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Measurements, mechanisms and models: Some important insights into the mechanisms of flow of fibre suspensions

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ABSTRACT

The complex nature of flowing fibre suspensions is reviewed. Up to four different ‘particles’ can exist simultaneously in fibre suspension flow making it a unique flow system. Investigations of flow phenomena are difficult due suspension opacity and fibre interference with the internal measuring devices. Some recent investigations and methods are described to elucidate flow mechanisms. These include modifying the suspension liquid using chemical and physical additives, changing the physical flow surface conditions, modifying the flow channel size, and changing the flow conditions. The application of heat transfer measurements is shown to be a valuable tool.

INTRODUCTION

Conventional, non-settling, non-aggregating particulate suspensions exhibit similar flow behaviour at the same solids concentration with friction loss curves always above the water curve. Particle density, size and size distribution produce some differences but these are usually minor. In contrast wood pulp fibres, certain polymeric filaments, and some high aspect ratio particles, develop ‘suspension structure’ which alters the nature of the suspension and hence flow characteristics. In general, most rigid particle systems can be defined by a mean size or a size parameter, but for asymmetric particle suspensions, the *state* of the suspension and factors such as fibre flexibility may overrule particle size and size distribution.

There are four different ‘particles’ in fibre suspension systems; fibres, floccettes, flocs, and networks[1]. Each on its own exhibits unique features. Fibres/filaments with high aspect ratios exist in suspension as separate entities at low concentrations like conventional particulate systems. They ‘connect’ with neighbouring eddies and can either aid in transmitting momentum or they can bend, deflect and absorb turbulent energy. This ‘competition’ leads to drag reducing character (friction loss below water) unlike conventional particulate systems.

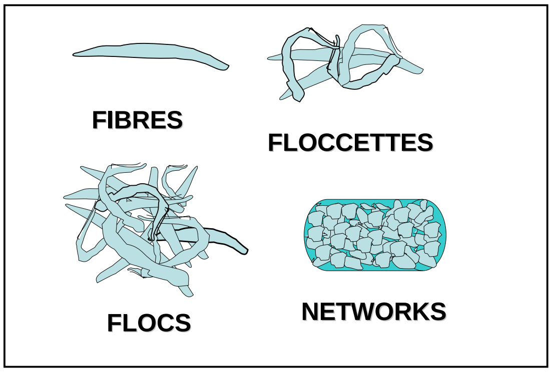

Figure 1 The four “particles” in wood pulp fibre suspensions

As population increases, free-fibre movement is inhibited and small unstable, dynamic aggregates form that allow other mechanisms to come into play. These new 'particles' (called floccettes) interact dynamically with the liquid and with themselves producing some special visco-elastic effects.

At slightly higher concentrations the floccette fibre bundles develop coherence and mechanical structure and are called flocs. It is not just a crowding phenomenon but a mechanical linkage of fibres giving the flocs special plastic-elastic characteristics. These agglomerates may have a range of sizes but take on a mean value depending on fibre type and fibre characteristics. This third type of floc 'particle' dominates in many practical applications and governs many processes.

The fourth 'particle' is termed a network and is made up of interconnected flocs that develop high interfloccular strength. Flow shear forces have to be sufficient to deform the flocs or dislodge and disperse them in a flow field. Networks usually take the shape of the vessel or conduit at the lower flow rates.

To make matters more complex, there are many situations where all four 'particles' co-exist and their individual contributions lead to some very important shear mechanisms. The friction loss curves for conventional particle systems are always above the water curve, but for fibre systems they are above the water curve only at the lower flow rates. Drag reduction at the higher flow rates makes these suspensions unique (this also occurs with some long-chain polymer systems).

Clearly classical fluid flow and non Newtonian models do not apply, and realistic models must be developed from a platform of understanding of the actual flow mechanisms[1]. Hence, when talking about fibre suspension flow, it is important to define not only what the 'particle' is, but also the state of the suspension, the flow conditions, and channel size. For example, in certain cases pipe friction loss can be lower in a roughened pipe than in a smooth pipe. Pipe friction loss levels can equal those for water over the *entire* range of flow rates in small diameter tubes even though the same suspension at the same concentration produces frictional losses levels many, many times higher in larger diameter pipes. Visco-elasticity can be observed in accelerating/decelerating flows.

