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Calculation of Sprinkler with Gas Saturation at Automatic Foam Fire-extinguishing Systems

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Abstract. **The article provides an example of calculating the elements of the sprinkler at automatic foam fire-extinguishing systems. There is Venturi tube at the core of the sprinkler. There are holes in the narrowest section for gas saturation of the extinguishing agent in data Venturi tube. This design allows the sprinkler to increase the effectiveness of fire-extinguishing foam due to its gas saturation, for example, the calculation of the hydrodynamic characteristics of the sprinkler taken universal foam. Data foam is approved for use in the Republic of Belarus. Injector elements are confuser, narrow (constriction) section and diffuser. To reduce losses, an injector inlet diameter is assumed to be the diameter of the output distribution pipe. This technique can be applied to the hydraulic design of automatic foam fire-extinguishing systems.**

Keywords: **Automatic fire-extinguishing systems, diffuser, dispersion, foam, gas saturation, injector.**

I. Introduction

It is considered that the best foam would be one that has a significant resistance and plentiful water, or low expansion foam and fine-meshed, evenly distributes the bubbles in the layer of foam [1], [2]. The degree of dispersion of the foam depends on the conditions of its production, including the characteristics of the sprinkler or nozzles [3], [4]. The effectiveness of foam (increasing multiplicity and dispersion of the foam) can be improved by means of gas saturation of fire-extinguishing agent. In [5], [6], the authors investigated the fluid mechanics in the sprinklers. Gas saturation is in a narrow section of the injector-sprinkler performed by the type of Venturi tube. As a result, a mathematical model of one-dimensional motion of a gas-liquid mixture has been obtained in the diffuser injector. The solution of this model allows determining the pressure loss in the injector, its geometric characteristics and hydrodynamic parameters [7].

II. General Regulations

Theoretical Basis of the Calculation of the Elements of the Injector

The calculation should be carried out in the fluid. Injector elements are confuser, narrow (constriction) section and diffuser.

In order to reduce the pressure loss on the initial diameter of the inlet confuser, we accept the diameter of distribution pipe:

$$D_{c.} = D_{p.} \qquad (1)$$

where:
$D_{p.}$ – the diameter of distribution pipe;
$D_{c.}$ – the diameter of confuser.

According to [8], we can plot the cone angle (convergence) by a factor of resistance confuser:

$$\xi = f\left(\alpha_{c.}, \frac{l_{c.}}{d_0}\right), \qquad (2)$$

where:
ξ – the drag coefficient of the confuser;
$\alpha_{c.}$ – the cone angle of the confuser;
$l_{c.}$ – the confuser length;
d_0 – the diameter of the narrow section.

The cone angle of the confuser is accepted in the range of 15^0–40^0.

Pressure loss in the confuser is determined using the Weisbach equation:

$$\Delta p_{c.} = \xi_{c.} \rho \frac{v_0^2}{2}, \qquad (2)$$

where:
ρ – the density of the extinguishing fluid (foaming agent);
v_0 – the velocity in the narrow section of the injector.

$$v_0 = \frac{4Q}{\pi d_0^2}, \qquad (3)$$

where:
Q – the consumption of the extinguishing liquid.

The resistance factor of the confuser can be defined according to [9]:

$$\xi_{конф.} = \begin{pmatrix} -0.0125 n_0^4 + 0.0224 n_0^3 - 0.00723 n_0^2 + \\ +0.004444 n_0 - 0.00745 \end{pmatrix} \times \times\left(\alpha_p^3 - 2\pi\alpha_p^2 - 10\alpha_p\right), \qquad (4)$$

where:
n_0 – the degree of the narrowing part of confuser,

$$n_0 = \left(\frac{d_0}{D_{c.}}\right)^2; \quad (5)$$

$$\alpha_p = 0.01745\alpha_{c.}. \quad (6)$$

For the final calculation of the confuser to find the value for the diameter of the narrow section of the injector, write the equation of Bernoulli for the inlet and the narrow section of confuser without specific energy provisions of sections because its value is disproportionately low compared to the rest of the equation:

$$p_{i.} + \rho\frac{v_{i.}^2}{2} = p_0 + \rho\frac{v_0^2}{2} + \Delta p_{c.}, \quad (7)$$

where:
$p_{i.}$ – the pressure at the inlet to the injector;
$v_{i.}$ – the velocity of the fluid at the inlet of the injector;
p_0 – the pressure in the narrow section.

