Virtual Laboratory Work in the Course of Hydromechanics
«The Study of Fluid Flow through Small Holes in a Thin Wall and Nozzles at a Constant Pressure into the Atmosphere»

PRINCIPLES OF INTERACTION WITH THE VIRTUAL MODEL OF THE LABORATORY EQUIPMENT

The simulation model of the laboratory equipment is an interactive geometric structure placed in a virtual three-dimensional space. Observation of objects is carried out using a virtual camera. In the basic (free) mode, the camera can rotate around the focus point (figure 1). The focus point of the camera can move in the vertical frontal plane. In addition, the camera can distance itself relative to the focus point for an arbitrary distance bounded by the dimensions of the work space of 3D scene.

Figure 1 – Principle of the Camera Control in Free Mode
Basic manipulations with the camera in a free mode are carried out using a computer mouse. Herewith pressing and holding the left mouse button with the accompanying movement of the mouse moves the focus point of the camera in the frontal plane of work space. Clicking and holding the right mouse button while moving the mouse causes the camera to rotate relative to the focus point. The angles of rotation (azimuth and elevation) of the camera are limited by the dimensions of the 3D work space. The distance between camera and focus point is changing by rotating the mouse scroll wheel in the forward and reverse directions.

**Note: in some virtlabs, the focus point may move in a horizontal plane!**

In addition to the free mode, the camera can switch to individual elements of the laboratory equipment. Switching the camera to the individual object is performed by hovering the mouse over the object with a subsequent single click of the left mouse button. In this case, the camera can take a static position or be able to move in a vertical plane by hovering the mouse pointer to the edges of the screen or using the keyboard arrow keys. The clicking on an arbitrary area of the screen is return of the camera to basic mode.

The interaction with the control elements of the simulational laboratory equipment is carried out by hovering the mouse over the object and then pressing (or a single click) the left (or right) mouse button. Specific of the control for different elements may vary. For example, continuously regulating elements (flow control valves, etc.) require holding the left or right mouse button to change their state. Elements of discrete action (gates or latches) require a single click of the left mouse button.

At the moment of hovering the mouse pointer over the object, manipulations with the camera are temporarily unavailable. Similarly, when manipulating the camera, it is not possible to perform actions on the controls elements of the lab equipment.

**VIRTUAL MODEL OF THE LABORATORY EQUIPMENT**

The simulation model of laboratory equipment (Figure 2) includes a pressure tank (1), in the side surface of which there is an opening closed by a lever valve (2). In front of the opening (outside the tank) a rotary turret (3) with a round hole and nozzles of various types is mounted. Turning the turret, you can install (against the hole) nozzles of the desired type or a round hole. The water into the tank is supplied by opening the valve (4). The pressure tank is equipped with an overflow device to maintain the water level at a constant elevation during the experiments.

To determine the head of the outflow $H$, the reservoir is equipped with a water-measuring tube with a scale (5), the zero of which is aligned with the center of the hole. Water flow at the outflow from the holes and nozzles is measured using a mobile measuring tank (6) and a stopwatch. The coordinates $X$ and $Y$ of arbitrary points of the trajectory of the jet are measured using a coordinate grid printed on the shield (7).
A small hole is a hole whose linear size does not exceed 0.1 $H$ (Figure 3). Here $H$ is the excess of the free surface of the liquid over the center of gravity of the hole.

The wall is considered thin if its thickness $\delta < (1.5...3.0)d$ (Figure 3). When this condition is satisfied, the value of $\delta$ does not affect the nature of the outflow of fluid from the orifice, since the outgoing jet of liquid touches only the sharp edge of the hole.

As the fluid particles move to the hole along curvilinear trajectories, due to inertial forces, the jet flowing out of the hole is compressed. Due to the action of inertial forces, the jet continues to shrink after exiting the hole. Experiments show that the jet is most compressed in cross-section $C-C$ at a distance of approximately $(0.5...1.0)d$ from the entrance edge of the orifice (Figure 3). This cross-section is called compressed. The compression ratio of the jet in this cross-section is estimated by the compression ratio $\varepsilon$:

$$
\varepsilon = \frac{\omega}{\omega_0},
$$

(1)
where \( \omega_c \) and \( \omega \) are the area of the compressed living section of the jet and the area of the hole, respectively.

\[
\frac{\omega_c}{\omega} \approx \frac{1}{1+\zeta}
\]

Figure 3 – The Outflow of Fluid from a Small Hole in a Thin Wall into the Atmosphere

