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METHOD OF CONTROLLING SELECTIVE WITHDRAWL THROUGH A HOLE IN A VERTICAL WALL

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This paper gives the results of experimental validation of a method of controlling selective withdrawl from the required layer of a stably density-stratified liquid which differs from traditional methods. The efficiency of the method is confirmed, and its advantages and drawbacks are noted.

Key words: *density-stratified liquid, motion to a sink, selective withdrawal, control.*

In the case of a stably density-stratified liquid, the particles located on the horizon of a sink have an advantage in moving to the sink. To entrain the particles above and below the horizon in the flow, it is necessary to spend additional energy to overcome buoyancy forces. This feature of stratified liquid flow to a sink is used for selective withdrawal from the required layer of a water body [1]. For example, for plant watering, it is desired to take water from the warmer upper layer of a water body, whereas for cooling turbines of a thermal plant in summertime, withdrawal from the colder lower layer is needed. Using this feature, it is possible to improve the ventilation effectiveness (in particular, of open cuts) and oil removal from the water surface. A negative effect of the above-mentioned feature of stratified-liquid flow is that the river thermal regime changes greatly after the construction of a high-head hydropower plant. In this case, water entrained in the water-inlet holes of turbines comes primarily from the layer in which the summer temperature is lower and the winter temperature is higher than the temperature in the river before the construction of the high-head hydropower plant.

There are numerous patents for devices designed to control selective withdrawal using the above mentioned feature of density-stratified liquid flow to a sink. We shall call this control method traditional. In such devices, a withdrawal hole is on the horizon from which water is to be taken. Since the position of this horizon is constantly changed, as a rule, it is also necessary to change the position of the hole. Moreover, it has been shown [2] that even at moderate flow rates, this control method is inefficient.

In [3, 4], alternative control methods were proposed in which the position of the withdrawal hole is not changed and the liquid from the required layer is driven to the hole by artificially created inertial forces.

In [3], the case of the location of a withdrawal hole near the bottom at distance from the coast of a water body. The inertial forces of rotational motion are used. Rotational motion around the vertical axis through the hole is created in the layer from which withdrawal is undesired, and in the layer from which water is to be taken, rotational motion is suppressed. This is done using the effect which leads to the formation of air vortices; for example, in the case of evacuation of a bathtub, air, whose density is approximately 800 times lower than the density of water, is sucked into the hole.

In the case of withdrawal from a fresh water body, the difference in density is a few tenth of percent. Accordingly, the energy expenses for creation of rotational motion decrease. In many cases, for example, in evacuation of a bathtub, rotational motion is created seemingly by itself, due to even insignificant uncontrollable asymmetry of the velocity field or geometry of the region occupied by the liquid. Asymmetry gives rise to vorticity, which is retained as the liquid moves to the sink. The vorticity is equal to the product of the liquid particle velocity and the distance to the axis of rotation. As the particle approaches the axis of rotation, this distance tends to zero and

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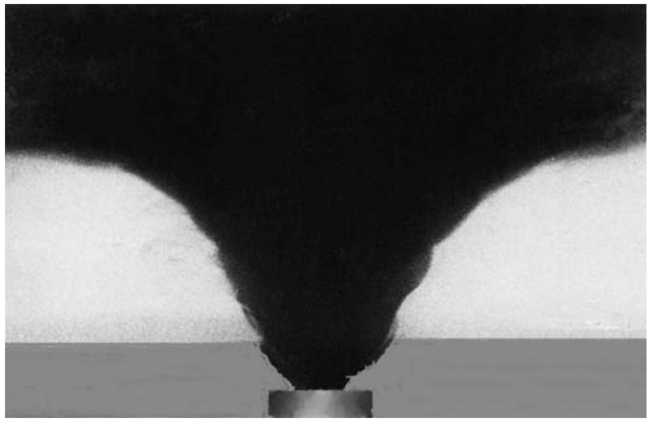

Fig. 1. Entrainment of a lighter liquid in a withdrawal hole located near the bottom of a water body [3, 5].