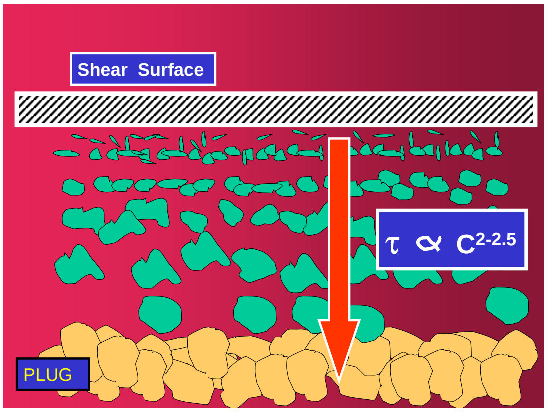

Figure 2 The existence of the four "particles" simultaneously in the transition flow regime of wood pulp fibre suspension flow

Flowing wood pulp fibre suspensions are not Newtonian; and they are *not* non Newtonian[1]. They should be classified separately like other special classes of inhomogeneous systems eg dense-phase flow, settling flows, gas-liquid bubble flows etc. The viscosity of inhomogeneous, non-laminar fibre suspension flows is still being used widely in error. Viscosity has no meaning except as a mathematical proportionality coefficient connecting wall shear stress and shear rate. Many have attempted to apply Newtonian models and erroneously assigned a 'viscosity' to the coherent plug flow regime, where a coherent plug in excess of 98% of the diameter still exists. Published research on MC flow and general fibre suspension flow including viscometry are still being published based on this misapplication.

Fibre suspensions are clearly different from conventional particulate slurries because these 'particles' interact, interconnect, and develop suspension structure. These inhomogeneous sub-units and structures produce several phenomena not often encountered in other conventional homogeneous systems. Consequently they produce flow models that are vastly different from classical models. In transition flow for example, a central coherent plug still exists with the annular shear layer having a range of floc sizes decreasing in size toward the wall where single fibres, fines and flocettes exist (see Fig. 2).

MEASUREMENTS, MECHANISMS AND MODELS

Measurements

Investigation of flow phenomena of fibre suspensions at moderate concentrations has been difficult due to suspension interference with the internal measuring devices, suspension opacity, and instrument limitations. Pressure drop determinations in pipe flow, torque measurements in viscometry, and photo/video and laser beam evidence have been the main quantifying techniques used. Velocity profiles have been measured successfully[2-5] and validated at fibre concentrations less than 1%, and NMR has been used[6] to obtain velocity and suspension concentration profiles. Various chemicals and additives have been used to validate postulates or prove untested ideas. More recently heat transfer measurements have also opened up new insights into fibre-liquid interactions.

Mechanisms

The mechanisms of fibre suspension flow have been the subject of intense investigation for many decades[7-9], including medium consistency flow[10-12]. These have been well documented and verified with widely varying techniques. They are not reviewed here, but some more recent developments to elucidate further some special flow mechanisms are summarised in this paper.

Models

Wood pulp fibre suspensions exhibit either plug flow at the lower flow rates, or drag reduction at the medium to higher flow rates. There are several sub-regimes in each of these flow domains that are unique to fibre suspension flow.

Several flow models have been proposed over the years [1, 13-15] mainly based on experimental evidence of these flow regimes. Unfortunately, some have disregarded these unique features and produced idealised models based on theories, mathematical concepts, and non Newtonian laminar shear flow models that do not apply to non-laminar, heterogeneous fibre suspension flow. These misconceptions have been embedded in the literature and have brought confusion and errors that have misled newer researchers. Some of the experimental evidence presented here may help to clarify some of the key issues.

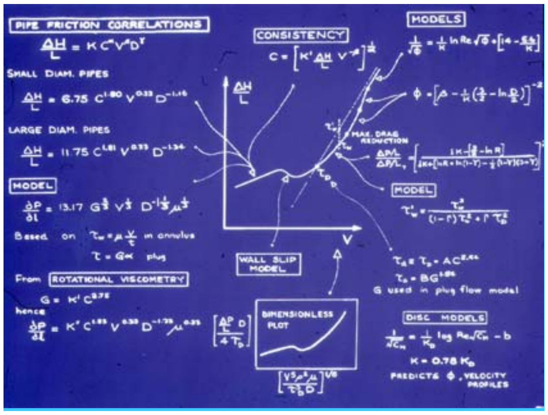

Figure 3 Some of the models that have been applied to fibre suspension flow in the plug flow, transition flow, and fully-developed turbulent flow regimes

SOME RECENT DEVELOPMENTS

Fibre suspensions are complex. Small differences in fibre dimensions, size distribution and physical properties often produce large differences in the flow characteristics. The nature of the flow also depends on ‘particle’ interactions, flow geometry, the type of shear field, the fluid properties, the presence of a third phase (air), and other additives. Some recent developments in our investigative work to elucidate and apply new findings are summarised here:

- Modifying the liquid using additives (chemical of physical)
- Changing the physical surface conditions
- Modifying the flow channel size
- Changing the flow conditions
- Using different measuring methods

Suspension liquid modification

One important way to study flocculation is to vary liquid properties[16-18]. In one series of experiments, water viscosity was increased by adding either small amounts of dissolved carboxymethyl cellulose CMC (<0.2% concentration) or sugar solution. Hydrophobic mineral oil was also used in one series of experiments. Increasing viscosity allowed fibres in a decaying turbulent shear field more time to straighten to some degree before coming to rest against other fibres. Floc coherence and the mean floc size were reduced resulting in less plug-like character.

