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EXPERIMENTAL STUDY OF PARAMETERS OF COAL-WATER MIXTURE FLOW IN PIPELINES

EKSPERYMENTALNE BADANIE PARAMETRÓW PRZEPŁYWU MIESZANINY WĘGIEL-WODA W RUROCIĄGACH

Coal-water mixtures (CWM) were investigated in steel pipelines of 21, 29 and 47 mm diameter and in plexiglass (transparent) pipelines of diameters of 24, 32 and 50 mm and two volume concentrations: 43% and 51%. The coal-water mixture had the features of Bingham's fluid. The results of changes of yield stress values and Bingham viscosity values are presented in relation to the concentration of the mixture.

To determine the Fanning friction factor *f* depending on the Reynolds number uses a classic Reynolds number, a generalized Reynolds number proposed by Kembłowski and Czaban, and the Reynolds number proposed by Metzner and Reed for non Newtonian liquids described by two parameter model and modified for liquid Bingham by Chhabra and Richrdsona.

The graphs $f = f(\mathrm{Re})$ show that the most accurate experimental results are approximated when the Reynolds number is calculated using the Metzner and Reed equation modified by Chhabra and Richardson for Bingham liquid flow.

The transition zone from laminar to turbulent flow was also analyzed. It has been found that the equation given by Wilson and Thomas and by Slatter can be used to determine the transition velocity from laminar to turbulent flow.

Keywords: Bingham flow, coal-water mixture, pipeline flow

Badano mieszaniny węgla i wody (CWM) w rurociągach stalowych o średnicy 21, 29 i 47 mm oraz w pleksiglasowych (przezroczystych) rurociągach o średnicach 24, 32 i 50 mm przy dwóch koncentracjach objętościowych: 43% i 51%. Mieszanina węgla i wody miała cechy płynu Binghama. Wyniki zmian wartości progu płynięcia i wartości lepkości Binghinga przedstawiono w funkcji koncentracji mieszaniny.

Określono współczynnik oporu Fanninga *f* w zależności od klasycznej liczby Reynoldsa, uogólnionej liczby Reynoldsa zaproponowanej przez Kembłowskiego i Czabana, oraz od liczby Reynoldsa zaproponowanej przez Metznera i Reeda dla cieczy nienewtonowskich opisanych przez model dwuparametrowy i zmodyfikowanej dla cieczy Binghama przez Chhabra i Richardsona. Wykresy $f = f(\mathrm{Re})$ pokazują, że

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wyniki eksperymentu są najdokładniej ekstrapolowane wtedy, gdy liczba Reynoldsa jest obliczana przy użyciu równania Metznera i Reeda zmodyfikowanego przez Chhabrę i Richardsona dla przepływu cieczy Binghama.

Przeanalizowano również strefę przejściową od przepływu laminarnego do turbulentnego. Stwierdzono, że równanie podane przez Wilsona i Thomasa oraz przez Slattera można wykorzystać do wyznaczenia prędkości przejścia od przepływu laminarnego do turbulentnego.

Słowa kluczowe: przepływ Binghama, mieszanina węgiel-woda, przepływ w rurociągu

1. Introduction

Rheological properties of CWM are mainly refers to the slurry viscosity and shear stress changing with the shear rate, which are the basic datum in the design of slurry transport and storage. The diversity of coals in their physical and chemical properties, e.g. particle size composition, concentration and ash content, what's more, experimental methods, variously impact the rheological properties of CWM (Singh et al., 2016; Chakravarthy et al., 2014; Panda, 2014; Mohapatra & Kumar, 2013; Cao et al., 2014).

Pipeline system is the main method in transportation of CWM. In the design of these pipeline system, the most important technical parameters is hydraulic gradient as it effects the requirement of system energy. The hydraulic gradient is related to rheological properties. Studies the rheological properties of CWM under different conditions can provide the basis for the design and optimize of pipeline system. Chen et al. (2011) used self-made L-pipe, and measured hydraulic drop through a combination of the flow characteristics of tailings paste slurry, then slurry rheological parameters were calculated on the basis of hydraulic drop. According to the rheological properties can establish the relationship of Reynolds number and friction factor. Haldenwang et al. (2012) established a pipe test system and used it to measure the rheological characterize of mixtures. They used the methods of Metzenr and Reed and other statistical methods to estimates the relationship of power-law friction factor and Reynolds number.

