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PREDICTION OF FLOW PARAMETERS OF MIXTURES FOR FILLING OF CAVINGS IN THE LIGHT OF LABORATORY MEASUREMENTS

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Effective and safe filling of voids in longwall with the caving mining system requires careful selection of fill mixtures and correct prediction of flow parameters in hydraulic transport systems in coal mines. On the basis of laboratory test results a new method for calculation of flow parameters in the transient flow regime has been presented, which adopts a modified Blasius formula with respect to lower friction factor values than calculated with formulas for turbulent flow. Additionally, a new approach to the subject of optimization of fly ash - water mixtures composition has been proposed, which has been derived from the relation between the density of the mixture and specific head losses calculated for constant flow rate.

KEY WORDS: filling of cavings, fly ash – water mixtures, transient flow, flow measurements, rheological properties of mixtures.

1. INTRODUCTION

Longwall system with roof caving is the dominant mining system in Polish hard coal mines. A significant part of the currently selected seams contains coal with a high propensity for spontaneous combustion. In order to eliminate the endogenous fire hazard, filling of cavings with the fine-grained, solids-water mixture is used. In the aim to avoid creating of underground water reservoirs and risk of flooding of mine workings, the mixtures used for filling should stabilize and solidify. For this reason, fly ash from hard coal combustion is used as a fill material, mostly without any additives (binders) to minimize costs of these operations, (Palarski et al. 2011).

Calculation of the flow parameters supported by rotational viscometry analysis of rheological properties of mixtures is often subject to considerable errors, therefore there is a need to use more accurate methods, such as laboratory studies of pipeline models, as it is being practiced in some research institutions.

The maximal permissible density is based on the observation that actual hydraulic transport systems, which are in use in coal mines nowadays, do not operate on a full feeding mode basis as it was the case in traditional backfill pipelines. The pipelines operate frequently in a partial feeding mode, in which pipelines are not fully filled up with a mixture during its flow. This situation creates an opportunity to increase the density of the mixture, which in turn generates a higher head loss, and consequently moves the operation mode toward a full feeding mode. From the other side, changing of mixture's density and apparent height of free mixture level in a vertical part of the pipeline (generally

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in the mine shaft, in which the pipeline is installed) leads to a variable range of horizontal distance, at which the fly ash – water mixture may be transported with satisfactory flow rate. In the aim of efficient and safe modification of this parameter, the rheological characteristic of the mixture must be known in a wide range of density.

2. MATERIALS AND METHODS

Mixtures of fly ash from coal combustion with by-products of semi-dry desulphurization processes and fresh water have been used for the tests conducted by Strozik (2018). Its apparent density was 2118 kg/m^3. In terms of particle-size distribution, 99.53% of the fly ash mass contains grains smaller than 0.1 mm, d_{50} = 0.04 mm Selected fly ash represents a typical example of an industrial waste widely used in Polish coal mines for the filling of cavings.

Range of mixture densities used in tests ranged from 1105 kg/m^3 up to 1605 kg/m^3, however interesting from the point of the view of mining practice, are in the first place the mixtures of densities closer to the upper limit of the considered range, which exhibit properties of non-Newtonian fluids. Analysis of flow parameters has shown that such properties possessed samples of mixtures with a density of 1447 kg/m^3 and larger. General parameters of tested mixtures of this group are presented in Table 1.

