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The Influence of Muddy Water Flow in Pipelines on the Operating Efficiency of Pumps and Changes in Hydraulic Parameters

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Abstract:

The article analyzes the hydraulic and energy-related problems that arise during the pumping of muddy water flows at pumping stations of the Amu Darya and its associated irrigation systems. The influence of sediment particles on flow parameters, specific hydraulic resistance, and pump operating efficiency is theoretically substantiated based on the law of conservation of energy. Formulas for determining head losses for finely and coarsely dispersed muddy mixtures, as well as the concept of critical velocity, are presented. Using a specific example, the head characteristics of a pipeline system under clean water and muddy water conditions are compared, and the increase in electrical energy consumption at a turbidity level of 5% is calculated. The obtained results are of practical significance for selecting optimal operating modes of pumps and reducing energy consumption.

Keywords: *muddy flow, pumping station, hydraulic resistance, pressure pipeline, head loss, critical velocity, energy consumption, irrigation system.*

Introduction

In our republic, one of the known problems is the high concentration of sediment in the water flow at many pumping stations that take water from the Amu Darya and its associated irrigation facilities. A high content of sediment particles negatively affects the hydraulic parameters of the flow in the water intake section and internal flow passages of the pump, leads to an increase in hydraulic resistance at the inlet of pressure pipelines, causes additional loads and increased vibrations in the pump, and results in a decrease in the pump's water delivery efficiency [1].

When pumping muddy flow (a mixture of sediment particles and water) through pressure pipelines using pumps, additional energy consumption is required. The main reasons for this are the increase in hydraulic resistance and the increase in the density of the muddy flow [2].

Methodology.

This study is based upon a theoretical and analytical research methodology to address the key aspects on the performance characteristics of hydraulic resistance, pump performance and energy consumption of the pressure pipeline system when supplied with muddy water flow. The methodological framework draws on classical hydraulic theory, the law of conservation of energy, and related ideas, and is further adjusted simulating the filled features of the muddy flows of water and suspended sediment particles [3]. The analysis is initiated by proposing the energy balance equation between two cross sections of a pressure pipeline, which includes kinetic, potential, and thermal energy of the muddy mixture. The distinctions between clear and turbid flow are represented using parameters like mixture density, sediment concentration, and solid particle and water velocities. Based on established analytical expressions from hydraulic mechanics, head loss equations for fine and coarse sediment mixtures in horizontal and inclined pipelines are derived. The empirical coefficients and dimensionless numbers (volumetric sediment concentration and Froude number) are then used to be indicative of the actual operating condition expected in irrigation pumping stations. To verify the theoretical framework of the theoretical model for the synthetic pipeline, a case study is developed with synthetic pump and pipeline system, wherein the system is examined under clean water and muddy water. Differences in hydraulic resistance, discharge and power demand are quantified by calculating the system head characteristics and comparing these characteristics to those derived from base condition data [4]. Sediment transport is then used to estimate the electrical energy required for similar volumes of water delivered, which provides a measure of the increased energy with sediment. Using this integrated analytical approach provides a uniform management to study both hydraulic and energetic performances of muddy flow pumping as well as offers a solid basement to refine operation modes of pumps and save energy losses from irrigation systems.

Result and Discussion.

The pressure pipeline is defined by coordinates at points 1 and 2, and the energy of the muddy flow passing through the cross-sectional areas located at a certain distance from each other can be expressed using the energy conservation equation as follows [5] (Figure 1).