In order to obtain results relevant for the actual transport process, experimental pressure drop tests were carried out at a flow rate of a mixture of different densities in pipelines of different diameters, which allowed to determine rheological properties of CWM.

2. Experimental stand and method of measurements

The pipeline laboratory stand was built on a steel structure covered with a 5 mm waterproof plate. The installation is equipped with six pipeline measuring sections:

- section of internal diameter of 50 mm made of transparent PLEXIGLASS material with the length of 3.6 m and a control distance of 1.6 m in length.
- section of internal diameter of 47 mm made of E235N steel 3.9 m long and a control section of 1.3 m or 2.6 m long.
- section of internal diameter of 32 mm made of transparent PLEXIGLASS material with the length of 3.6 m and a control distance of 1.6 m in length.
- section of internal diameter of 29 mm made of E235N steel 3.9 m long and a control section of 1.3 m or 2.6 m long.

- section of internal diameter of 24 mm made of transparent PLEXIGLASS material with the length of 3.6 m and a control distance of 1.6 m in length.
- section of internal diameter of 21 mm made of E235N steel 3.9 m long and a control section of 1.3 m or 2.6 m long.

Measurement sections are supplied from the discharge collector. After a straight section of the first measurement section, the knee is 180 degrees and the beginning of the next measurement section. Then the tested medium is discharged into the tank.

The tested medium circulates in the system in a closed circuit by the tank. The 300 liter tank is made of translucent plastic. The medium feeds the suction collector from the bottom of the tank. Return to the tank is carried out separately from each of the measured test sections.

The installation is equipped with three electromagnetic flowmeters TECHMAG S.C., which are installed on each of the three measurement loops. Flowmeters are designed for contaminated and concentrated medium. The second method used to determine the flow rate is the classical method of the measuring vessel. The installation has been designed so that it is possible to take a sample for the measuring vessel at the outlet of the pipe to the tank.

Each pipeline has four measurement cross-sections. In the measuring cross-section, the pressure is drawn from two 6 mm diameter holes at the perimeter, spaced at 135 degrees. A ball valve is installed at each pressure point.

Two differential pressure measuring systems were used in the installation. The first measurement system is based on differential pressure measurement using separating vessels. The medium flowing through the pipeline through the cross-section affects the calibrated separation vessel and

