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Flow in the main pipeline of the water-coal mixture

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Summary. Results of analytical research of water-coal mixture flow in the main pipeline are presented. It's received by the mathematical model solution of non-Newtonian liquid movement. The mathematical model considers effective viscosity, density and the module of elasticity of a mixture for pseudo-plastic reological model. Dependences of pressure and discharge change in various pipeline sections are received.

Key words: unsteady flow, water-coal mixture, mathematical model, hydrodynamic processes, long pipeline.

INTRODUCTION

Mathematical model's adequacy of hydraulic transport of the water-coal fuel (WCF) [9] depends on completeness of the description of hydrodynamic processes [12] in each of these elements [15]. In presented paper the results of research of non-Newtonian liquid flow are given for the long pipeline (the long pipeline is the pipeline, length of which is much bigger than length of a pressure wave, caused by operation of the piston pump[16]. In presented model reological characteristics of transported liquid, its compressibility and some other parameters are considered, oppose to the previous researches [18].

The method of mathematical simulation is used as the main research instrument, considering complexity and laboriousness of carrying out physical experiment [13].

OBJECTS AND PROBLEMS

Water-coal fuel represents rather stable mixture of water with fine-grinded coal (class S particles=0,05-0,25 mm) [19], which flow is alike movement of homogeneous liquid [5] with the increased density [9].

To describe the unsteady WCF flow the one-dimensional mathematical model of movement [4] is accepted, as diameter of the pipeline is much less than its length [20]:

$$\rho_{\text{см}}\frac{\partial V}{\partial t}+\rho_{\text{см}}V\frac{\partial V}{\partial x}=-\frac{\partial p}{\partial x}-\frac{2\tau_{\text{н}}}{R}, \tag{1}$$

and continuity of a flow [21]:

$$\frac{\partial p}{\partial t}+V\frac{\partial p}{\partial x}=-E_{\text{см}}\frac{\partial V}{\partial x}. \tag{2}$$

In these expressions:

V and p are average by cross-section flow values of liquid speed and pressure,

ρ_{cm} and E_{cm} are density and the volume module of elasticity of water-coal fuel,

R is pipeline radius,

τ_N is tangential stress on a wall,

t, x are current coordinates of time and length of the pipeline.

Water-coal mixtures are described by various reological models depending on physical properties [3]. To choose concrete model you have to define experimentally dependences of tangential stresses τ from shear rate γ [8]. We accept pseudo-plastic reological model, as water-coal fuels are transported by coal pipes. It is described by the equation [9]:

$$\tau = k\dot{\gamma}^{n},$$

where: *k* and *n* are experimental factors of model.

The Reynolds's number [1] defines the mode of liquid flow and the value of hydraulic friction factor. For our flow model is defined by expression [2]:

$$\mathrm{Re} = \frac{8V^{2-n}\left(2R\right)^{n}\rho_{см}}{k\left(6+\frac{2}{n}\right)^{n}},$$

and effective (conditional) viscosity [3]:

$$\mu_{ef} = \frac{\left(2R\right)^{1-n}k\left(6+\frac{2}{n}\right)^{n}}{8V^{1-n}}. \qquad (3)$$

Unsteady flow of water-coal fuel with insignificant variations of speed around average value is characteristic at operation of the multicylinder pump on a network equipped with the pneumatichydraulic accumulator. In this case it is possible to accept size of effective viscosity constant and equal μ_{ef} = 0, 85 Pas [2] according to experimental data [10].

Quasistationary value [4] of tangential stress in a laminar stream of WCF is proportional to speed of mixture movement [5]:

$$\tau_{н}^{кв} = \frac{4\mu_{э}}{R}V.$$

The rheological properties of coal oil/coal water mixtures play a vital role in their storage, transportation, atomisation and combustion. Therefore it is important to establish a criteria tor controlling their rheological properties so as to obtain highly loaded mixtures with acceptable fluidity while maintaining sufficient stability against sedimentation of particles.

