VALIDATION OF NUMERICAL MODELS FOR PREDICTION OF PRESSURE DROP IN HIGH CAPACITY LONG DISTANCE LIGNITE FLY ASH PNEUMATIC CONVEYING

by

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This paper will validate two basic concepts of numerical models for prediction of pressure change along the transport pipeline in the case of long distance and high capacity lignite ash pneumatic conveying. Application of various friction factor correlations and variation of given parameter, led to the total of fourteen different numerical models and program codes in FORTRAN. The input data for numerical models are based on comprehensive experimental research of high capacity and long distance Kolubara lignite fly ash pneumatic conveying system within 620 MWe thermal power plant unit under operating conditions. Numerical simulation results are validated against experimental data and subjected to statistical analysis methods. The functional dependence obtained by the least squares method was evaluated using mean squared deviation and correlation ratio. The predicted pressure changes show the best agreement, with the measured decrease of pressure amplitudes along the transport pipelines, for the model based on the momentum balance of air-ash mixture flow and friction factor correlation given by Dogin and Lebedev for the parameter $A = 1.4 \cdot 10^{-6}$. This model achieved the best correlation ratio of 93.99% for Pipeline 1 and 91.33% for Pipeline 2, as well as the best mean squared deviation of 9.58% for Pipeline 1 and 13.66% for Pipeline 2. Also, the fanning friction factor values are fully consistent with previously examined cases available in the literature. Numerical simulation model can be used for prediction of the ash pneumatic conveying capacity and pressure drop for the specified transport pipeline.

Key words: *lignite fly ash, pneumatic conveying, pressure drop, friction factor, numerical modeling*

Introduction

Coal-fired power plants currently fuel 38.4% [1] of global electricity. Thermal power plants in Serbia dominantly burn lignite from the Kolubara basin [2]. The most abundant byproduct of pulverized coal combustion in thermal power plants is fly ash [3]. The amount of ash that should be transported from the thermal power plant to the silo is increased when burning lower quality lignite [4, 5]. Pneumatic conveying systems are imposed as the best solution for fast conveyance of large fly ash quantities over long distances. Although seemingly simple in concept, the design of these systems is ambiguous. Creating optimal operating conditions is a serious issue [6], and difficulties in daily operation are a regular occurrence [4]. Frequent delays in the ash transport may lead to the shutdown of the thermal power plant [4,

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5, 7, 8]. Proper operation of pneumatic conveying system depends entirely on the characteristics of material, even on the single batch of the same material [9]. Unambiguity of fine and coarse ash long distance pneumatic transport systems design is described in [10], and halved material flow with increase in distance from 100 to 200 m, in [11]. Expanding pipes diameters with distance increase to slow down the particles and air velocity, maintain a constant Froude number [6], minimize erosion, particle degradation, pressure loss, and energy consumption [11] is the only approach to provide the possibility of optimizing pneumatic transport to lengths 3-4 km [12]. High capacity and long distance pneumatic conveying systems, resistant to all challenges in the transport of specific materials such as fly ash with uneven composition, have not yet been developed [7]. Disregarding specific material properties will likely lead to a multiple operational difficulties [6], nevertheless, detailed data on material characteristics is not sufficient to assess the minimum transport speeds, pressure drops, *etc.*, especially in the case of pneumatic transport over long distances and for large diameter pipelines. All requirements should be determined using pilot plants [13] or numerical models. Predominantly, models for pneumatic transport calculation are based on numerical simulations or pilot plants tests, while the phenomena in pneumatic transport are very diverse and complex. A review of existing models and correlations showed difficulties for their application, due to insufficiently defined conditions, constraints, or complex parameters that are not easy or are impossible to determine. There have been numerous attempts to model the pneumatic transport of fly ash and to develop a unique coefficient of friction for this type of two-phase flow. However, no fly ash is the same. It is common occurrence of fly ash with significant differences within the same plant, and the smallest variations in physico-chemical composition can alter their flow behaviors, thus further complicate the modeling process [6]. The general conclusion is that characteristics of the material that needs to be pneumatically transported must be known and well understood in order to avoid numerous problems in the operation of these systems [6], and that in 30 to 40 years we will be able to make a more serious step towards solving the problem of pneumatic transport [14].