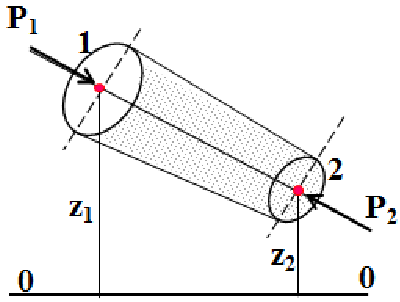

Figure 1. Diagram for determining the change in muddy flow energy between two points of the water flow

1- on point: $Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{1s.p}^2/2 + Q_w\cdot\rho_w\cdot\vartheta_{1w}^2/2 + Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_1$

2- on point: $Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{2s.p}^2/2 + Q_w\cdot\rho_w\cdot\vartheta_{2w}^2/2 + Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_2$ (1)

where, $Q_{s.p}$, $\rho_{s.p}$, $\vartheta_{s.p}$ are the flow rate, density, and velocity of sediment particles; Q_w, ρ_w, ϑ_w are the flow rate, density, and velocity of water; $Q_{m.f}$, $\rho_{m.f}$, $\vartheta_{m.f}$ are the flow rate, density, and velocity of the muddy flow; z_1 and z_2 are the geometric parameters that determine the potential energy of the flow at points 1 and 2.

Thus, in equation (1), the sum of the first and second terms represents the kinetic energy of the muddy flow, while the third term represents its potential energy. This equation accounts for the fact that, due to the large hydraulic size of the sediment particles and the frontal resistance acting on them, their velocity differs from that of the water flow ($\vartheta_{s.p}<\vartheta_w$).

Moreover, the movement of the muddy flow from point 1 to point 2 occurs due to the energy supplied by the pump, and a portion of this energy is spent to overcome frictional forces (viscous forces) [6]. It is known that this energy is also used to raise the temperature of the flow from t_1 at point 1 to t_2 at point 2. Taking this factor into account, equation (1) can be written in the following form:

$$Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{1s.p}^2/2+Q_w\cdot\rho_w\cdot\vartheta_{1w}^2/2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_1+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot t_1\cdot c_{m.f}/M$$

$$Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{2s.p}^2/2+Q_w\cdot\rho_w\cdot\vartheta_{2w}^2/2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot t_2\cdot c_{m.f}/M \quad (2)$$

where M is the mechanical equivalent of the heat I generated in overcoming the viscous force, and $c_{m.f}$ is the specific heat capacity of the muddy flow.

The work done to overcome the frictional force can be expressed as follows [7].

$$W_{f.f} = I/M = Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot c_{m.f}\,(t_2 - t_1)/M \quad (3)$$

For this case, the law of conservation of energy can be written in the following form:

$$Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{2s.p}^2/2+Q_w\cdot\rho_w\cdot\vartheta_{2w}^2/2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot t_2\cdot c_{m.f}/M - W_{f.f} + I/M +$$

$$+ Q_{m.f}(p_2 - p_2) = Q_{s.p}\cdot\rho_{s.p}\cdot\vartheta_{1s.p}^2/2+Q_w\cdot\rho_w\cdot\vartheta_{1w}^2/2+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot z_1+Q_{m.f}\cdot\rho_{m.f}\cdot g\cdot t_1\cdot c_{m.f}/M \quad (4)$$

Dividing the left and right sides of this equation by $Q_{m.f}\cdot\rho_{m.f}\cdot g$ and taking (2.3) into account, we can write (4) as follows.

$$(1-q)\,\vartheta_{1w}^2/2g + q\cdot\vartheta_{1s.p}^2/2g + z_1 + p_1/\rho_{m.f}\cdot g + h_{g.q} = (1-q)\,\vartheta_{2w}^2/2g + q\cdot\vartheta_{2s.p}^2/2g + z_2 + p_2/\rho_{m.f}\cdot g \quad (5)$$

бунда $q = Q_{s.p}\cdot\rho_{s.p}/Q_{m.f}\cdot\rho_{m.f}$; $1 - q = Q_w\cdot\rho_w/Q_{m.f}\cdot\rho_{m.f}$; $h_f = W_{f.f}/Q_{m.f}\cdot\rho_{m.f}\cdot g$

From equation (5), it is possible to determine the head loss that occurs when pumping muddy mixtures, which is important for identifying the optimal operating modes of pumps.

$$h_f = (1-q)\,\vartheta_{2w}^2/2g + q\cdot\vartheta_{2s.p}^2/2g + z_2 + p_2/\rho_{m.f}\cdot g - (1-q)\,\vartheta_{1w}^2/2g - q\cdot\vartheta_{1s.p}^2/2g - z_1 - p_1/\rho_{m.f}\cdot g \quad (6)$$

This equation shows that, during the transportation of muddy flow, the change in the value of h_f relative to clean water mainly depends on the amount of sediment particles in the flow and on the density of the muddy flow, which varies under their influence.

