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Laminární, přechodné a turbulentní proudění jemnozrnných suspenzí v potrubí

Laminar, transitional and turbulent flow of fine-grained slurries in pipelines

Summary

The contribution deals with flow behaviour of the slurries containing colloidal, clay and dust particles and simultaneously sometimes also coarse-grained particles. The slurry flow behaviour changes from Newtonian to non-Newtonian in dependence on the solid phase concentration and composition, especially on the content of colloidal particles. Flow behaviour of the fine-grained highly concentrated and sand slurries in the laminar, transitional and turbulent regimes was experimentally investigated in horizontal straight pipes with respect to the particle size distribution, volumetric concentration and slurry velocity.

The re-circulation pipe loop with horizontal hydraulically smooth stainless steel pipes of the inner diameters D = 17.5, 26.8 and 36 mm was used for measuring the slurry flow parameters. As model slurries water mixtures of kaolin, fly and bottom ash produced during process of desulphurisation in fluidic-type combustion chamber, sand slurries, and kaolin-sand slurries were used. Kaolin was added to the sand-water slurry to create a non-Newtonian carrier liquid. To compare the effect of Newtonian and non-Newtonian carrier a chemical agent with peptising effect was used to reduce internal attractive forces between kaolin particles and to change the slurry flow behaviour. Also the effect of time and intensity of shearing was studied for time dependent ash slurries.

Kaolin slurry has time-independent, yield pseudo-plastic response for volume concentrations higher than about 5 %. On the contrary, fluidic fly ash water mixture is time dependent and its shearing results in a substantial reduction of the hydraulic gradient in laminar region and in a marked decreasing of the laminar/turbulent transition velocity value. The similar effect can be reached by addition of coarser bottom ash particles.

The flow patterns are fundamentally different for the laminar and turbulent regime. The transition from laminar to turbulent regime results in an abrupt increase of the flow resistance. The transition from laminar to turbulent flow is very important for the save and efficient design and operation of dense slurry pipelining. The optimum operational condition is slightly above the laminar/turbulent transition point, where flow conditions and energy consumption should be often very attractive from operational and economic point of view.

Souhrn

Přednáška se zabývá tokovým chováním suspenzí obsahujících koloidní, jílovité a prachové částice a případně i hrubé částice v oblasti laminárního, přechodného i turbulentního režimu proudění. Chování suspenzí se mění od newtonského do nenewtonského v závislosti na koncentraci a zrnitostním složení pevné fáze, zejména na obsahu koloidních částic. Tokové chování jemnozrnných vysoce koncentrovaných a písčitých suspenzí bylo zkoumáno experimentálně v horizontálním přímém potrubí v závislosti na zrnitostním složení, objemové koncentraci a rychlosti proudění.

Pro měření byla použita potrubní trasa s horizontálním hydraulicky hladkým nerezovým potrubím o vnitřním průměru D = 17.5, 26.8 a 36 mm. Zkoumány byly vodní suspenze s kaolinem, úletovým a ložovým popílkem z fluidních kotlů s procesem odsiřování, pískem a pískem s přídavkem kaolinu. Kaolin byl přidáván do písčitých suspenzí za účelem vytvořit nenewtonskou nosnou kapalinu. Pro srovnání vlivu newtonské a nenewtonské nosné kapaliny bylo použito peptisační činidlo, které snížilo vnitřní přitažlivé síly mezi částicemi kaolinu a změnilo tokové vlastnosti suspenze. Dále byl zkoumán vliv doby a intenzity smykového namáhání pro časově závislé popílkové suspenze.

Kaolinové suspenze vykazují časově nezávislé nenewtonské chování, odpovídající pseudo-plastické kapalině s počátečním napětím pro objemové koncentrace vyšší než cca 5%. Na rozdíl od nich, hydrosměsi s obsahem fluidního úletového popílku jsou časově závislé a následkem smykového namáhání dochází k výraznému poklesu třecích ztrát v laminárním režimu proudění a zároveň ke snížení rychlosti přechodu do turbulentního režimu. Obdobný je i účinek přídavku hrubších částic ložového popela.

Tokové chování jemnozrnných koncentrovaných suspenzí se výrazně liší v laminární a turbulentní oblasti. Při přechodu z laminárního do turbulentního proudění dochází k náhlému zvýšení třecího odporu. Určení přechodného režimu proudění je velmi důležité pro bezpečný a efektivní návrh i provoz potrubní dopravy koncentrovaných suspenzí. Optimální provozní podmínky jsou dány rychlostí proudění těsně nad přechodem do turbulentního režimu, kde charakter proudění a energetická spotřeba mohou být velmi výhodné z hlediska provozní spolehlivosti a ekonomiky.

Klíčová slova: kaolinové suspenze, písčité suspenze, suspenze s fluidními popílky, experimentální výzkum, laminární proudění, turbulentní proudění, přechod z laminárního do turbulentního proudění, účinek zrnitostního rozdělení částic, účinek smykového namáhání suspenze

Keywords: Kaolin slurry, sand slurry, fluidic ash slurry, experimental investigation, laminar flow, turbulent flow, laminar/turbulent transition, effect of particle size distribution; effect of shearing

Contents

1. Introduction

The contribution presents results of experimental investigation of several fine-grained slurries and fine-grained slurries containing coarse-grained particles. It is focussed on the effect of particle size distribution and concentration on the hydraulic gradient vs. the slurry average velocity relationship, and the slurry flow behaviour in the laminar, transitional and turbulent regimes.

The flow pattern of fine-grained in-organic slurry depends strongly on solids concentration. If the solids content increases, the slurry flow behaviour changes from a Newtonian to non-Newtonian one, which can be generally described by the yield pseudo-plastic model.

Most knowledge on dense slurry flow behaviour has been concerned with the slurries consisting of either coarse-grained particles with settling tendencies or fine-grained particles creating a homogeneous, often non-Newtonian slurry. The flow behaviour of the slurry containing both coarser and very fine particles has not been till now sufficiently clarified. According to the slurry nature several types of predictive models exist, which can describe the slurry flow behaviour.