Table 1

General parameters of fine-grained mixtures used in laboratory tests in the range of non-Newtonian rheological characteristics

Number of mixture	Density ρm [kg/m^3]	Volume Concentration C_v [%]	Mass Concentration C_m [%]	Proportion W/S [-]	Amount of solids[1] u_{cs} [kg/m^3]
1[2]	1447	0.400	0.585	0.709	846.8
2	1486	0.435	0.620	0.614	920.1
3	1529	0.473	0.655	0.526	100.,2
4	1559	0.500	0.679	0.472	1059.0
5[3]	1605	0.541	0.714	0.400	1146.1

[1] mass of fly ash per 1 m^3 of mixture
[2] flow only in turbulent regime registered
[3] flow only in laminar regime registered

Research has been conducted in a laboratory facility equipped with a pipeline of diameter D = 0.08 m, operating in a closed circuit. The electronically controlled pump allowed for maximal flow velocity varying from around 3.5 m/s up to 6.0 m/s in relation to its rheological parameters. Pressure difference has been measured on a distance of 2.0 m located in the middle of 6.0 m long straight part of the pipeline to eliminate distractions resulted from piping curvatures. Measurements of the head loss have been taken after 15-25 minutes of flowing in the circuit, what is an adequate time of flow in a mine pipeline of round 5000 m length. In conditions of mine mixture preparation plants, saline water (industrial water) is used instead of fresh water, however, the difference in viscosity is negligible when the overall accuracy of the measurements is considered. The effect of the temperature of the mixture was corrected in the phase of determining the viscosity, taking as the reference the temperature of 20 °C.

3. RESULTS AND ANALYSIS

The results of the measurements of fly ash – water slurries described in Table 1 are presented graphically in Figure 1.

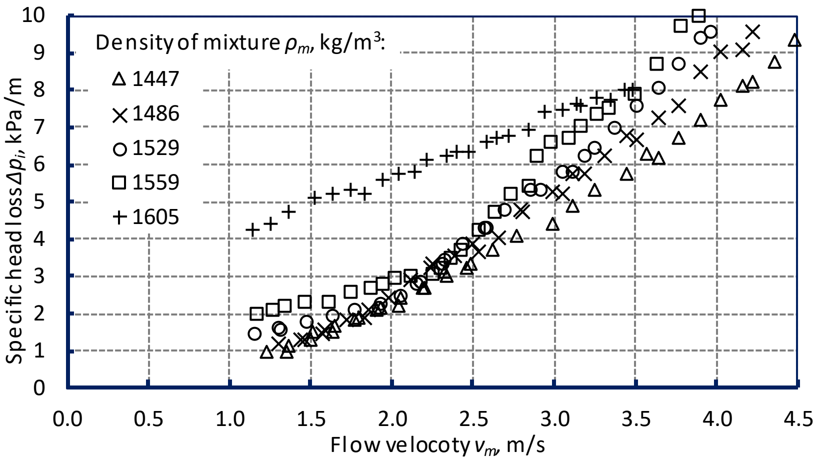

Figure 1. Results of specific head loss measurement in the function of flow velocity for mixtures with a density from 1447 kg/m^3 to 1605 kg/m^3

Analysis of grain-size distribution and particle fall velocity (sedimentation) has shown that mixtures of water and fly ash used in test flows in the pipeline facility may be considered as quasi-homogeneous, thus the application of theory and of actual liquids may be adopted.

The pressure head loss Δp that occurs during the flow of a mixture with an average speed v_m in a pipeline of diameter D and length L, has been described by well-known Darcy-Weisbach equation in the form:

$$\Delta p = \lambda \frac{L}{D} \frac{\rho_m v_m^2}{2} \tag{1}$$

where λ is the flow friction factor, which depends on Reynolds number Re, thus, it is variable dependent on the mixture's density and flow velocity.

In the analysis of pressure drop during flow, it is more convenient to use specific head loss, which is the ratio of total pressure drop along the pipeline to its length $\Delta p_i = \Delta p/L$.

Taking under consideration that both geometrical parameters of a pipeline and properties of a mixture represented by its density and viscosity are known, and also assuming that the local head losses (like turns or tees) may be ignored as insignificant in comparison to the linear friction in long pipelines, the only parameter, which makes the flow rate dependent on the head loss is the flow friction factor λ. However, for backfill transport system design, an appropriate safety factor for friction loss may be adopted, considering typically 8%-10% of total head loss of the sum of all local head losses on the pipeline route.

