# Consideration of Thermodynamic Processes Formation of Compressed Air Foam in Design Compressed Air Foam Systems

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**Abstract.** The main problem with creating compressed air foam systems is to properly regulate the flow of water and the flow of air that is fed into the mixing chamber to continuously provide a foam that must have adequate fire-fighting properties and remain stable over time. The process of obtaining compressed air foam is a thermodynamic process, which depending on the specified technological factors can be both isothermal and adiabatic. The nature of the process determines both the geometric and physical properties of the foam, and its possible fluctuations can lead to changes in the physical characteristics of the foam. The work provides recommendations for determining the type of thermodynamic process, which makes it possible to improve the accuracy when creating mathematical models of mobile plants for the production of compressed air foam.

## 1 Introduction

The main problem with creating compressed air foam systems is to properly regulate the flow of water and the flow of air that is fed into the mixing chamber to continuously provide a foam that must have adequate fire-fighting properties and remain stable over time. This is especially true when using autonomous mobile units for the production of compressed air foam (CAF) in which the flow control is determined directly by the structural characteristics of the actuators and the use of compressed air is used not only for its mixing with the liquid phase, but also as a source of energy for its movement.

The process of obtaining compressed air foam is a thermodynamic process, which depending on the specified technological factors can be both isothermal and adiabatic. In the work [1] established a direct relationship between the performance characteristics of the compressed air foam its geometric characteristics - the size of the bubbles and their homogeneity, which in turn are related to the ratio of the volume of foam obtained and the volume of the mixture with the foam, which are determined by the nature the process of foaming. Therefore, the nature of the process will determine both the geometric and physical properties of the foam, and its possible fluctuations can lead to changes in the physical characteristics of the foam.

When designing the path of moving the CAF, passing it through diffusers, confusers, or Laval nozzles, to calculate their aerodynamic characteristics it is important to determine what thermodynamic process takes place at certain pressure drops, changes in the velocity of foam movement at a given multiplicity at the exit of the installation. Methods for calculating the aerodynamic characteristics of the listed elements with the help of gas-dynamic functions have become widespread [2], but they are based on the assumption that all processes in these elements are adiabatic. At the same time, numerous experiments show that a process such as foam transportation is generally isothermal, in addition the type of process may depend on the selected technological modes or characteristics of the foam, for example, experimental data on determining the speed of sound in foam [3] that, depending on the density of the foam, this process can be both adiabatic and isothermal and also intermediate, and therefore the calculations should be based on different mathematical support. Particularly important is the accuracy of calculations when designing autonomous portable and mobile plants, where there is no auxiliary regulation of technological parameters. Such problems arise when investigating faster processes, such as moving the CAF in diffusers, or confusers at a speed exceeding the speed of sound in the CAF environment, which can range from 30 m / s to 70 m / s.

The paper provides recommendations for determining the type of thermodynamic process, which makes it possible to improve the accuracy when creating mathematical models of mobile plants for the production of CAF.

## 2 Literature analysis and problem statement

The use of compressed air foam is a new way of extinguishing fire. Therefore, the number of scientific works devoted to this topic is much smaller than in other areas of firefighting. The largest number of known studies is devoted to the use of compression foam to extinguish liquid combustible substances. Thus, in [4], the fire extinguishing efficiency of a compression foam feed system was evaluated at different ratios of the amount of compressed air and an aqueous solution of foaming agent for extinguishing fires of liquid combustible substances using a film-forming foaming agent AFFF 3%. It is experimentally determined that the ratio of 1: 7 under the same conditions is the most effective. However, the mathematical model of the installation used was not developed. Only the ratios of 1: 4, 1: 7, and 1:10 were investigated, which makes it impossible to speak of the purity of the experiment.

In the study [5], the effectiveness of extinguishing fires of liquid combustibles was compared with the use of class A (wetting) and AFFF (film-forming) foams. Compressed and air-mechanical foam systems were used. The concentration of class A foaming agents in the solution with water was 0.6%, and AFFF - 1.5%, 2%, 3%. Studies have shown that the time of extinguishing a conventional fire using SAFS is 1.7-2.4 times shorter than the time of extinguishing air-mechanical foam for different concentrations of foaming agent. In [6], the effect of the concentration of foaming agent on the extinguishing efficiency of model fires of solid and liquid combustible fires of compression foam was studied, where concentrations varied from 1.2% to 12%. Tests have shown that reducing the concentration of foaming agent from 12% to 2.2% reduced the quenching time by more than two times. With further decrease in the concentration of foam lost its extinguishing properties and the quenching time increased 1.2% was 39 seconds. However, these works did not find the optimal concentration of foaming agent in solution with water and did not aim to develop a mathematical model of compressed air foam systems.