Pipeline pressure drop in pneumatic conveying

One of the basic parameters for defining pneumatic conveying is pressure drop along the pipeline. A commonly used method for determining the pressure drop is by using friction factor correlations in modified Darcy-Weisbach equation. A large number of correlations, for calculation of the pressure drop in the two-phase mixture is developed [15-33], and most of them according to the two basic statistical models [34]. Twelve most commonly used correlations [15, 17, 18, 25, 26, 28-34] are evaluated against 1450 experimental data by fourteen different authors [34]. These correlations are described along with the corresponding parameters in [35, 36], and predominantly given in dimensionless form to correspond Darcy's expression for pressure drop. A large number of correlations is not easy to apply due to the difficult application to existing data, and correlations proposed in [20, 21, 23, 24] are omitted from the analysis [34]. The results of the research [34] showed that the expression given in [19] best correlates the examined data. Satisfactory results are obtained by correlations from [17, 29] for the calculation of the pressure drop, the correlation [15] fails, and the correlation [26] is not applicable for diameters less than 50 mm. The correlation from [25] consistently gives higher results, although it adequately correlates the data for coal dust for $A = 2\cdot10^{-6}$ [35, 37], and shows good agreement with the correlation given in [38]. The correlation presented in [24] is analyzed and successfully applied for the calculation of dense pneumatic transport of powdered coal and fly ash in horizontal and vertical pipelines [39]. Several other correlations for the friction factor from [40-45] are reviewed in [46]. Correlation between modified friction factor and modified Reynolds number is given [40]. Dependence of experimental and calculated Fanning friction factor values on the pipe wall for the flow of mixture of air and coal dust particles, from Reynolds number is given in [35]. The empirical method, reminiscent of the method in [18], for determination of friction factor as a function of Froude number, the ratio of solid and air mass flow, mean particle diameter and pipe diameter, with the corresponding empirical coefficients is given in [41]. One of the most common models for the calculation of pressure drop due to solid phase flow is given [45], where the value of the friction factor for solid phase must be calculated according to the expressions presented in [46-49]. Based on review of study from [40], the same author proposed an expression for the calculation of the pressure drop in horizontal pneumatic transport systems developed using Blasius friction factor for gas flow. Most of the correlations analyzed in [50] are created by modifying the correlations considered in [34], and a large number of complex parameters led to the same general conclusion, that they are difficult to apply. The computational approach to pneumatic conveying provided constant progress in this field, but the basic physical parameters of the process must be better understood in order for this progress to make sense [6]. Two models are used to calculate the pressure drop for five different materials and for five pipeline configurations [50]. One model is used for straight horizontal and vertical sections, and the other for elbows, valves and other pipeline sections. The mixture of solid and gas phase is considered to be a mixture with precisely defined characteristics, and the pressure drop of the mixture was calculated using the modified Darcy-Weisbach equation. After dimensional analysis a model for the transition to a real plant with an error of ±15% was formed. A 1-D model for stationary flow conditions and spherical particles, disregarding interactions between particles and the assuming solid phase motion in the form of discrete particles, is used in [51] for numerical simulations of vertical pneumatic gas-solid phase transport. This model has a conservative approach to variables for the gas phase, while the fourth-order Runge-Kutta method is used to solve the solid phase. The results obtained by the calculation were compared with the available experimental data and the results of the Euler-Lagrange calculation method, and showed good accuracy in vertical transport. Two models, one based on the momentum balance of the air-ash mixture flow and the friction factor correlation of Dogin and Lebedev [25] and second by Muschelknautz and Krambrock [24], were applied in [4] for prediction of pressure change along the pipeline, where the calculated pressure drop using correlation of Dogin and Lebedev [25] showed good agreement with the measured decrease of pressure amplitudes along the transport pipelines. Models with relatively good results, within ±30%, can lead to serious operational problems, such as inadequate capacity and pipelines congestion as confirmed with fly ash samples in [13]. The lack of existing correlations is found to be based on low values of air density, model limitations such as defining the particle size with one value, what is not feasible for fly ash, and that the most of models correspond to purely dilute or purely dense phase transport.

