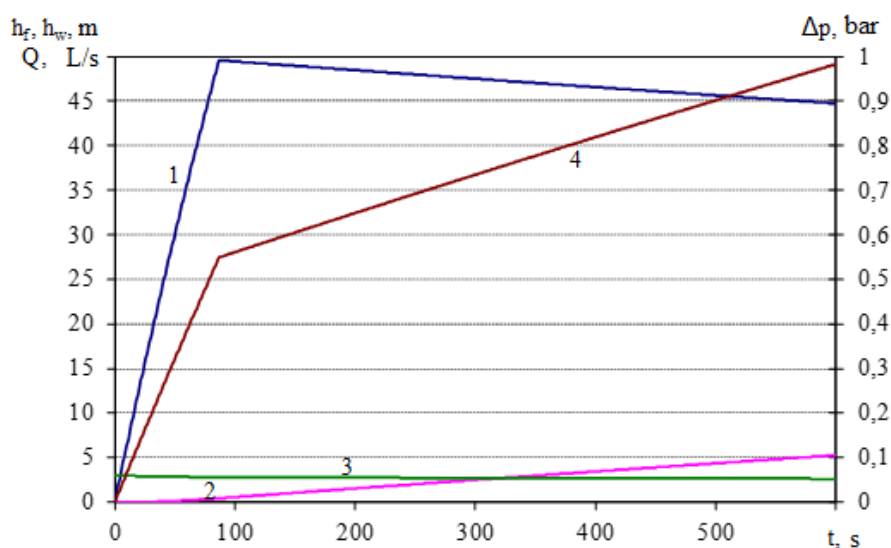


Fig. 5. Dynamics of foam parameter changes in a vertical pipe with a height of 50 m: 1 – foam column height; 2 – water column height; 3 – volumetric foam flow rate; 4 – pressure losses (on the right axis).

Analysis of the images in Fig. 4 and Fig. 5 indicates that pressure losses initially increase along with the growth of the foam column in the pipe. This occurs primarily due to the static pressure of the foam column and its friction against the inner surface of the pipe. When the foam reaches the top edge of the pipe, the pressure losses continue to grow, albeit more slowly. The reason for this is foam destruction and the subsequent formation of water. Unlike the foam, the water does not exit the pipe but flows down the walls, gradually accumulating at the bottom. The more stable the foam, the lower the rate of water formation and the lower the pressure losses (as seen by the smaller slope of line 4 in Fig. 4 compared to Fig. 5).

3 Conclusion

1. The properties of an aqueous fire-extinguishing agent based on sodium polyacrylate have been investigated. It was established that the introduction of a polymer gel-forming component promotes

the formation of a more stable compressed air foam structure capable of retaining moisture for a long duration.

2. The main physical characteristics of the generated compressed air foam were determined, including its density, expansion ratio, and stability. These are critical parameters for evaluating the efficiency of transporting and delivering the foam stream to a fire source.

3. Based on the obtained experimental characteristics of the foam, its delivery parameters to a height were calculated. This confirmed the feasibility of utilizing the studied system in high-rise firefighting technologies.

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