A COMPARATIVE STUDY BETWEEN UVP AND LDA TECHNIQUES FOR HIGHLY CONCENTRATED PULP SUSPENSIONS IN PIPE FLOW

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ABSTRACT

UVP and LDA techniques have been used simultaneously to perform velocity profile measurements in highly concentrated pulp fibre suspensions. Experiments were carried out non-invasively through a 5 mm thick Polymethyl methacrylate, (PMMA), pipe measurement section in an experimental pipe flow loop. Pulp suspension concentrations ranging from 0.74 %(w/w) up to 7.8 %(w/w) were analyzed at four different volumetric flow rates. Instantaneous radial velocity profiles showing pronounced plug-flow behavior and sharp velocity gradients close to the pipe wall were obtained using the UVP technique. Results show that both techniques can be used with good agreement and that accurate velocities thus were obtained in much more concentrated pulp fibre suspensions than what has been reported so far in the literature. Results further show that the LDA technique can work even in strongly opaque systems such as a 7.8 %(w/w) pulp suspension with a sustained penetration depth of up to several millimeters, but with loss of velocity gradient information at high concentrations.

Keywords: *UVP, LDA, velocity profile, pulp, fibre, non-invasive, plug-flow*

1. INTRODUCTION

Pulp suspensions are very complex opaque aqueous systems which contain regions of relatively high fibre concentration called flocs. These tend to form a continuous network structure throughout the suspension above a certain critical concentration and shear rate. The chemical and physical complexity has led to the fact that the relationship between the applied stress and microstructure (rheology) during flow remains poorly understood, despite extensive study for nearly half a century, according to Li et al. [11].

Pulp suspensions are subjected to strong shear forces during processing and detailed knowledge about the flow properties are in fact essential for controlling a modern pulp process.

Competition in the paper pulp industry has increased over the past years. The annual turnover currently surpasses many other industrial branches in countries such as Canada and Sweden. The ability to develop innovative and new competitive products also largely depends on the ability to understand and control the manufacturing process. Since the velocity profile contain the shear rate information, it is thus of great importance if it can be measured. Nevertheless, very little reliable data on velocity profiles in concentrated pulp suspensions during pipe flow can be found in literature.

Until recently, it has been difficult to determine instantaneous radial velocity profiles under actual process conditions. Various flow visualization, as well as sophisticated particle tracking/imaging velocimetry techniques has been continuously improved in the academic field. However, most of them still require extensive experimental know-how; require rather time consuming data acquisition; are essentially limited to transparent fluids and are not applicable to pulp fibre suspensions at concentrations outside the dilute range.

The optical point-wise Laser Doppler Anemometry (LDA) technique [5], the Nuclear Magnetic Resonance Imaging (NMRI) method based on the paramagnetic properties of the nuclei [4], and the Ultrasonic Velocity Profiling (UVP) technique, which employs the pulsed Doppler echo method, [24-26], constitute some of the most promising techniques for pulp suspensions.

NMRI has been used for measuring time-averaged velocity profiles of dilute pulp suspensions, [11-14], in up to 0.86 %(w/w) fibre concentration. Some drawbacks of the method used were, compared to UVP and LDA, expensive equipment and long observation times. More differences between these three techniques are discussed e.g. in [3].

Arola et al. [2], 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. [20] performed measurements of time-averaged velocity profiles in the steady flow of more concentrated 3 %(w/w) pulp suspensions using NMRI. At present, NMRI is not likely going to be implemented in industrial applications.

LDA was used by [6], to investigate air containing low concentrations of pulp in pipe flow. Kerekes et al. [10], studied water-pulp suspensions of 0.5 %. Steen, [21-22], later used transparent model pulp suspensions in order to study higher concentrations, 1.2 and 12 grams of fibres per liter in pipe flow. The same model system were later used by both [1] and [17-18] where measurement were also performed in a stirred tank using concentrations ranging from 3-20 %(w/w).

Few studies with comparative LDA and UVP results can be found in the literature. Some examples are [27], [28], [33], [19] and [16].