In equation (6), determining the velocity of sediment particles $\vartheta_{s.p}$ is a rather complex problem. The solution to this problem is given in based on the following equation [8].

$$\vartheta_{2s.p} = \vartheta_{2w} \frac{К_1}{К_1 - 1}\left[1 - \sqrt{1 - \frac{К_1 - 1}{К_1^2}\left(\frac{\rho_w}{\rho_p} + K_1\right) - \frac{1 - \rho_w/\rho_p}{К_1^2}(К_1 - 1)\frac{\vartheta_{1w}^2}{\vartheta_{2w}^2}}\right] \qquad (7)$$

where $К_1 = С\frac{3}{4}\frac{\rho_w}{\rho_p}\frac{S}{d}$; ρ_p is the density of a sediment particle with added (associated) mass, $\rho_p = \rho_{s.p} + K_p \cdot \rho_w$, K_p is the added mass coefficient, which is equal to 0.5 for a spherical sediment particle; S is the distance between the cross sections with coordinates defined by points 1 and 2 along the pipeline; d is the diameter of the spherical sediment particle.

If the pipe diameter does not change over the distance S, then, due to the negligible difference, it can be assumed that $\vartheta_{2s.p} = \vartheta_{1s.p}$

For the pumping of muddy mixtures, the head loss h_f in horizontally installed pressure pipelines for finely dispersed (particle size 0.05–0.15 mm) and coarsely dispersed (particle size 0.15–1.5–2.0 mm) hydro-mixtures is addressed in [9], where recommendations are provided for determining the values of specific hydraulic resistance in pipelines.

For example, for finely dispersed hydro-mixtures, the following formula is proposed.

$$i_{s.p} = i_w\left(1 + c_z \frac{\rho_{s.p} - \rho_w}{\rho_w}\delta\right) \qquad (8)$$

where $i_{m.f}$ and i_w are the values of specific hydraulic resistance in the pipeline for muddy flow and clean water, respectively; $\rho_{s.p}$ and ρ_w are the densities of the sediment particles and water; c_z is an empirical coefficient depending on the amount of sediment particles: if the particle size is less than 0.7 mm and their concentration does not exceed 5–6%, then $c_z = 1.0$; in general, c_z varies within the range 0.85–1.15; δ is the volumetric concentration of sediment particles, which is determined by the following formula.

$$\delta = (\rho_{m.f} - \rho_w)/(\rho_{s.p} - \rho_w) \qquad (9)$$

For the pumping of coarsely dispersed muddy flows, it is recommended to determine the specific hydraulic resistance of the head loss using the following formula [10].

$$i_{s.p} = i_w + c_1 \cdot a \cdot \delta \frac{\theta}{\vartheta_{m.f}}\sqrt{D/d_{nom}} \qquad (10)$$

where c_1 is a coefficient that accounts for the pipe diameter, c_1 = 0.3–0.4 for pipe diameters D=150–900 mm, c_1 = 0.5–0.6 for pipe diameters D=100–125 mm, c_1 = 1.5–1.6 for pipe diameters D = 63–100 mm, θ is the hydraulic size of the particles with diamete d_{nom}, a is the relative density coefficient of the sediment particles, which is determined by the following formula [11].

$$a = (\rho_{s.p} - \rho_w)/\rho_w, \qquad (11)$$

In pump station pressure pipelines, sections installed with an upward incline are encountered more frequently than horizontal sections. For such pipelines, when pumping muddy water, it is recommended to determine the specific hydraulic resistance using the following formula [12].

