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EFFECT OF SHEARING, COARSE PARTICLE AND DRAG REDUCING ADDITIVES CONTENTS ON FLOW BEHAVIOUR OF DENSE FLY ASH-WATER MIXTURES

P. Vlasák[*], Z. Chára[*], J. Konfršt[*]

Summary: *The dense fluidic ash-water mixtures are time dependent, their shearing results in the significant decrease of the pressure drop in the laminar region, also laminar/turbulent transition region were reached for lower flow velocity. Presence of bottom ash or chemical agent affects favourably the flow behaviour of dense fluidic ash-water mixtures. The paper is focussed on the experimental study of the effect of concentration, time and intensity of shearing and particle size distribution on the hydraulic gradient vs. the average velocity relationship in the laminar, transitional and turbulent regimes. The re-circulation pipe loop with smooth stainless steel pipes of the inner diameters D = 26.8 and 36 mm was used for measuring the ash-water mixtures flow parameters.*

1. Introduction

The slurry changes its flow behaviour in dependence on the solid phase concentration and composition, especially on the contents of colloidal and coarse-grained particles, their mutual interactions and slurry physical-chemical environment. Most knowledge on dense slurry flow in the pipe has been concerned with the slurries consisting of either coarse particles with settling tendencies or very fine particles creating homogeneous, often non-Newtonian slurry. The flow behaviour of the slurry containing both coarser and very fine particles has not been hitherto sufficiently clarified.

The flow behaviour of highly concentrated slurries with colloidal particles is strongly affected by the mutual particle-particle and particle-liquid interactions, by the effect of the attractive and repulsive forces between the solid particles. The presence of the fine solid particles, especially colloidal particles, in a Newtonian liquid evokes complex rheological behaviour of the slurry due to many physical and chemical factors acting on the both, liquid and solid components.

During the slurry flow, shear-induced translation and rotational motions of the particles cause hydrodynamic interactions, which result in particle-particle collisions and formation of temporary multiples. Such interactions lead to an increase in the rate of viscous energy dissipation and the slurry bulk viscosity.

[*] Ing. Pavel Vlasák, DrSc., Ing. Zdeněk Chára, CSc., Ing. Jiří Konfršt, Ph.D.: Institute of Hydrodynamics ASCR; Pod Paťankou 30/5, 166 12 Praha 6; tel.: + 420 233323748, fax: + 420 233324361; e-mail : vlasak@ih.cas.cz

Inter-particle interactions of non-hydrodynamic origin are the most significant in the systems with colloidal particles and usually evoke non-Newtonian behaviour of the slurry. The interactions originate from the random Brownian motion of particles and colloidal forces due to the van der Waals attractive forces and the electrostatic repulsive forces. In the highly concentrated fine-grained suspensions both types of the interactions are present, and their influence on the rheology is a function of the physical and electro-chemical characteristics of the particles, the nature of the carrier liquid and of the type and shearing intensity of the flow, Nguyen & Boger (1984), Vlasak et al (1999 a, 1999 b).

If the attractive forces acting in the slurry prevail, process of coagulation and sedimentation is initiated. However, a simultaneous existence of the repulsive forces enables to stabilise the slurry and keeps individual particles separated. The effect of the electro-static repulsive forces on the stabilisation process could quite well explain a mechanism of clay slurries liquefying, Satava (1973).

When solid particles are mixed with water, attractive and repulsive forces between colloidal particles initiate the process of coagulation, the particles tend to bunch into bigger aggregates since it decreases the total energy of the system. In the voluminous particle aggregates a great deal of water is fixed what contributes to the increasing of yield stress and apparent viscosity of the slurry. During the slurry flow a great deal of energy is consumed on aggregates deformation. To start the process of peptisation, i.e. to break the aggregates it is necessary to modify the physical-chemical environment or to introduce high level of turbulence to produce adequate repulsive forces, which destruct the aggregates. Water originally fixed in aggregates is liberated, the viscous friction can play a larger role and the slurry is liquefied. To prove these processes different fly ash slurries without or with the bottom ash content and chemical agent were measured on the experimental pipeline loop.

The paper deals with the flow behaviour of the slurries containing colloidal, clay, dust and also coarse-grained particles. It presents the results of experimental investigation of fly ash-water mixtures containing coarse-grained particles, i.e. bottom ash. Flow behaviour was experimentally investigated with respect to the flow velocity, volumetric concentration and solids composition. Also the effects of intensity and time of shearing and effect of change of slurry chemical environment for fluidic ash-water mixtures were studied.

