A Comparative Study of UVP and LDA Techniques for Pulp Suspensions in Pipe Flow

Johan A. Wiklund and Mats Stading
SIK, The Swedish Institute for Food and Biotechnology, P.O. Box 5401, SE-402 29 Göteborg, Sweden

A. Johan Pettersson and Anders Rasmuson
Dept. of Chemical Engineering and Environmental Science, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

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For the first time, noninvasive measurements in pulp suspensions at consistencies ranging from 0.74%(w/w) up to 7.8%(w/w) have been performed simultaneously using ultrasound velocity profiling (UVP) and laser doppler anemometry (LDA) in an experimental pipe flow loop. Results show that both techniques can be used to determine the plug flow velocity with good agreement in much more concentrated pulp suspensions than what has been reported so far in the literature. Instantaneous velocity profiles have been obtained noninvasively in pipe flow using the UVP technique, and it is shown that combined with simultaneous pressure drop measurements, the UVP technique can be used to determine the yield stress in-line. Results further show that LDA works, with limited penetration depth of up to several millimeters, even in strongly opaque systems, such as in 7.8%(w/w) pulp. Deviating results were however obtained in the near wall region and more work is needed. © 2005 American Institute of Chemical Engineers *AIChE J,* 52: 484–495, 2006

Introduction

Competition in the paper pulp industry has increased over the past 15 years. The annual turnover for the paper pulp industry currently surpasses many other industrial branches in countries like Canada and Sweden. Real-time control of quality parameters and process control is, thus, becoming increasingly more important. The ability to develop innovative and competitive products largely depends on the ability to control the manufacturing process. The control of temperature and mass flow is well developed, whereas there is insignificant control of for example rheological properties under actual processing conditions. The rheology of industrial suspensions, such as cellulose pulp depends on the processing conditions, which affect the microstructure during flow as well as the shear and elongational flow fields.

Cellulose pulp fiber suspensions flows differ considerably from conventional non-Newtonian, highly concentrated particulate suspensions. Pulp suspensions contain regions of relatively high fiber concentration called flocs, which tend to form a continuous rigid fiber network structure throughout the suspension above a certain critical consistency. This rigid fiber network extends across the pipe diameter at very low flow velocities and can be considered as a plug that moves at a constant velocity. As the flow rate increases, the fiber network plug begins to break up from its outer surface to form a mixed flow regime with a water and fiber annulus surrounding the rigid fiber plug in the center of the pipe. The stress required for break up is frequently called disruptive shear stress.[1] As the flow rate is still increased, the solid fiber plug gradually vanishes and the flow becomes fully turbulent and fluidized. However, it is well known that the mechanisms of flow and rheological behavior of cellulose pulp fiber suspensions in pipes is complicated to analyze, due to its complex characteristics.[2]

The chemical and physical complexity of pulp suspensions has, thus, led to the fact that the relationship between the

Correspondence concerning this article should be addressed to M. Stading at mats.stading@sik.se.

applied stress and microstructure (rheology) during flow remains poorly understood, despite extensive study for nearly half a century.[3]

Rheological data can be obtained in-line from a simultaneous recording of pressure drop and the corresponding flow rate, using various models, or from a variety of off-line rheometer configurations. However, obtained data often contradicts other data in the literature and strongly depends on the measuring geometries used. In addition, mentioned techniques are single shear rate measurements. The velocity profile contain the complete shear rate information and is, thus, of great importance if new and improved in-line techniques is to be considered.

Various flow visualization, as well as sophisticated particle tracking/imaging velocimetry techniques has been continuously improved. However, most of them still require extensive experimental know-how; their applications are essentially limited to transparent fluids, complete instantaneous radial velocity profiles are difficult to obtain and so on. In addition, most of these available techniques are not applicable to cellulose pulp fiber suspensions at consistencies outside the dilute range and have, therefore, found little practical use, especially outside the academic field.

The optical point-wise laser doppler anemometry (LDA) technique,[4] the nuclear magnetic resonance imaging (NMRI) method, based on the paramagnetic properties of the nuclei,[5] and the ultrasound velocity profiling (UVP) technique, which employs the pulsed Doppler echo method,[6-8] constitute the most promising techniques for obtaining instantaneous radial velocity profiles in concentrated cellulose fiber suspensions. Despite the potential of the new techniques, a limited number of experimental studies on pulp suspensions at applied consistencies have been published.

Ek at al.[9] used a forward scatter LDA system to investigate the pipe flow of air containing low consistencies of pulp fibers. Kerekes and Garner[10] studied water-pulp suspensions of 0.5% (w/w) using LDA. The penetration depth in pulp suspensions was found to be severely limited by the highly light scattering properties of pulp fibers. One solution to this is to use a fairly transparent model system. Steen[11] developed such a system, which he used for LDA measurements of suspensions with 1.2 and 12 g fibers/L in pipe flow.[12] The same model system was later used by both Andersson and Rasmuson[13] and Pettersson and Rasmuson,[14] where measurements were made in a stirred tank. The first study was conducted with fiber consistencies in the range of 3 – 20%(w/w). In the second study, the consistencies were in the range of 4 – 12%(w/w) fibers, but with an additional gas phase, which decreased the measuring depth.

NMRI has been used for measuring time-averaged velocity profiles of dilute pulp suspensions by Li et al.[1, 15-17] in up to 0.86%(w/w) fiber concentration. Some drawbacks of the NMRI technique are, compared to UVP and LDA, expensive equipment and long observation times. However, Arola et al.[18] managed to investigate velocity profiles of an aqueous 0.5%(w/w) pulp suspension using relatively short observation times in the order of milliseconds. Seymour et al.[19] performed measurements of time-averaged velocity profiles in the steady flow of more concentrated 3%(w/w) pulp suspensions using NMRI. Only a small number of research groups have concentrated on measuring fluid viscosity in steady pipe flow using NMRI techniques.[20-24]

Few comparative studies of LDA and UVP techniques can be found in the literature. Some investigations[25-28] performed experimentally similar experiments and obtained velocity profiles in flowing water that was seeded with tracer particles, such as nylon particles or hydrogen bubbles. The LDA was generally found to have a higher time and spatial resolution in the region of high-velocity gradients, but required considerably greater time and effort to obtain a complete velocity profile, as the measurements are point-wise. The relative error between LDA and UVP techniques was found to be less than two percent in one study. Ozaki et al.[29] compared averaged velocity and turbulence intensity profiles in water pipe flow. Excellent agreement was found between LDA and UVP technique in this study when the time averaged velocity distributions were compared.

