FLOW BEHAVIOUR OF NON-NEWTONIAN CLAY SLURRIES

Kamal El-Nahhas *, Nageh Gad El-Hak *, Magdy Abou Rayan **
and Imam El-Sawaf ***

* Ph.D., Suez Canal Authority, Egypt. E-mail: k_elnahhas@yahoo.com
** Professor, President of Mansoura University, Egypt. E-mail: mrayan@mans.edu.eg
*** Professor, Faculty of Engineering, Suez Canal University, Port Said, Egypt.
E-mail: iaelsawf@hotmail.com

ABSTRACT

Non-Newtonian flow behaviour in the laminar region is related to the rheological characteristics and the pressure losses could be predicted by integration of the constitutive rheological model. For turbulent flow, the prediction of the pressure losses stills one of the difficult theoretical and practical problems. The aim of the paper is experimentally investigate the flow behaviour of the non-Newtonian clay slurries. Kaolin and peptized kaolin slurries of different concentrations were tested by a pipeline test loop in both laminar and turbulent regimes. Predictive models were applied to fit the experimental data. The similarity of non-Newtonian turbulent flow behaviour with that of Newtonian one has been confirmed.

Key Words: Non-Newtonian, Slurry, Turbulent flow, Rheology

INTRODUCTION

The solid-liquid mixtures in the form of homogeneous slurries flowing in pipelines have been applied in a wide range of industrial sectors. Higher solids throughputs for economical considerations necessitate an increase in the solids concentration. When increasing the solids concentration, the homogeneous slurry can not be considered as two individual components. It could have non-Newtonian characteristics having more complicated rheological behaviour. The reliable prediction of the pressure drop accompanying the flow of non-Newtonian slurries is one of the most important practical problems. For laminar flow, this problem is well established as the relation between the pressure drop and the mean velocity could be derived by integration of the representative rheological model. However, the prediction of the pressure losses in the turbulent regime stills one of the difficult theoretical and practical problems. This difficulty results from that the turbulent flow behaviour could be found independent on the laminar rheological characteristics and it is similar to Newtonian turbulent flow behaviour.

The aim of the paper is experimentally investigate the flow behaviour of the non-Newtonian clay slurries. Kaolin slurries of different concentrations (ranging from C_v = 2.8% to the maximum possible one of 22.6%) were tested by a pipeline test loop (D =

17.5 mm) comprising both laminar and turbulent flow regimes. More concentrated kaolin slurries, which could be obtained by the addition of a peptizing agent, were also tested. The laminar flow predictive model and three turbulent flow models, which are different in their adoptive concepts, are reviewed and applied to fit the experimental data. Dependence of non-Newtonian turbulent flow behaviour on the rheological characteristics has been investigated. The similarity of non-Newtonian turbulent flow behaviour with that of Newtonian one has been confirmed by applying the Newtonian turbulent flow model to fit the non-Newtonian turbulent flow experimental data.

SLURRY RHEOLOGICAL CHARACTERISTICS

The relationship between the shear stress τ and shear rate γ, which is called the rheological model, has the simplest form for Newtonian fluids. In this case, the plot of this relation, which is called a rheogram, is a straight line passing through the origin and has a slope equals the fluid viscosity, μ, which is constant at a given temperature and pressure. It is represented by:

$$\tau = \mu\,\gamma = \mu \frac{du}{dy} \tag{1}$$

Homogeneous dense clay slurries tested in the laminar flow region often display non-Newtonian behaviour. For a non-Newtonian fluid, there is no single value for the shear stress/shear rate ratio. It is a function of the rate at which the fluid is sheared. The yielded pseudo-homogeneous model is often approximates the behaviour of a wide range of non-Newtonian slurries. It takes the form:

$$\tau - \tau_Y = k\gamma^n \tag{2}$$

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One of the most important practical problems in the flow of non-Newtonian fluids is the prediction of the pressure losses. Because non-Newtonian fluids usually have much higher apparent viscosity than that of most Newtonian fluids, the laminar flow would persist to much higher velocities. Furthermore, the difference in behaviour is much greater for laminar flow where viscosity plays an important role.

