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LAMINAR/TURBULENT TRANSITION OF DENSE NON-NEWTONIAN SLURRIES

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Summary: *Pipeline system should be operated out of transitional regime because of the flow instability at this area, sudden flow pattern change and origination of concentration waves. The optimum operational condition is slightly above the laminar/turbulent transition zone, where flow conditions should be often very attractive from an economic point of view. Results of experimental investigation of water mixtures of kaolin and fluidic ash in horizontal straight pipes are presented. It was found that laminar/turbulent transition zone can be characterised by unstable flow condition indicated by the pressure fluctuations.*

1. Introduction

Many materials of commercial and industrial interest are handled and transported in form of highly concentrated, frequently non-Newtonian slurries in pipes, what requires advantage knowledge of their flow behaviour. The concentrated slurry behaviour changes significantly if the laminar flow changes to the turbulent one. The paper deals with flow behaviour of fine-grained highly concentrated non-Newtonian slurries, i.e. water mixtures of kaolin or fluidic fly ash, in straight horizontal pipes in the laminar and turbulent regimes with special attention to laminar/turbulent transition (*L/T* transition). Results of the experimental investigation conducted on the pipe loop with hydraulically smooth pipes are presented.

Power consumption represents a substantial portion of the overall pipeline transport operational costs. For that reason great attention was paid to the reduction of hydraulic losses. One possibility of the power requirement reduction, beside the use of macromolecular or micelar additives (Zakin et al., 1970), is based on the change of the physico-chemical behaviour of the slurry (Vlasak et al., 1999; Vlasak & Chara, 2007 a) or the use of optimal particle size distribution (Vlasak & Chara, 2007 b; Vlasak et al., 2004 b). Kaolin slurry is the appropriate slurry for the study of flow behaviour and rheological parameters due to the change of physico-chemical environment as shown for example by Horsley & Snow, 1986. Vlasak et al. (1999) described the effect of two peptising agents (sodium carbonate and sodium water-glass) on three kinds of kaolin of the different chemical composition and size distribution. Similarly, Vlasak et al. (2006) described the effect of chemical agents on ash-water mixtures.

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The presence of fine solid particles evokes a complex rheological behaviour of the slurry. After mixing the fine particles with water, attractive and repulsive forces between the particles initiate the process of coagulation and peptisation, respectively. Behaviour of the slurry is strongly affected by inner forces acting between particles in the slurry. In the highly concentrated fine-grained suspension particle collisions hydrodynamic and non-hydrodynamic interactions exist. A mutual balance or dominance of repulsive or attractive forces could explain a mechanism of clay slurries liquefying or thickening. The coagulation process gives rise to the voluminous aggregates, where a large deal of water is fixed what contributes to the increasing of yield stress and viscosity of the slurry. During the slurry flow a great deal of energy is consumed on the aggregates deformation. The aggregates could be destroyed by the introducing high level of turbulence or by the change of the physico-chemical environment of the slurry. The presence of the peptising agent results in a significant decrease of the viscosity and yield stress. Non-Newtonian behaviour of the slurry, caused by the presence of colloidal particles, is strongly depressed by addition of the peptising agent.

The considerable decrease of the apparent viscosity and pressure drops can be reached if the aggregates are destroyed to individual particles and/or small clusters of particles. To validate this process the kaolin-water mixture of without and with peptising agent was tested for laminar and turbulent regimes.

2. Experimental equipment and procedure

The studied slurries were measured on the experimental pipeline loop to demonstrate the effect of the slurry parameters in the pipe flow under laminar and turbulent conditions. Attention was paid to the measurement of pressure drops/average slurry velocity relationship, with special regard to the laminar/turbulent transition and stability of hydraulic gradient and pressure fluctuation in different flow regimes.

2.1. Experimental equipment

The studied slurries were tested using the experimental re-circulation pipeline loop (see Fig. 1) with a hydraulically smooth stainless steel pipe of inner diameter $\boldsymbol{D}$ = 17.5, 26.8 and 36 mm. The slurry was forced by EPS-125-6-60 screw pump from an agitated open storage tank to the transport pipe. Phase advancer was used to control the flow rate. The measurement section was equipped with the Hottinger-Baldvin PD-1 differential pressure transducers monitored by the computer. The slurry flow-rate and concentration were measured by the electro-magnetic flow meter KROHNE-PROFILUX IFM 5080 K A and the mass flow meter KROHNE-CORIMASS-800 G+. At the pipe outlet a box divider was mounted, which allowed direct measurement of mass flow rate and of mixture density. The temperature of the slurry was maintained at around 18°C.

2.2. Used material

Two types of *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.The kaolin from Horni Briza was used. The kaolin mean diameter d_{50} was 2.8 μm and the kaolin density ρ_p is 2549 kg/m^3, the particle size distribution see Tab. 1.