The UVP technique has been extensively used over the past few years to obtain instantaneous velocity profiles, but most studies have so far been limited to the flow of water that contains seeding particles. Hirsimäki[30] used an early version of the UVP technique to obtain radial velocity profiles in pulp suspensions of consistencies up to 1%(w/w). Karema et al.[31, 32] characterized velocity fluctuations and studied paper formation by fluidization and reflocculation in wood pulp suspensions of consistencies up to 1%(w/w) using UVP. The UVP-PD rheometric concept (UVP combined with pressure drop data) has been tested with great success in a large number of fluids and highly concentrated suspensions, mostly food related systems. The methodology and results are described in a number of publications.[33-44] Choi et al.[45] compared velocity profiles and the rheological data obtained using UVP-PD and MRI-PD methods with good agreement. Wiklund et al.[41, 42] obtained instantaneous velocity profiles in, for example, pulp suspensions at consistencies ranging from 0.5 up to 3%(w/w) using UVP.

Recently, Raiskinmäki and Kataja[46] used UVP to determine velocity profiles in pulp suspensions at consistencies ranging from 0.5 up to 1%(w/w). In mentioned studies, a clear velocity gradient at the wall was found over some millimeters from the wall. Dietmann and Rueff [47] also used UVP in pulp suspensions at consistencies up to 2.1%(w/w), but in this work steeper profiles near the wall was found at corresponding flow velocities. When the flow rate was increased, a pronounced velocity gradient was found over some millimeters from the wall.

The aim of this study was to perform noninvasive velocity profile measurements using UVP and LDA in highly concentrated, nontransparent pulp suspensions during pipe flow, and through comparison evaluate the use of the techniques for this type of suspensions. A further aim was to calculate rheological properties, such as the yield stress in-line from simultaneous pressure drop and instantaneous velocity profiles measurements using the UVP-PD method. If successful, this method would provide the potential for a feasible in-line tool for rheological measurements of highly concentrated pulp suspensions. Even though the experiments in this study were conducted on pulp suspensions, the techniques are applicable to other nontransparent fluid systems.

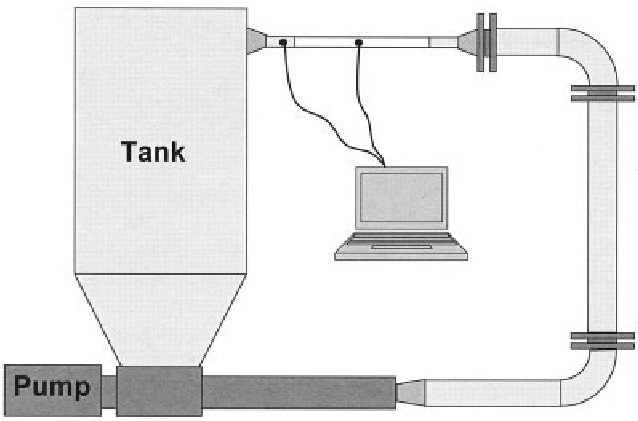

Figure 1. Experimental flow loop.

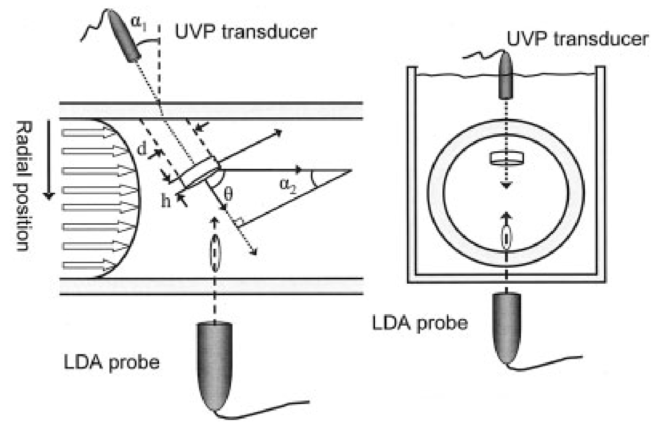

Figure 3. Cross-section of the LDA probe- and UVP transducer arrangement, measurement volumes, laser and ultrasonic beam paths through the PMMA wall material (light gray) and the surrounding box filled with acoustic coupling liquid (water).

Materials and Methods

Materials

Fully bleached kraft pulp samples were provided on two different occasions by Värö Bruk (mill), Sweden, but the composition was the same; 30 – 35%(w/w) pine and 65 – 7 0%(w/w) spruce. The pulp suspension taken from the mill had a fiber concentration of about 18%(w/w). Fiber length measurements showed that the fibers were not milled during the pipe flow experiments and that the length-weighted mean fiber-length was about 2.4 mm. The tests were performed at two different occasions, with fiber consistencies ranging from 0.6, 1.0, 1.9, 2.4 and 3.8%(w/w) in the first sequence, and 0.74, 2.5, 4.4, 6.0 and 7.8%(w/w), in the second one. During the first test sequence the concentration was gradually increased by adding more of the concentrated 18%(w/w) pulp. In the latter test sequence with higher consistencies, the concentrated pulp was diluted to 7.8%(w/w) in smaller vessels before being placed in the tank. The suspension was then diluted by adding water when the concentration was changed. This was an easier method for dealing with high pulp consistencies.

Experimental flow loop

The experimental flow loop consisted of a closed circulation system containing a tank, a pump, stainless steel pipes, a contraction and finally a smaller pipe section made of Polymethyl methacrylate, (PMMA), as shown in Figures 1 and 2. The open tank was placed on top of the pump, thus, supplying the pump continuously with fluid from the outlet at the bottom.

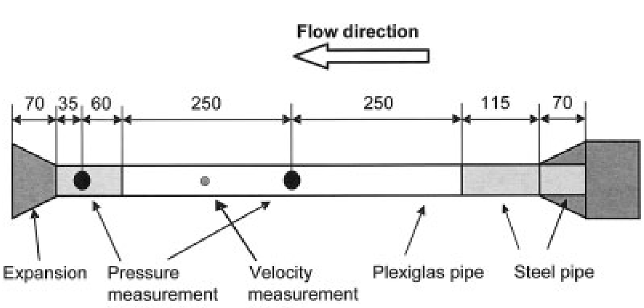

Figure 2. Experimental test section with distances in millimetres.

The PMMA pipe constituted the measurement section were the velocity measurements were performed. The test section arrangement was connected to the larger stainless steel pipe via a contraction that started 330 mm from the end of the last bend, as shown in Figures 2 and 3. The PMMA pipe had an inner dia. of 40 mm, a wall thickness of 5 mm, and a total length of 500 mm. The UVP/LDA velocity measurements were performed 70 mm from the end (that is, the left side) of the PMMA pipe section. The pressure was measured at two locations, as indicated in Figure 2. The pressure gauges used ranges from atmospheric pressure up to 4 bar overpressure with an error of 0.5% of the higher limit.