For dense homogeneous and pseudo-homogeneous slurries with non-Newtonian behaviour well known rheological models should be used. For heterogeneous slurries many empirical correlations exist, which can be after calibration successfully used for the specific condition of the given project [2, 3]. Understanding of mechanisms of the heterogeneous slurry flow makes possible to adopt the more complex models with physical background. The two-layer model may be used for description of the fully or partially stratified flow patterns, for prediction of threshold (deposition-limit) velocity, pressure drop due to friction, the thickness and translational velocity of the sliding-bed and also the value of mean slip between the solid and liquid phases [4].

When the slurry contains both, fine and also coarser particles in a highly dispersed form, and the quantity of the dispersed phase or the particle size increases, heterogeneity becomes more important and the slurry becomes complex homo-heterogeneous. This flow regime is more complicated than either homogeneous or heterogeneous flow since some kind of the conveyed solid behaves heterogeneously in a homogenous carrier.

Presence of fine solid particles in a Newtonian liquid evokes a complex rheological behaviour of the slurry. The slurries can change their behaviour from Newtonian to non-Newtonian in dependence on the solid phase concentration and composition, contents of colloidal particles, particle interactions and internal physical-chemical environment [19].

The flow behaviour of coarse-grained slurries containing also fine-grained particles is also discussed in the contribution. The effect of fine and coarse particles can be illustrated on different behaviour of the slurry containing fly ash only and fly ash/bottom ash in different proportion [18]. Due to addition of bottom ash the total content of very fine particles in the slurry decreases and consequently, the flow behaviour changes markedly.

2. Flow Regimes

Newton's law generally describes laminar flow of Newtonian fluids

$$\tau = \mu(-du/dr), \tag{1}$$

where τ, μ, u and r are the shear stress, dynamic viscosity, local velocity of liquid and cylindrical co-ordinate, respectively. Flow behaviour of non-Newtonian slurries in the laminar regime could be in general modelled as the yield pseudo-plastic fluid, i.e. by Bulkley-Herschel rheological model

$$\tau = \tau_y + K\ (-du/dr)^n, \tag{2}$$

where τ_y, K and n are the yield stress, the fluid consistency and the flow behaviour index, respectively. These parameters control the rheogram of the slurry and have to be determined experimentally [10]. The Bingham or power-law fluid models are special cases of it [2].

For the turbulent regime of non-Newtonian fluids several models can be used. Thomas and Wilson [9] developed a new analysis for the turbulent flow of non-Newtonian fluids. They suggest for the slurry mean velocity V_m

$$V_m = V_N + V_*\left[11.6(\alpha - 1) - 2.5\ln\alpha - \Omega\right], \tag{3}$$

where V_* is the friction velocity and V_N is the mean velocity for equivalent Newtonian flow, $\Omega = -2.5\ln(1-\xi) - 2.5\xi(1+0.5\xi)$ and $\xi = \tau_y / \tau_w$ represents the effect of the velocity profile in the logarithmic or core regions. The area ratio α for a yield pseudo-plastic fluid is given as $\alpha = 2(1+\xi\, n)/(1+n)$ [22].

Slatter [7] proposed a model for turbulent flow regime; he defined the roughness Reynolds number Re_r for the yield pseudo-plastic slurry

$$Re_r = 8\rho V_*^2 / [\tau_y + K\ (8\, V_* / d_p)^n], \tag{4}$$

where d_p is a representative particle diameter and ρ is slurry density. The mean velocity can be obtained by integration over the pipe cross section

$$V_m / V_* = \kappa^{-1}\ln(R/d_p) + B - 3.75, \tag{5}$$

where Karman's constant $\kappa = 0.40$ and coefficient $B = B_R = 8.5$ for the fully developed rough wall turbulent flow ($Re_r > 3.32$) or $B = B_s = 2.5\ \ln Re_r + 5.5$ for the smooth wall turbulent flow ($Re_r < 3.32$). For the fine-grained slurries the $d_p \sim d_{85}$ was found to be a good representation of the turbulent roughness effect of the solid particles in the slurry.

The transition from laminar to turbulent flow (L/T transition) is important for save and efficient design and operation of slurry pipelining. The optimum operational conditions are slightly above the L/T transition region, where flow conditions and energy consumption should be often very attractive from operational and economic point of view.

Similarly to Newtonian fluids, the laminar/turbulent transition can be defined using the Reynolds principle. The generally accepted value of the Reynolds number at the lower bound of the L/T transition is $Re = 2100$ [2]. In order to use the standard Newtonian theory Wilson [21] defined an apparent or secant viscosity μ'. Secant viscosity is not a constant for the given slurry, pipe diameter and flow rate. It must be evaluated at each given value of wall shear stress τ_w

$$\mu' = \tau_w \left(-du/dr\right)_w^{-1}, \tag{6}$$

where subscript w indicates values on pipe wall. Wilson recommended calculating Reynolds number of L/T transition as

$$\mathrm{Re}_{Newt} = \rho V_m D/\mu', \tag{7}$$

where ρ and D are the liquid density and inner pipe diameter, respectively.

However, Reynolds number generally ignores the fact, that at laminar flow condition due to the presence of the yield stress a plug flow pattern can exist. The facts that plug affects the flow stability in sheared annulus was taken into account by Slatter [7, 8]. Slatter rejected the plug-flow region as a non-fluid behaviour and plug regarded as a solid boundary. The flow of the sheared fluid in the annulus was only considered and for the mean velocity in the annulus V_{ann} Reynolds number was defined

$$\mathrm{Re}_3 = \frac{8\rho V_{ann}^2}{\tau_y + K\left[8V_{ann}/D\left(1-\tau_y/\tau_w\right)\right]^n}. \tag{8}$$

To compare different prediction criteria for L/T transition, a practical approach introduced by Shook and Roco [5] seems to be the most useful. Based on the empirically confirmed fact they establish as a critical point the intersection of the laminar and turbulent flow theoretical lines in wall shear stress over mean velocity graph.

