JOURNAL OF THEORETICAL AND APPLIED MECHANICS
52, 3, pp. 655-664, Warsaw 2014

THE USAGE OF HIGH SPEED IMPULSE LIQUID JETS FOR PUTTING OUT GAS BLOWOUTS

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The experimental examinations of gas flame suppression by a high speed impulse liquid jet generated by a powder impulse hydro-cannon have been carried out. The speed of the impulse jet depending on charge energy has ranged from 300 to 600 m/s. The speed of the jet head right near the flame has been measured by a laser non-contact measuring device, the flow has been photographed. It has been shown that the high-speed cloud of splashes with a big cross-section around the jet is being formed. It effectively forces down the flame of the gas on distances 5-20 m from installation.

Keywords: impulse liquid jet, powder impulse hydrocannon

1. Introduction

Oil and gas fountain fires are one of the most difficult species of industrial accidents at oil and gas fields. Huge amounts of carbon dioxide, oxides of carbon, nitrogen and sulfur are ejected into the atmosphere in such accidents. Fighting these fires requires using of enormous material and technical resources and can last for weeks. The height of high power burning torch reaches 80-100 m, heat intensity in such torch amounts to approximately several million kilowatts (Grace, 2003).

Fire monitors (hydromonitors), gas-extinguishing vehicles, pneumatic powder flame-suppressers (Povzik, 2004; Mamikonyants, 1971; Holand, 1997; Drayzdel, 1990; Polakov, 2012) are the most commonly used methods of gas blowout extinguishing in Ukraine and other CIS countries. Each of the specified fire-fighting methods has its advantages and disadvantages. However, there is still no universal and effective method for gas blowout extinguishing.

One of the most wide-spread methods of fires and gas blowout extinguishing is the use of water mist. The main active factors in the flame extinguishing by water mist are cooling of the burning material and forming of the vapor cloud confining the combustion source. A separating gas blowout quenching is observed using a high speed liquid jet, the jet of a finely dispersed spray is ripping off the torch. Experiments have shown that the disruption of diffusion flame torch occurs when the extinguishing speed of the liquid jet is about 80-100 m/s.

The present paper presents some experimental research on gas blowout extinguishing using high speed impulse liquid jets, which are obtained by impulse water cannon (IW). Studies carried out using model plants have provided promising results that demonstrated the possibility of torch extinguishing by means of such a method, and the prospects of this direction (Larin *et al.*, 2011; Semko *et al.*, 2013).

2. Outlines of the experimental procedure

The purpose of the experiments was to determine whether it is possible to put out gas blow-outs by an impulse water cannon, to determine the running speed of cross flow of the liquid in which the flame is extinguished, and to define the zone to which the jet should be aimed in order to guarantee the flame extinguishing process.

The gas blowout model has been calculated on the basis of aerodynamical similarity factor, which characterizes the processes of gas mixing with the surrounding atmosphere. It depends on pressure and gas jet thickness (Wooleys and Yarin, 1978; Spalding, 1985; Karpov, 1998)

$$\mathcal{K} = \frac{w_0^2}{2gd_0} \tag{2.1}$$

where w_0 is the gas outflow velocity [m/s], g – speed-up of free fall, d_0 – well diameter [m].

Gas blowout modeling for blow-out burning with output (1-3)$\cdot 10^6$ m^3/day has been carried out. The well diameter is calculated using standard drill equipment from 0.3 to 0.5 m. The modeling scale according to linear size M 1:100 for the modeling of blow-out diameter is in the range (3-5) mm.

Parameters of simulative flames for different conditions (output and well hole diameter) are provided in the Table 1.

Table 1. Parameters of different simulative flames in different condition

No.	Diameter of the model [mm]	Well hole diameter [m]	Gas blow-out [10^6 m^3/s]	Speed value [m/s]	Flow rate [m^3/s]
1	3	0.3	1	16.38	0.116
2	3	0.3	2	32.76	0.23
3	3	0.3	3	49.1	0.347
4	4	0.4	1	9.21	0.116
5	4	0.4	2	18.43	0.23
6	4	0.4	3	27.65	0.347
7	5	0.5	1	5.89	0.116
8	5	0.5	2	11.8	0.23
9	5	0.5	3	17.7	0.347

In the experiments, the simulative fire seat of gas blow-out corresponding to average parameters has been used.