Ultrasound velocity profiling (UVP) technique

The names ultrasound velocity profiling (UVP), ultrasound pulse doppler (UPD), ultrasound doppler velocimetry (UDV), and ultrasound doppler methods (UDM), are frequently encountered in the literature, but they all refer to variations of the same method or technique. The technique was originally developed to measure blood flow, but has been extended to measure flow in other fluids in research and engineering. The principle has been described, for example, in Takeda,[6-8] and only a short summary of the technique are presented in this text. A single transducer is mounted at a specific inclination angle to ensure a velocity component in the direction of the measuring line. The transducer emits a pulse train through acoustic coupling and wall material into the sample fluid, which contains moving particles or more precise, micron sized reflective surfaces, suspended in the flowing liquid. The reflected Doppler-shifted echo sign are recorded using the same transducer. The time interval between two successive pulses is available for echo reception and returning Doppler-shifted echo signals are, thus, only sampled at specific times in a narrow time window, called a gate or channel after each transmitted pulse.

The distance to a reflector inside a measurement volume somewhere on the measuring line is determined by a time-of-flight measurement which relates the ultrasound velocity in the

Table 1. Experimental UVP Parameters

Ultrasound frequency	2 MHz
Number of cycles per pulse	2
Active element diameter	10 mm
Beam divergence	2.2°
Bursts per profile/pulse repetitions per profile	90
Number of recorded channels	110–128
Number of recorded profiles per flow rate	1024
Sound velocity in suspensions	1485–1531 m/s
Doppler angle in suspensions	68.5–73°
Spatial resolution along measurement axis in suspensions	0.74 mm, lowest pulp consistency 0.77 mm, highest pulp consistency
Time resolution (single profile)	25–54 ms/profile
Pulse repetition rate	2.2 KHz, lowest flow rate 6.2 KHz, highest flow rate
Velocity resolution	10–24 mm/s

medium of interest c, to the distance x,traveled from the transducer

$$x = \frac{c \cdot t}{2} \tag{1}$$

where t is the time interval between transmitting and receiving the signal. From the Doppler-shift frequency of each channel, local velocity values can be calculated from the Doppler equation

$$v_i = \frac{c \cdot f_i^{Doppler}}{2f_0 \cos\theta} \tag{2}$$

where v_i is the velocity component value at channel i in the flow direction; c is the ultrasound velocity in the fluid medium; $f_i^{Doppler}$ is the Doppler frequency shift for channel i; f_0 is the basic (emitted) ultrasound frequency and θ is the Doppler angle. The latter is defined as the angle between the measuring line and the direction of the moving reflectors main velocity vector. From this information, complete instantaneous velocity profiles can be constructed.

The UVP technique has relatively small measurement volumes which can be considered as disk shaped. The disk dimensions are determined by the effective diameter of the piezoelectric element in the transducer that generates the ultrasonic pulses, and the number of cycles within the ultrasonic pulses. The axial height h or thickness of the measurement volumes is given by

$$h = \frac{c \cdot N}{2 \cdot f_0} \tag{3}$$

where N is the number of ultrasonic cycles, c is the sound velocity in the fluid and f_0 is the emitted ultrasound frequency. The lateral size, that is, the diameter and shape of the measurement volumes depends on the position of measurement volumes along the measurement axis as the beam diverges slightly. Practically, the UVP measurement volumes were slightly larger compared to the LDA measurement volumes in this study.

UVP and LDA equipment

The ultrasound velocity profiling (UVP) equipment used in these experiments was the latest available UVP-DUO-MX Monitor with a Multiplexer from Met-Flow SA, Switzerland. The UVP instrument was connected to a master PC for data acquisition and was controlled by software, version 3.0, from Met-Flow SA. All post-processing of raw data and analysis was performed in Matlab using novel GUI based software. The emitted ultrasonic pulses and the received echo were continuously monitored using a digital oscilloscope, Agilent Technologies, model 54624A, USA. Important UVP measurement parameters are listed in Table 1.

The Laser Doppler Anemometry instrument used in these experiments was a DANTEC FiberFlow Series 60X, Denmark, connected to two Burst Spectrum Analysers (BSA), that is, a DANTEC 57N10, which interpret the Doppler signal to velocities. The equipment was controlled by DANTEC's software Burst Ware, version 3.0. The laser connected to this device was a Spectra-Physics laser, model 2060A-64 (Germany). The LDA measuring volume had an ellipsoidal shape and in this configuration had a size in air of 76 $\times$76 $\times$ 715 μm in which the larger dimension was in the radial direction of the pipe. The dimension in the radial direction was then further "stretched" due to differences in the refractive index between air, water and PMMA, so that the length of the measuring volume was in reality 950 μm.

UVP Transducer and LDA Probe setup

In almost every study reported so far in the literature, the ultrasonic transducers have been inserted into the pipe wall at an inclination angle so that the transducer face is in flush contact with the fluid inside the pipe. However, in this study, the UVP transducer was mounted at an optimized inclination angle outside the pipe wall but inside the surrounding box fluid, as shown in Figure 3. The LDA probe was mounted so that the laser beams entered the pipe from beneath. All experiments were thus performed noninvasively through the 5 mm thick PMMA pipe measurement section using both techniques. The ultrasonic pulse- and laser beams were arranged so that the intersection between the beams was as close as possible to the centerline of the pipe. This LDA setup resulted in only the velocity component in the flow direction being measured, as was the case for UVP. However, the radial and tangential components were negligible in this study. The surrounding box was made of PMMA, filled with water and had an open surface on top. The box served two purposes; first, the water-filled box formed an acoustic coupling between the wall and the UVP transducer, thus increasing the transmitted acoustic energy. Second, it made the laser beams enter the water media from the air or water through a plane surface, not a curved one. Optical distortions were thus decreased. The temperatures in the surrounding box and the test section were kept as equal as possible (both in the range of 22 – 24°C) in order to minimize differences in sound velocity and, thus, the differences in acoustic impedance between the box fluid and the continuous phase in the pulp suspensions.

Measurement procedure

The wall positions in the recorded data were determined before the experiments in the LDA case, but during and after the experiments in the UVP case. The wall positions and, thus, the first and last UVP channel number containing data located inside the test pipe section were determined from a procedure that involves monitoring the echo amplitude, velocity gradient data in each recorded channel over time[48] and several statistical tests. In cases in which the measurement volume was located only partially inside the measurement tube closest to the vessel wall, only that part of the measurement volume located above the wall interface should contribute to the signal. A few correction procedures of the effect on measurement volumes at the wall-liquid interface have recently been suggested,[49-51] but they are still under debate. This effect and the effect of the curvature of the tube wall were, therefore, neglected for the sake of simplicity in this study, the latter in accordance with the mentioned articles.