There is a voluminous literature available on rheology of coal oil mixtures but there is limited work done on the effect of coal particle size distribution on rheology of coal oil mixtures. However, a few references are available on the effect of coal particle size distribution on rheological properties of coal water mixtures. The viscosity of the slurry was found to be minimum when htrcent by weight of fines was 25-30% of the total weight. The decrease in viscosity was attributed to the lubricating effect of smaller particles in the gaps between the bigger particles. Three parameters signifying the effects of particle size distribution were used to predict the shear viscosity of suspensions.

Data on the effect of particle size distribution on viscosity of coal oil mixture is very limited. Therefore this study aims to understand how coal particle size distribution influences the viscosity of coal oil mixtures.

Eight coal samples of different composition have been selected for the present study. The proximate analysis and other relevant information is given in Table 1.

Table 1. Proximate Analysis and other Details of Coal Samples

№	Coal, gm/cc	Sample Density	Moisture, %	Ash, %	Volaile Matter	Fixed Carbon, %
I	5.0	8	31	56	2,00	1.32
II	5.5	10.0	31.5	53	1.80	1.35
III	5.62	11.40	32,00	50.98	1.77	1.36
IV	6.9	13.0	29,82	50.28	1.74	1.38
V	6. 72	14.5	31.0	47.78	1.63	1.3
VI	6.10	16.0	27.40	50.5	1.60	1.41
VII	5.80	24.5	29.20	40. 5	1 .50	1.49
VIII	5.4	20.0	30.0	44.6	-	1,42

Viscosity of oil at 35°C = 680 m Pa.s,
40°C = 450 m Pa.s,
45°C = 340 m Pa.s,
Specific Gravity = 0.98/

The first seven samples have been used to study how the composition affects its size distribution which in turn influences the viscosity of coal oil mixtures (COMsb The initial size of samples was 90% between 16 and 20 Taylor mesh and 100% less than H inch. Each of these samples has been ground in a ball mill for one hour and particle size distributions have been found out by using sieves and Warman Cyclosizer for sub-sieve particles. The top size of these samples varied between 211 and 85 microns. The data has been fitted into Rosin-Rammler equation to represent size distributions. The Rosin-Rammler equation is given below:

$$\frac{R}{100} = e^{-\left(\frac{\chi}{k}\right)^n},$$

where: R is cumulative weight % of coal retained on the screen,

χ is weighted mean diameter of particles retained on the screen,

n is distribution modulus,

k is size modulus.

The values of ‘n’ for the first seven samples have been given in Table-1

The VIHth Coal sample has been used to prepare two sets of samples. In the first set the parameter ‘κ’ in Rosin-Rammler equation maintained constant and 'n' is varied. In the second set vice-versa. This has been done to find out how individually 'n' and 'k' affect the viscosity of coal oil mixtures. Six more samples have been prepared using VIHth coal sample to find out how the fines and maximum packing fraction affect the viscosity of COMs.

The viscosity of COMs has been measured by using Brookfield synchro- lectric viscometer (Model RVT). For determination of viscosity the coal oil mixture has been taken in stainless steel jacketed vessel whose dimensions are: inner diameter = 110 mm: outer diameter = 120 mm, height = 150 mm. Thermostated water is circulated through the jacket to maintain required temperature of COM. All the viscosity measurements have been done at 10 rpm.

All the coal samples selected for the study as can be seen from Table-I, belong to sub-bituminous rank. The ash content of these coal samples varies between 8 and 24 percent. These coal samples have been selected in such a way that their daf volatile matter and fixed carbon, varied within narrow limits. This is done to minimize the effect of these components on grindability and size distribution of coal. Only the mineral matter content is expected to influence grindability thereby the particle size distributions of these samples. It can be seen from the Table-I that as the ash content of the coal increases the distribution modulus 'n1 decreases indicating wider size distribution of the coal sample. Though the size modulus of these samples varied but it did not show any definite trend with respect to ash content of the coal.