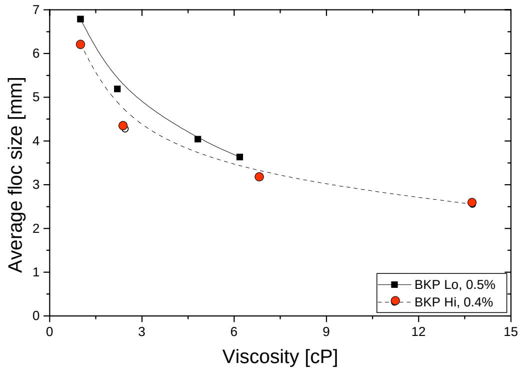

Figure 4 Effect of viscosity on floc size in grid flow for a low and a high coarseness bleached kraft pulp

The friction loss curve changed shape as shown in Fig. 6. The overall effect was similar to decreasing fibre concentration (making the network and floc strength weaker).

Drag reduction was still evident. The onset velocity of drag reduction was increased and the level of drag reduction reduced.

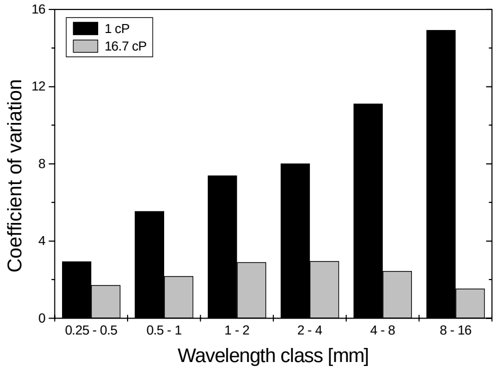

Figure 5 The effect of viscosity on floc size reduction and distribution

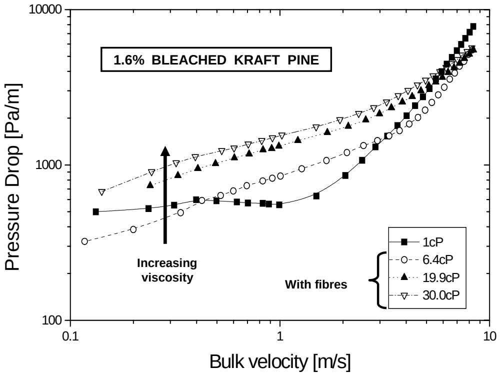

Figure 6 The effects of viscosity on pipe friction loss curves of a bleached kraft pine fibre suspension at 1.6% fibre concentration

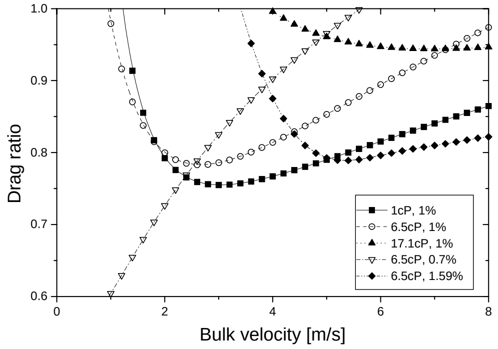

Figure 7 The effect of viscosity on Drag Ratio (pressure drop suspension to liquid ratio) for a bleached kraft pine pulp at 0.7%, 1.0% and 1.59% fibre concentration

The plug became less coherent with increasing viscosity as illustrated in Fig. 8 with the reduction in point velocity u to bulk velocity U ratio u/U nearer the pipe wall. This is also shown clearly in Fig. 9 with the centre line velocity $u_{centreline}$ to the bulk velocity U ratio ($u_{centreline}$/U) increasing with increasing viscosity. The plug becomes more parabolic in shape with increasing viscosity and with increasing flow rate.

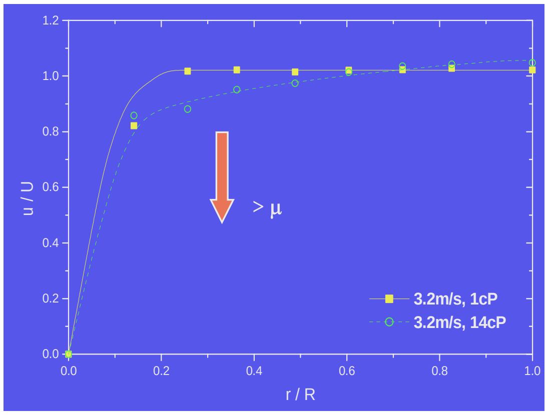

Figure 8 The effect of viscosity on the plug-like character of the velocity profile at the same fibre concentration