1. Laminar Flow

For laminar flow, the velocity distribution, and hence the relation between pressure drop and mean velocity, can be determined by integration of the rheological equation. This characteristic relation of the mean velocity according to the Herschel-Bulkley rheological model is:

$$V=\frac{nD}{2\tau_W{}^3 k^{1/n}}\left(\tau_W-\tau_Y\right)^{\frac{n+1}{n}}\left[\frac{\left(\tau_W-\tau_Y\right)^2}{1+3n}+\frac{2\tau_Y\left(\tau_W-\tau_Y\right)}{1+2n}+\frac{\tau_Y{}^2}{1+n}\right] \tag{3}$$

2. Turbulent Flow

For hydraulically smooth pipes, the flow mean velocity, V, in the turbulent region of a Newtonian fluid could be approximately obtained by the logarithmic law, considering that the viscous sub-layer usually occupies a very small portion of the pipe area, as:

$$\frac{V}{U_*}=2.5\ln\left(\frac{U_* D\rho}{\mu}\right) \tag{4}$$

Torrance [1] derived a model for non-Newtonian turbulent flow in smooth pipes using the yield pseudoplastic rheological model as following:

$$\frac{V}{U_*}=\frac{3.8}{n}+\frac{2.78}{n}\ln\left(1-\frac{\tau_Y}{\tau_W}\right)+\frac{2.78}{n}\ln\left(\frac{U_*^{2-n}\rho R^n}{k}\right)-4.17 \tag{5}$$

A predictive model has been developed based on a thickened viscous sub-layer by Wilson & Thomas [2] and Thomas & Wilson [3]. The mean velocity is given by:

$$\frac{\mathrm{V}}{U_*}=\frac{\mathrm{V}_N}{U_*}+11.6(\alpha-1)-2.5\ln(\alpha)-\Omega \tag{6}$$

The term Ω represents any effect of possible blunting of the velocity profile in the logarithmic core region of the flow. It depends on the ratio τ_Y/τ_w denoted by ξ, giving

$$\Omega=-2.5\ln(1-\xi)-2.5\xi(1+0.5\xi) \tag{7}$$

Examples of situations in which this model succeeds and some cases for which it fails are shown by Xu et al. [4]. Bartosik et al. [5] suggest that when the Wilson-Thomas model fails, the cause may arise in the assumption of a continuous fluid medium, which this method employs. Slatter [6] developed an alternative theory for non-Newtonian slurries based upon the concept of particle roughness turbulence effect and the classical Newtonian approach. A roughness Reynolds number was developed based on a representative particle size, d_{85}, and the Herschel-Bulkley rheological parameters;

$$\mathrm{Re}_r = \frac{8\rho U_*^2}{\tau_Y + k\left[\frac{8U_*}{d_{85}}\right]^n} \tag{8}$$

If $Re_r < 3.32$ then smooth wall turbulent flow exists and the mean velocity is given by:

$$\frac{V}{U_*} = 2.5\ln\left(\frac{R}{d_{85}}\right) + 2.5\ln(\mathrm{Re}_r) + 1.75 \tag{9}$$

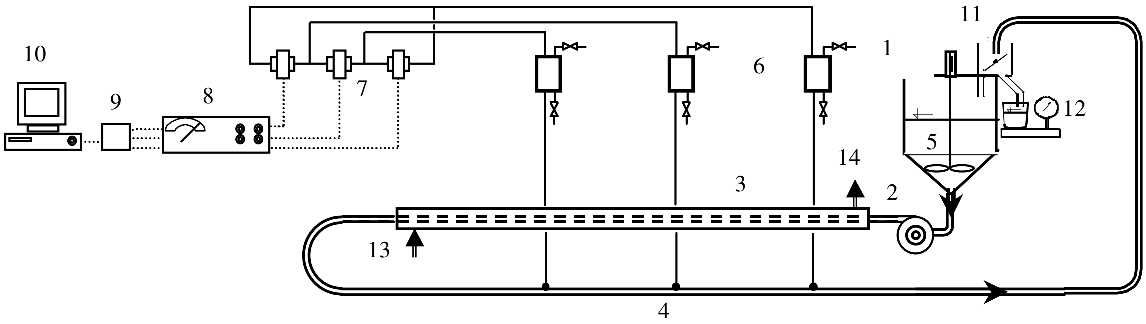
If $\mathrm{Re}_r > 3.32$ then fully developed rough wall turbulent flow exists and the mean velocity is given by:

$$\frac{V}{U_*} = 2.5\ln\left(\frac{R}{d_{85}}\right) + 4.75 \tag{10}$$

EXPERIMENTAL FACILITY AND TEST MATERIAL

1. Experimental Facility

The extended set of experiments was carried out at the hydraulic laboratory of the Institute of Hydrodynamics, Academy of Science of Czech Republic. An open-loop recirculation pipeline system was employed for testing the slurry flow behaviour, as shown in Figure 1. The slurry was forced by a screw pump driven by a variable speed motor 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 flows in a counter-flow direction to keep the slurry of different experiments in a 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 storage tank was equipped with an agitator to keep the slurry homogeneity. A stainless steel pipe of internal diameter 17.5 mm was used for measurements. The pipe was equipped with three pressure tappings connected through solids pods to differential pressure transducers and the readings were monitored and processed by a computer. At the downstream end of the test pipes a box divider was mounted to allow 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. If the plastic container was replaced by a glass calibrated cylinder, the slurry density and hence the volumetric concentration could also be determined.



1	holding tank	8	three channels carrier frequency amplifier
2	screw pump	9	analogue/ digital converter
3	double pipe heat exchanger	10	computer
4	test section	11	flow divider vessel
5	Stirrer	12	measurement of discharge & density
6	Sedimentation vessels	13	cooling water inlet
7	differential pressure transducers	14	cooling water exit

Figure 1 Schematic diagram of the experimental pipeline test loop

2. Test Material

The kaolin powder from Horni Briza (Czech Republic) was used for preparing a wide range of concentrations of homogeneous slurries. Table 1 shows mineralogy of this kaolin, which considerably influences the flow behaviour of the suspensions. Sodium carbonate was used as a peptizing agent to influence the rheological characteristics of slurries.

Table 1 The kaolin chemical composition

Comp.	SiO_2	AL_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	rest
Cont. %	50.33	35.06	0.67	0.93	0.07	0.2	1.38	0.09	11.27

Figure 2 presents the particle size distribution of the kaolin particles. The mean diameter is $d_{50} = 2.8\ \mu_{\mathrm{m}}$ and the kaolin density is $\rho_s = 2549$ kg/m^3.

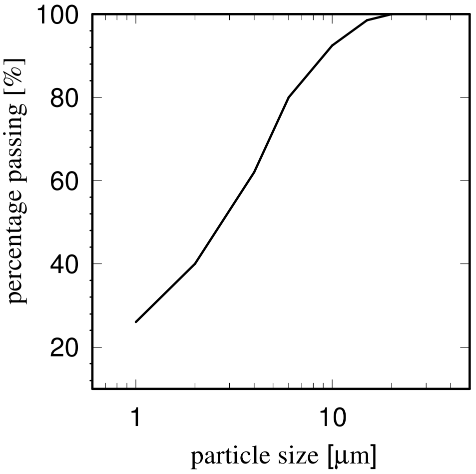


Figure 2 Particle size distribution for the kaolin solid material

RESULTS AND DISCUSSIONS

1. Rheological Characteristics

The experimental data measured by the pipeline test loop in the laminar region have been used to create the wall shear stress versus wall shear rate rheograms for the tested slurries. The wall shear stress is determined from the hydraulic gradient data. The wall shear rate is determined, using the Rabinowitsch-Moony method, from the pseudo-shear rate (*8V/D*) data; see El-Nahhas [7]. The rheograms for the slurries of solids concentrations of C_V = 8.9% and higher, which behave as non-Newtonian fluids are shown in Figures 3 and 4. The Herschel-Bulkley model satisfactorily describes the non-Newtonian tested slurries.

