ENERGY AND WATER MANAGEMENT FOR NON-NEWTONIAN SUSPENSIONS TRANSPORT BY PIPES

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ABSTRACT

Hydraulic transport of fine-grained suspensions through pipelines has been a progressive technology. Higher solids throughputs for economical considerations necessitate an increase in the solids concentration of the suspensions flowing in the pipelines. When increasing the solids concentration, the fine-grained suspensions could have non-Newtonian characteristics implying more complicated rheological behaviour. The suspension rheological behaviour is affected not only by the physical properties of its individual components but also by physical/chemical forces acting in slurry. One possibility for reducing the frictional losses in slurry pipe flow, and hence power requirement reduction, is based on change of physical-chemical behaviour of the slurry.

The aim of study is experimentally investigate the possibility of energy and water requirement reduction for the suspension transport by pipes. The physical/chemical environment of slurry could be changed by a peptizing process. Kaolin slurries of different concentrations were tested in a pipeline test loop comprising laminar and turbulent regimes. Modified suspensions produced by changing the physical/chemical characteristics of kaolin slurries by the addition of a peptizing agent with different amounts were also tested. The study showed that the peptizing process results an ability to obtain higher concentration slurries with a significant decrease in apparent viscosity and yield stress. Non-Newtonian behaviour of the slurry is depressed and the laminar/turbulent transition region is reached at lower flow velocity.

Keywords: Non-Newtonian, Slurry, peptizing, Rheology

INTRODUCTION

Hydraulic transport of dense fine-grained suspensions through pipelines could bring several environmental and economical advantages. The dense fine-grained suspensions could mostly have non-Newtonian characteristics implying more complicated rheological behaviour.The basic difference between Newtonian and non-Newtonian fluids is that the behaviour of a Newtonian fluid undergoing shear can be completely defined by one variable, the viscosity. The rheogram of a Newtonian fluid is a straight line which passes through the origin and has a slope equals the viscosity, μ, which is constant at a given temperature and pressure. The non-Newtonian behaviour is more complicated. Some non-Newtonian fluid rheograms may not be a straight line while attaining the passing from origin (power-law fluids), and other may attain the straightness while doing offset from the origin having a yield stress (Bingham fluids). The yielded pseudo-homogeneous model is a combination between the power law and Bingham models and is often approximates behaviour of wide range non-Newtonian which takes the form:

$$\tau - \tau_Y = k\left(\frac{du}{dy}\right)^n = k\gamma^n \tag{1}$$

where τ_Y is the yield stress, n is the flow behaviour index, and k is the fluid consistency index.

Frictional pressure losses in the slurry piping system determine the required pumping power that affect the size of the capital items such as pumps, motors, gearboxes and other. So there is an incentive to minimize the frictional pressure losses. The techniques for reducing the frictional pressure losses in homogeneous slurry pipe flow could be by altering the slurry rheological properties. The technique of drag reducing additives could have three broad groups; polymer, surfactant and fibre additives. Chung et al. [1] experimentally showed that dilute polymer solutions can significantly reduce pressure gradients of not only water but also water-particles mixture flows in the higher Reynolds-number range; drag reduction is as much as 80%. However, in the lower Reynolds-number range, pressure drops and friction factors for both water and water-particles mixtures are greater with polymer than without. Chara et al. [2, 3] showed that the surfactant agents lose their drag reduction ability when being subject to high shear stress, but quickly regain their effectiveness when they are flowing in a region of lower shear.

One possibility of the power requirement reduction, beside the methods discussed above, is based on change of physical-chemical behaviour of the slurry, as it was shown e.g. by Czaban [4] who used a fluxing agent for modifying the viscosity of a water, sand and cement mixture, i.e. for increasing the mixture fluidity. Therefore understanding of the inner structure and flow behaviour of slurry makes possible to optimize energy and water requirements. This will improve quality and economy of transport and obtain higher concentration or better processing of the slurry. The preparation of dense fine-grained suspensions for different applications involves the attainment of a high degree of particle stabilization and appropriate rheological properties, which could result in pressure loss reduction when flowing in pipes. The rheological behaviour of dense slurries is strongly affected not only by the physical properties of its individual components but also by physical/chemical forces acting in slurry and by mutual particle-particle and particle-liquid interactions. Vlasak et al. [5, 6 and 7] confirm the possibility of substantial reduction of the yield stress and viscosity of highly concentrated fine-grained slurries containing colloidal particles by a modification of their physical-chemical behavior.