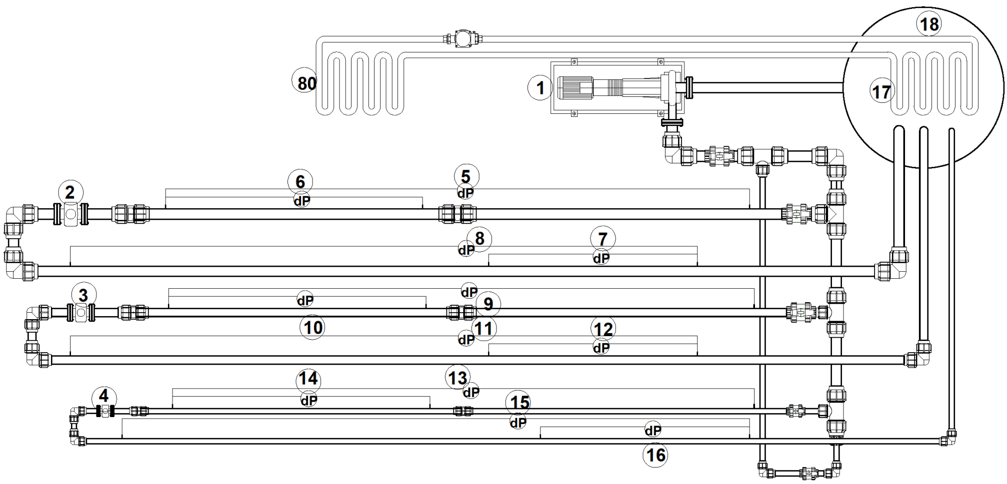

Fig. 1. Pipeline measurement stand
(1 – Pump, 2 – Flow meter DN 50, 3 – Flow meter DN 32, 4 – Flow meter DN 25, 5 – Measuring section Plexi ID 50 length 3625 mm, 6 – Control section Plexi ID 50 length 1615 mm, 7 – Measuring section Steel ID 47 length 3900 mm, 8 – Control section Steel ID 47 length 1300 mm, 9 – Measuring section Plexi ID 32 length 3625 mm, 10 – Control section Plexi ID 32 length 1615 mm, 11 – Measuring section Steel ID 29 length 3900 mm, 12 – Control section Steel ID 29 length 1300 mm, 13 – Measuring section Plexi ID 24 length 3625 mm, 14 – Control section Plexi ID 24 length 1615 mm, 15 – Measuring section Steel ID 21 length 3900 mm, 16 – Control section Steel ID 21 length 1300 mm, 17 – Cooling system, 18-Tank)

compresses the air that is in the upper part of the vessel. The air pressure difference between the two measurement sections is then measured using a pressure transducer or U-tube. The second measurement system used on the plant is to measure the pressure difference between the control crossings with the impulse tube filling water. The water completely fills the impulse tubes from the differential pressure transducer to the measuring cross section. The APR-2000ALW differential pressure transducers with a measuring range of 0-100 kPa from Appliance are used. Differential pressure transmitters are equipped with a display and two 1 / 4 NTP connectors.

The discharge collector was constructed from PEHD 100 DN 63 and PN 16 pipes. The collector connections are made using twisted connections. The collector is equipped with OMEGA structural vibration compensator and elongation compensator.

RX 50-160 Bialogon pump was used to supply the system. The pump is designed to pump concentrated suspensions and mixtures. The pump has been installed on a special frame to which also the motor and thrust bearing are attached. The pump packing is equipped with a mechanical seal. The pump unit is powered by the "Hitachi J300 E4" frequency inverter. Control of pump impeller rotation is possible from 0 to 2900 rpm. The power supply is equipped with a mobile pump control set.

3. Solid material used in experiment and range of investigation

The coal used in the experiment was derived from a mine in Poland. Particle size distribution was measured by Laser Particle Size Analyzer. The frequency distribution of the size of coal particles is presented in Figure 2. The particle size of the coal was from 3.89 to 418.60 µm, the average size being 104.90 µm.

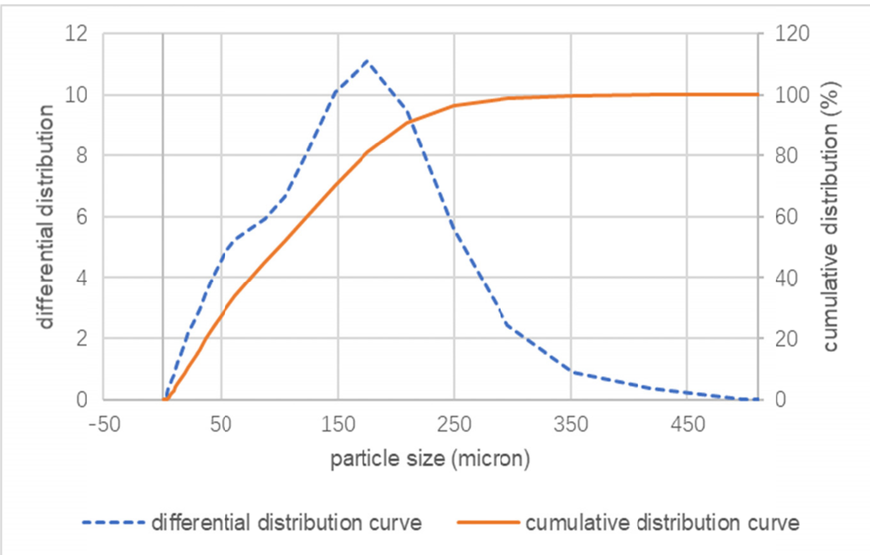

Fig. 2. Particle coal distribution from Laser Particle Size Analyzer

Coal-water mixture tests on the above was mentioned pipeline stand were carried out for two densities in three steel plexiglass diameters (50, 32 and 24 mm) and in three plexiglass steel diameters (47, 29 and 21 mm). A summary of the characteristics of the test mixtures is given in Table 1.

