Rheology of pulp fibre suspensions: A critical review

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Abstract

This paper reviews past studies on the measurement of rheological properties of pulp fibre suspensions. Such suspensions are complex fluids important in the manufacture of many pulp-fibre based products, such as communication papers, hygiene products, packaging, as well as other fibre-based materials. Pulp suspensions play a role in other biomass conversion processes as well. This review focuses on key properties of fibre suspensions, such as regimes of behaviour based on inter-fibre contact, apparent yield stress, apparent viscosity, and viscoelasticity. Difficulties encountered in measurement of these properties due to flow regime changes, heterogeneous mass distribution, and formation of depletion layers at solid boundaries is discussed and methods to overcome them are reviewed.

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Posthumous
1. Introduction

Flow of fibre suspensions is a key factor in manufacturing a diverse range of products, for example, fibre-reinforced composites, food stuffs, carpeting, and textiles (Tucker and Advani, 1994; Papathanasiou and Guell, 1997; Piteira et al., 2006; Umer et al., 2007). Of these industries, none is larger than pulp and paper manufacture. This is a major industry in almost all countries, producing communication papers, packaging, boxes, tissue, hygiene products, and an assortment of disposable products. Fibre for this industry comes from pulping biomass, mostly trees in modern times. As such, the industry is based on a sustainable, renewable, carbon-neutral resource.

There is growing interest in new uses of biomass. The world’s increasing population requires that more energy and products come from renewable resources and moreover ones that do not impinge upon the food supply. The forest biomass is a logical source. As in the case of pulp and paper, processing biomass for use outside the range of interest in this review, although in producing energy, examples range from bio-ethanol to electricity.

Suspensions of pulp fibres are processed in various ranges by flow of fibre suspensions plays a part. Kerekes et al. (1985) classified the ranges as follows: low consistency (Cm = 0–8%), where the suspension is a water–fibre slurry; medium consistency (Cm = 8–20%) created by dispersing a mat formed by vacuum filtration of low consistency suspension; high consistency (Cm = 20–40%) formed by mechanically pressing water from a medium consistency suspension and ultra-high consistency (Cm > 40%) formed by evaporative drying. At low consistency, the suspension is a two-phase slurry, changing at medium and higher consistencies into a three-phase heterogeneous mixture of water, fibres and air. At the higher gas contents, it is useful to use volumetric concentration, Cv, in place of mass consistency. These are related as follows:

\[ C_v = C_m \left( \frac{1}{\rho_f} + \frac{X_w}{\rho_w} + V_l \right) \rho_b \]

where Cm is the fibre mass fraction, \( \rho_f \) is the fibre density (kg/m³), \( \rho_w \) is the water density (kg/m³), \( \rho_b \) is the bulk density (kg/m³), \( X_w \) is the water adsorbed within the fibre wall (kg water/kg fibre) and \( V_l \) is the volume per unit mass of the hollow channel in the middle of the fibre referred to as lumen (m³/kg fibre).

All of the above consistency ranges are found in the processes for pulp and paper manufacture. They are likely to be important in new processes for fibrous biomass.

2. Background

2.1. Fibre properties and consistency ranges

Wood pulp fibres are hollow tubes having typical average length 1–3 mm and diameter 15–30 μm. There is a wide variability around these averages, even within one species. Accordingly, fibre length is specified by various weighted averages, a typical one being length-weighted average for fibre length to give weight to the longer fibres in the distribution.

Wood fibres are composites made up of spirally wound fibrils of cellulose. Some newer applications of wood pulp are being developed to exploit the unique properties of these fibrils. Examples are micro-fibrillated cellulose (MFC) and nano-crystalline cellulose (NCC). MFC are small fibrous particles of length 100–1000 nm and diameter 5–30 nm (Ankerfors and Lindström, 2010). NCC is smaller, in the range 20–200 nm in length (Dong et al., 2000; Pan et al., 2010). These fibril particles are in the Brownian range and generally behave as colloidal suspensions in the dilute range and as gels when more concentrated. They are outside the range of interest in this review, although in producing them, for example in homogenisers, grinders, refiners and like, rheology of pulp suspensions plays a part.

Suspensions of pulp fibres are processed in various ranges by mass consistency, C_m (mass of fibres divided by the total mass of suspension). Kerekes et al. (1985) classified the ranges as follows: low consistency (C_m = 0–8%), where the suspension is a water–fibre slurry; medium consistency (C_m = 8–20%) created by dispersing a mat formed by vacuum filtration of low consistency suspension; high consistency (C_m = 20–40%) formed by mechanically pressing water from a medium consistency suspension and ultra-high consistency (C_m > 40%) formed by evaporative drying.

2.2. Fibre contacts and forces

The large aspect ratio of pulp fibres (40–100) induces significant contact among fibres at all consistencies. This has a strong effect on suspension rheology. In the low consistency range, with increasing consistency the nature of contacts changes from occasional collisions, to forced contacts, to continuous contact. These contact regimes have been described by a crowding number, \( N_c \), defined as the number of fibres in a volume swept out by the length of a single fibre (Kerekes et al., 1985). This parameter can be expressed in terms of a volumetric concentration \( C_v \) fibre length \( L \), and diameter \( d \). Pulp fibres have a distribution of fibre lengths, variable diameters, and like all lignocellulosates materials, tend to swell in water. Accordingly mass is more suitable than volume for calculating numbers of fibres and thereby \( N_c \) (Kerekes and Schell, 1992) provide a mass-based expression for this calculation shown below.