Figure 1 is a schematic diagram of the experiment, and Fig. 2 is a picture of experiments carried out at the test site to determine the speed of the high impulse liquid jet at which the quenching of the torch occurs.

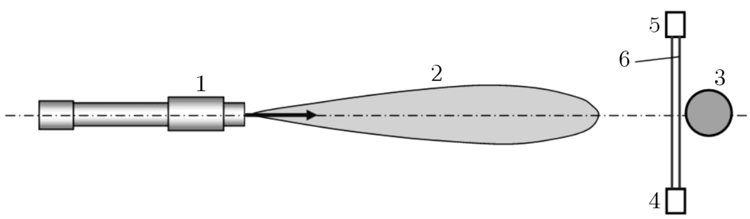

Fig. 1. A scheme of the experiment of extinguishing a gas torch; 1 – powder-IW, 2 – pulse jet, 3 – gas torch, 4 and 5 – blocks of speed meter, 6 – laser beams

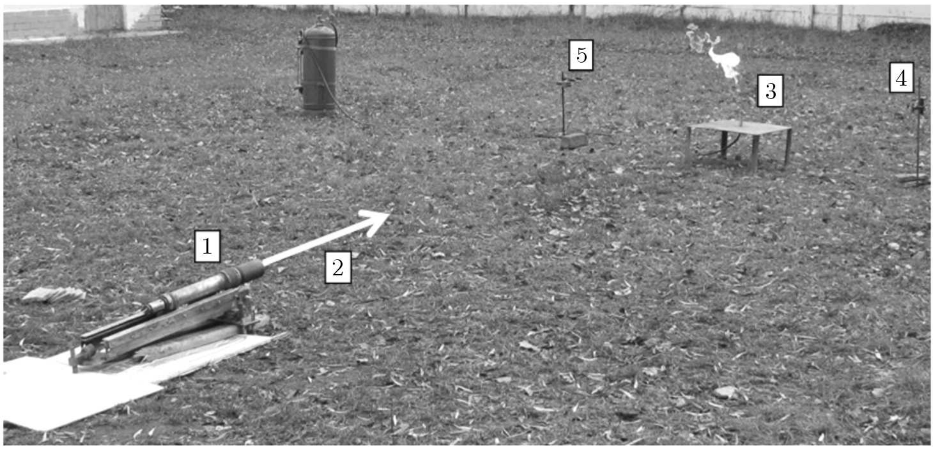

Fig. 2. The scheme of field tests of extinguishing a gas torch; 1 – powder-IW, 2 – pulse jet, 3 – gas torch, 4 and 5 – blocks of speed meter

A series of shots of high-speed water jets 2 have been produced towards the gas torch 3 from powder IW 1, which was located at a predetermined distance from the torch. The burnout of the torch was qualitatively recorded, as well as the speed of the high-speed jet was measured directly in front of the torch using a non-contact laser speed detector, which consists of two blocks 4 and 5. The mass of the powder charge and the distance from IW to the torch varied during the experiments, the last one was measured by a tape measure. Changing these two parameters allows adjusting the impulse jet speed before the torch in a wide range from 60 to 430 m/s, registered in the experiments.

3. Gunpowder impulse water cannon

A layout of the powder impulse hydro-cannon by means of which the experimental research was carried out is described in Fig. 3 (Semko, 2002, 2007). Barrel 4 of the powder water-cannon that ends with a conical nozzle 6 with collimator 7 is filled up with water 3.

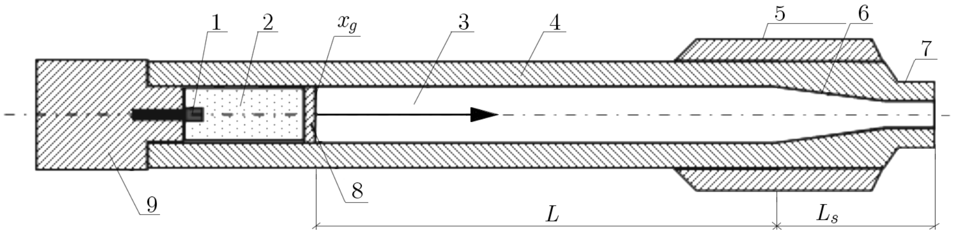

Fig. 3. Powder impulse water cannon; 1 – igniter, 2 – combustion chamber, 3 – water, 4 – barrel, 5 – binding belt, 6 – nozzle, 7 – collimator, 8 – wad, 9 – gate, L and L_s are length of the barrel and the nozzle with collimator, x_g is the coordinate of the contact surface