For heterogeneous slurries many empirical correlations exist, which can be after calibration successfully used [2, 3]. The classic work was done by Durand in the early 1950′s for the horizontal flow and mono-disperse particle size distribution [1]. Based on the experimental results the following relationship was proposed for so called Durand's function

$$\varphi = (i_s - i_o)/i_o.c_v = K\left[Fr/\sqrt{Fr_w\left(\rho_p/\rho_o - 1\right)}\right]^{-\alpha}, \tag{9}$$

where i_s and i_o are the slurry and carrier liquid pressure drops, respectively, c_v is the slurry concentration, $Fr = V_s^2 / gD$ and $Fr_w = w_{50}^2 / gD$ are the slurry and mean particle Froude numbers, ρ_o and ρ_p are water and particle density, respectively, w_{50} is the fall velocity of a medium particle. The Durand method provides a simple tool for a wide range of slurry conditions. Its disadvantage is in the low accuracy for the low and higher velocity range and the fact, that the model does not reflect different slurry flow patterns, especially fully-stratified and fully suspended flow pattern. Silin and Kobernik [6] found that the model could be used within the range $4 < Fr/Fr_w^{1/2} < 15$.

3. Experimental material and equipment

3.1. Experimental installation

The effect of a slurry composition, particle size distribution and volumetric concentration c_v on the flow parameters of kaolin slurry, sand and sand-kaolin slurries and fluidic fly and fly-bottom ash slurries was studied experimentally. The slurries were tested using an experimental re-circulation pipeline loop in which the test section consists of smooth stainless steel pipes of inner diameter D of 17.5, 26.8 or 36 mm, see Fig. 1.

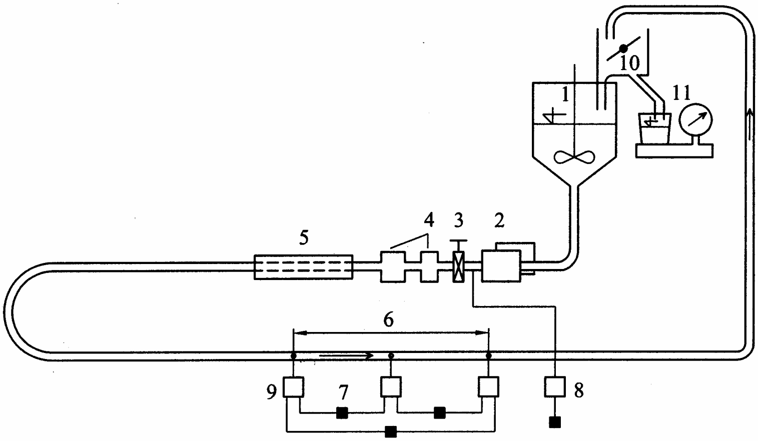

Figure 1 Layout of the experimental pipeline loop (1-slurry tank, 2-pumps, 3-control valve, 4-flow meters, 5-heat exchanger, 6-test section, 7-differential pressure transducers, 8-absolute pressure transducer, 9-pressure tapings with sedimentation vessels, 10-flow divider, 11-density and discharge measurement)

The slurry was forced by EPS-125-6-60 screw pump or by booster centrifugal pump WARMAN 3/2 C–AH from an agitated open storage tank to the transport pipe. Phase advancer was used to reach the different slurry flow rate [13]. The loop with a screw pump can operate in the laminar as well as turbulent regime up to the average slurry velocity V_s of about 5 m/s, with WARMAN pump up to 7.5 m/s. The measurement section was equipped with three pressure tapings connected with Hottinger-Baldvin PD-1 differential pressure transducers (measuring range up to 0.1 MPa, carrier frequency 5 kHz) monitored by computer.

The slurry flow-rate and concentration were measured by an electromagnetic flow meter KROHNE-PROFILUX IFM 5080 K A and a mass flow meter KROHNE-CORIMASS-800 G+. The loop also allowed the direct measurement of mass flow rate and of slurry density [17]. The temperature of the slurry was maintained at about 18°C by the heat exchanger. Main attention was paid to the effect of slurry average velocity, concentration, composition and the effect of time and intensity of shearing on the pressure gradient vs. the average slurry velocity relationship i_s/V_s.

3.2 Used material

Highly concentrated kaolin slurries without and with the peptising agent, i.e. kaolin-water slurry and kaolin-water-sodium carbonate slurry of different volumetric concentrations, varying from c_v = 3 to 35 %, were tested for the laminar, transitional and turbulent regimes. Several kinds of sand-water mixtures (concentration from c_v = 6 to 48 %) and also fluidic fly and fly/bottom ash-water mixtures of concentration varying from c_v = 18 to 31 % were measured.

Tab. 1 shows the particle size distribution of the kaolin from Horni Briza (d_{50} = 2.8 µm, ρ_p = 2546 kg/m^3). Three kinds of sand of uniform size distribution, e.g. the fine, medium and coarse mono-disperse quartz sands from Provodin (see Tab. 2), their mixtures (mass proportion 1:2:1 and 1:1:1 of fine, medium and coarse sand) and two natural poly-disperse sands (sand Zavada, sand Nova Ves, density of all sands ρ_p = 2650 kg/m^3), were used. Water as well as low and medium concentrated Kaolin slurries were used as the carrier liquid for the sand slurries. Total volumetric concentration c_v of the investigated sand slurries ranged from 6 to 48 % [20].

Table 1 Particle Size Distribution and Density of the Kaolin (Horni Briza)

d [µm]	< 1	1-2	2-4	4-6	6-10	10-20	20-30	d_{max} [µm]
(%)	28	12	22	21	11	6	0	20

To compare the effect of Newtonian and non-Newtonian carrier on the slurry flow behaviour, a chemical agent with a sodium carbonate was used to change the physical-chemical environment of the slurry and to depress the attractive inter-particle forces, which evoke non-Newtonian behaviour of the slurry. Due to the peptising agent the slurry flow behaviour changes from non-Newtonian to nearly Newtonian [14, 15].

