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THE HYDRODYNAMICS BEHAVIOUR OF AUTOMATIC EXTINGUISHING SYSTEM

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ABSTRACT

A simple way to increase the extinguishing water surface area is to atomize water into fine drops. The smaller drops are developed, the better use of water properties can be implemented and less water is consumed in fire fighting. The automatic impulse extinguishing is created. The main aim of the investigation is to develop the approach to investigate the dynamic and hydrodynamic processes in the extinguishing device. The mathematical model of the extinguishing device is presented, where the flow of liquid and gas and the interaction of liquid with the gas are taken into account. The flow of fluid in a hydraulic system is described by a system of equations of a hyperbolic type, which is solved by a characteristics method. An instance of the mathematical simulation of the activity extinguishing device is shown.

KEY WORDS

Extinguishing device, gas, liquid, dynamics, numerical methods

NOMENCLATURE

a_x	: acceleration along x axis
a_{gx}	: acceleration of gas along x axis
$C\,(Re,\,v)$	: function
c_g, c	: sound velocity in the gas and liquid
d	: internal diameter of a pipeline
E	: modulus of elasticity of a pipeline
e	: thickness of a wall of a pipeline
$\{\mathrm{F}(t,p,v)\}$	: vector of external forces and moments
F_{aero}	: air resistance force
f_{mv}	: force
f_{pv}	: function
G_{in}	: input mass flow
G_{out}	: output mass flow of gas (air)
$[\mathrm{J}]$	: Jacobian matrix,
$K\,(p)$	: bulk modulus of elasticity of liquid
L_2	: length of pipeline (second chamber).
$[\mathrm{M}]$	: matrix of mass
m_v	: mass of fast response valve mechanism
N	: number of drops
p; p_g	: pressure of fluid; pressure of gas
Q	: thermal quantum

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$\{q\}$: vector of displacement
$\{\dot{q}\};\{\ddot{q}\}$: vector of velocity; vector of acceleration
R : gas constant
$S(x)$: cross section area of a pipeline
S_{v1} : cross-section area of the first valve
S_{v2} : cross-section area of the second valve
T : temperature of fluid
$v;\ v_g$: velocity of fluid; velocity of gas
ε : ratio of gas volume in the liquid
γ : index of adiabatic process
$\varphi(\sigma)$: piecewise flow function
μ_1 : orifice discharge coefficient
$\rho;\ \rho_g$: density of fluid; density of gas
σ_{cr} : critical pressure ratio
τ : tangential liquid stress
$\Pi(x)$: perimeter
$\{\Psi\}$: vector of Lagrange multipliers
$\{\Phi\}$: vector of constraints

INTRODUCTION

The extinguishing systems comprise systems designed for the supply of the extinguishing materials (extinguish-ants) to fight fires. Water has been the most available and the most frequently used extinguishing material since times remembered. Water is distinguished for its distinctive physical and chemical qualities. For instance, it is noted for its heat absorption characteristics that the majority of the natural substances lack. For many years people have been trying to find better ways of delivering water to the scene of an accident and using it in the most effective way in fire fighting. It is not infrequent that damages resulting from inefficient application of water exceed those done by fire to the burned down property and other valuables. Water used in fire fighting tends to leak out and pollute the environment and severely deteriorate the ecological conditions in general. Although various up-to-date pumps, hoses, nozzles and sprayers are used to extinguish fires, water-based fire extinguishing technologies have not reached the top level of performance. Even using the modern centrifugal pumps, it is not possible to prevent water spillage on the scene of a fire accident. In fact, this leaking water is not involved in fire extinction but is being contaminated and wasted.

