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Research paper

Study on the Coal-Water Fuel Pipeline Transportation Taking Into Account the Granulometric Composition Parameters

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Abstract

The highly loaded coal-water fuel pipe flow was verified. The move of the coal-water fuel with the 60% of coal loading practically has not been studied, especially for the coal originated from Ukraine. Through experimental research it was discovered that the water-coal fuel of such concentrations has a Bingham rheological characteristic. The verification was carried out by comparing the results of numerical calculations and experimental research. As a result of the numerical calculations of the flow, near the axis of the tube, a zone of approximately the same velocity is obtained, which qualitatively coincides with the results of experimental studies and with the results of the analytical description of the Bingham flow. As a result of the calculation the pressure drop value was defined, costs and velocity distribution over the cross section of the pipeline in the straight line and in curve. The velocity distribution profiles of the water-coal fuel flow are built. To compare the results of the calculation and to validate the rheological model choice velocity calculations were performed using the proposed model of Bingham and Newtonian fluids at the same effective viscosity values.

Keywords: *Transportation, Coal-water fuel, Granulometric composition, Modeling, Rheological characteristics.*

1. Introduction

The most promising trend in coal technologies development is the use of coal-water slurries (CWS) as an alternative fuel for the needs of the heat and power complex of industrial enterprises [1, 2].

The expansion of the use of coal-water fuel (CWF) as an efficient coal technology calls for further research, aimed at improving the technologies of its preparation to reduce energy consumption for transportation. Concentration of coal particles, their granulometric distribution and physical and chemical properties, depending on the grade of the source coal have the most significant impact on CWF transportation processes by pipelines. Depending on the brand of initial coal when reaching the bimodal granulometric composition of the initial coal will reduce the hydraulic resistance and total energy costs for CWF transportation by the industrial hydro transport systems [3]. Thus, clarification of the CWF flow patterns in the industrial hydro transport systems (IHTS), development of the mathematical models for the description of technological processes of preparation and transportation of the highly loaded CWF can increase the efficiency of the hydro transport system, which is a topical scientific and practical problem.

Numerous theoretical and experimental studies of the coal-water fuel transportation have shown that the parameters of the energy efficiency of transportation are influenced by many factors of which one of the main is the fuel granulometric composition [4, 5]. The investigation of the granulometric composition influence on parameters and energy efficiency of transportation requires a significant amount of experimental studies and constant change of composition, which affects rheological indicators. Today, the numerical solution of fluid motion problems has become common at reasonable expense of time for calculation [6, 7]. Thus, it became possible to reduce the number of experimental studies by replacing part of the most valuable experimental research with theoretical numerals. For this purpose, it is necessary, first of all, to validate the mathematical models in order to obtain the least possible difference between the results of mathematical modeling and experimental research [8, 9]. After obtaining the least errors in the calculation of flow models, a range must be specified, in which these models have sufficient accuracy, and it should be emphasized in what range of parameters the obtained results and conclusions will be valid [10].

The calculations on the mathematical models of the processes, occurring during the transportation of coal-water fuel in the pipeline and various elements of the hydraulic systems, allow shortening the time to improve the methods of calculating the parameters of hydrotransport and get the most accurate system characteristics with the boundaries of their use [11, 12]. Therefore, the mathematical modeling is one of the most important and actual problems of the highly loaded coal-water fuel movement study [13].

2. Literature Survey

Currently, a lot of experience has been accumulated, a scientific database has been created and methods have been developed to determine energy consumption when transporting coal-water fuel. Significant contribution to the creation of scientific and methodological support and solving the abovementioned tasks was brought by researchers of EERC in the USA, Cape Breton Development Corporation in Canada, Snamprogetti in Italy, Salzgitter in Germany, AB Carbogel in Sweden, Elfsolaize in France, Japan COM, JGC and Nissho Iwai Coal Corp. in Japan, Janri CWM Corp. in