In this equation, \( L \) is the length-weighted average length of the pulp fibres (m); \( C_m \) is the mass consistency (%), and \( \omega \) is the fibre coarseness (weight per unit length of fibre, kg/m). The latter is a commonly measured property of pulp fibres. Accordingly, the constant has units kg/m³.

\[ N_c \approx 5.0 C_m \frac{L^2}{\omega} \]

In early work, Mason (1950) identified \( N_c = 1 \) as a “critical concentration” at which, collisions first occur among fibres in shear flow. In later work, Soszynski and Kerekes (1988a) and Kerekes and Schell (1992) showed that at \( N_c \approx 60 \) fibre suspensions have about three contacts per fibre. This is a critical value because fibres are restrained by three-point contact. Upon cessation of shear, fibres become locked in the network in a bent configuration. This elastic bending creates normal forces at contacts, and the resulting frictional force imparts mechanical strength to the network.

In later work, Martinez et al. (2001) identified another critical value of \( N_c \), \( N_c \approx 16 \), calling this a “gel crowding number”. Below this value, the suspension behaves as essentially dilute. In recent work, the limits \( N_c = 16 \) and 60 were shown to correspond respectively to the “connectivity threshold” and “rigidity threshold” of fibre networks as predicted by effective-medium and percolation theories (Celzard et al., 2009).

2.3. Forces on fibres and flocculation

In addition to friction forces, other forces may contribute to strength at contacts, such as forces from chemical flocculants, hooking of curved fibres, and surface tension when air content is
substantial (Kerekes et al., 1985). These forces impart mechanical strength to fibre networks.

In shear flow, fibres aggregate into local mass concentrations called flocs, which are typically a few fibre lengths in size. When $N < 60$, the flocs are loose aggregates, but when $N > 60$ the flocs adopt mechanical strength. Their size and strength are affected by the flow conditions, for example, shear history such as nature of the decaying turbulence in the wakes of pumps and mixers where most flocs form (Kerekes, 1983b). Having a larger concentration than the suspension average, flocs also have a larger strength than the suspension average. Consequently, fibre suspensions are heterogeneous in both mass and strength, an important factor in pulp suspension rheology.

The mechanism of floc formation has been studied in various past works. Kerekes (1983a, 1983b) examined the role of decaying turbulence in floc formation, and later Soszynski and Kerekes (1988b) studied the role of flow acceleration and turning on local fibre crowding to produce coherent flocs. Valuable insights have also been gained from particle level simulation techniques modelling fibres as chains of rigid rods connected with hinges (Ross and Klingenberg, 1998; Schmid and Klingenberg, 2000a, 2000b; Schmid et al., 2000). In summary, fibre suspensions display a large range of behaviour, from dilute slurries, to heterogeneous two-phase suspensions, to discontinuous three-phase mixtures of wet fibres in a gas. In commercial papermaking, pulp suspensions are formed into paper by filtration in the range $16 < N < 60$ to minimise both water usage and flocculation. However, most of the unit operations for processing pulp before papermaking take place at one or other of the higher consistency ranges.

### 2.4. Rheology of fibre suspensions

The complexities described above make the rheology of pulp suspensions complex. The suspension often cannot be treated as a continuum because fibres and flocs are large relative to the dimensions of the flow field. Both shear history and time in a given shear flow (thixotropy) may cause floc size and strength to differ among suspensions even when suspension averages are the same. Fibre orientation and migration away from solid boundaries create a depletion layer near walls, which complicates rheological measurements (Nguyen and Boger, 1992; Barnes, 1997; Swerin, 1998; Wikström and Rasmuson, 1998). Given these factors and those described earlier, not surprisingly defining and measuring rheological properties of fibre suspensions is complex.

### 3. Apparent yield stress

#### 3.1. General

Yield stress is arguably the most important rheological property of fibre suspensions. Unless it is exceeded, flow does not take place. As a rheological property, yield stress has various definitions and means of measurement. In the simple case of a Bingham fluid, it is the stress required to initiate continuous motion in the form of Newtonian flow. However, non-Newtonian fluids often exhibit no clear demarcation as found in a Bingham fluid. Indeed there is some controversy over whether yield stress is a true material property (Scott, 1933; Barnes and Walters, 1985). Accordingly, it is common to define an “apparent yield stress” by the method of measurement. There are several approaches for doing so that are relevant to fibre suspensions:

- **“Maximum viscosity”:** This apparent yield stress is the value of shear stress at which the instantaneous viscosity exhibits a maximum as shear stress is increased, as shown in Fig. 1.
- **“Apparent stress to initiate flow”:** This apparent yield stress is the intercept obtained by extrapolating shear stress to zero shear rate, usually from the linear portion of shear stress-shear rate curve (Fig. 2).
- **“Ultimate Shear Strength”:** This apparent yield stress is the maximum shear stress reached when strain is increased to initiate flow, after which the stress decreases. The maximum is commonly called the ultimate shear strength (Thalen and Wahren, 1964; Nguyen and Boger, 1985; Cheng, 1986; Liddell and Boger, 1996). The rationale here is that this stress must be exceeded for flow to take place.

