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# Research of processes of heat exchange in horizontal pipeline

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**Abstract.** The energy crisis, which becomes more evident in Russia, stems in many respects from unjustified high consumption of energy resources. Development and exploitation of principal oil and gas deposits located in remote areas with severe climatic conditions require considerable investments increasing essentially the cost of power generation. Account should be taken also of the fact that oil and gas resources are nonrenewable. An alternative fuel for heat and power generation is coal, the reserves of which in Russia are quite substantial. For this reason the coal extraction by 2020 will amount to 450-550 million tons. The use of coal, as a solid fuel for heat power plants and heating plants, is complicated by its transportation from extraction to processing and consumption sites. Remoteness of the principal coal mining areas (Kuzbass, Kansk-Achinsk field, Vorkuta) from the main centers of its consumption in the European part of the country, Siberia and Far East makes the problem of coal transportation urgent. Of all possible transportation methods (railway, conveyor, pipeline), the most efficient is hydrotransport which provides continuous transportation at comparatively low capital and working costs, as confirmed by construction and operation of extended coal pipelines in many countries.

## 1. Purpose of study

The operation of main pipeline is accompanied by a change in the properties of its elements. Linear aggregates are used to describe such systems. The linear unit contains the movements and jumps necessary for the calculation of the operation modes of gas pipeline. The process of operation of any unit (element) of gas pipeline system is determined by a set of characteristics [1-2]:

- the equation of the boundary of state space;
- equations of motion of the point of the vector of additional coordinates in state space;
- the ratio for calculating a new state as a result of a jump when it reaches an acceptable boundary and when an input signal is received;
- ratio for calculating coordinates of the original signals.

## 2. Materials and methods

In the USA, twelve coal pipelines with an overall length of about 20,000 km and a total throughput capacity of 263 million tons per year have been designed. The pipeline diameters vary from 560 to 1220 mm [3]. The coal pipelines traverse different climatic zones and high-seismicity zones. In Canada, the coal pipeline 1287 km in extent has been designed to connect five new coal mines with west ports. Its throughput capacity will amount to 10.2 million tons of coal per year.

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Despite the fall in prices for nonferrous metals many countries continue to build new large-scale and to reconstruct operating mining enterprises, where the pipeline transport is widely used for transportation of ore processing products.

The world's largest copper deposit Collahuasi in Chile is located at an altitude of 4500 m above sea-level in the Andes. As estimated, the prospective enterprise will produce up to 900,000 tons of copper concentrate per year to be transported to a port through the pulp pipeline 180 mm in diameter and 207 km in length. The pulp pumping station located at an elevation of 4300 mm pumps the pulp to a mountain pass to an altitude of 4800 mm, from whence the concentrate is delivered by gravity to a discharge port. This variant was considered along with the road and railroad transport and was chosen as the most cost-effective and environmentally safe. The enterprise will run at an unprecedented altitude above sea-level.

In Russia, the pipelines for transportation of solid mineral products were not more than 10-20 km in extent, and only at the end of the 80-ies the Belovo-Novosibirsk pilot coal pipeline 264 km in length with a throughput capacity of 3 million tons per year was built for transportation of coal-water pulp. The pipeline, as compared with railroad transport, allows the current and capital costs to be reduced by a factor of 1.5.

Intensive development of Siberian and Far North regions makes necessary investigation of the problems related to transportation of water, different mixtures and pulps under severe climatic conditions. Operation of water pipelines laid in eternally frozen ground [4], hydroplant pipelines [5], hydraulic mining pipelines transporting water-sand mixtures [6] is fraught with hazard of inner icing of pipes both with liquid moving through pipes and during downtime, which results in an increase in hydrodynamic resistance. Significant contribution to ice-thermal calculation of pipelines was made by Russian scientists and engineers (P.A. Bogoslovsky, A.M. Estifeev, D.N. Bibikov, Yu.A. Popov, V.M. Zhidkikh, N.N. Zenger, A.V. Lyutov).

Many researchers noted that it is not always necessary to strive to completely eliminate icing since costs of heating, thermal insulation of tubes and earth works are unjustifiably high (N.N. Zenger, V.P. Stegantsev, S.V. Khizhnyakov).