2. Experimental equipment and material

The fluidic ash-water mixtures were tested using an experimental re-circulation pipeline loop (see Fig. 1), in which the test section consists of hydraulically smooth stainless steel pipes of inner diameter D of 26.8 or 36 mm, Vlasak & Chara (2001), Vlasak et al. (2002, 2004 b). The measured mixtures were 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 three pressure tapings connected with the Hottinger-Baldvin PD-1 differential pressure transducers monitored by the computer. The slurry flow-rate and concentration were measured by electro-magnetic flow meter KROHNE-PROFILUX IFM 5080 K A and mass flow meter KROHNE-CORIMASS-800 G+.

At the downstream end of the test pipes a box divider was mounted, which allowed direct measurement of mass flow rate and of mixture density, Vlasak& Chara (1999 c), Vlasak et al. (2004 a). The installation makes possible to operate in the laminar and turbulent regime up to the average slurry velocity V_s about 5 m/s. The temperature of the mixture was maintained at about $t \approx 18$ °C by the heat exchanger situated at the beginning of the transport pipe. Main attention was paid to the effect of slurry average velocity, concentration, solids composition and the effect of time and intensity of shearing on the pressure gradient i_s vs. the average mixture velocity V_s relationship in the laminar, transitional and turbulent regimes.

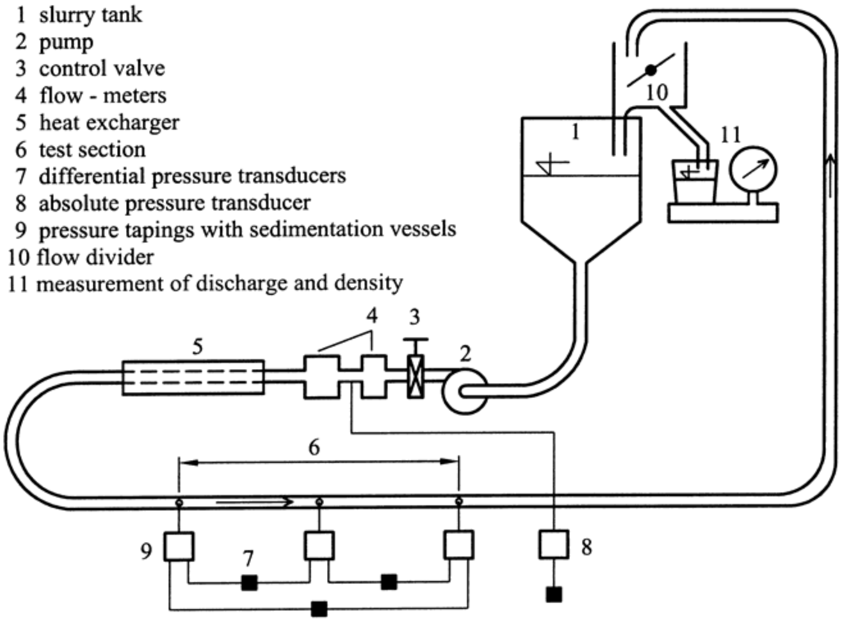

Fig. 1 Layout of the experimental pipeline loop

To prove the flow behaviour of ash-water mixtures two fly ashes from Trinec and from Porici and their mixtures with bottom ashes were used. The basic physical parameters are listed in Table 1. The mean diameter of fly ash Porici is only half of that of Trinec, the bottom ash Porici is significantly coarser compared with the Trinec bottom ash. Significant difference was also found in the contents of colloidal particles and particles less than 10 µm.

Table 1. Physical parameters of fluidic ash

Material			ash Trinec		ash 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 ratio	d<63 µm	%	95	4	96	4

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.The maximum concentrations of the both fly ashes are different in agreement with their particle size distribution. The higher is the contents of colloidal particles and smaller the mean diameter, the greater is tendency of the slurry to coagulate.

3. Experimental results and discussion

On the contrary to kaolin slurry the fluidic ash-water mixtures are time dependent, yield pseudo-plastic slurries, Vlasak & Chara (2001), Vlasak et al. (2004 a, b). The fluidic ash slurry can reach only relatively low solids concentrations since fly ash contains high percentage of colloidal particles. Concentration of the studied slurries is close to the liquid limit and even a relatively small change in concentration results in a rather expressive change of the pressure gradient.