The UVP technique has been extensively used over the past few years to obtain instantaneous velocity profiles, but very few studies on pulp suspensions can be found in the literature. Hirsimäki, [7], used an early ultrasonic profiling technique to obtain radial velocity profiles in pulp suspensions of concentrations up to 1 %(w/w). Karema et al. [8-9], characterized velocity fluctuations and studied paper formation by fluidization and reflocculation in wood pulp suspensions of concentrations up to 1 %(w/w) using UVP.

Wiklund et al. [30-31], obtained instantaneous velocity profiles in a steady laminar flow of 0.5-3 %(w/w) and later up to 7.8 %(w/w) paper pulp suspensions using UVP. Rheological data were obtained using non-linear regression analysis and the integrated form of the Herschel-Bulkley model and pressure drop data.

The aim of the present study was to perform velocity profile measurements non-invasively using UVP and LDA in highly concentrated, opaque aqueous pulp suspensions in pipe flow. A further aim was to evaluate the use of the techniques in this type of suspension through comparison.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 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 65-70 %(w/w) spruce. The pulp suspension taken from the mill had a concentration of about 18 %(w/w) of fibres. Fibre length measurements showed that the fibres were not milled during the pipe flow experiments and that the length-weighted mean fibre-length was about 2.4 mm. The tests were performed on two different occasions, with 0.61, 1.0, 1.9, 2.4 and 3.8 %(w/w) in fibre concentration during the first sequence and 0.74, 2.5, 4.4, 6.0 and 7.8 %(w/w) during the second one. During the first test sequence the concentration was changed by adding more of the concentrated 18 %(w/w) pulp. In the latter test sequence with higher concentrations, the concentrated pulp was diluted to 7.8 %(w/w) and lower concentrations in smaller vessels by adding water when the concentration was changed before being placed in the tank.

2.2 Experimental flow loop and Set-up

The experimental set-up and procedure is described in detail in [31]. However, relevant details are given here. The experimental flow loop consisted of a closed circulation system containing a tank, a pulp screw pump, stainless steel pipes, a contraction and finally a smaller pipe made of Polymethyl methacrylate (PMMA), which constituted the measurement section, 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.

The PMMA pipe section had an inner diameter of 40 mm, a wall thickness of 5 mm and a total length of 50 cm. the UVP transducer was mounted at an inclination angle above the pipe inside the surrounding box fluid. 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 and reflections were thus decreased.

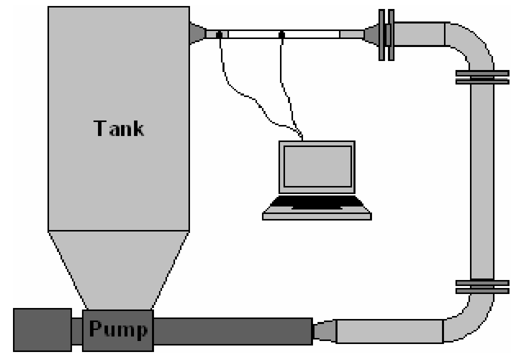

Figure 1. Schematic of the experimental flow loop.

The ultrasonic and laser beams were arranged so that the intersection between the beams was as close as possible to the centre of the pipe. Temperatures in the surrounding box and the test section were kept as equal as possible, 22-24ºC, in order to minimize differences in sound velocity and thus the acoustic impedance between the box fluid and the continuous phase in the suspensions studied.

UVP/LDA velocity measurements were performed, 70 mm from the tank inlet (i.e. upper left side of the PMMA pipe test section in figure 1). The pressure drop over the measurement section was measured continuously and the pressure gauges used ranges from atmospheric pressure up to 4 bar overpressure with an error of 0.5 % of the higher limit.

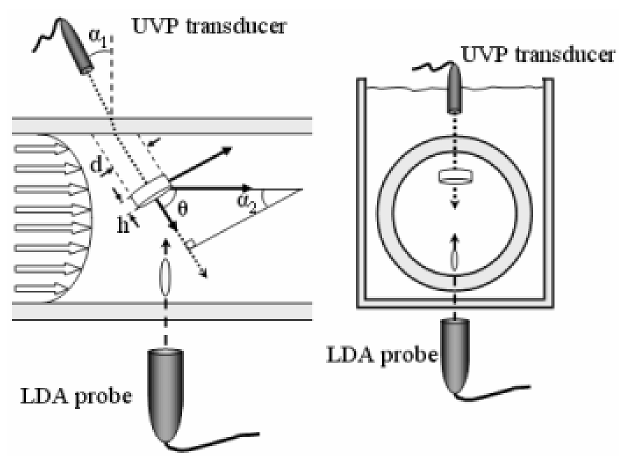

Figure 2. Schematic of the measurement section, ultrasound transducer and LDA probe configuration.