The study of the ice regime of pipelines as applied for hydropower plants showed that their inner icing, when in operation, is possible (P.A. Bogoslovsky). The fundamental difference in operation between pipelines in a system with centrifugal pumps and water pipelines of hydropower plants consists in the availabilty of feedback (pump ↔pipeline). Pumps at a specified flow rate develops the head necessary to overcome the forces of hydraulic resistance. Yu.A. Popov investigated the ice regimes of hydraulic mining pipelines with complicated production engineering applied and under time-varying weather conditions. On this basis he developed the fundamentals of the theory of water-sand mixture transportation under severe climatic conditions for hydraulic mining. The method of ice-thermal calculation of water pipeline system providing for alternate operation and idle of the hydraulic system is developed in study [6,7].

## 3. Carrying out the research

To prevent failures caused by freezing of transported liquids, it is necessary to envisage at the design stage, when calculating ice-thermal regimes of such pipeline systems, possible unfavorable operation conditions connected with changes of weather conditions, possible shutdowns, to calculate the thickness of thermal insulation, to consider several design versions to determine the optimal one.

When designing large-extent transport facilities, new problems arise and novel calculation methods should be elaborated, such as:

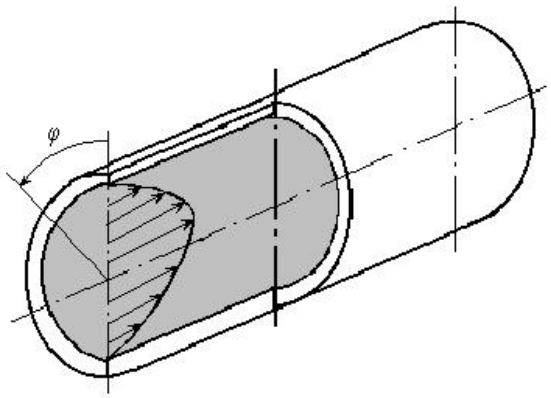
- establishment of relation between the hydrodynamic and thermal regimes in pipelines of hydrotransport systems;
- the effect of unsteady processes on the system performance reliability during start-up and shutdown;

- definition of mutual effect of the system «environment → (pump ↔ pipelines)»;
- elaboration of the method for installation of pipelines and devices compensating for temperature deformations.

The urgency of these problems has determined the line of scientific activities undertaken at Saint Petersburg Mining Institute (Technical University).

At the first stage, the theoretical and experimental works were carried out to investigate the effect of solid phase distribution over the pulp-carrying flow section on the intensity of heat transfer from flow to pipeline wall.

The presence of solid particles in the liquid-carrying flow complicates essentially the process of heat exchange with the pipe wall. For the hydrodynamically developed flow it is possible to consider non-Newtonian hydromixture as a dummy liquid with an increased density, since solid particles move with a local velocity of liquid [8]. Such model makes it possible to use in the thermal calculation the averaged characteristic $\lambda_П$ - the thermal conductivity of hydromixture in the radial direction [9]. The hydrodynamical axis of the flow is found to be displaced upwards, because large particles move in the near-bottom zone. The axial velocity of hydromixture $w_x$ will depend on angle φ which is measured in the plane perpendicular to the pipe geometrical axis from the vertical and varies in the range from 0 to π Figures 1.




**Figures 1.** Measurement in the plane perpendicular to the geometrical axis of the tube

Processing of the velocity profiles of pulp-carrying flows of different concentrations [10] makes it possible to take functional dependence $w_x(\varphi)$ as $\cos(\varphi/m)$, where $m$ is the experimentally defined constant. As estimated, $m \approx 3$. In this case, the velocity profile in the pulp-carrying flow can be taken as:

$$w_x(\varphi) = 2\, w_{av}(1-R^2)\cos\frac{\varphi}{3}, \quad (1)$$

where $w_{av}$ - average velocity of hydromixture motion, m/s; $R=r/r_0$ - reduced pipe radius; $r_0$ - pipe radius, m.