Charge of gun-powder 2 is separated from water charge 3 by means of wad 8. For reinforcement, the most stressed section of the barrel is strengthened by binding belt 5 fixed on the barrel with backward tension. Gun-powder charge 2 in the casing of the water cannon is fixed by gate 9, inside which there is igniter 1. At the start time, igniter 1 is actuated and fires gun-powder charge 2. Powder gases that are generated during powder burning start expulsing and ejecting water charge 3 through conical nozzle 6 in form of a impulse liquid jet. The outflow of liquid jet starts with a relatively small velocity that increases with the increasing the pressure of powder gases.

In order to build a mathematical model of the powder impulse water-gun shot, the following assumptions have been made. The fluid is considered as ideal and compressible, viscosity, heat conductivity and the influence of wad are neglected. The structure of the nozzle is assumed to be smooth, and radial flow components are not taken into account. The beginning of the coordinates corresponds to the nozzle inlet.

In the adopted approach, the quasi one-dimensional flow of the ideal compressible liquid in the powder impulse water gun is described by a system of equations of non-steady gas dynamics as follows

$$\frac{\partial \rho F}{\partial t}+\frac{\partial \rho v F}{\partial x}=0 \qquad \frac{\partial \rho v F}{\partial t}+\frac{\partial(\rho v^2+p)F}{\partial x}=p\frac{dF}{dx} \qquad p=B\Big[\Big(\frac{\rho}{\rho_0}\Big)^n-1\Big] \tag{3.1}$$

where t is time, x is a coordinate, v is speed, $F(x)$ is the area of cross section of the nozzle and barrel, p and ρ are pressure and density, $B = 304.5\,\mathrm{MPa}$, $n = 7.15$, $\rho_0 = 10^3\,\mathrm{kg/m^3}$ are constants in Tait's water state equation.

The initial and boundary conditions are the following

$$\begin{array}{llll} v(0,x)=0 & p(0,x)=0 & \rho(0,x)=\rho_0 & -L\leqslant x\leqslant L_s \\ p(t,L)=0 & p(t,x_g)=p_g & v(t,x_g)=v_g & \end{array} \tag{3.2}$$

where L and L_s are lengths of the barrel and nozzle with collimator, x_g is the coordinate of the contact surface, p_g and v_g are pressure and speed of powder gases on the contact surface.

The burning of the gunpowder is calculated according to the methodology described in the paper by Semko (2002, 2007) and according to the assumptions made in this paper that are standard for the problems of internal ballistics in artillery (Orlova, 1974). In the quasi-steady approximation, the gunpowder burning equations and initial conditions are as follows

$$\begin{array}{llll} \dfrac{dz}{dt}=\dfrac{u_1 p_g}{h_1} & Q_g=\dfrac{dm_g}{dt}=m_{p0}\sigma(z)\dfrac{dz}{dt} & \dfrac{1}{k-1}\dfrac{d(p_gV_g)}{dt}+p_gFu_g=qQ_g & \\ \dfrac{dV_g}{dt}=Q_g\Big(\dfrac{1}{\rho_p}-\alpha\Big)+v_gF & v_g=\dfrac{dx_g}{dt} & m_b=m_{b0} & z=0 \\ V_g=V_{g0} \qquad m_g=m_{g0} & p_g=p_{g0} & x_g=-L & \end{array} \tag{3.3}$$

where h_1 is a half of the powder grain thickness, z is the burnt layer thickness referred to h_1, u_1 is the constant of burning speed, p_g is the pressure of powder gases, Q_g is the speed of appearing powder gases, $\sigma(z) = 3(1 - 2z + z^2)$ is the relative area of burning of the gunpowder spherical grains, α is a correction for the volume of molecules, m_g and m_{p0} are the gas mass and the initial mass of powder, k is an the adiabatic index, q and ρ_p are the specific combustion heat and the density of gunpowder, V_g is the volume of powder gases, V_{g0}, m_{g0}, p_{g0} are parameters of the gas after the ignition.

