Effect of pipe rotation velocity on the flow rate in the automated coating system

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Abstract. The article is devoted to the study of the viscous fluid rotation in the confined space of an inclined rotating pipe in the automated system for applying a silicate coating to the inner surface of steel pipes. The authors proposed an automated coating method when the product is installed at the sloping position and rotates around its axis while processing. The thickness of the coating depends on the rotation velocity of the material. The dependence of the flow velocity of a viscous fluid on the angle of inclination of the pipe and the rotation velocity is obtained. It ensures the coating uniformity along the entire length of the product. The study of the rotation velocity dependence of the viscous fluid along the inner surface of the rotating pipe on the velocity of its rotation is carried out.

1. Introduction
The authors developed a new method of applying an enamel coating to the inner surface of steel pipes [1-3]. A peculiar feature of the proposed method in comparison to the known ones [4-6] is a sloping position of the processed pipe and its rotation around its axis while a technological process. The block diagram of the developed automated coating system is given in figure 1. The principle of its operation is described in detail in [3, 7]. The advantage of this position of the product is in the compactness of the installation; it can operate in small industrial areas. Moreover, an unusual pipe position improves productivity by eliminating the use of bulky vertical pipe lifting machines, ensuring economical application of the coated material and processing pipes of different diameters with minimal system adjustments.

The coating is based on the ability of a slip (a suspension of a mixture of ground silicate materials, which forms enamel upon firing) to create a uniform film on the pipe surface at a constant rotation velocity over the surface. It is necessary to maintain a constant level of material in the filling column for a uniform flow of the material along the inner surface of the pipe. It is controlled by non-contact (4) and hydraulic (14) level sensors, as well as a constant rotation velocity of the pipe monitored by a non-contact angular velocity sensor, i.e. a video camera (16) directed to the mark on the product (17). Besides these parameters, a rotation velocity of the material depends on its current temperature, controlled operatively by a temperature sensor (5). The thickness of the coating is affected by the average rotation velocity of the slip along the inner surface of the pipe and its temperature. The description of this dependence is done in the form of dependence graphs of technological tables thoroughly described in [8]. Thus, we have a problem of stabilizing the slip flow velocity along the inner surface of the inclined rotating pipe.
2. Study of the viscous fluid rotation in the confined space of the inclined pipe

Consider a case when the pipe rotation velocity $\omega$ is 0 rad. The linear velocities of slip particles at different distances from the center of the pipe differ from each other. Therefore, we determine the average linear velocity of the flow of all liquid particles [9] as $v=Q/S$, where $Q$ is the liquid flow rate, [m$^3$/s], $S$ is the cross-sectional area of the drain hole filled with the liquid. In our case it is equal to the area of the circle segment. Previously, the authors build a formula for the average linear velocity of a slip in the inclined pipe applying mathematical calculations described in [9-11]:

$$v(H) = \frac{\rho g H^2 \sin \beta \arccos \left(1 - \frac{H}{R}\right) \left(2 - \frac{H^2}{R^2}\right)}{8 \eta \left(\arccos \left(1 - \frac{H}{R}\right) - \left(1 - \frac{H}{R}\right) \sqrt{\frac{2 H^2}{R^2} - H^2}ight)},$$

(1)

where $\rho$ is density of the fluid (kg/m$^3$), $g$ is gravity acceleration, $H$ is fluid level above the lower edge of the drain hole, $\beta$ is inclination angle of the pipe, (rad), $R$ is radius of the processed pipe, $\eta$ is dynamic viscosity of the fluid (kg/(m·s)). In this case, it is assumed that the drain hole is no more than half filled, i.e. $H \leq R$.

The calculations procedures assume that $\rho$ is 2000 kg/m$^3$, $\beta$ is 0.3 rad, $\eta$ is 150 kg/(m·s). Hereinafter, the graphs are obtained from the relative height $H/R$ for the convenience of comparing the flow velocity with different pipe diameters and the filling level of the drain hole. The extremum of the graphs in figure 5 is explained by a strong decrease in the cross-sectional area $S$ at an almost unchanged fluid flow rate $Q$. The resulting graphs show that the linear velocity with a completely closed drain hole is zero.
Figure 2. The flow velocity of a viscous fluid in the confined space of inclined pipes of different diameters, $R_1 = 0.15 \text{ m}$, $R_2 = 0.2 \text{ m}$, $R_3 = 0.25 \text{ m}$.