The heat exchange equation for the pulp flow in a pipe is of the form:

$$2w_{av}(1-R^2)\cos\frac{\varphi}{3}\frac{\partial t}{\partial x} = \frac{a}{r_0^2}\left(\frac{\partial^2 t}{\partial R^2} + \frac{1}{R}\frac{\partial t}{\partial R} + \frac{1}{R^2}\frac{\partial^2 t}{\partial \varphi^2}\right), \quad (2)$$

where t - pulp temperature,
K; $a = \lambda_П/(c\rho)_П$;
$(c\rho)_П$ - volumetric heat capacity of pulp, J/(m$^3$·K);
x- the coordinate characterizing the pipe length, m.

Let us choose, as a characteristics value, wall temperature $t_c$, treating it further as a constant. If $t_0$ is the pulp constant temperature at the pipeline input, then by introducing the dimensionless variables:

$$\theta = \frac{t - t_c}{t_0 - t_c}; \quad X = \frac{ax}{2w_{av}r_0^2},$$

Eq. (2) can be of the form:

$$(1 - R^2)\cos\frac{\varphi}{3}\frac{\partial\theta}{\partial X} = \frac{\partial^2\theta}{\partial R^2} + \frac{1}{R}\frac{\partial\theta}{\partial R} + \frac{1}{R^2}\frac{\partial^2\theta}{\partial\varphi^2}. \tag{3}$$

The boundary conditions are of the form:

a) on the pipe surface, the temperature is specified as:

$$\theta = 0 \text{ at } R=1 \tag{4}$$

b) at the input cross-section ($x$=0), the temperature is constant:

$$\theta=1 \text{ at } X=1. \tag{5}$$

To estimate the temperature regime, let us choose the approximate method for solution of the boundary problem (3)-(5) based on the transformation of convolution of the functions $f_1*f_2$ [11]:

$$f_1 * f_2 = \int_0^X f_1(y)\, f_2(X - y)dy \tag{6}$$

Differential equation (3) written with the convolution transformation is of the form:

$$(1 - R^2)\cos\frac{\varphi}{3}(\theta - 1) = 1 * \nabla^2\theta, \tag{7}$$

where $\nabla^2$ - Laplace operator.

Eq. (7) is used to form the functional of the heat exchange process [11]:

$$I(\theta) = \iint_{(D)} [R(1 - R^2)\cos\frac{\varphi}{3}(\theta - 2) * \theta + \frac{1}{R} * \frac{\partial\theta}{\partial\varphi} * \frac{\partial\theta}{\partial\varphi} + R * \frac{\partial\theta}{\partial R} * \frac{\partial\theta}{\partial R}]RdRd\varphi \tag{8}$$

Integration domain $D$ covers the pipeline cross-section. The identity of this functional to Eq.(3) with conditions (4) and (5) is established by taking the first variation with respect to θ.
The approximate solution is found in the form of the function combination:

$$\theta_k = \sum_{i=1}^{k} \varphi_i(R, \varphi)g(X), \tag{9}$$

where k - the approximation number.

As is known from the theory of approximate solutions, the first approximation yields the predicted error not exceeding 10%, but with an appropriate choice of approximating functions $\varphi_I$, the error can be even less.

The first approximation is found in the form:

$$\theta_1 = (1 - R^2)\cos\frac{\varphi}{3}g(X) \tag{10}$$

It is seen that the coordinate function $\varphi_1$ satisfies identically the boundary condition in Eq. (5). By substituting $\theta_1$ into functional (8) and integrating with respect to the pipeline cross-section, let us obtain the numerical value of the coefficients:

$$I(\theta) = g * g \cdot 0.098974 - 2(1 * g)0.169167 + (1 * g * g)1.83085 . \tag{11}$$

By varying expression (11) with respect to the argument *g*, one gets:

$$\delta I(g) = [2g \cdot 0.098974 - 2 \cdot 0.169167 + 2(1 * g)1.83085] * \delta g .$$

As $\delta g \neq 0$, the extremality of functional (11) requires that:

$$g \cdot 0.098974 - 0.169167 + (1 * g)1.83085 = 0 . \tag{12}$$

The equivalent form of the differential equation is obtained by taking a derivative with respect to X:

$$g' + 18.498g = 0 , \tag{13}$$

with the boundary condition taking the form:

$$g(0) = 1.709. \tag{14}$$

By separating the variables in Eq.(13), integrating and using condition (14), one gets:

$$g = 1.709\exp(-18.5X) . \tag{15}$$

Finally, the first approximation for temperature is as follows:

$$\theta_1 = 1.709(1 - R^2)\cos\frac{\varphi}{3}\exp(-18.5X) \tag{16}$$

The results of the calculation made by Eq. (16) are tabulated. The average temperature of the pulp-carrying flow is calculated to analyze the error caused by the approximate method used.