Numerical models and experimental data

Two models for prediction of pressure change along the transport pipeline in the case of long distance and high-capacity Kolubara lignite ash pneumatic conveying are addressed. Different correlations and parameter variations applied in two numerical models give the total of fourteen different numerical simulations that are conducted. The input data for numerical models are obtained from comprehensive experimental research on 120 t/h Kolubara lignite fly ash pneumatic conveying system in 620 MWe thermal power plant unit, under operating conditions [4, 7]. The method for the numerical models validation was to find out how well addressed models predicted the pressure drop on approximately 600 m fly-ash pneumatic conveying through 4-stepped-diameter telescopic pipeline from considered thermal power plant to the silo, fig. 1, analyzed in papers [4, 7]. The results obtained using the model and the results of experimental measurements are subjected to statistical analysis methods, and the functional dependences obtained by the least squares method were evaluated by correlation ratio and mean squared deviation.

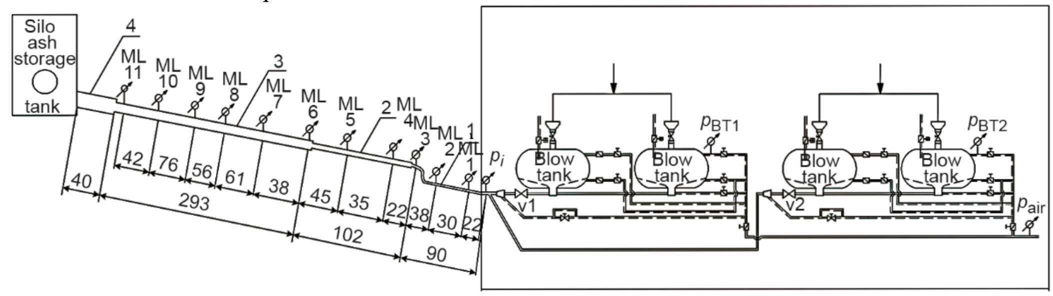

Figure 1. Lignite ash transport pipeline at the thermal power plant

Model based on the momentum balance of air-ash mixture flow and friction factor correlations by Dogin and Lebedev [25], Michaelidis [19], and Shimizu [28]

As presented in [7] the first model is based on the momentum balance of the air-ash mixture flow and various friction factor correlations given by different authors, Dogin and Lebedev [25], Michaelidis [19], and Shimizu [28]. The calculation methodology for this model is adopted from [35] and applied in [4, 7], where pressure change, dp, at distance, dx, along the pipe of diameter, D, and with the elevation change, dH, is calculated as a sum of frictional pressure drop, solids-gas mixture acceleration pressure drop, and hydrostatic pressure drop:

$$\mathrm{d}p = -4 f_\mathrm{m} \frac{\rho_\mathrm{g} u_\mathrm{g}^2}{2} \frac{\mathrm{d}x}{D} - \mathrm{d}(\rho_\mathrm{m} u^2) - \rho_\mathrm{m} \mathrm{g} \mathrm{d}H \tag{1}$$

Pressure drop due to solids-gas mixture acceleration is negligible in pneumatic conveying [52], therefore it is not considered. The Fanning friction coefficient for the air-ash mixture flow is denoted with f_m and is calculated using correlations given by various authors, u_g –is the air velocity, ρ_m is the mixture density, the air density is calculated from the perfect gas equation of state $\rho_\mathrm{g} = p/(\mathrm{R_g}T)$, $\mathrm{R_g}$ – the air gas constant, T – the air temperature (which is the same as the mixture temperature. It is determined for the pipeline inlet and the isothermal flow along the transport pipeline is assumed), and g – the gravity acceleration [4]. Compressible flow equations are not solved by this model, yet model considers the impact of pressure change on density.

The first friction factor correlation is given by Dogin and Lebedev [25]:

$$f_\mathrm{m} = f_\mathrm{g} + A\left(\frac{d_\mathrm{p}}{D}\right)^{0.1} \mathrm{Re}^{0.4}\,\mathrm{Fr}^{-0.5} \frac{\rho_\mathrm{p}}{\rho_\mathrm{g}} \dot{m}^* \tag{2}$$

As presented in [25, 35], coefficient A takes values from $1.0\cdot10^{-6}$ to $2\cdot10^{-6}$ with an increment of $1\cdot10^{-7}$, which leads to the total of 11 correlations, *i.e.*, 11 different models for numerical simulations.