The effect of slurry concentration c_v, average slurry velocity V_s and different course of shearing on hydraulic gradient i_s are shown in Fig. 2 for fly ash Porici. For gradual increasing of the slurry velocity several intervals of hydraulic gradient vs. slurry velocity relationship i_s /V_s can be distinguished due to the different effect of intensity of shearing. The effect of concentration is greater in the laminar region. The trend of ash slurry hydraulic gradient in the laminar region is similar to e.g. kaolin slurry, but the hydraulic gradient does not reach the value close to the water value for the laminar/turbulent transition point. After the laminar/turbulent transition is reached, the hydraulic gradient steeply increases with the growing slurry velocity and for fully turbulent region the hydraulic gradient becomes expressively higher than that of water alone.

For low velocity of the “fresh” slurry (V_s < 1 m/s) the hydraulic gradient i_s increases with growing slurry velocity V_s similarly as for the time-independent non-Newtonian slurry. For fully developed laminar flow the effect of shearing already influences the apparent viscosity of the fly ash slurry and the relative increment of hydraulic gradient becomes lower in comparison with time-independent non-Newtonian slurry. Shearing effect is more evident for more concentrated slurries (c_v > 20%) where even “plateau” on i_s /V_s diagram can be observed. The hydraulic gradient remains constant or even slightly decreases with the growing slurry velocity.

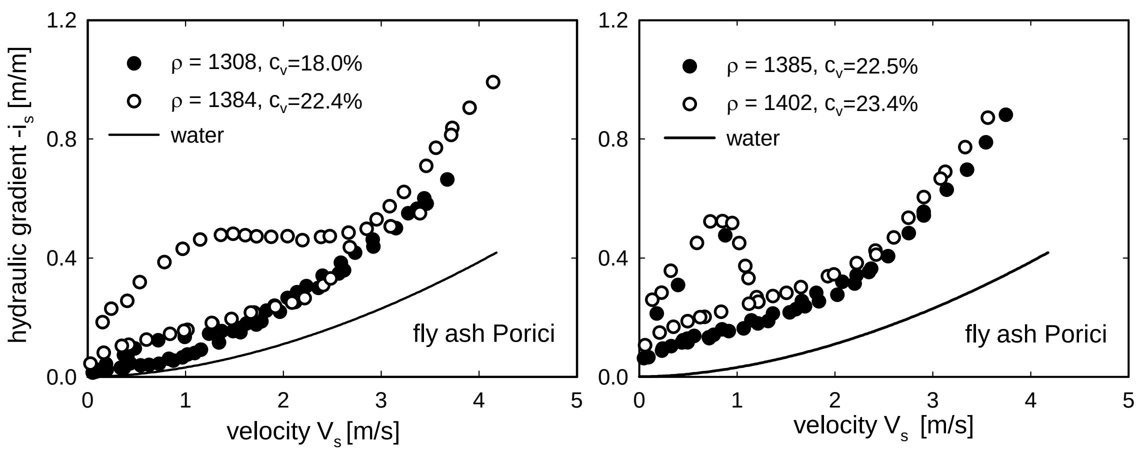

Fig. 2. Effect of slurry concentration and shearing (D = 36 mm)

The effect of different course of shearing is illustrated in Fig. 2. The “fresh” fly ash slurry Porici (concentration c_v = 22.5 %, ρ_s = 1385 kg/m^3) was shortly homogenised in the loop at the velocity less than 1 m/s. Afterwards the velocity was increased and kept for 2 minutes at value V_s =3.75 m/s, then quickly decreased on V_s = 0.5 m/s and again increased to V_s =3.5 m/s. Finally the velocity was again decreased to value close to zero and the measurement continued by standard way, i.e. the velocity was gradually increased up to V_s =3.5 m/s, then gradually decreased to minimum and again increased to value about V_s =1.6 m/s. The short time high intensity of shearing has even greater effect on the slurry apparent viscosity as long time shearing in laminar regime.

The effect of long time laminar shearing is documented in Fig. 3. The slurry with fly ash of Porici (c_v = 23.4 %, ρ_s = 1402 kg/m^3) was pumped in laminar regime (V_s =1.0 m/s) for 4 hours after mixing of ash with water. During this period the velocity grows up to V_s =1.25 m/s and 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 successive increasing or decreasing of the flow velocity has no effect on the slurry behaviour.