The average jet velocity \( \vartheta \) in a compressed \( C-C \) cross-section with \( p_0 = p_{atm} \) is calculated using the formula obtained from D. Bernoulli’s equation, compiled for cross-sections \( I-I \) and \( C-C \) (Figure 3):

\[
\vartheta = \varphi \sqrt{2gH} ,
\]

where \( \varphi \) is the velocity coefficient of the hole.

\[
\varphi = \frac{1}{\sqrt{\alpha + \zeta}} \approx \frac{1}{\sqrt{1 + \zeta}}
\]

Based on the equation of the jet trajectory flowing from the hole, another expression for the coefficient \( \varphi \) was obtained:

\[
\varphi = \frac{x_i}{2\sqrt{y_iH}}
\]

In formulas (3) and (4), \( \alpha \) is the Coriolis coefficient, \( \zeta \) is the resistance coefficient of the hole, \( x_i \) and \( y_i \) are the coordinates of an arbitrarily taken point of the jet trajectory.

Since the head is lost mainly near the hole where the velocities are large enough, only local head losses are taken into account when the water flow out from the hole.

The flow of fluid \( Q \) through the hole is calculated as

\[
Q = \varphi \varphi_c \alpha \sqrt{2gH} ,
\]

where

\[
\varphi \varphi_c = \mu
\]
Here, $\mu$ is the flow coefficient of hole, which takes into account the effect of hydraulic resistance and jet compression on the fluid flow. Taking into account the expression for $\mu$, formula (5) takes the form

$$Q = \mu \omega \sqrt{2gH},$$  \hspace{1cm} (7)

The values of the coefficients $\varepsilon$, $\zeta$, $\varphi$, $\mu$ for holes are determined experimentally. It is established that they depend on the shape of the hole and the Reynolds number. However, for large Reynolds numbers ($Re \geq 10^5$), the indicated coefficients do not depend on Re and for round and square holes with a perfect compression of the jet are: $\varepsilon = 0.62...0.64$, $\zeta = 0.06$, $\varphi = 0.97...0.98$, $\mu = 0.60...0.62$.

![Figure 4 – The Outflow of Fluid from the Outer Cylindrical Nozzle into the Atmosphere](image)

A nozzle is a tube of length $2.5d \leq L_N \leq 5d$ (Figure 4), attached to a small hole in a thin wall in order to change the hydraulic characteristics of the outflow (velocity, flow rate, jet path).

Nozzles are cylindrical (external and internal), conical (converging and diverging) and conoidal, i.e. outlined in the form of a jet flowing out of the hole.

The use of a nozzle of any type causes an increase in the flow rate of fluid $Q$ due to the vacuum that occurs inside the nozzle in the region of the compressed section $C-C$ (Figure 4) and causes an increase in discharge pressure.

The average flow velocity of the fluid from the nozzle $\bar{\zeta}$ and the flow rate $Q$ are determined by the formulas obtained from D. Bernoulli’s equation, written for sections $I-I$ and $B-B$ (Figure 4):
\[ \vartheta = \varphi_N \sqrt{2gH}, \quad (8) \]

where \( \varphi_N = \frac{1}{\sqrt{\alpha + \zeta_N}} \) is the nozzle velocity ratio, \( \zeta_N \) is the nozzle resistance coefficient.

For the output cross-section \( B-B \) the compression ratio of the jet is \( \varepsilon = 1 \), since the nozzles here work with a complete cross-section. Therefore, the flow coefficient of nozzle \( \mu_N = \varphi_N \).

The flow rate of fluid flowing from the nozzle is calculated by a formula similar to formula (7):

\[ Q = \mu_N \omega \sqrt{2gH} \quad (9) \]

LABORATORY WORK DESCRIPTION

**Laboratory Work Objectives:**

1. Based on the experimental data, determine the values of the coefficients: \( \mu_{\text{exp}}, \varphi_{\text{exp}}, \varepsilon_{\text{exp}}, \zeta_{\text{exp}} \), when water outflow through a small round hole with a diameter \( d = 20 \) mm with a constant pressure into the atmosphere. Determine values of the coefficients \( \mu_{N,\text{exp}} = \varphi_{N,\text{exp}} \) and \( \zeta_{N,\text{exp}} \) for external cylindrical and conical (converging and diverging) nozzles at \( H = \text{const} \).

2. Compare the values of the coefficients obtained in the experiments with the reference and calculate the relative deviations.