Table 2 Particle size distribution of the measured sands

sand	Provodin			Nova Ves	Zavada
	fine	medium	coarse		
mean diameter d_{50} [mm]	0.20	0.70	1.40	0.69	0.32
clay and dust [%]	0.02	0.03	0.04	0.2	3.0
$d = 0.063 - 0.25$ mm [%]	95.98	2.77	0.06	10.0	32.0
$d = 0.25 - 1.00$ mm [%]	4.0	96.3	3.9	54.8	63.0
$d = 1.00 - 2.00$ mm [%]	0	0.9	95.0	17.0	1.4
$d > 2$ mm [%]	0	0	1.0	18.0	0.6

For the ash-water mixture the fly ash from Trinec and from Porici and their mixtures with bottom ashes were used. The basic physical parameters are listed in Tab. 3. Parameters d, d_{50} , d_{max} and ρ_p are the particle diameter, mean particle diameter, maximal particle diameter, and the density of particle, respectively.

Table 3 Physical parameters of fluidic ash

Material		Trinec		Porici	
		fly ash	bottom ash	fly ash	bottom ash
ρ_p	kg/m^3	2 603	2 646	2718	2716
d_{50}	mm	0.014	0.300	0.008	0.450
d_{max}	mm	0.30	12	1.50	20
$d< 1$ µm	%	4		13	
$d<10$ µm	%	36		57	
$d<63$ µm	%	95	4	96	4

The fly ash from Porici differs considerably from the fly ash from Trinec, its mean diameter is only half of that of Trinec. Significant difference was also found in contents of very fine particles. The bottom ash from Porici is significantly coarser compared with the bottom ash from Trinec, its mean diameter is about 50% greater than that from Trinec. The volumetric concentration of the studied slurries ranged from 22% to 30% for the fly ash Trinec and from 18% to 23% for the fly ash Porici. The fly/bottom ash slurries reach slightly higher maximum concentration, i.e. 26% or 31%, respectively. It is due to the above mentioned different size distribution.

The maximum concentrations of the both fly ashes are different in agreement with their particle size distribution. The higher the contents of colloidal particles and smaller the mean diameter, the greater is the slurry tendency to coagulate. After mixing with water the colloidal particles create voluminous aggregates with a loose structure, where a large deal of water is fixed and the maximum slurry concentration is lower. It will be shown that shearing of the slurry or presence of coarse-grained particles helps to destroy the aggregates and a higher concentration of the ash slurry can be achieved.

4. Results and discussion

4.1. Kaolin slurry

The kaolin slurries were measured in the laminar, transition and turbulent regimes, and attention was paid to the hydraulic gradient i_s over mean slurry velocity relationship i_s/V_s and the flow stability in different regimes. The kaolin suspension was determined to be the time-independent, yield pseudo-plastic slurry. Fig. 2 documents the effect of slurry concentration on i_s/V_s relationship for the kaolin slurry and a yield pseudo-plastic behaviour of measured slurries for the concentration higher than 5%.

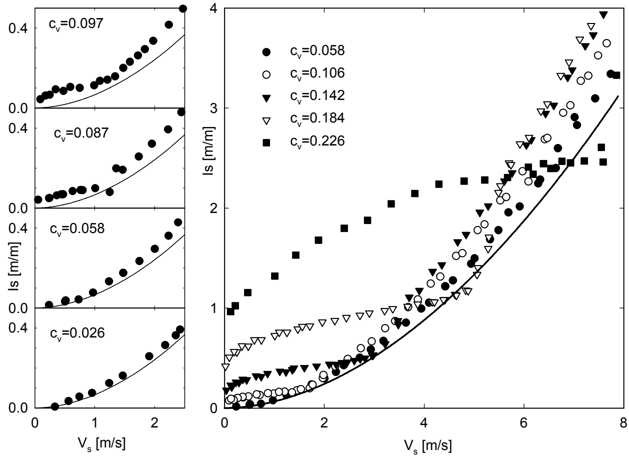

Figure 2 Effect of slurry concentration c_v. Kaolin slurry (D = 17.5 mm)

With increasing slurry velocity, the hydraulic gradient approaches the curve of water alone in the laminar region. Near the L/T transition point, the hydraulic gradient i_s could reach values even less than that reached of the clear water flow i_o [22]. However, in the transition zone, the hydraulic gradient sharply increases and a marked instability is characteristic for this region. Increase of the hydraulic gradient with growing flow velocity becomes less steep in the turbulent region; the value of slurry hydraulic gradient i_s becomes higher than that of water alone i_o.

Sensitivity analysis was used to find proper values of the flow behaviour index *n* of laminar and turbulent flow models since it strongly depend on the data evaluation. The best fitting value *n* for turbulent data depends on concentration [10]. Both Wilson and Slatter turbulent models well approximate the turbulent slurry flow if the value of *n* is correctly pre-determinate from turbulent experimental data. Dependency of the most suitable values of rheological parameters *n*, *K* and τ_y on volumetric concentration c_v was evaluated and the result is illustrated in Fig. 3.

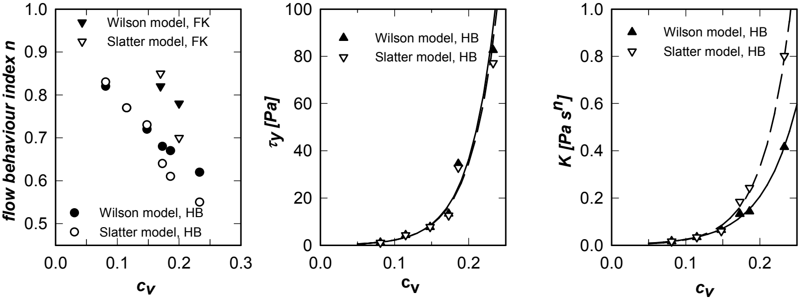

Figure 3 The effect of concentration c_v on the flow behaviour index *n*, yield shear stress τ_y and fluid consistency *K* (HB – kaolin Horni Briza, FK – fluidic fly ash Trinec)

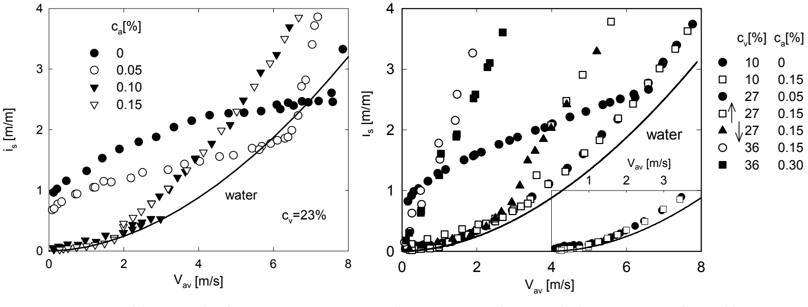

Figure 4 Effect of slurry concentration c_v and peptising agent/kaolin mass ratio c_a on hydraulic gradient i_s of kaolin slurry (*D* = 17.5 mm)