Two more numerical simulation models are determined by Fanning friction factor correlations for the air-ash mixture flow by Michaelidis [19] and Shimizu [28], eqs. (3) and (4), respectively [7]:

$$f_\mathrm{m} = f_\mathrm{g} + 0.076\frac{\dot{m}^*}{\sqrt{\mathrm{Fr}}} \tag{3}$$

$$f_\mathrm{m} = f_\mathrm{g}(1 + 0.379\dot{m}^*) \tag{4}$$

The friction factor in the rough pipe for the gas phase is calculated as given in [53]:

$$\frac{1}{\sqrt{f_\mathrm{g}}} = -1.8\log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{K}{3.7D}\right)^{1.11}\right] \tag{5}$$

The air temperature matches the mixture temperature and it is determined for the pipeline inlet and the isothermal flow along the transport pipeline is assumed [4, 7]. The density of the air-ash mixture is determined on the basis of their densities and volume fractions in the two-phase mixture. The ratio of the mass flow of ash and air is defined:

$$\dot{m}^* = \frac{\alpha_\mathrm{p}\rho_\mathrm{p}u_\mathrm{p}}{(1-\alpha_\mathrm{p})\rho_\mathrm{g}u_\mathrm{g}} \tag{6}$$

After defining the models, based on the basic physical laws that apply in the process of pneumatic transport of fly ash, described by systems of equations, a program codes in FORTRAN according to algorithm shown in [4, 7] is developed. Numerical integration subroutine, based on Runge-Kutta 4$^\mathrm{th}$ order method with adaptive step size, is used to solve differential equation of pressure change, for a given initial pressure and each of the sections of the telescopic pipeline. The pressure drops at the sections of where pipeline diameter changes are neglected, given their small value in relation to the pressure drop due to friction along the straight sections of the pipeline [6].

Model based on the Muschelknauz and Krambrock [24]

The second model is developed by Muschelknautz and Krambrock [24]. This model is applicable to flow in cases when the transported material fills the pipeline, as shown in fig. 2, and it is based on the calculation of the friction of the plug of solid particles on the pipe wall.

The pressure drop on the section of length, L, is determined according to:

$$\frac{p_\mathrm{f1}}{p_\mathrm{f2}} = \exp\left(\frac{\gamma\dot{m}^*\mathrm{g}Lu_\mathrm{g}}{\mathrm{R_g}T_\mathrm{g}u_\mathrm{p}}\right)\ [\mathrm{ms}^{-1}] \tag{7}$$

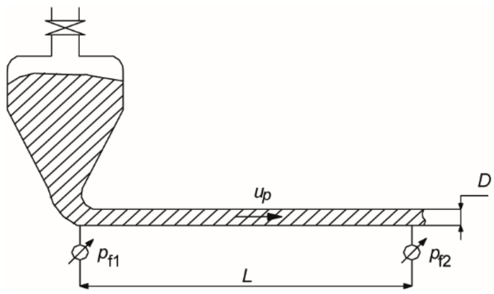

Figure 2. Pneumatic conveying system where the pipeline is filled with material [4, 7, 39]

As well as with the first model, the program code for numerical simulation is developed in FORTRAN, according to the algorithm presented [39], which is also described and applied in [4, 7].

Experimental data

As presented in [4, 7], there are two parallel, 4-stepped-diameter, telescopic pneumatic transport pipelines with the same dimensions, with the overall length of 565 m from the blow tanks to the silo. The experimental research included measurements of pressure change along the transport pipeline, analysis of operational parameters at the plant, as well as analysis of coal and ash samples. During measurements, the electric power at the generator varied in the range 606.4-622.6 MW, the lignite consumption was 756-786 t/h, while proximate analysis of Kolubara lignite coal samples showed the lower heating value 7343-7689 kJ/kg, moisture content 50.3-50.4%, and the mass fraction of ash 13.4-15%. Air-flow was 5500 m^3/h (at pressure of 1.103 bar and temperature 273.15 K). The physical density of the ash was in range 1800-2400 kg/m^3, the value of ash loose-poured bulk density 600 kg/m^3, and the mean ash particle diameter 115-141 μm. The detailed results of pressure measurement in the pneumatic ash transport are given in [4, 7], and the absolute error did not exceed ±2 kPa. The mean value of inlet air pressure in the initial cross-section for Pipeline 1 was 303 kPa, and it was equal to the mean value of the measured pressure amplitudes at the first active measuring location, and 300 kPa for the pipeline number 2. The maximum values of standard deviation were 28 kPa for Pipeline 1 and 34 kPa for Pipeline 2, determined by stochastic character non-stationary ash transport. Based on operational conditions and lignite characteristics during the performed measurements, the actual mass-flow of ash per pipeline was 77 t/h, [4, 7].

