Analysis of influence of pipeline roughness dispersion on energy consumption during fluid transportation

M A Vasilyeva¹, A A Volchikhina¹

¹ St. Petersburg Mining University, 2, 21-line VO, St. Petersburg, 199106, Russia
E-mail: saturn.sun@mail.ru

Abstract. The effect of the dispersion of effective roughness on the intensity of flow turbulence is considered in the paper. The results of the investigation of the effect of roughness parameters on the energy consumption of pumping equipment during the transportation of a liquid flow are presented.

1. Introduction

The area of transition of laminar flow to turbulent flow includes several qualitatively different zones in which the process of development and transformation of perturbations, which ultimately leads to turbulence, is subsequently implemented. At the end of the transition area, there is the zone in which Emmons spots appear, the increase in the number and size of which contributes to the final turbulence of the flow. This process of Emmons spots formation, leading to the decay of the laminar flow regime and the formation of a completely turbulent flow, is associated in practical dimensions with the notion of a "transition point" [1-3]. However, the mechanism of the phenomena occurring at this final stage of the transition is the most complex understanding and for the mathematical description [4, 5].

2. Materials and methods

When the liquid moves along the bed of the pipeline, a frictional force arises between the liquid and the pipe wall. At the walls of the fluid, particles are inhibited; inhibition is transferred to other layers of liquid [6]. Real pipelines will inevitably resist the current of the liquid, to overcome which it is necessary to have a supply of head. The total resistance consists of losses to friction in the pipeline and losses in local resistance.

In the future, only the loss of frictional pressure along the length of the pipeline will be taken into account, i.e. there are no local resistances, and there is also no elevation difference: \( H_H = 0 \). The total head will be numerically equal only to the frictional head loss, which is determined by the formula:

\[
\Delta H_f = i \cdot l,
\]

where \( l \) - basic (required) length, m
\( i \) - hydraulic gradient, mm/m.

\[
i = \frac{\lambda \cdot \theta^2}{2g \cdot d},
\]

\( \lambda \) - the coefficient of friction;
\( d \) - the equivalent diameter of the pipeline, m;
\( \theta \) - flow velocity, m/s;
\( g \) - acceleration of gravity, m/s².

Then the loss of pressure on friction will be determined by the formula:

\[ H_{fr} = \frac{\lambda \cdot \theta^2 \cdot l}{2g \cdot a}. \]

The head is not a geometric characteristic and cannot be identified with the height at which it is necessary to lift the pumped liquid. The necessary value of the pressure consists of several terms, each of which has its own physical meaning [7].

3. Dispersion of roughness

The surface of the pipeline along which the flow moves can be represented as the sum of two uncorrelated functions:

\[ f(\vec{p}) = f_1(\vec{p}) + f_2(\vec{p}) \]

where \( \vec{p} \) - the radius vector in the plane of the sample, \( f_1(\vec{p}) \) - surface with a Gaussian height distribution, \( f_2(\vec{p}) \) - the function describing the bumps (protrusions) on the surface, which for definiteness is taken as a random Poisson function:

\[ f_2(\vec{p}) = A \cdot \sum \varphi \cdot (\vec{p} - \vec{p}_m) \]

where \( A \) - amplitude of hillocks (projections).

If we take \( \varphi \cdot (\vec{p}_m) \) in the form of parallelepipeds with the base area \( S_0 \) and a height equal to unity, then the variance of the surface roughness of the pipeline under the condition \( < f_1 \cdot f_2 > 0 \) is determined:

\[ < f^2 > - < f >^2 = \sigma_g^2 + A^2 \cdot (p - p^2), \]

where \( p \) - the coefficient of filling the surface by random projections; \( p = \frac{S_m}{S_0}; \sigma_g^2 \) – roughness dispersion of a Gaussian surface.

With an increase in the amplitude of random emissions, the roughness variance grows as \( A^2 \).