2.3 UVP and LDA equipment and Parameters

The UVP-DUO-MX Monitor with Multiplexer and software, version 3.0 from Met-Flow SA, Switzerland was used in this study. The UVP instrument was connected to a master PC for data acquisition, analysis and post-processing of raw data. Emitted ultrasonic pulses and the received echo were continuously monitored using a digital oscilloscope, Agilent Technologies, model 54624A, USA.

The Laser Doppler Anemometry instrument utilized in these experiments was a DANTEC FiberFlow Series 60X, Denmark, connected to two Burst Spectrum Analysers (BSA), i.e. 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.

Table 1: Experimental UVP and LDA parameters

Ultrasound frequency	2 MHz
Number of cycles per pulse	2
Active element diameter	10 mm
Pulse repetitions per profile	90
Number of recorded channels/profiles	110 -128 / 1024
Number of recorded profiles/flow rate	1024
Sound velocity	1485-1531 m/s
Doppler angle in suspensions	68.5-73°
Spatial resolution in suspensions	0.74 - 0.77 mm
Time resolution (single profile)	24-54 ms/profile
Pulse repetition rate	2.2 KHz - 6.2 KHz
Velocity resolution	10-24 mm/s
LDA measurement volume in suspension (radial direction)	950 µm
Number of LDA repetitions per point	5000

2.4 Experimental procedure

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/s. The test sequences started with the lowest flow rate and were then increased during the experiments at each concentration. UVP and LDA data acquisition were triggered simultaneously but UVP data acquisition was much faster. The wall positions and thus the first and last UVP channel number located inside the test pipe section were determined from a procedure that involves monitoring the echo amplitude, velocity gradient and several statistical steps in each recorded channel over time.

A few correction procedures of the effect on measurement volumes at the wall-liquid interface have recently been suggested by [32], [15] and [23] but they are still under debate. This effect and the effect of the curvature of the tube wall were therefore neglected in this study, the latter in accordance with mentioned papers.

In order to reduce the signal noise induced by e.g. mechanical vibrations, a statistical procedure was employed in which fluctuations larger than two standard deviations from the median value in each channel were removed. Arithmetic time-averaged velocity profiles were then calculated from the remaining radial velocity profiles.

3. RESULTS AND DISCUSSION

The applicability and limitations of LDA technique for investigated pulp suspensions is discussed. The velocity profiles obtained using UVP and LDA as well as key findings from using the techniques are then presented, compared and discussed for the investigated flow rates and concentrations.

3.1 LDA applicability in pulp suspensions

The LDA technique requires a transparent system, but correct measurements are still performed some distance into the apparently opaque pulp suspensions. In the concentrations 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 6. The most reasonable explanation for LDA to work in this system is that even though these pulp suspensions, at first sight, look more or less opaque, they contain only a couple percent of fibres by volume, and the rest is water. This means that the laser beams can reach some millimeters into the suspension by means of passing between the fibres. 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 performed measurements will still be correct.

3.2 General comparative results for the pulp suspensions

When comparing the UVP and LDA results over the range of investigated concentrations, it was found that the absolute values of the velocities agree well. This is clearly shown in Figures 3-6. The velocity gradient information in the recorded velocity profiles on the UVP transducer side were clearly visible for all investigated flow rates, but completely lost in the LDA measurements for all but the lowest concentrations. It was also found that all investigated suspensions exhibited various degrees of plug flow behavior and as the flow rate decreased, the plug-flow region increased in size, that is, larger plug radius R_0 for all but the highest concentration 7.8 %(w/w). A decrease in the plug-flow region was also found as the concentration decreased.

Since the obtained velocities from two different independent techniques (UVP and LDA)agrees very well with those calculated from volumetric flow rate measurements, the obtained results implies that both techniques give, indeed, accurate velocity results for the investigated pulp suspensions.

