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CONVEYING OF COARSE PARTICLE IN NON-NEWTONIAN SLURRY

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Summary: *The paper deals with flow behaviour of slurries containing colloidal, clay, dust and 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 contents of colloidal particles. Flow behaviour of fluidic fly and bottom ash slurries, clay and sand slurries was experimentally investigated with respect to the solids composition, volumetric concentration and slurry velocity. The re-circulation pipe loop with smooth stainless steel pipes of the inner diameters D = 17.5, 26.8 and 36 mm was used for measuring the slurry flow parameters. Also the effect of time and intensity of shearing was studied for time dependent fluidic ash slurries.*

1. Introduction

The paper deals with the effect of particle size distribution and volumetric concentration on the flow behaviour of slurries containing colloidal, clay, dust and also coarse-grained particles. It presents the results of experimental investigation of kaolin and fly ash slurries containing coarse-grained particles, i.e. sand and bottom ash, respectively. Flow behaviour was experimentally investigated with respect to the solids composition, volumetric concentration and slurry velocity. Also the effect of time and intensity of shearing for time dependent fluidic ash slurries was studied. 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.

Most knowledge on dense slurry hydraulic transport 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 dense slurries is strongly affected by the mutual particle-particle and particle-liquid interactions. The behaviour of the system with colloidal particles is determined by a mutual effect of the attractive and the repulsive forces between the solid particles.

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During the slurry flow, shear-induced translation and rotational motions of the particles cause hydrodynamic interactions, which cause the increase of viscous energy dissipation and the slurry bulk viscosity. 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. In the highly concentrated fine-grained suspensions both types of the interactions are present (Vlasak et al, 1999).

The aim of this paper is to discuss the flow behaviour of heterogeneous slurries containing also fine particles. The paper presents results of experimental investigation of several fine-grained slurries, e.g. of fluidic fly and bottom ash slurries, sand-water mixtures and also sand-kaolin slurries. It is focussed on the effect of particle size distribution and concentration on the hydraulic gradient vs. the slurry average velocity relationship i_s / V_s and slurry flow behaviour in the laminar, transitional and turbulent regimes.

2. Experimental equipment and material

Flow behaviour of sand and sand-kaolin slurries, fluidic fly and bottom ash slurries were experimentally investigated. The re-circulation pipe loop with smooth stainless steel pipes of the inner diameters D = 17.5, 26.8 and 36 mm was used for measuring the slurry flow parameters with respect to the solid phase concentration and composition. The loop can operate in laminar as well as turbulent regime. The reached average slurry velocity depends on the used pipe diameter and varies from $V_s \approx 5$ m/s for pipe of D = 36.0 mm to $V_s \approx 8$ m/s for pipe of D = 17.5 mm and 26.8 mm.

Three kinds of quartz sand of uniform size distribution from Provodin (d_{50} = 0.2, 0.7 and 1.4 mm, ρ_s = 2650 kg/m^3) and natural poly-disperse the sand Zavada (d_{50} = 0.3 mm, ρ_s = 2650 kg/m^3) were used as experimental material for sand slurries investigation. Volumetric concentration c_v of the sand slurries varied from 6 to 45%. Kaolin from Horni Briza (d_{50} = 2.8 μm, ρ_k = 2546 kg/m^3) was added to the sand-water slurry to create non-Newtonian carrier liquid. To compare the effect of Newtonian and non-Newtonian carrier, a chemical agent with peptising effect was used to change physico-chemical environment of the slurry and to suppress attractive inter-particle forces, which evoke non-Newtonian behaviour of the slurry.

For ash-water mixture two different kinds of fine fly-ash from Trinec (d_{50} = 14 μm, ρ_{fT} = 2603 kg/m^3) and from Porici (d_{50} = 8 μm, ρ_{fP} = 2718 kg/m^3) and their mixtures with bottom ash (Trinec - d_{50} = 300 μm, ρ_{bT} = 2646 kg/m^3, Porici - d_{50} = 45 μm, ρ_{bP} = 2716 kg/m^3) were used as a solid phase. Total volumetric concentration c_v of the investigated fly ash slurries ranged from 18% to 30%, the fly/bottom ash slurries reached slightly higher concentration. The different maximum concentrations are given by the different size distribution of the used fly ashes. The fly ash from Porici is substantially finer and contains more colloidal particles, which after mixing with water create voluminous aggregates with loose structure, where a large deal of water is fixed and thus the slurry maximum concentration is lower.