In the work [7] the effect of the type of foam bubbles of the CAF system on the time of fire extinguishing was studied. Gasoline was used as the ignition source. The concentration of the foaming agent varied from 0.4% to 1%, the feed rate of the foaming solution - from 0.35 $m^3$ / h to 1.7 $m^3$ / h, and the rate of supply of compressed air - from 2.2 g / s to 2.7 g / s. There are three types of foam bubbles: wet, medium and dry. The lowest quenching time was observed with the use of dry foam. The authors did not perform any mathematical simulations of the installation.

Concerning the use of compression foam for extinguishing solid combustible substances, a study [8] compares the effectiveness of extinguishing such fires with compressed air foam and low-frequency air-mechanical foam. The results showed that to extinguish the conditional fire with compressed air foam requires half as much water and twice less time.

The author [9] carried out experimental studies, resulting in the data on the values of leakage currents in the flow of compressed air foam for different indicators from the barrel to the target, at different values of voltage and multiplicity. The results were processed using the multiple regression method and dependencies were obtained, which were applied to the software development to determine the possibility of safe use of compressed air foam for extinguishing live electrical equipment. However, the paper did not address the issue of modeling the work of the CAFS.

In the work [10], researchers determined that the losses of pressure in the hose line when applying foam to height depend on the multiplicity of foam and the pressure in the hose line, which was confirmed by a study [11], which showed that at a multiplicity of foam 8.5 pressure losses are 0.05 MPa for every 10 m of height at a height of foam up to 250 m and a pump pressure of 1.23 MPa. Thus, compared to air-mechanical foam, the pressure loss in the sleeve is halved. The authors did not consider the peculiarities of the work and installation parameters for the generation of compressed air foam.

A number of studies [8, 12, 13] have focused on finding the best ways to mix components in CAF. Thus, in [8, 12], existing methods of air intake into a CAFS mixing chamber were analyzed. Among the main design solutions identified are the two most common methods: vertical and coaxial gas-liquid mixing. The more efficient way of introducing air into the chamber is determined by the experimental method. The results showed that the foam formed by coaxial mixing methods has more effective fire-extinguishing properties than the foam formed by the vertical introduction of air into the mixing chamber. However, the authors did not perform mathematical modeling of the mixing chamber in the compression foam unit.

In the work [13], the authors conducted a study of foam formation through a porous body. It was noted that with increasing flow rate, the diameter of the foam bubble decreases. It is established that pore sizes play a large role in the formation of bubble size. Modeled dependences of the sizes of the diameters of the bubble, depending on the structural design of the porous body. However, the paper does not model the work of the CAFS as a whole.

Many works are aimed at modeling the operation of water extinguishing plants [14–16]. However, the peculiarities of the design of such means do not allow applying the mathematical models obtained to installations for the generation of compression foam. Thus, all known studies [4–11] are aimed mainly at the experimental determination of the effectiveness of the use of compressed air foam for extinguishing fires of various substances. In this case, experimental studies use CAFS with different parameters, mathematical modeling of which has not been carried out or was carried out in part. Therefore, an important and unresolved part of the problem of improving compressed air foam generating units is the development of a mathematical apparatus describing their operation.

## 3 Presentation of basic material

It is known that there are two hypotheses for the propagation of sound in the air: isothermal and adiabatic, and that, as a result of numerous experiments with the speed of sound in a gas environment, it is proved that it is an adiabatic process and that the speed of processes during the propagation of an acoustic wave causes the heat to not reach to neighboring gas parts [17].

It is proposed to consider two mathematical models of the formation of compression foam, the first of which is based on the hypothesis that the processes of foam formation are adiabatic, the second is isothermal and compare the theoretical results with the results of experiments. The movement of foam at speeds of up to 10 m / s (passage along the path) and more than 30 m / s (displacement in the reactor) is considered. For both cases, the formula of the speed of sound in the CAF is compared with the data of experiments on measuring the speed of sound in the foam. It should be noted that in [17] the authors performed a great deal of experimental work on establishing the dependence of the speed of sound in the CAF on its density. A number of experiments were carried out based on a mobile-designed and created in Ukrainian Civil Protection Research Institute, mobile-designed project, see. Fig. 1.

