Review

Flow of pulp fibre suspension and slurries: A review

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Abstract

This paper reviews recent experimental and modeling work on biomass multiphase flow of suspensions and slurries. Problems associated with fibre flows (e.g., fibre flocculation, velocity profiles, flow regimes) have received considerable attention for these processes, involving both liquid–solid and gas–liquid–solid systems. Advanced experimental techniques have been employed in efforts to understand the flows. However, each of these experimental techniques is somewhat limited in its application. In the modelling work, mechanistic models, including those based on CFD, are being developed, but turbulence and interactions among particles and between the particles and fluid have so far limited the success of such models. Future work is needed to improve biomass energy and materials conversion processes.
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Keywords: Biomass; Multiphase flow; Pulp fibre; Suspension; Slurry

1. Introduction

Biomass is uniquely important for energy and materials conversion processes given the abundance of biomass waste materials in some areas, its renewable nature and its favourable status with respect to greenhouse gases emissions. To achieve viable commercial processes, the biomass must typically be collected, sorted, transported, shredded or crushed, dried, fed, and finally reacted and processed in particulate or suspension form. However, biomass particles are atypical. Unusual characteristics commonly include a combination of relatively large mean particle sizes, wide size distributions, extreme shapes (including flakes, chips, fibres, slivers, splinters, stalks), pliability and flexibility, compressibility, and general heterogeneity (Mckendry, 2002; Cui and Grace, 2007). Biomass particles are highly anisotropic. In addition, they may defibrillate, causing particles to become coupled together or tangled. Given these factors, biomass particles present unique challenges when subjected to multiphase flow. Few studies of multiphase flow have focused on biomass particles. Methods of handling irregular particles are generally not very reliable, limiting the viability and potential of industrial biomass processes.

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To assist in the more effective utilization of biomass resources, we recently carried out a major review of published results on multiphase flow of biomass particles involving various energy and material conversion industrial processes. While many publications have dealt with development and improvement of biomass conversion processes, relatively few authors have characterized biomass flow characteristics. This paper summarizes work in the literature regarding biomass suspensions and slurries, with much of the available data relating to pulp fibres. Both experimental and modeling efforts are considered. For simplicity the terms "Suspension" and "Slurry" are used interchangeably.

2. Two-phase (liquid–solid) flow of suspension and slurries

Hemstrom et al. (1976) studied boundary layer development in pulp suspensions. In their experiments, the signals from two optical probes in a pipe wall 50 mm apart in the direction of flow were cross-correlated for several concentrations and velocities of one chemical pulp and one ground-wood pulp. Three flow regimes – "rolling friction" plug flow, laminar annular plug flow, and turbulent annular plug flow regimes – were identified and related to the characteristic pipe friction factor versus Reynolds number curve. In another part of the study, the concentration at a given point in an undisrupted fibre network was shown to be at first positively correlated, then negatively correlated, and finally uncorrelated with the concentration at increasing distances from the given point. The extent of the positive correlation region was taken to be a measure of the dominant "rolling friction" plug flow in the network.

Lee and Duffy (1976) analyzed drag reduction in pulp suspension in pipes, where under certain conditions for turbulent flow, the friction loss for wood pulp fibre suspensions was lower than for water at the same flow rate. Flow resistance and velocity profiles for turbulent flow of fibre suspensions were reviewed and analysed. Drag reduction also occurred when a rotating disk was immersed in an aqueous suspension of wood pulp fibres, and a method was proposed for predicting pipe friction loss and velocity profiles for fully developed turbulent flow in pipes from torque measurements obtained with the rotating disk. This method was successful over a limited range of experimental conditions.

Yokogawa et al. (1985) investigated the relationship between turbulence intensity and the non-uniformity of fibre concentration in the flow of pulp suspensions in a duct with various turbulence generators at the inlet. The concentration was found to become more uniform as the turbulence intensity increased. The test results were said to provide useful information for improving paper-machine head-boxes. Shimizu et al. (1986) from the same group reported experimental results showing the relationship between the pulp fibre concentration and the flow for turbulence generators of different shapes. The spatially-averaged concentration in the duct cross-section was measured by an optical method. The upstream conditions affected the uniformity of fibre concentration over a considerable distance. The results were correlated with the aid of a simply-defined non-Newtonian Reynolds number. Shimizu and Wada (1989) developed a paper-machine head-box for high-consistency sheet forming. Optical measurements were carried out to investigate the extent of dispersion and flocculation in the pulp suspension flow in rectangular divergent and convergent sections. Consistency fluctuations decreased in the divergent channel, but increased downstream. The effect of divergence angle corresponded to that in a two-dimensional diffuser. In the convergent flow case, flocs of size equal to the width of the duct were prominent.

Fibre suspensions are coherent networks possessing measurable strength. Therefore, before motion can be initiated to mix, transport or disperse fibre aggregates within a fibre suspension, external forces must be applied to disrupt the network. The suspension yield stress must therefore be considered in the design of process equipment in the pulp and paper industries. Bennington et al. (1990) determined the yield stresses for commercial wood pulp suspensions and synthetic fibre suspensions of low and medium consistency. The measured yield stresses represent inter-fibre failure of the network, rather than slip between the suspension and a solid surface. Measurements were carried out in a rotary viscometer at low yield stresses and in a concentric rotary shear tester at yield stresses exceeding 2500 Pa. While the yield stress depended primarily on the volume of the suspension occupied by the fibres, fibre physical properties also played a role. Tests with synthetic fibre suspensions showed that the yield stress depended on the aspect ratio and elastic modulus of the fibres. Tests with pulp fibre suspensions showed less dependence on fibre aspect ratio. The latter also displayed an increase in yield strength with decreasing elastic modulus, contrary to the synthetic fibres. The differences were attrib-

uted to network strength arising from mechanical interaction between the fibrillated portions of the pulp fibres. The experimental results were correlated with the volumetric concentration, C_v, in equations of the form

$$\tau_y = a C_v^b, \tag{1}$$

where a and b were constants for a given type of fibre. It was found that $b \approx 3$, in agreement with a theoretical model of fibre network strength based upon the interlocking of elastically bent fibres. The dependence of the yield stress on the fibre aspect ratio and modulus of elasticity was not adequately predicted by the model, suggesting that fibre bending alone did not account for the network strength over the concentration range investigated.

Ogawa et al. (1990) explored plug flow of pulp suspensions in a circular pipe. The pressure drop was measured using transducers, whereas, the velocity gradient at the pipe wall and the local velocity were determined by an electrochemical technique. From experimental relations between the pressure loss and the flow rate, and between the shear stress and the velocity gradient at the wall, the pulp suspensions appeared to behave in a Newtonian manner, though the viscosities derived assuming Newtonian behaviour undoubtedly differed from each other. On the other hand, both the measured velocity profile and the experimental relation between the velocity gradient at the pipe wall and the flow rate did not correspond to a Newtonian liquid. This inconsistency was explained by suggesting that the pulp suspension had a particular average viscosity for a given pulp fibre concentration and behaved as a Newtonian liquid at every radial position, but the viscosity varied radially due to radial variation in fibre concentration. A relation for the radial distribution of viscosity was presented. Velocity profiles based on this relation were in good agreement with measured profiles.