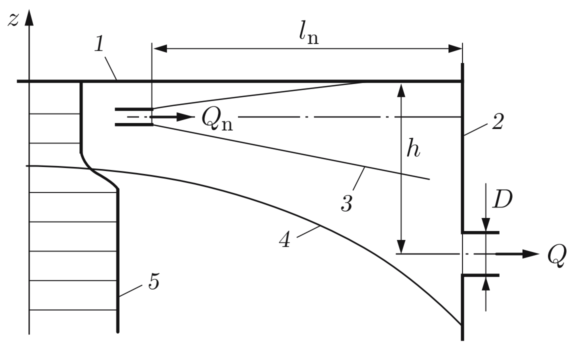

Fig. 2. Schematic of experiment: 1) free surface; 2) wall; 3) jet; 4) conventional interface between layers; 5) density distribution.

the velocity tends to infinity. According to the Bernoulli theorem, an increase in the velocity is accompanied by a reduction in pressure. As a result, strong rarefaction is created near the axis of rotation. Liquid from the layers in which vorticity is absent moves along the rarefied channel into the hole. In this case, the method proposed in [3] uses only an additional device to suppress rotation in the chosen layer. This device, having a fairly simple design, is crucial for this method.

More details of the method proposed in [3] and the results of its experimental validation are given in [5]. Figure 1 shows the entrainment of a lighter liquid in a withdrawal hole located near the bottom of a water body. In this case, the difference in density between the liquid in the upper and lower layers is 1.7% of the liquid density in the lower layer. The lighter upper layer is colored with ink. The interface between the layers is above the withdrawal hole at a distance equal to its six diameters. In the absence of the control action, water was entrained in the hole only from the lower layer. In this case, control action provided entrainment of 36% of the volume of water of lower density from the upper layer (for more detail, see [5]).

The second alternative method of controlling selective withdrawal has just been patented [4]. This paper gives the results of its experimental validation. It is employed in the case where the withdrawal hole is located in the lateral wall (Fig. 2). In this formulation of the problem, the type of symmetry changes. Instead of symmetry about the vertical axis, symmetry about the vertical plane is used. Accordingly, instead of the inertial forces of rotational motion, artificially created inertial forces of translational motion to the wall are used. In this problem, it is necessary that the liquid move from the specified layer in a horizontal direction; therefore, the use of the inertial forces of rotational motion does not give the desired result.

Figure 2 shows a schematic of the control action in the case where liquid is to be sucked primarily from the upper layer through a hole located in the lower layer. If a hole is in the upper layer, the action is enhanced. In the experiments described in this paper, stratification was created by varying the water temperature. The temperature of the upper layer was equal to room air temperature (18°C), which ruled out heat transfer through the free surface. The temperature of the lower layer was varied from experiment to experiment in the range of 6–12°C. Heat transfer through the channel walls (of Plexiglas 12 mm thick) was negligibly small. The density distribution on the vertical coordinate z at a great distance from the hole is described by the formula

$$\rho(z) = \rho_0\Big(1 - \frac{\varepsilon}{2+\varepsilon}\tanh\frac{2(z-z_*)}{\delta}\Big), \qquad \varepsilon = \frac{\rho_1}{\rho_2} - 1, \qquad \rho_0 = \frac{\rho_1+\rho_2}{2},$$

where ρ_1 and ρ_2 are the constant liquid densities in the lower and upper layers, respectively, z_* is the vertical coordinate on which $\rho = \rho_0$, and δ is the half-width of the thin layer separating the main layers.

Liquid was taken at a constant volumetric flow rate Q from a round hole of diameter D located at a depth h from the free surface. Inertial forces of translational motion were created artificially by injection of a round jet from a nozzle of radius $r_{\rm n}$ at a constant flow rate $Q_{\rm n}$ into the upper layer. The jet was directed horizontally. (It should be noted that the action can be optimized by varying the inclination of the jet to the horizon.) The nozzle was at a distance $l_{\rm n}$ from the wall. The liquid flow reflected from the wall deviates mainly downward because, to rise upward, it should overcome a great force proportional to the acceleration due to gravity g, whereas for downward motion, it is necessary to overcome only a small force proportional to the reduced acceleration εg.

The power of the jet issuing from the nozzle is defined by the formula $N_{\rm n} = \rho_2 Q_{\rm n}^3/(2\pi^2 r_{\rm n}^4)$. Moving to the wall, the jet entrains a large amount of the surrounding liquid and loses the initial power. According to [6], for a turbulent round jet, the following relations hold:

$$\frac{Q_1(x)}{Q_{\rm n}} = A\,\frac{x-x_0}{r_{\rm n}}, \qquad \frac{N_1(x)}{N_{\rm n}} = B\,\frac{r_{\rm n}}{x-x_0}.$$

Here Q_1 and N_1 are the flow rate and power in the jet at a distance x from the nozzle; $A \simeq 0.184$, $B \simeq 6.6$, and $x_0 \simeq 0$ are empirical coefficients.