As Fig. 4 shows, the flow behaviour of peptised kaolin slurry in the laminar region is considerably different [11, 12, 14]. For higher agent concentration the yield stress τ_y practically vanishes and the hydraulic gradient is close to that of water. Practically no difference between peptised and untreated slurry can be found in transient and turbulent regimes. The peptising agent affects the velocity value V_{TR} corresponding to the beginning of L/T transition. For the slurry concentration c_v = 23% and peptising agent/kaolin mass ratio c_a = 0.05% the value of L/T transition velocity V_{TR} decreases from about 7.8 to 6.3 m/s and simultaneously the slurry hydraulic gradient i_s drops by about 30%. In the transition and turbulent regions, the hydraulic gradient i_s of the peptised slurry again sharply increases.

For the higher peptising agent/kaolin content (e.g., peptising agent/kaolin mass ratio c_a = 0.10 or 0.15%) the peptised slurry shows only slight non-Newtonian behaviour. L/T transition point occurs at a slurry velocity V_{TR} = 3.0 m/s for c_a = 0.10% and at V_{TR} = 2.0 m/s for c_a = 0.15%.

4.2. Sand slurry

The effect of particle size distribution on the hydraulic gradient ratio i_s/i_w versus the average slurry velocity V_s relationship of sand slurries is illustrated in Fig. 5. The coarse sand slurry reaches the higher hydraulic gradient i_s than the fine sand slurry, the difference decreases with growing velocity. The slurries consisting of the both sand mixtures (mass mixture proportion 1 : 2:1 or 1 : 1: 1 of fine, medium and coarse sand) and natural sand Zavada reach nearly the same values of the gradient ratio i_s/i_w, which are very close to those of the fine sand for the slurry velocity V_s > 4 m/s. For V_s < 4 m/s the medium sand slurry reaches higher values of the gradient ratio i_s/i_w than the fine sand or both sand mixtures, very similar to that of the coarse sand. For 4 < V_s < 6 m/s the medium sand gradient ratio i_s/i_w is surprisingly less even than that of the fine sand, for the slurry velocity V_s > 6 m/s the fine sand gradient ratio i_s/i_w again increases and approaches values of the sand mixtures and even of the coarse sand.

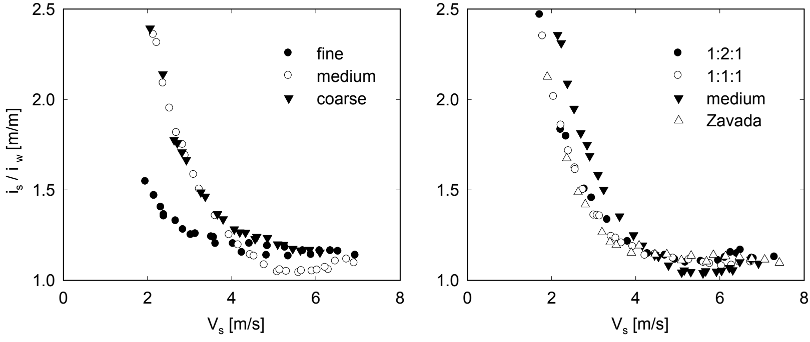

Figure 5 Hydraulic gradient ratio i_s/i_w vs. slurry velocity V_s for sand slurries (D = 26.8 mm, c_v = 23 %)

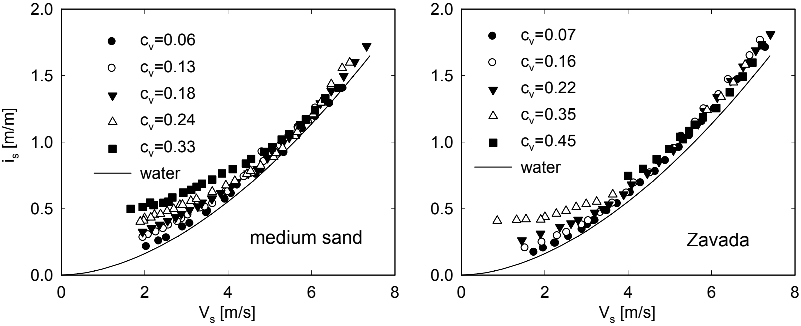

Figure 6 Hydraulic gradient i_s vs. slurry velocity V_s for sand slurries (D = 26.8 mm)

Poly-disperse sand slurries (sand mixture 1:1:1 or 1:2:1, sand Zavada) can reach even lower values of the pressure gradient i_s at the higher slurry concentration and velocity than the less concentrated slurry. This tendency, which can be explained due to the L/T transition of more concentrated slurry at the higher velocity V_{TR}, is illustrated in Fig. 6.

To describe the effect of Newtonian and non-Newtonian carrier slurry consisting of the sand conveyed in water, natural and peptised kaolin slurry were measured [15]. The relationship i_s/V_s for the slurry of total concentration c_v = 34 % is illustrated in Fig. 7. When sand is conveyed in the kaolin slurry with concentration $c_{v,K}$ = 13 %, the slurry exhibits a non-Newtonian behaviour. For the higher velocity range the hydraulic gradient i_s markedly increases compared to the water alone or sand-water slurry.