#### 3.2. Apparent yield stress of fibre suspensions

There have been two general approaches to measuring apparent yield stress of pulp fibre suspensions (Kerekes et al., 1985). The first, a “quasi-static” shear strength, employs conventional stress-controlled or rate-controlled rheometers or devices that rupture the fibre network at rest. The second, a “dynamic network strength”, is obtained in flowing suspensions by estimating the shear stress at the surface of plugs of fibre networks at the onset.
of plug surface disintegration. This gives a “disruptive shear stress” (Daily and Bugliarello, 1961; Meyer and Wahren, 1964; Mih and Parker, 1967; Duffy and Titchener, 1975; Bennington et al., 1990).

3.3. Modified rheometers

Narrow-gap, smooth-walled rheometers must be modified to measure pulp suspensions for reasons described earlier. To accommodate the size of fibres and flocs, gap size is increased. To overcome the depletion layer, rheometer walls may be roughened with asperities that are large relative to the thickness of the depletion layer. Swerin et al. (1992) and Damani et al. (1993) measured apparent yield stress of pulp suspensions in a parallel-plate rheometer having roughened walls of 105–125 μm and a gap size of 10 mm.

Oscillatory shear is another approach to measurement of apparent yield stress. The suspension is subjected to an oscillatory small-amplitude strain to measure material properties such as elastic and viscous modulus (Dealy and Wissbrun, 1990). Swerin et al. (1992), and Damani et al. (1993) used oscillatory rheometry to measure the apparent yield stress of softwood pulp suspensions from the product of the storage modulus \( G' \) and the critical strain for the onset of decrease of \( G' \) in oscillatory shear modes (Fig. 4). An important issue with this measurement is that small strains may cause strain and rupture only between flocs, not within them. Swerin et al. (1992) found the critical strain to be almost independent of the mass concentration, which suggests that the strain was confined to zones between flocs.

3.4. Vaned-geometry devices

Another approach to overcome issues of gap size and wall slip to measure apparent yield stress is by use of vaned rotors in housings having baffles, as shown in Fig. 5 (Head, 1952; Duffy and Titchener, 1975; Gullichsen and Harkonen, 1981; Bennington et al., 1990). This approach moves the shear layer away from the wall surface to a circle swept out by the tips of the rotor vanes, that is, into the body of the suspension. The shear plane lies in the circle swept out by the rotor tips.

Head (1952), Thalen and Wahren (1964a,b), Duffy and Titchener (1975), Gullichsen and Harkonen (1981), Bennington et al. (1990), Ein-Mozaffari et al. (2005), and Dalpke and Kerekes (2005) employed vaned-geometry devices to measure apparent yield stress of pulp suspensions. They applied increasing strain on the rotor and reported the apparent yield stress as the maximum stress sustained by the suspension at the onset of continuous motion. This corresponds to the “ultimate shear strength” discussed earlier. Most of the studies were for low and medium consistency pulp suspensions, but Bennington et al. (1995) extended measurement of apparent yield stress to high consistency which contained significant amounts of air.

In a device similar to Bennington’s, Derakhshandeh et al. (2010a) measured the apparent yield stress of pulp fibre suspensions using both a stress-controlled and rate-controlled rheometer together with measurements of velocity profile by an ultrasonic Doppler velocimetry (UDV). Thus, unlike previous approaches, which assumed the nature of velocity profiles in the rheometers, this approach measured velocity profiles directly (Fig. 6) and linked them to the shear stress evolution in the suspension, thereby measuring apparent yield stress using Eq. (3). All the suspensions were pre-sheared in a similar manner prior to the experimental testing to eliminate the effects of shear history and thixotropy.

\[
\sigma_y = \sigma_T \left( \frac{R_1}{R_p} \right)^2
\]

where \( R_1 \) is the vane radius, \( R_p \) is the radius of the sheared zone in the rheometer, and \( \sigma_T \) is the steady-state shear stress at the vane.

Fig. 3. Ultimate shear strength.

Fig. 4. Storage modulus (○) and loss modulus (●) as a function of strain. Critical shear strain (γ_c) defines the limit of the linear viscoelasticity region and is used to obtain the apparent yield stress of pulp suspensions (Swerin et al., 1992).

Fig. 5. Vane in baffled housing device used to study pulp fibre suspensions (Head, 1952).
tip. Local velocities were measured in the gap between \( R_1 \) and \( R_2 \). The results showed good agreement with apparent yield stress values obtained using the linear shear stress ramp method, i.e. the shear stress at which the instantaneous viscosity was a maximum, thereby verifying this simpler technique as a reliable measurement of apparent yield stress (Derakhshandeh et al., 2010a).

3.5. Findings of various approaches to measure apparent yield stress

All workers found the apparent yield stress to depend on a power of the consistency. At low consistency, the power dependence is for the difference between the consistency being tested and a threshold consistency at which networks form. The premise here is that consistencies below the threshold do not contribute to mechanical strength. Thalen and Wahren (1964a) defined the threshold by a sediment concentration, \( C_s \), as shown in Eq. (4) below. Later, Martinez et al. (2001) defined it by the gel crowding number \( N_C \) as shown in Eq. (5).

\[
s_y = (C_m - C_s)^b \tag{4}
\]

or

\[
s_y = (N - N_C)^b \quad \text{where} \quad N_C = 16 \tag{5}
\]

These equations apply for low consistency pulp suspensions, typically in the range in which paper is formed, typically \( C_m = 0.5\% - 1\% \). However, most processing of fibre suspensions takes place at larger consistencies, typically are 3% or more. In this range, the apparent yield stress equations can be simplified to:

\[
s_y = aC_m^p \tag{6}
\]

where \( C_m \) is consistency in \( \% \) and \( a \) has units Pa.

