Monitoring of Agglomerating Mature Fine Tailings in Pipe Reactor Flow

Alex van der Spek
ZDoor BV, Rotterdam, ZH, The Netherlands

John Viega
CiDRA Oil Sands, Wallingford ,CT, USA

ABSTRACT: The rheology of fluids is described by a constitutive equation which relates (wall) shear stress to (wall) shear rate. Polymer induced agglomerating of Mature Fine Tailings (MFT) will result in a varying relation between shear stress and shear rate as the reaction progresses. A velocity profiling method to monitor shear stress and shear rate in real time was developed and implemented on a field scale pipe reactor. Results indicate very little difference in the shape of the velocity profile between the turbulent flow of agglomerating MFT and the laminar flow of MFT in its native Bingham plastic state.
With the change in the rheology a different mechanism of energy dissipation will evolve. In laminar flow the pressure gradient required to drive the flow is linearly related to the rate of flow. In fully developed turbulent flow the pressure gradient is quadratically related to the rate of flow. A method is described to monitor the rate of energy dissipation per unit volume from array velocity measurements.
The spectrum of energy distribution over a variety of length scales is measured and compared to the Kolmogorov 5/3 law. Deviations from the latter indicate non turbulent or partially turbulent flow. Partial implementation on a field scale was accomplished using the same instrumentation as used in the velocity profiling method. Results from a field experiment show that periods of laminar and turbulent flow can easily be identified.

1 INTRODUCTION

Mature Fine Tailings (MFT) is a rheological fluid characterized by a non-Newtonian constitutive equation. Often a Bingham model or a Herschel-Bulkley model is applied to model the rheological behavior of MFT. Bingham fluids exhibit a yield point. Wall shear stresses below the yield point will not result in flow. Otherwise the shear stress increases linearly with the shear rate. Herschel-Bulkley fluids also exhibit a yield point but the shear stresses increase either super-linearly or supra-linearly with the shear rate. Herschel-Bulkley fluids are therefore capable of modeling dilatant or pseudo-plastic behavior. A comparison of the various constitutive equations for MFT is given in Figure 1. This figure is to scale and representative values for MFT were used. For reference the black line represents water at room temperature, water being a purely Newtonian fluid.

Dewatering of MFT can be accomplished by a variety of means. Evaporative drying, polymer assisted floccing and mechanical separation are all being used. The economic viability and technical complexity of these techniques is very different. It is fair to state that all means of MFT dewatering would benefit in some form or measure from an on-line measurement of the rheological parameters of the MFT. To date an instrument to do so is not available. The requirements for an on-line measurement of rheology of MFT will depend on the dewatering technique chosen. The method of control, feed-forward or feed-backward, will bring additional requirements.

In evaporative drying, for instance, the yield point of the MFT is of prime importance as this quantity determines the minimum shear stress for positive flow and thereby dictates the slope of the land on which the MFT is deposited. Obviously, a form of feed-back control is not practical in this case.

