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AERODYNAMIC INTERACTION OF DROP LIQUID WITH VENTILATION FLOWS IN CASE OF FIRE EMERGENCY

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Abstract

The paper provides a mathematical model of aerodynamic interaction between drop liquid and ventilation flows in a mine working with automatic firefighting units. Digital implementation of this model allows predicting the consequences caused by a sudden automatic starting of firefighting units. It will help to work out the measures aimed at proper ventilation of mine workings equipped with belt conveyers.

Keywords: aerodynamic interaction, drop liquid, ventilation flow, firefighting units

Being a fire-extinguishing substance water is the main agent of underground fire fighting. Dispersion of liquids (water) in the medium (ventilation flow) results in dispersed system formation. Dispersion of liquids in gases (air) is usually called spraying. In the process of liquids dispersion the use of turbulent (vortical) mixing to obtain homogeneous mixtures (especially in several parts of a mine working) always leads to the troubles in ventilation conditions. In order to obtain a dispersed system the Research Institute "Respirator" has created water atomizers with stream-centrifugal injectors of PB type, which are to be used in fire-extinguishing units described in [1]. In mine workings equipped with belt conveyers the fires are localized and extinguished in the following way. If the temperature rises above 72^0C fire-extinguishing units turn on automatically and form a water curtain. According to [1] such a curtain covers the whole cross-section of a working along the distance not less than 8 m. Automatic units of water fire-extinguishing are settled along the working at a definite distance from each other depending on the fire area (Figure 1).

The presence of liquid particles in ventilation flows leads us to the necessity of considering the motion of a two-phase medium (air + liquid). One should consider the most important peculiarities of the processes occurring in two-phase media. These peculiarities are a) thermal and mechanical interaction between the phases themselves and the interaction of the phases with hard boundaries (walls of the working); b) transitions from one phase to the other (that is evaporation and condensation). These factors are more intensive at high temperatures. There is one more fact that can be considered a specific feature of the given medium. The liquid can be regarded as non-condensable, whereas the air behaves as a compressible liquid if the temperature is high and the pressure varies. So the nature of two-phase flows motion is very complicated in comparison with hydro- and aerodynamics of uniform media. That is why a generalized analysis of theoretical and practical results is of great importance in this field. While studying these processes we will proceed from the theory of two-phase media with drop and bubble structures in nozzles and pipes [2]. As the study [2 - 4] was mostly aimed at solving the problems of liquid evaporation and further condensation on turbine blades, the given theory should be simplified and modified. And then it can be used to study the process of aerodynamic interaction between drop liquid and ventilation flows.

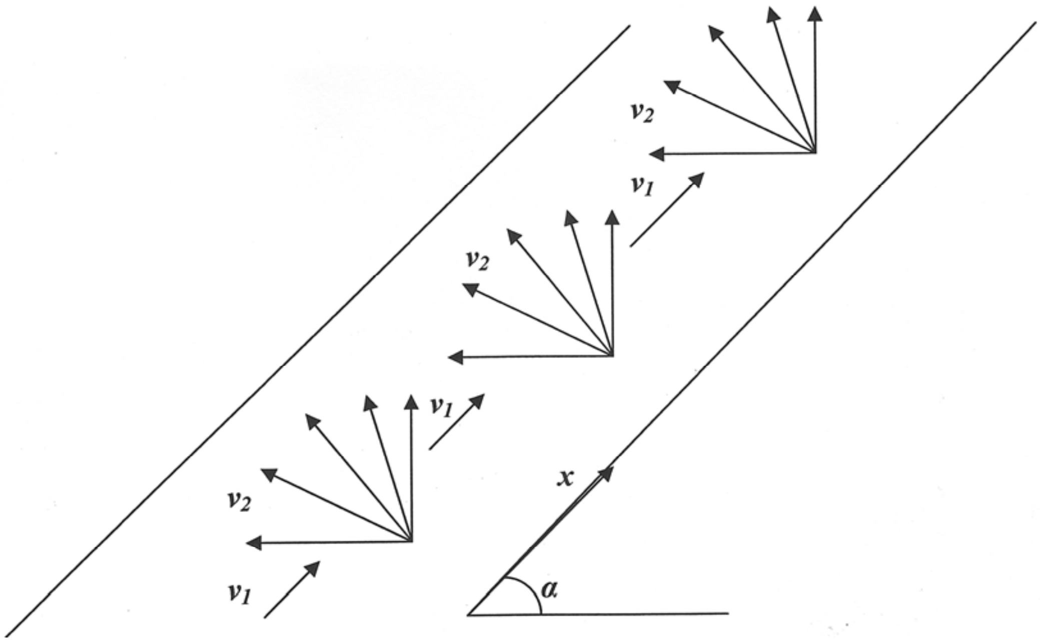

Figure 1. Scheme of a mine slope with a rising air flow v_1;
v_2 is the speed of water supply from firefighting units.