Bennington et al. (1991) studied motion of semi-bleached Kraft pulp suspensions of low and medium consistencies in a rotary shear tester at angular velocities up to 5000 rpm. Baffled housings, with rotors having lugs, imposed shear within the body of the suspensions and prevented slip at the walls. The torque was measured as a function of angular velocity, and high-speed photographs were taken through a transparent window to facilitate interpretation. The torque versus angular velocity curves and flow phenomena were found to depend on the mass concentration of the suspension, the gap width between the rotor and housing, and the air content of the liquid suspension. With little gas present, there was initially tangential flow in an active cavity whose radial extent increased with increasing angular velocity. When the flow reached the outer baffles, a marked transition occurred, probably corresponding to what had been called "fluidization" by Gullichsen and Harkonen (1981). As the gas content increased, gas congregated around the rotor, impeding the transfer of momentum to the suspension. The apparent viscosity of a 10%-by-mass suspension was of the order of 16 Pas for the conditions tested.

Oosthuizen et al. (1992) investigated the flow of water and fibres down a 20×40 mm channel near a 1 mm wide wall slot to provide a means of measuring the flexibility of fibres. The flow rates along the channel and from the slot were controlled separately. The flow was visualized by injecting dyed water into the channel, while fibre motion was similarly studied by adding dyed fibres into the flow. The trajectories of the fibres relative to the flow streamlines were investigated near the slot.

Bennington and Thangavel (1993) tested mixing of pulp fibre suspensions with the aid of a mixing-sensitive chemical reaction, the competitive consecutive chemical reactions starting with 1-naphthol (AA) and diazotized sulfanilic acid (BB).

$$AA + BB \xrightarrow{k_1} RR, \tag{2}$$

$$RR + BB \xrightarrow{k_2} SS. \tag{3}$$

The product distribution, Xs, was defined by

$$X_s = 2c_{ss}/(2c_{ss} + c_{RR}) \tag{4}$$

and was measured when the reactions were complete, where c_{ss} and c_{RR} are concentrations of components SS and RR, respectively. Mixing quality was determined in a 22 l stirred tank reactor from the distribution between the mono (RR)- and *bis* (SS)-substituted reaction products once the adsorption of the product dyes onto the suspended fibres had been correlated. The technique was found to be adequate for assessing micromixing

and turbulence intensity within a fibre suspension, provided that X_s was between 0.4 and 0.01. Thus, the mixing depended on both the energy dissipation within the mixer and the mass of fibres. For the conditions investigated, the rate of energy dissipation was typically less than 80 W/kg, and the suspension concentration less than 2.5% by mass. Relative to water, the turbulence levels were reduced both in the impeller zone and in a remote zone in the stirred vessel for fibre mass concentrations as low as 0.5%. The turbulence intensity decreased as the suspension mass concentration increased. This was attributed to energy dissipation by friction at fibre–fibre contact points as fibres move relative to one another, thereby removing energy from the turbulence cascade (smaller and smaller eddies).

Bose et al. (1997) experimentally studied hydrodynamics and dispersion in agitated vessels containing dilute liquid–liquid dispersions, and dilute liquid dispersions in synthetic fibrous slurries. The test section was a transparent cylindrical stirred tank of 250 mm height and 155 mm diameter, equipped with four baffles and a six-blade impeller. Sampling and microscopic image analyses were applied to measure the steady-state size distributions of molten wax particles in pure water and in aqueous slurries of nylon fibres. The average nylon fibre length and diameter were 6.22 mm and 19.5 μm, respectively. With pure water the molten wax particle size distributions were spatially homogeneous and bimodal everywhere, indicating locally isotropic turbulence. In tests with fibrous slurries at fibre consistencies less than 1%, the molten wax particle size distributions remained spatially homogeneous, in agreement with the locally isotropic turbulence assumption. However, they were unimodal everywhere, with narrow particle diameter spectra. Increasing the fibre consistency and impeller speed both led to smaller mean molten wax particles and narrower diameter ranges, suggesting that fibres hampered particle collision and coalescence. For a 1% fibre consistency, widespread flow stratification and flocculation were observed.

Develter and Duoffrey (1998) studied flow of wood pulp fibre aqueous suspensions in open channels, used in the pulp and paper industry for fibre suspension containment, tree log transport, spillage and storage tank overflows, and effluent removal. Data were obtained in four rectangular channels for water and a bleached pine Kraft fibre suspension at pulp volumetric concentrations from 0.5% to 2.25% for flow in channels of various widths and angles to the horizontal from 1 to 10°. Various flow mechanisms were deduced from visual observations. The flow resistance was successfully modelled by a relationship of the form

$$\frac{1}{\sqrt{f}} = b \log Re\sqrt{f} + a, \tag{5}$$

where f is the Darcy friction factor, and a and b are constants. Linear correlations were obtained for each fibre concentration, channel width and slope. The coefficients were found to be a function of pulp concentration, channel slope, width and surface roughness.

Chen et al. (2000) analytically and experimentally demonstrated a region of low fibre consistency near the interface between two layers in a stratified pulp flow of a multi-layer head-box. The fibre migration velocity was estimated by analyzing the equations of motion for the fibre particles. The difference between the centreline consistency and average consistency was measured in a cylindrical tube, proving the existence of a region of low consistency and showing the dependence of this consistency difference on the average pulp velocity.

Paul et al. (2000) found that increasing the viscosity of the suspending liquid in pulp suspensions resulted in a decrease of the disruptive shear strength of the fibre suspension through the connecting inter- and intra-floccular linkages. The effect was tested in pipe flow for a range of liquid properties, pulp types, and fibre concentrations.

In modern pulping, efforts are being made to process pulp suspensions of increased consistency (i.e., increased volume fraction of the dispersed fibres). When developing process machinery for increased pulp consistency, it is essential to understand and predict the behaviour of pulp suspensions subjected to different shear rates. At a certain shear rate and power input, the pulp suspension reaches a state, again called "fluidization", where the fibre network becomes totally disrupted. All fibres in a control volume are separated, so particles act independently rather than being in agglomerates (flocs). In this state, pulp suspensions can be efficiently contacted with chemical reactants, and separation of particles from each other is facilitated. Wikstrom et al. (2002) developed a new correlation for the onset of fluidization. This flow transition was found to depend on the pulp type, as well as on the consistency. A model was developed to relate the onset of fluidization to fibre properties, based on the load-carrying fibre contact points in a stationary fibre network and the bend-

ing of cantilevered hollow beams of length equal to that of fibre segments between contact points. At every fibre–fibre contact point a resulting force arises, due to fibre stiffness. The second moments of inertia were summed over each contact point between all acting fibres in the control volume, yielding

$$I_{tot} = I \cdot N_{fibre} \cdot n_c \tag{6}$$

and

$$\frac{n_c^3}{n_c - 1} \approx \frac{3N_{fv}}{4\pi} \text{ with } 1/d_f \gg 1, \tag{7}$$

$$N_{fibre} = \frac{C_v \rho_{sus} V}{C_o l_f}, \tag{8}$$

$$I = \frac{1}{4}\left(\frac{d_f^2 C_o}{2\rho_{fibre}} - \frac{C_o^2}{\rho_{fibre}^2 \pi}\right), \tag{9}$$

where I is the second moment of inertia, N_{fibre} the total number of fibres, n_c the number of contacts per fibre, N_{fv} the number of fibres per unit volume, C_o the coarseness, C_v the volume concentration of fibres, l_f the average fibre length, and ρ_{sus} the density of the fibre suspension. Using this model, the power dissipation at the onset of fluidization was correlated by a single equation for all pulps studied.