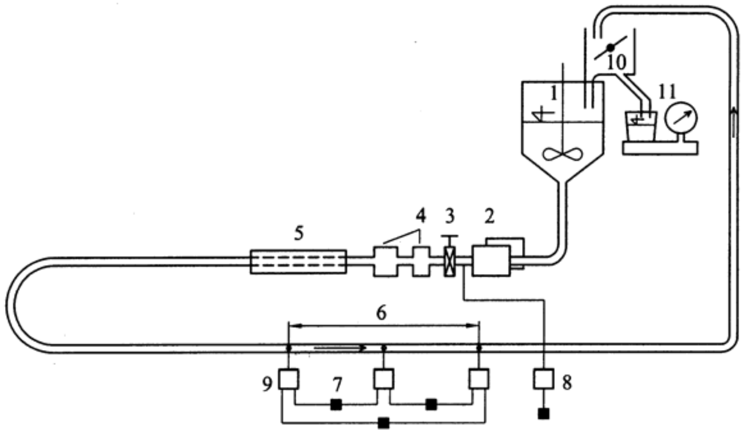

Fig. 1 Layout of the experimental pipeline loop (1-slurry tank, 2-pumps, 3-control valve, 4-flow meters, 5- heat exchanger, 6-test section, 7-differential pressure transducers, 8-absolute pressure transducer, 9-pressure tapings with sedimentation vessels, 10-flow divider, 11-density and discharge measurement)

Tab. 1 Particle size distribution of the Kaolin Horni Briza

d (μm)	< 1	1-2	2-4	4-6	6-10	10-20	20-30
(%)	28	12	22	21	11	6	0

Tab. 2 Physical parameters of fly and bottom ashes

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

Sodium carbonate was used as a *peptising agent*, the addition of sodium carbonate to the slurry supplies Na^+ cations for the compensation of the surface charge of bivalent ions. The calcium ions in the slurry are precipitated in the form of insoluble calcium carbonate. The peptising agent/kaolin mass ratio was varied from c_a = 0.05 to 0.30 %, which falls within the optimum efficiency range of additive (Vlasak et al., 1999).

For the *ash-water mixture* the fly ashes from Trinec and from Porici and their mixtures with bottom ashes were used. The particle size distribution is listed in Tab. 2 and on Fig. 2. Parameters d and d_{max} are the particle diameter and maximal particle diameter, respectively. 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. On the contrary 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 fly ash 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. 31% or 26%, respectively. The maximum concentration of the ash slurries differs in agreement with the ash particle size distribution. The higher the contents of colloidal particles and smaller the mean diameter, the lower concentration is reached.

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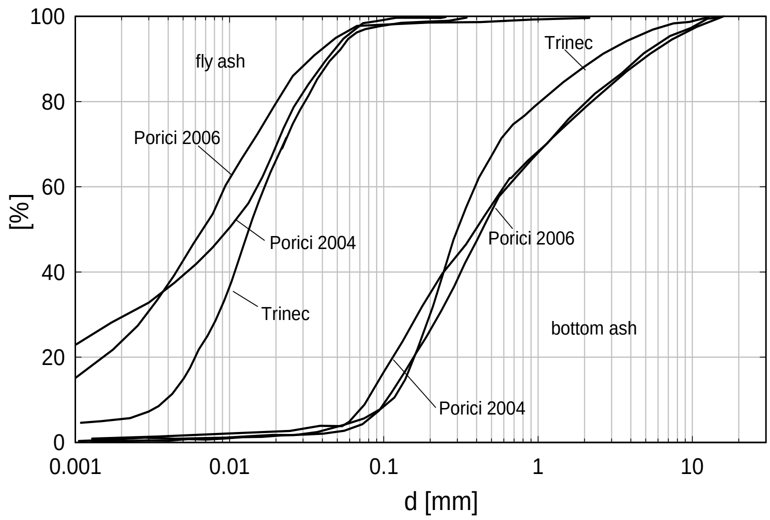


Fig. 2 Particle size distribution of measured fly and bottom ash

3. Results and Discussion

3.1. Kaolin slurry

The kaolin slurries without peptising agent were determined to be time-independent, yield pseudo-plastic suspension. Fig. 3 shows the effect of the slurry concentration c_v on hydraulic gradient/average slurry velocity relationship i_s / V_s of the kaolin slurries. Their flow behaviour can be well approximated by Herkley-Berschel model for concentration higher than about 5%. With increasing slurry velocity, but still in the laminar region, 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 of the water (Wilson et al., 1997). In the transition zone the hydraulic gradient sharply increases and a marked instability is characteristic for this region. In the turbulent region the hydraulic gradient increases with growing flow velocity less steeply, however the value of slurry hydraulic gradient becomes significantly higher than that of water alone. Both Wilson and Slatter turbulent models (Thomas & Wilson , 1987; Slatter, 1995) well approximate the turbulent slurry flow if the value of $\boldsymbol{n}$ is correctly pre-determinate from turbulent experimental data (Vlasak & Chara, 1999).