Values for \( a \) and \( b \) measured in earlier studies were summarised by Kerekes et al. (1985). The studies examined yield strength in various ways, including shear strength of pulp plug surfaces in flowing suspensions, and defined these strengths in differing ways. In addition, many other factors differed among the studies, such as wood species and pulping method. Not surprisingly, results varied considerably. Values of \( a \) were in the range 1.8 < \( a \) < 24.5 (Pa) and \( b \) in the range 1.69 < \( b \) < 3.02. Many key variables contributing to these differences were not measured or reported. For example, Dalpke and Kerekes (2005) found fibre length to be very important, with longer fibres causing larger apparent yield stress.

At consistencies \( C_m > 8\% \), fibre suspensions generally contain substantial air. Bennington et al. (1995) measured the apparent yield stress in ranges of consistency having up to 90% air content by volume, obtaining the following expression for apparent yield stress

\[
s_y = 7.7 \times 10^3 C_m^{2.2} (1 - \varphi_g)^{1.4} A^{0.6} \tag{7}
\]

\( 0.004 \leq C_m \leq 0.5 \) and \( 0 \leq \varphi_g \leq 0.9 \)

where \( \varphi_g \) is the fractional gas content, \( A \) is the fibre axis ratio with the pre-factor numerical constant in Pa. This equation is valid for both mechanical and chemical pulps. At high gas contents, it was found that apparent yield stress could be well described by fibre volume fraction \( C_v \) (Bennington et al., 1990):

\[
s_y = aC_v^p \tag{8}
\]

All the measurements of apparent yield stress have considerable scatter, often as much as 100%. To determine an average value, Bennington et al. (1990) defined a relative apparent yield stress to be that measured in a single test divided by the average apparent yield stress for all tests performed under the same experimental conditions. Using the relative apparent yield stress, experimental data were compared on a normalised basis and approximated by a Gaussian distribution. The coefficient of variation for the apparent yield stress of pulp suspensions found to be 20% and for synthetic fibres to be 45%.

Scatter in the data is due to many factors, including how apparent yield stress is defined and the method of measurement. For example, apparent yield stresses obtained by quasi-static methods were all larger than those measured using dynamic methods. Other difference are illustrated in the methods and definitions employed in studies of Gullichsen and Harkonen (1981), Bennington et al. (1990), Swerin et al. (1992), Wikström and Rasmuson (1998), Dalpke and Kerekes (2005), and Derakhshandeh et al. (2010a). An example is given in Table 1 for apparent yield stress of a bleached softwood kraft pulp.

Fig. 6. Velocity profiles across the gap for SBK pulp suspensions at several mass concentrations. Solid lines are the best fits to the data by the Herschel–Bulkley model with constants listed in the insert (Derakhshandeh et al., 2010a).

### Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>Measurement method</th>
<th>( \sigma_y (\text{Pa}) )</th>
<th>( C_m = 3% )</th>
<th>( C_m = 6% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bennington et al. (1990)</td>
<td>Baffled concentric-cylinder, ultimate shear strength</td>
<td>176</td>
<td>1220</td>
<td></td>
</tr>
<tr>
<td>Swerin et al. (1992)</td>
<td>Couette cell, oscillatory experiments</td>
<td>19.3</td>
<td>117</td>
<td>60</td>
</tr>
<tr>
<td>Damani et al. (1993)</td>
<td>Parallel plate geometry, oscillatory experiments</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Wikström and Rasmuson (1998)</td>
<td>Baffled concentric-cylinder, ultimate shear strength</td>
<td>131</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>Ein-Mozaffari et al. (2005)</td>
<td>Concentric-cylinder, ultimate shear strength</td>
<td>350</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Dalpke and Kerekes (2005)</td>
<td>Vane in large cup geometry, ultimate shear strength</td>
<td>130</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Derakhshandeh et al. (2010a)</td>
<td>Vane in large cup geometry, ultimate shear strength</td>
<td>248</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Derakhshandeh et al. (2010a)</td>
<td>Vane in large cup geometry, maximum viscosity</td>
<td>194</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Derakhshandeh et al. (2010a)</td>
<td>Velocimetry–rheometry</td>
<td>137</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
The values range from 19.3 to 350 Pa for a consistency of 3%, and from 60 to 1220 Pa for a consistency of 6%.

3.6. Modelling apparent yield stress

Several workers developed mathematical models of fibre networks to predict apparent yield stress. Bennington et al. (1990) derived an equation based on network theory that included fibre aspect ratio and Young’s modulus as follows:

\[ \sigma_y = cE A^2 C_v^{-1} \]  

(9)

where \( A \) is the fibre aspect ratio, \( E \) is the fibre’s Young’s modulus, \( c \) is a constant and \( C_v \) is the volume concentration of the pulp suspension. All fibres were assumed to be rod-like with a common area moment of inertia. In later work, Wikström and Rasmussen (1998) considered differing area moments of inertia for pulp fibres and modified Eq. (9) by using the fibre stiffness (the product of elastic modulus and area moment of inertia). This modification led to the following equation proposed for the apparent yield stress values:

\[ \sigma_y = cE A^2 \left[ 1 - \frac{d^4}{D^4} \right] C_v^{-1} \]  

(10)

where \( d \) and \( D \) are the inner and outer diameters of the fibres.

4. Shear viscosity

4.1. Suspensions of synthetic fibres

Relatively few studies have been devoted to measuring the viscosity of pulp suspensions, although there have been a substantial number for the simpler case of synthetic (plastic, glass) fibres of uniform size and shape. Although this review is focused on pulp fibres, there are sufficient similarities to synthetic fibres to warrant a brief discussion here.