Yan et al. (2003) developed an experimental flow loop to study fibre flocculation in suspensions and to simulate the flow conditions in a paper-machine head-box. It was equipped with a radial distributor feeding a step diffuser, after which the flow contracted into a two-dimensional nozzle. The flow system was also equipped with an additional flow contraction, to investigate accelerations during forming. The conditions for the secondary contraction could be changed to vary the acceleration rates. The flow system was also equipped for dosage of retention/formation aids to study their effects on fibre flocculation at velocities up to 16 m/s. Fibre suspension flows were studied with a high-speed video camera and transmitted infra-red laser light pulses. Images were recorded either separately before and after the secondary contraction, or along the secondary contraction. Images of fibre flocculation were evaluated in terms of power spectra and wavelet transforms. Rheological information on the fibre flocs was obtained by comparing the fibre flocculation before and after the secondary contraction, or by comparing the shapes of fibre flocs during the secondary contraction. The effects of chemicals on fibre flocculation were studied by comparing the fibre flocculation with and without addition of chemicals.

The rheological properties of mixed pulp fibre suspensions were investigated by Chen et al. (2003) with the aid of a parallel-plate type rheometer. The effects of shear rate and mixture ratios of softwood and hardwood Kraft pulp fibres on flocculation of the fibres were evaluated using a high-speed video camera. The flowing suspensions showed three zones of different flocculation conditions. Long fibres influenced the flocculation more profoundly than short ones. The fibre orientation was analysed in polar coordinates by the two-dimensional fast Fourier transform technique. The fibre orientation in the flow direction was rather irregular, even for high shear rates. This method was useful to evaluate the flow behaviour and fibre orientation.

Duffy and Abdullah (2003) studied fibre suspension flow in pipes of small diameter. Friction loss measurements for a TMP (thermo-mechanical pulp) suspension were obtained in a flow loop containing three small-diameter, hydraulically-smooth pipes of internal diameter 3.8, 4.7 and 7.5 mm at stock volume concentrations up to 1.9% and velocities exceeding 10 m/s. Below a fibre concentration of ∼1%, the friction loss surprisingly corresponded with data for water, even though classical laminar and turbulent flow did not exist. Between concentrations of 1.0% and 1.9%, the curves fell slightly below the water curve at higher flow rates. Turbulence damping was not thought to be the cause of this, as reduction in friction loss was more pronounced at lower fibre concentrations. The friction loss curves differed greatly from those for large-diameter pipes where friction loss was much higher than for water at low flow rates, and much lower than for water at high flow rates. The results provided insights into mechanistic differences between fibre suspension flows in small and large conduits.

In an extension of the work described in the previous paragraph, Duffy et al. (2004) reported that the flows of fibre suspensions in small diameter pipes differently profoundly from those in larger ones. Side-by side build-up of flocs across the pipe could not occur in the smaller tubes. Instead, flow extrusion into the small

tubes produced either a single axial-floc with long fibre pulps, or multiple end-on-end, cylindrical flocs, with weaker flocs resulting from shorter hardwood fibres. More elongated floc structures indicated that fibres near the wall attached differently and were more directionally aligned, causing them to be more likely to deflect from the wall as the shear rate increased. The resulting thin water shear layer was vital for pulp-water similarity over the entire range of flow rates. Experiments with medium-consistency pulp suspensions showed that the boundary shear layer could be controlled to reduce shear forces and resistance to flow. Floc mobilization and structured flow patterns constituted the major mechanism of mixing. Results were presented for a laboratory screw press for a screw with variable pitched flights, and the data were compared with those for a constant pitch, variable-diameter screw.

Parsheh et al. (2005) investigated the influence of turbulence on the orientation of stiff opaque rayon fibres in a dilute density-matched suspension at high Reynolds number in a planar contraction. The test section was constructed of Plexiglas to allow visualization. The stiff fibres were nominally 3.2 mm long and 57 μm in diameter, with a specific gravity of 1.14. Nearly homogeneous isotropic grid-generated turbulence was introduced at the contraction inlet. A laser-Doppler velocimetry (LDV) system determined the instantaneous velocity field of single-phase water flow inside the contraction. The fibres were visualized using a laser sheet and high-speed camera. The anisotropic orientation was modelled accurately by a Fokker–Planck equation. The results showed that rotational diffusion was strongly influenced by inlet turbulent characteristics and decayed exponentially with convergence ratio. The effect of turbulent energy production in the contraction was found to be negligible. The flow Reynolds number had a negligible effect on the development of orientation anisotropy, and the influence of turbulence on fibre rotation was negligible for rotational Peclet numbers >10. Parsheh et al. (2006a,b) extended this work to investigate the influence of shape of planar contractions on the orientation distribution of stiff fibers suspended in turbulent flow and the closure approximations for fiber orientation distribution in contracting turbulent flows.

3. Three-phase systems involving fibres

Lindsay et al. (1995) studied the hydrodynamics of three-phase slurry columns containing water, fibres and air. Such systems are relevant to flotation de-inking, a critical but poorly understood separation process in the production of recycled paper. Two transparent bubble columns were used, one for quiescent liquid and the other for cocurrent air and liquid flow. Water and dilute aqueous pulp slurries were tested by γ-densitometry to obtain local gas hold-ups. Results for pulp slurries differed significantly from those for water alone. In a quiescent flow system, fibre flocculation and networking dominated the flow field, promoting bubble coalescence and gas channelling, and leading to shorter gas residence times and lower gas hold-ups than for water alone. On the other hand, for cocurrent flow, gas hold-up and interfacial area could be greater in pulp slurries than for water alone. The bulk flow of the slurry induced bubble coalescence into bubbles large enough to break through the network and rise rapidly, while the network impeded the rise of small bubbles. Results were explained in terms of the effects of fibres and flocs on the flow. A simple method was utilized to estimate radial gas hold-up distributions based on chord averaged hold-up values, E_i, assuming axisymmetric flow,

$$E_i = \frac{1}{L} \int_0^L \varepsilon(r(l)) \mathrm{d}l \tag{10}$$

with

$$r(l) = \left(r_i^2 + \left[\frac{L}{2} - l \right]^2 \right)^{1/2} \tag{11}$$

and

$$L = 2\sqrt{R^2 - r_i^2}, \tag{12}$$

where l is the distance along a chord of length L, and $r(l)$ is the radial distance from the centre of the column to a point on the chord. The computed radial gas distributions indicated centreline hold-ups up to ~40% higher

than the chord-averaged hold-up for the centremost chord. The experimental results showed that the hydro-dynamics, and therefore transport processes, in three-phase pulp slurries cannot be simulated using models and correlations based on non-fibrous data. Systematic experimental studies addressing three-phase fibrous systems are therefore needed.