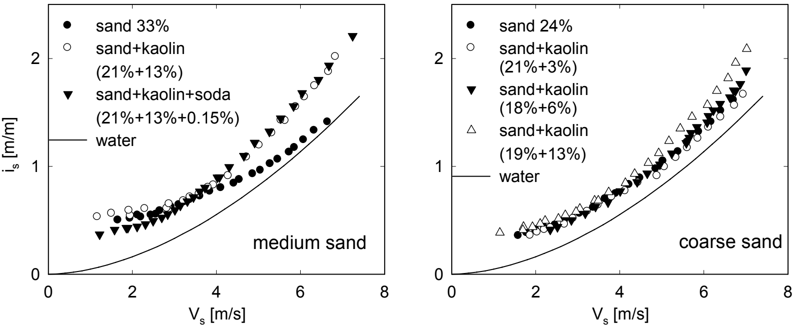

Figure 7 Effect of carrier liquid rheological properties on i_s /V_s relationship for sand slurries (D = 26.8 mm)

When the carrier kaolin slurry is peptised (to avoid the slurry non-Newtonian behaviour), i_s in the laminar region becomes markedly lower

[16]. However, for the slurry velocity $V_s > 3$ m/s the peptised medium sand-kaolin slurry ($c_{v,S} = 21\%$, $c_{v,K} = 13$ %) reaches the higher hydraulic gradient i_s than the medium sand slurry ($c_{v,S} = 33$ %) and practically the same as the untreated sand-kaolin slurry. This confirms that the favourable effect of the slurry peptisation in transitional and turbulent regions can vanish. The same trend was observed for the coarse sand. The addition of small kaolin contents (concentration of kaolin about $c_{v,K} = 3\%$) favourably affects the flow behaviour of the sand-kaolin slurry.

The low and medium concentrated sand-water mixture can be described e.g. by Durand model. Modified Durand method was used for the experimental data processing and scale up. Durand function (see Eq. 9) can be rearranged

$$\varphi = K\left[Fr_w\left(\rho_p / \rho_o - 1\right)\right]^{\alpha/2}.Fr^{-\alpha} = B.Fr^{-\alpha}, \qquad (10)$$

and the material parameters B and α can be determined from the experimental data processing [3]. Eq. (10) can be represented by a linear relationship in log-log plot of Durand function φ vs. slurry Froude number Fr, see Fig. 8. It is obvious that the method gives acceptable results for the Froude numbers less than 60, i.e. for the slurry velocity $V_s < 4$ m/s. The great scattering of experimental data shows that the method is improper for the higher velocity range, where the slurry flow behavior is different from behavior expected for Durand model [20]. The material parameters evaluated for the measured sand slurries in a velocity range $V_s < 4$ m/s are given in Tab. 4.

Table 4 Material parameters of sand slurries

sand	B	α	sand	B	α
fine	35.8	0.90	mixture 1:1:1, 1:2:1	80.4	1.06
medium	159.8	1.18	Nova Ves	82.9	1.10
coarse	88.4	0.98	Zavada	83.5	1.09

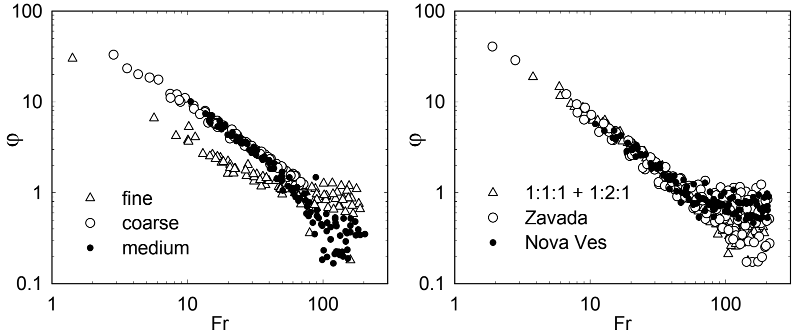

Figure 8 Plot of Durand function φ vs. slurry Froude number Fr

4.3. *Fly ash slurry*

In contrast to the kaolin or sand slurries the fluidic ash-water mixtures are time dependent, yield pseudo-plastic slurries [13, 17]. The trend of hydraulic gradient in laminar and turbulent regimes is similar, but the hydraulic gradient does not reach value close to the water value for L/T transition point. The effect of the slurry concentration c_v, average slurry velocity V_s and shearing on hydraulic gradient i_s is shown in Fig. 9. For the gradually increasing slurry velocity V_s several intervals of relationship i_s / V_s can be distinguished. For low velocity range of the "fresh" slurry (V_s < 1 m/s) hydraulic gradient i_s increases with growing slurry velocity V_s similarly as for the time-independent non-Newtonian slurry. For the fully developed laminar flow the relative increment of hydraulic gradient i_s becomes lower in comparison with time-independent non-Newtonian slurry. Shearing effect is more evident for the concentrated slurries where even "plateau" on i_s / V_s diagram can be observed.

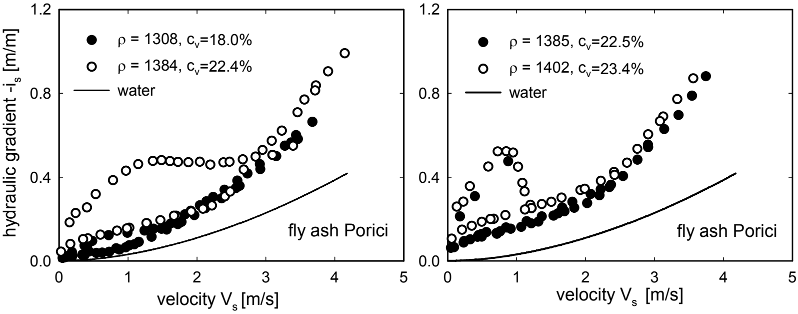

Figure 9 Effect of slurry concentration c_v and slurry velocity V_s on pressure gradient i_s (D = 36 mm)

The effect of different course of shearing is illustrated in Fig. 9, too. The "fresh" fly ash slurry Porici (c_v = 22.5 %) was shortly pumped at a slurry velocity V_s < 1 m/s. Afterwards V_s was increased and kept for 2 minutes at the value V_s = 3.75 m/s, then V_s was decreased to the value close to zero and gradually increased up to V_s =3.5 m/s. Compared to the slurry with concentration c_v = 23.4 % pumped in laminar regime with velocity V_s = 1.0 m/s for period of 4 hours, it was found that the short time high intensity (turbulent) shearing has a similar effect as long time shearing in a fully developed laminar regime on the slurry flow behaviour. During the period of 4 hours the velocity grows from V_s = 1.0 m/s up to V_s = 1.25 m/s and the hydraulic gradient decreases from i_s = 0.50 to i_s = 0.26 m/m. After about 2.5 hours the slurry becomes stabilised and further laminar shearing has no effect on the slurry behaviour, see Fig. 10.