References to many of the major studies of synthetic fibres can be found in review papers and literature surveys in papers on the subject, for example Ganani and Powell (1985), Bennington and Kerekes (1996), Petrie (1999), Kerekes (2006), and Eberle et al. (2008). Some studies are particularly relevant to pulp fibre suspensions. Nawab and Mason (1958) measured the viscosity of dilute suspensions of thread-like rayon fibres in castor oil. They employed a bob and cup viscometer equipped with a microscope to check for wall slippage. Fibre aspect ratio had a strong effect on suspension viscosity and its shear dependence. In other work, Blakeney (1966) examined the effect of fibre concentration on the relative viscosity of suspensions of straight, rigid nylon fibres with aspect ratio of about 20. He found that at \( C_r > 0.0042 \), viscosity increased dramatically with concentration. Interestingly, this condition is \( N \approx 1. 

Ziegel (1970) measured the viscosity of suspensions of glass rods, glass plates and asbestos fibres in high viscosity polymer fluids and compared them with those of spherical particles. Horie and Pinder (1979) measured the viscosity of suspension of nylon fibres over a wide range of consistency and shear rates; they found thixotropy and that thickness of the shearing layer in the viscometer to depend on time of shearing.

Kitano and Kataoka (1981) employed a cone-plate rheometer to study the steady shear flow properties of suspensions of vinylon fibres in silicone oil up to \( C_m = 7\% \). Ganani and Powell (1986) studied the rheological behaviour of monodisperse glass fibres both in Newtonian and non-Newtonian suspending media at fibre volume fractions of 0.02, 0.05, and 0.08. Milliken et al. (1989) employed falling-ball rheometry to measure viscosity of monodisperse randomly oriented rods in a Newtonian fluid. Suspensions exhibited Newtonian behaviour at \( C_r < 0.125 \) and a sharp transition at \( C_r > 0.125 \) at which viscosity depended on third power of concentration. This corresponds to \( N = 33 \).

Petrich et al. (2000) studied the relationship between the fibre orientation distribution, fibre aspect ratio, and the rheology of fibre suspensions. They measured both specific viscosity and normal stress differences. Chaouche and Koch (2001) examined the effect of shear stress and fibre concentration on the shear-thinning behaviour of rigid fibre suspensions. They showed that fibre bending and a non-Newtonian suspending liquid played a major role in shear-thinning behaviour of suspension at high shear rate values. Switzer and Klingenberg (2003) modelled the viscosity of fibre suspensions. They showed viscosity to be strongly influenced by fibre equilibrium shape, inter-fibre friction, and fibre stiffness.

4.2. Shear viscosity of pulp suspensions

Steenberg and Johansson (1958) studied flow behaviour of suspensions of unleached sulphite pulp in a custom-made parallel-plate viscometer. They measured shear stress-shear rate relationships over a wide range of flow velocity and consistencies up to 2.5%. They observed two transition points: a maximum at low shear rates and a minimum at high shear rates. These correspond to similar observations in pipe flow (discussed later). The transition points shifted towards higher shear rates as the gap clearance decreased. They measured viscosities at shear rates above the second transition point where pulp was considered to be a fully sheared medium. At these high shear rates, they found Newtonian behaviour up to about \( N \approx 100 \), with viscosity slightly larger that water. This work showed that various flow regimes may exist in rheometers.

In another early study, Guthrie (1959) measured the apparent viscosities of pulp suspensions at \( C_m < 2\% \) to calculate Reynolds numbers in a pipe. He found viscosity increased dramatically with consistency above a critical value of \( C_m = 1.4\% \). Above this, pulp suspension viscosity showed no significant dependence on the fibre length over the length range of 0.2–0.67 mm. The likely explanation for this observation is that consistency 1.4% at fibre length 0.67 mm give about \( N = 20 \), which is near the gel crowding number. Below this the suspension behaves as dilute and length would not be expected to be important. An abrupt change in suspension behaviour at this point is to be expected.

Chase et al. (1989) surveyed the variation of torque versus rotational rate of hardwood and softwood pulp suspensions to study the effects of fibre concentration and freeness on the viscosity parameter. For both suspensions, viscosities increased linearly with consistency. The viscosity of hardwoods decreased linearly with freeness, while the viscosity of softwoods increased initially and then decreased with a decrease in freeness. They also concluded that pulp behaves as a Bingham plastic fluid on the basis that pulp exhibits an apparent yield stress.

Chen et al. (2003) studied the flow behaviour of pulp suspensions in a modified parallel-plate rheometer. The lower plate was replaced with a Petri dish to prevent the suspension overflow, but no modification was made to minimise wall slippage. Softwood and hardwood bleached kraft pulps were mixed in different ratios but the total mass concentration kept at 0.05%, giving a very dilute suspension i.e. \( N \approx 5 \). They measured shear stress as a function of shear rate and performed stress relaxation experiments. Using a CCD camera, they identified three flow regimes as illustrated in Fig. 7. In the first regime, Newtonian flow was observed at low shear rates. In the second regime, they observed unstable flow, with jumps in the shear stress dependant on shear rate. The stress jumps were attributed to the flocculation of pulp fibre suspensions. They measured a mixture of softwood and
hardwood pulp at \(C_m = 0.05\% \ (N \approx 5)\). The third region was found to be a dynamic equilibrium zone, which showed Newtonian behaviour at high shear rates.