Fig. 1. Experimental mobile installation
for the generation of compression foam

**3.1 Calculations of CAF temperature at relatively low speeds (from 0.1 m / s to 10 m / s) to determine its volume**

Typical for portable plant arrangement is the use of compressed air not only for mixing with the liquid phase, but also as a source of energy for its movement. Compressed air in mobile installations is contained in cylinders under a pressure of about 20 MPa. After the passage of this air through the entire installation path (in case of fire extinguishing), this pressure is reduced to normal, which corresponds to the adiabatic temperature drop, which in normal modes roughly corresponds to:

$$T_x = T_{NC} \cdot \left( \frac{p_{NC}}{p_{bal}} \right)^{\frac{k_2 - 1}{k_2}} = 65{,}514\,K \quad , \qquad (1)$$

where is the:
$T_{NC}$ = 20°C – the initial temperature of the compressed air in the balloon,
$P_{NC}$ = 0,1 MPa – normal atmospheric pressure,
$P_{bal}$ = 20 MPa – the value of the pressure in the cylinder,
$k_2$ = 1,4 – the adiabatic index for air.

Due to the active mixing of the liquid and gas phases, the exchange of thermal energy between the two phases occurs. Then you can write down the system of equations:

$$G_{air} \cdot c_p \cdot \left( T_{mix} - T_x \right) = G_{liq} \cdot c_{liq} \cdot \left( T_{NC} - T_{mix} \right)$$
$$G_{air} = G_{liq} \cdot \left( k_m - 1 \right) \cdot \frac{\rho_{air_{NC}}}{\rho_{liq}} \quad , \qquad (2)$$

where is the:
$G_{air}$ - mass air flow, kg / s,
$G_{liq}$ - mass flow of liquid phase, kg / s,
$c_p$ = 1,005·10$^3$ - specific heat of air at constant pressure, m$^2$ / s$^2$ · K,
$c_{liq}$ = 4.19·10$^3$ - the specific heat of the liquid phase (accepted for water), m$^2$ / s$^2$ · K,

$T_{NC}$ = 20°C – the initial temperature of the compressed air in the balloon,
$T_x$ - the temperature according to formula (1), K,
$T_{mix}$ – the temperature of the mixture of liquid and gas phases, K,
$\rho_{air\_NC}$ = 1,204 kg / m$^3$ – air density under normal conditions,
$\rho_{liq}$ = 1000 kg / m$^3$ – the density of the liquid phase,
$k_m$ ~ 8 – the value of the coefficient of multiplicity of the foam, taken in this calculation.

The solution of this system of equations, taking into account formula (1), will be the value of the resulting temperature of the mixture of liquid and gas phase, $T_{mix}$:

$$T_{mix}=T_{NC}\cdot\frac{c_{liq}\cdot\rho_{liq}+c_p\cdot\left(\frac{p_{NC}}{p_{bal}}\right)^{\frac{k_2-1}{k_2}}\cdot\rho_{air_{NC}}¿(k_m-1)}{c_{liq}¿\rho_{liq}+c_p¿\rho_{air_{NC}}¿(k_m-1)}= \quad 19{,}539°C \tag{3}$$

This calculation shows that processes such as the formation of CAF and its movement at low speed (from 0.1 m / s to 10 m / s), are isothermal due to:

– effective mixing
– relatively large relative mass fraction of the liquid mixture, namely ρliq / km ~ 100 times greater than the gas
– relatively large specific heat of the liquid mixture, namely, ~ 4 times greater than the gas.

### 3.2 Obtaining the formula of the speed of sound for fast (approximately equal to the speed of sound of foam, from 30 m / s to 70 m / s) processes in CAF based on the adiabatic hypothesis

The density of air contained in the CAF bubbles during the adiabatic process can be calculated by the formula:

$$\rho_{air}=\rho_{air_{NC}}\cdot\left(\frac{p}{p_{NC}}\right)^{\frac{1}{k_2}}, \tag{4}$$

where, P is the external pressure of the medium in which the foam is located,

Then the total density of the foam under external pressure will be equal:

$$\rho_{foam}=\frac{G_{liq}+G_{air}}{Q_{liq}+Q_{air}}, \tag{5}$$

where is the:
$G_{air}$ - mass air flow calculated according to the second equation of the system of equations (2) kg / s,
$Q_{liq}$, $Q_{air}$ – the volume flow of the liquid phase and, accordingly, the gas, kg / s, calculated by the formulas:

$$Q_{liq} = \frac{G_{liq}}{\rho_{liq}}$$

$$Q_{air} = (k_m - 1) \cdot Q_{liq} \cdot \rho_{air} \quad . \qquad (6)$$

Then, substituting these values (Eq. (6)) and Eq. (4) into Eq. (5) and simplifying, we obtain the foam density values by the adiabatic hypothesis, which is under the influence of external pressure:

$$\rho_{foam} = \frac{\rho_{liq} + (k_m - 1) \cdot \rho_{air_{NC}}}{1 + (k_m - 1) \cdot \left( \frac{p_{NC}}{p} \right)^{\frac{1}{k_2}}} \quad . \qquad (7)$$

Now, based on the known acoustic wave propagation velocity formula [2] and the adiabatic hypothesis, we find the velocity formula in the foam environment:

$$c_{adiab} = \sqrt{\frac{dp(\rho_{foam})}{d\rho_{foam}}} \quad . \qquad (8)$$

where, $p(\rho_{foam})$ – the function found by solving equation (7) with respect to p. Then, substituting this value into formula (8), we obtain:

$$c_{adiab} = \sqrt{\frac{k_2 \cdot p_{NC}^{\frac{1}{k_2}} \cdot (k_m - 1)^{k_2} ¿ \left(\rho_{liq} + \rho_{air_{NC}} ¿ (k_m - 1)\right) \cdot \rho^{k_2 - 1}}{\left(\rho_{liq} + \rho_{air_{NC}} ¿ (k_m - 1) - \rho_{foam}\right)^{k_2 + 1}}} \quad . \qquad (9)$$

Finding the value of $k_m$ from equation (7) and substituting in (9), we obtain the adiabatic velocity of sound in the foam as a function of the foam density:

$$c_{adiab}(\rho_{foam}) = \sqrt{\frac{k_2 \cdot p_{NC} \cdot \left( \rho_{air_{NC}} \cdot \left( \frac{p}{p_{NC}} \right)^{\frac{1}{k_2}} - \rho_{liq} \right)}{\rho_{foam} ¿ (\rho_{foam} - \rho_{liq})}} \quad .$$

(10)

This formula is based on the assumption that, when the sound vibrations in the foam propagate, the determining thermodynamic process is adiabatic.

### 3.3 Obtaining the formula of the speed of sound for fast (approximately equal to the speed of sound of foam, from 30 m / s to 70 m / s) processes in CAF based on the isothermal hypothesis

The density of the air contained in the CAF bubbles during the isothermal process can be calculated by the formula:

$$\rho_{air} = \rho_{air_{NC}} \cdot \left( \frac{p}{p_{NC}} \right) , \tag{11}$$

where, $P$ is the external pressure of the medium in which the foam is, $P_a$

Then, substituting the values of formulas (6) and formula (4) into formula (9) and simplifying it, we obtain the foam density value by the isothermal hypothesis, which is under the influence of external pressure:

$$\rho_{foam} = \frac{\rho_{liq} + (k_m - 1) \cdot \rho_{air_{NC}}}{1 + (k_m - 1) \cdot \left( \frac{p_{NC}}{p} \right)} . \tag{12}$$

Now, based on the known acoustic wave propagation velocity formula [2] and the isothermal hypothesis, we find (similar to the adiabatic hypothesis) the velocity sound formula in the foam environment as a function of the foam density:

$$c_{isotherm}(\rho_{foam}) = \sqrt{\frac{dp(\rho_{foam})}{d\rho_{foam}}} = \sqrt{\frac{p \cdot (p \cdot \rho_{a_{NC}} - p_{NC} \cdot \rho_{liq})}{p_{NC} \cdot \rho_{foam} \cdot (\rho_{foam} - \rho_{liq})}} .$$

(13)

This formula is based on the assumption that, when the sound vibrations in the foam propagate, the determining thermodynamic process is isothermal.

A graphical comparison of the values of the foaming process parameters, which express the dependence of the speed of sound on the compressed air foam density, derived from two hypotheses: adiabatic and isothermal is shown on Fig. 2.