EXPERIMENTAL TEST SETUP

The experiments were carried out at the Hydraulic Laboratory of the Institute of Hydrodynamics of the Academy of Science of the Czech Republic.

1. Test Material

Kaolin hydro-mixture is one of appropriate slurries for significant change of flow behaviour and rheological parameters due to the change of physical-chemical environment. So, the kaolin material was used to prepare the tested slurries. The kaolin mass median diameter d_{50} = 2.8 μm and its density ρ_s = 2549 kg/m3. Table 1 shows a content of main chemical compounds of the kaolin, which considerably influences the mutual particle-particle and particle-liquid interaction and consequently flow behaviour of the suspensions.

Table (1) The kaolin chemical composition

compound	SiO_2	AL_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	residue
content %	50.33	35.06	0.67	0.2	1.38	0.09	0.93	11.34

Sodium carbonate was used as a peptizing agent. It can supply the slurry by Na^+ cations for the compensation of the surface charge of bivalent ions.

Kaolin-water slurries of different volumetric concentration, varying from C_V = 2.8% up to maximum possible concentration of about C_V = 23%, were tested in laminar, laminar/turbulent transition and turbulent regimes. When adding the peptizing agent to the kaolin slurries, higher concentrated peptized slurries (up to about C_V = 35%) could be obtained and tested. The ratio of the peptizing agent mass to kaolin powder mass (C_a) was varied from C_a = 0.05 to 0.30 %.

2. Experimental Pipeline Test Loop

An open-loop stainless steel recirculation pipeline system of internal diameter D = 17.5 mm was employed for studying the slurry flow behaviour. A screw pump driven by an electric motor with a speed regulator forced the slurry from an open storage tank to delivery pipe. The flow rate could be changed stepwise by changing the rotor rotation speed. The upward branch of the piping loop is surrounded by a shell in which cooling water flowing in a counter-flow direction to keep the slurry of different experiments at narrow range of temperatures. The test section was located on the back branch of the pipeline and its length to diameter ratio exceeded 400.

The pipe was equipped with three pressure tappings connected with differential Hottingger-Baldvin pressure transducers and the readings were monitored by a computer. At the downstream end of the test pipes a box divider was mounted that allows diversion of the discharge to a plastic container for weigh testing. Since the divider arm was connected to an electric stopwatch, the mass flow rate was precisely measured. The slurry density and hence the volumetric concentration could also be determined. Calibration experiments with clear water, which was periodically run, showed that the pipe used in the test section behaved as a smooth pipe. For more details, see El-Nahhas [8].

RESULTS AND DISCUSSIONS

An area in which slurries require a more careful treatment than single-phase fluids is that of the friction gradient or energy gradient. The friction loss associated with the flow of slurry in a pipe is clearly represented in the form of the pressure or hydraulic gradient. However, the expression of pressure loss as a “wall shear stress, τ_w” (in Pa) is so common in slurry pipelining. The development of the wall shear stress, τ_w with increasing the mean velocity v, which represents a characteristic resistance curve, has been obtained during every experimental run by the pipeline test loop. Before subsequent slurry tests, the clear water measurements were carried out to establish the hydraulically smooth-wall pipe characteristic.

Resistance curve plots for dense kaolin slurries of different solids concentrations are shown in Figure 1. It is shown that the curve shapes have been dependent on solids concentration. For all presented concentrations, the non-Newtonian behaviour is obviously observed. The features of non-Newtonian characteristics were indicated by the difference between laminar and turbulent flow behaviour on the velocity-wall shear stress relation curve, see El-Nahhas et al. [9].