Results and discussions

The numerical simulations of pressure changes along pneumatic transport pipelines are performed using numerical simulations models and programe code developed in FORTRAN, for the assumed quasi steady-state transport conditions. The experimental data used to obtain results is as follows. The air mass-flow rate of 5500 Nm^3/h, the ash mass-flow rate 77 t/h, thus the ratio of ash and air mass-flow rates was 11.63. The inlet air pressure for Pipeline 1 was 303 kPa, and 300 kPa for Pipeline 2, while the air-ash mixture temperature was 373.15 K. The results are obtained with the mean ash particle diameter of 0.128 μm and physical density of ash 2100 kg/m^3. The pressure drops at the sections of where pipeline diameter changes and local pressure losses are neglected given their small value in relation to the pressure drop due to friction along the straight sections of the pipeline [6]. The results of the pressure drop calculation for Pipelines 1 and 2, for each of the models, *i.e.* their comparative presentation against the experimental data are given in graphically, figs. 3 and 4. The mean squared deviation and correlation ratio of each model against the experimental values for the considered pipelines are given in tabs. 1 and 2, respectively.

The diagrams in figs. 3 and 4 clearly indicate the best agreement of the numerical simulations results against the experimental data for the model where the Dogin and Lebedev [25] correlation was applied, for the value of the coefficient $A = 1.4\cdot10^{-6}$. According to statistical analysis, this numerical model achieved the best mean squared deviation of 9.58% for Pipeline 1 and 13.66% for Pipeline 2, as well as the best correlation ratio of 93.99% Pipeline 1 and 91.33% for Pipeline 2. The model based on the correlation [25] gives quite satisfactory agreement against the experimental data for the values of the coefficient A of $1.3\cdot10^{-6}$ and $1.5\cdot10^{-6}$. The correlation by Muschelknautz and Krambrock [24] gives a slightly larger pressure drop, compared to the correlation [25] for $A = 1.4\cdot10^{-6}$ and is in agreement with the mentioned correlation for $A = 1.6\cdot10^{-6}$. The predicted pressure, using the model based on the correlation [25] for the values of the parameter A in range $(1.6\text{-}2.0)\cdot10^{-6}$ and the correlation of

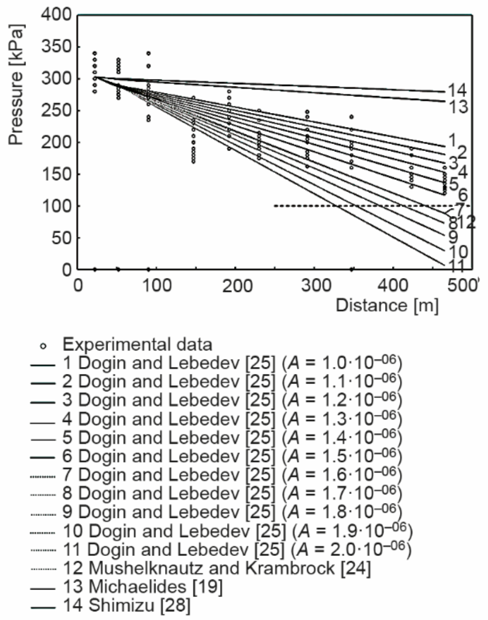

Figure 3. Measured pressure amplitudes and calculated pressure changes along the transport Pipeline 1 for Kolubara fly ash pneumatic conveying [7]