More recently, Derakhshandeh et al. (2010b) studied the flow behaviour of 0.5–5% pulp suspensions using both conventional and coupled DSD-rheometry techniques. These concentrations are larger than those of Chen by a factor of 10–100, raising \(N\) to \(N=50\) and 500. The lower value corresponds to the onset of network strength while the higher limit is well in the range of substantial network strength. They observed shear-thinning behaviour, and beyond a critical level of shear stress, Newtonian behaviour. Suspension viscosity increased with fibre consistency, fibre length, and suspension pH. In the Newtonian regime at high shear rates, viscosity was found to depend on consistency to approximately the third power.

These studies clearly show that differing flow regimes may exist in rheometers caused by differences in fibre orientation, a depletion layer, and the onset of shear over the entire gap as opposed to a depletion layer near the wall. No consistent picture has been established of when these regimes exist.

To avoid wall effects and ensure flow throughout the vessel, Bennington and Kerekes (1996) measured viscosity by an indirect approach. They created turbulence in a large-gap device and obtained viscosity from the relationship between power dissipation and microscale turbulence. They noted, but did not measure, the dependence of viscosity on shear rate. They found viscosities to depend upon the third power of consistency for fibre mass consistencies over 1% as shown below:

\[
\mu_a = 1.5 \times 10^{-11} C_m^{3.1}\]  

where \(C_m\) is mass consistency and \(\mu_a\) is in Pa s. Interestingly, the consistency dependence of the pulp viscosity is similar to that of suspensions of rod-like particles in Newtonian fluids (Milliken et al., 1989; Powell and Morrison, 2001).

Another approach to characterizing the viscosity of a pulp suspension is by considering flocs rather than fibres as the suspended solid, specifically flocs to be solid spheres. This is possible in some case of low velocity flows. Van de ven (2006) used this approach to correlate spouting velocity to fibres mass in spouted beds.

Other recent work has addressed the question of viscosity of pulp suspensions in narrow channels much smaller than a fibre length. In this case, continuum conditions clearly do not exist and therefore the suspension cannot be considered as a fluid. Consequently, a meaningful viscosity cannot be measured. For practical applications in process equipment, Roux et al. (2001) introduced the concept of a “shear factor”, a parameter to be multiplied by velocity divided by a gap size.

4.3. Extensional viscosity of fibre suspensions

Extensional (elongational) viscosity is the resistance of a fluid element to stretching on in flow. There are few studies of extensional viscosity of pulp fibre suspensions although there have been some for synthetic fibres. Mewis and Metzner (1974) measured apparent extensional viscosity of glass fibre suspensions in the range \(N > 60\). They found the extensional viscosity to be one to two orders of magnitude greater than that of the suspending fluid. Ooi and Sridhar (2004) employed filament stretching technique to study extensional flow of fibre suspensions in Newtonian and non-Newtonian fluids.

Studies on extensional flow of pulp fibre suspensions have largely been confined to measuring stretching and rupture of individual flocs. This work was stimulated by early findings of Kao and Mason (1975) which showed that flocs ruptured primarily in tension rather than shear, suggesting that extensional flows were likely to be more effective than shear flow in dispersing flocs in papermaking.

Kerekes (1983a) employed a high speed camera to study the behaviour of 0.5% long-fibred pulp suspensions in entry flow into constrictions. These strong flocs were found to stretch by a ratio up to 5:1 before rupture. The necessary degree of contraction in the sharp-edge constriction to create this elongational strain was such that flocs came into contact with constriction edges, which introduced shear on the floc. In other work, Li et al. (1995) examined pulp suspensions in extensional flows by nuclear magnetic resonance imaging technique. They measured the axial velocity profiles for hardwood kraft pulps of 0.5% flowing through a 1.7:1 tubular contraction. James et al. (2003) employed a novel extensional flow apparatus to apply constant extensional strain rates in fibre flocs. They examined softwood kraft pulp at \(C_m = 0.01\% \ (N \approx 1)\) and found a critical extensional strain rate of \(\sim 3\ s^{-1}\) required to rupture these weak flocs. More recently, Yan et al. (2006) designed a flow device to simulate the extensional flow in paper-machine headboxes. They observed that about 20% of the flocs in a 2:1 contraction ruptured in this extensional flow.

5. Viscoelasticity

Pulp fibre suspensions exhibit elastic as well as viscous behaviour and therefore are considered viscoelastic. As in the case of measuring viscosity, measuring viscoelasticity in fibre suspensions is not simple. Here too some relevant work was carried out on suspensions of synthetic fibres.

One approach to measurement has been by normal stress differences. Nawab and Mason (1958) were the first to observe viscoelasticity in concentrated fibre suspensions at \(N > 56\) in the form of the Weissenberg or rod-climbing effect. Kitano and Kataoka (1981) employed a cone-plate rheometer to study the steady shear flow properties of suspensions composed of vinylon in silicone oil up to \(C_m = 7\%\). First normal-stress differences increased with fibre concentration, aspect ratio, and shear rate. Petrich et al. (2000) measured the first normal stress difference of a glass fibre suspension using a parallel-plate rheometer. They found that, for fibre suspensions, the first normal stress difference is directly proportional to the shear rate. It is of interest to note that a similar dependence was found between first normal stress difference and shear rate in dilute suspensions of rigid, axisymmetric Brownian particles in a Newtonian fluid (Brenner, 1974).
Another approach to measuring viscoelasticity is by oscillatory shear. Here the Boltzmann superposition principle is employed whereby a relaxation spectrum determined by a single experiment for small amplitude oscillatory shear, and this is used to determine the response in any other case (Dealy and Wissbrun, 1990). This approach is only valid when the deformation is either small or very slow.