The viscosity of coal oil mixtures has been measured at five different coal volume fractions ranging from 25 to 45%. For clarity sake the results of only four coals are presented here. It was estimated that viscosity increases as coal volume fraction in COM increases, higher values of viscosities are observed at higher 'n' values. For the coals of the same rank, as the ash content increases the grindability decreases, therefore coals with higher mineral matter content when ground for same duration of time may give particles of broader size distribution. This is reflected in the smaller 'n' values for coals having high ash content indicating broader particle size distribution. A broader size distribution would normally lead to higher maximum packing fractions, which in turn results in higher relative mobility of coal particles in the coal oil mixture. Consequently COMs of broader coal particle size distributions will have lower viscosities. The reason for samples of broader particle size distributions giving rise to higher maximum packing fractions is that the smaller particles may enter the gaps between the bigger particles thereby apparently not occupying any space. The smaller particle entering the bigger particles may even act as lubricant resulting in lower values of slurry viscosity. Viscosity of coal oil mixture increases as coal concentration increases because of increased inter particle friction. Above 40% coal concentration the increase in viscosity is very steep.

In the second set of experiments coal oil mixtures have been prepared by using VIIlth coal sample. In the first group of experiments the 'n' in Rosin-Rammler equation varied between 1.2 and 2.0 at κ = 65 um. It was found that the viscosity of COM does not very much with 'n' if κ is kept constant. Unlike the previous case where the top size of particles in samples varied, here the top size of particles in all samples remained constant. Only the distribution is varied. Apparently within the range of 'n' values studied there is not much variation in maximum packing fraction therefore there is no variation in the viscosity of COM. It was also shown viscosity values of COM at different 'k' values. The viscosity decreases as the 'k' value increases. The same trend has been observed at both 25 and 30% coal concentrations. As the 'k' value of the sample increases its coarseness increases therefore the specific surface area decreases resulting in lower values of viscosity of COM.

Finally six more samples have been prepared using the VHIth coal sample. The particle size distributions of these samples have been given in Fig.6. The average particle size of these samples varied bet-ween 127.5 and 18.5 microns. In this case it is not possible to represent the data by Rosin- Rammler equation. For the six samples the maximum packing fractions have been calculated using the formula given by Patton which is given below:

$$\left(\varphi_m\right)_i = \sum_{i=1}^{nf} \sum_{j=1}^{nf} \Phi_{ij}\varphi_j ,$$

where: *nf* – is the number of size fractions φ_j refer to respective volume,

fractions $\Phi_{ii} = \Phi_{jj} = 0.639$ and Φ_{ij} represent coefficients to be used *ii ij,* in relating to larger particle group to a smaller and vice-versa. The value Φ_{ij} is given by:

$$\Phi_{ij} = 0.639 \pm \left(\frac{\varphi_{mo} - 0.639}{1.15 - 1.017\varphi_{mo}} \right),$$

where: φ is the maximum packing concentration for binary mixtures.

In the aSove equation positive sign applies when a coarse size fraction is blended with a finer size fraction and the negative sign applies otherwise.

The smallest of (Φ_{ij} ф). values is taken as maximum packing fraction for the sample. The necessary data is taken from reference [21]. Consequently the COM of sample I has less viscosity than COM of sample II. At all three concentrations studied it is observed the viscosity of COM is minimum when fines content is around 20-25%. The same trend has been observed at all the three concentrations studied. The reason for smaller values of viscosity when fines content is around 20-25% may be due to maximum packing fraction effect as well as lubricating effect of fines as mentioned earlier. But as the fines content in the sample increases the viscosity of COM increases because of increased specific surface area which results in higher inter particle friction leading to tighter viscosities.

The following conclusions can be drawn from the present study:

COM of broader coal particle size distributions have smaller values of viscosity. The composition of coal influences its particle size distribution.

Maximum packing fraction of coal sample influences the viscosity coal oil mixtures. Higher the maximum packing fraction of the coal sample smaller will be the viscosity of COM.