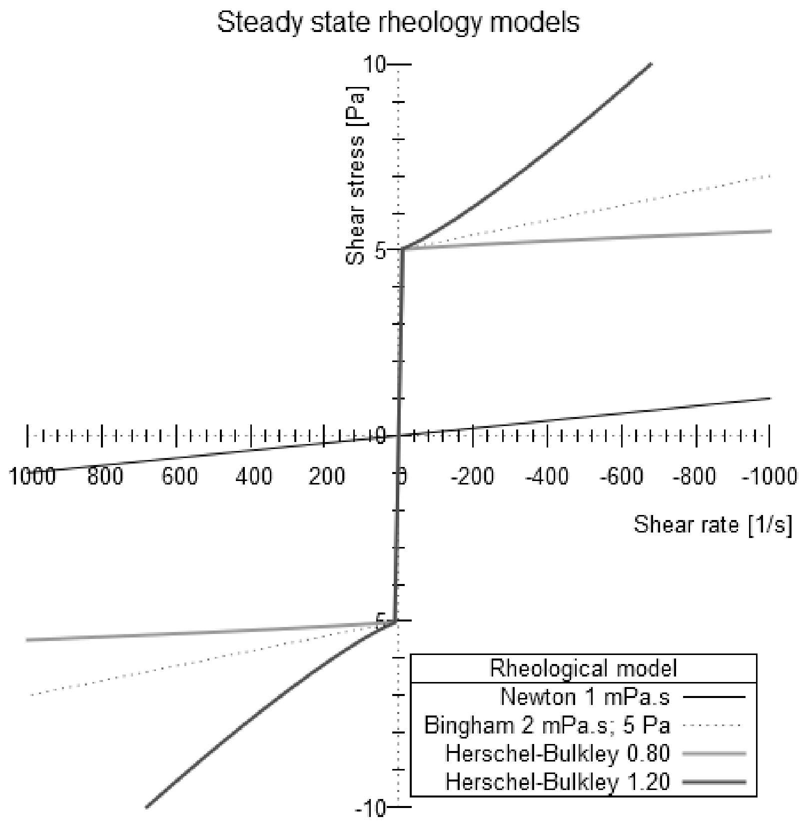

Figure 1. Comparison of various rheological models.

In mechanical drying, similarly, the MFT's plastic viscosity will determine size of and the required power of the drying machinery.

In polymer assisted floccing however; it is important not to shear newly formed flocs apart and hence a measure of the mixing intensity or the energy dissipated at length scales comparable to the flocs is important. In case the chemical reaction occurs in a pipe reactor, feed-back control on the flow rate and chemical dosing may be implemented using a measured quantity related to mixing intensity. In case the polymer is injected just upstream of the drainage points to the drying cells only feed-forward control based on the rheology of the untreated MFT is practical.

It appears, therefore, that two different sets of measurements may be necessary. Rheological parameters such as yield point and plastic viscosity which are commonly determined by laboratory determination of the shear stress to shear rate relation. Furthermore, flow parameters such as the average rate of shear, the mixing intensity or the power dissipation specific to the length scale of the flocs are important for feed-back control of chemically assisted dewatering.

1.1 *Rheological parameters*

The wall shear stress is an important quantity in pipe flow of any rheological fluid. An integral momentum balance across a control volume inside the pipe shows that the wall shear stress, $\tau_{R,}$ is easily determined from a measurement of the pressure gradient in the line (Bird, 1960):

$$\tau_R = \frac{R}{2}\frac{dp}{dx} \qquad (1).$$

Here R is the inside radius of the pipe and dp/dx is the pressure gradient along the axial dimension of the pipe. The shear stress at the wall is the maximum shear stress that can occur. In laminar flow of MFT the profile of the shear stress is linear as the momentum balance equation is of first order.

The wall shear rate is much more difficult to determine in any on-line instrument as it requires the measurement of a velocity profile in the line. The resolution of the velocity profile must be sufficient to extract the gradient of the velocity profile at the pipe wall.

Alternatively we may assume that the flow is of a particular type, e.g. Bingham plastic flow. For such a type of flow the velocity profile may be calculated (Bird, 1960) and hence the velocity gradient at the wall and thereby the wall shear rate is known.

When the type of flow is unknown but it is known that the flow is laminar the shear rate at the wall may still be evaluated from a cross plot of the flow rate and the pressure gradient. This is an application of the Rabinowitsch-Weissenberg (Bird, 1960) equation and is standard practice in many rheological problems. The technique is not well suited to real-time control as historical data is required to evaluate the slope of the flow rate versus pressure gradient plot.

1.2 *Flow parameters*

The rate of energy dissipation per unit mass determines mixing intensity and average shear rate. In pipe flow the rate of energy dissipation per unit mass, ε, can be expressed as:

$$\varepsilon = \frac{1}{\rho} V \frac{dp}{dx} \qquad (2).$$

Here ρ is the density of the fluid, V the velocity and dp/dx the pressure gradient. The above equation (2) does not, however, specify any particular scale of length at which energy is dissipated. As long as energy is dissipated on scales much larger or much smaller than a representative dimension of flocs, such flocs will not be affected. Compare this to the stirring of a large vessel. Even though a lot of power is dissipated, the stirring may not be effective in dispersing small pockets of material concentration because only small amounts of power are dissipated at this scale.

The theory of homogenous isotropic turbulence by Kolmogorov predicts that energy is dissipated only at certain, small, length scales. At length scales much larger than this smallest scale the spatial distribution of power is given by a 5/3 power law in the inverse of the wavenumber k. It is of interest here to determine the fraction of the total power that is effective at the length scale of flocs.