$$i_{m.f} = i_w(1 + a \cdot \delta) \quad \text{When } Fr_a > 10 \qquad (12)$$

$$i_{s.p} = i_w\left[1 + 10 \cdot a \cdot \delta \frac{g \cdot D}{(\vartheta_{m.f} - \vartheta_{s.p})^2}\right] \quad \text{When } 1 < Fr_a < 10 \qquad (13)$$

where Fr_a is the Froude number of the muddy flow, which is determined as follows:

$$Fr_a = \frac{(\vartheta_{m.f} - \theta)^2}{a \cdot g \cdot D} \quad (14)$$

In muddy water flows in pipelines, there is a concept called the critical velocity of the flow, which is considered the velocity at which the head loss is minimized and is close to the threshold value at which sediment particles may settle. This velocity can be determined using the following formula [13].

$$\vartheta_{cr} = \theta + 3\sqrt{a \cdot \delta \cdot g \cdot D} \quad (15)$$

For coarsely dispersed muddy flows in a horizontal pipeline, the critical velocity can be determined using the following formula.

$$\vartheta_{cr} = (6.5 - 7.5)\sqrt{D} \cdot \sqrt[3]{\frac{a \cdot \delta \cdot \theta}{\sqrt{d_{nom}}}} \quad (16)$$

The graphs showing the dependence of the hydraulic resistance coefficients on the flow velocity for muddy flows in a horizontal pipeline are presented in Figure 2 [9].

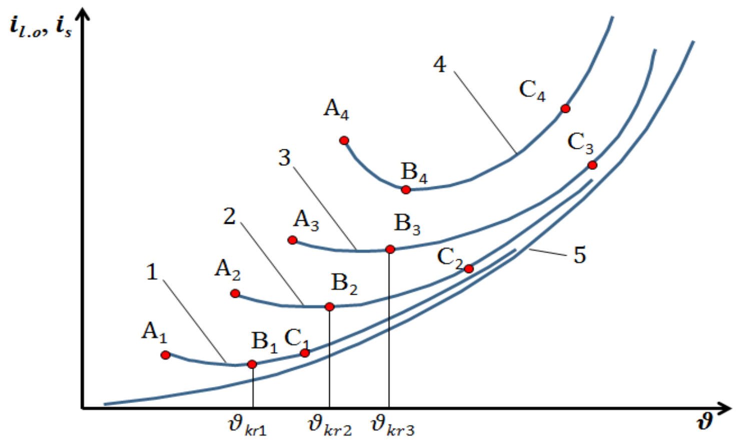

Figure 2. Graphs of the dependence of the specific hydraulic resistance coefficient on the flow velocity in horizontal pressure pipelines.

1, 2, 3, 4 – graphs of $i_{m.f}$ vs. ϑ for muddy flows with densities $\rho_1 < \rho_2 < \rho_3 < \rho_4$; 5 – graph of i_s vs. ϑ for clean water.

As can be seen from the graphs, as the density of the muddy flow increases, the values of the hydraulic resistance coefficient also increase, and their minimum values (indicated as point B on the graphs) correspond to the critical velocity of the flow, which has been confirmed by both theoretical and experimental studies [9].

At flow velocities corresponding to the range between points A and B shown on the graphs, sediment settling may occur; therefore, the probable velocity values are taken within the range between points B and C.

For example, the D1250–65 pump delivers a muddy flow with a flow rate of Q=0,28 m^3/s through a pressure pipeline with a diameter of D =0,4 m, a length of L=150 m, and an upward incline of 25°, to a height of H_G = 22 m. In this pipeline, we determine the limiting flow velocity ϑ_{cr} and the specific hydraulic resistance coefficient $i_{l.o}$.

Sediment particle density $\rho_{s.p}$ =2000 kg/m^3, water density ρ_w =1000 kg/m^3, muddy flow density $\rho_{m.f}$=1050 kg/m^3, mean particle diameter d_{nom}= 0.5 mm, hydraulic size θ =5.24 sm/s [14].