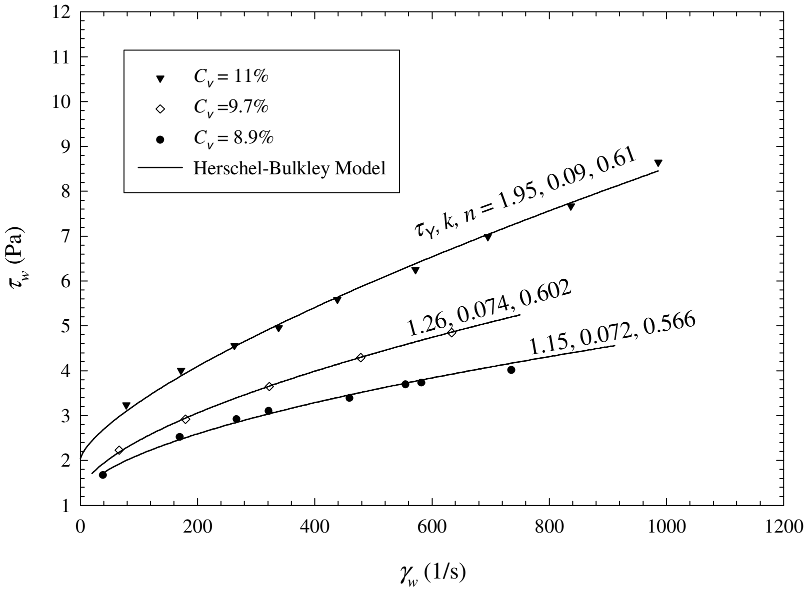


Figure 3 Rheograms of low-concentrated kaolin slurries

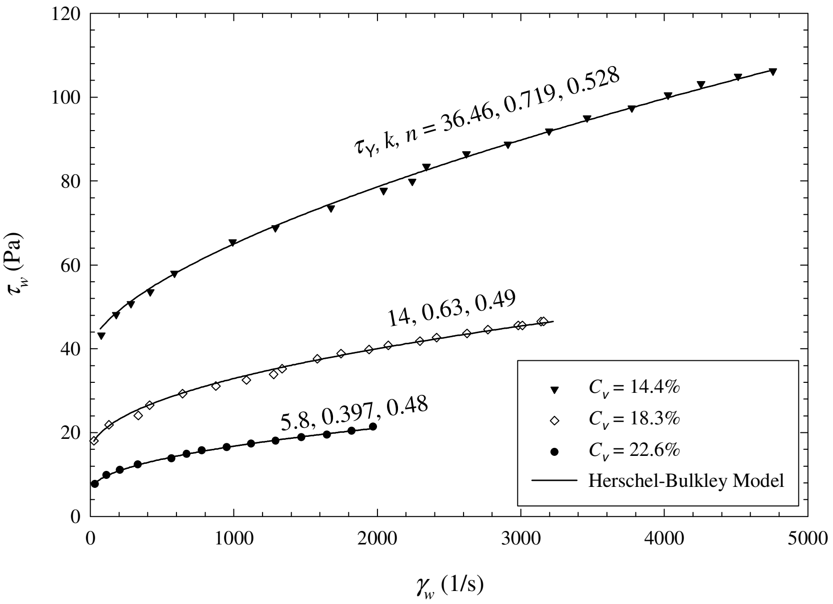


Figure 4 Rheograms of high-concentrated kaolin slurries

2. Flow Behaviour of Non-Newtonian Slurries

The pressure loss in slurry pipelines is commonly expressed as a hydraulic gradient (in m water head per m length of pipe). The development of the hydraulic gradient i with increasing the flow mean velocity V, which is called the resistance curve, has been obtained for the tested slurries. The curve shape was observed to be dependent on solids concentration. Analyses of the developed resistance curves showed that the tested kaolin slurries have started to show non-Newtonian features for the volumetric concentrations of C_V = 8.9% and higher, see Rayan et al. [8]. Figure 5 shows the resistance curves for four dense slurries (C_V = 11, 14.4, 18.3 and 22.6%). It could be noted that the laminar flow regime, observed at lower velocities, is characterized by the low-slope flat curve in the $V - i$ plots. Hence, it tends to be attractive economically. As the mean velocity increases in the laminar region, the flow curve get near to the pure water curve. Increasing the mean velocity, at the beginning of the laminar/turbulent transition region, the slurry flow curve could have some points under clear water curve, e.g. slurries of C_V = 18.3% and 22.6%. This could confirm the principal mechanism of drag reduction for non-Newtonian slurries in turbulent flow region associated with thickening of the viscous sub-layer that has been described by Wilson & Thomas [2]. In the transition zone, the hydraulic gradient steeply increases accompanied with high level of instability and pressure fluctuations. This phenomenon has been studied by El-Nahhas et al. [9]. After the turbulent region is reached, the slurry flow curve can become linear, but it goes higher than that of clear water. It can be also seen that, the laminar/turbulent transition velocity increases with increasing the solids concentration of the slurries.