The ash from Porici considerably differs from the ash from Trinec. Densities of the both, fly and bottom ashes from Porici are slightly higher than that from Trinec. The mean diameter of fly ash from Porici is only half of that of Trinec. On the contrary bottom ash from Porici is significantly coarser compared with the bottom ash from Trinec, the mean diameter is about 50% greater and bottom ash from Porici contains a considerable proportion of very coarse-grained particles. Significant difference was also found in contents of colloidal particles less than 1 μm – 13% for fly ash from Porici in comparison with only 4% for Trinec, i.e. three times more. Contents of particles less than 63μm is nearly the same for the both materials, however, fly ash from Porici contains 57% of particles less than 10 μm on the contrary to only 36% for ash from Trinec.

3. Experimental results and discussion

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. 1. The effect of size distribution depends on the slurry velocity. The coarse sand slurry reaches higher 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 hydraulic gradient ratio, which for $V_s > 4$ m/s are very close to those of the fine sand. The course of the medium sand slurry is interesting. For the average slurry velocity lower than 4 m/s it reaches higher values of the hydraulic gradient ratio than the fine sand or the both sand mixtures, very similar to that of the coarse sand. For $4 < V_s < 6$ m/s the medium sand hydraulic gradient ratio is surprisingly less even than that of the fine sand, for $V_s > 6$ m/s the hydraulic gradient ratio of the fine sand again increases and approaches values of the sand mixtures and even of the coarse sand.

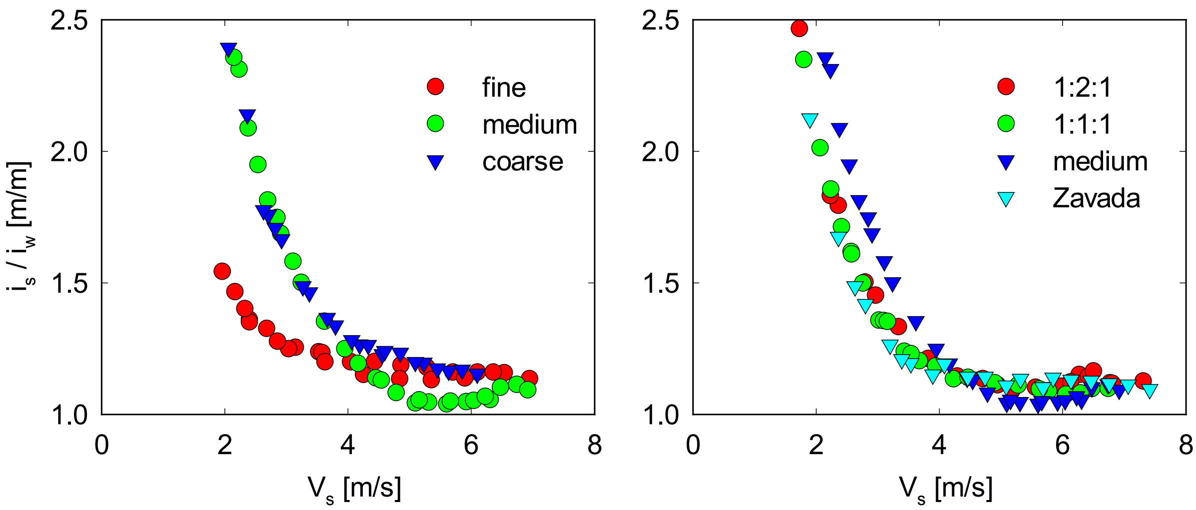

Figure 1 Hydraulic gradient ratio i_s/i_w vs. average slurry velocity V_s for sand slurries ($D = 26.8$ mm, $c_v = 23$ %)

For the slurry concentration exceeding value of $c_v \approx 20$ % the flow behaviour of sand slurry exhibits some attributes of a non-Newtonian behaviour, see Fig. 2. The pressure gradient tends to reach the water alone curve with an increasing flow velocity, however, for the higher slurry velocities the difference between slurry and water pressure gradients again increases. Poly-disperse sand slurries (sand mixture 1:1:1 or 1:2:1, natural poly-disperse sand Zavada) can reach even lower values of the pressure gradient at higher slurry concentration and average velocity than the less concentrated slurry. This tendency, which can be explained due to the laminar/turbulent transition of more concentrated slurry at the higher velocity, is illustrated for the sand Zavada in Fig. 2.