Using oscillatory strain in a parallel-plate rheometer, Swerin et al. (1992) measured viscoelastic properties of pulp suspensions in the consistency range of 3–8% in terms of storage and loss modulus. Storage and loss moduli were found to increase with fibre mass concentration and to be independent of the applied frequency. A power-law equation was proposed to predict the storage modulus as a function of fibre mass concentration.

Damani et al. (1993) employed the same approach and found the elastic modulus to be independent of the applied frequency. This is consistent with the results of Swerin et al. (1992). The level of strain was found to have a significant effect on the elastic modulus, especially at low fibre concentrations.

Later, Swerin (1998) examined the viscoelasticity of two fibre suspensions with different fibre sizes (0.9 and 2.8 mm) up to \( C_m = 1\% \) in the presence of flocculants. All measurements were performed in the oscillatory mode using a roughened cup-and-bob geometry to minimise wall slippage. By measuring the variation of elastic and viscous modulus versus straining frequency, with and without flocculants, it was shown that the effect of flocculants on the modulus was very large because they caused significant flocculation. The storage modulus was found to increase with an increase in frequency, while the viscous modulus was almost independent of the frequency.

Stickel et al. (2009) measured the viscoelasticity of bio-mass slurries having average fibre lengths of 0.1 mm and aspect ratio of 1–20 using both parallel-plate and vaned geometries. They found that elastic and viscous moduli depended slightly on frequency. The elastic modulus was larger than the viscous modulus by about an order of magnitude.

A limitation of these oscillatory methods is the use of small strains. This is likely to produce strain and rupture between flocs rather than within them. In many processes, flocs must be dispersed as well, and therefore this rheological measurement may have limited value.

### 6. Fluidisation of pulp suspensions

Fluidisation describes a state of pulp suspensions in which elements of the suspension move relative to one another such that the suspension adopts properties of a fluid. An important property is pressure energy and the ability to recover this from kinetic energy (obey the Bernoulli equation). For example, this feature permits use of centrifugal pumps, even for medium consistency suspensions, in place of displacement pumps to transport the suspension.

To attain fluidisation, apparent yield stress must be exceeded throughout the suspension. The stresses necessary for these pulp suspensions can generally only be attained in the turbulent state. For this reason, the terms fluidisation and turbulence in pulp suspensions are often used interchangeably.

Gullichsen and Harkonen (1981) pioneered the use of fluidisation for pumping. They determined the conditions necessary for fluidisation in a rotary device. Based on their findings, they developed a centrifugal pump capable of handling pulp suspension up to 15% consistency. In later work a number of workers studied fluidisation in more detail (Bennington et al., 1991; Hietaniemi and Gullichsen, 1996; Bennington and Kerekes, 1996). It was found that fluidisation could occur at two levels, floc level and fibre level, because of their large difference in apparent yield stress (Kerekes, 1983b; Bennington et al., 1991; Hietaniemi and Gullichsen, 1996). Floc level fluidisation was sufficient for pumping, but fibre-level fluidisation was necessary in some processes, for example micro-scale mixing of fast-reacting chemicals with pulp. Both scales are commonly found in mixing vessels as well as in other process equipment, often along with zones having no relative velocity at all (dead spots).

Fluidisation has been difficult to quantify because methods to measure velocity in concentrated fibre suspensions are lacking. Accordingly, indirect methods have been employed. One method is by the torque necessary to produce turbulent motion in a vessel of prescribed dimensions (Gullichsen and Harkonen, 1981). Another is method by the power dissipation per unit volume, \( \varepsilon_f \), necessary for the onset of fluidisation (Wahren, 1980). An issue in this characterisation is the presence of large gradients of power dissipation in vessels, making power dissipation equipment-specific. Bennington et al. (1991) addressed this by determining power dissipation as a function of equipment size, as shown by Eq. (12) below

\[
\varepsilon_f = 4.5 \times 10^4 C_m^{2.5} \left( \frac{D_f}{D_R} \right)^{-2.3}
\]

where \( 1\% < C_m < 12\% \), \( D_f \) is the outer housing diameter, \( D_R \) is the rotor diameter with \( \varepsilon_f \) the power dissipation/unit volume (w/m³).

Bennington et al. (1991) observed fibre-level at the rotor vane tips and largely floc-level fluidisation in zones away from the rotor. The power dissipation at the impeller tip was obtained by extrapolating Eq. (12) to zero gap size \((D = D_f)\). This showed that power dissipation for fibre-level fluidisation is about an order of magnitude greater than that for floc-level fluidisation in the vessel.

Other recent studies have extended knowledge of pulp suspension fluidisation (Hietaniemi and Gullichsen, 1996; Chen and Chen, 1997; Wikstrom and Rasmuson, 2002). The latter workers measured the onset of fluidisation using a vaned narrow-gap viscometer, defining the onset of fluidisation as the condition at which the Power Number becomes constant with Reynolds number (based on rotational speed) as is common for turbulent flow in mixing vessels. They developed a correlation which gave values similar to those of Gullichsen and Harkonen (1981), but smaller than those of Bennington and Kerekes (1996). This suggests that floc-level rather than fibre-level fluidisation was measured.