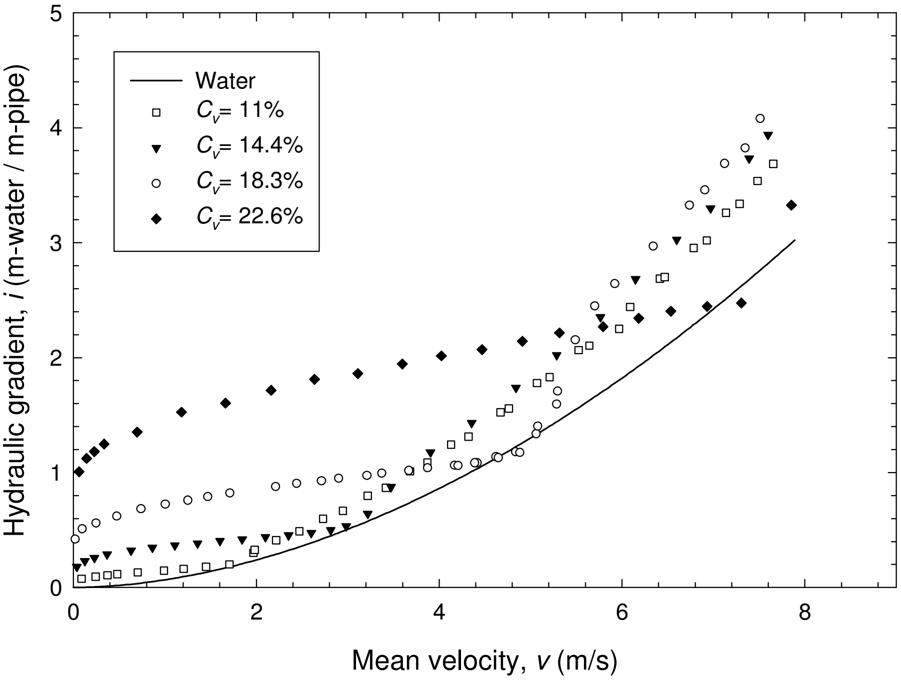


Figure 5 Resistance curves for dense kaolin slurries

2.1. Prediction of Laminar and Turbulent Flow Behaviour

The experimental data of the laminar and turbulent flow behaviour has been compared with the theoretical predictions. Figures 6 and 7 present plots of the wall shear stress τ_w versus the pseudo-shear rate ($8v/D$) of the pipeline test loop experimental data in both laminar and turbulent flow regions for the slurries of volumetric concentrations C_V = 14.4 and 18.3%. Also, these figures show the predictions of the various theoretical models for laminar and turbulent flow behaviour. The rheological parameters extracted from the above-presented rheograms (Figures 3 and 4) were used as input parameters for laminar and turbulent flow models. The experimental laminar flow data points are in excellent agreement with the theoretical prediction by Equation 3. The three studied turbulent flow models underestimate the experimental data. The Slatter [6] model, which is the nearest one to the experimental data, takes in his adoptive concept considerations the particle roughness turbulence that affects the boundary layer. Both Wilson & Thomas and Torrance models treated the slurry as a continuum that may be true in the laminar region only. However, if modified rheological parameters (τ_Y, k, and n) are used as input parameters for the turbulent flow models, the models could match the experimental data, [10]. In this case and as shown in Figure 8, the laminar flow model underestimates the experimental data. Therefore, the turbulent flow models require the input rheological parameters to be determined by experimental measurements in turbulent flow regime.