The sound velocity in the suspensions was measured at different temperatures prior to and after the flow loop experiments, and the ultrasonic beam inclination angles were measured using digital image analysis. Ultrasound beam paths through the wall interfaces as well as the true Doppler angles were also calculated for the suspensions studied. When the location of the LDA measuring volume was traversed through the edge of the wall, a very strong reflection of the laser light occurred. The measuring volume was widest at the center in the length direction, that is, halfway between the ends. This resulted in that the reflection of the laser was strongest when the center of the volume was at the pipe wall. By carefully traversing the volume as the amplitude of the reflected light was observed, the wall position could be determined with an approximate accuracy of 0.1 mm. Thus, the positions in the LDA measurements were obtained from the pipe wall to the center of the measuring volume.

The tank was filled with the suspension, agitated mildly, the pump was then set to the desired flow rate and the flow was allowed to attain the steady-state. Four volumetric flow rates were investigated; 0.87, 1.45, 2.04, and 2.63 L per s. The test sequences started with the lowest flow rate, and the flow rate was then increased during the experiments. The procedure was repeated for all pulp consistencies. For each flow rate, each velocity point measured with the LDA was measured 5,000 times, validated, and an arithmetic mean value was then finally calculated. UVP data acquisition was much faster than LDA, in the order of tenths of milliseconds per profile. In the UVP case, 1024 radial velocity profiles were recorded and validated simultaneously as the LDA measurements for each flow rate. In order to reduce the signal noise present in some of the recorded velocity profiles, a statistical procedure was employed in which fluctuations larger than two standard deviations from the median value in each measurement channel were removed. Volumetric flow rates were obtained via integration of the radial velocity profiles and arithmetic time-averaged profiles were then calculated. The pulp fibers were used as natural seeding particles and no additional seeding particles were added.

Rheological analysis

Nondilute cellulose fiber systems are known to behave almost like solids and do not flow until a critical yield stress τ_0 is exceeded.[52] When the applied stress is greater than the yield stress value, it results in the formation of a rigid moving plug in the center of the pipe with a plug radius R_0. For such systems, the velocity profile thus exhibits a plug flow region in the center of the pipe ($0 < r < R_0$), where the shear stress is less than the yield stress, and a shearing region of complex composition close to the pipe walls ($R_0 < r < R$), where the shear stresses exceeds the yield stress τ_0. Here, r corresponds to a radial coordinate and R to the outer pipe radius. For fluid systems with a yield stress and presumed power-law behavior above the yield stress value, the Herschel-Bulkley model can be used

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{4}$$

Here, τ_0 is the yield stress, K the consistency index, $\dot{\gamma}$ the shear rate, and n, the flow exponent. Using the integrated form of this model, the radial velocity profile will be given by:

$$v(r) = \left(\frac{\Delta P}{2LK}\right)^{1/n} \cdot \frac{1}{1 + \frac{1}{n}} \cdot \left((R - R_0)^{1+(1/n)} - (r - R_0)^{1+(1/n)}\right) \tag{5}$$

where L is the distance between the pressure sensors. The critical radius R_0, which defines the outer boundary of the plug, is correlated to the yield stress according to

$$R_0 = \frac{2L}{\Delta P} \cdot \tau_0 \tag{6}$$

Mih and Parker[53] showed experimentally that the yield stress or so-called "disruptive shear stress" of pulp suspensions could be determined using this correlation.

Initial experiments performed by Wiklund et al.[41, 42] showed that it was possible to obtain plug radius and thus rheological data, such as the yield stress, using the UVP-PD method for cellulose pulp systems of consistencies up to 3% (w/w). This is often not possible using conventional rotational off-line rheometers due to compression and drainage of the sample in the measuring geometry. In this work, the UVP-PD method[39, 48, 54-57] was applied to determine the plug radius R_0 and, thus, the yield stress using the left half or that is, the near transducer side of the velocity profiles obtained using UVP and pressure drop data, ΔP.

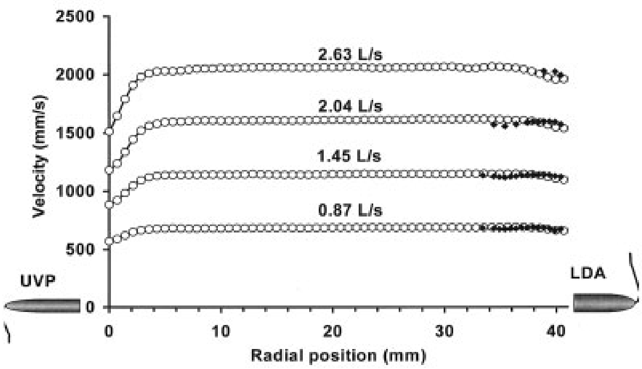

Figure 4. Velocity profiles for pulp consistency 1.9%(w/w) at volumetric flow rates; 0.87, 1.45, 2.04 and 2.63 L/s from bottom to top.

UVP (open circles) and LDA (filled diamonds).

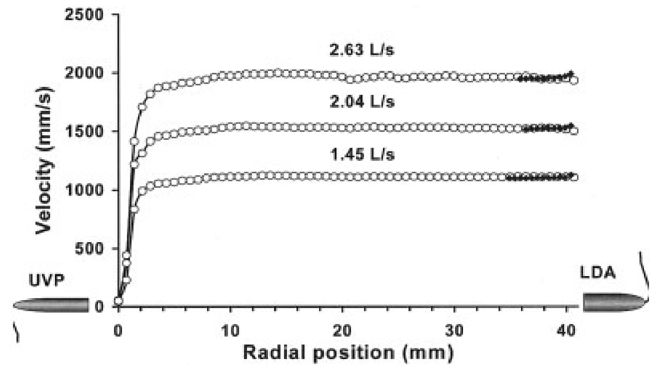

Figure 6. Velocity profiles for pulp consistency 6.0%(w/w) at volumetric flow rates; 1.45, 2.04 and 2.63 L/s from bottom to top.

UVP (open circles) and LDA (filled diamonds).

The magnitude of the plug radius R_0 was initially estimated for all flow rates from the time-averaged velocity profiles, by studying when the velocity in each channel reached 90% of the plug velocity. This value was chosen based on the velocity resolution of the UVP. The obtained plug radius values R_0, and the average pressure drop ΔP that corresponded to each volumetric flow rate were then used in the nonlinear fitting method employed for evaluating the Herschel-Bulkley parameters R_0, n and K. However, it should be noted that the Herschel-Bulkley model should be used with caution for suspensions where a concentration gradient may exist and where one also might find a region of mixed flow near the wall. The yield stress τ_0 was finally calculated using Eq. 6.