China, Federal State Autonomous Educational Institution of Higher Professional Education, Scientific & Production Enterprise JSC “Sibecotekhnica”, Siberian Federal University in Russia. A major contribution to the development of the coal-water fuel technologies in Ukraine was made by scientists of the Geotechnical Mechanics Institute at the National Academy of Sciences in Ukraine, Donetsk National Technical University, Scientific Production Association “Hymec”, V. Dahl East Ukrainian National University, Institute of Renewable Energy at the National Academy of Sciences of Ukraine, UkrNDIhidrovuhillya, Institute of Physical-Organic Chemistry and Coal Chemistry at the National Academy of Sciences of Ukraine and Institute of Colloid Chemistry and Water Chemistry at the National Academy of Sciences in Ukraine and others. In recent times, a lot of works deal with Bingham liquids flow mathematical modeling [1, 2, 4, 5, 7, 11, 12, 14, 15, 29, 30]. The works [1, 2] are devoted to the modeling of the coal and water slurry flow, but for coal in Chinese and Indian regions. For the coal mined in Ukraine research on coal-water fuel that is transported with the high concentration, for the time being, was not carried out. In [1, 15] the flow of liquids in curves is simulated, but the regression dependences for the whole variety of rheological parameters are not shown. The article [16] gives an exact solution of the characteristics of the fluid motion, but only by pipeline, which does not allow to use the obtained correlations for turns and in channels with change in cross-sectional area.

As shown by an analysis of the works, the parameters of the CWF transportation by industrial hydraulic transport are mostly influenced by properties of the initial coal, concentration and granulometric composition of the suspension, as well as the speed of transportation, on which the rheological properties and energy costs in general depend on [4, 5, 7, 14].

The experience of exploiting IHTS has shown – traditional approaches to solving CWF energy cost reduction are ineffective. The author's calculations made it possible to evaluate the scale of influence of the ratio of particles of fractions and various concentrations of the solid phase on the specific pressure losses during the CWF hydro transportation [1, 23, 24, 25]. The analysis of the obtained preliminary results has shown that the increase of IHTS energy efficiency by reducing hydraulic resistance can be achieved by choosing the rational granulometric composition of the CWF, which provides the necessary rheological properties; - minimum values of specific pressure losses are observed in the range of solid phase concentration 60 to 65%.

3. Formulation Research Problem

To describe the fluid behavior we put the theorem on the principal vector changes of the system momentum. This theorem determines the relationship of the individual derivative of the principal vector of momentum of the “liquid” volume with the principal vector of external volume and surface forces, applied to the particles of liquid, which are located in the volume and on the surface, respectively, limiting it [17, 18]:

$$\frac{d\bar{V}}{dt} = \bar{F} + \frac{1}{\rho} DivT . \qquad (1)$$

where $\bar{V}$ – velocity vector; $\bar{F}$ – body forces vector; ρ – ambient density; t – time.

Tensor of stress:

$$T\begin{pmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{pmatrix} . \qquad (2)$$

To close the mathematical model o equations of momentum it is necessary to add the continuity equation. Coal-water fuel can be considered as an incompressible fluid [1, 2, 10, 15], then we have

$$div\bar{V} = 0 , \qquad (3)$$

Or

$$\frac{\partial V_1}{\partial x_1} + \frac{\partial V_2}{\partial x_2} + \frac{\partial V_3}{\partial x_3} = 0 . \qquad (4)$$

We put the theorem on the change in the principal vector of the system momentum, taking into account the averaging and omitting the averaging signs in the future:

$$\begin{cases} \frac{\partial \bar{V}}{\partial t} + \left(\bar{V} \cdot \bar{\nabla}\right)\bar{V} = \bar{F} - \frac{1}{\rho}\overline{grad\, p} + \frac{1}{\rho}\overline{Div\left(T_M + T_T\right)}; \\ div\bar{V} = 0. \end{cases} , \qquad (5)$$

where T_M and T_T – molecular and turbulent components of the viscous stresses tensor.

The values of the molecular components of the stress tensor are determined according to the rheological model of the visco-plastic fluid [4, 7, 11]:

$$T_M = 2\left(\eta + \frac{\tau_0}{\mathrm{H}}\right)S , \qquad (6)$$

The system of equations (5) is unclosed since the connection between the turbulent constituents of the stress tensor T_T with the parameters of the averaged flow is unknown and it should be determined by means of additional correlations, that is, model of turbulence. One of the best models of turbulence to calculate most of the flows, including the Newtonian ones, is considered to be the Menter’s model (SST) [18-20]:

$$T_T = 2\mu_t S + \frac{2}{3}kE , \qquad (7)$$

where μ_t – eddy viscosity; k – turbulence kinetic energy.