TABLE 1

Chracteristic parameters of investigeted coal-water mixtures

Weight concentration Cs (%)	Volume concentartion Cv (%)	Mixture density ρ (kg/m^3)
51	43	1178
59	51	1207

4. Results and discussion

The measurement results are shown graphically in Figures 3 and 4 in the form of flow curves in the coordinate system – shear stresses on the pipe wall τ_w and shear rate G.

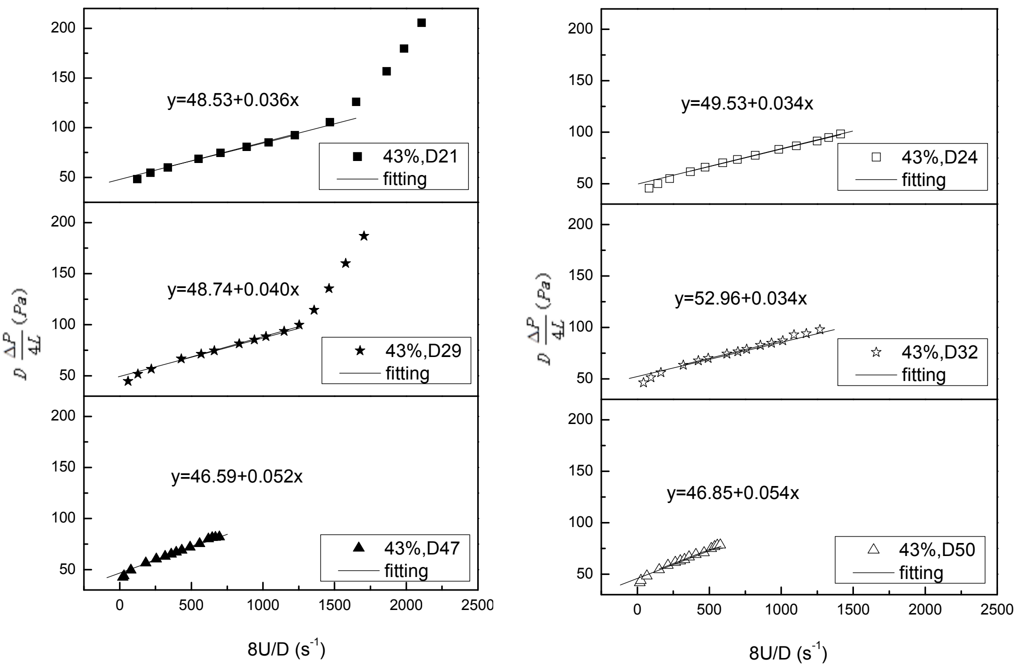

Fig. 3. Flow curves for mixture flow with a volume concentration of 43%

The shear stress on the pipe wall is calculated from the formula:

$$\tau_w = \frac{D\Delta p}{4L} \tag{1}$$

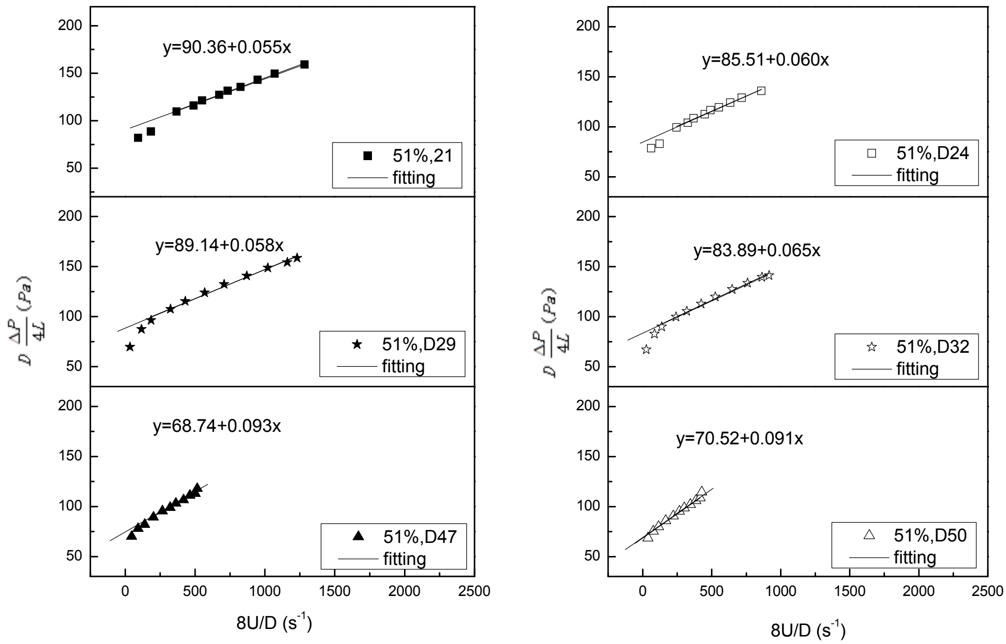

Fig. 4. Flow curves for mixture flow with a volume concentration of 51%

while the shear rate of the equation:

$$G = \frac{8v}{D} \tag{2}$$

As can be seen in figure 3 and 4, all measured flow curves of the coal-water mixture $\tau_w = f(\mathrm{G})$ are characteristic for non-Newtonian liquids since they do not pass through the origin of the coordinate system.

The measured flow curves were approximated with the Bingham liquid equation:

$$\tau_w = \tau_y + \eta G \tag{3}$$

As a result of approximation, values for the characteristic parameters of the Bingham liquid were obtained, for the yield stress τ_y and for the plastic viscosity η, which are summarized in Table 2.

Comparing the parameters of the Bingham model obtained for the mixture concentration of 43% and 51% in individual pipelines, these values are very close to the appropriate concentration, which confirms the correctness of the measurements made and allows one separate equation for each concentration of the mixture to be determined.

In figure 5, for the volume concentration of $C_v = 43\%$ for all measured pressure drop values, the parameters of the Bingham model are: yield stress $\tau_y = 52.19$ [Pa] and plastic viscosity (Bingham) $\eta = 0.034$ [Pa·s]. For volume concentration $C_v = 51\%$ these values are respectively: $\tau_y = 84.90$ [Pa] and $\eta = 0.062$ [Pa·s], and the flow curve for this concentration is shown in Fig. 6.

TABLE 2

Yield stress and plastic (Bingham) viscosity for tested coal-water mixture

Volume concentration	**Pipeline diameter (mm)**	**Yield stress τ_y**	**Plastic viscosity η**
43%	24	49.52	0.034
	32	52.96	0.034
	50	46.85	0.054
51%	24	85.51	0.060
	32	83.89	0.065
	50	70.52	0.091

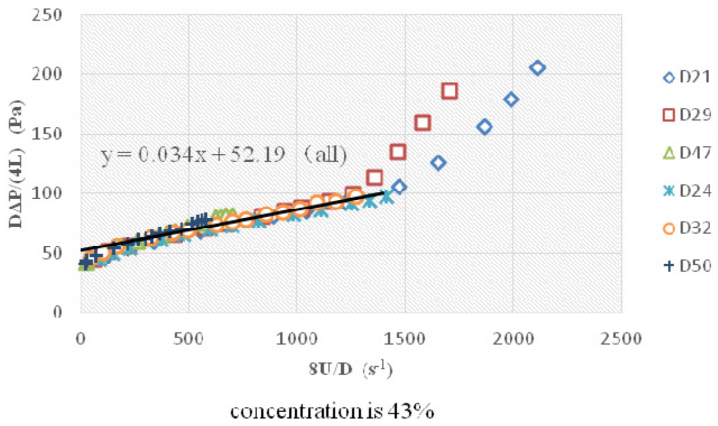

Fig. 5. Bingham model plot for all measured flow points of a 43% volume mixture in six different diameter pipelines

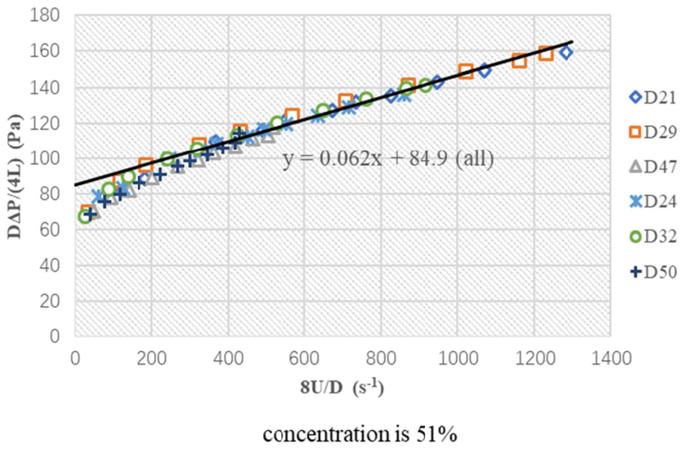

Fig. 6. Bingham model plot for all measured flow points of a 51% volume mixture in six different diameter pipelines