Transform the equation in terms of:

$$v_{i.} = v_0\left(\frac{d_0}{D_{i.}}\right)^2 \quad (8)$$

and (5) from (8) after the transformations the diameter of the narrow section can be expressed:

$$d_0 = \sqrt[4]{\frac{8Q^2\rho}{\pi^2\left[p_{i.} - p_0 - \Delta p_{c.}\right]}}. \quad (9)$$

In the first approximation, calculation of the injector flow path due to the complexity of the process should be done by successive approximations [13]. The diameter of the narrow section can be determined without taking into account the pressure loss in the confuser or $\Delta p_c = 0$:

$$d_0 = \sqrt[4]{\frac{8\rho Q^2}{\pi^2\left(p_{i.} - p_0\right)}}. \quad (10)$$

The next step is to calculate the narrow section in terms of providing the necessary multiplicity of foam. To provide the necessary multiplicity of foam, the flow of air will be:

$$Q_{air.} = Q(K-1). \quad (11)$$

where:
K – the multiplicity of foam (given multiplicity).

Considering the flow of air as the outflow through a small hole in a thin wall, a well-known formula can be written [10]:

$$Q_{air} = \mu S_{air}\sqrt{\frac{2\Delta p_{air}}{\rho_{air}}}, \quad (12)$$

where:
μ – the discharge coefficient of small holes $\mu = 0.62$ [6];
Δp_{air} – the differential pressure between the outside air pressure and vacuum pressure in the narrow section of the injector;
ρ_{air} – density of air, because the fire suppression system in a building is assumed to be 1.29 kg/m^3;
S_{air} – the total cross-sectional area of holes for suction (supply) of air flotation given multiplicity,

$$S_{air} = \frac{n_{air}\pi d_{air}^2}{4}, \quad (13)$$

where:
n_{air} – the number of holes for air;
d_{air} – the diameter of holes for air.

Thus, the diameter of the holes for air will be:

$$d_{air} = 2\sqrt{\frac{Q_{air}}{\pi\mu\sqrt{\frac{2\Delta p_{air}}{\rho_{air}}}}}, \quad (14)$$

or

$$d_{air} = 2\sqrt{\frac{Q(K-1)}{\pi\mu\sqrt{\frac{2\Delta p_{air}}{\rho_{air}}}}}. \quad (15)$$

The basic calculation is the determination of the diffuser injector pressure drop in the flow of two-phase fluid, the density of which is a function of pressure, changing the non-uniform two-phase fluid flow in the diffuser.

In [11], the dependence to determine the pressure drop in the flow of two-phase fluid in the diffuser injector for non-uniform motion:

$$\Delta p = \frac{2\tau}{tg\frac{\alpha_d}{2}}\ln\frac{D}{d_0} + \frac{8\rho_{mt.}Q^2}{\pi^2}\left[\frac{\rho^2}{\rho_{mt.}^2\left(2l_d tg\frac{\alpha_d}{2} + d_0\right)^4} - \frac{1}{d_0^4}\right], \quad (16)$$

where:
D – the diameter of the outlet section of the injector, which may be taken as the diameter of the inlet section of the sprinkler:

$$D = D_{sp.};\tag{17}$$

τ – the shear stress at the wall of the diffuser;
α_d – the cone angle of the diffuser;
$\rho_{mt.}$ – the density of the two-phase aerated fluid in the diffuser;
l_d – the length of the diffuser.