Density and volume module of elasticity of mixture [6]:

$$\rho_{cm} = \frac{\rho_m \rho_b}{\rho_m + k_m\left(\rho_b - \rho_m\right)}, \tag{4}$$

$$E_{cm} = \frac{E_b E_m \left[\rho_m + k_m\left(\rho_b - \rho_m\right)\right]}{\rho_m E_m + k_m\left(\rho_b E_b - \rho_m E_m\right)}, \tag{5}$$

where: E_b, E_m are volume modules of elasticity of water and of solid phase in a mixture [7],

ρ_{in}, ρ_m are densities of water and solid phase,

k_m is mass concentration of solid phase in mixture.

We receive system of the differential equations in total derivatives for each *i* point of a set *N* of splittings on length of the pipeline, replacing in the equations (1) and (2) partial derivatives on length of the pipeline with finite-difference analogs:

$$\left.\frac{dV}{dt}\right|_i = \frac{1}{\rho_{cm}}\left(\frac{8\mu_e}{R^2}V_i + \frac{p_i - p_{i-1}}{\Delta x}\right) - \frac{V_i^2 - V_{i-1}^2}{2\Delta x}, \quad (6)$$

$$\left.\frac{dp}{dt}\right|_{i-1} = -\frac{V_i + V_{i-1}}{2}\frac{p_i - p_{i-1}}{\Delta x} - E_{cm}\frac{V_i - V_{i-1}}{\Delta x}. \quad (7)$$

Flow speed at the beginning of the pipeline $V = V\ (0,\ t)$ is necessary boundary condition for mathematical model integration. It is defined by work of the pump and pressure at the end of the pipeline $p = \mathrm{p}\ (l,\ t)$, where l is length of the pipeline.

The system of differential equations (6)...(7) and equations (4)...(5) was numerically integrated by Runge-Kutta's method with Merson's criterion. Adequacy of the accepted model and method of integration was estimated by comparison experimental data provided in literature with data received on model, modified for this case.

Installation consisted of pipeline diameter of 25,4 mm and length of 36 m. The line was joint to a tank in which constant pressure was maintained. Pressure sensors were installed on the pipeline, its transfered directly to the computer through analog-digital convertor (ADC).

ADC has analog inputs to connect the signals sources and digital outputs to transmit transformed data to the computer. The computer with special software manages ADC devices and accepts data for consequent processing and analysis.

The measuring system is constructed on the basis of the personal computer, it consists of three basic elements: signal sources, ADC system and software [11].

Unsteady pressure measurement was carried out by means of inductive sensors of the pressure signal of which was amplified and transformed by the amplifier. Thereby, pressure change was transformed to proportional signal in the form of tension of direct electric current which was signaled on ADC input.

There is large number of ADC varieties. However all ADC devices have common parameters, it allows creating universal system of data collection from analog-digital devices.

The software is very important in the course of registration and data collection as the software defines final quality and computer system efficiency. In experiments the adapted PowerGraph system, which allows connecting practically any analog-digital converters, was used. It gives advantages to software users: first of all, it is large choice of system hardware (from simple and cheap measuring devices to complex and expensive research installations), secondly, all this variety is uniform universal system.

Satisfacting speed coincidence of pressure waves distribution, frequency of own fluctuations and extent pressure waves attenuation is received.

Let's note that adequacy was defined by comparison of transients in system (reaction to abrupt liquid speed change). The gradient of speed and pressure in this case is much higher, than at liquid flow in main pipeline therefore the offered mathematical model of non-Newtonian liquid flow will describe obviously adequately hydrodynamic processes in the real pipeline [11].

The developed mathematical model of WCF flow in main coal pipeline was used for determination of regularities of water-coal mixture flow in the pipeline diameter of 0.5 m and length of 20 km at average speed of movement V_{cp} = 0.1-0.7 m/s that is characteristic for industrial coal pipelines.

Pulsing nature of speed change of water-coal mixture in inlet section (main pump outlet) and active loading in the form of throttle in outlet section (it is caused by system of latches on inlet in transitional pump station existence) are accepted as boundary conditions [17].

Diagrams of pressure change in various sections of the pipeline are shown on Fig. The oscillation amplitude of pressure in inlet section of the pipeline is defined by discharge pulsations on pump outlet. The amplitude is practically constant and is not influenced by reflected waves because of big extent of the main pipeline. The oscillation amplitude of pressure changes due to superposition of direct and reflected pressure waves reducting the length of pipeline to 2-3 km [14].