This is due to the fact that part of this water fails to absorb the entire possible heat and tends to evaporate. This is also explained by the high tension of the water surface, which does not allow it to penetrate into the burning substances. It is evident that the more we will atomize the water, the more of the surface area we will be able to obtain from the same volume of water, which will directly contact with the fire heat and thus water properties will be used more efficiently. For instance, if water were poured as if from the bucket, its features would be used only at 5 % efficiency. Thus, the increase of the surface area of the extinguishing water augments the efficiency of the water consumption as well. The simple way to increase the extinguishing water surface area is to atomize water into fine drops. The smaller drops are developed, the better use of water properties can be implemented and less water is consumed in fire fighting. The pressure energy of the pressurized and out-flowing water through the opening (i.e. fire nozzle) is transformed into a jet kinetic energy. If we use the energy of the compressed air or other gases to eject water through the nozzle (instead of the compressed water energy) the jet speeds could be much faster. The water droplet speed within the jet sprayed out in an ordinary way reaches tens m/s, while using the compressed air energy the water droplet speed can reach hundreds m/s. Furthermore, because of such speeds, water spray is atomized into fine droplets due to the air resistance (even up to 2 microns in diameter). Consequently, the extinguishing water cover area enlarges as well as the water efficiency. The devices with such properties can be usable in portable version. This is very important to extinguishing small fires. Small fires by statistics reach more than 50% of all fires. When water is supplied in fine droplets, it is possible to reach the use of all of its properties as close as 100%. In addition, the factor of the possible damage of the property and other valuables by water flooding is eliminated completely: facilities that are not within the extinguishing area remain safe from being flooded. The majority of fires could be addressed while using portable effective extinguishing devices.

Scheme of an automatic hydraulic and pneumatic nozzle is presented in Figure 1 [1,2].

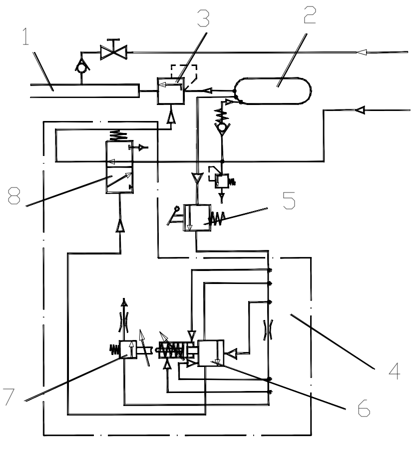

Figure 1 Scheme of automatic hydraulic and pneumatic nozzle

An automatic hydraulic and pneumatic nozzle consists of a water chamber (1), a compressed air chamber (2), a fast response valve (3), a fast response valve automatic control mechanism (4), and compressed air and water sources. The water chamber (1) is supplied from water source or reservoir; the compressed air chamber (2) is supplied from the compressed air source or reservoir. The expanding air expels water from the water chamber (1) due to that water jet is divided into fine droplets. After having activated the fast response valve automatic control mechanism (4) process is repeated constantly and water jets are ejected in series. The fast response valve automatic control mechanism (4) has three valves (6,7 and 8).

The water drops move with the velocity V_1 , absorb the environment heat with temperature T_a and steam in the same breath (Figure 2).

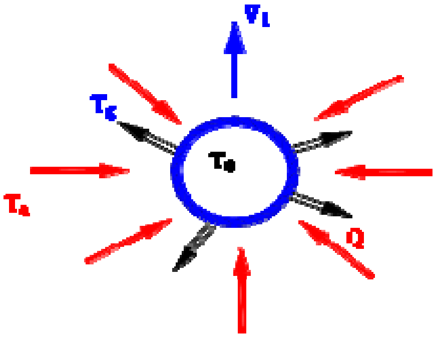

Figure 2 Scheme of drop thermal interchange

The change of thermal flow is directly proportional for the number of drops:

$$\frac{dQ}{dt} = C(Re, v)N^{5/3} \tag{1}$$

The dependence surface area of one litre water drops from the drops diameter in Figure 3 is presented.

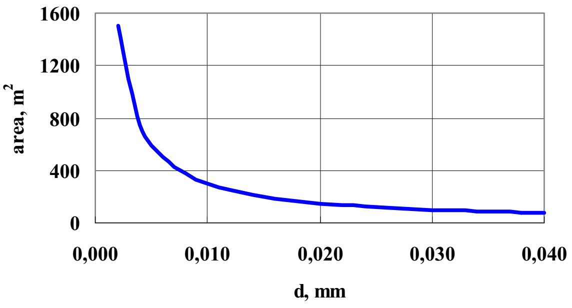

Figure 3 Dependence between surface area of drop and its diameter

II. MATHEMATICAL MODEL OF EXTINGUISHING DEVICE

The extinguishing device consists of two chambers (air container and water compartment) and two valves. The first valve is the fast reaction valve. The second valve opens when the pressure reaches particular pressure. When the fast reaction valve begins to open, the second chamber divides in two volumes. In the first volume there is a high pressure of air and in the second volume there is a high pressure of water.