4.1. Fanning friction factor

Fannig factor of linear resistance is euqal:

$$f = \frac{D\Delta p}{2\rho L v^2} \tag{4}$$

and depends on the Reynolds number and the roughness of the pipeline. In the laminar flow zone, the Fanning factor of resistance depends only on the Reynolds number, which defines the equation:

$$f = \frac{16}{\mathrm{Re}} \tag{5}$$

where for non-Newtonian fluids Reynolds numbers determine the equations characteristic for a given liquid model.

The classic Reynolds number is:

$$\mathrm{Re} = \frac{\rho v D}{\eta} \tag{6}$$

Metzenr and Reed (1955) first provided the definition of Reynolds number for non-Newtonian liquids in the form:

$$\mathrm{Re}_{MR} = \frac{\rho v^{2-n} D^{n'}}{K' 8^{n'-1}} \tag{7}$$

where n' and K' are non-Newtonian liquid parameters described by a two-parameter model (eg. Bingham model, Herschel-Bulkley model). On the basis of this equation, Chhabra and Richardson (2008) have set the values n' and K' for Bingham's model. According to their proposition, the values n' and K' are calculated as follows:

$$n' = \frac{1 - \frac{4}{3}z + \frac{z^4}{3}}{1 - z^4} \tag{8}$$

and

$$K' = \tau_y \left[\frac{K}{\tau_w \left(\frac{4}{3}z + \frac{z^4}{3} \right)} \right]^{n'} \tag{9}$$

where z is ratio of yield stress τ_y to wall shear stress τ_w.

Figure 7 shows the dependence of Fanning's coefficient f on the Reynolds number calculated from the classical formula (6) and the pattern of Metzenr and Reed that Chhabra and Richardson adapted for the flow of the Bingham mixture with equations (8) and (9). As you can see in this graph, the points for which the Reynolds values are calculated from equations (9), (8) and (7) lie on the line $f = 16 / \mathrm{Re}$ representing the laminar flow. The values of $f = f(\mathrm{Re})$ for the classical Reynolds number determined from equation (6) are clearly outside the line for laminar flow.

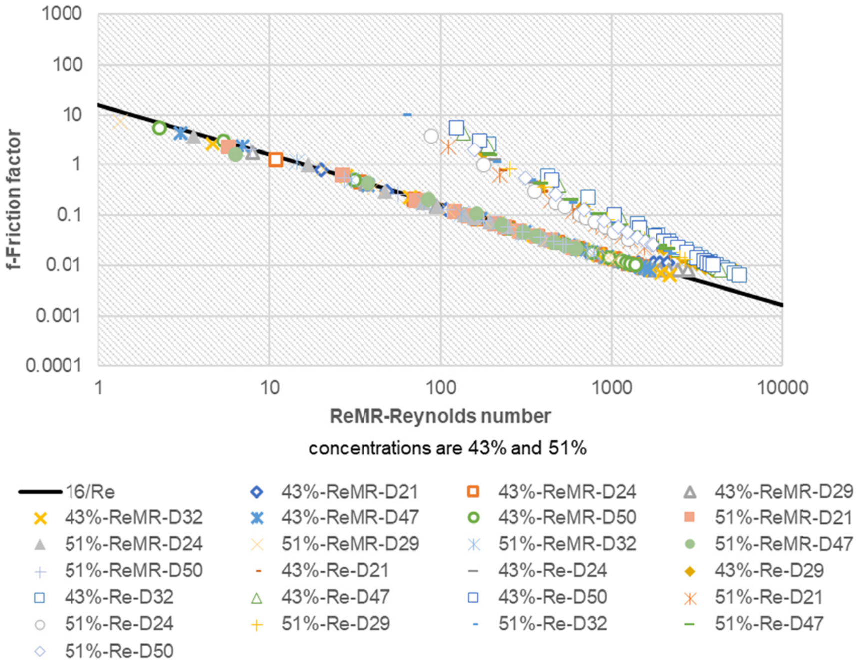

Fig. 7. The dependence of the Fanning factor *f* on the Reynolds number calculated according to the Metzenr and Reed formula modified by Chhabra and Richardson and on the classical Reynolds number