Although fluidisation generally occurs in a turbulent regime, fluid-like behaviour at a floc level can be attained under some non-turbulent conditions. One example is the flow induced in a rotary device at slow rotational speeds just above the apparent yield stress (Bennington et al., 1991). Another example was found in spouted beds (Van de ven, 2006).

### 7. Applications in pipe flow

In concluding this review, it is useful to illustrate how the rheology described above affects one of the most important flows—pipe flow. A key early study by Robertson and Mason (1957), followed by numerous other studies cited in the review papers in the Introduction, identified three regimes of flow behaviour, which take place with increasing velocity. These regimes give an “S” shaped friction loss curve as shown in Fig. 8 where pipe friction loss, \( \Delta H \) (Pa), has been plotted against pipe flow velocity, \( V \) (m/s).

At low velocity, a “plug flow” exists in which the suspension scrapes along the wall, with some rolling of fibres at the wall (Region 1). As velocity increases, a clear water annulus...
develops between the pulp plug and pipe wall (starting at peak of Region 1). Shear is concentrated in this annulus. With increasing velocity, the size of this annulus increases in greater proportion than the velocity increase, thereby causing a decrease in wall shear and consequently a decrease in friction loss with increasing velocity (Region 2 between peak and minimum). As velocity increases further, the annulus turns turbulent, pulling and mixing fibres in the annulus (Region 2, minimum). This starts the "mixed flow regime". As velocity increases further, the size of the turbulent annulus increases and the plug core decreases. At a point in this mixed regime, the friction loss of the suspension becomes less than that of the water flowing alone at the same rate, i.e., the flow exhibits "drag reduction". As velocity increases further, in Region 3 eventually a fully "turbulent regime" is attained over the whole diameter.

The above regimes occur in the low consistency range. Clearly, the range of flow behaviour is very broad, extending from mechanical friction at the wall to turbulent drag reduction. In the case of drag reduction, pulp fibre suspensions are one of the earliest and most consistent solid–liquid suspensions in which this phenomenon has been observed. The phenomenon is also found in suspensions of synthetic fibres (Kerekes and Douglas, 1972).

At medium consistency, suspensions are virtually always in plug flow. Furthermore, in this range, the suspension is compressible because of its high air content, and therefore pressure, as well as pressure difference, is important for flow. A larger pressure causes the suspension to compress and thereby exert greater mechanical force on the wall, which leads to greater friction loss (Longdill and Duffy, 1988).

Attempts have been made over the years to model friction loss of pulp suspensions in pipe flow, for example Daily and Bugliarello (1961), Luthi (1987), and Pettersson (2004), but these have found limited use. Reasons for this are many, as discussed in this paper and by Duffy (2003, 2006). Accordingly, predictions of friction loss in pipe flow in the pulp and paper industry are commonly made by empirical procedures (Duffy, 1978) that have been adopted as industry standard methods (Tappi Press TIS 0410-12).

8. Summary and conclusions

This review has described the various methods and approaches used over the years to measure key rheological properties of pulp suspensions. Although most of the studies have been for wood pulp, the findings are clearly applicable to other fibrous biomass as well. For the most part, the studies have been published in the pulp and paper literature, which also contains a wealth of additional information on pulp suspensions. The review papers cited in the Introduction can serve as a useful guide to this body of knowledge.

Nomenclature

- \( a \) constant (Pa)
- \( b \) constant (–)
- \( L \) fibre length (mm)
- \( D \) outer diameter of fibre (mm)
- \( d \) inner diameter of fibre (mm)
- \( A \) fibre aspect ratio (–)
- \( E \) fibre’s modulus of elasticity (Pa)
- \( C_m \) fibre mass concentration (%)
- \( C_v \) fibre volume concentration (%)
- \( C_s \) sediment concentration (%)
- \( V_L \) lumen volume per unit mass of fibre (m³/kg fibre)
- \( X_w \) water mass located in the fibre wall (kg water/kg fibre)
- \( N \) crowding number (–)
- \( N_G \) gel crowding number (–)
- \( D_R \) outer housing diameter (m)
- \( D_R \) rotor diameter (m)
- \( t \) time (s)
- \( R_t \) vane radius (mm)
- \( R_y \) yielding radius (mm)
- \( r \) local radius within the gap of the rheometer (mm)
- \( u(r) \) local velocity across the gap of the rheometer (mm/s)
- \( G_0 \) storage modulus (Pa)
- \( G_00 \) loss modulus (Pa)
- \( D \) pipe friction loss (Pa)
- \( V \) pipe flow velocity (m/s)

Greek letters

- \( \gamma \) strain (%)
- \( \dot{\gamma} \) shear rate (s⁻¹)
- \( \phi_g \) volume fraction of gas phase in suspension (–)
- \( \eta \) instantaneous viscosity (Pa s)
- \( \mu_a \) apparent viscosity (Pa s)
- \( \rho_b \) bulk density (kg/m³)
- \( \rho_f \) fibre density (kg/m³)
- \( \rho_w \) water density (kg/m³)
- \( \sigma \) shear stress (Pa)
- \( \sigma_T \) steady-state shear stress at the vane (Pa)
- \( \sigma_P \) apparent yield stress (Pa)
- \( \epsilon_f \) power dissipation/unit volume (w/m³)
- \( \omega \) fibre coarseness (g/m)

Abbreviations

SBK bleached softwood kraft pulp suspension
HW hardwood pulp suspension
UDV ultrasound Doppler velocimetry

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References