The dynamic model of the extinguishing device is shown in the Figure 4. Cross-section area S_{v1} of the first valve is the function of time. Cross-section area S_{v2} of the second valve depends on the pressure $p(t, x = L_2)$ (Figure 5). The second air volume and water the compartment is separated by the surface G (Figure 4).

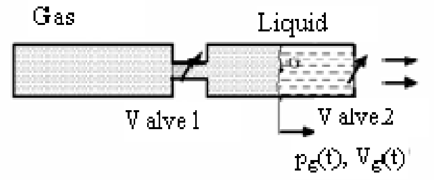

Figure 4 Scheme of extinguishing device

According to the first law of thermodynamics, the whole thermal energy moved with gas is spent for the change of the internal energy and for the work of the expansion of gas in a volume.

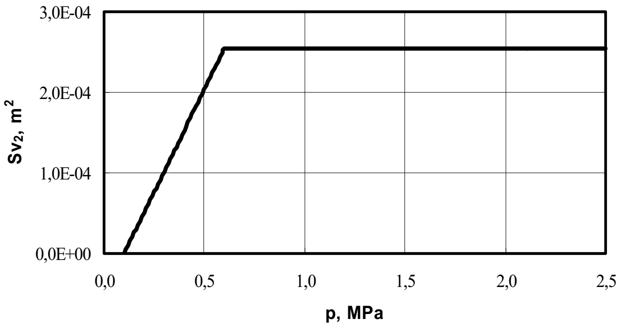

Figure 5 Dependence of cross-section area of second valve on pressure

The continuity and movement equations of viscous and compressible fluid in pressure pipe have the following form [3-7]:

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$$\frac{\partial}{\partial t}\left[S(x)\rho\right]+\frac{\partial}{\partial x}\left[S(x)\rho v\right]=0 \qquad (2)$$

$$\begin{gathered}\frac{\partial}{\partial t}\left[S(x)\rho v\right]+\frac{\partial}{\partial x}\left[S(x)\left(p+\rho v^2\right)\right]+\Pi(x)\tau+\\+\rho S(x)a_x+\rho g S(x)sin(\theta)-p\frac{\partial S(x)}{\partial x}=0.\end{gathered} \qquad (3)$$

An equation of one-dimensional movement of gas and liquid can be written as the system quasi-linear differential equations:

$$\frac{\partial \mathrm{u_g}}{\partial t}+\mathrm{B_g}\frac{\partial \mathrm{u_g}}{\partial x}=\mathrm{f_g}, \qquad (4)$$

$$\frac{\partial \mathrm{u}}{\partial t}+\mathrm{B}\frac{\partial \mathrm{u}}{\partial t}=\mathrm{f} \qquad (5)$$

where $\mathrm{B}_g=\begin{bmatrix} v_g & c_g^2\rho_g \\ \dfrac{1}{\rho_g} & v_g \end{bmatrix}$; $\mathrm{U}_g^T=\left[p_g, v_g\right]$;

$$\mathrm{f}_g^T=\begin{Bmatrix} -\dfrac{c_g{}^2\rho_g v_g}{S(x)}\dfrac{\partial S(x)}{\partial x} \\ -g\,sin(\theta)-\dfrac{\lambda(Re,\Delta)\left|v_g\right|v_g}{2D}-a_{gx}(t)+\dfrac{p_g}{\rho_g S(x)}\dfrac{\partial S(x)}{\partial x} \end{Bmatrix}$$

