Determining the consumption coefficient for modeling the coating system for inner surface of rotating pipe

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Abstract. The article is devoted to determining the flow coefficient in mathematical modeling of the operation of a new device for coating the inner surface of pipes for rooms with a limited height. A new method for coating the inner surface of a pipe in a confined space, in which the pipe being worked is in an inclined position and rotates around its axis during the process, is described. The thickness of the coating depends on the speed of movement of the material. The more precisely the speed stabilizes, the more uniform the protective coating is. The authors considered methods for determining the flow coefficient; the methods for its determination were described. The numerical values of the flow coefficient for a specific liquid-pipe pair have been obtained.

Nowadays, there are methods and devices for coating the inner surface of pipes based on the controlled discharge of coating material (slip) from a pre-filled pipe [1-3]. They have a number of disadvantages associated with the vertical installation of pipes during processing. For example, for carrying out a technological procedure, a room with high ceilings is required; manipulation of lifting mechanisms takes a lot of time and energy. Also, devices which implement well-known methods have low maintainability and do not provide the necessary control of the movement of the coating material in the system. The theoretical justification of the existing methods and dynamic modes of the coating control system is described in this work [4].

The article is devoted to the refinement of the parameters of mathematical modeling of the operation of a new device for coating the inner surface of pipes for rooms with a limited height. A control system which includes electromechanical pumps and gate valves controlled by a single module is proposed. A feature of the installation is an inclined position of the processed pipe, whereby the coating material moves in its cavity without pressure, and its flow is controlled by the level of the material in the filling column, as shown in figure 1. This ensures the rotation of the pipe during processing, and the coating material flows from its free end into the receiving container. [5] The flow coefficient determines the nature of the movement of a viscous fluid inside a rotating inclined pipe.

Before describing the ongoing processes, the accepted assumptions should be indicated: fluid is incompressible; fluid moves without turbulence; the angular velocity of rotation of the pipe $\omega$ is so small that vortex motion does not occur and is taken into account in the coefficient $\mu$. The angular velocity of rotation of the pipe is chosen so that each elementary fluid particle passes from one edge of the pipe to the other in one rotation:
\[ \omega \leq \frac{V(H)}{L}, \]

where \( V(H) \) – material rate through section, \( L \) – pipe length.

Figure 1. The coating system for surface.

1 – processed pipe, 2 – filler frame, 3 – switch-off valve, 4 – contactless sensor of level, 5 – heat sensor, 6 – processing module of information and control, 7 – collecting channel, 8 – circulating pump, 9 – receiving container, 10 – drain adapter, 11 – electric driver, 12 – pipe rotating mechanism, 13 – filling pump, 14 – baffle gate, 15 – level hydraulic sensor assembly, 16 – contactless sensor of level.

In this case, the instantaneous fluid flow through the hole of arbitrary shape when draining is determined by the following formula [6]:

\[ dQ = \mu dS \sqrt{2gH}, \]  

(1)

where \( dQ \) is the instantaneous flow rate, \( \mu \) is the flow rate, which is determined empirically, depends on the shape of the hole and the conditions of the liquid approaching the hole, its viscosity, as well as on the roughness of the drain pipe and rotation speed, \( dS \) is the elementary sectional area, \( g \) is the acceleration free fall, \( H \) is a liquid level above the lower edge of the drain hole, segment height.

Mathematical modeling of the motion of a viscous coating material in the cavity of an inclined rotating pipe was performed [7]; figure 2 presents this process. The research was based on the elements of mathematical modeling of the processes presented in the following works [8,9].
During the mathematical transformations, the formulas given in [10,11] were used. The result of mathematical modeling is a formula for determining the velocity of a fluid through the given section:

\[ V(H) = \frac{Q(H)}{S(H)} = \frac{4\mu\sqrt{2gR}}{15}\sqrt{2 - \frac{H}{R}} + \left(\frac{4H}{R}\right) + \left(1 + \left(\frac{3H^3}{R^3}\right)\right) \]

where \( S(H) \) is a cross-sectional area of the pipe occupied by the liquid, in our case equal to the area of the circle segment, \( R \) is the radius of the drain hole. In the process of deriving a formula for determining the velocity of a fluid, the formula for determining the cross-sectional area of a pipe occupied by a fluid has been obtained [7]:

\[ S(H) = R^2\left[\arccos\left(1 - \frac{H}{R}\right) - \left(1 - \frac{H}{R}\right)\sqrt{\frac{2H - H^2}{R^2}}\right]. \]

The formula (2) was calculated in the Mathcad program at \( \mu = 0.1 \) for pipes of different radii, presented as graphs in figure 3. Based on the obtained dependences, it is possible to determine the technological modes of coating. The speed of the material determines the thickness of the coating in accordance with the technological tables [12].