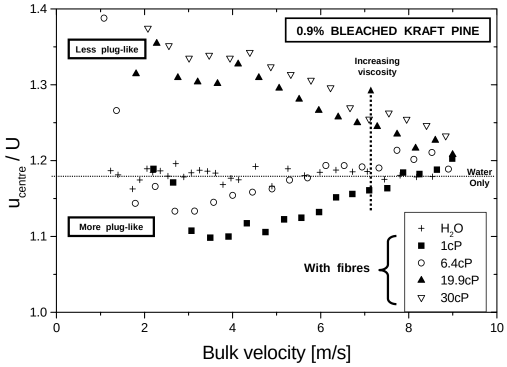

Figure 9 The effect of viscosity on velocity ratio (centreline to bulk velocity ratio) for a range of velocities showing less plug-like character with increasing viscosity

The changes in flow mechanisms (from visual and photographic observation, and measurements of pressure differential, velocity profile and turbulence), all validate the previous postulates of the flow mechanisms of fibre-water suspensions in plug and transition flow. In effect, increasing liquid viscosity produced a more homogeneous suspension which allowed for improved processing capability.

Experiments in a pressure screen[18] showed that increasing liquid viscosity increased fibre acceptance, reduced reject thickening, reduced screen pressure drop, reduced pump power, and increased throughput. Screen aperture size could be reduced to maximise contaminant removal while maintaining good fibre throughput.

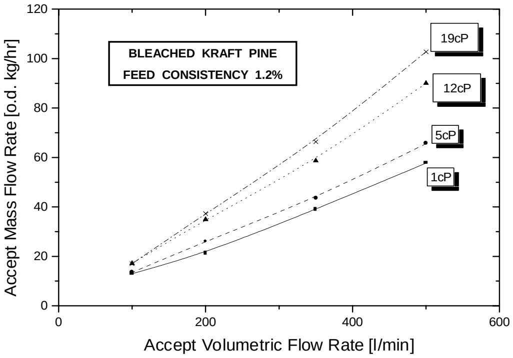

Figure 10 The effect of increasing viscosity on screen capacity showing increasing accept mass flow rate with increasing volumetric flow rate

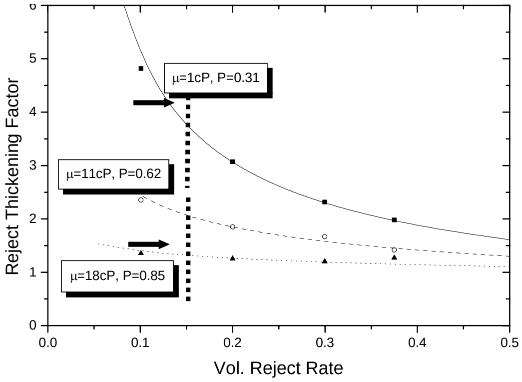

Figure 11 The effect of increasing viscosity on reject thickening and volumetric reject rate

Suspension hydrodynamics can also be affected with the addition of small amounts of other ‘particles’. It had already been observed that drying and rewetting the pulp, pulp bleaching, and pulp refining, all shifted the curve maxima to lower velocities by lowering the network strength. To shift the maxima in the friction loss curve to higher velocities small quantities of cut wool fibres were added to the suspension. The jagged wool fibre surfaces improved fibre interlocking and hence floc strength. Pipe friction loss in the plug flow region before the maxima also increased but the maxima were shifted to higher flow rates. This reinforced the concept of network strength dictating the conditions in the plug flow regime. The network strength of the suspension is therefore an important parameter for plug flow.

Modifying the flow surface

Experiments were carried out with pipes having internally-patterned rough surfaces. It was found that although pipe friction loss was higher at low flow rates, the maxima in the friction loss curves occurred at a much lower velocity and friction loss fell below that for the same pulp flowing in a smooth pipe. In some cases the reductions were of the order of 50%. At low flow rates the peripheral flocs could move into the roughness hollows. As the velocity increased the flocs had less time to deform into the lower regions and in essence, began to ‘skip from peak-to-peak’. A water layer developed in the troughs and at the peaks at slightly higher shear rates. This ‘lubricated’ the asperities allowing a reduction in frictional drag. This mechanism persisted over a good range of flow rates until local wall turbulence set in and increased the frictional resistance again.

Hence in the normal region of industrial pipeline flow, frictional resistance (and hence the pump power) can be lower than for the same pulp suspension flowing in a smooth pipe. The roughness pattern and the flow velocity are related for specific fibre suspension conditions. This shows the importance of floc elasticity in providing a unique visco-elastic characteristic to the flow.

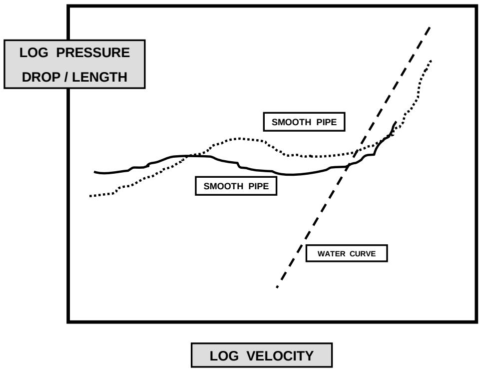

Figure 12 Schematic comparison of friction loss curves for rough and smooth pipes (same diameter and fibre concentration)

In screening, surface topography, hole geometry/design, and boundary layer flow are all highly significant. It was proposed that as the velocity gradient was steepest near the screen surface, fibres would tend to align themselves in the direction of flow. Hence arranging slots predominantly in the flow direction would give the elongated fibres better opportunity to pass through[19]. The slotted screen had the same percentage flow area as the holes for direct comparison. In addition the slots were narrower and hence the rejection of deleterious particles increased with a simultaneous increase in fibre acceptance.