**The Order of the Work and the Processing of Experimental Data:**

1. Open the water supply valve, fill the tank with water so that the overflow pipe works.

2. Turn the turret to install a round hole with a diameter of \( d = 20 \) mm and fix the turret in this position.

3. Open the lever valve and ensure the outflow of water at a constant head \( H \), measure it, as well as the coordinates \( x_K \) and \( y_K \) of an arbitrarily chosen point \( K \) of the flow jet.

4. Measure the water flow \( Q \) using a mobile measuring tank and a stopwatch (the measured volume of water must be at least 50 liters).

5. Record the measurement results into the table 1.

6. Using a rotary turret, alternate install the external cylindrical and conical (converging and diverging) nozzles, measure for each of them the water flow \( Q \) and the head \( H \) (the latter should be kept constant in experiments and equal to the head when flowing out of a round hole).

7. Record the measurement results into the table 1.

8. Process the experimental data by performing all the calculations provided by the table 1.

9. Give a conclusion of the results of the work.
<table>
<thead>
<tr>
<th>№</th>
<th>Measured and Calculated Values</th>
<th>Units</th>
<th>Experimental Results</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Round Hole</td>
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<td></td>
<td></td>
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<td>Outer Cylinder</td>
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<td></td>
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<td>Conical Convergent</td>
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<td></td>
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<td></td>
<td>Conical Divergent</td>
</tr>
<tr>
<td>1</td>
<td>The diameters of the hole and nozzles at the outlet $d$</td>
<td>m</td>
<td>$2,0 \cdot 10^{-2}$</td>
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<tr>
<td>2</td>
<td>Round hole and outlet nozzles $\omega = \pi d^2/4$</td>
<td>m²</td>
<td>$2,0 \cdot 10^{-2}$</td>
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<tr>
<td>3</td>
<td>The volume of water in the meas. tank $W$</td>
<td>m³</td>
<td>$2,0 \cdot 10^{-2}$</td>
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<td>4</td>
<td>Time of filling the meas. tank with water $t$</td>
<td>s</td>
<td>$2,6 \cdot 10^{-2}$</td>
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<td>5</td>
<td>Water flow $Q = W/t$</td>
<td>m³/s</td>
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<tr>
<td>6</td>
<td>Waterflow head $H$</td>
<td>m</td>
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<td>7</td>
<td>The coordinates of an arbitrary point $K$ of the jet trajectory flowing from a circular hole</td>
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<td></td>
<td>$x_k$</td>
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<td></td>
<td>$y_k$</td>
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<td>8</td>
<td>The flow rates of the hole and nozzles (by experience) $\mu_{\text{exp.}} = Q/\omega \sqrt{2gH}$</td>
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<td>9</td>
<td>Nozzle velocity ratios (by experience) $\varphi_{\text{N exp.}} = \mu_{\text{N exp.}}$</td>
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<td>10</td>
<td>Hole velocity ratio (by experience) $\varphi_{\text{exp.}} = x_k/(2y_k H)$</td>
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<td>11</td>
<td>The resistance coefficient of the hole and nozzles (by experience) $\zeta_{\text{exp.}} = 1/\varphi_{\text{exp.}}^2 - 1$</td>
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<td>12</td>
<td>The compression ratio of the hole and nozzles (by experience) $\varepsilon_{\text{exp.}} = \mu_{\text{exp.}} / \varphi_{\text{exp.}}$</td>
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<td>13</td>
<td>Reference values of the coefficients of flow, velocity, resistance and compression for the hole and nozzles</td>
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<tr>
<td></td>
<td>$\mu_{\text{ref.}}$</td>
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<td></td>
<td>$\varphi_{\text{ref.}}$</td>
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<td>$\zeta_{\text{ref.}}$</td>
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<td>$\varepsilon_{\text{ref.}}$</td>
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<td>14</td>
<td>Relative deviations of coefficients of flow, velocity, resistance and compression for the hole and nozzles</td>
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<td>$\Delta \mu = (\mu_{\text{ref.}} - \mu_{\text{exp.}})/\mu_{\text{ref.}}$</td>
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<td>$\Delta \varphi = (\varphi_{\text{ref.}} - \varphi_{\text{exp.}})/\varphi_{\text{ref.}}$</td>
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<td>$\Delta \zeta = (\zeta_{\text{ref.}} - \zeta_{\text{exp.}})/\zeta_{\text{ref.}}$</td>
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<td>$\Delta \varepsilon = (\varepsilon_{\text{ref.}} - \varepsilon_{\text{exp.}})/\varepsilon_{\text{ref.}}$</td>
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