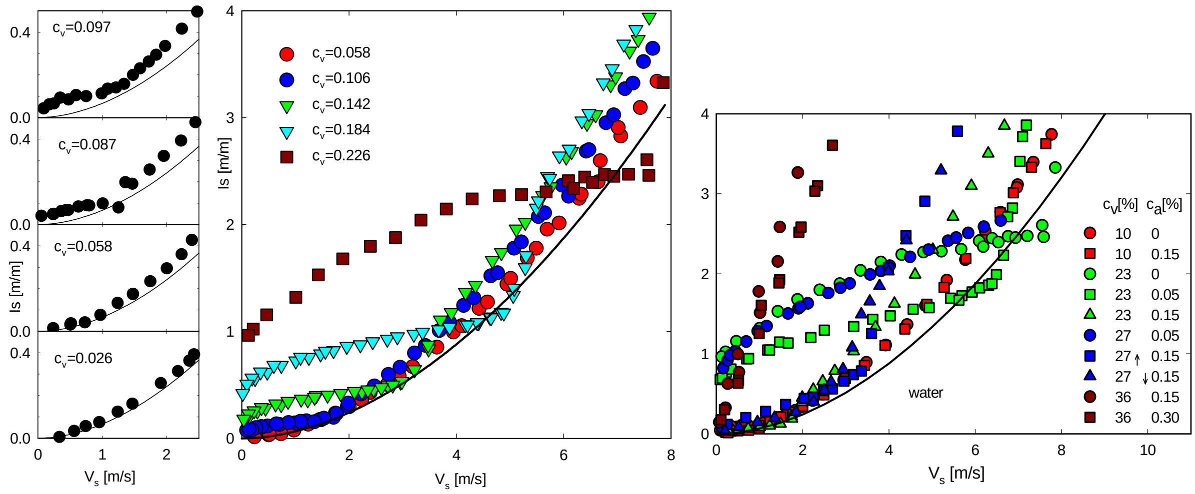


Fig. 3 Effect of slurry concentration $\boldsymbol{c_v}$. Kaolin slurry and peptising agent/kaolin with mass ratio $\boldsymbol{c_a}$ ($\boldsymbol{D}$ = 17.5 mm)

The flow behaviour of peptised kaolin slurry is considerably different, especially in the laminar region, see Fig. 3. Efficiency of a peptising agent depends on the slurry concentration $\boldsymbol{c_v}$, peptising agent/kaolin mass ratio $\boldsymbol{c_a}$, and on the flow regime. Even relatively low concentrations of the peptising agent result generally in marked decreases in both yield stress and apparent viscosity. For the higher agent concentration the yield stress $\boldsymbol{\tau_y}$ practically vanishes and the hydraulic gradient/velocity relationship is very close to the water-alone curve, On the contrary, practically no difference between peptised and untreated slurry can be found in transient and turbulent regimes (Vlasak et al., 1999; 2002).

The peptising agent affects the velocity value $\boldsymbol{V_{TR}}$ corresponding to the beginning of the L/T transition. For the slurry concentration $\boldsymbol{c_v}$ = 23% and peptising agent/kaolin mass ratio $\boldsymbol{c_a}$ = 0.05% the value of the L/T transition velocity $\boldsymbol{V_{TR}}$ decreases from about 7.8 to 6.3 m/s and simultaneously the slurry hydraulic gradient $\boldsymbol{i_s}$ drops by about 30%.

For the higher peptising agent content (e.g., peptising agent/kaolin mass ratio $\boldsymbol{c_a}$ = 0.10 or 0.15%) the peptised slurry shows only a slight non-Newtonian behaviour. L/T transition occurs at a slurry velocity $\boldsymbol{V_{TR}}$ = 3.0 m/s for $\boldsymbol{c_a}$ = 0.10% and at $\boldsymbol{V_{TR}}$ = 2.0 m/s for $\boldsymbol{c_a}$ = 0.15%. Peptised slurry behaves practically as a Newtonian liquid in turbulent region. In the transition and turbulent regions, the hydraulic gradient of the peptised slurry again sharply increases. Similar behaviour was observed at a slightly higher slurry concentration of 26%.

3.2. Fly Ash slurry

Different behaviour was observed for ash-water slurries. In contrast to kaolin slurries the fluidic ash-water mixtures are time dependent, yield pseudo-plastic slurries (Vlasak & Chara, 2001; Vlasak et al., 2004 a). The trend of the hydraulic gradient $\boldsymbol{i_s}$ in the laminar and turbulent regime is similar, but the hydraulic gradient does not reach the value close to the water value for the L/T transition point. The effect of the slurry concentration, slurry velocity and shearing on hydraulic gradient is shown in Fig. 4.