The slurry with fly ash of Trinec (c_v = 0.264, ρ_s = 1423 kg/m^3) was about 30 minutes pumped in the laminar regime at velocities less than 2.5 m/s. Then about next 2.5 hours the slurry was pumped in the laminar regime at velocity about $V_s \approx$ 1.76 m/s. The effect of shearing time on the hydraulic gradient was found similar as that of the slurry Porici. Then the slurry was pumped with gradually growing velocity up to $V_s \approx$ 5.0 m/s and then the velocity was again gradually decreased up to minimum and again increased. It was found that the resultant value of the hydraulic gradient was due to the turbulent shearing markedly lower than after 3 hours of only laminar shearing, see the points at the slurry velocity V_s = 1.777 m/s and time of pumping about 250 minutes.

The turbulent shearing has greater and permanent effect on the slurry hydraulic gradient. The effect of shearing on the hydraulic gradient in the laminar region and also on the laminar/turbulent transition point position is evident from considerably different course of i_s /V_s relationship for stabilised and "fresh" slurry.

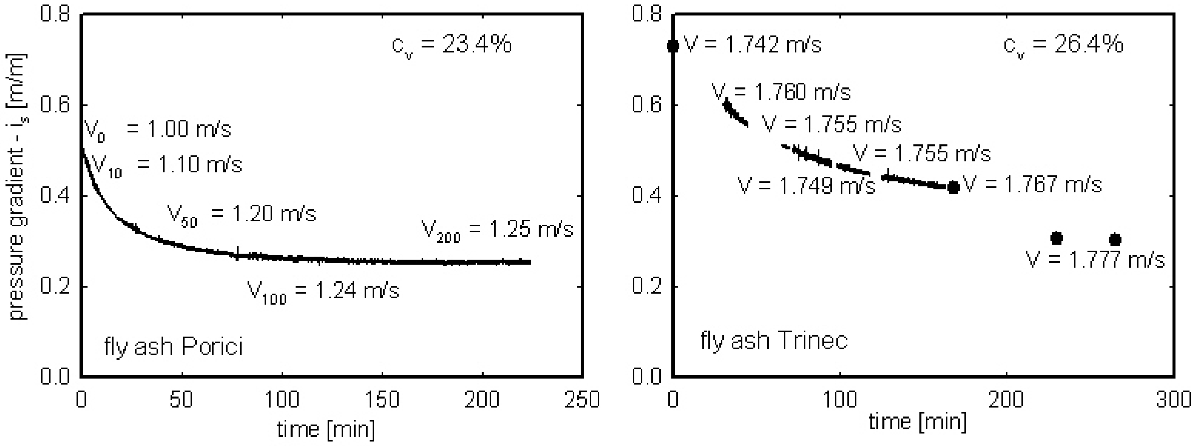

Fig. 3 Effect of time and intensity of shearing (Porici, D = 36 mm; Trinec, D = 26.8 mm)

Laminar flow of 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 experimental data, separately for "fresh" and stabilised slurry.

Dependence of the hydraulic gradient i_s on the slurry concentration c_v, flow velocity V_s and time of shearing for fluidic ash slurries from Trinec is illustrated in Fig. 4. Four different concentrations of fly ash slurry from c_v = 22.4 to 29.5%) were measured in the laminar, intermediate and turbulent regimes.