To analyze the results of laboratory studies of fly ash - water mixtures flow, a generalized Reynolds number formula has been applied after Mandlener et al. (2009) in a form:

$$Re = \frac{\rho {v_m}^{2-n} D^n}{\frac{\tau_0}{8}\left(\frac{D}{v_m}\right)^n + K\left(\frac{3m+1}{4m}\right)^n 8^{n-1}} \tag{2}$$

where

$$m = \frac{nk\left(\frac{8v_m}{D}\right)^n}{\tau_0 + k\left(\frac{8v_m}{D}\right)^n} \tag{3}$$

τ_0 – yield stress, Pa,
n – structure index,
k – consistency index,

which has been developed for Hershel-Bulkley fluid, although by structure index value $n = 1$, the Hershel-Bulkley model is reduced to Bingham rheological model.

Depending on the value of the Reynolds number, the flow of a mixture could occur in laminar, transient, and turbulent flow regimes that exhibit different impact on the value of the flow friction factor.

Friction loss in fully developed laminar flow in a pipe can be precisely described using the Buckingham-Reiner equation. Their expression can be written as:

$$\lambda = \frac{64}{Re}\left[1 + \frac{He}{6Re} - \frac{64}{3}\left(\frac{He^4}{\lambda^3 Re^7}\right)\right] \tag{4}$$

where He is the Hedström number, which can be formulated as:

$$He = \frac{\tau_0 Re^2}{\rho_m v_m^2} \tag{5}$$

Due to the complexity of the solution more often employed is its explicit approximation given by Swamee & Aggarwal (2011):

$$\lambda = \frac{64}{Re} + \frac{10.67 + 0.1414(He/Re)^{1.143}}{\left[1 + 0.0149(He/Re)^{1.16}\right]}\left(\frac{He}{Re}\right) \tag{6}$$

Between the laminar and turbulent flow regimes extends the transient zone, where laminar flow transforms into turbulent and vice versa. Unsustainable turbulences of variable cross-section surface, beyond which the flow remains laminar occur in the stream. Because during the measurements the maximal noticed value of Re was less than 40000, the Blasius formula has been used to determine the value of λ accordingly Albright (2008):

$$\lambda = \frac{0.316}{\mathrm{Re}^{0.25}} \tag{7}$$

which is correct for flows characterized by Reynolds number values ranging from about 4000 up to 80000. This range of Re values is considered as a transitional zone due to not fully developed turbulent conditions. On the pipe wall occurs laminar sublayer of the thickness greater than the roughness of the pipe wall, the flow friction factor is nonlinearly dependent on Re.

For mixtures of density from 1486 kg/m^3 up to 1605 kg/m^3 their rheological properties were calculated using the Bingham model. Derived values of rheological parameters along with the assessment of estimation quality coefficients are presented in Table 2. Correlation of the rheological properties of tested mixtures with the Hershel-Bulkley model was also considered, but the calculated structure index n consequently equals zero. Therefore, the Bingham model was considered to be adequate for the description of considered mixtures.

Table 2

Bingham model rheological parameters of tested fly ash – water mixtures

Density of mixture ρ_m [kg/m^3]	Viscosity coefficient μ [Pa·s]	Yield stress τ_0 [Pa]	R^2 [%]	MAPE [%]
1447	0.032630	0.58897	99.942	1.631
1486	0.057522	1.99440	99.795	1.034
1529	0.073264	3.63408	99.144	1.492
1559	0.083166	7.64272	99.228	0.687
1605	0.125557	24.54228	99.256	1.169

Practical calculation of flow parameters of fly ash - water mixtures requires knowledge of rheological parameters of the mixture at any concentration of solid particles. For the whole range of mixtures prepared with the fly ash used in tests, an exponential dependence of the concentration of the mixture on the viscosity is being observed which after correction of coefficients can be expressed as:

$$\mu = \mu_c + (2Cv)^{4.554} \tag{8}$$

where: μ_c =0.001 Pa·s (viscosity of water in 20^{o}C)