$$\mathrm{f}^T=\begin{Bmatrix} -\dfrac{c^2\rho v}{S(x)}\dfrac{\partial S(x)}{\partial x} \\ -g\,sin(\theta)-\dfrac{\lambda(Re)|v|v}{2D}-a_x(t)+\dfrac{p}{\rho S(x)}\dfrac{\partial S(x)}{\partial x} \end{Bmatrix};$$

sound velocities c_{g} and c is equal to:

$$c_g=\sqrt{\gamma RT}; \qquad c=\sqrt{\frac{K(p)/\rho}{1+\dfrac{K(p)\cdot d}{E\cdot e}+\dfrac{\varepsilon}{\gamma}\left[\dfrac{K(p)}{\gamma p}-1\right]}}.$$

The change of pressure of the volume is determined from the following equation:

$$\frac{dp}{dt}=\frac{\gamma RT}{V}\left(G_{in}(p,p_{in})-G_{out}(p,p_{out})\right)-\frac{\gamma p}{V}\frac{dV}{dt}, \qquad (6)$$

G_{out} is determined on the formula Sen-Venan and Vencel [1]:

$$G_{out}(p,p_{out})=$$
$$=\begin{cases}\mu_1 S_{v1}(t)K_1(T)p\varphi\left(\sigma=\dfrac{p_{out}}{p}\right) & if\ \ p\geq p_{out}\\ \mu_1 S_{v1}(t)K_1(T)p_{out}\varphi\left(\sigma=\dfrac{p}{p_{out}}\right) & if\ \ p_{out}>p\end{cases}, \qquad (7)$$

$$K_1\ (T)=\sqrt{\frac{1}{RT}}. \qquad (8)$$

To take account of the subsonic and sonic flow, the piecewise flow function $\varphi(\sigma)$ is defined as follows:

$$\varphi(\sigma)=\begin{cases}\sqrt{\left(\dfrac{2\gamma}{\gamma-1}\right)\left(\sigma^{\frac{2}{\gamma}}-\sigma^{\frac{\gamma+1}{\gamma}}\right)}, & if\quad \sigma_{cr}<\sigma\leq 1\\ \sqrt{\gamma\left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}, & if\quad 0<\sigma\leq\sigma_{cr}\end{cases} \qquad (9)$$

where σ_{cr} is the critical pressure ratio given by

$$\sigma_{cr}=\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}.$$

The dynamics model of the fast response valve automatic control mechanism (4) (Figure 1) consists of four masses and eight chambers with variable pressures.. The system of equation of fast response motion valve automatic control mechanism have the following form:

$$m_{vi}\frac{d^2 q_{vi}}{dt^2}=f_{mv,i}\left(q_v,\dot{q}_v,p_v\right)\quad (i=1,..,,4), \qquad (10)$$

$$\frac{dp_{vj}}{dt}=f_{pv,j}\left(q_v,\dot{q}_v,p_v\right),\quad (j=1,...,6). \qquad (11)$$

For quality work fireman have forces acting on the extinguishing device when out flowing water through the fire nozzle. The main force is recoil force. The dynamics model of fireman is created. The fireman with the extinguishing device is considered as multi-body system. The dynamics model consists from eleven rigid bodies.

The recoil force acting along the extinguishing device axis is equal:

$$F_x=-S_{v1}\left(p_1-p_2\right)+\left(S_2-S_{v2}\right)p_{lyq}\left(x_G\right)-F_{aero}, \qquad (12)$$

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$$F_{aero} = \begin{cases} \frac{1}{2}\rho S_{v2} v_{2,}^{2} \quad if \quad x_G \le L_2 \\ \frac{1}{2}\rho_{gas} S_{v2} v_{2,}^{2} \quad if \quad x_G > L_2 \end{cases} \tag{13}$$

The system of equations describing the movement of the extinguishing device and fireman is as follows [8]:

$$\begin{bmatrix} [M] & [J]^T \\ [J] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{q}\} \\ \{\Psi\} \end{Bmatrix} = \begin{Bmatrix} \{F(q,\dot{q},t)\} \\ \{U(q,\dot{q})\} \end{Bmatrix}. \tag{14}$$