Results and Discussion

The measured axial arithmetic mean velocity profile data from both the UVP, and the LDA method are presented, compared and discussed for the different pulp consistencies and flow rates. LDA and UVP transducer positions are included and indicated in Figures 4–8 for clarification. Important issues regarding the use of the two methods in pulp suspensions are discussed. Finally, results from the rheological and pressure drop analysis are presented and discussed.

Velocity profiles - General observations

Results from this study show that both the UVP and LDA methods were applicable to the investigated pulp systems. The measured plug velocities and profile data are shown in Figures 4 – 7 with both the UVP and the LDA results included in each figure. Results from four consistencies, 1.9, 4.4, 6.0 and 7.8%(w/w), are presented. As shown in Figures 4 – 8, it was possible to obtain a single instantaneous and complete velocity profile across almost the pipe test section using the UVP technique. It was also found that the LDA technique works even in strongly opaque systems like a 7.8%(w/w) pulp suspension with a sustained penetration depth of up to several millimeters, as shown in Figure 7.

When comparing the UVP and LDA velocity results over the range of investigated consistencies, it was found that the absolute values of the plug velocities agree well. Deviating results were, however, obtained in the near wall region which is discussed later.

Measurements were performed from opposite sides of the measurement section, but the agreement between LDA and

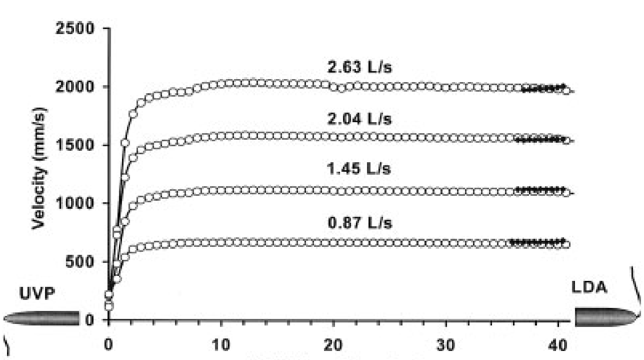

Figure 5. Velocity profiles for pulp consistency 4.4%(w/w) at volumetric flow rates; 0.87, 1.45, 2.04 and 2.63 L/s from bottom to top.

UVP (open circles) and LDA (filled diamonds).

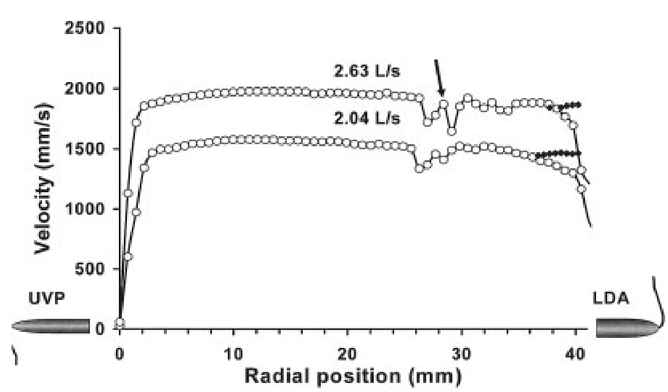

Figure 7. Velocity profiles for pulp consistency 7.8%(w/w) at volumetric flow rates; 2.04 and 2.63 L/s from bottom to top.

UVP (open circles) and LDA (filled diamonds).

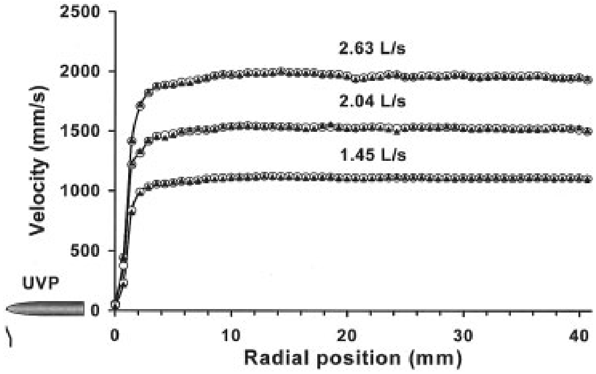

Figure 8. Arithmetic mean velocity profile over 1024 (open circles) and 10 sequential (filled tetrahedrons) velocity profiles for pulp consistency 6.0%(w/w).

Volumetric flow rates from bottom to top; 1.45, 2.04 and 2.63 L/s.

UVP results in the plug flow region therefore implies that the positioning of the UVP transducer and LDA probe should be of minor importance for the results in this study. The only discrepancy was observed at the highest concentration 7.8%(w/w) where the plug velocities were found to be slightly lower with the LDA method. However, the timescales for data acquisition are very different since UVP requires tenths of milliseconds compared to minutes for LDA. Nevertheless, since the results are from two different independent techniques, the agreement of the results implies that both methods give, indeed, accurate plug velocities for pulp suspensions. Volumetric flow rates obtained using a volumetric flow meter and the ones from the UVP method, obtained via integration of the left half of the radial velocity profiles, are presented in Table 2. These good agreements between these results further imply that accurate plug velocities were obtained using both methods.

Results further show that all investigated consistencies exhibited various degrees of plug flow behavior. The plug-flow region was found to be fairly constant with a plug radius R_0 of around 17.4 mm for all but the lowest concentration 1.9%(w/w), where it was slightly smaller. Our results from UVP data in this study show a large plug-flow region. Since the plug radius R_0 was found to be fairly constant, for all but the lowest concentration 1.9%(w/w) where it was slightly smaller, the result also strongly indicates the existence of a shear layer close to the pipe wall. The thickness of the layer was found to be in the order of a few mm with a possible fiber concentration gradient. The existence of such layer is consistent with earlier experiments by Wiklund et al.[41, 42] in pulp suspensions ranging from 0.5 up to 3%(w/w) using UVP.

The existence of such a layer is also supported by recent results from UVP velocity profile measurements.[46] In this work, a clear velocity gradient at the wall was found over some mm from the wall in pulp suspensions at consistencies ranging from 0.5 up to 1%(w/w). Dietmann and Rueff[47] also used UVP in pulp suspensions at consistencies up to 2.1%(w/w), but in this work steeper profiles near the wall was found at corresponding flow velocities. However, when the flow rate was increased a pronounced velocity gradient was found over several mm from the wall.

The existence of such a layer is further supported by results from NMR imaging experiments. NMR imaging results obtained by Li et al.[3, 16-18] in pulp suspensions with low consistencies, up to 0.86%(w/w), supports the implication of the existence of such a shear layer with a concentration gradient, in the order of a few mm. However, the highest pulp concentration analyzed by NMR imaging so far in literature was 3%(w/w) by Seymour et al.[19] as far as known by the authors. In this work, velocity profiles were obtained using NMR imaging in 3%(w/w) pulp, but also in a 6.3%(w/w) tomato pulp. The plug radius was determined for both systems. A shear layer in the order of a few mm, with large velocity gradients in the region closest to the pipe wall, were observed for the 6.3%(w/w) tomato pulp,. In this study, no velocity gradient in the region closest to the pipe wall the in the 3%(w/w) pulp was detected. However, the thin water annulus formed around the plug region was expected. The velocity resolution in the region close to the pipe walls was however limited in this study using the NMRI technique.