The fly ash slurry Trinec (c_v = 26,4 %) was for 3 hours pumped in the laminar regime at a velocity about $V_s \approx 1.75$ m/s. The effect of shearing was found similar as that of the slurry Porici. The effect of shearing is higher for higher slurry concentration, the hydraulic gradient decreases markedly with the time of pumping during initial period of flow.

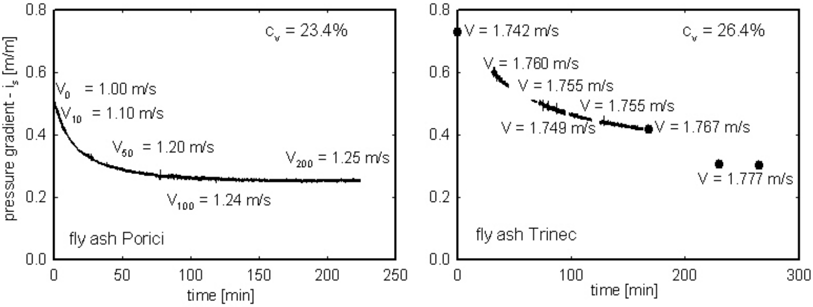

Figure 10 Effect of shearing on fly ash slurry (Porici, D = 36 mm; Trinec, D = 26.8 mm)

Dependence of the pressure gradient i_s on the slurry concentration c_v, slurry velocity V_s and shearing for the ash slurry from Trinec is illustrated in Fig. 11. Four different concentrations of the fly ash slurry were measured in the laminar, intermediate and turbulent regimes. Laminar flow of the ash slurry can be well described by Bulkley-Herschel model. For the turbulent region two models, i.e. Wilson-Thomas [22] and Slatter [8] were used. The both models represent well the experimental data; however, they are very sensitive on the values of rheological parameters, especially on the flow behaviour index n. The rheological parameters should be evaluated from turbulent experimental data, see Tab. 5.

Table 5 Fly ash slurry Trinec rheological parameters

Slurry concentration	rheological parameters determined from					
	stabilised slurry turbulent data			stabilised slurry laminar data		
c_v [%]	τ_y	K	n	τ_y	K	n
22.4	2.135	0.0252	0.90	2.14 */	0.025 */	0.90 */
25.7	4.337	0.0451	0.88	3.071	0.1728	0.68
26.4	5.616	0.0420	0.89	5.536	0.0466	0.87
29.5	9.774	0.1324	0.81	11.520	0.0427	0.96
*/ very low number of laminar experimental data of stabilised slurry						

To describe the effect of fine and coarse particles contents the slurry consisting of the fly ash and the bottom ash was measured [17]. The addition of bottom ash causes the decreasing of the hydraulic gradient i_s and also the higher solids concentration c_v can be reached, see Fig. 12. The "fresh" slurry from Porici with bottom ash reaches markedly lower hydraulic gradient i_s in the laminar region, e.g. for the slurry velocity V_s = 1.5 m/s more than twice. The effect of coarse particles for stabilised slurries is significantly less. In the turbulent region the both slurries reach nearly the same value of the hydraulic gradient i_s, however the only fly ash slurry reached L/T transition for markedly higher velocity than the fly/bottom ash one. For the "fresh" fly ash slurry for $V_{TR} \approx 3.4$ m/s, for the "fresh" fly/bottom ash slurry $V_{TR} \approx 2.1$ m/s, for the stabilised slurry the transition point is reached for substantially lower velocity, i.e. $V_{TR} \approx 2.4$ m/s and $V_{TR} \approx 1.6$ m/s, respectively. The similar favourable effect of a bottom ash was found for the ash slurry from Trinec, too.

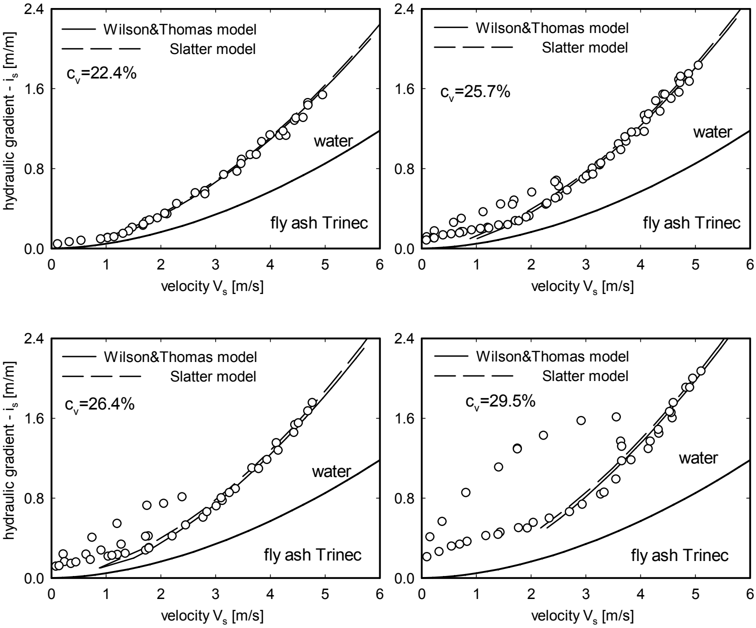

Figure 11. Approximation of hydraulic gradient i_s by turbulent models for fly ash slurry (Trinec, D = 26.8 mm)

The effect of variable proportion of the bottom ash and slurry concentration is shown in Fig. 13 f. For the slurry with 10% of the bottom ash the radical change in the course of i_s / V_s relationship appears near the velocity value V_s = 1.4 m/s, where the sudden reduction of the hydraulic gradient i_s can be observed. Due to the shearing effect the hydraulic gradient slightly decreases with increasing flow velocity and for the velocity value $V_s \approx 2.3$ m/s it reaches minimum. Then it again gradually increases with the growing velocity up to the L/T transition point. In the intermediate or turbulent region the hydraulic gradient again steeply increases.