There:

$$\{U(q,\dot{q})\} = -\frac{\partial}{\partial\{q\}^T}\left(\left[\frac{\partial\{\Phi\}}{\partial\{q\}^T}\right]\{\dot{q}\}\right)\{\dot{q}\} - 2\left[\frac{\partial^2\{\Phi\}}{\partial\{q\}^T \partial t}\right]\{\dot{q}\} - \frac{\partial^2\{\Phi\}}{\partial t^2}, \tag{15}$$

$$[J] = \left[\frac{\partial\{\Phi\}}{\partial\{q\}}\right]. \tag{16}$$

III. THEORETICAL ANALYSIS

An example of the extinguishing device is considered. The following data of the extinguishing device were used: the length of the water compartment is 0.25 m, the volume of the air container is equal to $V_1=1.5\cdot10^{-3}\,m^3$, the initial pressure in the air container is 2.0 MPa, the inner diameter of the water compartment is equal to 0,025 m. The time integration step is equal to $2.0\cdot10^{-6}\,s$. Dependences of displacements of fast response valve automatic control mechanism upon time first mass is presented in Figures 7a.

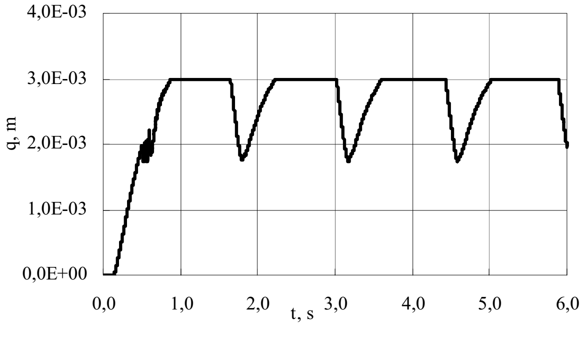

Figure 7a Dependences of displacements: first mass

The displacements of valves of the automatic control mechanism upon time fast response valve (3) are shown in the Figure 7b.

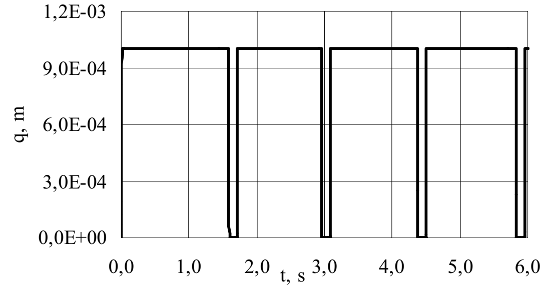

Figure 7b Dependences of displacements: fast response valve 3

The pressures in the chambers of valves of the automatic control mechanism are shown in the Figure 8. The forces acting on the extinguishing device are shown in the Figure 9.

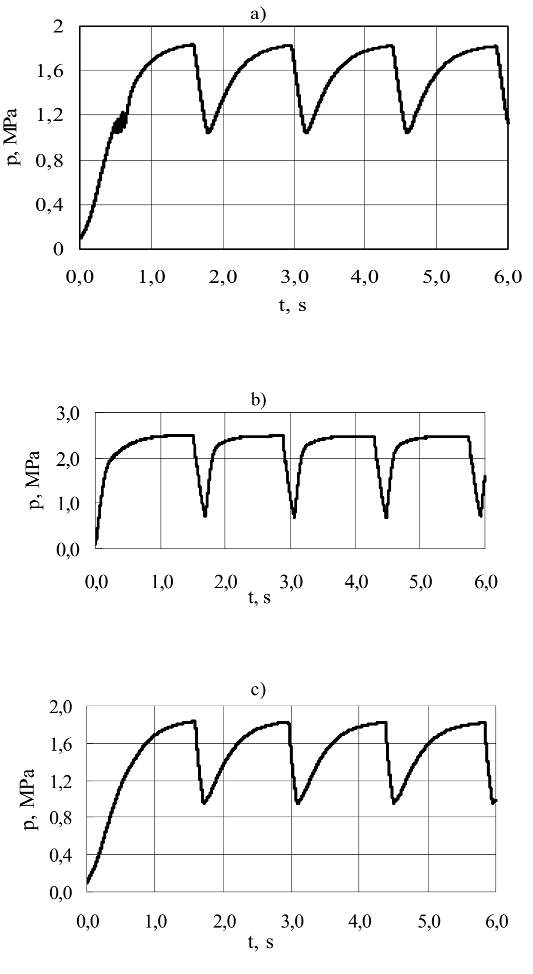

Figure 8 Dependences of pressures: a) first chamber; b) chamber of valve (3) c) compressed air chamber (2)