To determine the density of the two-phase fluid in [11] a formula is written:

$$\rho_{mt.} = \frac{\rho\left(p + p_{atm.}\right)}{p + Kp_{atm.}},\tag{18}$$

where:
p – the pressure at the exit of the diffuser;
$p_{atm.}$ – the atmospheric pressure.

Considering:

$$2l_d tg\frac{\alpha_d}{2} + d_0 = D = D_{sp.}\tag{19}$$

Equation (18) can be written as follows:

$$\Delta p = \frac{2\tau}{tg\frac{\alpha_d}{2}}\ln\frac{D}{d_0} + 0,811\rho_{mt.}Q^2\left[\frac{\rho^2}{\rho_{mt.}^2 D^4} - \frac{1}{d_0^4}\right].\tag{20}$$

The shear stress at the wall of the diffuser for a uniform motion is defined as follows [12]:

$$\tau' = \rho_{mt.}v_*^2,\tag{21}$$

where:
v_* – the friction velocity (or the rate of shear stress on the wall), defined as follows [12]:

$$v_* = \frac{v}{5.75\lg\frac{a}{\Delta} + 8.5},\tag{22}$$

where:
Δ – the equivalent roughness;
a – the distance from the wall of the channel to the layer, moving at an average velocity v.

To determine a, using the ‘one-seventh’ Karman's law [12]:

$$\frac{v}{v_{\max}} = \left(\frac{a}{r}\right)^{\frac{1}{7}},\tag{23}$$

where:
r – the radius of the channel,

hence:

$$a = \frac{D}{2}\left(\frac{v}{v_{\max}}\right)^7.\tag{24}$$

According to [12]:

$$\frac{v}{v_{\max}} = 0.75 - 0.9.\tag{25}$$

Shear stress on the wall of the cone is equal to [11]:

$$\tau = k\tau',\tag{26}$$

where:

k – the coefficient reflecting the non-uniform motion and depending on the angle of cone diffuser and being equal 0.996^{α_d} [11].

Thus, all elements of the injector are determined and can be calculated for specific values and parameters for the design of automatic foam fire-extinguishing systems [14].

Example of Calculating the Sprinkler with Pre-aeration with Manufacturer’s Characteristics

1. Flow of extinguishing agent (foaming agents):

Q = 1.06 l/s.= 1.06 ·10-3 m^3/s.

2. Required foam:

n = 10.

3. The pressure at the outlet of the injector taken to be the pressure at the inlet of the sprinkler:

$p = 1.5$ atm $= 1.5 \cdot 98100 = 147150$ Pa = 0.147 MPa.

4. The inlet pressure to the injector taken to be 5 m (0.5 atm) is more than the output of the sprinkler (the first approximation):

$p_{i.} = p_{out.} + 0.5 = (1.5 + 0.5)\cdot 98100 = 0.1962$ MPa.

5. The density of the extinguishing agent:

$\rho = 1000$ kg/m^3.

Calculation of the Injector

A. *Confuser*

Injector inlet diameter equals the diameter of the output distribution pipe:

$D_{c.} = 16$ mm $= 16\cdot10^{-3}$ m.

The cone angle confuser $\alpha_{c.} = 25^o$.

Specify the pressure drop in the injector (the first approximation):

$\Delta p = p_{i.} - p = 49050$ Pa (0.5 atm) = 0.049 MPa.

Determine the diameter of the narrow section (the first approximation):

$$d_0 = \sqrt[4]{\frac{8\cdot\rho\cdot Q^2}{\pi^2\cdot(p_{i.}-p_0)}}.$$

Pressure in the narrow section $p_0 = -0.5$ atm.

$$d_0 = \sqrt[4]{\frac{8\cdot1000\cdot(1.06\cdot10^{-3})^2}{3.14^2\cdot(2-(-0.5))\cdot98100}} = 7.8\cdot10^{-3}\,\text{m}.$$

Velocity in the narrow section of the confuser:

$$v_0 = \frac{4\cdot Q}{\pi\cdot d_0^2} = \frac{4\cdot1.06\cdot10^{-3}}{3.14\cdot(7.8\cdot10^{-3})^2} = 22.2\ \text{m/s}.$$