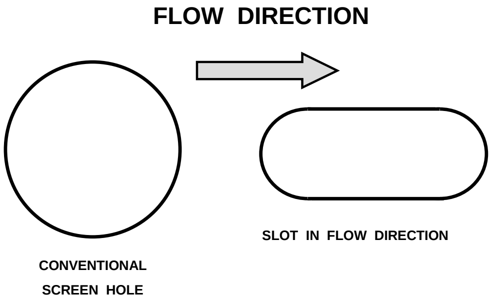

Figure 13 Diagrammatic representation of a screen slot in the flow direction to increase fibre acceptance and improved suspension cleaning

In effect the screen would be a more efficient barrier to foreign unwanted particles while providing a better opportunity for the flexible fibres to pass in their more preferred fibre orientation. This indeed was the case[19]. The overall effect was similar to increasing the fluid viscosity of the liquid medium to improve the hydraulic drag on the fibres and hence increase passage ratio.

Modifying the flow channel size

Another important insight comes from the affect of the channel dimension on flow[20, 21]. Flocs exist at fibre concentrations above about 0.5%. Most industrial pipes and flow channels are large enough for flocs to exist side-by-side. Plug flow occurs at low to moderate flow rates and the entire shear is confined to the flocs embedded in the peripheral plug layer adjacent to the wall. In essence the bulk of the plug is undisrupted and undisturbed. As the conduit width or pipe diameter is sequentially reduced the number of adjacent flocs that can fit side-by-side pipe markedly deceases. The plug becomes less coherent as diameter decreases, and more side-by-side flocs are mobilised.

A new and different type of ‘plug structure’ develops when the channel size is a little smaller than about twice the characteristic floc size. The new plug is more uniform and is like an extruded network array of fibres. Its structure depends on the inlet geometry to the small channel, acceleration rate, and the characteristics of the fibres. Norman et al.[22] were the first to highlight this in their novel medium consistency flowbox. They actually referred to the bulky sheet formed as a continuous floc.

This phenomenon was investigated further[20, 21] in a series of experiments using a range of pipes in series and parallel. The pipe diameters ranged from 3mm to 28.8mm. This allowed the collection of data simultaneously so the fibre concentration and temperature would be identical.

Three surprising findings resulted. Firstly, as the pipe diameter was systematically decreased, the separate friction loss curves for the fibre suspension became more aligned to the respective water curve. At the lowest pipe diameters close to the mean floc size, the pulp and water curves coincided over the full range of flow rates studied (up to 3m/s). The plug-like network structure was clearly evident but the friction loss was entirely identical to water alone. This had not been reported before at fibre concentrations well above 1%.

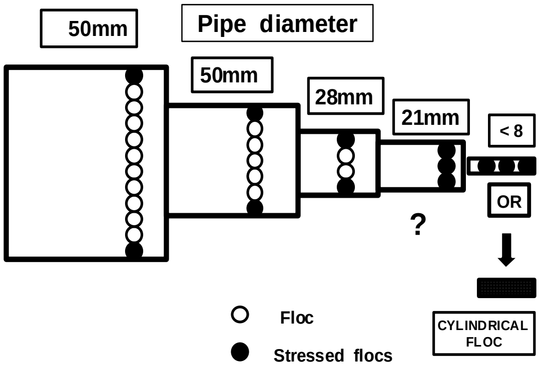

Figure 14 Diagrammatic comparison of plug flow in large and small pipes

Of course in conventional industrial pipe sizes, the pulp friction loss curve happens to cross the water curve (single point case) in the plug regime (>98% of the plug unsheared), but that has no comparative significance. It is in essence a special condition of plug flow where the outer fibre layers are producing a local turbulent shear mechanism around the plug to reduce pipe friction that happens to correspond with the water-only value at that point. At small differential velocities near that point there is no correspondence. This is totally different from water-only at that point which is at the fully-developed turbulence state.

The network structure in small diameter conduits is remarkably different from normal plug structure in larger pipes. This ‘extruded plug’ structure reduced the frictional drag to that equivalent to water alone over the entire range from 0 to 3m/s.

This is illustrated in Fig. 15 for a short-fibre eucalypt pulp.