It can be seen that, with increase of volumetric concentration, the transition between laminar and turbulent flow generally occurs at higher velocities. The maximum possible concentration was C_v = 22.6% whose plot did not have any point in the turbulent regime. For the last data point (at about $v \approx 7.8$ m/s) the onset of transition region seems to begin. The value of the maximum obtained concentration depends on the nature of kaolin hydro-mixture and mutual physical-chemical behaviour of kaolinite crystal and water. Higher concentration of kaolin slurries could be obtained by adding some quantity of a peptizing agent to slurry, which reaches near the greatest slurry concentration. Due to the peptizing agent activity the attraction forces in the slurry decrease, the repulsion forces prevail and the aggregates of kaolin particles are destroyed, also the inner structure of the slurry is changed. The slurry becomes peptized and therefore it is possible to mix more kaolin to the slurry and increase the volumetric concentration, see Rayan et al. [10].

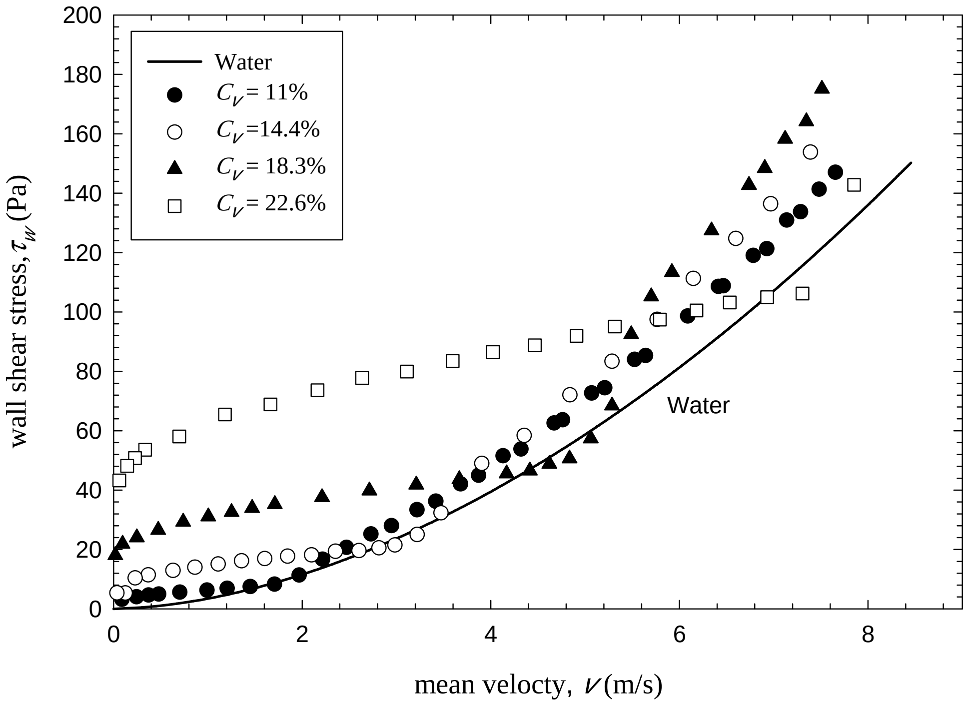

Figure 1. Resistance curves of dense kaolin slurry

Based on the above discussion, sodium carbonate was added to the kaolin slurry of the greatest concentration (C_V = 22.6%) by different ratios (C_a = 0.05, 0.10 and 0.15%). The change in the flow behaviour was observed and it is shown in Figure 2. For C_a = 0.05% it could be noticed that the laminar/turbulent transition occurred at a lower velocity, $V \approx 6.3$ m/s, and the turbulent regime was possible to be obtained at higher velocity. At laminar flow region, the wall shear stress was reduced by about 30%.