To determine how this condition affects the pump's operating mode, we calculate the pipeline system head characteristics for both clean water and muddy flow, and then represent them on the pump performance curve [15]. For this, the pipeline head characteristic $H = H_G + k{\cdot}Q^2$ is calculated for different values of Q in both cases, and the graph is plotted (Figure 3).

In the above equation, the value of k is calculated.

$$k_w = \Delta H_w / Q^2 = 2{,}19/0{,}28^2 = 27{,}93$$

$$k_{m.f} = \Delta H_{m.f} / Q^2 = 3{,}09/0{,}28^2 = 39{,}41$$

Thus: $\Delta H_w = 27{,}93\ Q\ ;\quad \Delta H_{m.f} = 39{,}41Q^2$

$$H_w = H_G + k_w{\cdot}Q^2 = 22 + 27{,}93\ Q^2\ ;$$

$$H_{m.f} = H_G + k_w{\cdot}Q^2 = 22 + 39{,}41Q^2$$

The results of the calculations are presented in Table 2.

Table 2.

Q, $м^3/c$	0,04	0,08	0,12	0,16	0,20	0,24	0,28	0,32
Q^2	0,0016	0,0064	0,0144	0,0256	0,04	0,0576	0,0784	0,102
ΔH_c, м	0,045	0,179	0,402	0,715	1,12	1,61	2,19	2,85
$\Delta H_{m.f}$, м	0,063	0,252	0,567	1,00	1,576	2,27	3,09	4,02
H_c, м	22,04	22,18	22,40	22,71	23,12	23,61	24,19	24,85
$H_{m.f}$, м	22,06	22,25	22,57	23,0	23,58	24,27	25,09	26,02

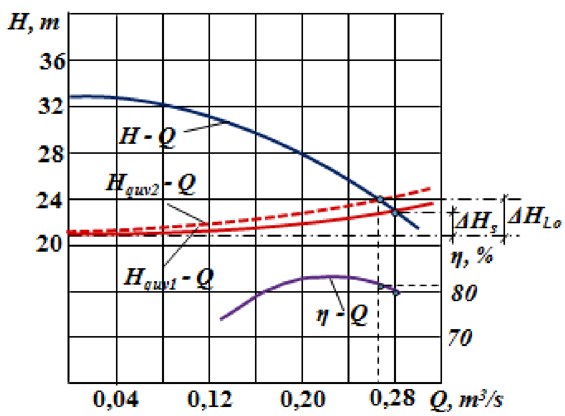

Figure 3. Graphs of the pipeline system head characteristics for the D1250–65M–O pump.

Based on the results presented in Table 2, we plot the pipeline system head characteristic curves.

Conclusion.

The results of the calculations show that when pumping muddy flow, the specific hydraulic resistance coefficient in the pressure pipeline increased by 41%, which caused the pump flow rate to decrease from 0.28 m^3/s to 0.265 m^3/s. To assess the impact on energy consumption, the electrical energy is calculated as:

$$E_w = 9{,}81{\cdot}Q_w{\cdot}H_w{\cdot}T/\eta_w = 9{,}81{\cdot}0{,}28{\cdot}23{,}3{\cdot}500/0{,}8 = 40000\ kW{\cdot}h$$

where the pump operating time is taken as T=500 h.

During this period, the pump delivers $V = Q_w \cdot T \cdot 3600 = 0{,}28{\cdot}500{\cdot}3600 = 504000$ m^3 of water. According to the requirements, the pump must deliver the same volume of water even if it is muddy, and for this, it will consume the following amount of electrical energy.

$$E_{m.f} = \frac{V \cdot H_{m.f}}{367 \cdot \eta_{m.f}} = \frac{504000 \cdot 24}{367 \cdot 0{,}81} = 40690\ kW \cdot h$$

Thus, when pumping muddy water with sediment particles making up 5%, according to the calculations above, this can lead to an additional electricity consumption of 690 kWh.

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