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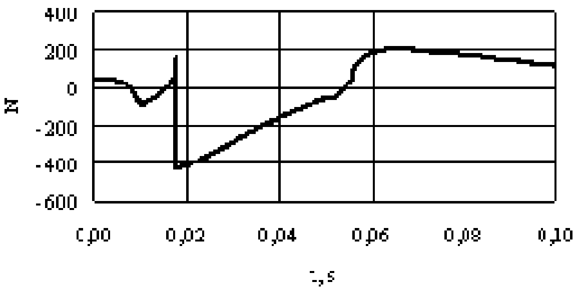

Figure 9 Dependence of recoil force upon time

In the Figure 10 are shown distribution of the cloud of water drops in the different moments of time.

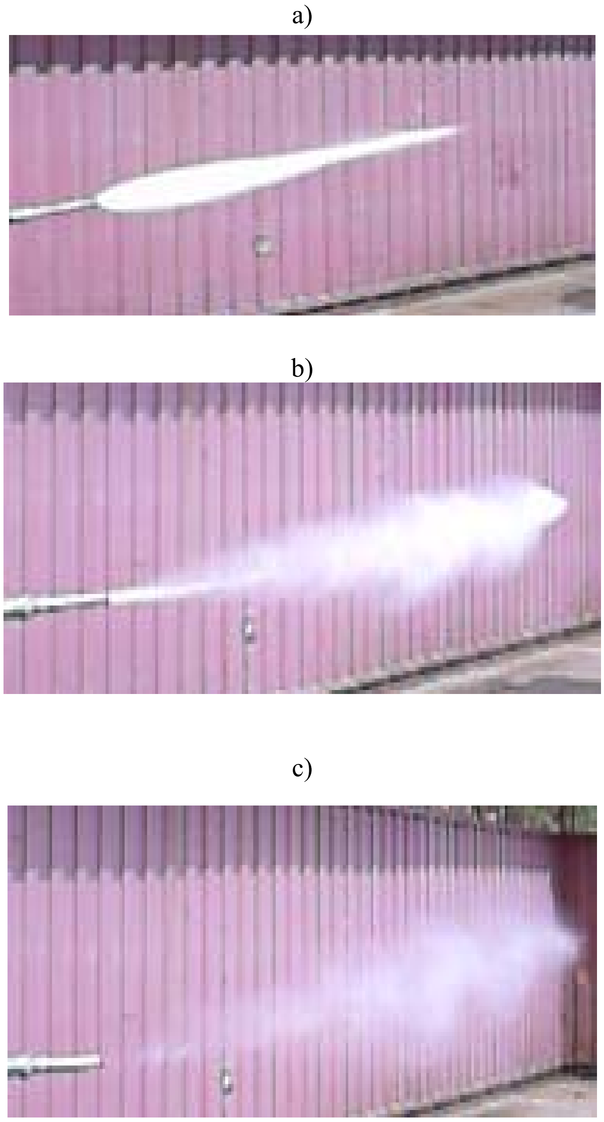

Figure 10 Distribution of the cloud of drops of water

IV. CONCLUSION

A new automatic impulse extinguishing is created. The approach for simulating hydrodynamic processes of the extinguishing device has been developed. The composed mathematical model of the extinguishing device takes into account wave motion of a liquid. The Differential equations, describing hydrodynamic processes inside the extinguishing device, help analyze the movement of liquid and gas better and more precisely. The period of vibration of fast response valve is about 1.4 s and this time can be regulated by changing stiffness of valves. At the end of a pipeline of the extinguishing device the maximum velocity of liquid reaches 60 m/s.

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