The compression ratio:

$$n_0 = \left(\frac{d_0}{D_{c.}}\right)^2 = \left(\frac{7.8}{16}\right)^2 = 0.24$$

$$\alpha_p = 0.01745\cdot\alpha_{c.} = 0.01745\cdot25 = 0.436\,.$$

$$\zeta_{c.} = (-0.0125\cdot n_0^4 + 0.0224\cdot n_0^3 - 0.00723\cdot n_0^2 + 0.00444\times n_0 - 0.00745)\cdot(\alpha_p^3 - 2\pi\alpha_p^2 - 10\alpha_p) = (-0.0125\cdot0.24^4 + 0.0224\cdot0.24^3 - 0.00723\cdot0.24^2 + 0.00444\cdot0.24 - 0.00745)\cdot(0.436^3 - 2\cdot3.14\cdot0.436^2 - 10\cdot0.436) = 0.04$$

Losses in confuser are as follows:

$$\Delta p_{c.} = \zeta_{c.}\cdot\rho\cdot\frac{v_0^2}{2} = 0.04\cdot1000\cdot\frac{22.2^2}{2} = 9860\text{Pa} = 0.00986\ \text{MPa}$$

B. Calculation of Air

Calculation of air to produce foam with a multiplicity $n = 10$:

$$Q_{air} = Q\cdot(n-1) = 1.06\cdot(10-1) = 9.54\cdot10^{-3}\,m^3/\text{s}.$$

Difference between the atmospheric pressure and absolute pressure is

$$\Delta p_{air} = p_{atm} - p_0^{abs} = 1 - 0.5 = 0.5\text{atm} = 0.04905\text{MPa}$$

Number of holes accepted to be $m = 6$.

Diameter of holes to provide air:

$$d_{air} = \frac{2}{m}\sqrt{\frac{Q\cdot(n-1)}{\pi\cdot\mu\cdot\sqrt{\frac{2\Delta p_{air}}{\rho_{air}}}}} = \frac{2}{6}\cdot\sqrt{\frac{1.06\cdot(10-1)\cdot10^{-3}}{3.14\cdot0.62\cdot\sqrt{\frac{2\cdot49050}{1.29}}}} = \frac{2}{6}\cdot\sqrt{\frac{10.8\cdot10^{-3}}{1.95\cdot\sqrt{76047}}} = 1.4\cdot10^{-3}\,\text{m} = 1.4\ \text{mm}.$$

C. The Losses in the Diffuser Injector

$$\Delta p_d = \frac{2\cdot\tau}{\mathrm{tg}\frac{\alpha_d}{2}}\cdot\ln\frac{D}{d_0} + 0.811\cdot\rho_d\cdot Q^2\cdot\left[\frac{\rho^2}{\rho_d^2\cdot D^4} - \frac{1}{d_0^4}\right],$$

Density of the two-phase flow in the diffuser:

$$\rho_d = \frac{\rho\cdot(p+p_{atm})}{p+n\cdot p_{atm}} = \frac{1000\cdot(1.5+1)}{1+10\cdot1} = 182\ \text{kg/m}^3.$$

The cone angle of the diffuser accepted to be $\alpha_d = 8.5^o$.

$$a = r\cdot\left(\frac{v}{v_{max}}\right)^7,$$

$\frac{v}{v_{max}}$ taken to be 0.8.

$$a = \frac{16}{2}\cdot(0.8)^7 = 1.68\cdot10^{-3}\,\text{m}.$$

Dynamic velocity:

$$v_* = \frac{v_{mt}}{5.75\cdot\lg\frac{a}{\Delta} + 8.5}.$$

Equivalent roughness for non-ferrous metals accepted to be $\Delta = 0.002$ mm = $2\cdot 10^{-6}$ m.