The above equations are common in calculating turbulent flow. If the flow is laminar, then these equations are greatly simplified and there is no need to calculate pulsating component or use of turbulence models.

The averaged turbulence characteristics are related to the turbulent viscosity of the following equation [19]:

$$\nu_T = \frac{a_1 k}{\max\left(a_1\omega, \Omega F_2\right)} , \qquad (8)$$

where k – kinetic turbulence energy; $a_1 = 0{,}31$ – empirical coefficient; ω – specific (per unit volume) dissipation rate; Ω – absolute magnitude of vorticity; F_2 – mixing function:

$$F_2 = \tanh\left[\left[\max\left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2\omega}\right)\right]^2\right], \qquad (9)$$

where y – distance from the wall; β^* – constant equal to 0,075.

In this work mathematical modeling was performed at such values of the model constants: $\sigma_{k1} = 0{,}85$; $\sigma_{k2} = 1$; $\sigma_{\omega 1} = 0{,}5$;

$\sigma_{\omega 2}=0{,}856$; $\alpha_1=5/9$; $\alpha_2=0{,}44$; $\beta_1=3/40$; $\beta_2=0{,}0828$, caused by equation $\phi=\phi_1 F_1+\phi_2\left(1-F_1\right)$ [19].

The advantages of this model of turbulence are the insensitivity to the boundary conditions in the external flow and the influence of the turbulence structure on the side of the fluid layers located upstream [16-20].

Parameters τ_0, η – initial shear stress and structural viscosity were programmed on the basis of experimental studies on the rheological parameters of coal-water fuel.

Universal "hard" boundary conditions that allow you to calculate the flow field were applied.

On the solid walls, taking into account the adhesion of the liquid, the following boundary condition was taken: $\bar{V}\big|_b=0$. At the inlet of the channel, the input speed was set as: $V\big|_b=V_{\text{in}}$. In the outlet section of the channel, the static pressure is zero: $p\big|_b=0$.

For the characteristics of turbulence on the solid surface, the following boundary conditions are taken [19]. Equal zero flow of turbulence kinetic energy: $Fk=0$.

The specific velocity of turbulence energy dissipation on a solid wall was calculated from the dependence [19]:

$$\omega=10\frac{6\nu}{\beta_1\left(\Delta y\right)^2}, \tag{10}$$

where Δy – adjoining step adjoining step.

In the inlet section of the channel, the specific dissipation velocity was calculated from the dependence:

$$\omega_\infty=\left(1\rightarrow 10\right)\frac{V}{L_\infty}, \tag{11}$$

where L_∞ – approximate length of the calculated area.

In the inlet section, the kinetic turbulence energy was calculated on the basis of vortex viscosity:

$$k_\infty=\nu_{t\infty}\omega_\infty, \tag{12}$$

where $\nu_{t\infty}=10^{-(2\rightarrow 5)}\nu$ – vortex viscosity in the inlet section.

For the best solution of small details of the geometry of the computational domain and in the region of high gradients parameters of the calculated variables, an adaptive locally refined grid is used. The approximation of the calculated variable is performed as a reconstruction scheme, has an advanced order of accuracy [21].

The calculation of coal-water fuel flow through the channel on the proposed mathematical model takes a long time, which is about 3 hours when a medium-power personal computer is used (CPU 5200 MHz, RAM 8192 Mb), which indicated the complexity of the processes described by it and the need to use powerful computer technology for calculating the flow, especially with the complex elements of the narrowing of flows or curves.

4. Experimental Setup and Dataset

Using the above mathematical model and numerical means of calculation is possible only with specialized software due to the complexity of the computational procedures exclusively by the computer means. Today, there are quite a lot of software products able to calculate liquid and gas flows: OpenFoam, Ansys Fluent, Cosmos FlowWorks, Ansys CFX, FlowVision and many others. Some of these packages are exclusively commercial, some, such as OpenFoam, is non-profit with the option to work under a license GPL, which allows them to make the necessary changes (adjusting mathematical models) without losing the license, and hence the right to use (including commercial ones). In this paper, the mathematical modeling is conducted in the software complex AnsysCFX under the student license.