The calculations have been made numerically by the methodology of Godunov and Rodionov (Semko, 2007, 2002; Reshetnyak and Semko, 2009). Hereinafter some calculation results are provided for a powder impulse water-gun with the following parameters: the mass of water charge – 450 g and the diameter of nozzle and jet – 15 mm.

In Fig. 4, graphs of the dependence of the jet outflow speed and internal pressure of the water-gun beginning from the time needed for the powder charge with a mass of 30 g are provided (normal operation conditions of the hydro-cannon). Curve 1 shows the outflow speed, 2 – pressure of powder gases, 3 – water pressure in the barrel of hydro-cannon.

As it is seen in the figure, the jet outflow of the impulse hydro-cannon starts from zero speed. While the powder is burnt, the outflow speed grows fast and reaches the maximum value of 685 m/s in 1.5 ms from the shot beginning. The powder burns out later, by the time point $t_g = 1.57\,\mathrm{ms}$ (on the graph it is pointed out by the dotted line). The jet outflow speed by this

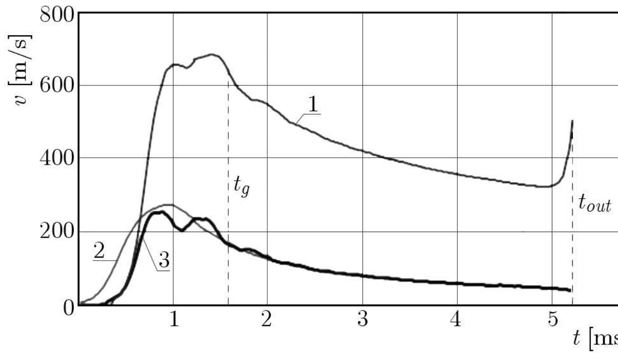

Fig. 4. Courses of the jet outflow speed and internal pressure of hydro-cannon with time; 1 – outflow speed, 2 – powder gas pressure, 3 – water pressure in barrel, $t_g = 1.57\,\mathrm{ms}$ – powder burning time, $t_{out} = 5.2\,\mathrm{ms}$ – water jet outflow ends

time reduces a little till 647 m/s. After powder burning out, the outflow speed decreases slowly till 320 m/s. The jet outflow ends by the time point $t_{out} = 5.2\,\mathrm{ms}$ with a small portion of water kick by powder gases with a higher speed.

Curve 2 that describes powder gases pressure in the water-cannon has a typical form that is characteristic for barreled cannon weapons. The maximum pressure of powder gases reaches 275 MPa by the time point 0.95 ms. Afterwards, the pressure of powder gases steadily declines till 40 MPa at the end of the shot. Water pressure in the barrel of the hydro-cannon (curve 3) does not exceed the powder gases pressure and it has a pulsating nature, that reflects the wave processes inside the installation during the firing process that are connected with the compression and depression waves that are reflected from the cutoff point of powder gases and the nozzle exit section. Pressure pulsations are insignificant and they influence a little the speed of the impulse jet outflow. The liquid pressure in the installation and the jet outflow speed are perfectly in line with the Bernulli equation for an incompressible liquid and steady-flow process (Semko, 2002; Orlova, 1974). The maximum outflow speed of the impulse liquid jet in the hydro-cannon calculated on the basis of liquid pressure inside the installation at this point amounts to 678 m/s that differs from the exact calculation in the non-steady formulation for the compressible fluid by 1%. The provided calculation results show that the parameters of the powder hydro-cannon can be obtained with a good accuracy in a simpler quasi-steady formulation not considering compressibility of the liquid.

In Table 2 calculation results of the maximum outflow speed of the impulse liquid jet of powder hydro-cannon for different gun-powder charges are provided.

Table 2. Dependence of hydro-cannon parameters an gun-powder mass

Powder mass [g]	30	25	20	15	10	5
Maximum jet speed [m/s]	686	600	504	405	298	178
Maximum pressure of powder gases [MPa]	275	205.9	143	89.8	46.5	16.8

As it has been expected, diminishing of the powder mass (firing energy) reduces the maximum jet speed and the pressure inside the installation, and the reduction is much faster for the pressure than the speed. For example, for a powder charge of 10 g (powder mass is 3 times less than in the regular operation mode), the maximum outflow speed decreased by 2.3 times and the pressure went down by 6 times. The correlation between speed and pressure conforms satisfactorily to the Bernulli equation for incompressible liquids, according to which the pressure is proportional to the squared speed. A significant decrease of the maximum pressure inside the installation with insignificant diminishing of the maximum liquid jet speed is a positive factor for the strength properties of the installation: the lower is the pressure in the installation, the thinner its casing can be, the lower can be its mass and, as a consequence, the higher its mobility is.