The existence of a fiber concentration gradient from the wall and a few mm into the pulp suspension is also further supported by earlier measurements by Pettersson et al.[58]. They presented velocity profiles up to a couple of millimeters from the walls that were obtained using LDA. The results further indicated a thickness of the shear layer of less than one mm. Results from this study shows that there are discrepancies between velocities obtained in near wall region using UVP and LDA, just as what has been found when comparing different studies in the liter-

Table 2. Experimental Results for Pulp Consistencies 1.9–7.8%(w/w)

Consistency % (w/w)	Flow Rate (dm^3/s)	Flow Rate − UVP (dm^3/s)	$\Delta P/L$ (kPa/m)	R_0 (mm)	τ_0 (Pa)	n	K	R^2
7.8	2.63	2.39	35	17.5	302	0.11	166	0.94
	2.04	2.10	20	17.4	177	0.09	114	0.98
6.0	2.63	2.43	18	17.3	159	0.10	91	0.95
	2.04	1.91	16	17.3	138	0.09	88	0.94
	1.45	1.39	14	17.4	122	0.09	79	0.94
4.4	2.63	2.62	7	17.4	61	0.09	38	0.96
	2.04	2.09	8	17.4	73	0.08	49	0.98
	1.45	1.47	6	17.4	51	0.08	34	0.98
	0.87	0.72	6	17.2	52	0.11	33	0.97
1.9	2.63	2.65	1.6	16.1	13	0.10	8	0.99
	2.04	2.10	1.9	16.6	16	0.09	10	0.99
	1.45	1.46	2.2	16.0	17	0.09	12	0.95
	0.87	0.89	2.1	16.8	17	0.07	14	0.86

ature. This implies that it is important to perform more work on the area in order to discover the source of these discrepancies and to be able to account for possible measurements errors using both techniques.

UVP in pulp suspensions

Results in this study obtained using the UVP method also show, for example, in Figure 4, a decrease in penetration depth toward the pipe wall on the far side, and the effect of various measurement artifacts. This resulted in velocity fluctuations close to the pipe wall or apparent constant plug behavior of the velocity profile, in which the velocity gradient information is lost from the center of the pipe toward the far end wall from the transducer. This is clearly visible in Figures 4–6. Consequently, all velocity profiles were truncated at the last measuring volume that originated from a position inside the pipe measurement section. The various factors and artifacts which all influence the quality and shape of velocity profiles obtained using the UVP method are discussed in detail below.

Effects of interfaces and multiple reflections on UVP velocity profiles

Fixed and moving interfaces are known to reflect and modify the shape of the emitted pulses and the acoustic field. The intensity of the acoustic field received from a location inside the flowing suspension depends on the material, the shape and the number of these interfaces along the beam path. In addition, ultrasonic waves reflected multiple times inside a solid wall interface enlarge the ultrasonic beam inside the flowing suspension and modify its shape. These reflections, thus, make it more difficult to accurately predict the exact size, and the shape as well as the location of the measuring volume when performing noninvasive measurements through multiple interfaces or thick wall materials.

In most commercial software, such as the one provided with the UVP equipment used in this study, the ultrasound refraction and velocity difference at interfaces and in different media are not taken into consideration.[59] Despite this, instantaneous radial velocity profiles were nevertheless obtained through noninvasive measurements through a 5 mm thick PMMA measurement section using the UVP technique in this study. The possibility to perform noninvasive measurements in pulp suspensions using UVP, at consistencies ranging from 0.74%(w/w) up to 7.8%(w/w) is, thus, illustrated with results from the four highest consistencies in Figures 4–8.

The irregular shape of the ultrasonic pulse beam in the near-field region close to the transducer make the results less reliable in some cases if measurements are performed within this region. In this study, the focal point was therefore positioned as close to the wall-liquid interface inside the tube as possible, and this effect was, therefore, minimized.

Forward scattering is always present in fluid systems containing a large number of scattering particles. Ultrasound is forward-scattered by a moving scattering particle (fibers in this case) contained in the flowing suspension toward the far pipe wall interface where it is then reflected back toward the transducer. Since the reflected ultrasound waves still propagate within the test medium, the flow velocity is detected a second time. The distance associated with the received echo from the ultrasound path from transducer to scattering particle to far pipe wall interface and back to the transducer is, therefore, associated to an incorrect position that might even be located outside the flowing liquid.[59] The effect becomes more pronounced near the far pipe wall with higher concentration of scattering fibers. As a result, the velocity gradient could be smoothed at the far wall, as shown in Figures 4–6, simply due to the experimental settings used where contribution from several "imaginary" velocity components could be misinterpreted as a single velocity. Therefore, it is very common to obtain nonzero velocities, and the apparent constant plug behavior toward the far wall, as shown in the presented Figures 4-6, with the UVP method in systems containing a large number of scattering particles. However, too high amplification of the received signal (discussed in the following section) could cause the same effect, and is believed to have had the biggest impact on the shape of the obtained velocity profiles toward the far pipe wall.

It was also observed in this study that the UVP transducer was sometimes shifted slightly from its position at the centerline of the measurement section due to mechanical vibrations. Consequently, the scattering and multiple reflection effects were even more pronounced in some cases. Since all of the velocity profiles in Figures 4–6 exhibited constant plug behavior toward the far end wall from the transducer it is reasonable to believe that multiple reflections influenced the shape of the velocity profiles in this region. Furthermore, multiple reflections from the pipe walls are also believed to have caused the local drop in velocity, indicated by an arrow in Figure 7. The same phenomena was observed for both volumetric flow rates at the highest concentration 7.8%(w/w) and is, thus, considered to be a measurement artifact rather than a decrease in penetration depth due to absorption of ultrasound energy.

The ultrasound pulse beam diverges slightly and some negative effects due to divergence and spectral broadening[60, 61] might have contributed very slightly to the partial loss in velocity gradient resolution and introduced unreliable velocity components toward the far end wall from the transducer. This is primarily true if several fibers moving with different velocities were occupying the measurement volume at the same time. However, this effect is assumed to be of minor importance in this study since measurements were performed over a very limited distance.