1.3 *Field experiment*

We present field data taken on a pipe reactor of length L1 where Mature Fine Tailings (MFT) is treated by polymer flocculent in order to release water and allow the MFT to dry. All three of the instruments on the pipe reactor are capable of measuring volumetric flow rate, a velocity profile and spectra of the energy dissipated. Differential pressure data was not available.

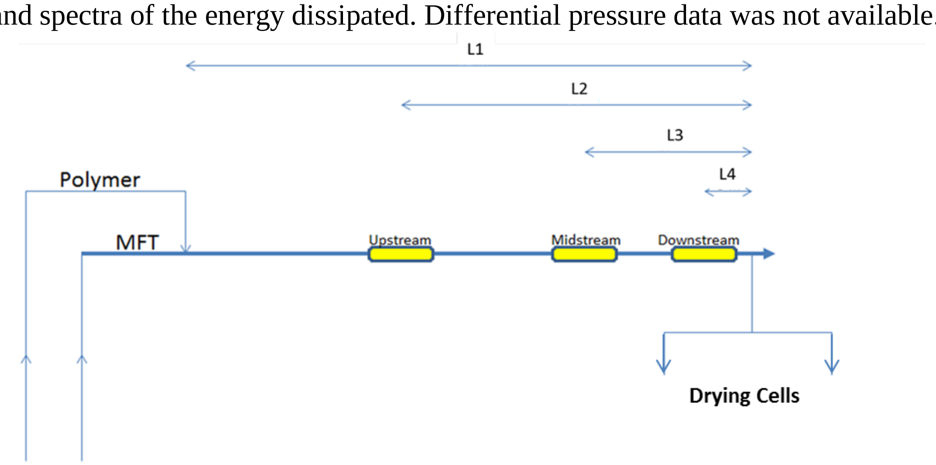

Figure 2. Schematic of the field set up.

2 VELOCITY PROFILING

A segmented array of strain sensitive elements attached to the outside circumference of a pipe may be used as a velocity profile meter (Rothman, 2009). The velocity profile is thus obtained at 5 different positions in the pipe from the top to the bottom. Such velocity profiles are measured at three locations in the pipe reactor as indicated in Figure 2.