In the case of a surface with a random distribution of projections in the approximation of small \( p \):

\[ \psi(q) = e^{-q^2 \frac{\sigma_g^2}{4} - 4p \sin^2(qA/2)} \]

where \( \sigma_g \) – root-mean-square roughness of a Gaussian surface, \( q \) – the normal to the surface component of the swirl vector of the flow, \( q = \frac{4\pi}{\lambda} \sin \theta \).

On the basis of this, the effective roughness can be written in the form:

\[ \sigma_{eff}^2 = \sigma_g^2 + \frac{4p}{q^2} \sin^2 \left(\frac{qA}{2}\right). \]

Thus, surface irregularities such as random peak emissions will affect the mean square roughness and head loss in different ways.

In order to assess the influence of the roughness of the internal surface on the energy efficiency of the process of transporting liquid through the pipeline, a comparative calculation of the power losses of the pumps was performed to overcome the frictional resistance when using pipes with different
parameters Ra, μm.

Hydraulic calculation is an important part of the process of selecting pipe accessories for pipeline construction. Most often at a given flowrate Q, it is necessary to determine the required diameter of the pipeline d and the pressure loss H taking into account the effective speed of movement and the physical properties of the pumped liquid. When moving the fluid, the pump must develop the pressure necessary to overcome the frictional resistance along the length of the pipeline.

The power required to transport a given volume of fluid and spent on overcoming the frictional force, the value of which depends on the value of the parameter of the physical roughness of the surface material of the pipe can be determined by the formula:

\[ N_{loss} = 0.4 \cdot \rho \cdot \lambda \cdot d_{in} \cdot v^2, \]

where \( \lambda = f(Ra) \),

Ra – height parameter of surface roughness, μm;

d_{in} – inner diameter of pipe, mm;

\( v \) – average velocity of fluid flow in the pipe, m/s.

As a nominal value for estimating the power consumption, energy is spent for pumping water through a pipe with a surface roughness, regulated by SP 40-102-2000 "Design and installation of pipelines for water supply and sewerage systems of polymeric materials" Ra=3.35 μm.

The main parameters for performing the calculations are given below:

Ra = 0.3 ÷ 5.0 μm;

d = 100 ÷ 1000, mm;

\( v \) = 1.1 m/s;

l = 1000 m.

The calculation of the pump power is performed. Based on the results obtained, the power variation graphs are plotted (Fig. 1).
The values of the power variation $\Delta N$, displayed on the graphs, show an exponential increase in values with a change in the roughness value $Ra$.

To estimate the effect of the roughness value, calculations were made of the power losses at different flow rates in the effective velocity zone. Data for calculation: a diameter of pipelines - 500 mm, a range of productivity 150 - 240 l/s.

Based on the results of the calculations, a family of power loss graphs is given (Figure 2).
Figure 2. Power loss at different flow rates in the effective speed zone

The green line, corresponding to the function $N_{\text{com}}=f(q, Ra)$ at $Ra = 0.304 \, \mu m$, is almost linear - the head loss depends only on the flow parameters.

The blue line corresponding to the parameter $Ra = 3.35 \, \mu m$ is exponential in perspective - with a further increase in consumption, losses will increase faster.

The red line, corresponding to the parameter $Ra = 5.65 \, \mu m$, exhibits an exponential growth with an increase in flow rate. This suggests that the size of the power losses is influenced, in addition to the flow parameters, by the surface properties of the pipeline: the value of the physical roughness parameter and the roughness variance.

4. Conclusion

Taking into account the accepted simplifications and assumptions, considering only the difference in diameters and, as a consequence, the flow rate, as well as roughness parameters (0.304 $\mu m$ and 0.41 $\mu m$, respectively), based on a preliminary calculation, it can be concluded that a pump that pumped less rough water pipes will have a power of 16% less than the pump pumping over a less smooth pipe with a smaller diameter. The mass of the liquid, as an inertial parameter, will not have a significant effect. Its influence will indirectly affect the calculation of pumping stations, taking into account the geometry of the route.

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