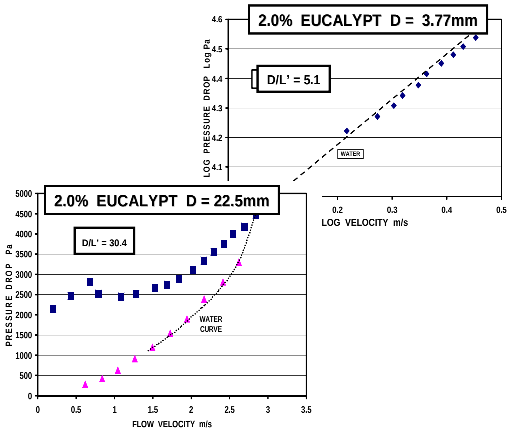

Figure 15 Comparison of pipe friction loss data for a eucalypt pulp obtained simultaneously in large and small pipe sizes

The second feature was that the new extruded network or floc remained coherent along the pipe length for long distances. Longer chemical softwood pulp fibres naturally produced single, long, axial-networks (typically 1m long or more) with more coherence than with hardwood pulps. Short-fibred hardwood pulps produced a series of end-on-end, long, cylindrical flocs (20 to about 50mm long) because the fibre network integrity was less. The fact that fibres accelerating into the small tubes were more aligned in the flow direction meant that they could readily retract from the wall to produce a well developed water layer over the entire range of flow velocities. Clearly this entry phenomenon occurs in screening.

The third factor is that there was no measured or observed evidence of drag reduction (even at 0.5% and 1.0% fibre concentration) which is normally caused by turbulence damping. Fibres in small tubes at 0.5 - 2% concentration are not free to more independently and hence the plug structures are retained even at high shear rates with no drag reduction.

These experiments verify the previously proposed mechanisms of flow but increase the understanding of how channel dimensions and the entry conditions change the fundamental structure of fibre suspensions and the plug structure in particular.

Changing flow conditions - visco-elastic suspension behaviour

Systematic experiments[23] were performed to investigate suspension behaviour over a wide range of acceleration and deceleration rates. Both longitudinal pressure differential and point absolute pressure data were recorded. The data were compared with the steady-state friction loss curves and some selected results are presented in Figure 16.

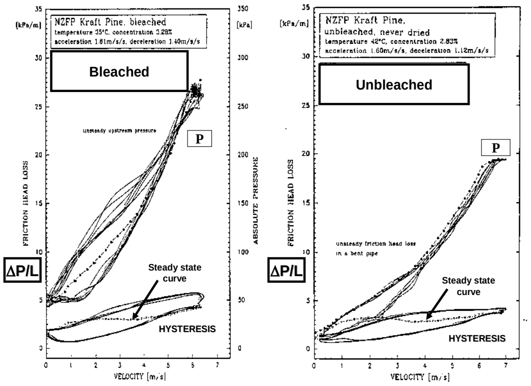

Figure 16 Hysteresis friction loss curves for bleached and unbleached kraft pine pulps at approximately the same fibre concentration and acceleration/ deceleration rates

Clearly each type of pulp produced a unique hysteresis envelope at the same fibre concentration and set of acceleration/ deceleration rates. Suspension acceleration caused dynamic de-flocculation as fibres and flocs were torn from the central plug as indication of the true fibre network strength. On deceleration the returning flow curve characterised the rebuilding of the network from the centreline out. Apart from the systematic trends it was shown that the hysteresis envelope actually characterised the suspension and these could be used to monitor variations in suspension properties and fibre quality. Further work carried out with mechanical pulps verified this.

The results presented in Fig. 16 for a bleached and an unbleached kraft pine pulps are at approximately 3% fibre concentration. The envelope shapes and their relative position to the steady-state curve show how small changes in fibre flexibility (elastic and plastic character) affect floc strength and network coherence. The shape of the absolute pressure hysteresis curves also demonstrates these effects.

Hyteresis-type curves have been observed before but no systematic research has been reported. Bennington et al.[24] observed the effected in their rotational viscometer operating at 8-10% fibre concentration but concluded the effect was due to suspension inhomogeneity and torque measuring errors (see Fig. 17).

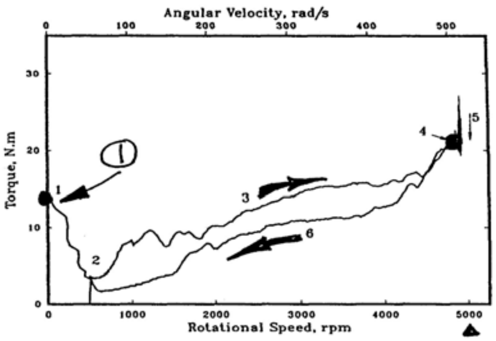

Figure 17 Hysteresis curves from experiments using a rotational viscometer (after Bennington et al.[24])

The findings in our research were then applied to a practical pumping problem of transporting fibre suspensions. An AC variable-speed motor driving the pump was used to cycle the motor speed over a narrow range of speeds. Small hysteresis curves developed, but the mean level of friction loss and hence pump power decreased. In essence the outer suspension layers were continuously ‘activated’ by the variations in bulk flow rate (pulsing), producing a different flow field near the inner pipe wall and a lower frictional resistance.