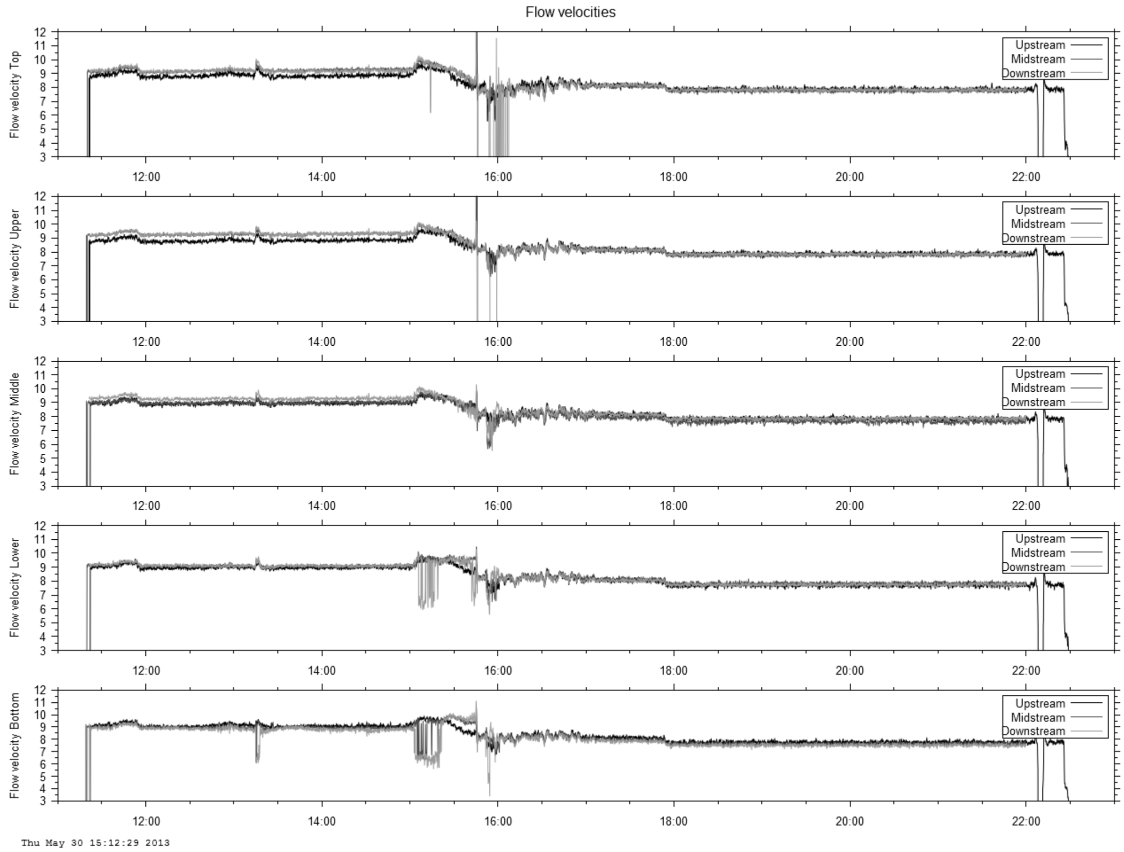

Figure 3. Velocity profiling data.

Around 16:00 the line was switched over from one drying cell to the next. Consequently before 16:00 there was chemical flocculent present in the line and after 16:00 there was none. Therefore the data shown here represents the velocity profile in both treated and untreated MFT, the latter presumably flowing in laminar state.

In Figure 3 the velocity data is shown from top to bottom in 5 different panels, as it would occur in the pipe. The three lines in each panel represent the upstream, midstream and downstream meter respectively. Thus it is easy to compare how the velocity profile progresses downstream as the reaction between MFT and chemical occurs.

First and foremost there does not appear to be any dramatic difference between the velocity profile of untreated MFT (after 16:00) and treated MFT (before 16:00). It is also apparent that the magnitude of the velocity is about the same for all positions in the pipe. This indicates that the velocity profile is almost uniform. A rectangular flow profile is expected for both turbulent flow and for Bingham type flow. The former may well be present in the treated MFT where water is being released upon floccing. The latter is almost certainly present in untreated MFT as a result of the high yield point.

Observe that the upstream meter's top and upper velocity are slightly below the same for the midstream and downstream meter in the period before 16:00. This is the law of mass conservation in action. As there is a tendency of the MFT flocs to settle the velocity in the lower parts of the pipe is slightly lower there. As a result the top and upper velocity must be slightly larger.

The tendency of the MFT flocs to settle may be substantiated by the two periods of time visible at around 13:15 and 15:00. There the bottom and lower velocity for the downstream meter show a steep, sudden decrease which is associated with bedding of solid material.

Bedding is an unwanted phenomenon in a pipe reactor. Fortunately only two periods of short duration were found.

In order to derive a representative gradient of the velocity at the wall from a measured velocity profile it is necessary to find in the measured 5 velocity points an appreciable variation in velocity towards the wall. If that were the case an approximate profile may be constructed by interpolation from which a gradient can be obtained. It goes without saying that the measured velocity profiles do not lend themselves to such a procedure.

3 ENERGY DISSIPATION

The same segmented array of strain sensitive elements as is used for velocity profiling may also be used to infer a quantity closely related to the dissipation of energy in the flow. The way velocity is extracted from array sensors is explained in detail elsewhere (O'Keefe, 2009). The fundamental result however is a map of frequency versus wavenumber for any form of coherent power propagating through the array of sensors. If such power is found to be concentrated on a line (termed a 'ridge' in array processing) of constant slope then that slope itself is inversely proportional to a velocity. The magnitude of the power is not given further consideration.