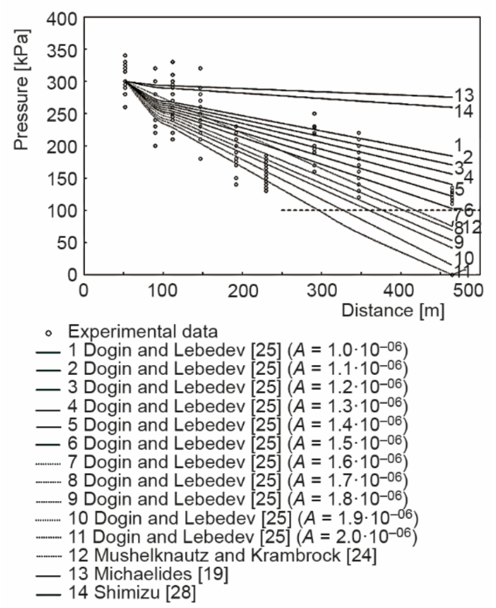

Figure 4. Measured pressure amplitudes and calculated pressure changes along the transport Pipeline 2 for Kolubara fly ash pneumatic conveying [7]

Table 1. Mean squared deviation and correlation ratio for the Pipeline 1 [7]

		Mean squared deviation [%]	Correlation ratio [%]
1	Dogin and Lebedev [25] ($A = 1.0 \cdot 10^{-6}$)	23.47	70.09
2	Dogin and Lebedev [25] ($A = 1.1 \cdot 10^{-6}$)	19.46	79.72
3	Dogin and Lebedev [25] ($A = 1.2 \cdot 10^{-6}$)	15.43	86.85
4	Dogin and Lebedev [25] ($A = 1.3 \cdot 10^{-6}$)	11.82	91.58
5	Dogin and Lebedev [25] ($A = 1.4 \cdot 10^{-6}$)	9.58	93.99
6	Dogin and Lebedev [25] ($A = 1.5 \cdot 10^{-6}$)	10.99	93.18
7	Dogin and Lebedev [25] ($A = 1.6 \cdot 10^{-6}$)	18.16	84.73
8	Dogin and Lebedev [25] ($A = 1.7 \cdot 10^{-6}$)	22.84	75.65
9	Dogin and Lebedev [25] ($A = 1.8 \cdot 10^{-6}$)	29.00	57.26
10	Dogin and Lebedev [25] ($A = 1.9 \cdot 10^{-6}$)	37.02	–
11	Dogin and Lebedev [25] ($A = 2.0 \cdot 10^{-6}$)	44.77	–
12	Muschelknautz and Krambrock [24]	18.06	84.79
13	Michaelides [19]	47.99	–
14	Shimizu [28]	53.28	–

Table 2. Mean squared deviation and correlation ratio for the Pipeline 2 [7]

		Mean squared deviation [%]	Correlation ratio [%]
1	Dogin and Lebedev [25] ($A = 1\cdot10^{-6}$)	28.40	68.14
2	Dogin and Lebedev [25] ($A = 1.1\cdot10^{-6}$)	24.20	77.39
3	Dogin and Lebedev [25] ($A = 1.2\cdot10^{-6}$)	20.14	84.08
4	Dogin and Lebedev [25] ($A = 1.3\cdot10^{-6}$)	16.27	88.88
5	Dogin and Lebedev [25] ($A = 1.4\cdot10^{-6}$)	13.66	91.33
6	Dogin and Lebedev [25] ($A = 1.5\cdot10^{-6}$)	13.81	90.98
7	Dogin and Lebedev [25] ($A = 1.6\cdot10^{-6}$)	20.12	83.82
8	Dogin and Lebedev [25] ($A = 1.7\cdot10^{-6}$)	24.70	75.54
9	Dogin and Lebedev [25] ($A = 1.8\cdot10^{-6}$)	28.38	66.11
10	Dogin and Lebedev [25] ($A = 1.9\cdot10^{-6}$)	36.74	32.12
11	Dogin and Lebedev [25] ($A = 2.0\cdot10^{-6}$)	47.19	–
12	Muschelknautz and Krambrock [24]	21.56	94.99
13	Michaelides [19]	54.26	–
14	Shimizu [28]	59.80	–