The specific nature of the dependence of the outflow speed of the liquid jet of the hydro-cannon on time (a fast increase in the beginning of outflow from zero to maximum, and afterwards a drop practically up to zero) determines patterns of diffusion of the impulse jet. At the beginning of the outflow process, the fastest particles of outflowing from the hydro-cannon nozzle liquid go through the lower, escaped earlier ones. Consequently, in the stream there occurs radial flow that leads to an increase in the jet cross section. The speed of radial flow v_r can be estimated on the basis of Bernulli equation for the excess pressure in the jet that occurs in collision of the faster backward section of the jet with its slower front section that escaped earlier (Chermenskiy, 1970; Dunne and Cassen, 1956; Noumi and Yamamoto, 1992). These estimations show that the speed of radial flow is proportional to the square root of the excess pressure $v_r \sim \sqrt{\Delta p} \sim \Delta v$, that in turn is proportional to the square of speed difference Δv of the co-crashed liquid sections. That is why at the initial phase of the outflow, speed of the head of the jet increases until the high-speed sections have not reached the head of the stream. Afterwards, the jet head diminishes due to deceleration by air. The radial flow causes thickening of the jet and formation around it of a halation of splashes that moves with the speed that differs to a little extent from the speed of the jet core.

4. Experiments of the simulative/model gas blow-out putting out by means of a hydro-cannon

The distance from IW to the torch and the amount of the powder charge varied during the experiments, they determine the speed of the impulse jet liquid. The distance from the position of IW to the torch was measured by a tape measure, and the aiming was performed by means of a special laser sight, which was mounted on the trunk of the impulse water cannon. The speed of the impulse jet liquid at which the quenching of the gas torch occured was measured during the experiments. Measuring the velocity of the head of the liquid impulse jet was carried out by means of a non-contact laser speed meter of our own design.

A series of fire shots have been made from distances of 5, 10, 12 and 15 meters for powder charges of 5, 10 and 15 g. In the experiments, the speed of the impulse jet head section before the torch has been measured, the jet has been photographed and video filmed at its different diffusion stages. The speed of the head section of the jet has been measured by means of a non-contact laser speed measuring device that allowed recording the speed in the range from 50 to 3000 m/s.

The results of the experiments are shown in Table 3.

It can be concluded from the analysis of the experimental results that the rate of the impulse liquid jet head which provides for hearth extinguishing of the model fire gas fountain ranges from (80-90) m/s, which confirms the experimental studies obtained by other authors. Figure 5 shows fragments of videorecording of the gas flame quenching by the high speed impulse liquid jet. Here 1 stands for the impulse jet of the liquid, 2 – gas torch, 3 – speed detector modules. Figure 5a, 5b and 5c are the initial, middle and final stages of the gas torch extinguishing, and Fig. 5d – size of the torch. A band out of the dark material with subdivisions is visible on the background of the picture. The distance between big labels is 1 meter, and between small ones is 0.5 m. The distance from the facility to the torch is 10 m. The photos also show speed meter modules 3 that are installed at a distance of two meters from each other.

The jet flew 3.5 meters on the first photo (Fig. 5a). The form of the jet at this time corresponds to the middle phase of spreading. The head part of the spray and the veil of splashing in the rear are clearly visible, the cross-section of splashing is many times larger than the diameter of the jet.

Table 3. Results of experimental research

No.	Powder mass [g]	Distance from the hydro-cannon to the torch [m]	Speed at the torch [m/s]	Result of putting out the torch: extinguished (+) and not extinguished (–)
1	5	5	227	+
2		10	87	+
3		15	63	–
4		12	71	–
5	10	5	338	+
6		10	105	+
7		15	69	–
8		12	82	+
9	15	5	428	+
10		10	125	+
11		15	78	–
12		12	108	+