**Table 1.** Dimensionless temperature θ as a function of *X*, φ, *R*.

| *X* | θ | | | | |
|---|---|---|---|---|---|
| | φ | *R=0.1* | *R=0.3* | *R=0.5* | *R*=0.7 R=0.9 |
| 0.01 | π/6 | 0.810 | 0.745 | 0.614 | 0.417 |
| | π/3 | 0.773 | 0.711 | 0.586 | 0.398 |
| | π/2 | 0.712 | 0.655 | 0.540 | 0.367 |
| | 2π/3 | 0.630 | 0.579 | 0.477 | 0.325 |
| | 5π/6 | 0.529 | 0.486 | 0.400 | 0.272 |

| | | | | | |
|---|---|---|---|---|---|
| | π | 0.411 | 0.378 | 0.312 | 0.212 |
| | π/6 | 0.387 | 0.355 | 0.293 | 0.199 |
| | π/3 | 0.369 | 0.339 | 0.279 | 0.190 |
| 0.05 | π/2 | 0.340 | 0.312 | 0.258 | 0.175 |
| | 2π/3 | 0.301 | 0.276 | 0.228 | 0.155 |
| | 5π/6 | 0.252 | 0.232 | 0.191 | 0.130 |
| | π | 0.196 | 0.180 | 0.149 | 0.101 |
| | π/6 | 0.153 | 0.141 | 0.116 | 0.079 |
| | π/3 | 0.146 | 0.134 | 0.111 | 0.075 |
| 0.10 | π/2 | 0.135 | 0.124 | 0.102 | 0.069 |
| | 2π/3 | 0.119 | 0.110 | 0.090 | 0.061 |
| | 5π/6 | 0.100 | 0.092 | 0.076 | 0.051 |
| | π | 0.078 | 0.072 | 0.069 | 0.040 |

$$\theta_{av} = \frac{\iint\limits_{(D)} w_x \theta R dR d\varphi}{\iint\limits_{(D)} w_x R dR d\varphi} = 0.9479 \exp(-18.5X) \qquad (17)$$

The estimation of approximation at the input cross-section can be obtained by comparing the boundary condition at the input (5) and the value of Eq.(17) at X=0:

$$\theta_{av} = 0.9479 \cong 0.95.$$

It is seen that the approximate solution yields an error of ~5%.

The pulp temperature can be estimated by Eqs.(16) and (17) with an accuracy sufficient for the engineering calculations.

The results of the experiments with water comply with the dependence given by M. Mikheev in [11]:

$$Nu = 0.026 Re^{0.8} Pr^{0.4}.$$

In this case, the error did not exceed ±7%.

The experimental data on heat exchange between the pulp and the pipe wall were processed in compliance with the obtained criteria dependence:

$$Nu = 0.026\, \mathrm{Re}_p^{0.8} \cdot \mathrm{Pr}_p^{0.4} \left( \frac{C_1}{C_2} \right)^{0.15} \cdot \left( \frac{\lambda_3 - \lambda_1}{\lambda_2} \right)^{0.42}, \qquad (18)$$

where $Re_p$ - Reynolds number of pulp;
$Pr_p$ - Prandtl number of pulp;
$C_1$ - liquid heat capacity;
$C_2$ - heat capacity of solid particles;
$\lambda_1$ - thermal conductivity of liquid;
$\lambda_2$ - thermal conductivity of solid particles;
$\lambda_3$ - thermal conductivity of pulp.

## 4. Conclusions

The obtained formula is recommended for thermal calculations of the pipelines intended for transportation of the non-Newtonian pulp.

The aim of the experimental investigations was to obtain the dependence for calculation of the heat transfer coefficient when the pulp flows through the pipeline.

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