Several intervals of the pressure gradient vs. slurry velocity relationship $\boldsymbol{i_s/V_s}$ can be distinguished. For the fully developed laminar flow the relative increment of hydraulic gradient $\boldsymbol{i_s}$ becomes lower in comparison with that of time-independent non-Newtonian slurry. Shearing effect is more evident for the concentrated slurries where even "plateau" on $\boldsymbol{i_s /V_s}$ diagram can be observed. After the L/T transition is reached, hydraulic gradient steeply increases with the growing slurry velocity. The slope of $\boldsymbol{i_s /V_s}$ relationship becomes slightly less after the slurry reaches the fully turbulent region, however the value of the slurry hydraulic gradient becomes expressively higher than that for water alone.

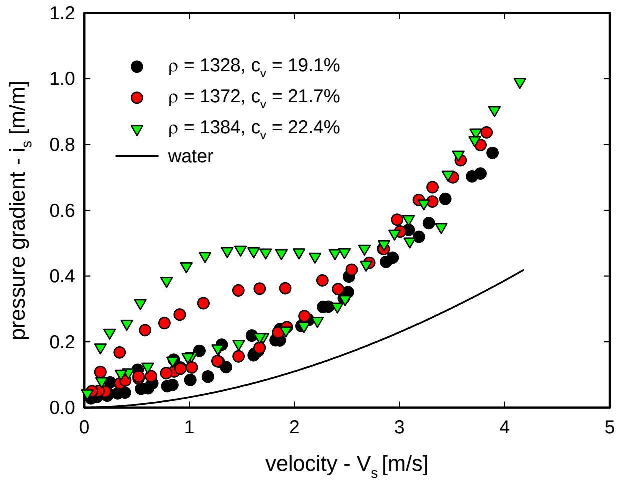


Fig. 4 Effect of slurry concentration $\boldsymbol{c_v}$ and flow velocity $\boldsymbol{V_s}$ on pressure gradient $\boldsymbol{i_s}$ (Fly ash Porici, $\boldsymbol{D}$ = 36 mm)

For the higher concentration due to the effect of shearing time, the hydraulic gradient decreases markedly with the time of pumping during initial period of flow (see Fig. 5). Difference in the hydraulic gradient near the transition point is more than 50% of the original value. The L/T transition is reached for the considerably lower value of slurry velocity for the long time-sheared slurry. The turbulent shearing has a greater effect on decreasing of the slurry hydraulic gradient. The effect of shearing on the hydraulic gradient in the laminar region and also on the L/T transition point position is evident from considerably different course of $\boldsymbol{i_s/V_s}$ relationship for stabilised and "fresh" slurry.

Laminar flow of a concentrated fly ash slurry can be well described by Bulkley-Herschel model. The rheological parameters, i.e. yield stress τ_y, fluid consistency K and flow behaviour index n are dependent on the particle size distribution and density, carrier liquid properties, slurry concentration and also the history of shearing. The rheological parameters should be determined from the experimental data, separately for the "fresh" and stabilised slurry.

For the evaluation of experimental data and prediction of the hydraulic gradient over the slurry velocity relationship $\boldsymbol{i_s /V_s}$ in the turbulent region two turbulent models, i.e. Wilson – Thomas and Slatter, were used (Thomas & Wilson, 1987; Slatter, 1995). Both models represent well the experimental data in the turbulent region and their mutual difference is negligible, however they are very sensitive on the values of used rheological parameters, especially on the value of the flow behaviour index $\boldsymbol{n}$. The rheological parameters should be evaluated from turbulent experimental data. The approximation of hydraulic gradient versus slurry velocity relationship according to both turbulent models is shown in Fig. 5.

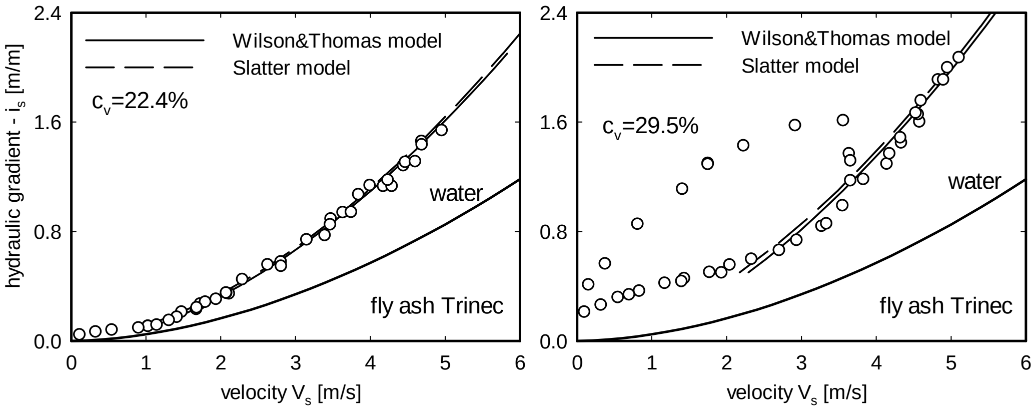


Fig. 5 Approximation of hydraulic gradient $\boldsymbol{i_s}$ by turbulent models for fly ash slurry (Trinec, $\boldsymbol{D}$ = 26.8 mm)

3.3 Fly ash/bottom ash slurry

The addition of bottom ash changes the quality of an inter-particle interaction and inner structure of the slurry, which becomes so called homo-heterogeneous. It suppresses attractive inter-particle forces and causes the decreasing of the hydraulic gradient or makes possible to reach the higher solids concentration.