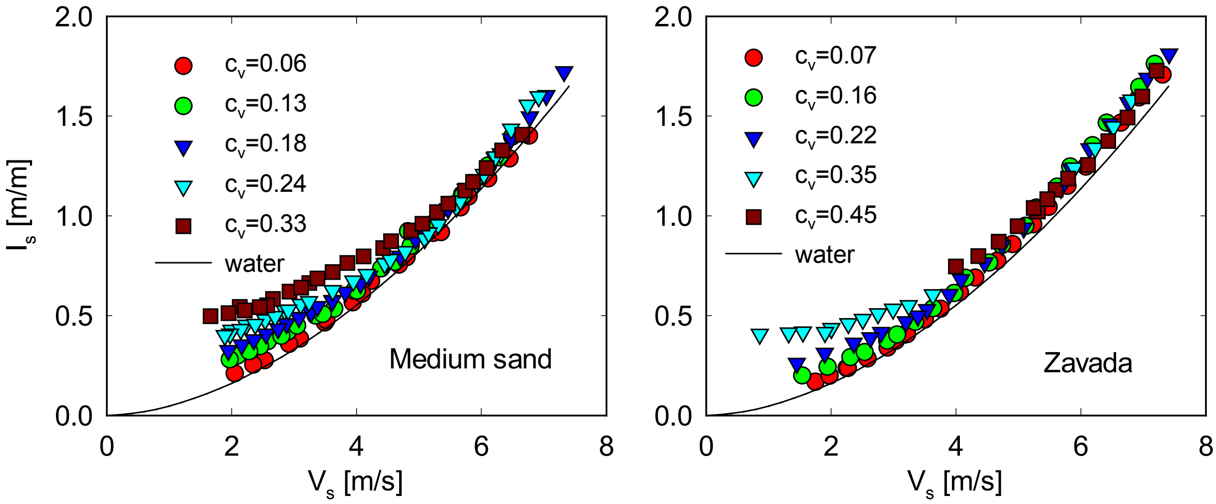

Figure 2 Hydraulic gradient i_s vs. average velocity V_s for sand slurries (pipe D = 26.8 mm)