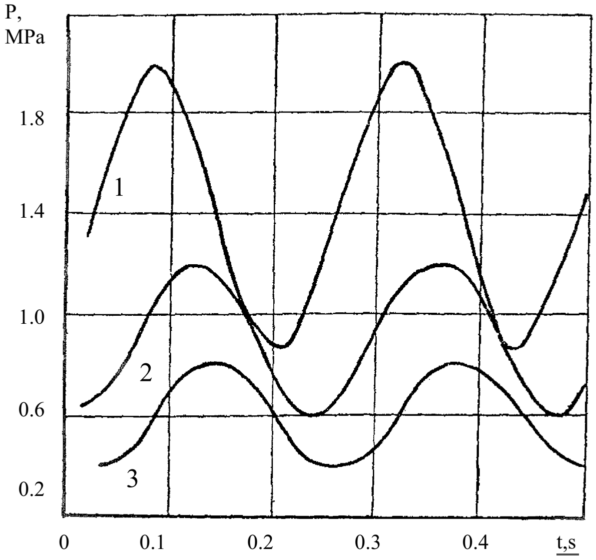

Fig. Pressure change in the main pipeline

Curve *2* and 3 (Fig.) show pressure change in pipeline sections at distance 6 and 9 km from initial pipeline section accordingly. Apparently, there is intensive damping, and practically, through 8-9 km of pressure pulsation wave processes completely decline.

The degree of pressure change damping of water-coal mixture depends on hydraulic friction factor and the WCF viscous properties. The frequency of pulsations is increasing and resistance factor is increasing as well, that leads to strengthening of damping degree.

CONCLUSIONS

1. We observe considerable divergences between data of physical and numerical experiment in a zone of the lowered pressure, when modeling the unstationary processes, which are accompanied with pressure decline below the atmospheric.
2. The possible reason of such a mismatch can be influence of undissolved air in working liquid, processes of allocation and dissolution of gas on value of elasticity volume module.
3. It is necessary to supplement the system of equations (4)...(7) with equations of gas diffusion from bubbles to liquid and equations of movement of walls of gas bubbles in that case.

REFERENCES

1. **Andriychuk N. D., 2012.:** Compressibility of water coal suspensions for hydrotransport Systems / Andriychuk N. D., Pilavoa of M of Century, Gusentsov Y.A.//«NOVYNY ON NAUCHNY PROGRESS-2012», Tom 8, 2012, Sofia: "BYALGRAD-BG" OOD, 3-7. (in Russian).
2. **Andriychuk N. D., 2013.:** Hydraulic systems for WCF: modeling, optimization/N D. Andriychuk, M. V. Pilavov, A.A.Kovalenko. – Lugansk: VNU publishing house of V. Dahl, 2013. – 239. (in Russian).
3. **Baranov S.N., 1991.:** Chemistry and Physics of Coal: Sb. nauch. tr./ USSR AN.: S.N.Baranov. – Kiev: Sciences, 1991. – 112. (in Russian).
4. **Chernetsky N.B., 2007:** Issledovaniye of reologichesky characteristics of the water coal fuel created on the basis of coals of Donbass / N by B. Chernetsky, A.M.Shvornikova, E.A.Varakuta, N.I.Bragin //Visnik of V. Dahl's National Unsversity. – 2007. – No. 3 (109) of h. 2. – 213. (in Russian).
5. **D.Shilling, B. Bonn, U.Kraus., 1986.:** Coal gasification: Mountain the business raw materials-energy / – M: Subsoil, 1986. 175. (in Russian).
6. **Damman W. A., 1992.:** Method and means of generating gas from water for use as a fuel//Pat. Number: 5,159,900, F02B 43/08, Date of Pat.: Nov. 3, 1992.
7. **Elizabeth Gusentsova., 2011.:** Error of Average Flow Measurement in Ventilation System Channels. Lublin/Elizabeth Gusentsova, Alim Kovalenko, Manolis Pilavov//TEKA, Tom XI A. – 2011. 99-107.
8. **Foret T., 2007.:** System method and apparatus for treating liquids with wave energy from plasma//Pub. No.: US 2007/0253874 A1, C02F 1/467 (2006.01), Pub. Date: Nov. 1, 2007.
9. **Forty S.I., 2001:** Reologys of liquid / Forty S.I. – Lugansk: VNU publishing house of V. Dahl, 2001. – 48. (Russian)
10. **Hodakov G. S., 2007.:** Water coal suspensions in power(power engineering specialist)//Power system. – 2007. – No. 1. 35-45. (in Russian).
11. **Kovalenko A.A., 2009.:** Calculation of viscosity of water coal fuel / A.A. Kovalenko, L.I.Risukhin, A.M.Shvornikova, E.S.Gusentsova // VNU publishing house of V. Dahl. Scintific magazine – electronic scientific