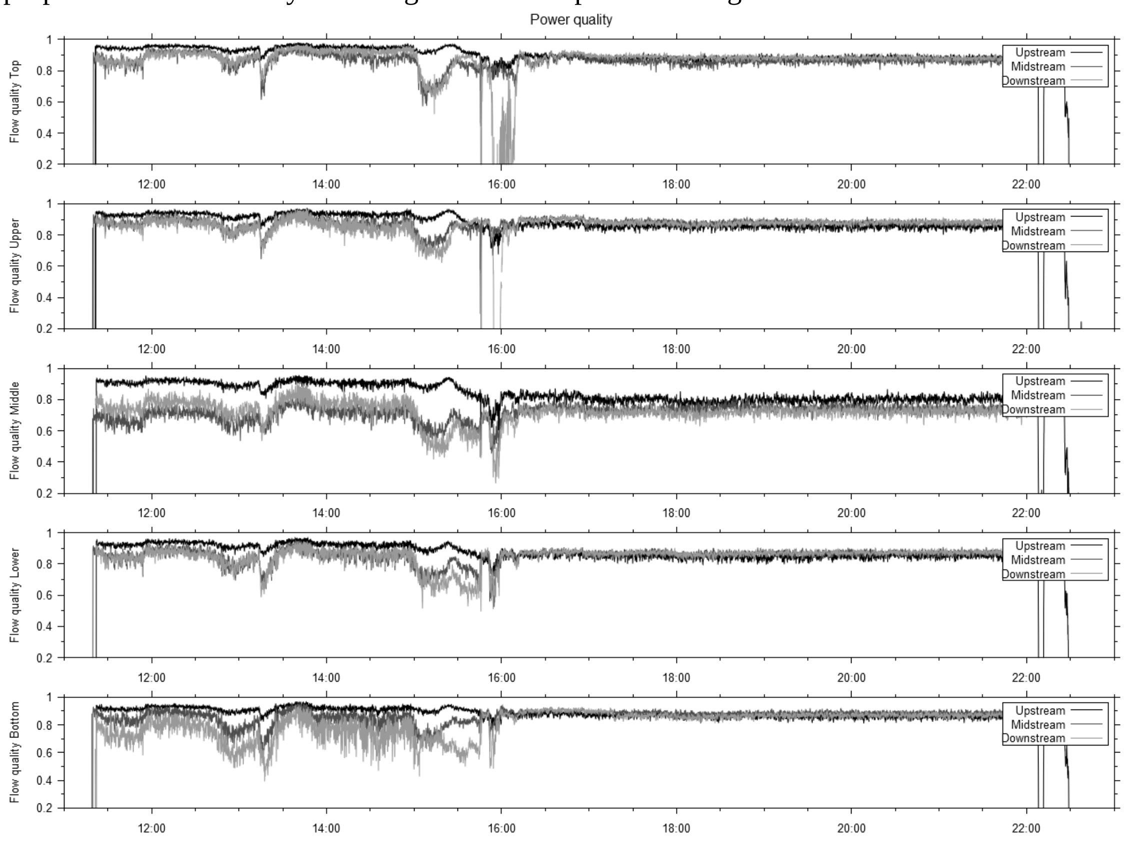

Figure 4. Power quality data.

In Figure 4 above we plot, in the same manner as the velocity data in Figure 3, a measure of the actual (normalized) power of a constant velocity ridge along the line of constant slope. Thus the above Figure 4 complements Figure 3.

Observe that contrary to the velocity data, i.e. the slope of the ridge, there now appears a dramatic difference between the period before 16:00 and the period of time after 16:00. This difference is visible in all positions, top, upper, middle, lower and bottom sensor array and it is visible in all three locations, upstream, midstream and downstream. The difference manifests itself in both the magnitude of the power quality as well as in the fluctuation thereof.

The transition in flow around 16:00 from treated to untreated MFT, presumably being paired with a transition of the flow from turbulent and settling to laminar is very easily observed. It should be noted that the upstream meter, being located upstream of the “T-off” valve shows little effect. Apparently about half way down from the point of chemical injection (equivalent to about 10 s of reaction time at the prevalent flow velocity) the floccing and settling of MFT is not yet occurring.

Contrariwise, downstream of the upstream location, at the midstream position a significant change in the power quality has occurred. This is evident from the changes in the value as well as in the range and the fluctuations occurring. By binning the power quality data in representative time periods of 2 hours it is easier to visualize the change in the power quality progressing down the line through the reaction zone where MFT forms flocs and settles. Such binning is shown in Figure 5, below.