Let us consider the case where it is required to take liquid at a flow rate Q_2 from the upper layer. To move liquid at this flow rate from the upper layer to the horizon with the hole, it is necessary to spend additional power to overcome buoyancy forces:

$$N_* = \rho_2\varepsilon g(Q_2 - Q_{20})h_0 = \rho_2\varepsilon g(\beta-\beta_0)Qh_0,$$

where h_0 is the depth of the hole relative to the conventional interface between layers at which $\rho = \rho_0$, Q_{20} is the flow rate of the liquid moving from the upper layer in the absence of the control action, $\beta = Q_2/Q$ is the coefficient of entrainment of the liquid from the upper layer, and β_0 is the value of the coefficient β in the absence of the control action.

We impose the following conditions: $Q_1(l_{\rm n}) \geqslant Q_2$ and $N_1(l_{\rm n}) \geqslant N_*$, i.e., near the wall, the jet flow rate should be not lower than the specified value of Q_2, and the jet power not lower than N_*. This leads to the following conditions on the control parameters $Q_{\rm n}$, $r_{\rm n}$ and $l_{\rm n}$:

$$Q_{\rm n} l_{\rm n} \geqslant \frac{(\beta-\beta_0)Qr_{\rm n}}{A}, \qquad \frac{Q_{\rm n}^3}{l_{\rm n}} \geqslant \frac{2\pi^2(\beta-\beta_0)Qr_{\rm n}^3\varepsilon gh_0}{B}.$$

We introduce the dimensionless quantities

$$l_{\rm n}^0 = \frac{l_{\rm n}}{r_{\rm n}}\,\frac{\sqrt[4]{ab}}{b}, \qquad Q_{\rm n}^0 = \frac{Q_{\rm n}}{Q}\,\frac{1}{\sqrt[4]{ab}},$$

where

$$a = \frac{2\pi^2 r_{\rm n}^4(\beta-\beta_0)\varepsilon gh_0}{BQ_{\rm n}^2}, \qquad b = \frac{\beta-\beta_0}{A}.$$

In this case, the conditions formulated above can be written in the following universal form:

$$Q_{\rm n}^0 l_{\rm n}^0 \geqslant 1, \qquad (Q_{\rm n}^0)^3/l_{\rm n}^0 \geqslant 1. \tag{1}$$

A curve of the dependence $Q_{\rm n}^0(l_{\rm n}^0)$ which corresponds to the equality sign in formulas (1) is given in Fig. 3. If the specified parameters are such that the point corresponding to them is below this curve, the imposed condition is not satisfied. The expected effect of the control action is possible only for combinations of parameters which correspond to the set of points above the curve in Fig. 3.

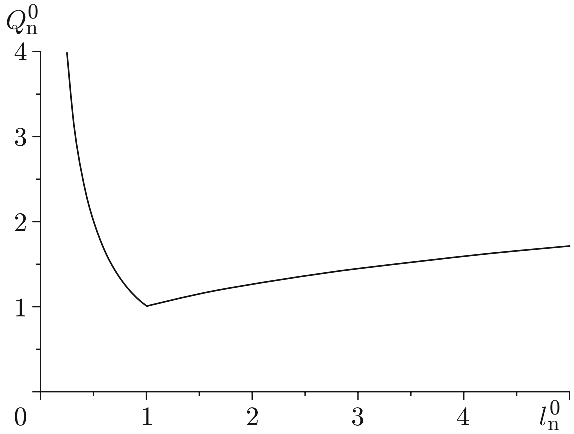

Fig. 3

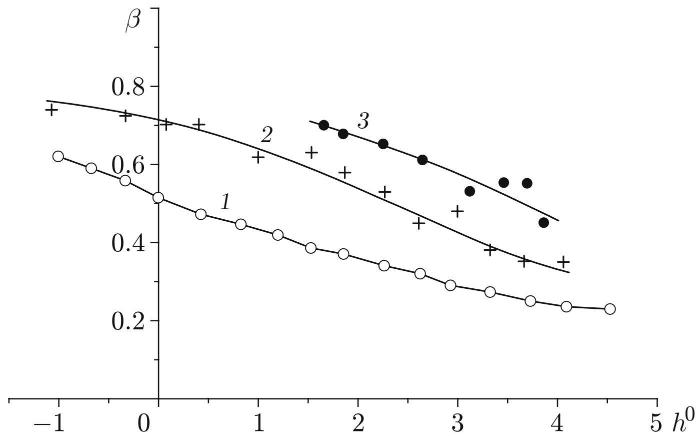

Fig. 4

Fig. 3. Dependence $Q_n^0(l_n^0)$ which satisfies the equality in formulas (1) ($\beta - \beta_0 = 0.1$).