While developing the mathematical model we will take the following assumptions:

at the entrance to an arbitrarily oriented working the air is a uniform medium, which does not contain any admixtures;

sprayed liquid streams are injected codirectionally or antidirectionally into the air flow, which has subsonic velocity (the velocity of these liquid streams being higher than the velocity of the air flow);

the areas of air and liquid streams mixing have rated length and are situated at a given distance from each other;

the medium formed in the process of mixing is a mixture of air and liquid drops (coagulation and fragmentation are not taken into account);

the air is the carrying continuous phase and incompressible liquid drops (uniformly distributed in the ventilation flow) are the discrete phase;

viscous effects within each phase are ignored and only viscous interaction between the phases is taken into consideration;

mechanical interaction of liquid drops with the air is confined to gas-dynamic resistance only (this resistance appears if the vectors of phases motion velocities do not agree with each other);

in general the flow is transient and univariate; it is directed along a working of arbitrary length (Figure 1).

As it is known [5,6] the equation of ventilation flow continuity (the mixture of the air and liquid drops) can be presented as follows:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho \upsilon}{\partial \tilde{o}} = -I_2 , \qquad (1)$$

where ρ is the mixture density, kg/m^3; v is the velocity of the mixture flow, m/sec; I_2 is the loss of liquid mass (the drops collide with the walls of the working and then, affected by gravitation, they subside to the ground), kg/(s∗m^3); τ is the time since the moment when firefighting units had been turned on, sec; x is the coordinate in the direction of ventilation flow motion, m.

The flow consists of two phases: the first one is continuous (the air), the second one is discrete (liquid drops in the flow). So it is possible to consider each of the phases separately.

Each phase will occupy a certain part of the flow section. Let us call it the specific content of the phase:

$$\varepsilon_i = S_i / S, \tag{2}$$

where S_i is the part of the section area occupied by the i^{th} phase, m^2.

It is obvious that airborning of water drops in a turbulent ventilation flow (limited by the walls of the working) will be pulsing. As a result the drops will crush, collide with each other and with the walls of the working and remain on the walls. So evaporation is not the only factor which reduces the number of drops in the ventilation flow. Proceeding from the nature of mass exchange processes [6] we assume that the change of the liquid phase along the working is proportional to its perimeter and consumption of the liquid passing through the section of the working:

$$\mathrm{I}_2 = \frac{\mathrm{k}_{\text{ст}}\Pi}{\mathrm{S}}\varepsilon_2\rho_2\upsilon_2, \tag{3}$$

where $\mathrm{k}_{\text{ст}}$ is the coefficient which characterizes the frequency of drops collision with the walls and the losses under the influence of gravitation on the ground; Π is the perimeter of the working, m; S is the area of the cross-section of the working, m^2.

Continuity equation (1) falls into two equations (for each phase). If we take into account liquid loss caused by the collision of drops with the walls the equation will be as follows:

$$\frac{\partial \varepsilon_1 \rho_1}{\partial \tau} + \frac{\partial \varepsilon_1 \rho_1 \upsilon_1}{\partial x} = 0;$$

$$\frac{\partial \varepsilon_2 \rho_2}{\partial \tau} + \frac{\partial \varepsilon_2 \rho_2 \upsilon_2}{\partial x} = -\frac{k_{cm}\Pi}{S}\varepsilon_2\rho_2\upsilon_2, \tag{4}$$

Let us consider the mass contents of the phases (air and liquid) in a unit of the volume of the working (kg/m^3):

$$m_1 = \varepsilon_1\rho_1; \quad m_2 = \varepsilon_2\rho_2$$

Expressing the corresponding parameters through the mass content of the phases we will obtain the following equation instead of (4):

$$\frac{\partial m_1}{\partial \tau} + \frac{\partial m_1 \upsilon_1}{\partial x} = 0;$$

$$\frac{\partial m_2}{\partial \tau} + \frac{\partial m_2 \upsilon_2}{\partial x} = -\frac{k_{cm}\Pi}{S} m_2\upsilon_2, \tag{5}$$

From the second equation (5) it follows that the mass of liquid drops in the flow will decrease and get lost on the walls of the working proportionally to the mass flow of the liquid.