**Figure 2.** Demonstration of mathematic simulation.
1 – slip, 2 – filler frame, 3 – level sensor, 4 – drain adapter.

**Figure 3.** Dependence of velocity on the relative filling height of the drain hole for different pipe diameters \( R_1 = 0.3 \) m, \( R_2 = 0.2 \) m, \( R_3 = 0.15 \) m, \( R_4 = 0.1 \) m.
The analysis of the graphs in Figure 3 allows determining the height of the liquid level, which must be maintained to ensure the given material velocity. For example, if with a pipe with a radius of 0.1 m it is necessary to ensure a material velocity of 0.05 m/s, then it is required to maintain a level in the discharge column of $H/R=0.23$, i.e., $H=0.02$ m. The calculation results are in good agreement with the known data given in [12], in particular, on the ranges of variation of speed at the indicated geometric parameters of the pipe. In the proposed mathematical model, factors related to the angle of inclination and roughness of the pipe, as well as the properties of the coating material and the angular velocity are not taken into account in a detailed form. In latent form, the listed parameters are taken into account by the coefficient $\mu$.

One way to determine the coefficient $\mu$ is an experimental research for a specific pipe and type of flowing liquid. Moreover, to determine the required parameter, the experiment can be carried out in two ways. The first method is that for a given level $H$ with known pipe sizes, we fix the time $t_0$ during which a given volume of liquid $P_0$ will pour out. The second method is that for a given level $H$ with known pipe sizes, we measure how much liquid $P_0$ will pour out over a given time $t_0$.

Thus, the relationship between the measured values has the following form:

$$P_0 = V_0S(H)t_0,$$  \hspace{1cm} (4)

where $P_0$ is the volume of liquid, $V_0$ is the liquid velocity, $t_0$ is the time it takes to drain.

From (4) we express $V_0$ and equate to formula (2) obtained in mathematical modeling:

$$V_0 = \frac{P_0}{S(H)t_0} = \frac{4\mu\sqrt{2gR}}{15\left(2-\frac{H}{R}\right)^{1/2}} \left\{\frac{4H}{R} \left(\frac{2H}{R} + 1\right) \left(\frac{16}{R^2} + \frac{3H^2}{R^2}\right)\right\}.$$

Knowing the formula for determining the cross-sectional area $S(H)$ (3), from equality (5) we express the coefficient $\mu$ for a studied liquid-pipe pair:

$$\mu = \frac{15P_0}{4R^{1/2}t_0\sqrt{2gR}} \left\{\frac{4H}{R} \left(\frac{2H}{R} + 1\right) \left(\frac{16}{R^2} + \frac{3H^2}{R^2}\right)\right\} \left\{\frac{2H}{R} - \frac{H^2}{R^2}\right\} \left\{\arccos \left(\frac{1-H}{R}\right) - \sqrt{1-\left(\frac{1-H}{R}\right)^2}\right\}.$$

It follows from expression (6) that the flow coefficient is individual for each combination of pipe and applied material. In this regard, for a more accurate simulation, an experiment should be performed several times for each liquid-pipe pair with different fixed $H$. For example, when filling 0.5 m$^3$ of liquid at $H/R = 0.4$, 3.5 s were used, then we get $\mu=0.15$.

Determination of the flow coefficient $\mu$ allows getting more accurate mathematical model of the movement of viscous liquid in the cavity of an inclined rotating pipe in the coating system on the inner surface of the pipe.

Using the proposed method in production allows increasing labor productivity, since it does not require its vertical installation associated with the use of lifting mechanisms. It also allows the pipe to be inclined during the coating process and allows processing in production rooms with relatively low ceilings. The economical consumption of material is realized through the collection of surplus in the receiving tank. The uniformity of the coating is provided by a constant speed of movement of the material along the entire length of the pipe and at each point of the inner surface due to rotation. Improving the quality of the coating is achieved through operational control of the temperature of the applied material.
The problem under consideration can be used when taking into account the flow rate in sewerage and drainage systems through non-pressure pipelines, in drainage systems of treatment facilities, as well as in the hydrocarbon process industry.

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