However, the results also show, e.g. in Figures 4-6, a decrease in penetration depth for LDA and the effect of various artifacts (discussed below) for the UVP method.

3.3 Flow behavior at < 2 %(w/w) pulp concentrations

Good agreement for the two techniques in the shape of the velocity gradient close to the far end wall from the UVP transducer side was found for low concentrations and high flow rates in this study, as shown in Figure 3.

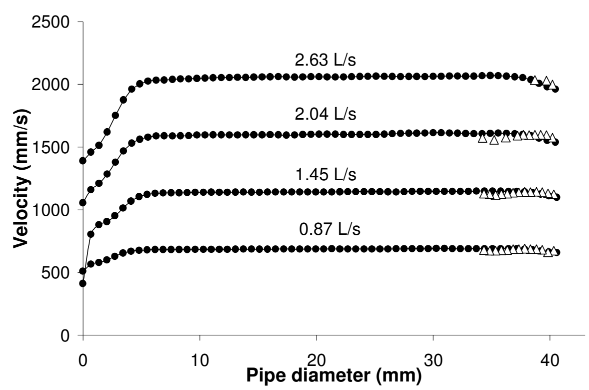

Figure 3. Velocity profile data for 1.9 %(w/w) pulp suspension for four volumetric flow rates. UVP (filled circles) and LDA (open triangles).

However, the velocity gradient information in the recorded velocity profiles on the UVP transducer side were quite distorted for the lowest flow rates, but less for the two highest flow rates. This effect was difficult to account for but mechanical vibrations were observed in this experiment which may have pushed the UVP transducer slightly from its optimal position in such way that the first points close to the wall were actually recorded within the near field zone. This effect may also have been caused by wall effects, but no such phenomena were observed for other concentrations and flow rates.

3.4 Flow behavior at 4-6 %(w/w) pulp concentrations

When comparing the UVP and LDA results over the intermediate concentration range, it was found that the absolute values of the velocities agree very well. This is clearly shown in Figures 4-5. The velocity gradient information in the recorded velocity profiles on the UVP transducer side were clearly visible for all investigated flow rates, but completely lost in the LDA measurements.

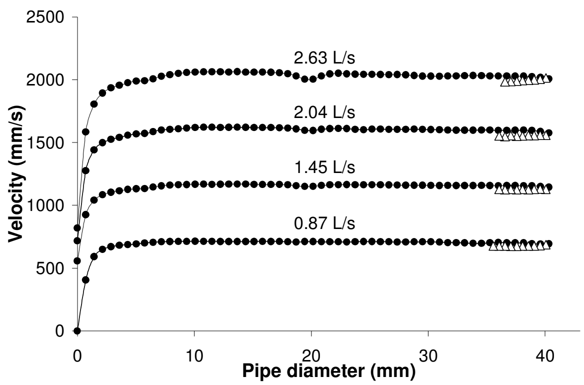

Figure 4. Velocity profile data for 4.4 %(w/w) pulp suspension for four volumetric flow rates. UVP (filled circles) and LDA (open triangles)

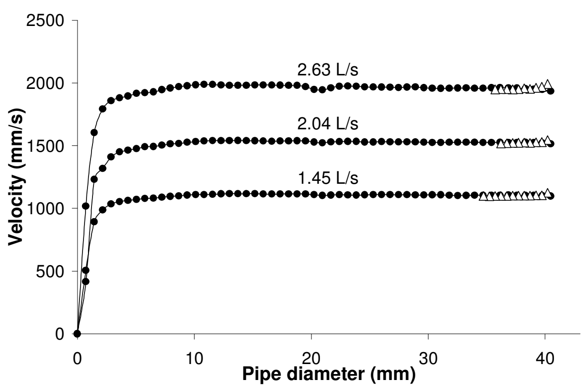

Figure 5. Velocity profile data for 6.01 %(w/w) pulp suspension for three volumetric flow rates. UVP (filled circles) and LDA (open triangles)

It was also found that investigated suspensions in this concentration range exhibited pronounced plug flow behavior. As the flow rate decreased, the plug-flow region increased in size, that is, larger plug radius R_0.