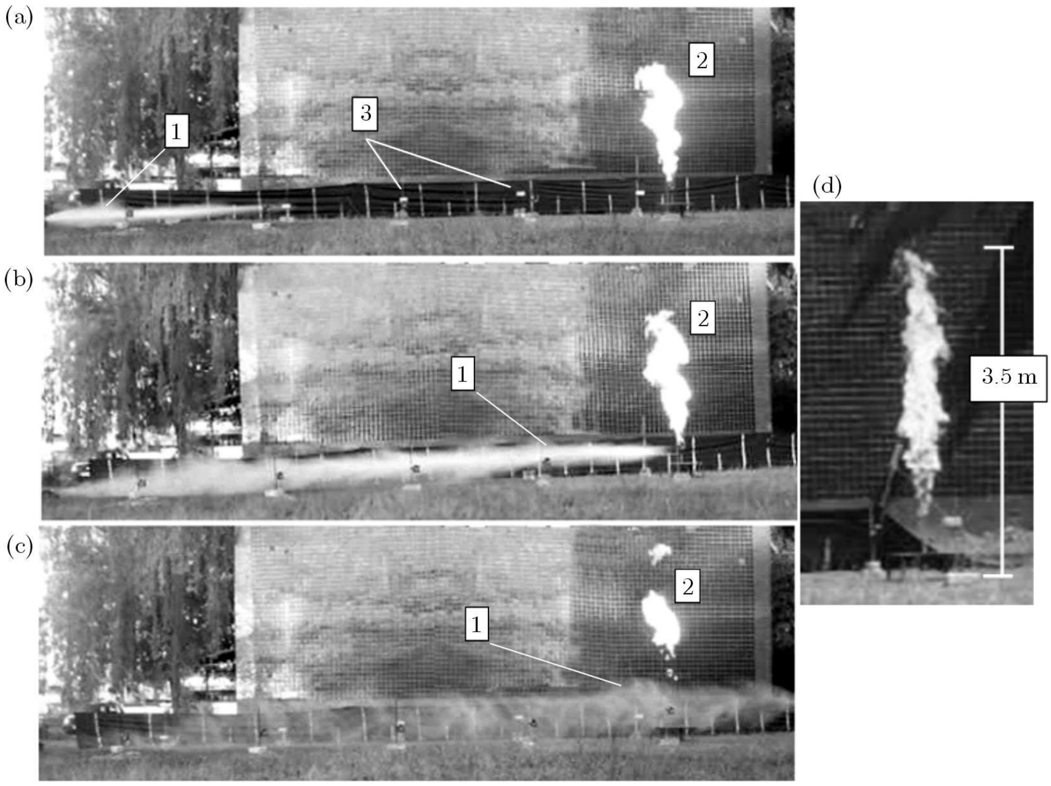

Fig. 5. Experiments on extinguishing of the gas torch; 1 – pulse jet of liquid, 2 – gas torch, 3 – system of speed measurement of the jet head

The jet flew about 9 meters on the second photo (Fig. 5b). The head part of the jet is clearly visible. It is located at a distance of about one meter from the torch. The whole jet is surrounded by a veil of spray, its transverse dimension reaches 0.5 m in some places. The head part of the jet has a pointed shape and is intensely eroded by the air.

In the third photograph (Fig 5c), the jet cuts the torch from the borehole and stops the supply of combustible mixture, which leads to the flame quenching. The upper part of the flame still burns and the lower part is ripped by the impulse liquid jet. The impulse liquid jet speed is much higher than the speed of the gas inflow from the wellbore to the flame combustion zone that contributes to the disruption of the flame and stops the torch combustion.

The analysis of video recordings in Fig. 5 showed that the jet flies to the gas flame (b), and isolates the combustion zone from the supply of the fresh fuel mixture (c) and (d). Subsequently, in (d) the jet impact area increases. Between the burner and flame a gap is being formed made of a mixture of gas, air and liquid drops. The concentration of the gas in the gap area is below the lower flammability limits, which prevents the resumption of combustion. The resumption of combustion is also prevented due to the fact that the speed of afterburning of the combustible gas is higher than the rate of supply of new combustion products.

5. Generalization of the results of model experiments on full-scale tests

Application of the theory of similarity allows formulation of the requirements for laboratory models to conduct science-based experimental research on models, identification of ways of processing and generalization of the experimental data in order to transfer the model experiments to full-scale tests (Sedov, 1977). It is known that the modeling is based on the consideration of similar physical phenomena. The processes will be similar if:

- they are described by the same equations
- the initial and boundary conditions are identical up to the constants
- the same similarity criteria are equal.