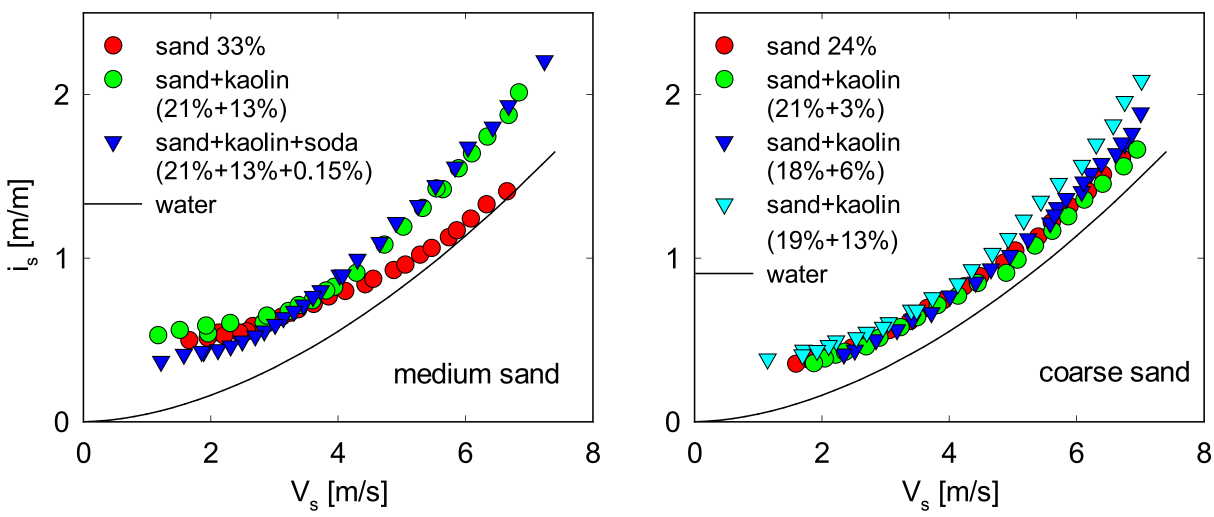

Figure 3 Effect of carrier liquid rheological properties on the hydraulic gradient i_s vs. average velocity V_s relationship for sand slurries (pipe D = 26.8 mm)

To describe the effect of fine particles contents and of Newtonian and non-Newtonian carrier on the flow behaviour, slurry consisting of the sand conveyed in water, natural and peptised kaolin slurry was measured (Vlasak et al., 2002 a). The hydraulic gradient/average velocity relationship i_s/V_s for the slurry of total concentration $c_v = 34$ % is illustrated in Fig. 3. When sand is conveyed in the kaolin slurry with concentration $c_v = 13$ %, the slurry exhibits a non-Newtonian behaviour in the laminar regime. For higher velocity range the hydraulic gradient i_s markedly increases compared to the water alone or sand-water slurry.

When the carrier slurry is peptised, the hydraulic gradient in the laminar region becomes markedly lower (Vlasak et al., 2002 b). However, for the slurry velocity $V_s > 3$ m/s the peptised medium sand - kaolin slurry ($c_v = 21\%+13$ %) reaches higher hydraulic gradient than the medium sand slurry ($c_v = 33$ %) and practically the same as the untreated sand-kaolin slurry ($c_v = 21\%+13$ %). This confirms the fact that favourable effect of the slurry peptisation in transitional and turbulent regions can vanish.

The same trend was observed for coarse sand, where also effect of increasing kaolin contents (for constant total slurry concentration $c_v = 24\%$) is documented. For the low velocity range the effect of different kaolin contents seems to be negligible, with increasing velocity the hydraulic gradient increases with growing kaolin contents. However, the addition of small kaolin contents (concentration of kaolin about 3%) favourably affects the flow behaviour of the sand-kaolin slurry.

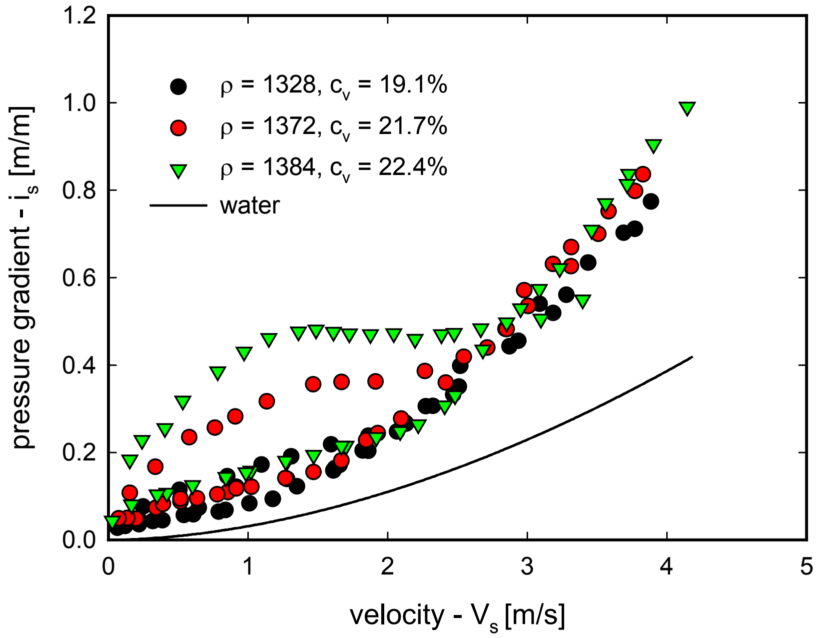

Figure 4 Effect of slurry concentration c_v and flow velocity V_s on pressure gradient i_s. Fluidic fly ash Porici slurry ($D = 36$ mm)

The fly ash slurries contain high percentage of colloidal particles and thus they can reach only relatively low solids concentrations. Concentration of the studied slurries is close to the liquid limit. Even a relatively small change in concentration results in a rather expressive change of the pressure gradient, especially in the laminar region. Fig. 4 shows the effect of slurry concentration c_v and average slurry velocity V_s on hydraulic gradient i_s for fluidic fly ash from Porici.