For the numerical calculations verification the experimental research of the coal-water fuel flow by the direct pipeline were made and pressure loss is found to realize a predetermined flow velocity or slurry velocity. The installation for the physical research included measuring equipment with the accuracy sufficient for the verification of calculations, and then to test the adequacy. The maximum error in determination of the pressure losses did not exceed 1%. For numerical calculations, a three-dimensional model of the test bench with all sizes was constructed (Figure 1).

In most calculations, the grid consisted of 0.5 million elements, and was constructed in such a way as to provide the parameter Y+<2. The calculations were made in a stationary setting.

Fig. 1: Three-dimensional model of experimental installation

Figure 2 shows a grid split on the hexagonal elements of the pipe model, in which the loss of pressure was modeled. To determine the required number of elements, four calculation options were performed with the following amount of the elements with elements: 100 thousand, 250 thousand, 400 thousand and 500 thousand. It was found that with the number of elements more than 400 thousand the results practically cease to change, which proves the sufficiency of the next use for this task of a grid of 500 thousand elements. The boundary layer was provided with 15 elements.

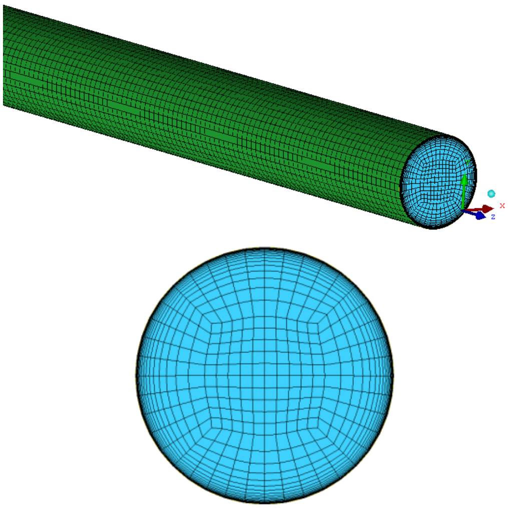

Fig. 2: Grid split of the pipeline geometric model

The results of the calculation by the mathematical model are compared with the results of the experimental studies. Maximum error of calculation was 4.7%, which confirms the possibility of using the above mathematical model in further research.

According to the comparison of the calculation accuracy it does not really matter which model to choose for the calculation: Laminar or Menter's model, but with regard to the universality of using the model, the model SST is more versatile and can be used for any kinds of currents. Comparison of the calculation of the velocity profile by the Laminar model and SST-model is shown in Figure 3. It attributed the speed to maximum speed at the axis, designed for Newtonian fluids.

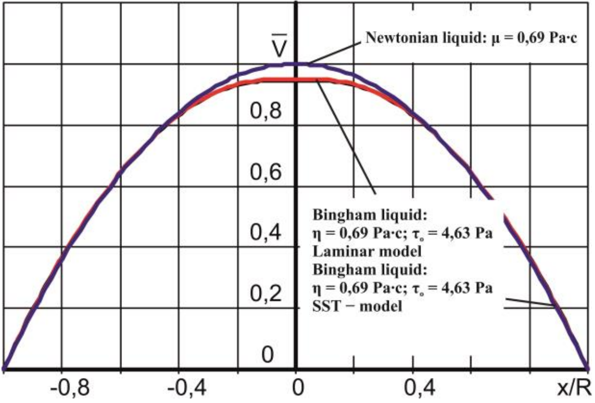

Fig. 3: Comparison of velocity profiles in the calculation with the different models (Re=30)

If the average velocity of the fluid flow reaches the values at which the Reynolds number will reach critical values and there will be a transition to a turbulent flow calculation model should be chosen SST model, but even at lower velocity, with Re<30, the use of the SST model almost does not lead to significant errors, in addition, the velocity profiles for the laminar model and the SST model almost coincide.