Effects of UVP hardware, software, parameters and transducers

The quality of the obtained velocity profile strongly depends on the basic frequency of emitted ultrasound, the operational voltage, the number of cycles per pulse and the signal amplification. In this study, a 2 MHz transducer was used since a lower frequency would have increased the penetration depth toward the far side from the transducer, but significantly lowered the spatial resolution. A higher basic ultrasound frequency of 4 MHz was tested, which would have increase the spatial resolution, but the penetration depth was then significantly lowered. The opposite generally applies to the number of cycles per pulse used. In order to minimize the thickness of the measurement volume and thus also to avoid the possibility of several pulp fibers occupying the measurement volume the number of cycles per pulse was set to 2 in this study. However, the minimum number of cycles per pulse that can be used without losing signal quality, or characteristics strongly depends on the transducer characteristics and the acoustic properties of the investigated system.

As shown in Figures 5–8, a 2 MHz transducer working at the highest allowed voltage was found to be optimal for the investigated pulp suspensions as the main focus was to try obtaining a good signal from close to the pipe wall and throughout at least half the pipe diameter.

As discussed earlier, it was expected to see the local velocity reaching zero at both sides of the pipe as has been found with, for example, NMR imaging for lower consistencies up to ~1%(w/w). In this case, the UVP profile data presented in Figures 4–6 and 8 suggest otherwise, but can be explained since mainly high amplification of the incoming echo signal from the far side of the pipe was used in order to sustain the penetration depth across the entire pipe diameter. Surprisingly, it was found that the velocity approached zero near the wall at both sides of the pipe for the final experiments at the highest pulp consistency. For this consistency, the amplification levels used were apparently more in the optimal range. This is clearly shown in Figure 7. A further analysis of the data thus suggests that too high amplification levels of the signal were most likely used for the three lowest consistencies presented in Figures 4–6. This unfortunately affected the profile shape on the far transducer side, resulted in the apparent constant velocity effect and strongly contributed to the local velocity not reaching zero at the far side of the pipe. Consequently, the data suggests that too high amplification levels of the incoming echo signal from the far side of the pipe and not multiple scattering effects had the strongest influence on the shape of the obtained velocity profiles.

In addition, the time-averaged UVP velocity profiles presented in Figures 4–8 also appear to be slightly wider than the actual pipe as a result of the effects discussed earlier. The illusion of velocity profiles being slightly wider than the actual pipe could also be caused by error in sound velocity and Doppler angle determination. However, when comparing the UVP, LDA and flow rate data it was found that the absolute values of the plug velocities agree very well. This implies that correct sound velocity values and Doppler angles were indeed used when calculating the velocity and radial distance. In addition, one must introduce a large error in Doppler angle determination in order to explain broadened profiles due to an incorrect Doppler angle. Further investigations are needed to fully explain, predict and accurately compensate for mentioned effects when the UVP method is applied to pulp suspensions of high consistencies.

Time-averaging effects on UVP velocity profiles

Figure 8, which corresponds to a pulp concentration of 6.0%(w/w), clearly demonstrates that it was possible to obtain instantaneous velocity profiles across the pipe test section with high accuracy using the UVP technique with just a few tenths of milliseconds between each successive profile. Results in Figure 8 indicate that an arithmetic average of 10 randomly selected, sequential profiles describes the plug flow behavior in great detail, and that only slightly improved profiles are obtained if more profiles are used in arithmetic average calculations. Time-averaging effects could also explain the small discrepancies between the volumetric flow rates listed in Table 2 since the UVP measurements were performed over a very limited period of time compared to the total measurement time.

LDA in pulp suspensions

The LDA technique is generally known to require a transparent system. Nevertheless, velocity data was still obtained from some distance into the apparently opaque pulp suspension. In the consistencies presented in the figures, a maximum penetration depth of up to 7 mm was achieved. However, in a suspension as high as 7.8%(w/w) the penetration depth was reduced to 3-4 mm, as shown in Figure 7. The explanation for this is that even though these pulp suspensions, at first sight, look more or less opaque, they contain only a couple percent of fibers by volume, and the rest is water. This means that the laser beams can reach some mm into the suspension by means of passing between the fibers. What happens is somewhat similar to ordinary LDA measurements of water when the water is seeded with particles that have a rather low concentration. If the seed particle concentration is increased, there will be a loss in penetration depth, but the measurements performed will still be correct. In the pulp suspension case, the fibers can be seen as seed particles at a high concentration, thus, giving a penetration depth in the order of millimeters. However, results from this study also showed that the LDA method was not able to detect the expected velocity gradient or that is, a shearing region close to the pipe wall and the reasons for this remain unclear and requires further investigations.

Rheological modeling

The left half that is the near transducer side of the recorded UVP velocity profiles were used for the rheological analysis. In Table 2, the pressure drop, the plug radius R_0, yield stress as well as fitted parameters are presented together with goodness of fit values, R^2, as an indication of the accuracy of the nonlinear regression. In this study, the goodness of fit values were found to be $R^2 \geq 0.94$ using the Herschel Bulkley model, which at a first glance suggests that the model is suitable for pulp suspensions. Results show that the pulp suspensions are highly shear-thinning with a flow index n equal to approximately 0.1, for all investigated consistencies. Results further show that the obtained flow index values were more or less constant for all flow rates which is consistent with findings by for example, Wiklund et al.[41, 42] for the 3%(w/w) pulp suspension investigated in mentioned publications.

As discussed earlier, the plug-flow region was found to be fairly constant with a plug radius R_0 of around 17.4 mm, except for the lowest concentration 1.9%(w/w) where it was slightly smaller. The accuracy of the smallest velocity gradients near the pipe center was however limited by the velocity resolution of the UVP. When the velocity resolution is comparable in size to the difference in velocity of two neighboring measurement volumes, it is difficult to accurately measure the shear rate[45] and, thus, also to determine the plug radius R_0. The magnitude of the plug radius R_0 is directly coupled to the pressure drop and the yield stress, which should be independent of flow rate and only change with fiber concentration. However, the yield stress varied slightly with flow rate in these experiments, especially for the highest concentration 7.8%(w/w), as shown in Table 2. Fluctuations in pressure drop were in this case pronounced and these fluctuations, thus, influenced the magnitude of the yield stress and consistency index K, which generally increased slightly with increasing concentration and flow rate. The consistency index values should, therefore, be taken with caution. The difference in yield stress at the highest concentration (7.8%) is, thus, believed to be caused primarily by fluctuations in pressure drop rather than in determining the R_0 accurately enough at this concentration. Consequently, the reason for the variation in yield stress with flow rate, especially at the highest concentration is assumed to be experimental errors in the pressure measurements.