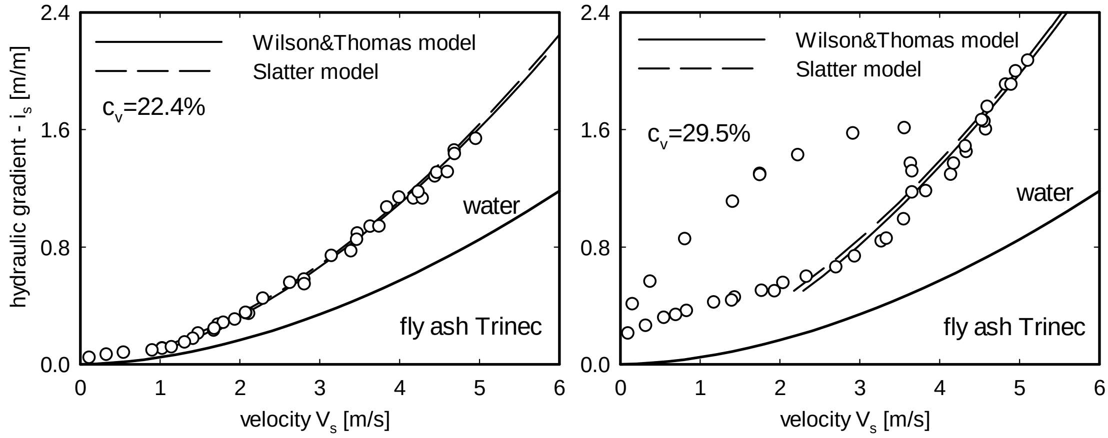

Fig. 4 Hydraulic gradient approximation by turbulent models (D = 26.8 mm)

For the evaluation of experimental data and prediction of the slurry hydraulic gradient vs. velocity relationship i_s /V_s in the turbulent region two turbulent models, i.e. Wilson –Thomas and Slatter, were used, Thomas & Wilson (1987), Wilson at al. (1997), Slatter (1996,1999). The both models are very sensitive on values of used rheological parameters, especially on the flow behaviour index n. The approximation of hydraulic gradient vs. velocity relationship according to the both turbulent models is shown in Fig. 4, where also experimental data of the "fresh" and stabilised slurry in the laminar and turbulent regions are illustrated.

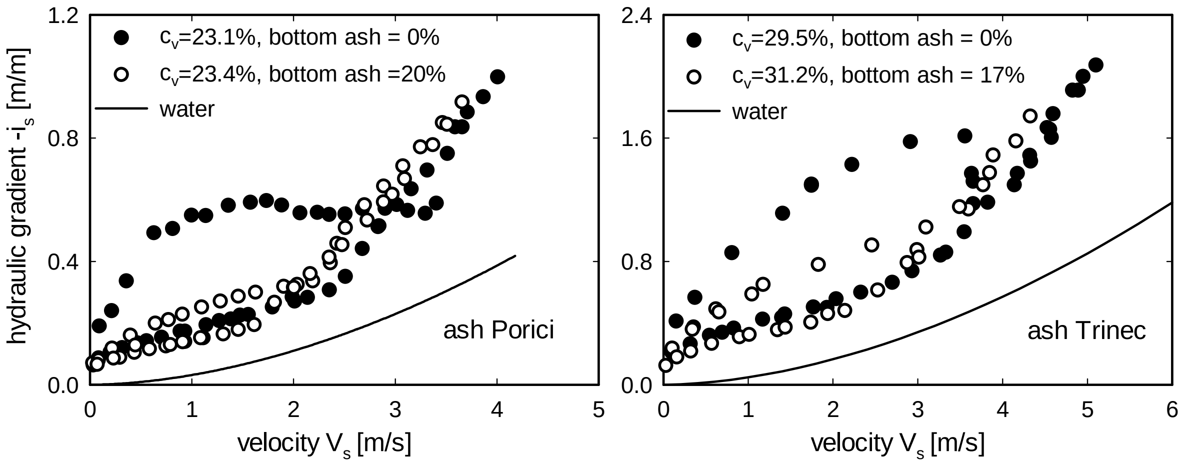

Fig. 5 Effect of bottom ash addition (Porici, D =36 mm; Trinec, D =26.8 mm).

To describe the effect of fine and coarse particles contents the ash-water mixtures consisting of the fly ash and the bottom ash was measured, Vlasak et al. (2004 a). The bottom ash addition effect on the flow behaviour of ash-water mixture is documented in Fig. 5. The slurry containing only fine fly ash and the same slurry with contents of 20% of bottom ash were compared. The "fresh" slurry with bottom ash reached in the laminar region markedly lower hydraulic gradient i_s, (for V_s = 1.5 m/s more than twice), the effect of coarse particles addition for stabilised slurry was significantly less. In the turbulent region the both slurries reached nearly the same values of the hydraulic gradient, which depends more on the slurry concentration than on particle size distribution. The only fly ash slurry reached laminar/turbulent transition for markedly higher velocity than the fly/bottom ash one. The similar effect of bottom ash was found for slightly coarser slurry from Trinec.

The effect of variable proportion of the bottom ash and slurry concentration is shown in Fig. 6 for the slurry Porici. For the slurry with 10% content 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 i_s value due to the shearing effect can be observed. The hydraulic gradient slightly decreases and for the velocity value $V_s \approx$ 2.3 m/s reaches minimum, then gradually increases up to the laminar/turbulent transition point. In the intermediate or turbulent region the hydraulic gradient again steeply increases. For the slurry containing 30% of the bottom ash the sudden reduction of i_s is missing, the maximum reduction is 54% for the "fresh" slurry and only 25% for stabilised slurry at the slurry velocity V_s = 1.35 m/s.