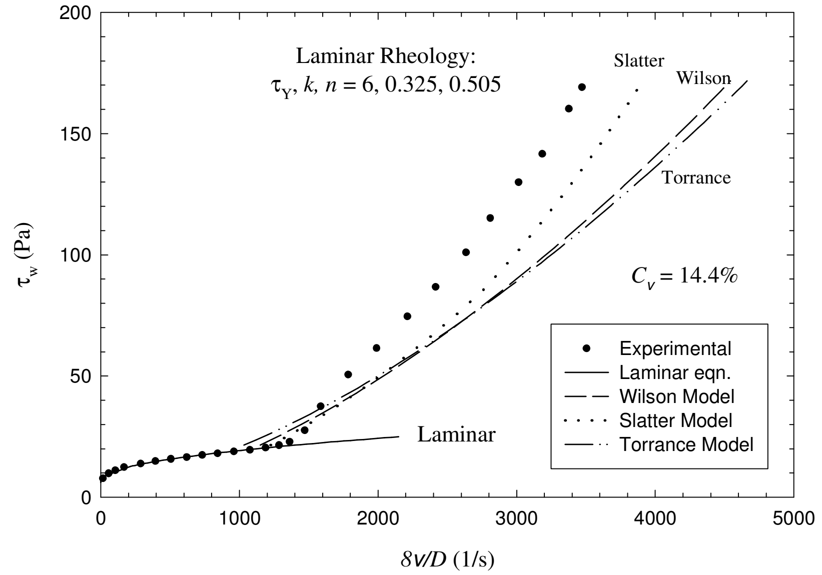


Figure 6 Laminar and turbulent flow predictions of a slurry (C_v =14.4%)

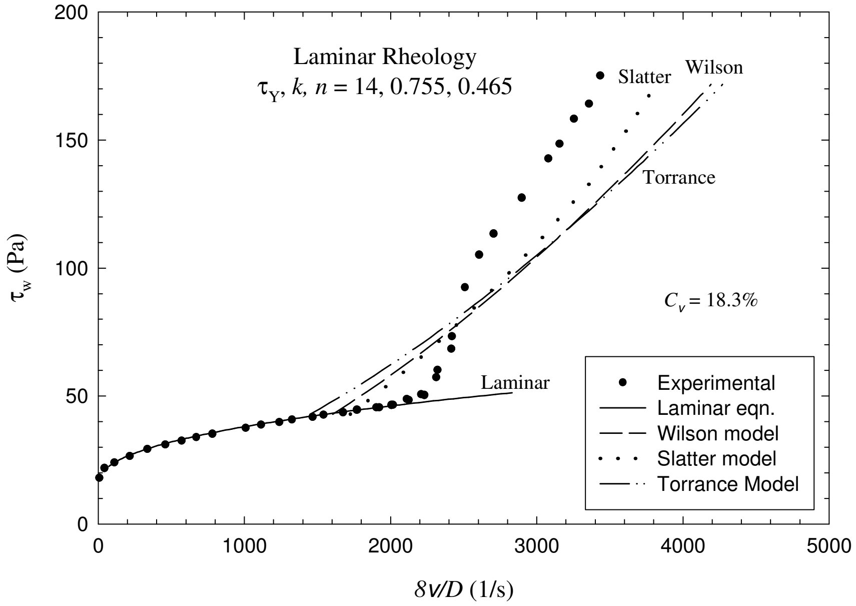


Figure 7 Laminar and turbulent flow predictions of a slurry (C_v =18.3%)

2.2. Peptizing Effect on Laminar and Turbulent Flow Behaviour

Addition of sodium carbonate as a peptizing agent to kaolin slurries results in significant change in the rheological characteristics. It decreases the apparent viscosity and yield stress, see Rayan et al. [8] and Vlasak et al. [11&12]. Figure 9 presents the flow behaviour of two natural kaolin slurries (C_V = 18.3 and 22.6%) compared with two peptized kaolin slurries (C_V = 22.6 and 26%) with sodium carbonate/kaolin mass ratio of C_a = 0.15%. It could be noted that the presence of the peptizing agent enabled to obtain a higher-concentrated slurry (C_V = 26%) which could not be obtained naturally. The change in the rheological characteristics, caused by the peptizing process, closely affects the laminar flow behaviour. In spite of the higher concentrations of the peptized slurries, the yield stress vanishes and the hydraulic gradient (or wall shear stress) is much lower than that of the natural slurries. Their resistance curves (τ_w -v relation) in the laminar region are very close to that of pure water. However, in the turbulent flow region the resistance curve is going higher than that of both water and natural kaolin slurry. This could ensure that the turbulent flow behaviour is independent on the rheological characteristics.