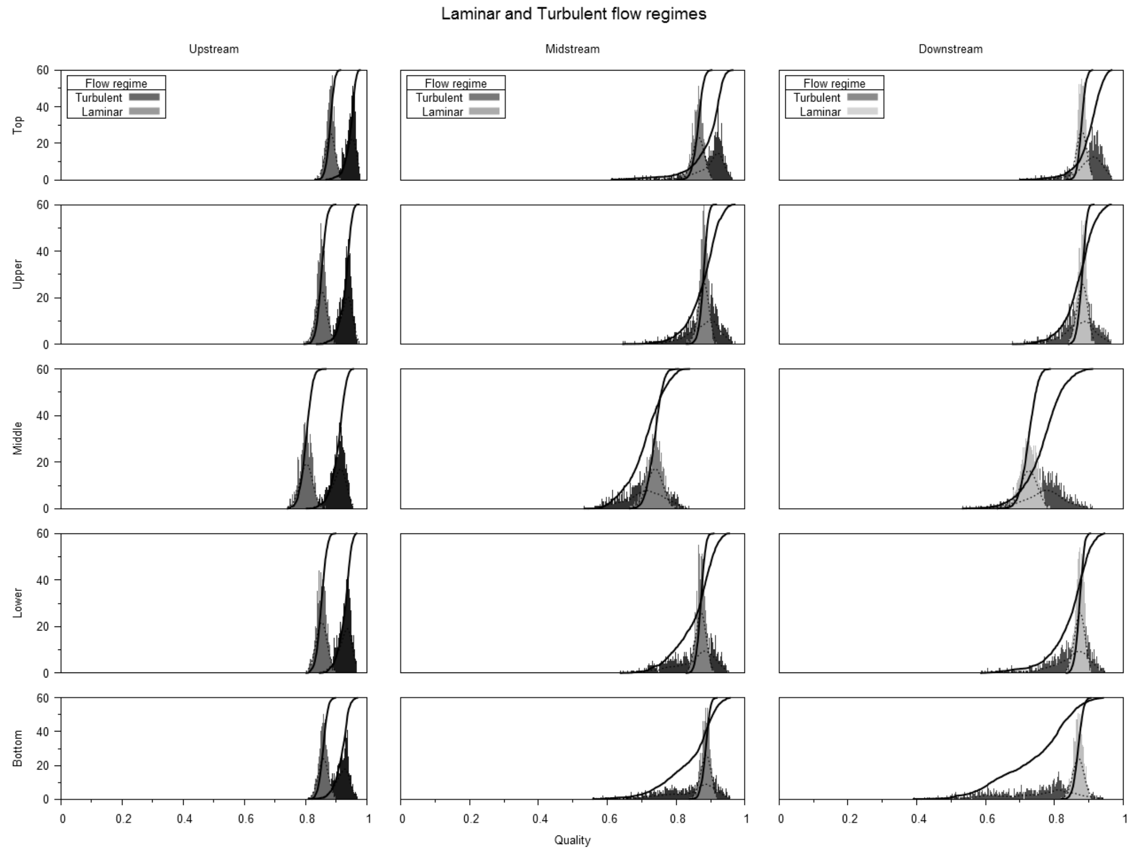

Figure 5. Histograms of power quality.

Note that the horizontal axes are all on the same scale of 0 to 1 in normalized power quality. Likewise all left hand vertical scales run from a 0 count to a count of 60. All right hand vertical scales are from 0 to 1 to indicate the cumulative as given by black lines.

Observe how the middle sensor array consistently results in somewhat smaller power qualities. This occurs irrespective of the location of the meter on the pipe reactor and irrespective of the flow regime. It is not understood why this is the case.

In the flow periods termed ‘laminar’ both the location and the width of the binned power quality data does not appear to change much either by meter location or by sensor array position. Contrariwise, in the flow period termed ‘turbulent’ the change is dramatic and occurs on both the midstream and downstream meter.

4 INTERPRETATION

The results obtained in the field trial were contrary to expectation. It was expected to find little to no variation in the power quality between periods of flow of treated and untreated MFT. It was expected to see larger variation in the velocity profiles between the two periods. A beginning of an interpretation may be found in the Kolmogorov theory of homogenous isotropic turbulence (Davidson, 2009). According to this theory the important scales for length, time, velocity and shear rate (the inverse of the time scale) are given by simple formulae in terms of the kinematic viscosity of the fluid υ and the rate of energy dissipation per unit mass ε. For representative values of MFT in this work the scales are given in Table 1, below.