For mixtures exhibiting yield point, its value may be obtained from dependence:

$$\tau_0 = 466022 C_V^{16.097} \tag{9}$$

The influence of density of examined fly ash - water mixtures on their Bingham viscosity and yield point has been illustrated in Figure 2. The volume concentration of a mixture can be easily replaced by density, more convenient in practical applications. Rapidly increasing values of rheological parameters by higher density (and concentration of solid phase respectively) may lead to serious failures in pipelines transporting thick mixtures, for avoiding of which, adequately high precise preparation of mixtures and control of flow rate in the pipeline should be provided – see Hollinderbäumer & Mez, (1998). This is particularly important in the case of gravitational transport systems, the operation of which is practically impossible to control.

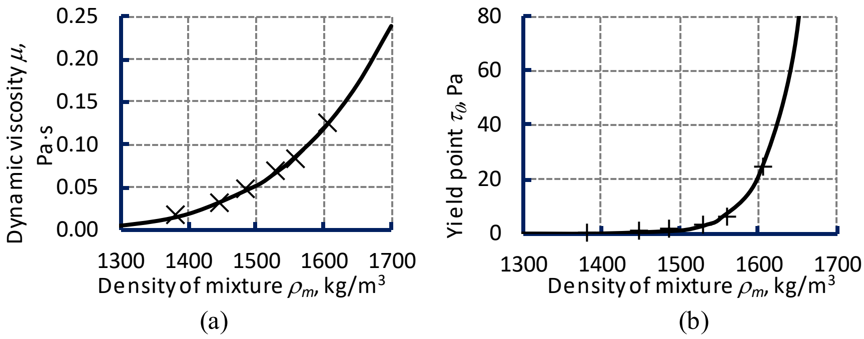

Figure 2. Correlation between the volume concentration, coefficient of viscosity (Bingham) and yield point (b) estimated for the fly ash-water mixtures investigated in the research

Industrial experience shows that the flow in the systems of hydraulic transport of fine-grained mixtures often occurs in the transient flow area. Some of the measurement points were also obtained in the transient flow area.

Taking under consideration that the parameters of turbulent flow correlate positively with Reynolds number using Blasius, Equation 7, an analogical formulation has been proposed for the description of the dependence $\lambda_{tr}(Re)$ in the transient area of flow in the form:

$$\lambda = \frac{aS+b}{Re^{0.25}}, \tag{10}$$

where a is an estimation coefficient and S the relative density of the mixture.

The proposed modification is expected to reflect the observation that in the transient flow area specific head loss values are slightly smaller than predicted by equations for the turbulent flow regime. Additionally, it can be seen that this effect becomes more significant with the increasing mixture's density. In the aim to maintain dimensionless form of λ_{tr}, the relative density of a mixture has been applied. Finally, the following non-linear estimation of $\lambda_{tr}(Re)$ relation has been formulated:

$$\lambda_{tr} = \frac{0.135S+0.110}{Re^{0.25}}. \quad (11)$$

Figure 3 shows approximated dependence of specific head loss Δp_i on the Reynolds number in laminar, transient, and turbulent flow regimes on the example of flow curve measured for the mixture of density ρ_m = 1559 kg/m^3.

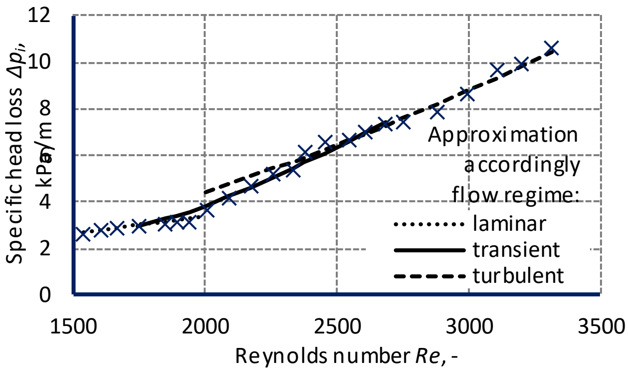

Figure 3. Approximation of the specific head loss dependence on Reynolds number for the mixture of density 1559 kg/m^3 in the full range of flow using equations for laminar, transient, and turbulent flow regimes (6), (11) and (7) respectively