To describe the effect of fine and coarse particles contents the slurry consisting of the fly ash and the bottom ash was measured (Vlasak et al., 2004 a). The addition of bottom ash causes the decreasing of the hydraulic gradient. The "fresh" slurry from Porici with a bottom ash reaches markedly lower hydraulic gradient in the laminar region, e.g. for the slurry velocity $\boldsymbol{V_s}$ = 1.5 m/s more than twice, see Fig. 6.

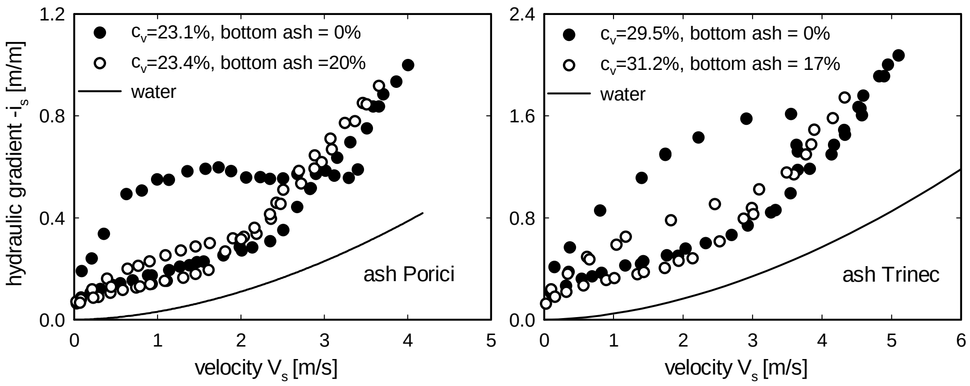
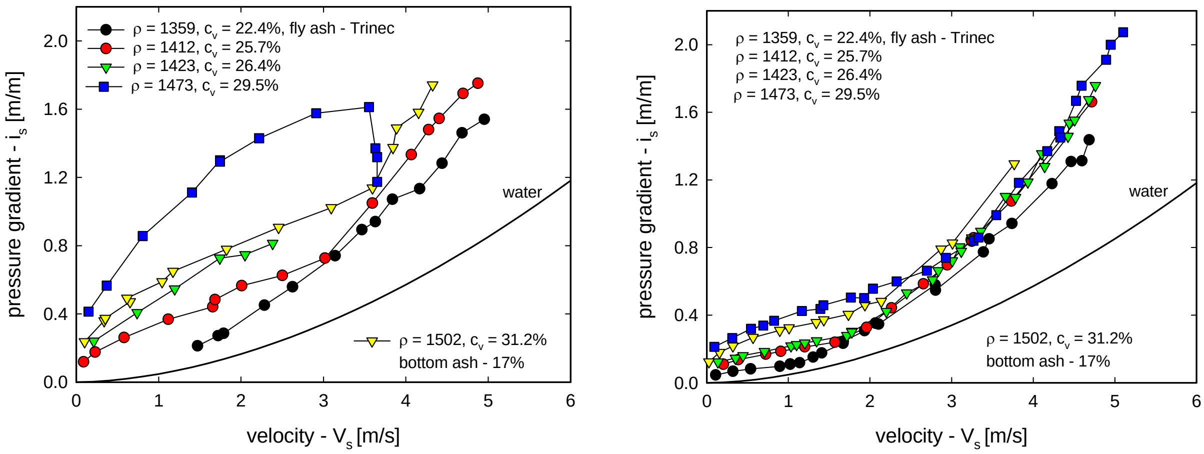


Fig. 6 Effect of bottom ash (ash Porici, $\boldsymbol{D}$ =36 mm and ash Trinec, $\boldsymbol{D}$ =26.8 mm)

The effect of coarse particles for the stabilised slurries is significantly less. In the turbulent region both slurries reach nearly the same value of the hydraulic gradient, however the only fly ash slurry reached the L/T transition for the markedly higher velocity than the fly/bottom ash one. The "fresh" fly ash slurry reached the L/T transition for $\boldsymbol{V_{TR}} \approx$ 3.4 m/s, the "fresh" fly/bottom ash slurry for $\boldsymbol{V_{TR}} \approx$ 2.1 m/s, the stabilised slurry reached the transition point 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.