Table 1. Kolmogorov scales

	Formula	*Value*	*Unit*
Length	$\sqrt[4]{(\nu^3/□)}$	0.2	mm
Time	$\sqrt{(\nu\ /\ ▪)}$	5	ms
Velocity	$\sqrt[4]{\nu}$ □	4	cm/s
Shear rate	$\sqrt{(\varepsilon/\nu)}$	200	1/s

It is concluded that the Kolmogorov length scale is much larger than the typical particle sizes of the fines (< 44 μm) that make up MFT. It is only when such fines are flocculated that the Kolmogorov length scale may be approached. In the case that the particles are smaller than the length scale at which energy is dissipated such particles do not influence the energy dissipation in any way or form.

It is also concluded that the Kolmogorov length scale is much smaller than the length scale to which a sensor array with a spacing of 61 mm is sensitive to. Apparently measured power spectra by an array of sensors are thus not affected by either the small scale eddies nor by the large scale effects which are on the order of the pipe diameter.

It is precisely in this range that the shear rate as given by the formula in Table 1 may be used as a representative value of the average rate of shear. However, what is of more interest is the spatial distribution of rate of shear or in other words the variation thereof with length scale.

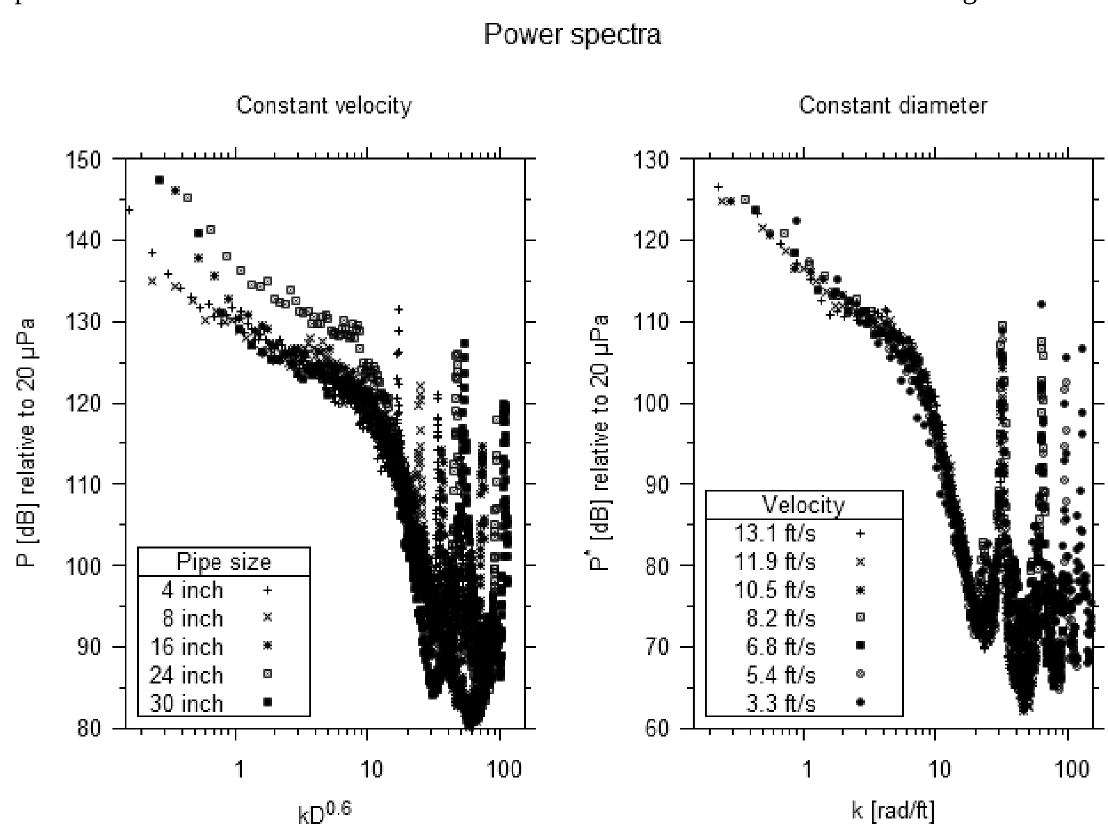

Figure 6. Vortical power spectra in turbulent flow of water.