To find the optimal values of the initial shear stress and structural viscosity, a numerical experiment was conducted on the basis of experiment planning methods in order to reduce pressure loss. For conducting a numerical experiment, factors were chosen which can significantly affect the pressure loss during the transportation of the coal-water fuel (τ_0, η). Other geometric and mode flow parameters did not varied (D=50 mm, ρ=1262 kg/m^3, V=0.5 m/c, c=60%). With the prior information about the characteristics of the coal-water fuel flow, the value of the factors is determined, at which the results are close to optimal. These points were considered when planning as a zero (basic) level – τ_0=3 Pa, η=0.55 Pa·c. [21, 26, 27, 28].

As a result, the planning matrix was obtained (Table 1), which contains nine experimental points. The estimated pressure loss depending on the rheological parameters of the coal-water fuel is shown in Figure 4. The planning pressure loss was selected as the objective function.

In accordance with the planning matrix, numerical experiments were conducted by the mathematical model (Experiments 1 to 9), substituting the appropriate values into it $\eta(x_1)$ and $\tau_0(x_2)$ according to Table 1

Table 1: Experiment planning matrix

Experiment #	x_1	x_2	x_1x_2	x_1^2	x_2^2	Δp
1	-1	-1	1	1	1	10740
2	-1	1	-1	1	1	11940
3	1	-1	-1	1	1	18100
4	1	1	1	1	1	19335
5	-1.41	0	0	2	0	9810
6	1.41	0	0	2	0	20200
7	0	-1.41	0	0	2	14150
8	0	1.41	0	0	2	15900
9	0	0	0	0	0	15000

We approximate the loss of pressure by the quadratic polynomials, using the Padé method of approximation [22]. In this case, the regression equation has the form:

$$y = a_o + a_1x_1 + a_{11}x_1^2 + a_{22}x_2^2 + a_{12}x_1x_2 \qquad (13)$$

Taking into account the Cochran criteria the significance of the coefficients was determined and the values of the ordinates of characteristics were found

$$\begin{aligned} y_{on} &= 15000 + 3690x_1 + 615x_2 + \\ &+ 5{,}47x_1^2 + 16{,}3x_2^2 + 8{,}75x_1x_2 \end{aligned} \qquad (14)$$

After replacing the encoded values with the real ones, the response surface can be calculated as follows:

$$\Delta p = 442 + 24200\eta + 345\tau_0 + 243\eta^2 + 7{,}2\tau_0^2 + 39\eta\tau_0 \qquad (15)$$

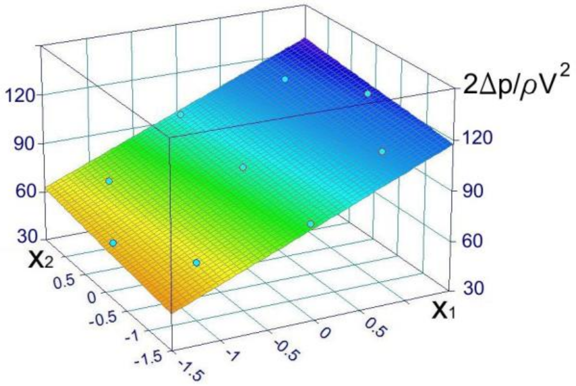

Fig. 4: The pressure loss depending on the rheological parameters of the coal-water fuel

As it can be seen from the Figure 4, the surface that corresponds to the coefficient of pressure loss looks almost flat. That is, with an increase in the initial shear stress and structural viscosity the coefficient of pressure loss increases in the range of Reynolds numbers Re<50. At laminar flow and the considered values of the factors of the minimum the response function was not found.

5. Results and Discussion

In curved pipes and channels (angle bends, leadaways) due to the curvature of the flow there are centrifugal forces, directed from the center of curvature to the outer wall of the pipe. This causes an increase in pressure at the outer wall and its decrease at the internal one during the transition of the flow from the rectilinear section of the pipeline to the curved. Leadaways imply decimal curved sections, in which with equal input and output sections of curvature of both walls (external and internal) are arcs of concentric circles [15]. When designing and optimizing the flow of the coal-water fuel it is essential to know the value of pressure loss at bends in leadaways with a radius of curvature of different values. Figure 5-7 shows the results of calculating the coal-water fuel flow with different radius of curvature.