period of shearing : less than 1 hour over 1 hour

Fig. 7 Effect of sheering time on pressure gradient $\boldsymbol{i_s}$ (ash Trinec, $\boldsymbol{D}$ = 26.8 mm)

Dependence of the pressure gradient on the slurry concentration, flow velocity and time of shearing for the fly ash from Trinec is illustrated in Fig. 7 for the time period less or more than 1 hour from the beginning of pumping. The effect of shearing on the pressure gradient in the laminar region and also on the change of the L/T transition point position is evident from the considerably different course of $\boldsymbol{i_s/V_s}$ relationship for stabilised and “fresh” slurry. Simultaneously the favourable effect of bottom ash addition can be observed. The slurry with content of 17% of the bottom ash and 83% of the fly ash reaches for total solids concentration $\boldsymbol{c_v}$ = 31.2% in the laminar region markedly lower values of pressure gradient $\boldsymbol{i_s}$ compared to only fly ash slurry of substantially lower total concentration $\boldsymbol{c_v}$ = 29.5%. The effect of coarse-grained particles is not so significant for stabilised slurry in the turbulent region.

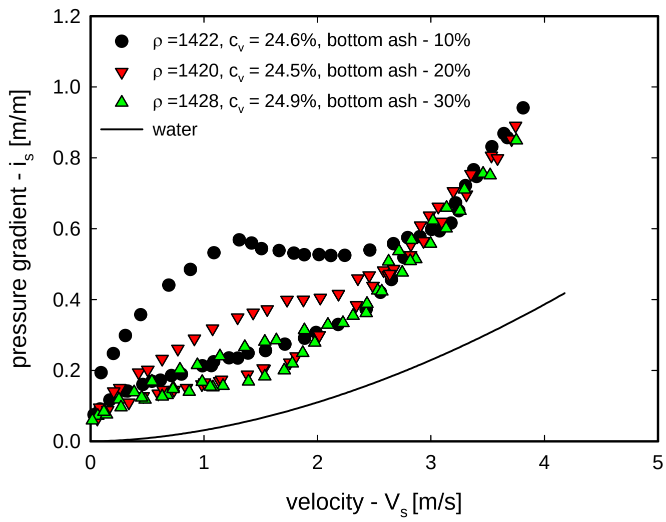


Fig. 8 Effect of variable proportion of the bottom ash (ash Porici, $\boldsymbol{D}$ = 36 mm, $\boldsymbol{c_v} \sim 25\%$)

Fig. 8 shows the effect of variable proportion of the bottom ash on the pressure gradient vs. average slurry velocity relationship $\boldsymbol{i_s/V_s}$ for slurries with fly and bottom ash from Porici.

Effect of the time of shearing is more significant for the slurry with lower proportion of coarse-grained particles. For fully developed laminar flow at slurry velocity about $\boldsymbol{V_{av}}$ = 1.4 m/s the pressure gradient $\boldsymbol{i_s}$ reduces about 35 - 40% when the bottom ash proportion grows from 10% to 20%. When the bottom ash proportion increases from 10% to 30% the pressure gradient reduces even about 50 - 55%.

3.4. Laminar/turbulent transition

With increasing velocity, at the beginning of the L/T transition zone, the hydraulic gradient steeply increases. This phenomenon is accompanied by a high level of instability and the occurrence of pressure fluctuations. During the slurry flow measurement we observed in more detail the inner structure of the slurry flow, especially of differential pressure fluctuation with regard to the laminar, transitional and turbulent regimes.