Heat transfer measurements

Heat transfer measurements to fibre suspensions were used first to elucidate the mechanisms of flow and to see if heat transfer coefficient values could be used to predict friction loss[25-27]. This was initially successful but more importantly some new insights were obtained. It was found at fibre concentrations in excess of about 2% that the heat transfer coefficient h_c were highest up to the maximum point in the friction loss curve (plug flow) and then decreased below the equivalent water-only h_c values. However for pressure drop, the decrease below the water-only curve occurred at even higher flow rates; that is at the onset of drag reduction. The heat transfer reduction at the curve maxima showed that the decrease was caused by a mechanistic change from predominantly conduction due to fibre-wall drag, to thermal energy transfer across a laminar shear wall layer as previously proposed. This heat transfer decrease also validated the fact that fibre-wall drag dominated up to the maximum in the friction loss curve. However, for momentum transfer reduction after the water curve was crossed, turbulent fibre-liquid interactions in the thin annular layer were proven to be the cause of this reduction using the heat transfer experiments.

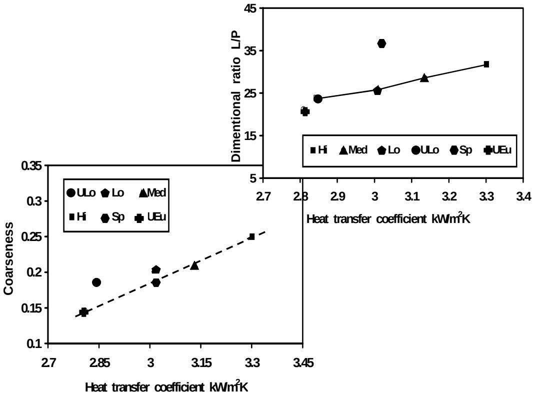

Figure 18 Fibre length to fibre perimeter ratio L/P, and fibre coarseness as a function of heat transfer

coefficient for low-to-high coarseness radiata pine pulps, and a eucalypt and a spruce pulp

Different effects were observed[28] at very low fibre concentrations (< 0.4%) where fibres move more freely and independently. At the lowest flow velocities heat transfer was often equal to or greater than that for water but very quickly decreased below the water values to a minimum level. Heat transfer increased again with increasing velocity. Significant differences in the curve shapes and heat transfer lowering with changing pulp types, fibre dimensions, and fibre physical properties, were obtained. Clearly different degrees of turbulence modification occurred which were a function of these variations.

The strong and systematic differences in heat transfer coefficient h_c with fibre properties[29, 30] were compared at a fixed fibre concentration and flow velocity (at the minimum in the heat transfer curve). One example of the many obtained are given here in Fig. 18.

Naturally this led to some very good correlations between heat transfer coefficient and some handsheet paper properties from papers made from these fibres. Good correlations were also obtained between certain fibre and paper properties and both pressure differential values and heat transfer coefficient. One comparison is presented in Fig. 19 with handsheets made for the same low-to-high coarseness fibres. The overall correspondence between heat transfer coefficient h_c and pressure differential for the flowing fibre suspensions is validated in Fig. 20.

As a consequence it was clear that for fibre systems (virtually unflocculated at low concentrations), it is possible to monitor fibre 'quality' before the paper is made, predict the outcome, and take remedial action in time to maintain a more consistent pulp quality supply. This does not work with at higher concentrations with flocs or larger networks as the fibre-fibre forces in the closer array and floc deformation responses dominate over the fibre-liquid direct interactions.

This work was been extended to investigate model polymer fibre suspensions to endeavour to isolate the various contributions of fibre geometry, fibre elasticity and population[31-33]. The results have also been validated using a small-scale annular flow loop by different researchers.

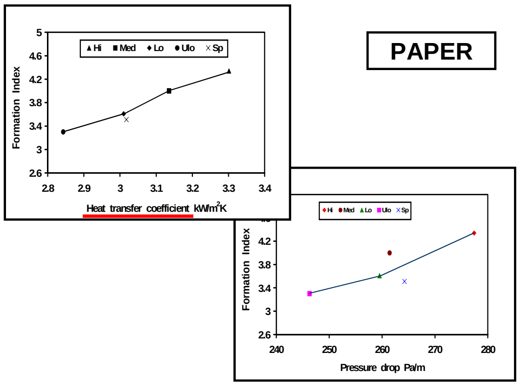

Figure 19 Paper formation index as a function of heat transfer coefficient and pipe friction loss for low-to-high coarseness radiata pine pulps, and a spruce pulp