Muschelknautz and Krambrock [24] (lines 7-12 in diagrams), reaches atmospheric pressure at distances significantly shorter than the total length of the pipeline, thus have not been further considered. The predicted values of pressure change along the pipeline obtained using a model based on correlation [25], for the values of parameter A less than $1.3\cdot10^{-6}$ and greater than $1.6\cdot10^{-6}$, significantly underestimate the experimental, although a good correlation for coal dust is confirmed in [37] for value of parameter $A = 2.0\cdot10^{-6}$. Models based on correlations by Michaelidis [19] and Shimizu [28] significantly underestimate experimental values. The mean squared deviations are 47.99% (Pipeline 1) and 54.26% (Pipeline 2) for correlation by Michaelidis [19], that is 53.28% (Pipeline 1) and 59.80 % (Pipeline 2) for the correlation by Shimizu [28]. This is most likely lack of friction factor correlation, due to not taking into account pipe diameter, mean particle diameter, gas and solid phase densities, as well as Reynolds number, but are primarily based on solid and gas phase flow ratio $\dot{m}^*$.

Data for friction factor f_m *vs.* Reynolds number, obtained by authors in [22, 26, 27] are graphically presented in a form of a diagram in [35]. The diagram from [35] is used to graphically present the fanning friction factor values, that are calculated using validated model based on the correlation [25] for $A = 1.4\cdot10^{-6}$. The obtained results are plotted against values of other authors in fig. 5, and are fully consistent with previously examined cases available in the literature.

As stated in [35], the values of the friction coefficient according to [37] are significantly higher than those according to [26] due to the non-stationary transport regime, what corresponds to numerically obtained values in experimentally considered case.

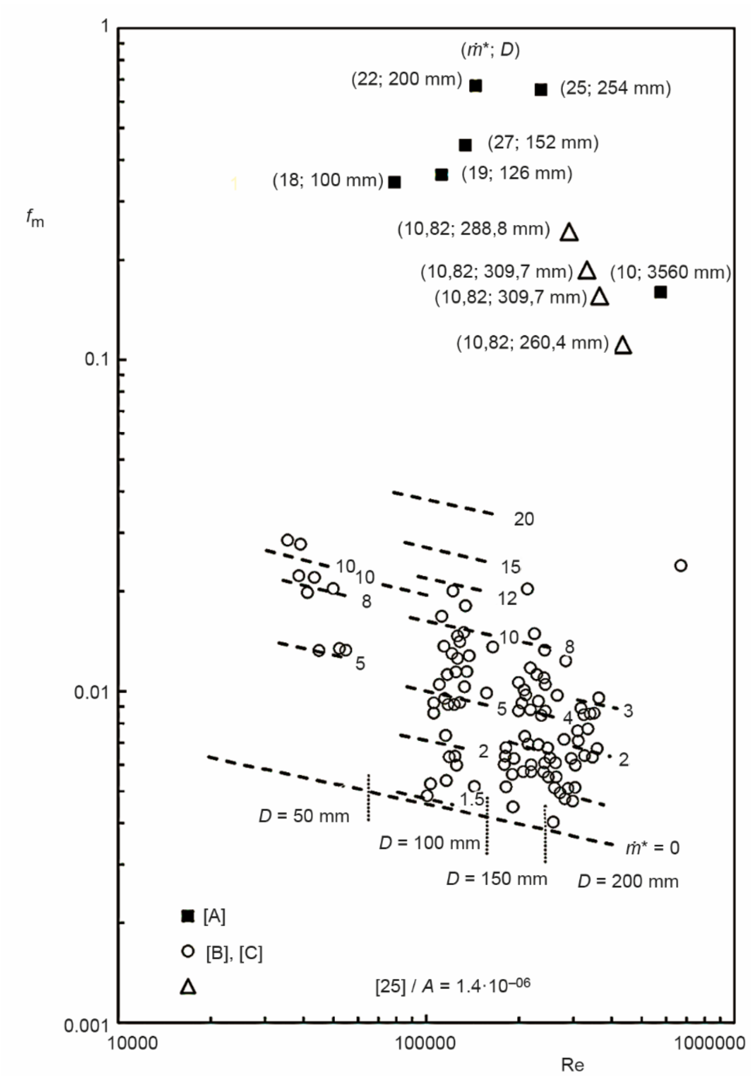

Figure 5. Dependence of experimental and calculated values of the fanning friction factor on the pipe wall for case of flow of mixture of air and coal dust particles, from Reynolds number, with numerical simulation results [7, 35]