By way of example in Figure 6 the spectra of vortical eddies in turbulent flow are given for a range of pipe sizes but at a constant velocity (left hand panel) and for a range of velocities (right hand panel) but at a constant pipe diameter. The graphs shown here are measured using similar array type sensors albeit without segmentation as this is only required for velocity profiling. The data originates from calibrations done in a high accuracy flow loop. As such there is no connection with the MFT field experiments reported here. Yet the graphs help to interpret the power quality data resulting from the MFT field experiment. It should be noted here that the "peaks" appearing in the spectra are a well understood artifact of array processing.

The Kolmogorov theory of homogenous isotropic turbulence predicts that the latter should all fall on the same curve when the power is scaled by the rate of energy dissipation as is seen to be the case. The theory also predicts that the spectra should collapse to the same curve when the wavenumber is scaled to the pipe diameter. With the exception of the 24 inch pipe this is indeed the case. The relation between the rate of energy dissipation per unit mass ε, wave number k and the power spectrum P(k) is given by Kolmogorov's celebrated 5/3's law:

$$P(k) = c\varepsilon^{2/3} k^{-5/3} \qquad (3).$$

Here c is a universal, dimensionless coefficient. The formula links the length scale to the energy dissipation rate per unit mass. Length scale should here be taken as the inverse of the wave-number. The power quality as given in the Figures 4 and 5 is a normalized sum of P(k) between two bounds. The lower bound being the length scale corresponding to the pipe diameter. The upper bound being given by the distance between the individual sensors of an array.

The power quality is therefore a not just a measure of the amount of dissipated power but also, whenever such power is dissipated at length scales between the upper and lower bound of the (inverse) wavenumber of the length scale itself. It may be postulated that when flocs of MFT are of similar size as this length scale, i.e. the size of "eddies" in turbulent flow significant effects occur. In such cases that this leads to breaking down of the flocs by shear action should be taken to prevent this.

5 CONCLUSIONS AND RECOMMENDATIONS

Regardless of the dewatering methodology, on-line instrumentation for the measurement of the rheological parameters of MFT is necessary to control the process and to cope with the variations in the properties of MFT.

Measured velocity profiles in pipe flow of MFT show a nearly uniform velocity profile as is expected for flow of a Bingham plastic. MFT which is floccing and releasing water after treatment with polymer also show a nearly uniform velocity profile as is expected for turbulent flow.

The size of fines in MFT is much smaller than the Kolmogorov length scale in typical flows of MFT. The hydraulic power in the flow is therefore dissipated without being influenced by the fine particulate material. Flocs of MFT, formed by polymer injection will grow to sizes comparable to the length scale at which hydraulic power is dissipated.

Sonar based array processing techniques are sensitive to any form of (coherent, hydraulic) wave power propagating through the sensors making up the array at length scales dictated by the distance of the sensors. Power quality is a measure derived from sonar based array sensing which responds to both the magnitude of and the length scale at which energy is dissipated.

Measured values of (normalized) power quality in agglomerating MFT show large fluctuations and cover a wide range whereas in native MFT power quality shows narrow distributions centered at one particular value.

In the pipe reactor the agglomeration of MFT under the influence of polymer is not noticeable in the beginning of the line. Only in the second half of the pipe reactor does normalized power quality indicate the formation of flocs of length scales much larger than the Kolmogorov length.

There is virtually no tendency of such flocs to settle into a bed. Measured velocity profiles show only short, intermittent periods of bedding. At times that bedding is suspected the normalized power quality shows lower values on average. The latter indicates that power dissipation is significantly affected on length scales comparable to the distance between sensors.

Normalized power quality is neither a direct measure of the amount of energy being dissipated nor is it directly indicative of the precise length scale at which hydraulic power is dissipated. Development of a measure that does both is possible using Kolmogorov theory and detailed array processing quantities. Average rate of shear may then be calculated at a different length scales. The rheology of agglomerating MFT may then be characterized at a multitude of scales.

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