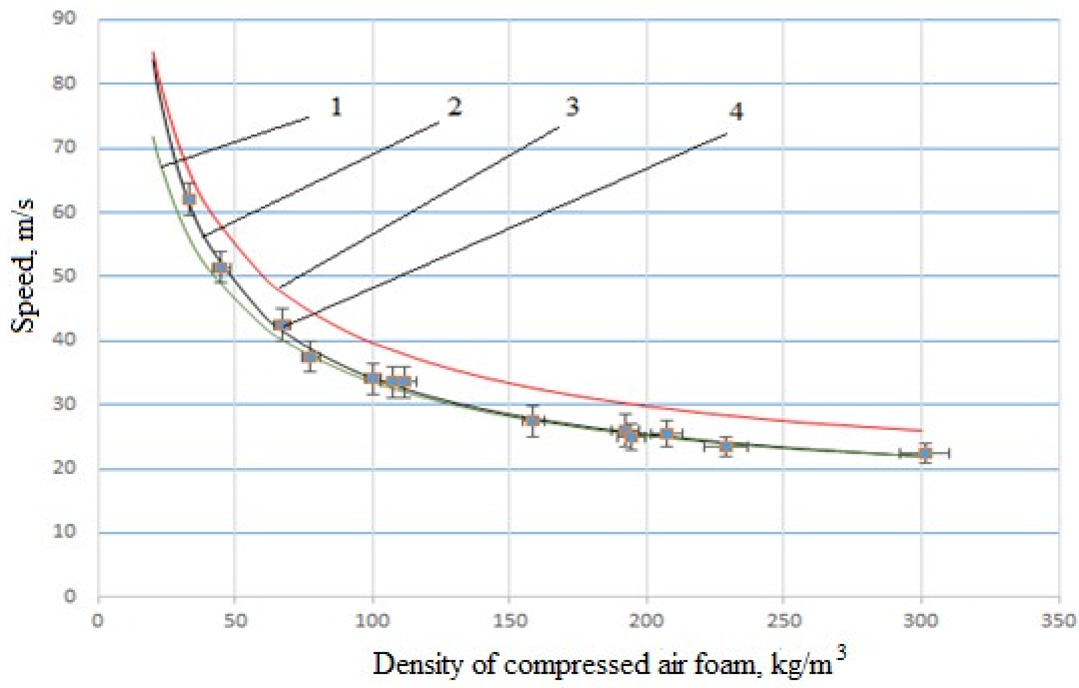


Fig. 2. Dependence of the speed of sound in the compressed air foam, depending on the density, where:

1 - the dependences of the speed of sound on the isothermal hypothesis were found;
2 - the regression curve is based on the experimental data given in [17] by the least squares method:

$$c_{foam} = 646,525 \cdot \rho_{foam}^{-0.734} + 12,139$$

3 - the velocities of sound velocity were found by the adiabatic hypothesis;
4 – the values of the experimental data given in [17].

Analyzing the above results, we note that at a density of CAF from 100 kg / m$^3$ to 300 kg / m$^2$, which corresponds to the compression low and average multiplicity, there is a very exact match between the results of the calculations of the speed of sound according to the isothermal hypothesis and the experimental data. When the CAF density is below 40 kg / m$^3$, which corresponds to the CAF of the high multiplicity, there is a more exact match between the results of the sound velocity calculations according to the adiabatic hypothesis and the experimental data. In particular, when the density of the CAF from 40 kg / m$^3$ to 100 kg / m$^2$, which corresponds to the average CAF multiplicity, the average value obtained on the basis of both hypotheses coincides with the experimental data..

## 4 Conclusions

The process of formation of the CAF and its movement at low speed compared to the speed of sound of this foam (usually from 0.1 m / s to 10 m / s) are isothermal.

Comparative analysis of the processes occurring at higher speeds compared to the speed of sound (usually from 30 m / s to 70 m / s and above) obtained formulas with experimental data gives grounds to claim that:

– o at a density of CAF from 100 kg / m$^3$ to 300 kg / m$^2$ (this corresponds to the CAF of low and medium multiplicity) there is a very exact coincidence with the results of theoretical calculations according to the isothermal hypothesis

– at a density of CAF from 40 kg / m$^3$ to 100 kg / m$^2$ (this corresponds to the average CAF multiplicity) there is a tendency to gradual transition to coincidence with the results of theoretical calculations according to the adiabatic hypothesis.

– at a density of CAF of up to 40 kg / $m^2$ (this corresponds to the CAF of high multiplicity) there is a coincidence with the results of theoretical.

The given recommendations for determining the type of thermodynamic process make it possible to improve the accuracy when creating mathematical models of plants for the production of CAF. .

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