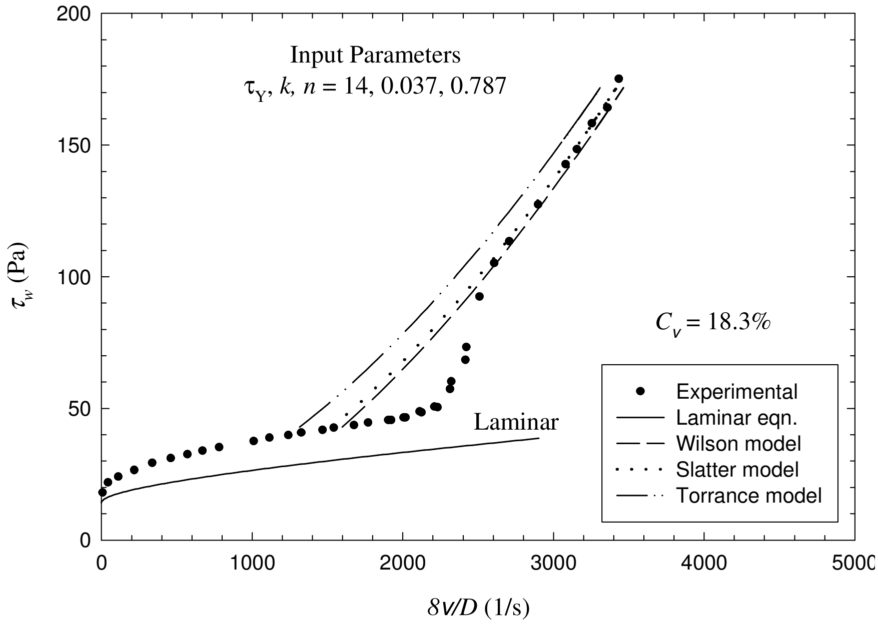


Figure 8 Laminar and turbulent flow predictions of kaolin slurry (C_V =18.3%) using modified input parameters

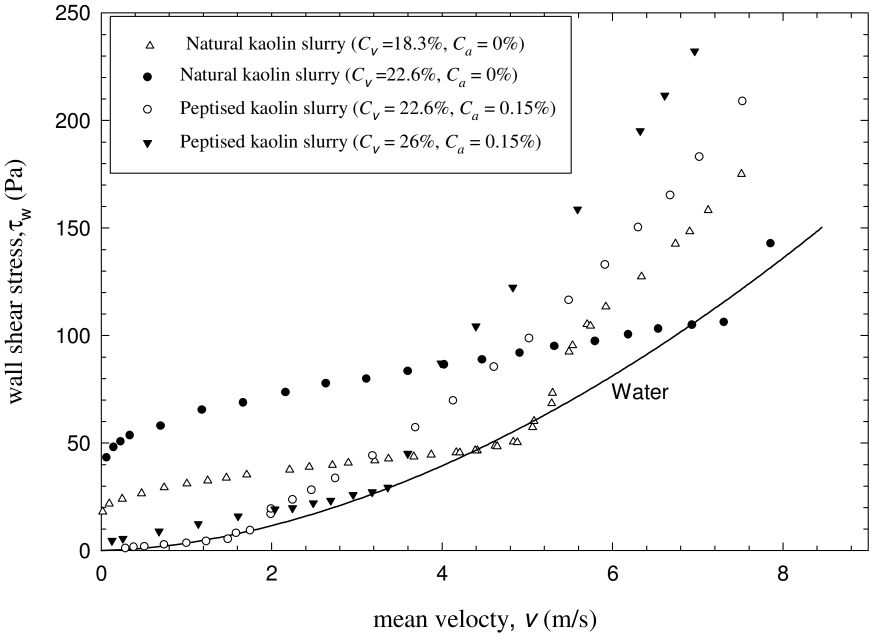


Figure 9 Peptizing effect on laminar and turbulent flow behaviour

2.3. Newtonian Approximation for Turbulent Flow Prediction

The similarity of the turbulent flow behaviour of non-Newtonian slurries with that of Newtonians has been confirmed. The logarithmic relation of Newtonian liquids (Equation 3) has been applied to fit the experimental turbulent flow data of the tested non-Newtonian slurries. El-Nahhas & Vlasak [13] replaced the Newtonian viscosity, μ, which is meaningless for the non-Newtonian fluids, by a characteristic shear-independent parameter C_μ. Equation 3 could be rewritten as:

$$\frac{V}{U_*} = 2.5\ln\left(\frac{U_* D\rho}{C_\mu}\right) \tag{10}$$

Figure 10 presents the experimental turbulent flow data for three natural kaolin slurries ($C_V = 11$, 14.4 and 18.3%) and two peptized kaolin slurries ($C_V = 22.6$ and 26% having $C_a = 0.15\%$). The data points are fitted very well by Eqn. 10. It could be shown that the single parameter, C_μ, in Equation 10, which encapsulates the effect of the solids presence, is direct proportional to the solids concentration regardless the change in the rheological characteristics and laminar behaviour caused by peptizing effect.