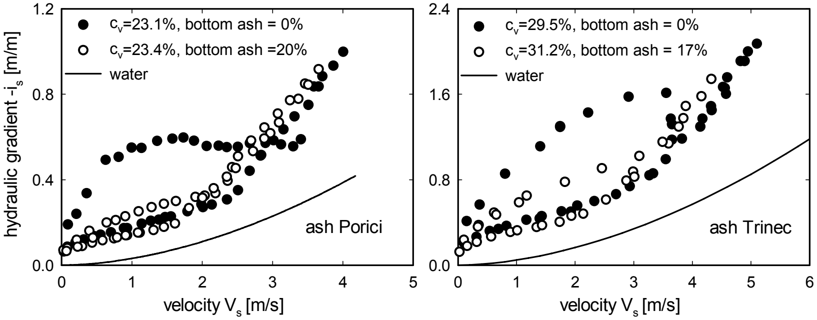

Figure 12 Effect of bottom ash (ash Porici, D = 36 mm and ash Trinec, D = 26.8 mm)

When the bottom ash proportion grows to 30% the maximum reduction of hydraulic gradient is more than 50% for the "fresh" slurry and only 25% for the stabilised slurry at V_s = 1.35 m/s. For the slurry with 30% proportion of the bottom ash the sudden reduction of the hydraulic gradient is missing, but the hydraulic gradient i_s reaches significantly lower values in the laminar region. For the "fresh" slurry with 20% of the bottom ash and total concentration c_v = 23.4 or 26.1% the plateau effect was observed for the higher values of the total concentration only. The hydraulic gradient i_s is nearly constant for the concentration c_v = 26.1% in the velocity range from $V_s \approx 1.0$ m/s to $V_s \approx 3.0$ m/s. For stabilised slurry this effect is missing.

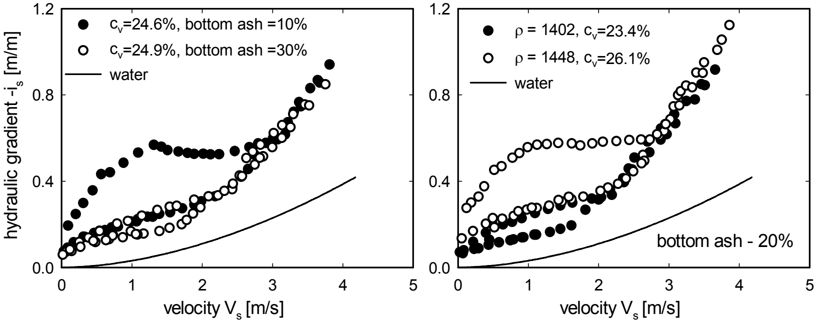

Figure 13 Effect of slurry concentration c_v and slurry velocity V_s on pressure gradient i_s (fly / bottom ash Porici, D = 36 mm)

Similarly as it was shown in Figs. 12 and 13 the difference between the hydraulic gradient of the slurries with different proportion of the bottom ash is negligible in the turbulent region, but the slurry with higher contents of the bottom ash reached L/T transition for the markedly lower velocity. Consequently, it is possible to use lower operational velocities for the slurry with bottom ash, which brings the significant reduction of pressure losses.

The effect of the time of shearing is more considerable for the slurry with higher contents of very fine particles and a lower proportion of the bottom ash. The flow behaviour of dense slurries with colloidal particles is strongly affected by the mutual particle-particle and particle-liquid interactions, by the attractive and the repulsive forces acting between solid particles in the slurry. After mixing of fly ash with water attractive forces between particles initiate the slurry coagulation. For the higher slurry concentration and contents of colloidal particles voluminous aggregates with a loose structure, where a large deal of water is fixed, are formed and a viscous friction can act only in a small-scale. More energy is consumed on the aggregate deformation.

An intensive shearing or addition of coarse particles depresses the effect of attractive inter-particle forces and results in the destruction of the aggregates. Water originally fixed in aggregates is liberated and the slurry becomes peptised, the viscous friction can play a larger role - an apparent viscosity decreases and the slurry is liquefied [4, 18]. The favourable effect of the bottom ash addition or shearing is significantly lower in the intermediate and turbulent region.

5. Conclusions

The study revealed a time-dependent yield pseudo-plastic behaviour of the fluidic fly and fly/bottom ash slurries and the possibility of substantial reduction of the flow resistance by mechanical treatment or by arrangement of the particle size distribution. The higher contents of colloidal or very fine particles the greater is the tendency of the slurry to coagulate.

An intensive turbulent or long time laminar shearing or addition of the bottom ash evokes the significant changes of the flow behaviour of fluidic ash slurries. The hydraulic gradient decreases markedly, the L/T transition is reached at lower flow velocities, and also the higher ash slurry concentration can be reached. A remarkable hysteresis was observed as a result of the shearing for the fluidic ash slurries in the laminar region. The effect of shearing is more significant for higher slurry concentrations and for the fly ash slurry than for the fly/bottom ash slurry.

The flow behaviour of the fluidic ash slurries can be approximated by Bulkley-Herschel model in the laminar region. In the turbulent region the Wilson or Slatter models can be used. The rheological parameters are dependent also on the history of shearing and should be determined from the experimental data of the respective flow regime, separately for "fresh" and "stabilised" slurry.

The sand slurry exhibits some attributes of a non-Newtonian behaviour for the slurry volumetric concentration $c_v > 20\ \%$. The effect of size distribution for the sand slurry depends on the flow velocity. The coarse sand slurry reaches a higher hydraulic gradient than the fine sand slurry, the difference decreases with growing velocity. The poly-disperse sand slurries reach nearly the same values of hydraulic gradient as the fine sand slurry.

High-concentrated sand-kaolin slurries show also the non-Newtonian behaviour. At the low and medium slurry velocities the flow resistance grows with the increasing total concentration, at the high velocities the effect of concentration can be opposite.

When the carrier kaolin slurry is peptised, hydraulic gradient in the laminar region becomes markedly lower, the favourable effect vanishes in the transitional and turbulent regions. However, the addition of small contents of kaolin favourably affects the flow behaviour of the sand-kaolin slurry.

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Curriculum Vitae

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