The correct determination of the Reynolds number when calculating the linear resistance coefficient is a guarantee of a well-defined loss of energy. On the other hand, simplified methods of calculating energy losses are being sought. In the case of Bingham's fluid flow a correct but relatively complex method is that which uses a different dimensionless number. Bingham's laminar flow describes the classic Reiner-Buckingham equation:

$$v = \frac{D\tau_w}{8\eta}\left[1\frac{4\tau_y}{3\tau_w} + \frac{1}{3}\left(\frac{\tau_y}{\tau_w}\right)\right] \tag{10}$$

from which it is difficult to calculate the shear stress τ_w. In precise calculations, two numbers can be added, as Hedström suggested at one time (1952). According to his proposal, the factor of linear resistance is a function of the classical Reynolds number (6) and the number of Hedström. This method Thomas and Wilson (2007) consider as a relatively accurate way of determining the factor of linear resistance for Bingham fluid flow.

Simplification of calculations by introducing a generalized Reynolds number suggested, inter alia, Kembłowski (1973) and Czaban (1990) who defined the generalized Reynolds number as follows:

$$\mathrm{Re}_B = \frac{\rho v D}{\eta + \dfrac{\tau_y D}{6v}} \tag{11}$$

This defined Reynolds number reduces all measured points to one line as shown for the measurements made for the flow of the coal and water mixture tested (Fig. 8).

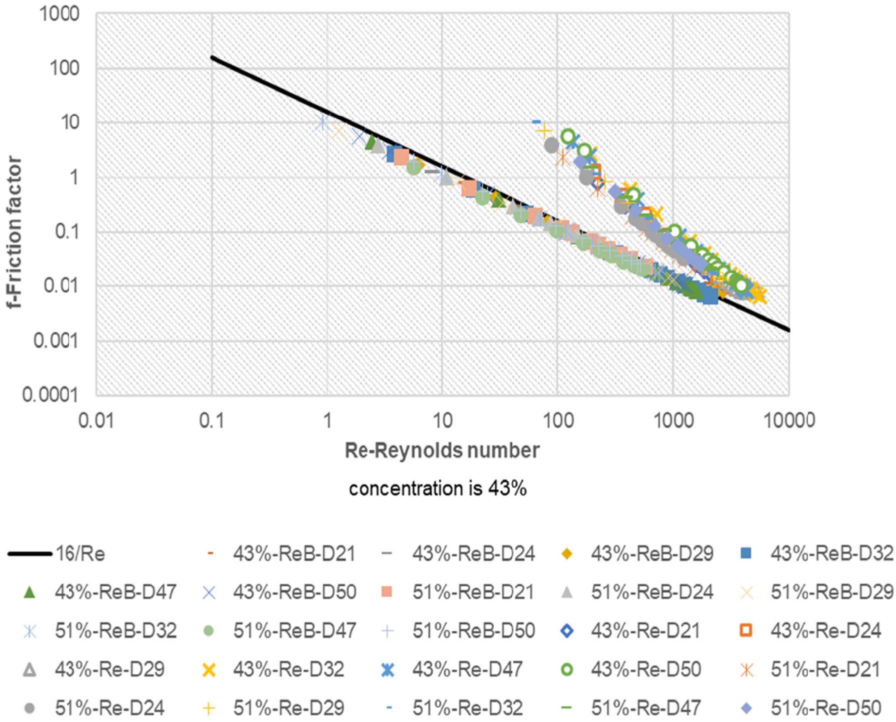

Fig. 8. The dependence of Fanning's factor *f* on the generalized Reynolds number and on the classical Reynolds number

As can be seen from the comparison of graphs in figure 7 and 8, the use of the Metzenr and Reed equations modified by Chhabra and Richardson gives more accurate results than the use generalized Reynolds number (11) in the calculation.

4.2. Critical velocity of transition from laminar flow to turbulent flow

In considerations concerning non-Newtonian flows, it is important to know the parameters of this flow at the moment of transition from laminar to turbulent. In the flow of Newtonian fluids this moment is the Reynolds number of Re = 2100. In non-Newtonian flows, the transition from laminar to turbulent flow has long been a subject of research and interest.