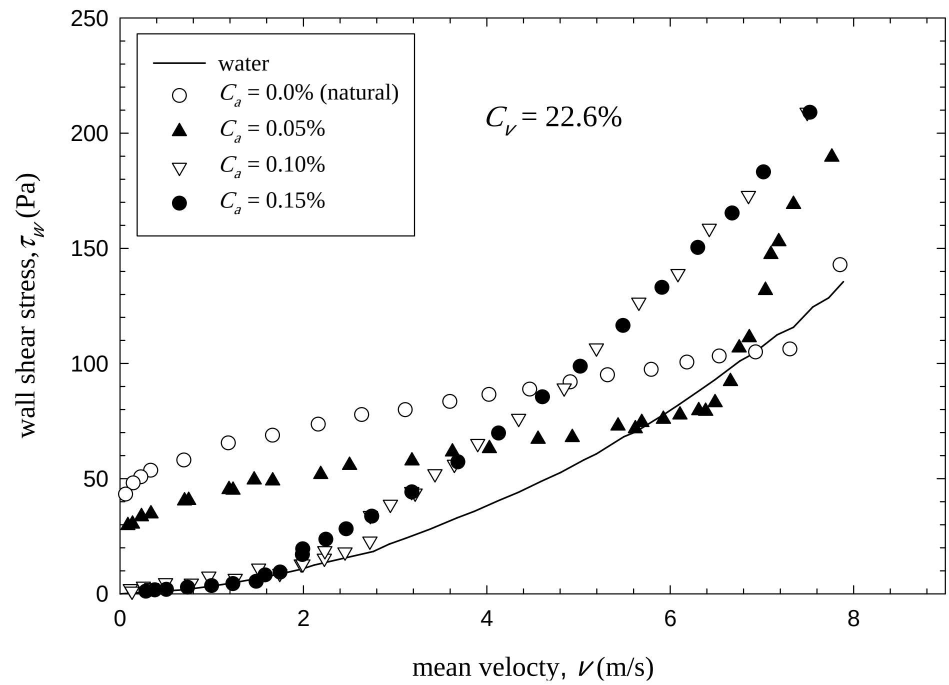

Figure 2. Peptizing effect on the flow behaviour of the densest kaolin slurry

Increasing the peptizing agent/kaolin mass ratio up to C_a = 0.1%, the yield stress vanishes and a great reduction of wall shear stress occurred at laminar region. The laminar/turbulent transition velocity is more decreased to about $V \approx 3.0$ m/s (for details about the transition condition see El-Nahhas et al. [11]). After the transient region, wall shear stress goes up and continues in turbulent region with a steeper slope. Reference could be made to El-Nahhas and Vlasak [12] for details about turbulent behaviour.

Increasing C_a to 0.15 %, more reduction in wall shear stress at laminar region could be observed to an extent that the data points are located on the water plot. Laminar/turbulent transitional velocity is about $V \approx 2.0$ m/s and behind it and at turbulent region the slurry wall shear stress/velocity relationship continues along the same path as the slurry with C_a = 0.10%.

According to the slurry piping operation system the optimum peptizing agent to kaolin ratio, C_a, could be determined. For example, referring to Figure 2, if the velocity in the present slurry piping system could not exceed 2 m/s, the optimum ratio is $C_a \approx 0.15\%$. If the velocity could be higher up to $V \approx 3$ m/s, the optimum ratio is $C_a \approx 0.10\%$. For velocities higher than 5 m/s the peptizing ratio $C_a \approx 0.5\%$ is better than both two higher ratios and for velocities higher than 6.7 m/s the benefit from peptizing vanishes

As discussed above, due to the peptizing agent activity the attraction forces in the slurry decrease, the repulsion forces prevail and the aggregates of kaolin particles are destroyed. Therefore it is possible to mix more kaolin to the slurry and increase the volumetric concentration up to C_V = 26%. Figure 3 compares the behaviour of the densest natural slurry (C_V = 22.6%) with that of a slurry with concentration C_V = 26% obtained by peptizing process with two peptizing ratios C_a = 0.05% and 0.15%.

