Disruptive shear stress measurements of fibre suspension using ultrasound Doppler techniques

Pasi Raiskinmäki[1] and Markku Kataja[1]

[1]*VTT PROCESSES, Pulp and Paper Industry,*
P.O.Box 1603, FI-40101 JYVÄSKYLÄ, Finland

ABSTRACT

In this study, a pulsed ultrasonic Doppler velocimeter (PUDV) is applied in rheological measurement of wood fiber suspensions in a straight pipe flow. In particular, we measure the critical shear stress needed to disrupt the fiber network at the plug flow regime that occurs at low or moderate flow rates. According to the results the dependence on consistency of the disruptive shear stress can be approximated by a power law.

INTRODUCTION

Fiber suspension flows differ considerably from conventional particulate suspension flows[1]. When a fiber suspension with fiber concentration above the sedimentation concentration (that is typically of the order of 0.5-1 % by weight) flows in a long straight tube at low velocity, fibres form rigid fibre network plug that moves at a constant velocity with the flow. At very low flow velocities, the fibre plug is in a direct contact with the wall inducing high shear stress (high loss). As the flow rate is increased, a thin layer of pure water (a 'lubrication' layer) is created next to the wall. Characteristic to this flow regime is that the wall friction is approximately constant, and may even degrease with increasing flow velocity. As the flow rate increases further, turbulent flow appears near the walls and the fiber plug begins to brake from its outer surface. Thus, in this transient or mixed flow regime a turbulent fibre annulus surrounds a rigid fibre plug in the middle of the tube. As the flow rate is still increased, the solid fibre core gradually vanishes and a fully turbulent or 'fluidized' flow regime assumes. At this regime, wall friction may be even smaller than that for pure fluid (drag reduction regime[2]). The different regimes of fiber suspension flow are described above is illustrated in Fig. 1**.**

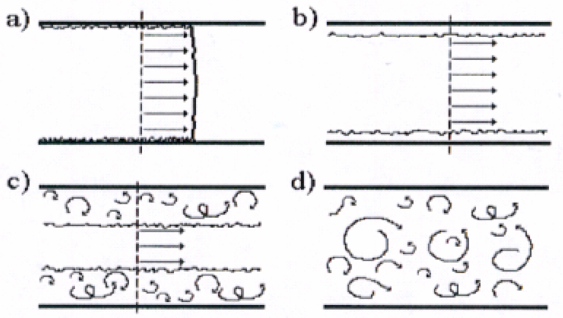

Figure 1. Flow regimes of fiber suspensions. **(a)** Plug flow regime. **(b)** Plug flow regime with lubrication layer. **(c)** Transient or mixed flow regime. **(d)** Turbulent flow regime. (The figure is reprinted from Modelling the Flow of Pulp Suspensions in Pipes, Bertel Myreen, Jaakko Pöyry Oy.)

Even though this behaviour of fiber suspensions is qualitatively quite well known, the exact dynamics of lubrication layer formation and fiber network break-up are not understood in detail that would *e.g.* allow accurate prediction of losses in straight tube flow.

Using the novel pulsed ultrasound Doppler technique it is possible to gain quite new information on the details of such flows and of the relevant rheological properties of fibre suspension. One of the important parameters that affect the flow behaviour is the disruptive shear stress of the fiber suspension. In addition to pipe flows, this parameter is important in order to understand many key processes of paper-making, where a fluidized state of fibre suspension needs to be created and sustained. One motivation of this work was to develop the method, based on PUDV techniques, which can be used to measure the critical disruptive shear stress of the fiber suspension in a straight pipe flow. The method is based on measuring a large number of instantaneous velocity profiles and finding the profile of the fluctuating velocity across the pipe. The turbulent annulus is distiquishable from the coherent core region due to its higher velocity fluctuations and lower spatial velocity correlation.

MEASUREMENT METHODS

The experiments were made in an acrylic flow loop with tube diameter 40 mm for birch and pine fiber suspensions. The volume flow rate in the tube was controlled by adjusting the rotation speed of the centrifugal pump and measured using a magnetic flow meter. The flow line was also equipped with differential pressure transducer for loss measurement. The distance between pressure taps was 1 m. The velocity profile across the tube was measured using PUDV technique (Signal Processing-DOP2000) shown in Fig. 2.

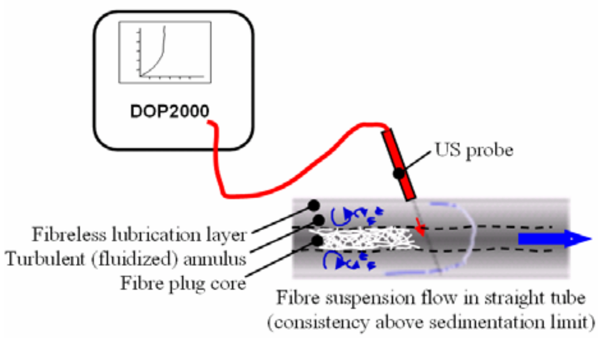

Figure 2. The pulsed ultrasound Doppler velocimeter (Signal Processing-DOP2000).