Comparing the obtained yield stress values with comparable data from the literature, that is, based on measurements with similar measuring method, pulp quality and consistency, rather good agreements was found. In this work, the yield stress for the 1.9%(w/w) was found to be approximately 16 Pa. Soszynski[62] presented yield stress results for consistencies of 1.30 and 2.93%(w/w) with approximately 4 Pa and 23–42 Pa depending on the flow velocity. Dietemann and Rueff [46] obtained a rather lower yield stress of 9.5 Pa for pulp consistency at 2.1%(w/w), which could be explained by the rather short fibers used. Raiskinmäki and Kataja[45] presented measurements of 2.0%(w/w) of pine with a yield stress of about 22 Pa. Pettersson et al.[58] performed measurements in comparable 2.0%(w/w) pulp and found that the yield stress to be in the range of 15–19 Pa. Thus, rather good agreement with literature data was found.

Note also that the obtained yield stress values should be taken with caution due to phase separation effects. As discussed earlier, the results suggest the existence of a fiber concentration gradient with more or less constant thickness from the wall and a few mm into the suspension, which is also consistent with earlier measurements by Pettersson et al.[58] In practice, our results further imply that the shearing region close to the pipe wall is quite thin, in the order of mm, as shown in Figure 5. It, thus, becomes quite difficult to describe such systems using, for example, the Herschel-Bulkley rheological model. Consequently, the results show that the UVP method can be used to evaluate the plug radius R_0 and to obtain rheological parameters, such as the yield stress and flow exponent n, from a nonlinear regression using experimental data and, for example, the Herschel Bulkley model. However, a closer evaluation of the results suggest that this and similar models do not unambiguously describe the flow of pulp suspensions.

Pressure drop

Pressure drop measurements and the graphs of pressure drop as a function of flow velocity can be used to indicate what type of flow that is achieved for pulp suspensions in pipe flow. Such measurements can be found in the literature,[62, 63] and the graphs of pressure drop as a function of flow velocity have an S-shape (given constant concentration), that is, an initial increase in a local maximum continued by a decrease in a local minimum, followed by a continuing increase. However, the graphs in Figure 9 are not S-shaped. The reason is that the graphs in Figure 9 are from different regions of the S-shaped curve. If the concentration is increased, each region in the S-shaped profile, that is, for instance the local maxima and minima, will turn up at higher velocities. Therefore, the graphs of different consistencies in the figure will be (different) regions of the S-shaped curve.

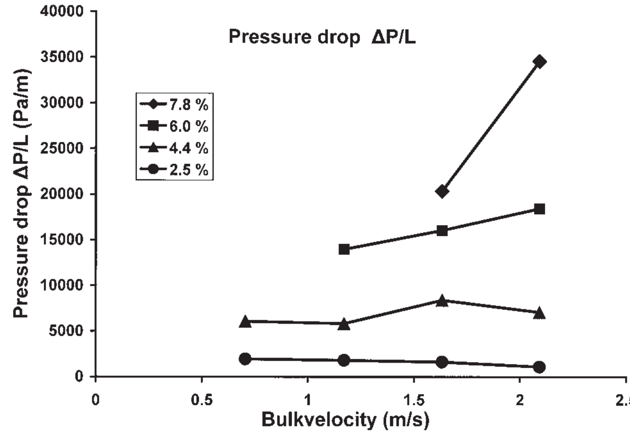

Figure 9. Pressure drop vs. the bulk velocity for constant pulp consistency.

The 7.8%(w/w) concentration is in the region of the increase before the local maximum, the 6.0%(w/w) is just before the maximum, in the concentration of 4.4%(w/w) the maximum can be detected and 2.5%(w/w) is just after the maximum. Soszynski[62] has presented a great deal of data from the literature, and one set of data was for pulp at a concentration of 2.26%(w/w), which agrees very well with the measurements here for the concentration of 2.5%(w/w). The pulp referred to and the pulp used in this investigation was comparable in, for example, fiber length, type of production (for example, kraft pulp) and, of course, concentration. Unfortunately, this was the only comparable data found in the literature and Figure 9 could, thus, not be plotted showing a full set of measurements (consistencies ranging from ~2 to 8% (w/w). In the literature,[63] the region before the local minimum was found to be plug flow, while the region after the minimum is called transient flow and is followed by turbulent flow. Figure 9 shows that all tests were performed in the plug flow region which was also found when studying the velocity profile measurements.

Conclusions

In this study, it was shown that both LDA and UVP techniques can be used with good agreement to measure accurate velocities in pulp suspensions of much higher consistencies than what has been reported so far in the literature. For the first time, noninvasive measurements in pulp suspensions at consistencies ranging from 0.74%(w/w) up to 7.8%(w/w) were performed simultaneously using LDA and UVP techniques in an experimental pipe flow loop. No special seeding particles were necessary as the pulp fibers were found to work sufficiently for both LDA and UVP techniques.

Furthermore, results show that the UVP technique could be optimized in such way that velocity gradient information close to the pipe wall could be obtained, and with a sustained penetration depth even for the highly concentrated 7.8%(w/w) pulp suspension. The demonstration of LDA as a possible measuring technique, with a sustained penetration depth of up to several millimeters for these seemingly opaque systems like a 7.8%(w/w) pulp suspension, will offer LDA as an option in research on pulp suspensions. It was further shown that the UVP method can be used to evaluate the plug radius R_0 and to obtain rheological parameters, such as the yield stress and flow exponent n, in-line, from a nonlinear regression using experimental data and, for example, the Herschel Bulkley model. However, a closer evaluation of the results suggest that this and similar models do not unambiguously describe the flow of pulp suspensions. Nevertheless, the UVP-PD method might be feasible and powerful in-line method in the future for pulp suspensions of high consistencies that is, above 1-2% (w/w) since it can provide important information about the plug radius and, thus, be used to determine the yield stress directly in-line.

Results from this study showed that there are discrepancies between velocities obtained in near wall region using UVP and LDA, but also between different studies in the literature. Thus, studying the shearing region with a supposed fiber concentration gradient close to the pipe wall becomes important if rheological modeling of pulp suspensions is to be made. More work is, thus, needed on pulp suspensions of high consistencies.

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Notation

- c = sound velocity, m/s
- d = diameter of UVP measuring volume, m
- f_0 = basic ultrasonic frequency, MHz
- h = thickness of UVP measuring volume, m
- K = consistency index, Herschel Bulkley rheological model
- L = distance between pressure sensors, m
- n = flow exponent, Herschel Bulkley rheological model
- N = number of ultrasonic cycles per pulse
- ΔP = pressure drop, Pa
- r = radial coordinate, m
- R = pipe radius, m
- R_0 = plug radius, m
- v = velocity, m/s

Greek letters

- α_1 = transducer inclination angle
- α_2 = angle between direction of flow and measurement axis
- $\dot{\gamma}$ = shear rate, 1/s
- θ = Doppler angle
- τ = shear stress, Pa
- τ_0 = yield stress, Pa

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