4. CALCULATION OF THE FLOW DISTANCE RANGE

Due to the limited efficiency of the mixture preparation plant, during the flow of mixture in the pipeline, the apparent mixture level in the vertical part of the pipeline is varying in relation to the total length of the pipeline, density, and rheological properties of the mixture. The low apparent level of a mixture compared to the total level difference between the inlet and outlet of the pipeline creates an opportunity to increase the density of the mixture, which is beneficial from the point of view of application results (like i.e. better binding properties, mechanical strength after solidification, etc.).

Considering a pipeline of a constant diameter of D = 0.150 m and height difference ΔH = 500 m, transporting a mixture with a constant flow rate Qm = 100 m^3/h, the Reynolds number Re and maximal transport distance L_{max} depend on the density and rheological properties of a mixture. Figure 4 summarizes the calculation results obtained using Equations 6 and 7 without considering the transient flow area and with the implementation of Equation 11 in the range of Re from 2100 to 2500. Mixtures of density 1555 kg/m^3 and higher flow in the laminar regime and their flow range are rapidly decreasing, i.e. for the mixture of density 1650 kg/m^3, the L_{max} value is only 1280 m. By the density of about 1680 kg/m^3, the Lmax value is close to 500 m, so the mixture flow will be very small with a high risk of clogging the pipeline. The transient flow regime will occur by the flow of mixtures of density in the range of 1525 – 1555 kg/m^3. In this area, the extension of L_{max} is visible when drag coefficient values λtr will be used. The difference in predicting L_{max} value could be important while considering λ_{tr} in the transient regime instead of values calculated from turbulent flow results in L_{max} by about 500 m longer. Alternatively, instead of L_{max}, the mixture density could be adjusted, i.e. from 1530 to 1550 kg/m^3, which could positively influence the technical parameters of filling of cavings. L_{max} values for mixtures of density greater than 1605 kg/m^3 are extrapolated and illustrate the strong trend to reduce the flow range by increasing density.

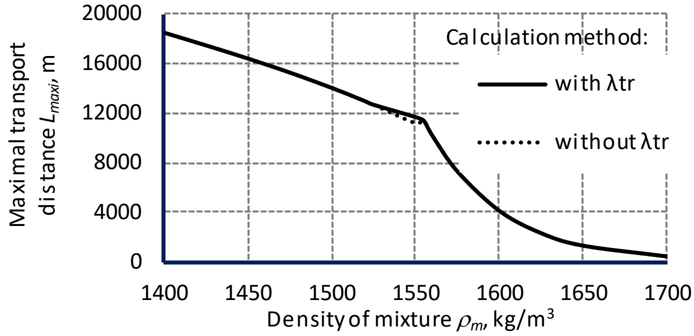

Figure 4. Maximal range of transport distance for fly ash – water mixtures made from fly ash used in tests, constant flow rate Qm = 100 m^3/h, pipe diameter D = 0.15 m

5. CONCLUSIONS

Results from flow tests of mixtures conducted for a large range of mixture's density allow optimizing the value of the density of fly ash – water mixtures used in coal mines for filling of cavings. Due to the gravitational operation mode of mine hydraulic transport systems, the only useful mixture's parameter is its density. Having a reliable relation between the physical properties of a mixture and the drag coefficient λ, it is possible to maximize the density for a given transport length or to predict the maximal transport range for a mixture of a given density. While the flow often occurs in the transient regime, the realistic values of flow parameters on the base of laboratory measurements may be used for practical calculations.

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