Reese et al. (1996) studied the behaviour of three-phase pulp slurry systems containing 0.1–1.0% fibres by weight. The pulp phase swelled to several times its original volume in water. The overall hydrodynamic behaviour, including the regime transitions, of a multi-bubble, three-phase pulp slurry was explored by measuring the overall gas hold-up and determining bubble properties by means of a light transmittance probe. The hydrodynamic behaviour of a three-phase pulp slurry, even at very low pulp consistencies, differed from that of a gas–liquid system, with the differences becoming more pronounced as the consistency increased. The pulp led to increased bubble coalescence near the gas inlet at the bottom of the column. Increased coalescence reduced the overall gas hold-up of the three-phase slurry compared to a bubble column without fibres at the same gas velocity. Large bubbles led to an increase in the turbulence of the system and to an increase in the liquid–pulp axial dispersion, both undesirable characteristics in flotation for de-inking recycled paper. The increased coalescence also narrowed the operating conditions for the dispersed bubble regime as the pulp consistency increased. At low pulp concentrations (0.1% and 0.25% by wt.), the fibres were uniformly distributed in the axial direction, even at low gas velocities. At higher concentrations (0.75% and 1% by wt.) fibres accumulated in the lower portion of the column. An intermediate concentration (0.5%) gave transitional behaviour. The characteristics of bubbles injected through a single bubble injector were studied in a small rectangular column by flow visualization and particle image velocimetry. The bubbles were significantly affected by the pulp fibres. Over the injection frequency range tested (2.1–11 s^{-1}), bubbles were flatter and rose more slowly in the slurry than in the pure liquid. These findings led to a proposed mechanism for increased bubble coalescence, with flatter bubbles rising more slowly in the lower portion of the column, leading to increased bubble–bubble interactions and a greater probability of coalescence.

Xie et al. (2003a,b) investigated the hydrodynamics of pulp–water–gas three-phase slurry flows in a short, vertical circular column. The pulp consistency was varied in the 0.0–1.5% range in a test section of inner diameter 50.8 mm and length 1.8 m. The slurry was mixed prior to entering the test section by a patented mixer with controlled cavitation that generated finely dispersed micro-bubbles. Flow structures, gas hold-up, and the geometric and population characteristics of gas bubbles in the three-phase flow were observed by gamma-ray densitometry and by flash X-ray photography at superficial velocities of the gas and liquid/pulp mixture from 0–26 cm/s and 21–51 cm/s, respectively. Five distinct flow regimes were identified: dispersed bubbly flow, characterized by isolated micro-bubbles entrapped in fibre networks; layered bubbly, featuring bubbles rising in a low-consistency annular zone near the channel wall; plug flow; churn-turbulent flow; and slug flow. The dispersed and layered bubbly regimes could be maintained only at very low gas superficial velocities or gas hold-ups. Flow regime maps were constructed with phase superficial velocities as coordinates. The regime transitions were found to be sensitive to consistency. Both the dispersed and the layered bubbly flow regimes could be represented by a homogeneous-mixture model, with

$$\bar{\varepsilon} = \frac{U_g}{U_g + U_l}. \tag{13}$$

The drift-flux model,

$$\bar{\varepsilon} = \frac{U_g}{C_0(U_g + U_l) + U_{gd}} \tag{14}$$

could be applied to the remainder of the data, with the plug and churn-turbulent flow regimes treated together, and the slug flow regime treated separately.

Xie et al. (2003a, 2004) used a neural network approach to classify flow regimes in gas–liquid–fibre flows based on frequency domain analysis of pressure signals. The feasibility of a transportable artificial neural network (ANN)-based technique for identifying flow regimes was examined in three-phase gas/liquid/pulp fibre systems based on pressure signals. Experimental data were obtained in a vertical, cylindrical column 1.8 m high and 50.8 mm in diameter, with air/water/Kraft softwood paper pulp. The pulp concentration was varied from 0.0 to 1.5% by wt. Local pressure fluctuations were recorded at three different positions along the column

using three independent, but similar, transducers. A neural network was designed, trained and tested for the classification of flow regimes, using as input characteristics of the power spectrum for one of the normalized pressure signals. A scheme was also examined in which the three sensors fed separately trained networks, with confirmation requiring endorsement from at least two of the three sensors. This scheme improved the agreement between the model predictions and the data. The neural network trained and tested for one sensor predicted the flow regimes reasonably well when applied directly to the normalized pressure power spectrum density characteristics of the other two sensors, indicating good transportability. Further improvement was achieved by adjusting the power spectrum density characteristics of the other sensors before providing them as input to the already-trained network. However, for sensitive processes, redundant sensors are required for fault tolerance.

Akbar et al. (2004) studied the interfacial surface area concentration in a short vertical column of a solid–liquid–gas slurry in which aqueous fibrous paper pulp was mixed with nitrogen and carbon dioxide gas. The pulp consistency in the water/pulp mixture was 0–2.2%. The flow regimes were identified visually, and the void fraction was measured by gamma-ray densitometry. CO_2 absorption was determined with sodium hydroxide as the alkaline agent in water. Statistical analysis of the experimental data indicated a strong dependence of interfacial area on average gas superficial velocity and void fraction and a relatively weak dependence on pulp consistency and liquid superficial velocity. The average interfacial surface area concentration decreased with increasing consistency up to 1.6%, but increased significantly when consistency was increased further to 2.2%. The results confirmed that pulp affects all major hydrodynamic processes, including the interfacial surface area concentration. The data were also correlated empirically.

4. Flow measurement techniques

Cleveland et al. (1989) measured the solids volume fraction of a two-component slurry (solid phase flowing in water) by radio-frequency diagnostic techniques. The slurry flowed in a conducting pipe which served as a wave-guide. By measuring the speed of radio waves propagating in the flowing slurry and comparing the speed to that for water alone, the solids fraction of the material could be estimated. The method was extensively tested in pulp slurries and found to accurately determine the consistency, i.e., solids volume fraction, of such streams.

Based on nuclear magnetic resonance (NMR) imaging, Li et al. (1995) investigated pipe flow at velocities up to 3 m/s of hardwood Kraft pulp suspensions with fibre concentrations in the 0.5–0.92 wt% range. The axial velocity profiles for the pulp suspensions undergoing steady, pressure-driven flow through a horizontal circular pipe were directly visualized. Transition from steady plug flow to fully turbulent flow, through a mixed flow regime with steady plug flow in the central regions, was observed for all suspensions tested. Images at high bulk flow rates indicated that fluidization of pulp suspensions was a dynamic process and that the fibre network in the flowing pulp suspensions underwent reversible rupture and formation. When the turbulence intensity of the flow was sufficiently high to rupture the fibre network, as in turbulent flow of dilute pulp suspensions, disruption of fibre flocs dominated, and the flocs in the suspension were transient. However, for lower turbulence intensity, as in the central regions of the higher-consistency suspensions, flocs did not form and rupture instantaneously; instead over long time intervals, the flocs appeared to be coherent entities. The long-time average image in this case showed a plug core in the central regions, although the suspension exhibited fully turbulent flow on a short time scale. The volume fraction of the fluidized pulp suspension was linearly correlated to the mean bulk flow. Fluidization of the pulp suspension in pipe flow and the minimum fluidization flow rate were strongly dependent on the consistency.