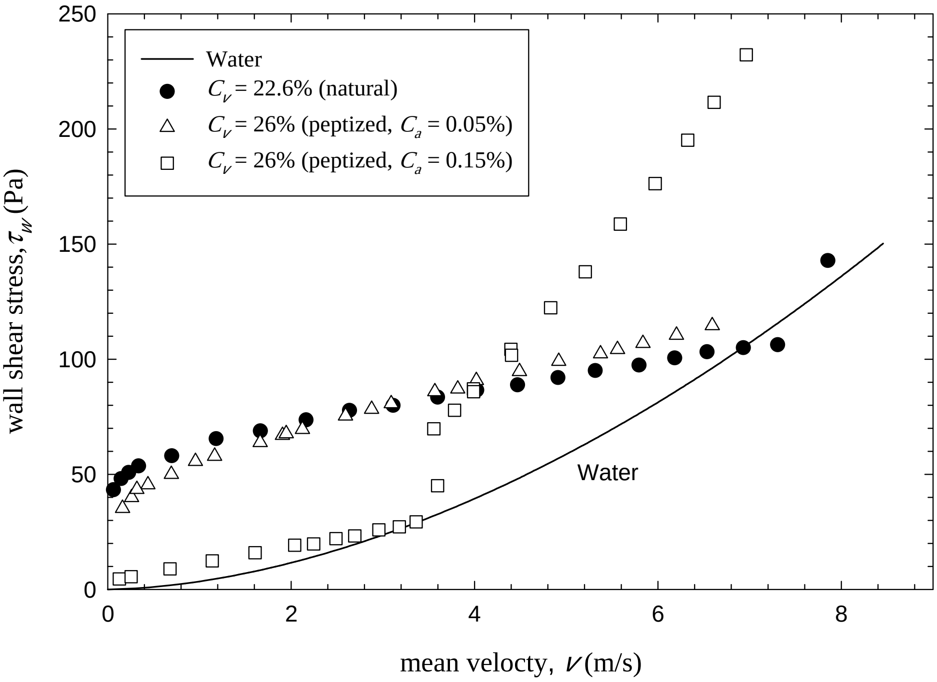

Figure 3. Flow behaviour of high-concentrated peptized slurry, C_V = 26%

As shown in the Figure, a great economical benefit of the peptizing effect could be obtained. First, higher concentration slurry that is impossible to flow naturally in pipes is obtained by the addition of the peptizing agent with the ratio C_a = 0.05%. The accompanied friction loss is lower than that of the lower concentration natural slurry within a velocity range up to $V \approx 4$ m/s. Increasing the peptizing ratio to C_a = 0.15% vanishes the yield stress. The slurry wall shear stress is slightly higher than the corresponding one of the pure water within a velocity range up to $V \approx 3.6$ m/s.

It was observed during the measurements that some slurries, specially peptized slurries, have hysteresis on the wall shear stress /mean velocity relationship. Figure 4 shows the hysteresis of the peptized kaolin slurry of C_V = 26% and C_a = 0.15%. It is shown that there is no significant difference between the acceleration and deceleration paths in turbulent flow regime. However, in laminar and transition flow regimes the wall shear stress of the deceleration path are lower than that of acceleration path and the transition velocity is lower. This may be due to increasing the effect of the peptizing process after that the mixture undergone to turbulence and high shear stresses.