Velocity without gas saturation is

$$v = \frac{4\cdot Q}{\pi\cdot D^3} = \frac{4\cdot 1.06\cdot 10^{-3}}{3.14\cdot(16\cdot 10^{-3})^2} = 5.3 \text{ m/s.}$$

Rate of two-phase flow in the output section is

$$v_* = \frac{29}{5.75\cdot \lg\dfrac{1.68}{0.002} + 8.5} = 1.14 \text{ m/s.}$$

The shear stress at the wall of the diffuser for a uniform motion is

$$\tau' = \rho_{mt}\cdot v_*^2 = 182\cdot 1.14^2 = 236 \text{ Pa}$$

Shear stress on the wall of the diffuser is

$$\tau = k\cdot\tau' = 0.967\cdot 236 = 228 \text{ Pa},$$

where

$$k = 0.996^{\alpha^d} = 0.996^{8,5} = 0.967 .$$

Based on the equations above,

$$\Delta p_d = \frac{2\cdot 228}{\mathrm{tg}\dfrac{8.5}{2}}\cdot \ln\frac{16}{7.8} + 0.811\cdot 182\cdot(1.06\cdot 10^{-3})^2 \times$$

$$\times\left[\frac{1000^2}{182^2\cdot(16\cdot 10^{-3})^4} - \frac{1}{(7.8\cdot 10^{-3})^4}\right] = 4451 + 31510 = 35960 \text{ Pa.}$$

D. Pressure Losses in the Injector

$$\Delta p = \Delta p_{c.} + \Delta p_{d.} = 9860 + 35960 = 45820 \text{ Pa} = 0.47 \text{ atm.}$$

Uncertainty is

$$\eta = \frac{0.5 - 0.47}{0.5}\cdot 100\% = 6\%.$$

E. Required Pressure at the Inlet to the Injector

$$p_{i.} = 1.5 + 0.47 = 1.97 \text{ atm} = 193257 \text{ Pa} = 0.193 \text{ MPa.}$$

F. Dimensions of the Injector

Confuser:

$$l_{c.} = \frac{D_{c.} - d_0}{2\mathrm{tg}\dfrac{\alpha_{c.}}{2}} = \frac{16 - 7.8}{2\mathrm{tg}\dfrac{25}{2}} = 18.5 \text{ mm.}$$

Diffuser:

$$l_{d.} = \frac{D_{d.} - d_0}{2\mathrm{tg}\dfrac{\alpha_{d.}}{2}} = \frac{16 - 7.8}{2\mathrm{tg}\dfrac{8.5}{2}} = 55.2 \text{ mm.}$$

Injector:

$$l_{inj} = l_{c.} + l_{c.} = 18.5 + 55.2 = 74 \text{ mm.}$$

III. CONCLUSIONS

Sprinkler and injector design parameters are presented in the tables below:

TABLE I

ESTIMATED PARAMETERS OF SPRINKLER

Parameters of sprinkler	
Flow rate, Q (l/s)	1.06
Inlet diameter, D (mm)	16
Working pressure in front of the sprinkler, P (MPa)	0.15
Required foam	10
Inlet pressure to the injector, P (MPa)	0.19
Density of the extinguishing agent, ρ (kg/m^3)	1000

TABLE II

ESTIMATED PARAMETERS OF INJECTOR

Parameters of injector	
Necessary pressure in front of the injector, P, (MPa)	0.19
Cone angle of the confuser, $\alpha_{c.}$ (°)	25
Inlet section diameter, D (mm)	16
Narrow section diameter, D (mm)	7.8
Number of the holes	6
Diameter of the holes of the diffuser, D (mm)	1.4
Cone angle of the diffuser, $\alpha_{d.}$ (°)	8.5
Outlet section diameter, D (mm)	16
Confuser length, $l_{c.}$ (mm)	18.5
Diffuser length, $l_{d.}$ (mm)	55.2
Injector length, l_{inj} (mm)	74

Thus, the authors obtained the calculations of the experimental model of sprinkler pre-aeration of fire extinguishing agent that will allow developing design documentation for the sprinkler with pre-aeration fire extinguishing agent.

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