Knowledge of the moment of transition from laminar to turbulent motion is an important information for transport system designers, because in turbulent flow energy losses are growing much faster with velocity than it is in laminar flow. This is clearly visible on the graph made on the basic of measurements for a mixture with a volume concentration of 43% (Fig. 9). In this figure, a straight line crossing the vertical axis of the shear stresses represents the laminar flow that occurs until the line intersects with the second straight line, which represents the turbulent flow (Fig. 9). In non-Newtonian fluids, just as for Newtonian fluids, the actual transition from laminar to turbulent flow is not sudden and does not correspond to the intersection of the afore mentioned straight lines in figure 9.

Under real conditions this fact occurs in a certain shear rate zone, called the transition zone, and many factors affect the size of this zone. Assuming that Fanning's linear loss factor *f* describes the relationship of $f = 16/\mathrm{Re}_B$ and that the transition from laminar flow to turbulent takes place at $\mathrm{Re}_B = 2100$, the dependence that determines the critical velocity of change of flow type is reached:

$$v_C = X\sqrt{\frac{\tau_y}{\rho}} \tag{12}$$

Particularly attention should be paid to the fact that critical velocity does not depend on the diameter of the pipeline.

Different values for the X factor can be found in the literature. Thus, Slatter and Wasp reported (2000) that the value of $X = 26$ for large pipelines does not define the term "large pipelines". Thomas and Wilson at work (1987) reported $X = 21$, Slatter in another work (1997) gives $X = 19$. These values are shown in figure 9 lines and you can see that these values are in the transition zone. For the flow of the mixture with a volume concentration of 43% in a pipe with a diameter of 29 mm, the value of X falls within the range given by the other authors and can be assumed to be $X \sim 22$.

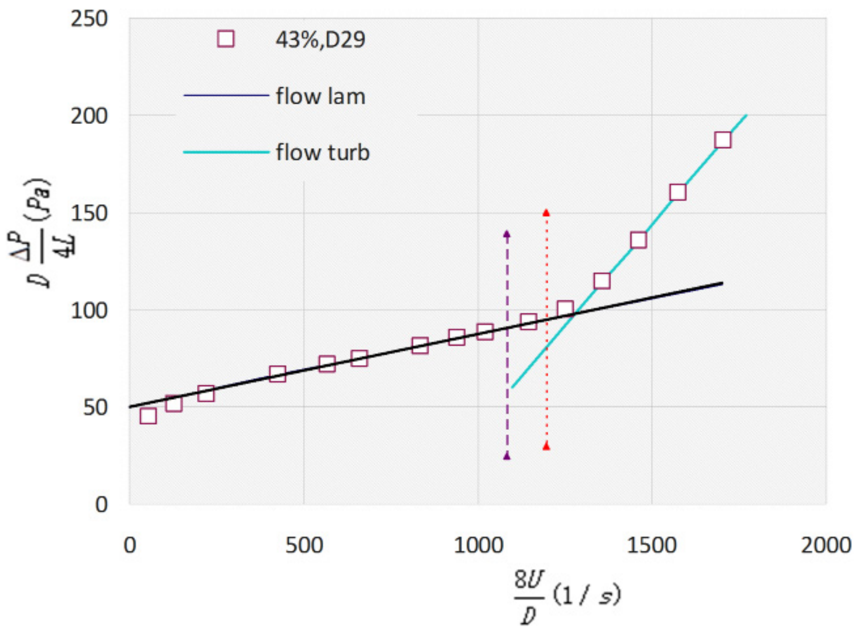

Fig. 9. Flow curves for mixture with 43% volume concentration in pipeline of 29 mm with critical velocity (left vertical line X=19, right vertical line X = 21)

5. Conclusions

1. The coal-water mixture tested had non-Newtonian liquid properties as described by the Bingham model.

2. The critical velocity of transition from laminar to turbulent flow can be determined from formula (12).

3. The tests performed confirmed that for the calculation of the Fanning friction factor for the non-Newtonian mixture described by the Bingham model, the equation of Metzner and Reed modified by Chhabra and Richardson should be used.

Acknowledgements

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