The measurement is based on using a transmitter to send short ultrasound bursts through the tube wall and into the flow. Target particles (fibers) moving with the flow scatter the sound which is detected by the transmitter. The distance of the particle is found by the time-of-flight method using the known velocity of sound, and the velocity of the particle from the measured Doppler shift of the echoed sound. (The device thus measures the velocity component in the direction of the ultrasound beam.) Within the present measurement, 32 pulse emissions were used to construct a single velocity profile, and 3000 profiles were collected during 20 seconds. The mean velocity profile was calculated as the average of these 3000 individual profiles, and the fluctuating velocity component was determined as the deviation of each individual velocity value from the mean velocity at a given position across the tube. The individual velocity profiles given by the PUDV method suffer from a noise intrinsic to the measuring principle. The measured absolute value of the fluctuating velocity may thus not be very accurate. For the present purpose we are, however, only interested in relative values of fluctuations at different parts of the tube. In addition, the intrinsic noise is highly uncorrelated, and can be eliminated from the measured spatial velocity correlations.

For unidirectional, axisymetric flow in circular pipe, the total shear stress (τ_T) at the flow core with distance r from the centre line of the pipe is given by

$$\tau_T = \frac{r}{2}\frac{\Delta P}{L}, \tag{1}$$

where $\Delta P/L$ is the pressure drop per unit length along the tube. The total wall shear stress thus vanishes at the centerline of the tube and increases linearly to its maximum value $\tau_w = \tau_T(r=R)$ at the tube wall (see Fig. 4). At the wall, the total shear stress is caused by the friction between fibers and the wall and by fluid viscosity. In the flow regime where lubrication layer exists, the total shear stress is caused entirely by fluid viscosity. Well inside the tube there are several mechanisms that can contribute to total shear stress, such fluid viscosity, turbulent stress of the fluid phase and of the fibre phase, as well as the intrinsic stress within the fibre phase. The latter the may include frictional stress that arises e.g. from friction at 'sliding' contacts between fibres, and structural stress that is a consequence of deformation of the fibre network. In turbulent flocculated state, the total intrinsic stress of the fibre phase is very complicated and no general constitutive relations for describing the stress state in such conditions have been found. Instead, the stress state within the rigid fibre plug in a mixed flow regime is considerably more straightforward, since no significant turbulent motion of the fibres is presented, and the turbulent motion of also fluid phase must be strongly attenuated by the presence of fibres. Furthermore, the mean velocity profile of the fluid phase is flat in the core region and therefore also the viscous stress of the fluid phase is small. We therefore conclude that most of the total shear stress within the rigid fibre core is carried by the structural stress of the fibre network. Consequently, we can use the value of the total shear stress at the boundary of the fibre plug as an estimate of the disruptive shear stress of the fibre network.

RESULTS

Figure 3 shows an example of a measured averaged velocity profile (solid line) and the measured range of velocity fluctuations (the grey area around the mean velocity profile). Also shown are the schematic behaviour of the total shear stress inside the tube, and the position of the fiber plug core as determined from the measured data (see below). The disruptive shear stress τ_d is approximated by the value of the total shear stress at the boundary of the fiber plug.

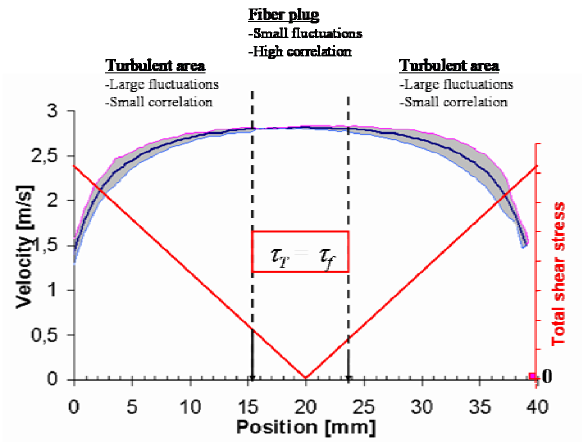

Figure 3. The averaged velocity profile (solid line) and the velocity fluctuations (grey area) of fiber suspension (birch, consistency 1%). The position of the fiber plug core is also shown. τ_f indicates the shear stress of the fiber phase.

Examples of the average velocity profiles at various flow rates measured by the PUDV are shown in Fig. 4. The Reynolds number calculated according to the viscosity of water is approximately 20 000 for the lowest, and 120 000 for the highest flow rate, indicated profile changes from the plug flow profile to the nearly turbulent flow profile when the flow rate increases. For pure water, the flow would thus be fully turbulent (and the profiles considerably more peaked) at all flow rates. Notice, that the profiles shown give the average velocity of the fibre phase. As the fibre consistency is quite high, the velocity difference between fluid (water) and fibres is evidently quite small.