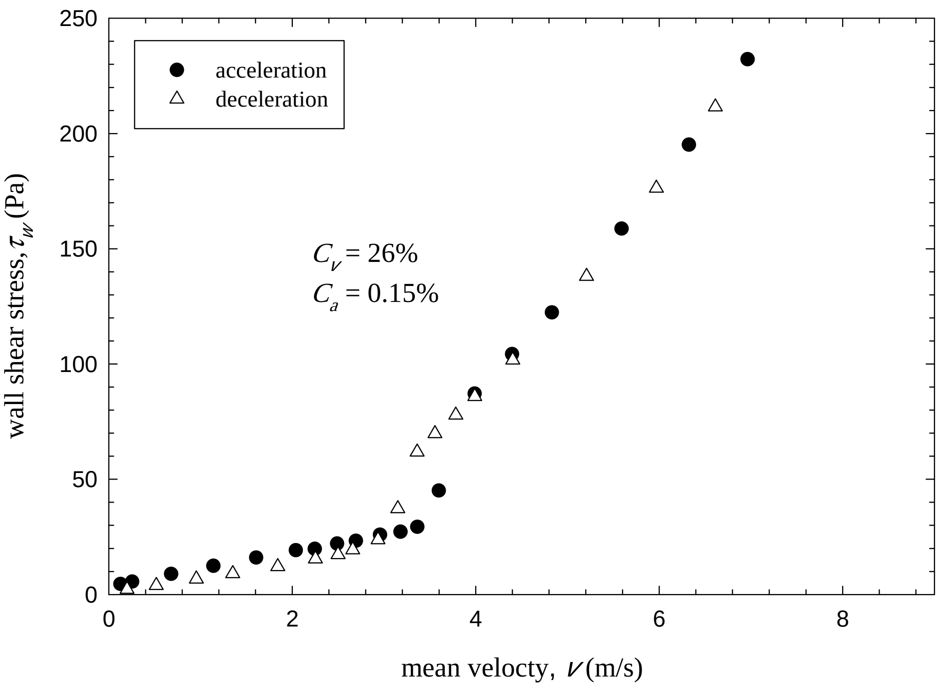

Figure 4. Hysteresis of peptized kaolin slurry

Also, very high concentration slurry of about C_V = 35% could be prepared after peptizing. Figure 5 shows the flow behaviour of this slurry peptized by peptizing ratios C_a = 0.15% and 0.3%. The peptizing effect suppresses the yield stress, but the slurry wall shear stress/velocity relationship could be approximated by linear dependence with very steep slope.

The above analyses confirms that peptization of slurry by addition of peptizing agent can serve to significant change of flow behaviour of kaolin slurries. The addition of peptizing agent can help to reach much higher concentration of solids (water saving) and/or lower energy consumption (energy saving) for pipeline transport and handling of kaolin slurries. Economical studies should make a balance between resulted water and energy benefits.