Fig. 4. Entrainment coefficient of the liquid from the upper layer versus hole depth relative to the interface between the layers ($D = 1.72$ cm, $Q = 0.32$ liter/sec, $\delta/D = 10.5$, $r_n/D = 0.145$, $l_n/D = 47$, and $\varepsilon = 0.00072$): $Q_n/Q = 0$ (1), 0.063 (2), and 0.073 (3).

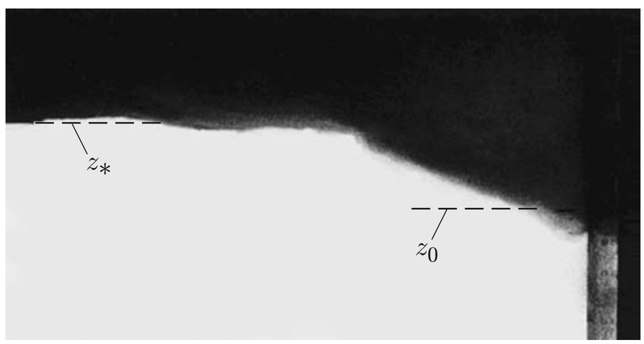

Fig. 5. Entrainment of the lighter liquid of the upper layer in a withdrawal hole ($Q_n/Q = 0.073$, $h^0 = 4$, and $\beta = 0.53$; the values of the remaining parameters the same as in Fig. 4).

We consider the following example. Let $Q = 100$ m^3/sec, $h_0 = 20$ m, $\varepsilon = 0.002$ and $r_n = 0.3$ m. We impose the condition $\beta - \beta_0 = 1$, i.e., only liquid from the upper layer should enter the hole. Estimates obtained using the formulas given above show that, in this case, it is necessary to specify values $Q_n^0 = 0.0482$ and $l_n^0 = 115$. At a distance of 35 m from the nozzle to the wall, the jet flow rate should be not lower than 4.8 m^3/sec. At the exit from the nozzle, a dynamic pressure of 14 m H_2O is lost. The pump producing the jet is chosen taking into account the obtained values of the dynamic pressure and the flow rate. An Op2-110 standard axial pump (flow rate of 4.9 m^3/sec at a pressure of 15.7 m H_2O) satisfies the required conditions.

Figure 4 gives some results of experimental validation of the proposed method ($h^0 = h_0/D$ is the relative depth of the hole relative to the conventional interface between the layers). Stratification was produced by temperature variation, which is typical of fresh water bodies. Therefore, the parameter ε was small, and the characteristic half-width of the washed zone δ was great. The withdrawal hole was located in the lower part of the washed zone; therefore, even in the absence of the control action, the liquid was sucked away from both layers (curve 1 in Fig. 4). The control action by using the jet considerably increases the relative amount of the liquid sucked away from the upper layer and the hole depth relative to the interface between the layers (curves 2 and 3 in Fig. 4).

The process of taking liquid from the upper layer using the proposed control method is presented in Fig. 5. The upper layer is colored with ink. The dashed lines shows the positions of the conventional interface between the layers z_* and the horizontal axis of the hole z_0.

It should be noted that water drift from the upper layer to the hole also occurs in the presence of wind directed onto a dam. Opposing wind leads to a reduction in the efficiency of the method considered. Favorable conditions for its use are created in the presence of ice cover.

As a rule, in traditional methods of controlling selective withdrawal, additional energy is spent only for controlling the devices used to place a withdrawal hole in the required layer. In the method considered here, the energy expenditure for controlling are higher. Estimates and experiments have shown that for the parameter values chosen in the example considered above, the power spent for control should be approximately equal to 4% of the turbine power.

An advantage of the alternative method of controlling selective withdrawal over traditional methods is that, with an appropriate choice of control action parameters, there are no restrictions on the total rate of liquid withdrawal. A disadvantage of this method is that it may be inefficient in the case of a strong adverse wind.

Conclusions. Experiments showed that with an appropriate choice of control action parameters, motion of liquid from the required layer to a hole in a vertical wall by means of a jet leads to a considerable increase in the amount of liquid from this layer entrained in the hole.

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