In addition, the results also showed the effect of various artifacts for the UVP method which resulted e.g. in a visible constant plug behavior of the recorded velocity profile, in which the velocity gradient information is lost towards the far end wall from the transducer side.

3.5 Flow behavior at >7.8 %(w/w) pulp concentrations

Pronounced plug flow behavior was also found for the highest pulp concentration of 7.8 %(w/w), as shown in Figure 6. It is interesting to note that the plug-flow region seemed to decrease in size (smaller plug radius, R_0) as the flow rate decreased for this concentration, which is in contrast to lower concentrations.

Furthermore, the local drop in velocity for both volumetric flow rates which is indicated by an arrow in Figure 6, which corresponds to the highest concentration, is also believed to be a UVP measurement artifact. This artifact was most likely caused by, multiple reflections from e.g. the pipe walls and not caused by a decrease in penetration depth due to attenuation of ultrasound.

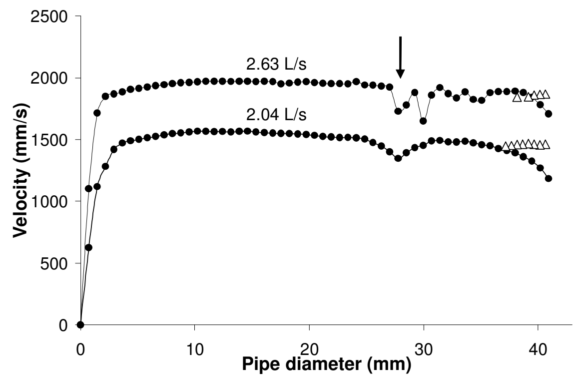

Figure 6. Velocity profile data for 7.81 %(w/w) pulp suspension for two volumetric flow rates. UVP (filled circles) and LDA (open triangles).

Although the velocity gradient information in the recorded velocity profiles on the far UVP transducer side was visible for both investigated flow rates, it was also influenced by wall effects and ultrasound attenuation. Therefore, especially in Figure 6, it would be more accurate to compare the LDA measurements with the UVP results from the opposite side of the pipe, i.e. close to the UVP transducer. Doing this, good agreements were found even at the highest concentration in absolute velocities.

3.6 Time-averaging effects on UVP velocity profiles

Figure 7, which corresponds to a pulp concentration of 6.0 %(w/w), clearly demonstrates that it was possible to obtain a single instantaneous and complete velocity profile across the pipe test section with high accuracy using the UVP technique for only a couple of milliseconds.

Results in Figure 7 indicate that an arithmetic average of 10 sequential profiles (open circles) describes the plug flow behavior in great detail and that only slightly better profiles are obtained if more ~1000 profiles (filled circles) are used in arithmetic average calculations. The trend was the same for all suspensions.

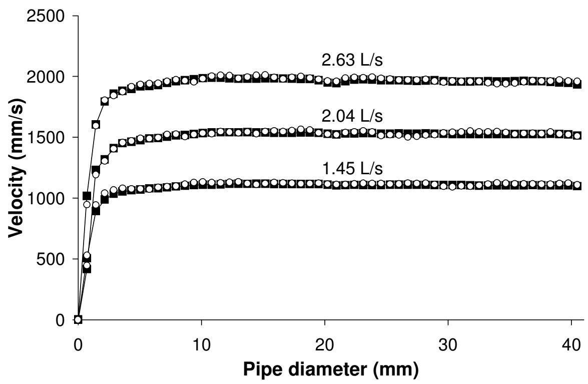

Figure 7. Arithmetic mean velocity profile data over ~1000 (filled circles) and 10 sequential (open circles) UVP profiles for 6.01 %(w/w) pulp suspension for three volumetric flow rates.

3.7 UVP related measurement artifacts and effects

As mentioned above, it was observed in this study that almost all of the obtained velocity profiles exhibited visible constant plug behavior throughout the pipe towards the far end wall from the transducer side. In this far region the velocity gradient information was lost. This artifact was most likely caused by e.g. multiple reflections from e.g. the pipe walls and the large number of scattering fibres and not by a decrease in penetration depth due to attenuation of ultrasound.