The trend of hydraulic gradient found out in the laminar region is similar to the well-known course of e.g. kaolin slurry, but with increasing slurry velocity 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, hydraulic gradient steeply increases with growing slurry velocity. The slope of hydraulic gradient vs. slurry velocity relationship i_s /V_s becomes slightly less after the slurry reaches fully turbulent region, however the value of the slurry hydraulic gradient becomes expressively higher than that for water alone.

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 decreasing of the hydraulic gradient or makes possible to reach higher solids concentration.

On the contrary to kaolin slurry or ash slurry from slag-type boilers (Vlasak et al., 2004) the fluidic ash-water mixtures are time dependent, yield pseudo-plastic slurries. Several intervals of hydraulic gradient vs. slurry velocity relationship i_s /V_s can be distinguished, apparently according to the different effect of intensity and time of the shearing acting on the slurry in a pipe.

At first, the area of low velocity laminar flow of a fresh mixed slurry, where hydraulic gradient i_s increases with increasing average slurry velocity V_s in correspondence with the course of time-independent non-Newtonian slurry. At second, the area of fully developed laminar flow where the effect of shearing already influences apparent viscosity of the ash slurry and the increment of hydraulic gradient becomes lower in comparison with time-independent non-Newtonian slurry. Effect of shearing becomes more evident for higher slurry concentrations (c_v > 20%) where plateau effect on i_s /V_s diagram can be observed. The hydraulic gradient remains constant or even slightly decreases with the growing slurry velocity, e.g. for the slurry concentration c_v = 22.4% and velocity range from V_s = 1.5 m/s to 2.8 m/s.

Fig. 5 shows also the effect of variable proportion of the bottom ash. Effect of the time of shearing is more considerable for the slurry with lower proportion of coarse-grained particles. For the slurry with 10% contents of bottom ash the radical change in 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 is evident. The reduction is a result of more intensive shearing and mutual effect of both slurries components, the fly and bottom ash. For increasing flow velocity the hydraulic gradient slightly decreases unless the velocity reaches near the value V_s = 2.5 m/s where the laminar/turbulent transition point is situated. With growing velocity the hydraulic gradient again increases relating to transition to intermediate and turbulent flow region. The slurry with contents of 20% of bottom ash shows similar behaviour, but the change is not so marked and comes for higher velocity value about V_s = 1.8 m/s. For the slurry velocity V_s = 1.4 m/s the hydraulic gradient i_s reduces about 35 – 40% when the bottom ash contents grows from 10% to 20% and even about 50 - 55% when the bottom ash contents increases to 30%.

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 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 (Vlasak et al., 2002 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. 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 coarse-grained particles addition or shearing is significantly lower in the intermediate and turbulent region. Difference in the hydraulic gradient near the transition point could be even more than 50% of the original value of non-sheared fly fluidic ash slurry.