Figure 3. The flow velocity of a viscous fluid in the confined space of inclined pipes of different diameters, $\beta_1 = 0.15 \text{ rad}$, $\beta_2 = 0.3 \text{ rad}$, $\beta_3 = 0.5 \text{ rad}$.

Figure 3 shows graphs of the linear velocity change (1) at different angles of the inclined pipe. It is shown that the smaller the angle of inclination, the lower the velocity of the fluid flow at fixed values $\rho = 2000 \text{ kg/m}^3$, $\eta = 150 \text{ kg/(m-s)}$, $R = 0.2 \text{ m}$. The graphs demonstrate that if a pipe slope is absent, the fluid flow velocity is zero. The analysis of the functions in figures 2 and 3 helps to conclude that the obtained expression (1) is correct.

3. Study of the viscous fluid rotation in the confined space of the inclined rotating pipe

The average velocity of the circular rotation is defined as the velocity of the center of mass of the filled pipe segment [10]: $v_\theta = \omega r$, where $r$ is a coordinate of the center of gravity of the sectional area occupied by the fluid; it depends on the filling height of the pipe’s confined space $H$, $\omega$ is the rotation velocity of the pipe around its axis, (rad/s). The total average slip velocity $v_\Sigma$ is a vector sum of the circular rotation velocity and the average linear velocity: $v_\Sigma = \sqrt{r^2 \omega^2 + v^2}$. After transformations, a mathematical expression was obtained on the basis of the mathematical calculations described in [9, 10, 12]. It describes the dependence of the average slip velocity on the fluid level in the filling column and on the angular velocity of the pipe rotation, taking into account the parameters of the processed product and the viscous fluid:

$$v_\Sigma(\omega) = \sqrt{\frac{2R}{3} \left( \frac{2 \eta}{R} - \left( \frac{H}{R} \right)^2 \right)^3} \omega^2 \left( \frac{\rho g H^2 \sin \beta \arccos \left( \frac{1}{\sqrt{R}} \right) \left[ 1 \cdot \frac{H}{R} \right]^2}{8 \eta \left( \arccos \left( \frac{1}{\sqrt{R}} \right) \right) \left[ 2 \cdot \frac{H}{R} - \frac{H^2}{R^2} \right]^2} \right).$$

(2)

According to the formula (2), graphs of the dependence of the total average speed of the slip movement on the pipe rotation velocity were obtained. The following values were taken: $\rho = 2000 \text{ kg/m}^3$, $\eta = 150 \text{ kg/(m-s)}$, $\beta = 0.3 \text{ rad}$, $R = 0.2 \text{ m}$. The dependences are presented at different fluid levels above the lower edge of the drain hole $H$ (figure 4). The graphs demonstrate that with an increase in the pipe rotation velocity, the component of the linear fluid rotation of expression (2) becomes less significant.

Figure 5 presents graphs of the total average fluid velocity dependence on the pipe rotation velocity at different angles of inclination $\beta$ according to formula (2). The following values were taken for calculations: $\rho = 2000 \text{ kg/m}^3$, $\eta = 150 \text{ kg/(m-s)}$, $H = 0.04 \text{ m}$, $R = 0.2 \text{ m}$. The graphs demonstrate that at large angles of inclination $\beta$, an increase in the rotation velocity $\omega$ does not significantly affect the total average fluid flow velocity, as at small values of $\beta$. The velocity values of the viscous fluid correspond to the known data [13]. The obtained expression (2) is correct.
The total average fluid flow rate in the confined space of the inclined rotating pipe. 
$H_1 = 0.02 \text{ m}, \ H_2 = 0.04 \text{ m}, \ H_3 = 0.06 \text{ m}, \ H_4 = 0.08 \text{ m}, \ H_5 = 0.1 \text{ m}.$

The total average fluid flow velocity in the confined space of the inclined rotating pipe. 
$\beta_1 = 0.15 \text{ rad}, \ \beta_2 = 0.3 \text{ rad}, \ \beta_3 = 0.5 \text{ rad}, \ \beta_4 = 0.8 \text{ rad}.$

The analysis of the dependencies in figures 4 and 5 makes it possible to assess the influence of individual parameters of the coating system on the velocity of slip velocity in the pipe confined space. The obtained dependences make it possible to determine the optimal technological mode of coating, providing the required coating thickness. It is proposed to obtain a law to control the slip velocity on the basis of the obtained mathematical model of the velocity of a viscous fluid in the confined space of the inclined rotating pipe. It ensures a uniform coating applying the automated coating system.

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