Arola et al. (1998) applied nuclear magnetic resonance (NMR) imaging to determine velocity profiles of water and an aqueous 0.5% by wt. wood pulp suspension flowing through a cylindrical pipe in the vicinity of a 1:1.7 expansion. Images were obtained for various flow rates and axial positions. For water, both laminar and turbulent flows were investigated. Pulp suspension flows were studied upstream and downstream of the expansion. The expansion imparted shear layer instabilities that disrupted the fibre floc network. The flow field downstream of the abrupt expansion plane for the pulp suspension behaved like a confined jet. The flow instability and fluidization of the fibre network were characterized by analyzing both the intensity distribution and

shape of the NMR velocity profiles as functions of downstream position and observation time. The fibre reflocculation length was proportional to the bulk flow rate, and the mean reflocculation time was ∼510 ms.

Better understanding of bubble dynamics in air/water/fibre suspensions is important in paper-making processes, including flotation de-inking and gaseous bleaching. However, conventional visualization techniques to view gas bubbles in pulp suspensions are ineffective because these systems are opaque at consistencies relevant to the paper industry. Heindel and Monefeldt (1998) used flash X-ray radiography (FXR) to visualize air flows and to provide stop-motion images of air bubbles in a opaque suspension of unprinted old newspaper (ONP) at various consistencies and air injection rates. The technique was effective because air had a significantly different X-ray attenuation coefficient than water or wood pulp, these two having similar attenuation coefficients. Qualitative observations of these air/water/fibre flows were reported and compared with those for a simple air/water system. Radiographic images revealed that the gas flow was altered substantially by the fibres.

Bubble size control is very important when gas is introduced into a liquid. However, bubble size is difficult to measure in fibre suspensions. Heindel and Garner (1999) studied the effect of fibre consistency on bubble size, using flash X-ray radiography (FXR) images for softwood Kraft pulp suspensions at consistencies from 0 to 1.5%. Bubble size distributions were determined at a fixed gas flow rate. The fibres promoted formation of large bubbles, which promoted churn-turbulent flow conditions. The bubbles also helped to maintain favourable mixing. Small bubbles with effective bubble diameters, d, ⩽2 mm, were characterized by various distribution functions. A single log-normal distribution adequately predict the distribution for $d \leqslant 12$ mm for all consistencies investigated.

Garner and Heindel (2000) used flash X-ray radiography to visualize and make measurements on bubbles, suspensions of old newspaper, copy paper and northern bleached softwood Kraft. The flow conditions were churn-turbulent in the fibre suspensions, whereas, bubbly flow was observed for an air/water reference condition. Bubble sizes were measured in the various systems, and bubbles were classified as either small ($d \leqslant 12$ mm) or large ($d > 12$ mm). The number of small bubbles decreased, whereas, the number of large bubbles increased as fibre length increased. Small bubbles followed similar log-normal size distributions,

$$\text{Cum}_{\text{LN}} = \int_0^x \frac{1}{y\sigma_{\text{LN}}\sqrt{2\pi}} \times \exp\left[-\frac{1}{2}\left(\frac{\ln(y) - \mu_{\text{LN}}}{\sigma_{\text{LN}}}\right)^2\right] dy \tag{15}$$

with

$$\mu_{\text{LN}} = \ln(\mu_{\text{m}}) - \frac{1}{2}\sigma_{\text{LN}}^2 \tag{16}$$

and

$$\sigma_{\text{LN}}^2 = \ln\left[1 + \left(\frac{\sigma_{\text{b}}}{\mu_{\text{b}}}\right)^2\right], \tag{17}$$

where y is a dummy variable, x is the parameter of interest (e.g., bubble diameter), μ_{LN} and σ_{LN} are the log mean and standard deviation of the natural logarithm of the bubble diameters, respectively, and μ_{b} and σ_{b} are the arithmetic mean and standard deviation of the bubble diameters. Small bubble sizes were independent of fibre type in this study.

Xu and Aidun (2001) evaluated and applied pulsed ultrasonic Doppler velocimetry (PUDV) to measure velocity profiles in fibre suspension channel flow. Experiments showed that PUDV was an accurate non-invasive method for measuring fibre velocity profiles of fibre suspensions, with high repeatability and sensitivity to small changes in velocity. After selecting suitable measuring parameters, PUDV could measure fibre suspension flows up to velocities comparable to those in papermaking. Fibre suspension channel flow showed five flow regimes in fibre concentration-flow rate parameter space. The flow characteristics helped to explain inconsistent results in the literature. Xu and Aidun (2005) studied fibre suspension flow in a rectangular channel using PUDV. The natural flexible cellulous wood fibers had an average length of 2.3 mm and a average diameter of ∼35 μm. When saturated with water, the fibre density was similar to that of water. Five types of flow behaviour were observed. Turbulent velocity profiles of fibre suspension were correlated with fibre concentration and Reynolds number. Fibres and flocs in the suspension reduced the turbulence intensity and thus,

turbulent momentum transfer. However, formation of fibre networks tended to increase momentum transfer. The relative contributions of these two factors determined the shape of the velocity profile.

To understand the complex interactions between papermaking flow and the uniformity of pulp suspensions, Kuhn and Sullivan (2001) developed a "Dynamic Panoramic View" (DPV) system, based on particle image velocimetry (PIV), to measure flocculation intensity in a developing turbulent pulp suspension flow. Large eddy simulation and Reynolds averaged Navier–Stokes numerical techniques were employed to simulate time-varying turbulent flows and flocculation in fibre suspensions. The same techniques were also applied to analyze a grid-generated decaying turbulent flow field.

Islek et al. (2004) studied the impact of turbulence and swirl generated by twisted fins inside a single tube in the tube bank of a paper-making machine with a two-component laser-Doppler velocimeter (LDV). By controlling the flow of the pulp slurry leaving the head-box, fibre orientation could be controlled within the slurry. Vorticity inside the head-box tubes was coupled with an automatic on-line control system to regulate the interaction between the turbulent flow and the fibre suspension. In initial studies, tapered fins with 0° and 180° twist, corresponding to the extreme cases of 0 and maximum axial vorticity, were studied at a pipe-based Reynolds number of 7.5×10^4. The LDV elucidated radial profiles of the mean and RMS fluctuations of the streamwise velocity component.

Pettersson (2004) analyzed flow and mixing of medium-consistency pulp suspensions relevant to the pulp and paper industry. Turbulence at high shear rates was investigated in three-phase systems in a stirred tank using laser Doppler anemometry (LDA). Introducing gas into the suspension was found to decrease the system's ability to transport momentum. Gas bubbles also directly influenced the turbulent properties of the suspension.