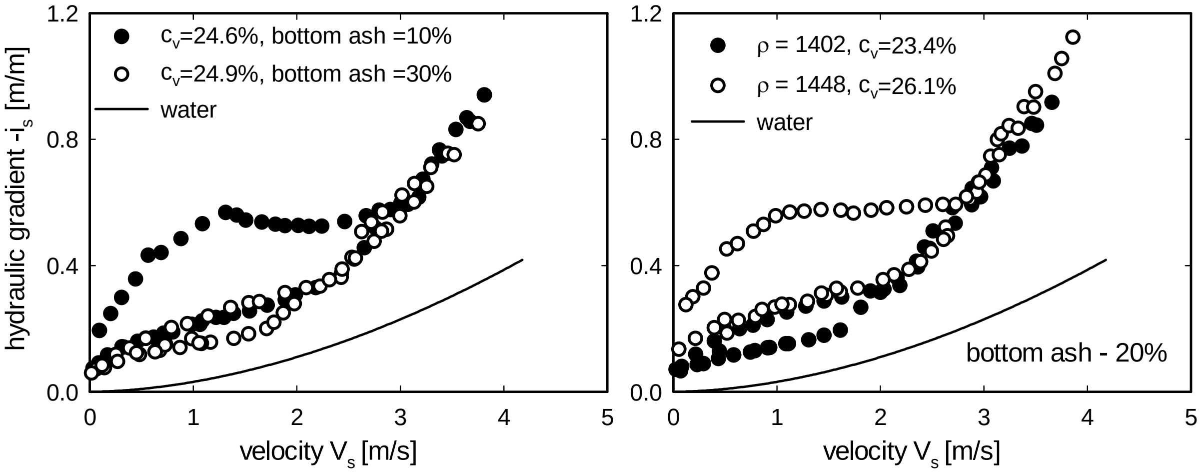

Fig. 6 Effect of slurry concentration c_v and flow velocity V_s on pressure gradient i_s. (Fluidic fly / bottom ash Porici, D = 36 mm)

The difference between the hydraulic gradient values of the slurries with different contents of bottom ash is negligible in the turbulent region, but the slurry with higher contents of the bottom ash reaches laminar/turbulent transition point for markedly lower velocity. The intermediate region is reached at the slurry velocity V_s = 2.3 m/s instead of 3.1 m/s for the "fresh" slurry and at V_s = 1.7 m/s instead of 2.15 m/s for the stabilised one. The slurry with bottom ash can also reach higher concentration than only fly ash slurry.

In Fig. 6 the slurry with fly ash from Porici with 20% of the bottom ash and total concentration c_v = 23.4 and even 26.1% is illustrated. For the "fresh" slurry the plateau effect was observed for the higher value of the total concentration in the velocity range from $V_s \approx$ 1.0 m/s to $V_s \approx$ 3.0 m/s, where the hydraulic gradient is nearly constant. For stabilised slurry this effect is missing.

The hydraulic gradient reduction is a result of less contents of very fine particles and mutual effect of both the slurries components, the fly and bottom ash. The effect of shearing is more considerable for the slurry with higher contents of very fine particles and lower proportion of the bottom ash.

An intensive shearing or addition of coarse particles depresses the effect of attractive inter-particle forces and results in the destruction of the aggregates and the viscous friction can play a larger role - an apparent viscosity and the yield stress decrease and the slurry is liquefied Vlasak et al. (1999 a, b). The effect depends on the total slurry concentration and velocity, both the fine and coarse particles proportion and on the contents of colloidal particles. The higher is contents of colloidal or very fine particles, the greater is the tendency of the slurry to coagulate. By shearing or by addition of the coarse particles the value of laminar/turbulent transition velocity and hydraulic gradient in the laminar region markedly decreases. The favourable effect of the bottom ash addition or shearing is significantly lower in the intermediate and turbulent region.