Given that the phenomena in pneumatic transport are very diverse and complex to be expressed by a single correlation, their application is still in the field of industrial design in order to ensure sufficiently smooth operation. Attempts to generalize and simplify empirical experiences have not yet been successful. However, the applied numerical simulation model based on correlation of Dogin and Lebedev [25], for the value of parameter $A = 1.4 \cdot 10^{-6}$, gives satisfactory results and can be used for prediction of the fly ash pneumatic conveying capacity and pressure drop for the specified transport pipeline.

Conclusion

Two basic concepts of numerical models to predict pressure drop in high capacity and long distance lignite fly ash pneumatic conveying are addressed. Application of various friction factor correlations and variation of given parameter, led to the total of fourteen different numerical models and program codes in FORTRAN. The input data for numerical models are based on comprehensive experimental research of high capacity and long distance Kolubara lignite fly ash pneumatic conveying system within 620 MWe thermal power plant unit, under operating conditions. The results obtained using the numerical simulations are validated against experimental data, and are subjected to statistical analysis methods. The functional dependence obtained by the least squares method was evaluated using mean squared deviation and correlation ratio. The predicted pressure changes show the best agreement, with the measured decrease of pressure amplitudes along the transport pipelines, for the model based on the momentum balance of air-ash mixture flow and friction factor correlation given by Dogin and Lebedev [25] for the parameter $A = 1.4 \cdot 10^{-6}$. This model achieved the best correlation ratio of 93.99% for Pipeline 1 and 91.33% for Pipeline 2, as well as the best mean squared deviation of 9.58% for Pipeline 1 and 13.66% for Pipeline 2. Also, the fanning friction factor values are fully consistent with previously examined cases available in the literature. Therefore, this numerical simulation model can be used for prediction of conveying capacity and pressure drop of the specified transport pipeline. The general conclusion is that the characteristics of the material that needs to be transported pneumatically must be known and well understood in order to avoid numerous problems in the operation of these systems, and it is predicted that in the next few decades we will be able to make a more serious step towards solving the problem of pneumatic transport of materials like fly ash.

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Nomenclature

D – pipe of diameter, [m]
$\mathrm{d}H$ – elevation change, [m]
d_p – mean particle diameter, [m]
$\mathrm{d}p$ – pressure change along the pipe, [Pa]
$\mathrm{d}x$ – distance of pipe where pressure change is calculated, [m]
f_g – friction factor for solid phase, [–]
f_m – friction factor of the mixture of gas and solid, [–]
Fr – Froude number ($=u_\mathrm{g} g^{-1/2} D^{-1/2}$), [–]
g – gravitational acceleration, [ms^{-2}]
K – equivalent sand roughness, [m]
$\dot{m}^*$ – ratio of mass-flow of ash and air [$=\alpha_\mathrm{p}\rho_\mathrm{p}u_\mathrm{p}(1-\alpha_\mathrm{p})^{-1}\rho_\mathrm{g}u_\mathrm{g}$], [–]
p_g1 – inlet air pressure, [Pa]
p_g2 – outlet air pressure, [Pa]
Re – Reynolds number ($=\rho_\mathrm{g}u_\mathrm{g}D/\mu_\mathrm{g}$), [–]
$\mathrm{R_g}$ – air gas constant, [Jkg^{-1}K^{-1}]
T_g – air temperature, [K]
u_g – gas velocity, [ms^{-1}]
u_p – particle velocity, [ms^{-1}]

Greek symbols

μ_g – dynamic viscosity of the air, [Pa·s]
α_p – ash volume fraction in the mixture with air [$= 1/(1+\rho_\mathrm{p}\dot{m}^{*-1}\rho_\mathrm{g}^{-1})$], [–]
γ – material coefficient (= 0,.6 according to [39]), [–]

ρ_g – air density (= pRgT_g), [kgm^{-3}]
ρ_m – mixture density (= $\alpha_g\rho_g+\alpha_p\rho_p$), [kgm^{-3}]
ρ_p – particle density, [kgm^{-3}]

Subscripts

g – air (gas)
m – mixture
p – particle

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