professional issue. – 2009. – No. 3E. (in Russian).

12. **Kuzmin V.I., Pashkov G.L., Kartsev N.V., Okhlopkov S.S., Kychkin V.R., Suleymanov A.M., 2005.:** Way of extraction of rare-earth metals and yttrium from coals and waste from their burning//the Patent RU2293134, 2005.05.26. (in Russian).
13. **Pilavov M. V., 2011.:** A current of viscous-plastic liquids in pipelines of hydrotransport systems /M. V. Pilavov, A.A.Kovalenko, D.A.Kapustin//V_snik National technical univercity «HP I» No. 33, 2011. – Kharkov: NTU «HP I». 252-256. (in Russian).
14. **Pilavov M. V., 2011.:** Complex hydraulic systems: modeling, optimization/ V. Pilavov, A.A.Kovalenko, G.V. Kalyuzhny. – Lugansk: VNU publishing house of V. Dahl, 2011. - 112. (in Russian).
15. **Rabovitser I.K., Nester S., Bryan B., 2006.:** Plasma assisted conversion of carbonaceous materials into synthesis gas//Pub. No.: US 2007/0186472 A1, B01J 19/08 (2006.01), Pub. Date: Aug. 16, 2007.
16. **Reddy G.V., 1989.:** Effect of coal partict size distribution on viscosity of coul oil micsture (COMs): Proceedings of the 14 innernational conference, Florida, USA. – 1989
17. **Shcherba A.A., Zakharchenko S.N., Solomentsev I.M., 2007.:** Efficiency of sewage treatment from organic pollution by electrophysical methods // Water i vodoochistka the technologist. – 2007. – No. 2. 38-42. (in Russian).
18. **Svinoroev Y., 2011.:** Application of complex power fuel made of coal-enterprises wastes production technology using new binding materials//TEKA, Tom XI A. – 2011. 258-266.
19. **Svytly Y.G., 2009:** Gdravlchny transport/ Yu.G.Svytly, – Donetsk: Vidavnichiya dim, Donetsk viddilennia NTSh, 2009. – 436. (in Russian).
20. **Zatsepin G. N., 1974.:** Properties and water structure. – Publishing house of the Moscow University, 1974. – 167. (in Russian).
21. **Zhukov M.F., Kalinenko R.A., Levitsky A.A., Polak H.P., 1990.:** Plasmochemical processing of coal. – M: Science, 1990. – 200. (in Russian).

ТЕЧНИЕ ВОДОУГОЛЬНОЙ СМЕСИ В МАГИСТРАЛЬНОМ ТРУБОПРОВОДЕ

Яна Гусенцова

Аннотация. Приведены результаты аналитического исследования течения водоугольной смеси в магистральном трубопроводе, полученные с помощью решения математической модели движения неньютоновской жидкости. Математическая модель учитывает эффективную вязкость, плотность и модуль упругости смеси для псевдопластичной реологической модели. Получены зависимости изменения давления и расхода в различных сечения: трубопровода.

Ключевые слова: неустановившееся течение, водоугольная смесь, математическая модель, гидродинамические процессы, длинный трубопровод