4. Drag reducing additives

Similarly as for kaolin slurry the flow behaviour of the ash-water mixture could be controlled by a physical-chemical environment change, which affects the attractive and repulsive forces between the solid particles and between particles and carrier liquid Vlasak et al. (1999 a, b, 2004 b). Effects of two different kinds of chemical additives were studied for fly ash-water mixture with fly ash from Porici, the both affect significantly rheological quality and flow behaviour of fly ash slurry and helps to reach higher solids concentrations and/or lower pressure drops during the slurry flow in a pipe. With increasing concentration of the chemical agent the apparent viscosity decreases.

The effect of activation of the slurry by addition of drag reducing agent was studied by flow out process of the slurry from specialised cylindrical ring with diameter/high ratio is equal 36 : 29 . The ring putted down on glass desk was filled by slurry, and then was lifted up and the slurry spontaneously flew out and created circular “cake”. The cake final diameter is relevant to apparent viscosity of the mixture, the lower is the viscosity, the greater is the diameter, results of the measurement are in Table 2.

Table 2. Effect of drag reducing agents on fly ash (Porici) slurry apparent viscosity

Drag reducing agent	Agent concentration [‰]	Cake diameter [mm]	Drag reducing agent	Agent concentration [‰]	Cake diameter [mm]
A	0	74	**B**	0	60
	0.8	80		0.15	72
	1.6	81		0.30	77
	2.0	90		0.60	82
	4.0	95		1.20	81
	8.0	97		2.40	74
	12.0	97		6.00	65
	Slurry density : 1 440 kg/m^3			Slurry density : 1 474 kg/m^3	

The above mentioned ash-water mixtures without and with the drag reducing agents were also tested on the experimental pipeline loop (see Fig. 1) to demonstrate the effect of drag reducing additives on ash-water mixture flow behaviour in the pipe flow under laminar and turbulent conditions, see Fig. 7. Attention was paid to the pressure drop/average slurry velocity relationship, with special regard to the agent concentration, i.e. the percent mass ratio of the agent with respect to ash mass content. The temperature of the slurry was maintained at around 15 °C.

The investigation confirms that the addition of drag reducing agent can serve to reduce the yield stress and viscosity of ash-water mixture and can help to reach the lower energy consumption for pipeline transport.

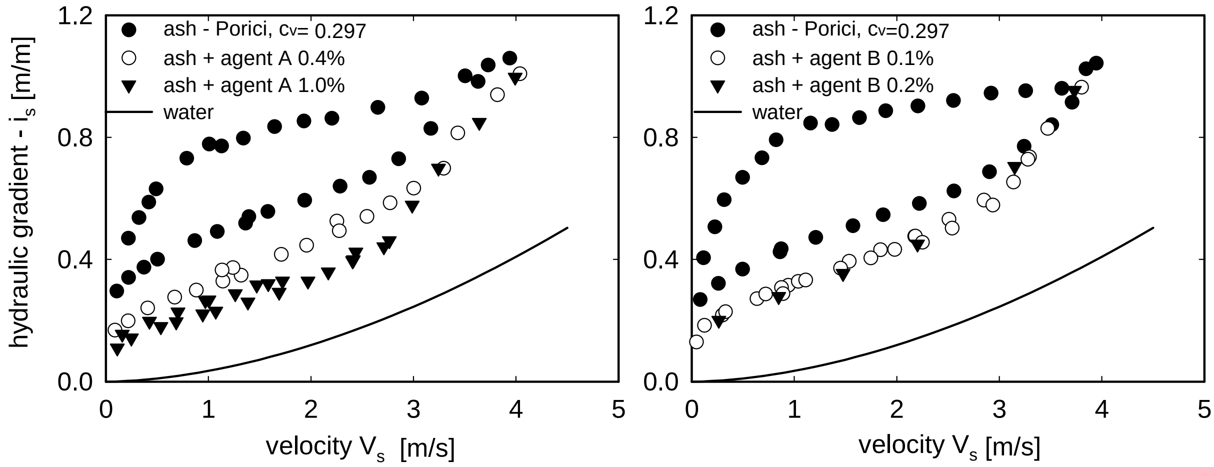

Fig. 7 Effect of drag reducing additives on ash-water mixture flows out. (fly ash Porici, D = 36 mm)

5. Conclusions

The study revealed the possibility of substantial reduction of the flow resistance by mechanical treatment and by arrangement of particle size distribution or by addition of chemical agents.

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 history of shearing and should be determined from experimental data of respective flow regime, separately for “fresh” and stabilised slurry.