The equation of ventilation flow motion in the field of gravity force can be presented in the following way [5, 6].

$$\rho(\frac{\partial \upsilon}{\partial \tau} + \upsilon\frac{\partial \upsilon}{\partial x}) = -\frac{\partial P}{\partial x} - \rho g \sin\alpha - F_1, \tag{6}$$

where g is the acceleration of gravity, m/s^2; α is the slope angle of the working; radian; F_1 is the friction force between the flow and the walls of the working, Pa/m.

The formula for defining the friction forces, which appear when the continuous phase touches the walls of the working, will be as follows [5]:

$$F_1 = \frac{\lambda \Pi}{8S}\varepsilon_1\rho_1\upsilon_1|\upsilon_1|, \tag{7}$$

Here λ is the friction resistance coefficient.

Instead of (5) we obtain a set of motion equations for both phases taking into account their mechanical interaction [2] and friction loss:

$$\varepsilon_1\rho_1(\frac{\partial \upsilon_1}{\partial \tau} + \upsilon_1\frac{\partial \upsilon_1}{\partial x}) = -\frac{\partial \varepsilon_1 P}{\partial x} - F_1 - F_2;$$

$$\varepsilon_2\rho_2(\frac{\partial \upsilon_2}{\partial \tau} + \upsilon_2\frac{\partial \upsilon_2}{\partial x}) = -\frac{\partial \varepsilon_2 P}{\partial x} - \varepsilon_2\rho_2 g \sin\alpha + F_2, \tag{8}$$

where F_2 is the force of aerodynamic interaction between the phases, Pa/m^3.

Now let us define the force of aerodynamic interaction between the phases. In the mechanics of rigid bodies the force, which acts from the part of the flow upon the body, is equal to [5]:

$$F = C_x\frac{\pi d_\kappa^2}{4V}\frac{\rho\upsilon^2}{2},$$

where V is a certain volume of the working, m^3; Pa∗m^2; C_x is the coefficient of motion resistance; d_k is the diameter of a spherical body (drop), m. Let us use this formula for the relative motion of all liquid drops in a certain unit of volume. Taking into account the sign we obtain:

$$F_2 = C_x\frac{S_n}{V}\frac{\rho_1|\upsilon_1 - \upsilon_2|(\upsilon_1 - \upsilon_2)}{2}, \tag{9}$$

where S_n is the surface area of all drops in a certain volume of the channel, m_2.

The volume content of the liquid phase can be presented in the following way

$$\varepsilon_2 = \frac{n\pi d_\kappa^3/6}{V}.$$

So the ratio of the midsection area of liquid drops to a certain volume of the working will be equal to:

$$\frac{S_\Pi}{V} = \frac{n\pi d_\kappa^2/4}{V} = \frac{n\pi d_\kappa^3/6}{V}\frac{n\pi d_\kappa^2/4}{n\pi d_\kappa^3/6} = 3\varepsilon_2/2d_\kappa,$$

where n is the number of liquid drops in a unit of volume.

As a result we obtain the following formula instead of (11):

$$F_2 = \frac{3C_x}{4d_\kappa}\varepsilon_2\rho_1|\upsilon_1 - \upsilon_2|(\upsilon_1 - \upsilon_2)\,, \tag{10}$$

Formula (10) corresponds completely to the formula given in [2] if the direction of resistance force is taken into account. From (10) it follows that the drops of small diameter (in case of counter motion) will have the greatest influence upon the ventilation flow. It can be explained in the following way. The number of drops increases. So the total area of their surface grows, while their volume content in the flow remains the same.

Substituting formulas (7) and (10) in (8) we will have:

$$\varepsilon_1\rho_1(\frac{\partial\upsilon_1}{\partial\tau} + \upsilon_1\frac{\partial\upsilon_1}{\partial x}) = -\frac{\partial\varepsilon_1 P}{\partial x} - \frac{\lambda\Pi}{8S}\varepsilon_1\rho_1\upsilon_1|\upsilon_1| - \frac{3C_x}{4d_k}\varepsilon_2\rho_1(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,;$$

$$\varepsilon_2\rho_2(\frac{\partial\upsilon_2}{\partial\tau} + \upsilon_2\frac{\partial\upsilon_2}{\partial x}) = -\frac{\partial\varepsilon_2 P}{\partial x} - \varepsilon_2\rho_2 g\sin\alpha + \frac{3C_x}{4d_k}\varepsilon_2\rho_1(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,, \tag{11}$$