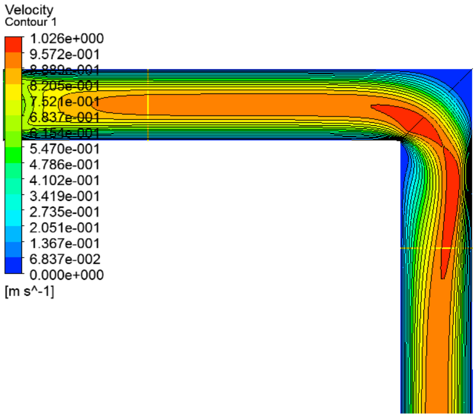

Fig. 5: The distribution of velocity of the coal water fuel during the rotation on 90° with a curvature radius $\bar{R}=0$, $\mathrm{Re}=30$

The radius is related to the diameter of the pipeline. All three drawings illustrate fluid flow calculations at an average speed of 0.5 m/s and with rheological parameters: η=0.68 Pa·c, τ_0=4.49 Pa.

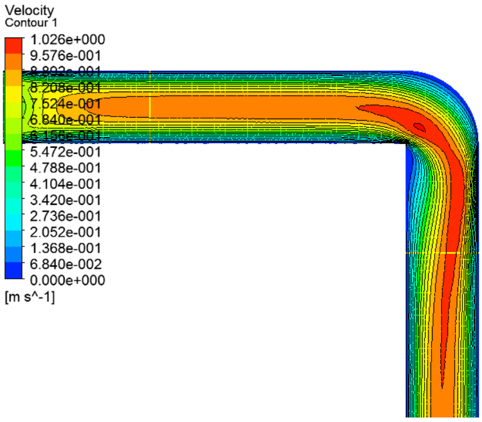

Fig. 6: Distribution of the flow velocity of the coal-water fuel during the rotation on 90° with a curvature radius $\bar{R}=0{,}5$, $\mathrm{Re}=30$

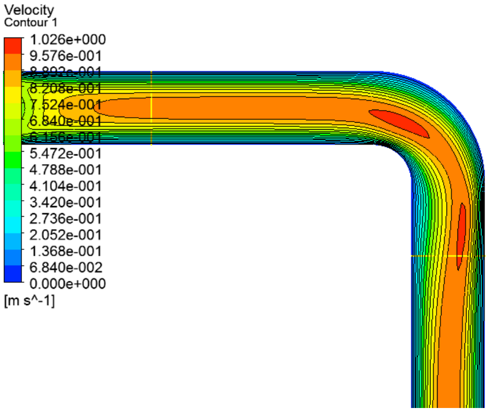

Fig. 7: Distribution of the flow velocity of the coal-water fuel during the rotation on 90° with a curvature radius $\bar{R}=1{,}0$, $\mathrm{Re}=30$

According to the calculations, the lowest pressure losses were obtained for rotation with a curvature radius $\bar{R}=1{,}0$. With increasing Reynolds numbers flow separation is observed after rotation, and an increase in the coefficient of hydraulic resistance.

6. Conclusion

According to the results of theoretical research on the motion of the coal-water fuel, taking into account the parameters of bimodality and granulometric composition the following conclusions could be drawn.

The results of numerical calculations qualitatively coincide with the analytical description of the Bingham flow and with the results of experimental studies. Using the model without taking into account the rheological law is inadmissible, because the error in calculating the velocity profile reaches values of almost 40% during the calculation of the fluid flow with the numbers Re<5. According to the comparison of the calculation accuracy it does not matter which model to choose to calculate: Laminar or SST model, but with regard to the universality of using the model, the SST model is more versatile and it can be used for any kind of flows (Laminar or turbulent). The least error is the calculations of the flow with numbers, that is, the greater the velocity of the Bingham's fluid flow and the Reynolds number, the less error of calculation by SST-model turbulence. In general, the error does not exceed 20%, but with increasing numbers Re>30 is 0.5%, which is an acceptable result, and suggests that in the future the software package Ansys CFX and SST-model can be used during the calculations of the coal-water fuel flow.

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