Fixed and moving interfaces reflect and modify the field of the acoustic pulse. In the wall region close to the transducer, multiple reflections by the wall and the irregular shape of the ultrasonic pulse beam in the near-field region may imply that the results are less reliable in this region in contrast to the LDA technique which does not suffer from this effect. 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.

However, mechanical vibrations were observed, e.g. for the lowest concentration which may have pushed the UVP transducer slightly from its optimal position in such way that the first points close to the wall were actually recorded within the near field zone. The non-zero velocity phenomenon and irregular shape of the velocity profile at the interface wall close to the transducer was therefore observed only for the 1.89 %(w/w) concentration in this study, as shown in Figure 3.

It is well known that the ultrasonic pulse beam can be forward-scattered by a moving seeding particle (fibre in this case) contained in the flowing suspension towards the far pipe wall interface. This acoustic energy is thus backscattered a second time in the direction to the transducer. The distance associated with the path transducer far pipe wall interface-scatterers is therefore located outside the flowing liquid. As a result, imaginary velocity components were most likely added to the real velocity profile, especially near the far pipe wall interface as pointed out by, e.g. Wang et al. [29].

The local drop in velocity for both volumetric flow rates indicated by an arrow in Figure 6, which corresponds to the highest concentration, is believed to be caused by this effect.

It was also found that the velocity profiles thus did not reach the expected zero velocity at the far interface wall and thus often appear to be slightly wider than the actual pipe diameter due to mentioned measurement artifacts. The illusion of velocity profiles being slightly wider than the actual pipe could also be enlarged by error in sound velocity and Doppler angle determination.

However, when comparing the UVP and LDA absolute velocity values it was found that they agree very well. Since the entire beam path was calculated and accounted for these findings implies that the correct sound velocity and Doppler angles were used when calculating the velocity and radial distance. Other phenomena than those discussed may also be involved in this case.

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 non-invasive measurements through multiple interfaces or thick wall materials.

In most commercial software, such as the one used with the UVP equipment used in this study, the ultrasound refraction and difference in sound velocity in multiple media are not taken into consideration, as pointed out by Wang et al. [29].

Consequently, these findings imply that measurements of the profile close to the pipe wall interface at the far end from the transducer side are less reliable due to mentioned artifacts since many of those are not compensated for. All velocity profiles were therefore truncated at the last measuring volume that originated from a position inside the pipe measurement section.

Further investigations are needed to fully explain, predict and compensate for the effects of mentioned artifacts for the investigated and similar pulp suspensions.

4. CONCLUSIONS

In this study, UVP and LDA techniques were used simultaneously to perform velocity profile measurements in highly concentrated pulp fibre suspensions in an experimental pipe flow loop. It was shown that both techniques can be used with good agreement to obtain accurate velocity (LDA) and velocity profile (UVP) data in much more concentrated fibre suspensions than what has been reported so far in the literature. No special seeding particles were needed as the pulp fibres were found to work sufficiently for both LDA and UVP techniques. It was also demonstrated that LDA had a sustained penetration depth of up to several millimeters for these seemingly opaque systems such as a 7.8 %(w/w) pulp suspension. Furthermore, results showed that the UVP technique was sensible to various artifacts that could result in a visible constant plug behavior of the recorded velocity profile, in which the velocity gradient information is lost towards the far end wall from the transducer side. However, the UVP method could be optimized in such way that the penetration depth was sustained almost through the entire measurement section even for the highly concentrated 7.8 %(w/w) pulp suspension.

5. ACKNOWLEDGEMENTS

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7. NOTATION

α_1	=	transducer inclination angle
α_2	=	angle between direction of flow and measurement axis
c	=	sound velocity, m/s
θ	=	Doppler angle
d	=	diameter of the measuring volume of the UVP, m
f_0	=	basic ultrasonic frequency, MHz
h	=	thickness of UVP measurement volume, m
L	=	distance between pressure sensors, m
L/s	=	Volumetric flow rate, liters per second
N	=	number of ultrasonic cycles per pulse
r	=	radial coordinate, m
R	=	pipe radius, m
R_0	=	plug radius, m
v	=	velocity, m/s
(w/w)	=	mass percentage pulp fibers