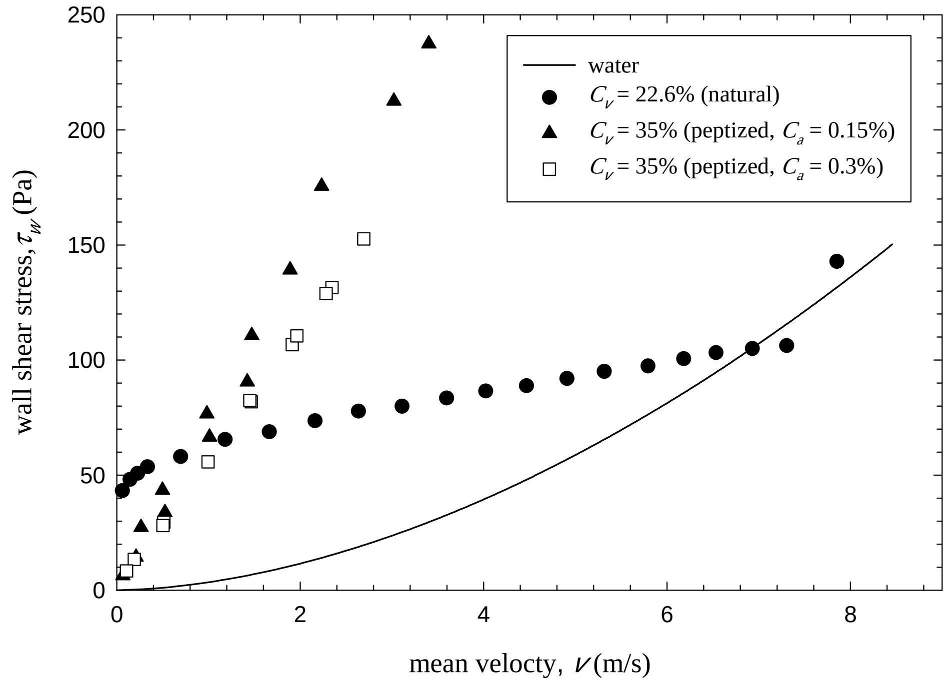

Figure 5. Flow behaviour of very high-concentrated peptized slurry, C_V = 35%

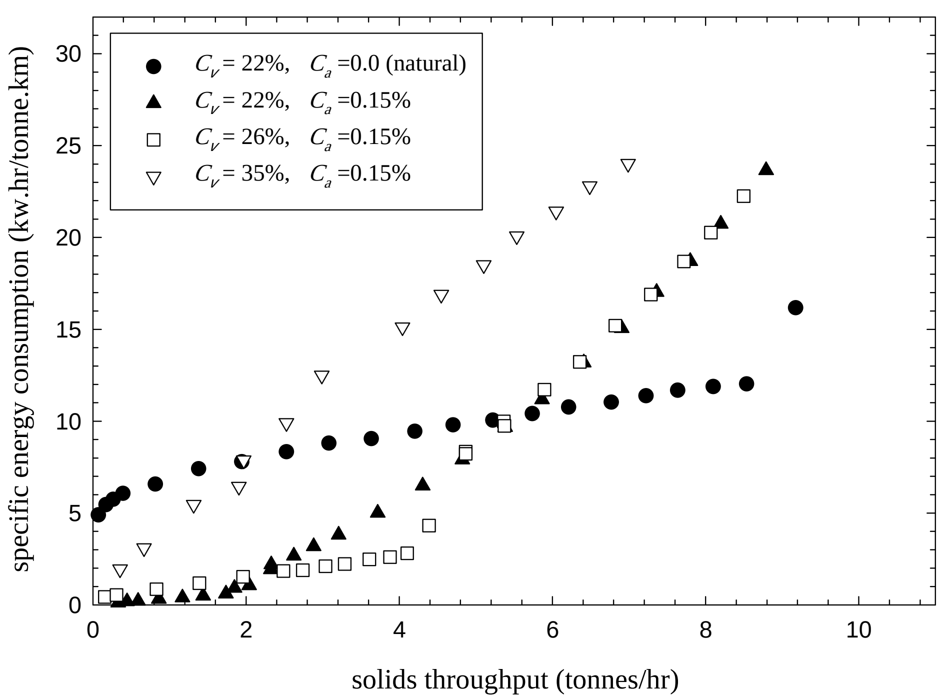

Figure 6. Specific energy consumption of natural and peptized kaolin slurries

When studying the slurry energy dissipation in a piping system, the specific energy consumption, *SEC*, could be a very useful parameter. It determines the energy required to move a given quantity of solids over a given distance in a pipeline and it is given as

$$SEC = 0.2778 \frac{i\,g}{S_s C_V} \quad (2)$$

where *SEC* is in units of [kW.hr/tonne.km], *i* is the slurry hydraulic gradient, S_s is the solids specific gravity, and C_V is the slurry volumetric concentration. The *SEC* has been plotted against solids throughput (the amount of dry solids delivered at the pipeline outlet over a time period). Figure 6 shows these plots for the densest natural slurry and peptized slurries. It is confirmed that the energy and water management could be well obtained by adjusting the different effective parameter; working velocity range, slurry concentration and peptizing ratio.

CONCLUSIONS

From the above discussions the following conclusions could be drawn:

- When increasing solids concentrations of the tested kaolin slurries, the non-Newtonian behaviour has been obviously observed. The Herschel-Bulkley rheological model fitted the behaviour of dense kaolin slurries.

- As increasing the solids concentration of non-Newtonian slurry, flocculation of the colloidal particles results in increasing the yield stress and apparent viscosity. So the viscous forces prevail and the laminar/turbulent transition occurs at higher velocities.

- The control of physical-chemical behaviour and of the inner structure of slurry enables to optimize both the energy and water consumption, to improve quality and economy of the transport and processing of the slurry. Accordingly, the peptization of kaolin slurries can help to reach much higher concentration of solids and lower energy consumption for pipeline transport and handling of kaolin slurries.

- Addition of sodium carbonate as a peptizing agent to dense kaolin slurries strongly depresses non-Newtonian behaviour, caused by presence of colloidal particles, resulting in decreasing the apparent viscosity and yield stress. Effectiveness of the peptizing process depends on solids concentration, peptizing agent amount, and acting shear stress or flow velocity ranges.

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NOMENCLATURE

		Units
C_a	peptizing agent/kaolin mass ratio	[-]
C_V	volumetric concentration	[-]
D	pipe internal diameter	[m]
d_{50}	diameter of which 50% (by mass) of the particles are finer	[m]
g	gravitational acceleration	[m/s^2]
i	hydraulic gradient	[m water/m pipe]
k	consistency index	[kgm^{-1}s^{n-2}]
n	flow behaviour index	[-]
SEC	specific energy consumption	[kW.hr/tonne.km]
S_s	solids specific gravity	[-]
u	local fluid velocity in the pipe-axis direction	[m/s]
V	mean velocity	[m/s]
y	vertical distance in a pipeline cross–section	[m]
γ	shear rate	[1/s]
μ	dynamic viscosity	[kg/ms]
ρ	density	[kg/m^3]
ρ_s	solid density	[kg/m^3]
τ	shear stress	[kg/ms^2]
τ_w	wall shear stress	[kg/ms^2]
τ_Y	yield stress	[kg/ms^2]

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