Dietemann and Rueff (2004) studied fibre suspension flow by Doppler ultrasound velocimetry and image analysis. The objective was to determine the conditions corresponding to different flow regimes, using a combination of pressure loss, velocity profiles based on Doppler ultrasound velocimetry, and high-speed video images. Experiments were carried out with pulp suspensions at consistencies up to 2.1% in a transparent duct of diameter 80 mm for velocities up to 8 m/s. Different flow regimes were evident. The width of the plug, both in the plug and mixed flow regimes, could be determined from the profiles. The pressure drop curves enabled stress profiles to be correlated with the size of the plugs. Flocs near the wall, where stress was maximum, were visible with the high-speed camera. Although the floc size decreased when the velocity increased, many flocs were still present near the wall in the turbulent regime, showing that the fibres were not as well dispersed as one might expect from the measured velocity profiles and pressure losses.

5. Modelling

Dinh and Armstrong (1984) developed a rheological equation of state for a suspension of stiff fibres in a Newtonian liquid. The constitutive equation gave the stress as a function of the strain tensor and fibre orientation vector. An expression was also obtained for the evolution of the fibre orientation. The development was restricted to homogeneous flows. In start-up of shear or elongational flow, the fibre orientation and rheological properties depended only on the total applied strain. In the model, the viscosity was identical to that of the Newtonian liquid, because of the fibre alignment in the shear planes and lack of inclusion of fibre thickness in the model.

Advani and Tucker (1987) reviewed the properties of a set of even-order tensors, used to describe the probability distribution function of fiber orientation in suspensions and composites containing short rigid fibres. These tensors offered a concise representation of the orientation state, free from assumptions about the shape of the probability distribution function. Equations of change for the second- and fourth-order tensors were derived, which could then be used to predict the orientation of fibres during processing. A second-order description and a closure approximation did nearly as well as the fourth-order system. A closure approximation was required in the equations of change for orientation tensors. Numerical predictions of orientation states in suspensions using linear, quadratic, and hybrid closures were compared for simple shear and pure shear. The linear closure worked well when the fibre orientation remained nearly random, but caused an artificial instability for highly aligned suspensions. The quadratic closure approximation performed well for highly aligned states, but introduced steady-state errors for more random states. A hybrid closure approxima-

tion, combining previous linear and quadratic forms, performed best for planar orientation. The accuracy of the closure approximations was also explored by calculating the mechanical properties of solid composites with three-dimensional fibre orientations. Again the hybrid closure worked best over the full range of orientation states. The compact nature of the tensor description also saved considerable computation time for two-dimensional fibre orientations, and facilitated three-dimensional calculations.

Hourani (1988a,b) developed a theoretical model based on the mass-action law and the energy spectrum of turbulent flow to provide quantitative relationships describing flocculation in pulp suspension flow. Electrostatic contributions were estimated by minimizing the free energy of bound counter-ions using the Poisson–Boltzmann field. The model was supported by experiments based on digital signal analysis of light transmission through flowing pulp. Hourani then tried to quantify the primary effects and the interactions of selected factors such as consistency, velocity, temperature and fibre surface characteristics with floc size distribution, and hence with the uniformity of fibre dispersion. Fibre dispersion improved as consistency, fibre length and temperature decreased, with the first two of these being most important. Velocity had a complex influence, with flocculation usually minimized by increasing velocity in turbulent flow. The electrostatic field strongly influenced the floc size distribution.

Shaqfeh and Fredrickson (1990) developed a theory to describe the hydrodynamic properties of suspensions containing randomly placed, slender fibres with high aspect ratios. The theory was based on calculating a propagation tensor to describe the average velocity field created by a point force in the suspension. The ''best one-body approximation'' was then used to calculate the wave number-dependent, ensemble-average stress for both aligned and isotropically oriented dilute and semi-dilute dispersions.

Shaqfeh and Koch (1990) proposed a kinetic theory to predict particle orientation due to hydrodynamic interactions in uniaxial and planar extensional flows. The displacement of the orientation vector was calculated for both asymptotic dilute and semi-dilute flows. Dispersion was predicted to increase and then reach a maximum as the concentration increased. Koch (1995) modelled the orientational diffusion resulting from hydrodynamic fibre–fibre interactions in a general linear shear flow. The constants in the expression for the diffusivity were determined from calculations of orientation diffusion in pure extensional flows. The model was tested against experimental and theoretical studies of orientational dynamics in simple shear flows.

Soszynski (1992) studied plug flow of fibre suspensions through pipes. Previously published experimental data concerning plug flow with a clear water annulus were analyzed based on solving the Navier–Stokes equations for the plug flow regime between the maximum and the minimum on the friction loss versus velocity curve. The model predicted the annulus thickness, the shear stress at the plug surface and the ratio of plug velocity to bulk velocity. Occurrences of maxima and minima were related to the upstream flow conditions.

Fu et al. (1998) established a partial fundamental model for pulp flows in cylindrical pipes based on two-phase fluid dynamics. The solid phase consisting of fibres was found to play a critical role in determining the flow behaviour in pipes of circular cross-section.

Olson and Kerekes (1998) analysed fibre motion in turbulent flow, and derived equations of mean and fluctuating velocities in rotation and translation for rigid thin inertialess fibres in a turbulent fluid. Fluid velocities varied nonlinearly along the length of the fibre. Rotational and translational dispersion coefficients were derived from the equations of fluctuating fibre velocity. The resulting dispersion coefficients were shown to decrease as the ratio of fibre length to Lagrangian integral length scale of the turbulence increased.

Olson et al. (2004) proposed an Eulerian model of a turbulent fibre suspension flowing through a planar contraction to predict the fibre orientation distribution for pulp suspension flow through a papermachine headbox. The one-dimensional model accounted for the convection of orientation distribution of the mean fluid velocity and dispersion caused by turbulent velocity fluctuations. Each was described by a dimensionless dispersion coefficient and a dimensionless velocity gradient in terms of the headbox contraction ratio (duct inlet-height-to-outlet-height ratio). A numerical solution compared well to experimental results in the literature. Fibre orientation distributions were calculated for a range of dimensionless dispersion coefficients and contraction ratios. The dimensionless dispersion coefficient was a function of the headbox length, inlet flow velocity and the rotational dispersion coefficient. The contraction ratio approximated the average dimensionless acceleration of the fluid. Increasing the contraction ratio over the industrial range of 5–50 significantly increased the alignment of fibres leaving the headbox, whereas varying the inlet fluid velocity over a practical range provided only small changes in the fibre orientation distribution. These predictions agreed with exper-

imental observation. This study also suggested that fibre orientation is approximately dependent on a single dimensionless Peclet number that is a function of the fluid contraction ratio, inlet velocity, contraction length and rotational dispersion coefficient.

Shin and Koch (2005) simulated the rotational and translational motion of fibres in fully developed isotropic turbulence for a range of Reynolds numbers, based on slender-body theory. The translational and rotational fibre motion was related to the fluid velocity along the fibre length. For fibre lengths exceeding the size of the smallest eddies, the translational and rotational motion was attenuated by filtering associated with spatial averaging. The translational diffusivity of the fibres was predicted using a simple theory that neglected coupling between fibre orientation and the local direction of the fluid velocity. However, the coupling of fibre orientation with the axes of extension and rotation was found to greatly reduce the amplitude of the rotary motions and the rotational dispersion coefficient. The rotational dispersion coefficient was found to be of the same order as the inverse integral time scale. Its variation with Reynolds number suggested that rotational dispersion was influenced by the scales of turbulence over the limited range of Reynolds numbers investigated.