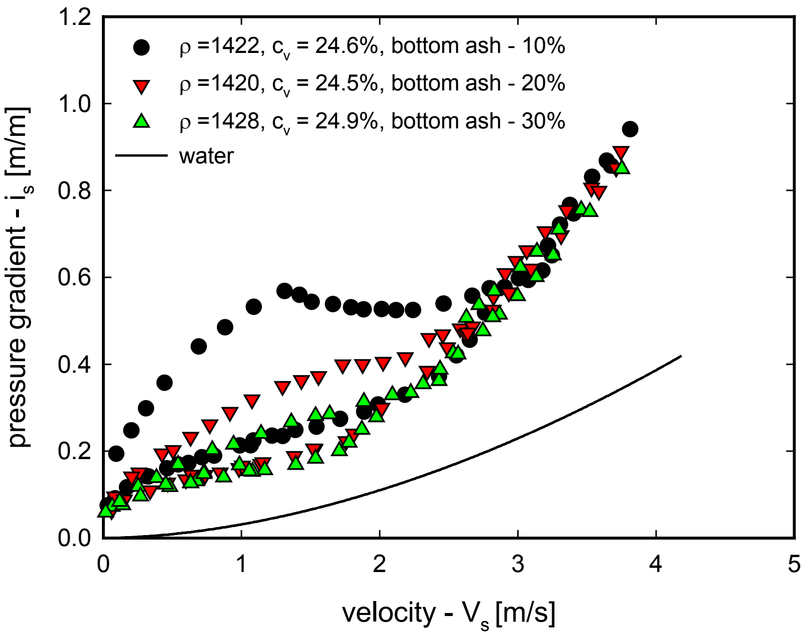

Figure 5 Effect of slurry concentration c_v and flow velocity V_s on pressure gradient i_s. Fluidic fly and bottom ash Porici slurry (D = 36 mm)

Dependence of the hydraulic gradient i_s on the slurry concentration c_v, flow velocity V_s and time of shearing for fly ash slurries from Trinec is illustrated in Figs. 6 and 7. Four different concentrations of fly ash slurry and one concentration of fly/bottom ash slurry in the laminar, intermediate and turbulent regimes were measured. The measurement was realised for fresh slurries (i.e. time period less than 1 hour from the beginning of pumping) and for stabilised slurries (i.e. after 1 hour of pumping in the experimental loop, including intensive shearing in the turbulent regime).

The effect of shearing on the hydraulic gradient in the laminar region and also on the change of laminar/turbulent transition point position is evident from considerably different course of i_s / V_s relationship for stabilised and “fresh” slurry. The favourable effect of bottom ash on the slurry flow behaviour can be observed, too. The slurry with the bottom ash of total solids concentration c_v = 31.2% reaches markedly lower values of hydraulic gradient i_s in laminar region than only fly ash slurry of lower concentration c_v = 29.5%. The lower value of hydraulic gradient i_s for stabilised slurry in laminar region (after 1 hour of pumping) is kept, even that the difference in hydraulic gradient is not so considerable. The effect of coarse-grained particles is not so significant in the turbulent region, however, significant shift of the laminar/turbulent transition point towards to lower velocity is evident. Consequently, it is possible to use lower operational velocity for stabilised slurry, what brings the significant reduction of pressure losses.

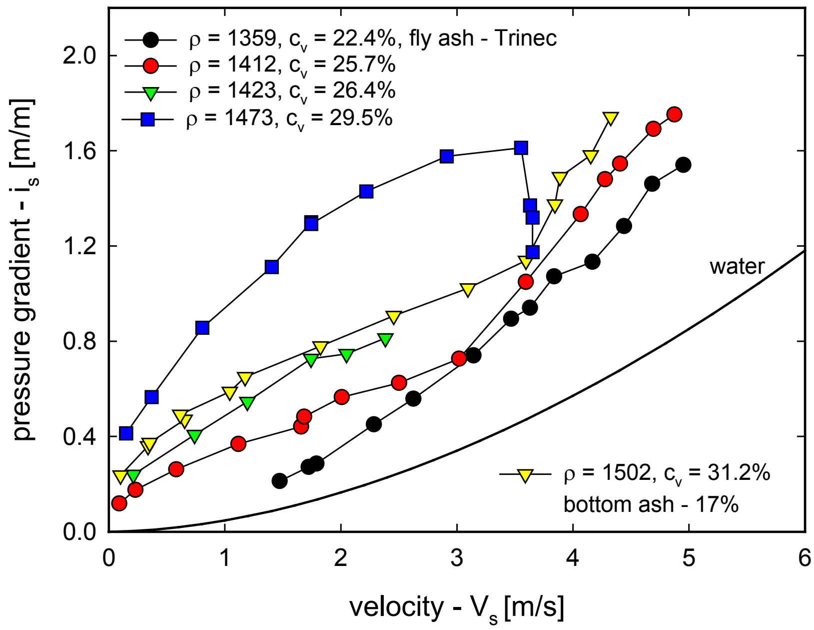

Figure 6 Effect of slurry concentration c_v and flow velocity V_s on pressure gradient i_s. Period of shearing less than 1 hour. Fluidic ash Trinec slurry (D = 26.8 mm)