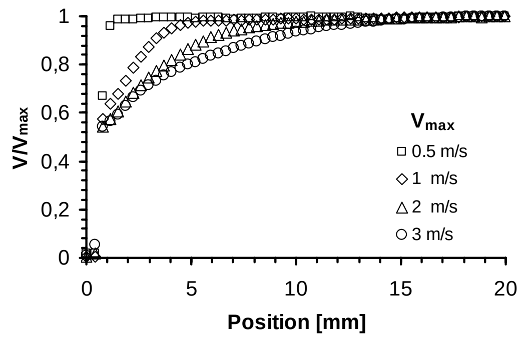

Figure 4. Averaged velocity profiles of fiber suspension (pine at consistency 0.5% by weight) for several flow rates measured by the pulsed ultrasound Doppler velocimeter. The diameter of the tube is 40 mm. The velocity values are scaled by the maximum velocity of each profile.

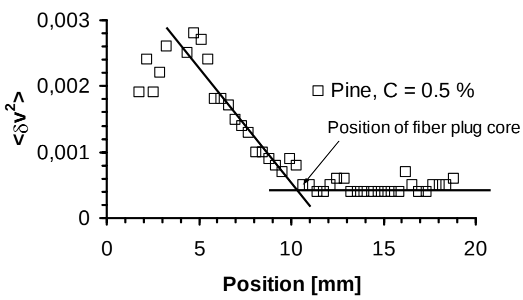

Figure 5. Turbulent intensity, as measured by PUDV, as a function of distance from the tube wall. The crossing point of two fitted solid lines indicates the position of the surface of fiber plug core.

Figure 5 shows the measured values of turbulent intensity across the tube. The intensity values shown are found as the value at zero correlation length of the spatial velocity correlation function, corrected for the device noise. The position of the fiber plug core surface is determined by fitting two lines to the measured velocity fluctuations data, and taking the crossing point as shown in Fig. 5. The resulting radius of the fiber plug as a function on flow velocity is shown in Fig. 6 for pine at consistency 0.5 %.

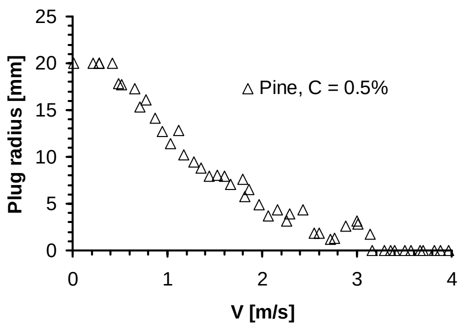

Figure 6. The measured fiber plug radius as a function of flow velocity for pine at consistency 0.5 %.

Finally, the measured values of disruptive shear stress τ_d are shown in Fig. 7 as a function of fiber consistency for birch and pine suspensions. According to the results shown, the dependence on consistency of the disruptive shear stress can be approximated by a power law of the form

$$\tau_d = kC^n , \tag{3}$$

where k is the material parameter for the specific suspension, and C is the consistency expressed as a percentage. The fitted values of k and n for Birch and Pine fibres are given in Table I. We notice that in spite of the different experimental method used here, the present results are consistent with the earlier results obtained by Dalpke and Kerekes[3] using a specific rotational viscometer and with the results obtained by Duffy and Titchener[4] using several different methods. The present method is, however, based on direct non-intrusive measurement of the position of the fibre plug core surface in a straight tube flow.

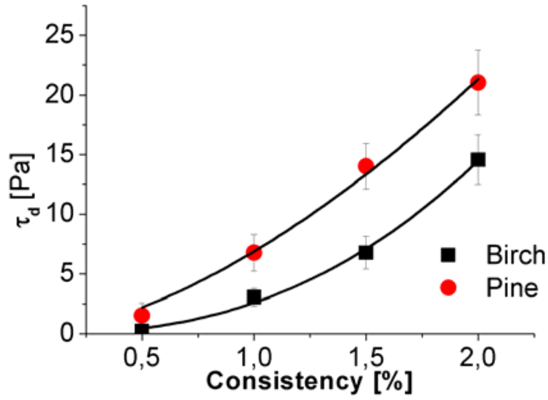

Figure 7. The disruptive shear stress τ_d as a function of consistency for pine and birch fiber suspensions. The solid lines give the fitted values according to Eq. 3.

Table I. Values of fitting parameters for correlation between consistency and disruptive shear stress, Eq. 2.

Fibre type	*k* [Pa]	*n*
Birch	2.6±0.4	2.5±0.2
Pine	6.9±0.4	1.6±0.1

CONCLUSIONS

The pulsed ultrasonic Doppler –method is applied in the analysis of the disruptive shear stress of wood fibre suspensions at consistency exceeding the sedimentation consistency. The measurement is done in a straight tube flow. It is based on observing the location of the fibre plug surface by utilizing measured spatial velocity correlation function. The results show approximate power-law dependence of the disruptive shear stress on fiber consistency. The method can be utilized *e.g.* in characterizing the effects of different fiber treatments and added chemicals on wood fibre suspensions found in paper-making.

ACKNOWLEDGMENTS

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