6. Conclusions and recommendations

This paper reviews biomass multiphase flow research on aqueous pulp fibre suspension and slurries reported in the open literature. Interparticle forces become important, even at volumetric concentrations of 1% or less and become dominant for the intermediate- and high-consistency flows characteristic of many pulp processing operations. Interactions among particles cause flocculation and affect flow regimes, mixing and contacting between phases. Advanced experimental techniques and special flow devices, such as nuclear magnetic resonance imaging, pulsed ultrasonic Doppler velocimetry, particle image velocimetry, flash X-ray radiography, dynamic panoramic viewing and laser Doppler anemometry are helping to resolve some flow issues. However, each of these experimental techniques is somewhat limited in its application. Advanced flow models are in their infancy for such flows, but are of considerable importance. Few modelling efforts have been reported for multiphase flows of pulp suspension and slurries. Effective mechanistically-based models, validated by experiments, are needed to identify the effects of operating conditions and fibre properties on two- and three- phase suspensions and slurries. Mechanistic models, including CFD, have not yet been able to provide accurate methods of simulating concentrated biomass multiphase flows, due to the complexity of these processes, in particular the nonlinear interactions among the particles and between the particles and fluid.

Fibre multiphase flows differ greatly from flows involving smooth spherical particles. The latter have been studied widely, while biomass multiphase flows, despite their widespread importance, have received limited attention. As a result, industrial biomass processes are being limited and their potential is not being realized. Thus, further work is needed on multiphase flow of biomass materials to understand and optimize industrial energy and material conversion processes. The extreme properties and heterogeneous nature of biomass particles create challenges in processes involving biomass particles. Research in this area is difficult, but potentially rewarding in terms of aiding the ability of these materials to be used effectively.

New flow measurement techniques with advanced software should be deployed to elucidate biomass multiphase flows. Such techniques include capacitance tomography, X-ray tomography, MRI, PDA or PDPA, gas/particle/liquid tracking techniques, optical probes and imaging techniques.

CFD should also be pursued for these systems, although such flows are so complex, especially for high-consistency systems, that progress is likely to be limited in the short term. While it is unlikely that CFD can lead to near-term break-throughs for flows as complex and dense as those considered here, work in this area will help to resolve issues related to important sub-problems such as interparticle forces in dense systems with fine particles, interactions between fluid and material properties, and complex particle shapes for biomass granular materials. It is essential that CFD fluid dynamicists communicate effectively with experimentalists for the mutual benefit of both groups in achieving progress in multiphase flow research.

Other aspects requiring further work for pulp fibre suspensions include the fibre concentration distribution, fibre motion, flocculation (floc formation and splitting), rheological characteristics of suspensions, residence time distributions, contacting of solids and liquid, mixing and mass transfer in aqueous suspensions of fibres,

the influence of fibre and liquid properties, the effect of bubbles, and flocculation. Future work is also needed to optimize operating conditions for industrial processes, and to help guide process design and operation.

Acknowledgements

References

Advani, S., Tucker, C.J., 1987. The use of tensors to describe and predict fiber orientation in short fiber composites. J. Rheol. 31, 751–784.

Akbar, M.K., Ghiaasiaan, S.M., Karrila, S., 2004. An experimental study of interfacial surface area concentration in a short vertical column subject to paper pulp–water–gas three-phase flow. Chem. Eng. Sci. 59, 1079–1086.

Arola, D.F., Powell, R.L., McCarthy, M.J., Li, T.Q., Odberg, L., 1998. NMR imaging of pulp suspension flowing through an abrupt pipe expansion. AIChE J. 44, 2597–2606.

Bennington, C.P.J., Kerekes, R.J., Grace, J.R., 1990. The yield stress of fibre suspensions. Can. J. Chem. Eng. 68, 748–757.

Bennington, C.P.J., Kerekes, R.J., Grace, J.R., 1991. Motion of pulp fibre suspensions in rotary devices. Can. J. Chem. Eng. 69, 251–258.

Bennington, C.P.J., Thangavel, V.K., 1993. The use of a mixing-sensitive chemical reaction for the study of pulp fibre suspension mixing. Can. J. Chem. Eng. 71, 667–675.

Bose, F., Ghiaasiaan, S.M., Heindel, T.J., 1997. Hydrodynamics of dispersed liquid droplets in agitated synthetic fibrous slurries. Ind. Eng. Chem. Res. 36, 5028–5039.

Chen, K., Chen, L., Hou, Q., 2000. Migration of fibers away from interface in stratified flow of pulp suspension. TAPPI Engineering Conference. Proc. 2000 TAPPI Engineering Conference. TAPPI Press, Atlanta, GA, United States, pp. 539–544.

Chen, B., Tatsumi, D., Matsumoto, T., 2003. Fiber orientation and flow properties of pulp fibre suspensions under shear flow conditions. Sen'i Gakkaishi 59, 471–478.

Cleveland, W.G., Mease, N.E., Gaiqalas, A.K., 1989. Determination of solids fraction in slurries by radio frequency diagnostic techniques. In: AIChE Symp. Series, vol. 85, no. 267, pp. 52–58.

Cui, H.P., Grace, J.R., 2007. Fluidization of biomass particles: A review of experimental multiphase flow aspects. Chem. Eng. Sci. 62, 45–55.

Develter, P., Duoffrey, G., 1998. Flow of wood pulp fibre suspensions in open channels. Appita J. 51, 356–362.

Dietemann, P., Rueff, M., 2004. A study of fibre suspension flow by means of Doppler ultrasound velocimetry and image analysis. In: Ninetieth Ann. Mtg. Technical Section, Canadian Pulp and Paper Association, Preprints, vol. A, pp. 225–230.

Dinh, S.M., Armstrong, R., 1984. A rheological equation of state for semiconcentrated fiber suspensions. J. Rheol. 28, 207–227.

Duffy, G.G., Abdullah, L., 2003. Fibre suspension flow in small diameter pipes. Appita J. 56, 290–295.

Duffy, G.G., Ramachandra, S., Xu, J.Q., 2004. Developments in processing fibre suspensions. In: Proceedings of the Fifth-eighth Appita Annual Conference and Exhibition, vol. 2, pp. 433–442.

Fu, P.L., Chen, K.F., Liu, H.B., 1998. Mathematical model for pulp suspension flows in circular pipes. Zhongguo Zaozhi Xuebao/Trans. China Pulp and Paper 13, 62–66.

Garner, A.E., Heindel, T.J., 2000. Effect of fibre type on bubble size. J. Pulp Pap. Sci. 26, 266–269.

Gullichsen, J., Harkonen, E., 1981. Medium consistency technology. II. Storage dischargers and centrifugal pumps. TAPPI J. 64, 113–116.