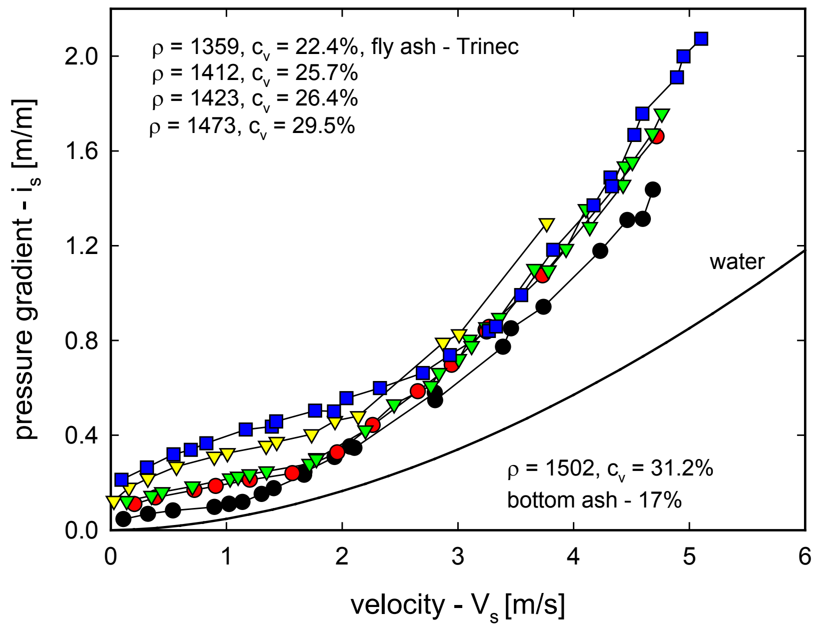

Figure 7 Effect of slurry concentration c_v and flow velocity V_s on pressure gradient i_s. Period of shearing more than 1 hour. Fluidic ash Trinec slurry (D = 26.8 mm)

4. Conclusions

The present study revealed a yield pseudo-plastic behaviour of fluidic fly and fly/bottom ash slurries, on the contrary to the kaolin slurry the fluidic ash slurries are time dependent.

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 concentration, at high velocities the effect of concentration can be opposite.

An intensive turbulent and even long time laminar shearing or addition of coarse-grained particles, i.e. bottom ash, can evoke the significant change of the flow behaviour of fluidic ash slurries. The hydraulic gradient of the fluidic ash slurry decreases markedly and the laminar/turbulent transition is reached at lower flow velocities.

Effect of shearing is greater for the fly ash slurry than for the fly/bottom ash slurry. With increasing portion of the coarse-grained particles in the slurry the slurry apparent viscosity gradually decreases. The effect grows with total concentration of the slurry.

4. Acknowledgements

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5. References

Vlasak, P., Chara, Z., Stern, P. (1999) Effect of peptisation on flow behaviour of clay suspensions, in: *Proc. of HYDROTRANSPORT 14*, BHR Group, Maastricht (The Netherlands), pp. 347-358

Vlasák P., Chára Z., Konfršt J. & Matousek V. (2002 a) Conveying of sand in Newtonian and non-Newtonian carrier, in: *Proc. of 11th Int. Conf. On Transport & Sedimentation of Solid Particles*, Gent (Belgium), pp. 193-201

Vlasák P., Chára Z. & Konfršt J. (2002 b) Thinning of kaolin slurry, in: *Proc. of Engineering Mechanics 2002*, Svratka (Czech Rep.), pp. 311-312, (CD-full text).

Vlasak, P., Chara Z. & Konfrst J. (2004) Effect of concentration and shearing time on flow behaviour of ash-water slurries, in: *Proc. of HYDROTRANSPORT 16*, BHR Group, Santiago de Chile (Chile), in press