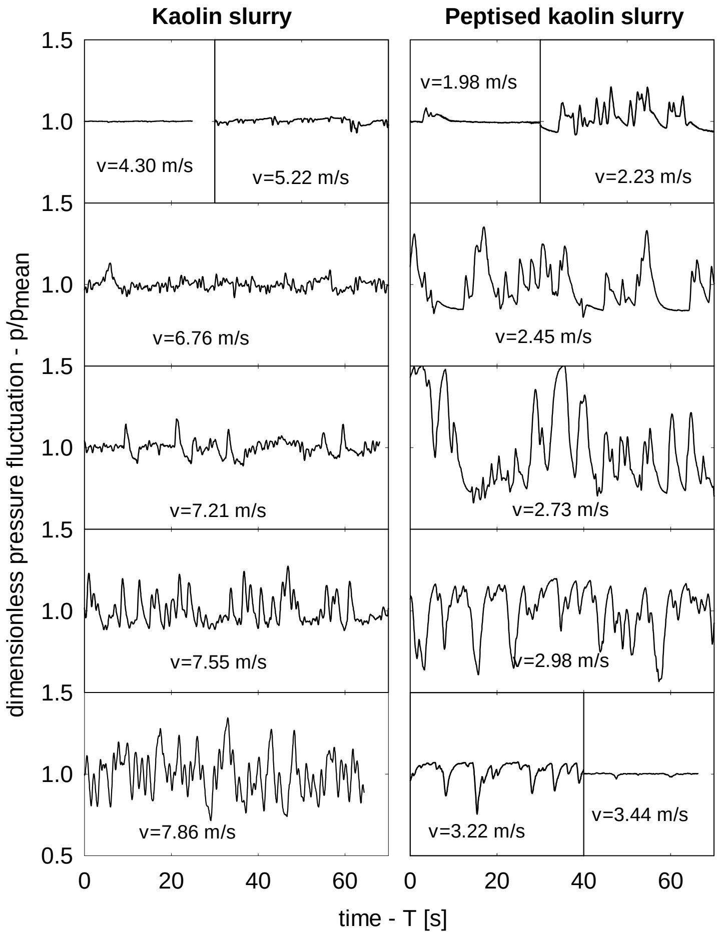


Fig. 9 Effect of slurry velocity on dimensionless pressure fluctuation $\boldsymbol{p/p_{mean}}$ for kaolin slurry ($\boldsymbol{c_v}$ = 23%) and peptised kaolin slurry ($\boldsymbol{c_v}$ = 23%, $\boldsymbol{c_a}$ = 0.10%)

Different patterns of the differential pressure fluctuation were noted for the laminar, transitional and turbulent regimes. In the laminar regime, if any pulsation exists, pressure fluctuations are small and can be observed at lower slurry concentrations only. When pressure fluctuations occur they are negligible, of small amplitude and temporally limited. Fig. 9 illustrates the dimensionless differential pressure fluctuation $\boldsymbol{p/p_{mean}}$ as a function of time, plotted for different kaolin slurry velocities (Vlasak et al., 2002).

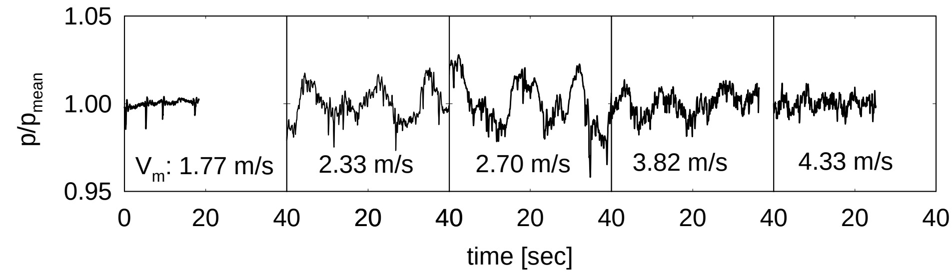


Fig. 10 Effect of slurry velocity on dimensionless pressure fluctuation ***p/p_mean*** for fly ash slurry (c_v = 29,5 %)

A high level of instability, eddy formation and occurrence of pressure fluctuation are characteristic for the L/T transition region, the amplitude of pressure fluctuations is increasing with increasing slurry velocity. For the fully developed transition regime the pressure pulsations are symmetrical, but for the initial part of the transition regime pulsations seem to grow from the mean value of pressure. This can be explained by the fact that inertial forces prevail over the viscous ones, which are weak to put down turbulent pulsations. It can be documented especially for peptised slurry with less viscosity value. For velocities close to the turbulent region the pressure record becomes gradually smoother. For the fully developed turbulent regime pressure pulsations change the frequency. The frequency of fluctuation becomes higher and due to filtration of pressure signal the record of pressure gradient seems to be relatively smoother and stable, as it is well documented on the peptised kaolin slurry. The same trend was confirmed for the fly ash-gypsum slurry, see Fig. 10. Effect of average slurry velocity on dimensionless root mean square of pressure fluctuation p_{RMS}/p_{mean} for kaolin slurry without and with peptising agent is shown in Figs.11 and 12, respectively. The peaks in pressure fluctuation determine L/T transition region. The higher the slurry concentration, the higher the flow velocity, and also the amplitude of pressure fluctuation in transition area. Similar pattern is illustrated in Fig. 12, where the effect of peptising agent ratio is illustrated. The higher the peptising agent content, the higher the amplitudes of pressure fluctuation and the transition area is reached at a lower flow velocity.

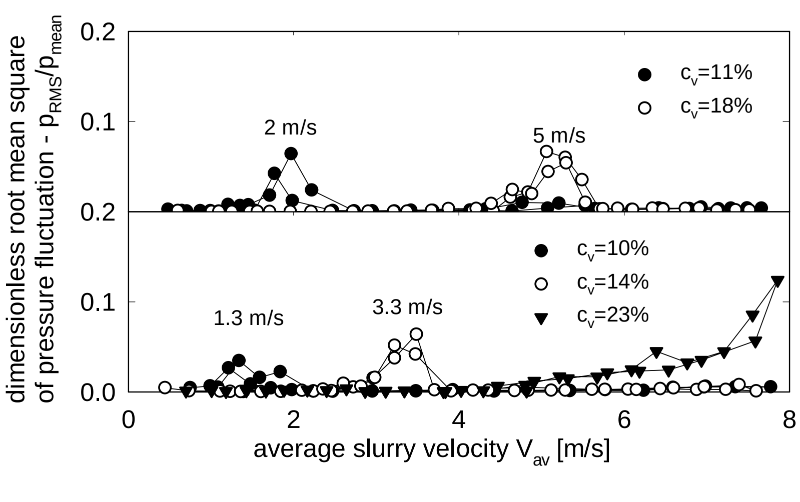


Fig. 11 Effect of average velocity and concentration of kaolin slurry on dimensionless root mean square of pressure fluctuation of kaolin slurry