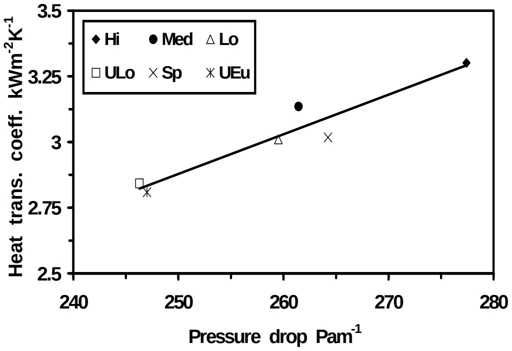

Figure 20 Correspondence between heat transfer coefficient and pressure differential in suspension flow. Pulps are low-to-high coarseness radiata pine pulps, and a eucalypt and a spruce pulp

Studying the unique behaviour of fibres (at low concentration with virtually no flocs) in a shear field brought up the question of what additional gains could be derived from their behaviour. It was postulated that fibres relatively free to move would possibly dislodge vapour bubbles from heated surfaces to minimise hot spots, or possibly act as micro-mixers to reduce thermal and mass concentration gradients. This is explored in the next topic.

Heat transfer fouling mitigation

The fouling of heat exchangers is a real and important problem in the process industries. In many cases either particles or crystals form at the heat transfer surface and increase the thermal resistance. Some inverse-solubility salts deposit easily on hot surfaces, lower the heat transfer coefficient, and ultimately decrease the thermal duty so the exchanger has to be taken off-line and cleaned more frequently. Low concentrations of fibres were therefore used to investigate their effects on fouling and it was shown that in many cases the onset of fouling was either delayed, reduced, or stopped altogether[34-36]. The initial studies used super-saturated calcium sulphate solution as a hostile fouling environment.

With just 0.25% long fibre kraft pine pulp a heat exchanger that normally lasted less than 3 days did not foul at all over a 47 day experiment period (total fouling mitigation). At 0.15% fibre concentration, fouling commenced at about 11 days but the fouling resistance asymptotically reached a level of about 1/3 of that of the exchanger fouled by the solution only. This led to extensive studies to examine how fibre characteristics such as length, length-to-diameter ratio, stiffness, coarseness and population, affected the rate of fouling mitigation. Model fibres were also used to great effect. Fibres indeed acted as 'micro-mixers' to even out the concentration gradients and so prevent the transport of deleterious materials to heated surfaces.

Value of heat transfer measurements

Pressure transducers, pressure differential transmitters, impact probes, and laser or light beams, have been the main devices uses to investigate fibre suspension flow. Heat transfer measurements offer another way to study fibre suspension flow problems. Embedded thermocouples at the wall or micro-thermocouples located in the suspension can be used as alternatives. Steam or hot water can be injected into the flow at various points to examine the state of the flow and the effects of turbulence, floc/floccette or fibre motion, and network disturbance. They also provide information for frequency analysis and can be used to separate out bulk effects and localised shear layer effects. The examples given here are to illustrate the value of these simple measuring and evaluative techniques.

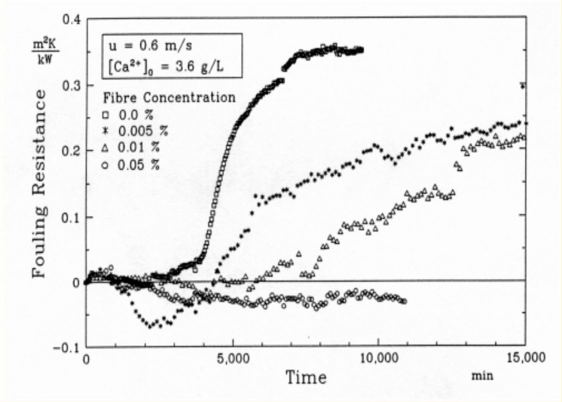

Figure 21 The effect of small quantities of fibre on heat transfer fouling resistance and on the mitigation of fouling

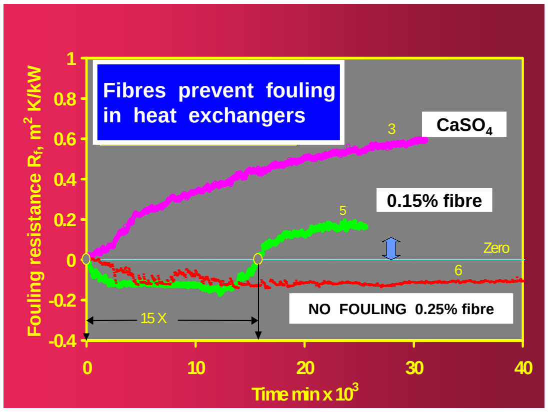

Figure 22 Heat transfer fouling resistance versus time with the addition of 0.15% and 0.25% kraft pine long fibres. Complete mitigation at 0.25% fibre concentration

CONCLUSIONS

The mechanisms of flow of wood pulp fibre suspensions have been reviewed and some new data, experiments and insights have been presented to validate previous postulates and open up new concepts. The new ideas derived from these simple experiments have potential for some new practical possibilities. Some of these developments have already been applied in industrial applications.

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