The obtained combined equation can be simplified if we take into account (as we did earlier) mass contents of the phases. As a result we will have:

$$m_1(\frac{\partial\upsilon_1}{\partial\tau} + \upsilon_1\frac{\partial\upsilon_1}{\partial x}) = -\frac{\partial\varepsilon_1 P}{\partial x} - \frac{\lambda\Pi}{8S}m_1\upsilon_1|\upsilon_1| - \frac{3C_x}{4d_k}\frac{1}{\varepsilon_1\rho_2}m_1m_2(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,;$$

$$m_2(\frac{\partial\upsilon_2}{\partial\tau} + \upsilon_2\frac{\partial\upsilon_2}{\partial x}) = -\frac{\partial\varepsilon_2 P}{\partial x} - m_2 g\sin\alpha + \frac{3C_x}{4d_k}\frac{1}{\varepsilon_1\rho_2}m_1m_2(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,, \tag{12}$$

When transient aerodynamic processes take place, the air becomes compressible and behaves as ideal gas. We will present the equation of its state as follows [5]:

$$P = \rho_1 R T_0\,, \tag{13}$$

where P is the pressure in a random point of the working, Pa; R is the universal gas constant, Pa m^3/(kg K).

T_0 is the mean temperature in the places where water curtains are located, k.

Substituting formula (13) in equations (12) we will have:

$$m_1(\frac{\partial\upsilon_1}{\partial\tau} + \upsilon_1\frac{\partial\upsilon_1}{\partial x}) = -RT_0\frac{\partial m_1}{\partial x} - \frac{\lambda\Pi}{8S}m_1\upsilon_1|\upsilon_1| - \frac{3C_x}{4d_k}\frac{1}{\varepsilon_1\rho_2}m_1m_2(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,;$$

$$m_2(\frac{\partial\upsilon_2}{\partial\tau} + \upsilon_2\frac{\partial\upsilon_2}{\partial x}) = -\frac{RT_0}{\varepsilon_1\rho_2}\frac{\partial m_1 m_2}{\partial x} - m_2 g\sin\alpha + \frac{3C_x}{4d_k}\frac{1}{\varepsilon_1\rho_2}m_1m_2(\upsilon_1 - \upsilon_2)|\upsilon_1 - \upsilon_2|\,, \tag{14}$$

The obtained set of equations (5) and (14) is closed as it contains four functions: mass contents of the phases (m_1 and m_2) and their velocities (v_1 and v_2). Other parameters can be taken as constants with a certain approximation. So, as the volume content of water in the air flow is very small, we will suppose that $\varepsilon_1 \approx 1$ in equations (14).

Initial and boundary conditions should be added to combined equations (5) and (14):

1) $m_1(x,0) = m_{10}$; $m_2(x,0) = 0$; $\upsilon_1(x,0) = \upsilon_{10}$; $\upsilon_2(x,0) = 0$;

2) $m_1(0,\tau) = m_n$; $m_2(0,\tau) = m_V$; $\upsilon_1(0,\tau) = \upsilon_0$; $\upsilon_2(0,\tau) = \upsilon_V$, (15)

where the parameters with index “10” denote the initial distribution of air mass content in the working and the air velocity; the parameters with indexes “n” and “V” denote mass contents and velocities of air and water at the beginning of water curtain. In this case we should assume that moisture (drops) had been absent in the ventilation flow before water curtains were turned on. Combined equations of continuity (5) and motion (14) of a discrete system with initial and boundary conditions (15) are solved with numerical methods (step-by-step for each water curtain); the origin of coordinates is chosen in the place where the water curtain is located. The air content on the boundary is corrected, because it must correspond to the depression applied to the working:

$$m_н = \rho_0 + h / RT_0$$

And the air velocity (at the entrance to the working) must correspond to the condition $m_1(L, \tau) = \rho_0$ where ρ_0 is the air density under normal conditions, kg/m^3; h is the depression applied to the working, P_a.

Solution to this problem becomes even more complicated, if the moisture evaporates in the zone of high temperatures. That is why we should take into account the rate of steam consumption which corresponds to a given temperature.

Conclusion

So the developed mathematical model of aerodynamic interaction between drop liquid and ventilation flows (and its computer implementation) allows predicting the consequences caused by a sudden automatic starting of firefighting units. It will help to work out the measures aimed at proper ventilation of mine workings equipped with belt conveyers.

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