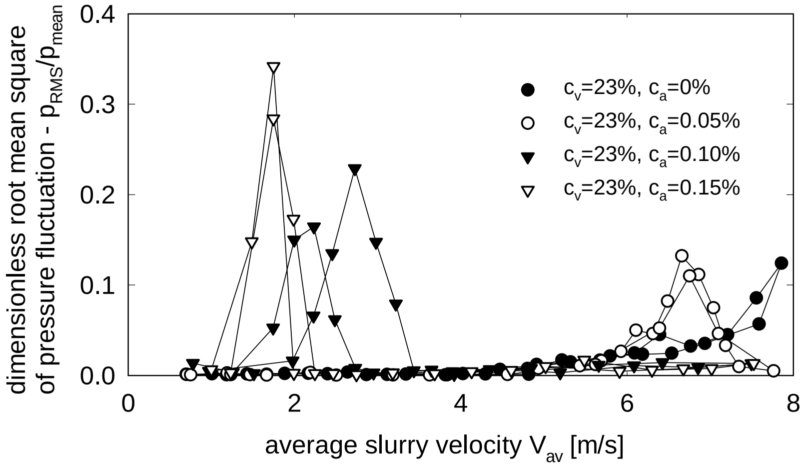


Fig. 12 Effect of slurry velocity and sodium carbonate/kaolin mass ratio on dimensionless root mean square of pressure fluctuation of peptised kaolin slurry

4. Conclusions

For hydraulic transport of fine-grained material the laminar regime seems to be advantageous due to the low energy consumption and wear rate, however it brings a risk of the material deposition in the pipe or even pipe blockage. On the contrary, turbulent flow brings a higher energy consumption, wear rate and material degradation. The laminar/turbulent transition regime is dangerous due to its instability. The most advantageous operational conditions were found in the turbulent region, slightly above the transition regime. The location of the L/T transition is very important for the proper design, safe and efficient operation of dense slurry pipelines. From the experimental investigation of fine-grained highly concentrated slurries, i.e. water mixtures of kaolin and fluidic fly ash the following conclusions were drawn:

The kaolin slurry is a time-independent, yield pseudo-plastic suspension. Its flow behaviour can be approximated by Bulkley-Herschel model in the laminar region and by Wilson or Slatter models in the turbulent region.

Addition of peptising agent can serve to change the flow behaviour of kaolin slurry, can help to reach much higher concentration of solids and results in a significant decrease in the apparent viscosity and yield stress, and the L/T transition region is reached at significantly lower flow velocity. For high peptising agent content the transition from non-Newtonian to Newtonian behaviour was observed. The effect of the peptising agent is larger in the laminar regime and for the higher kaolin concentration.

The water mixtures containing fluidic fly and fly/bottom ashes are time-dependent yield pseudo-plastic slurries. whose flow behaviour can be approximated by Bulkley-Herschel model in the laminar region and by Wilson or Slatter models in the turbulent region. The rheological parameters are dependent also on the history of shearing and should be determined from experimental data of the respective flow regime, separately for “fresh” and “stabilised” slurry.

An intensive turbulent or long time laminar shearing or addition of the bottom ash results in the significant changes of the flow behaviour of the fly ash slurries. The pressure drops decrease markedly, the L/T transition is reached at lower flow velocities, and also the higher ash slurry concentration can be reached. The effect is significantly lower in the intermediate or turbulent region and it is higher for the fly ash slurry than for the fly/bottom ash slurry.

The intersection method is very practical to determine the L/T transition. A high level of instability and occurrence of pressure fluctuation is characteristic for the L/T transition zone. Pressure fluctuation can be used as indicator of the L/T transition regime.

The control of the physical-chemical behaviour, of the inner structure and time and intensity of shearing acting on a slurry makes possible to optimise both the energy and water consumption, to improve quality and economy of the transport, handling and processing of the fly ash slurry.

The study revealed the possibility of substantial reduction of the flow resistance and velocity of the L/T transition by mechanical treatment, by the arrangement of particle size distribution or by addition of chemical agents. Consequently, it is possible to use lower operational velocity, what brings the significant reduction of pressure losses.

Acknowledgement
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