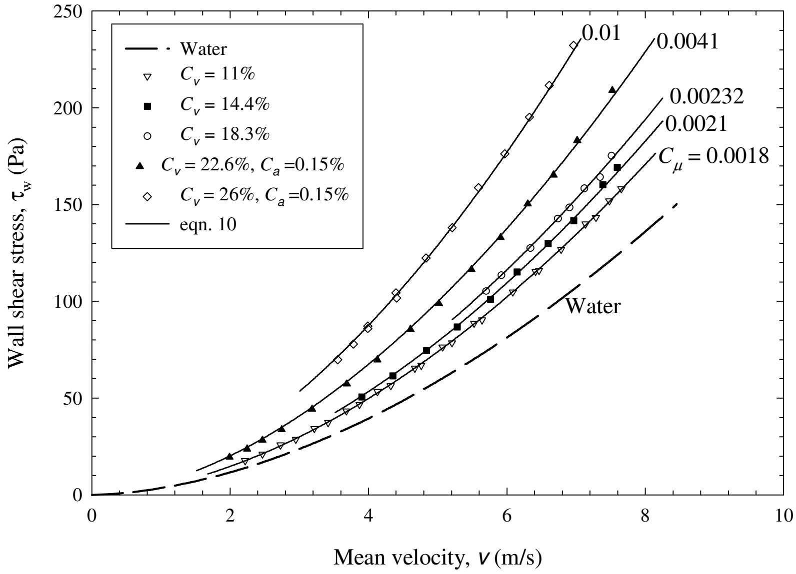


Figure 10 Turbulent flow prediction of kaolin and peptized-kaolin slurries by Newtonian approximation

CONCLUSIONS

The Herschel-Bulkley rheological model has described the tested dense kaolin slurries, which behave as a non-Newtonian fluid, very well. Reliable prediction of the pressure losses in the laminar flow region of non-Newtonian slurries has been well established by integrated rheological model. The laminar rheological parameters were used as input parameters for the turbulent flow predictive models of Torrance, Wilson & Thomas and Slatter, which are different in their adoptive concepts. The three models underestimate the experimentally measured turbulent flow behaviour. The Slatter model that takes the particle roughness effect into account is the nearest model to the experimental situation. The logarithmic law that applied for Newtonian turbulent flow in hydraulically smooth pipes has fitted the non-Newtonian turbulent flow experimental data very well. The Newtonian viscosity in the logarithmic law is replaced by a shear-independent parameter which is found direct proportional to the solids concentration regardless the change in the rheological characteristics caused by peptizing effect. Therefore, the turbulent flow behaviour could be found independent on the rheological characteristics.

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NOMENCLATURE

		Units
C_a	peptizing agent/kaolin mass ratio	[-]
C_v	volumetric concentration	[-]
C_μ	characteristic parameter	[kg/m.s]
D	pipe internal diameter	[m]
d_{50}	mass median particle diameter	[m]
d_{85}	diameter of which 85% (by mass) of the particles are finer	[m]
k	consistency index	$[kgm^{-1}s^{n-2}]$
n	flow behaviour index	[-]
R	pipe radius	[m]
Re	Reynolds number	[-]
Re_r	roughness Reynolds number	[-]
u	local fluid velocity in the pipe-axis direction	[m/s]
U_*	shear velocity $(\tau_w/\rho)^{0.5}$	[m/s]
V	mean velocity	[m/s]
V_N	mean velocity for the equivalent smooth-wall flow of a Newtonian fluid with viscosity μ_a	[m/s]
y	vertical distance in a pipeline cross-section	[m]
Ω	a parameter defined by equation (7)	[-]
α	ratio of areas under the non-Newtonian and Newtonian rheograms	[-]

γ	shear rate	[1/s]
γ_w	wall shear rate	[1/s]
μ	dynamic viscosity	[kg/ms]
μ_a	apparent viscosity	[kg/ms]
ρ	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]
ξ	ratio τ_Y/τ_w	[-]

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