Heindel, T.J., Monefeldt, J.L., 1998. Observations of the bubble dynamics in a pulp suspension using flash X-ray radiography. TAPPI J. 81, 149–158.

Heindel, T.J., Garner, A.E., 1999. Effect of fiber consistency on bubble size. Nord Pulp Pap. Res. J. 14, 171–178.

Hemstrom, G., Moller, K., Norman, B., 1976. Boundary layer studies in pulp suspension flow. TAPPI J. 59, 115–118.

Hourani, M., 1988a. Fiber flocculation in pulp suspension: Part 1: Theoretical model. TAPPI J. 71, 115–118.

Hourani, M., 1988b. Fiber flocculation in pulp suspension: Part 2. Experimental results. TAPPI J. 71, 186–189.

Islek, A.A., Parsheh, M., Yoda, M., Aidun, C.K., 2004. The impact of turbulence and swirl on the flow in the tube bank part of a paper mill headbox. In: 2004 TAPPI Spring Technical and International Environmental Conference, TAPPI, pp. 417–428.

Koch, D.L., 1995. A model for orientational diffusion in fiber suspensions. Phys. Fluids 7, 2086–2088.

Kuhn, D.C.S., Sullivan, P.E., 2001. Analysis and measurement of the flocculation intensity of flowing pulp suspensions. Proc. 2001 TAPPI Papermakers Conference, Cincinnati, OH, US. TAPPI Press, pp. 391–397.

Lee, P.F.W., Duffy, G.G., 1976. Analysis of the drag reducing regime of pulp suspension. TAPPI J. 59, 119–122.

Li, T.Q., Weldon, M., Odberg, L., McCarthy, M.J., Powell, R.L., 1995. Pipe flow behaviour of hardwood pulp suspension studied by NMRI. J. Pulp Pap. Sci. 21, 408–414.

Lindsay, J.D., Ghiaasiaan, S.M., Abdel-Khalik, S.I., 1995. Macroscopic flow structures in a bubbling paper pulp-water slurry. Ind. Eng. Chem. Res. 34, 3342–3354.

Mckendry, P., 2002. Energy production from biomass (part 1): Overview of biomass. Bioresource Technol. 83, 37–46.

Ogawa, K., Yoshikawa, S., Suguro, A., Ikeda, J., Ogawa, H., 1990. Flow characteristics and circular pipe flow of pulp-suspension. J. Chem. Eng. Jpn. 23, 1–6.

Olson, J.A., Frigaard, I., Candice, C., Hamalainen, J.P., 2004. Modelling a turbulent fibre suspension flowing in a planar contraction: The one-dimensional headbox. Int. J. Multiphase Flow 30, 51–66.

Olson, J.A., Kerekes, R.J., 1998. The motion of fibres in turbulent flow. J. Fluid Mech. 19, 47–64.

Oosthuizen, P.H., Chen, S., Kuhn, D.C.S., Whiting, P., 1992. Fluid and fibre flow near a wall slot in a channel. In: Seventy-eighth Annual Meeting – Technical Section, Canadian Pulp and Paper Association, Preprints, B, Canadian Pulp and Paper Association, pp. 49–52.

Parsheh, M., Brown, M.L., Aidun, C.K., 2005. On the orientation of stiff fibres suspended in turbulent flow in a planar contraction. J. Fluid Mech. 545, 245–269.

Parsheh, M., Brown, M., Aidun, C.K., 2006a. Fiber orientation in a planar contraction: Shape effect. Int. J. Multiphase Flow 32, 1354–1369.

Parsheh, M., Brown, M., Aidun, C.K., 2006b. Investigation of closure approximations for fiber orientation distribution in contracting turbulent flow. J. Non-Newtonian Fluid Mech. 136, 38–49.

Paul, S.T., Duffy, G.G., Chen, X.D., 2000. New insights into the flow of pulp suspensions. In: APPITA Annual General Conference, vol. 2, pp. 645–654.

Pettersson, J., 2004. Flow and mixing of pulp suspensions. Doktorsavhandlingar vid Chalmers Tekniska Hogskola, n 2130, p. 103.

Reese, J., Jiang, P., Fan, L.-S., 1996. Bubble characteristics in three-phase systems used for pulp and paper processing. Chem. Eng. Sci. 51, 2501–2510.

Shaqfeh, E.S.G., Fredrickson, G.H., 1990. The hydrodynamic stress in a suspension of rods. Phys. Fluids A 2, 7–24.

Shaqfeh, E.S.G., Koch, D.L., 1990. Orientation dispersion of fibres in extensional flows. Phys. Fluids A 2, 1077–1093.

Shin, M., Koch, D.L., 2005. Rotational and translational dispersion of fibers in isotropic turbulent flows. J. Fluid Mech. 540, 143–173.

Shimizu, T., Yokogawa, A., Suzuki, M., Nakamura, I., 1986. Study on flow characteristics of pulp suspension: 2nd report – flocculation measurements of a thick fiber suspension. Bulletin JSME 29, 1487–1493.

Shimizu, T., Wada, K., 1989. Study on flow characteristics of pulp suspension. Nippon Kikai Gakkai Ronbunshu, B Hen/Trans. Japan Soc. Mech. Engrs, B 55, 3314–3319.

Soszynski, R.M., 1992. Plug flow of fiber suspensions in pipes. A case of clear water annulus. Ann. Mtg. – Technical Section, Canadian Pulp and Paper Association, Preprints, pt B, pp. 77–80.

Wikstrom, T., Ronnmark, Y., Rasmuson, A., 2002. A new correlation for the onset of fluidisation in pulp suspensions. Nord Pulp Pap. Res. J. 17, 374–381.

Xie, T., Ghiaasiaan, S.M., Karrila, S., 2003a. Flow regime identification in gas/liquid/pulp fiber slurry flows based on pressure fluctuations using artificial neural networks. Ind. Eng. Chem. Res. 42, 7017–7024.

Xie, T., Ghiaasiaan, S.M., Karrila, S., McDonough, T., 2003b. Flow regimes and gas holdup in paper pulp–water–gas three-phase slurry flow. Chem. Eng. Sci. 58, 1417–1430.

Xie, T., Ghiaasiaan, S.M., Karrila, S., 2004. Artificial neural network approach for flow regime classification in gas–liquid–fiber flows based on frequency domain analysis of pressure signals. Chem. Eng. Sci. 59, 2241–2251.

Xu, H.J., Aidun, C.K., 2005. Characteristics of fiber suspension flow in a rectangular channel. Int. J. Multiphase Flow 31, 318–336.

Xu, H., Aidun, C., 2001. Velocity profile of fiber suspension flow in a channel. TAPPI Engineering/Finishing and Converting Conference and Trade Fair, 357–369.

Yan, H.W., Lindstrom, T., Norman, B., 2003. A flow loop system for study of fibre suspension flocculation under simulated forming conditions. In: International Paper and Coating Chemistry Symposium, Technical Association of Pulp and Paper Industry Press, Montreal, pp. 167–173.

Yokogawa, A., Suzuki, M., Shimizu, T., 1985. Study on flow characteristics of pulp suspension flow – measurement of turbulence intensity and fiber concentration unevenness. B. JSME 28, 846–853.