Consider first the similarity criteria for the jet cannon. The movement of the liquid in IW is described by the following equations in a dimensionless form

$$\frac{L}{TV}\frac{\partial\rho}{\partial t}+\frac{\partial\rho u}{\partial x}=-\frac{\rho u}{F}\frac{dF}{dx} \qquad \frac{L}{TV}\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{1}{\rho}\frac{\partial p}{\partial x}\frac{P}{\rho_0V^2} \tag{5.1}$$

where L, V, T, P, and ρ_0 are the scale of length, velocity, time, pressure and density, respectively.

In equation (5.1), the similarity criteria appeared: $L/(VT) = \mathrm{Sh}$ – Strouhal number and $P/(\rho_0V^2) = \mathrm{Eu}$ – Euler number.

Thus, the similarity of impulse water cannons is provided by the following conditions $\mathrm{Eu} = idem$, $\mathrm{Sh} = idem$.

Now analyse the similarity criteria for the impulse liquid jet. High velocity fluid flow interacts strongly with the atmospheric air. Crushing to drops and spray atomization starts at a rate of 100 m/s. The final droplet size depends on the jet velocity, air density and physical properties of the fluid during spray fluid atomization under the influence of the aerodynamic forces. Spraying of the jet is a very complex physical phenomenon that is difficult to describe mathematically. Typical forces in the process are: liquid aerodynamic forces $F_f \sim \rho_f u_f l^2$, aerodynamic forces of the gas $F_g \sim \rho_g u_g l^2$, viscous forces $F_\mu \sim \mu ul$ and surface tension forces $F_\sigma \sim \sigma l$, where l is the characteristic size. The Reynolds number $\mathrm{Re} = \rho_f u_f l/\mu$, the Weber number $\mathrm{We} = \sigma/(\rho u^2 l)$ and the dimensionless combination $\mathrm{Rl} = \mu^2/(\sigma\rho l)$ can be taken as similarity criteria for the jet. The last one includes the Rayleigh stability condition of the jet and can be represented as a function of the Reynolds and Weber numbers $\mathrm{Rl} = 1/(\mathrm{Re}^2\mathrm{We})$. Then the dimensionless diameter of atomized liquid spray should be a function of the criteria Re and We: $d/l = f(\mathrm{Re}, \mathrm{We})$. The influence of the viscosity and size of a small jet is determined only by the Weber number at higher Reynolds numbers, which will be the criterion for modeling

$$\frac{d}{l}=f(\mathrm{We})=f\Big(\frac{\sigma}{\rho u^2 l}\Big) \tag{5.2}$$

Let us now deal with the similarity criteria for the gas torch. Experiments show that the height of the gas jet nozzle depends on the diameter and velocity of the gas jet. Consequently, the criterion determining the length of the torch should include nozzle diameter, speed of gas that flows from the well and the acceleration of gravity indicating the force of gravity.

Experimental studies by Wooleys and Yarin (1978) showed that the mixing processes during combustion of the gas in a torch depend on the dynamic pressure of the jet, which determines the kinetic energy of the flow and its transverse size (diameter). On the basis of these three values, the following dimensionless criterion can be composed that defines the dimensionless length of the freely burning torch

$$K_F = \frac{w_0^2}{2gd_0} \tag{5.3}$$

The physical meaning of the aerodynamic similarity criterion consists in the fact that it characterizes the processes of gas mixing with the surrounding atmosphere; these processes depend on the pressure and gas jet thickness. It differs from its linear Froude parameter (the characteristic size is the diameter of the jet).

6. Conclusions

Experimental studies of the modeling of gas torch extinguishing by means of high speed impulse liquid jets generated by an impulse powder water cannon have been carried out. In the experiments, the velocity of the liquid drops cross-flow providing for the model fire gas blowout extinguishing has been measured by means of a non-contact laser speed detector. Furthermore, a special area has been determined by observing IW jet, the hitting of this area will provide for flame extinguishing. The maximum design speed of the impulse jet, depending on the energy charge, was 300-600 m/s, which is in line with the measured values.

Further research in this field must be focused on the parameters optimization of the powder IW, selection of a rational design of IW, study of the dynamics of the impulse liquid jet in air and jet interaction with the torch.

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Manuscript received November 28, 2013; accepted for print January 26, 2014