The flow resistance increases with the increasing ash contents, the effect is higher in the laminar regime. A remarkable hysteresis was observed as a result of shearing for the fluidic ash slurries in the laminar region.

An intensive turbulent and even long time laminar shearing or addition of the bottom ash results in the marked change of the flow behaviour of the fluidic ash slurries. It results in the significant decreasing of the flow resistance in the laminar region and the velocity of the laminar/turbulent transition.

The effect of shearing is more significant for the higher slurry concentrations and is higher for the fly ash slurry than for the fly/bottom ash slurry. The addition of bottom ash causes decreasing of the hydraulic gradient in the laminar region and decreasing of the velocity of the laminar/turbulent transition. The higher ash slurry concentration can be reached. Consequently, it is possible to use lower operational velocity for fresh or stabilised slurry with bottom ash contents, what brings the significant reduction of pressure losses.

The control of the physical-chemical behaviour, of an 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 slurry.

6. Acknowledgements

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7. References

Horsley, R. R. & Snow, R. J. (1988) The rheology of some Australian mine tailings, in: Progress and Trends in Rheology II, (Eds. H. Giesekus & M. F. Hibberd), Prague (Czechoslovakia), 17-20 June, 1988, Steinkopff, Darmstadt, pp. 344-346

Nguyen, Q.D. & Boger, D.V. (1984) Exploiting the rheology of highly concentrated suspensions, in: Proc. of IX. Int. Congress on Rheology, Acapulco (Mexico), 8-13 October, Ed. B. Mena, pp.153-171

Satava V. (1973) Teorie ztekucovani keramickych litych brecek a optimalizace procesu liti. *Sklar a keramik*, XXIII, pp. 195-199 (in Czech)

Slatter, P.T. (1996) Turbulent flow of non-Newtonian slurries in pipes, *J. Hydrol. Hydromech*, **44**, 1, pp. 24-38

Slatter, P.T. (1999) The turbulent flow of non-Newtonian slurries in pipe, in: Proc. of Problems in Fluid Mechanics and Hydrology, (Ed.: P. Vlasak), IH ASCR, Prague (Czech Republic),23-26 June 1999, pp. 247-256

Thomas, A.D. & Wilson, K.C. (1987) New analysis of non-Newtonian flow – yield-power-law fluids, *Can. J. Chem. Eng*, **65**, pp. 335-338

Vlasak, P., Chara, Z., Stern, P. (1999 a) Liquefying of dense clay-water mixtures, in: Proc. of Problems in Fluid Mechanics and Hydrology, (Ed.: P. Vlasak), IH ASCR, Prague (Czech Republic), 23-26 June 1999, pp.190-198

Vlasak, P., Chara, Z., Stern, P. (1999 b) Effect of peptisation on flow behaviour of clay suspension, in: HYDROTRANSPORT 14, BHR Group, Maastricht (The Netherlands), 8-10 September 1999, pp. 347-358

Vlasak, P. & Chara Z. (1999 c) Laminar and turbulent flow experiments with yield-power law slurries. *Powder Technology*, **104**, pp. 200-206

Vlasak, P. & Chara, Z. (2001) Laminar and turbulent flow of dense Kaolin and ash hydromixtures, *Handbook of Conveying and Handling of Particulate Solids*, (Ed.: A. Levy, H. Kalman), Elsevier Sciences, pp. 473-482

Vlasak, P., Chara, Z., Stern, P., Konfrst, J., El-Nahhas, K. (2002) Flow behaviour and drag reduction of kaolin suspensions, in: HYDROTRANSPORT 15, BHR Group, Banff (Canada), 3-5 June 2002, pp. 345 – 360

Vlasak, P., Chara, Z., Konfrst, J. (2004 a) Effect of concentration and shearing time on flow behaviour of ash-water slurries, in: HYDROTRANSPORT 16, BHR Group, Santiago de Chile (Chile), 26-28 April 2004, Vol. I, pp. 93-105

Vlasak, P., Chara, Z., Konfrst, J. (2004 b) Effect of size distribution on flow behaviour of dense fluidic ash-water slurries, in: 12th Int. Conf. On Transport & Sedimentation of Solid Particles, 20-24 September 2004, Prag (Czech Republic), 659-669

Wilson, K.C., Addie, G.R., Sellgren, A., Clift, R. (1997) *Slurry transport using centrifugal pumps*, 2nd Ed., Blackie Academic and Professional (Chapman & Hall), London