Near wall studies of pulp suspension flow

Johan Wiklund[1*] , Helena Fock[2], Anders Rasmuson[2] and Mats Stading[1,3]

[1] SIK - The Swedish Institute for Food and Biotechnology, P.O. Box 5401, SE-402 29 Göteborg, Sweden (*Corresponding author, e-mail: johan.wiklund@sik.se).

[2] Department of Chemical and Biological Engineering, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

3Materials and Manufacturing Technology, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Understanding the flow behaviour of pulp suspensions is very important in the design and operation of process equipment and paper mills. Pulp suspension flow is an opaque two-phase flow system, consisting of water and pulp fibres that aggregate and form coherent networks, resulting in very complex flow behaviour above a certain concentration. An Ultrasound Velocity profiling (UVP) technique was used in this study to investigate pipe flow of pulp suspensions in the near wall region. The study was performed at two concentrations and at four bulk velocities. The results showed that the mean velocity profiles exhibit a distinct plug at the centre of the pipe surrounded by a sharp velocity gradient. The plug size increases when the concentration increases or the bulk velocity decreases. The demodulated echo amplitude profile indicates a concentration profile in the near wall area, with a decreasing amount of fibres close to the pipe wall.

Keywords: Velocity profile, ultrasound, Doppler, pulp, wall layer

1 INTRODUCTION

1.1 Background

Detailed knowledge of the flow behaviour of pulp suspensions is important in the design and operation of process equipment and paper mills. This study focuses on the flow of concentrated fiber suspensions near the wall in a square pipe.

A pulp suspension flow is a two-phase flow system consisting of pulp fibres and water that tends to aggregate and form coherent networks above a certain fibre concentration. Since the shearing mechanisms are not the same throughout the suspension it is misleading to use a non-Newtonian flow model with a yield stress, [1]. Pulp suspension flow in pipes exhibits some extra flow regimes in the area between the pipe walls and the pulp network besides the usual laminar and turbulent flow regimes of common Newtonian and non- Newtonian fluids. The flow regimes originate in the different shearing situations occurring in the suspensions, mainly in the region close to the wall. These flow effects are of great importance for the frictional behaviour of the pulp suspension flow as well as for the pressure drop in the system. Flow phenomena, such as forming of flocs and water annulus occur in this region. Extensive reviews of pulp suspension flow in pipes have been published by for example [2].

The Ultrasound Velocity profiling (UVP) technique is well suited for opaque non-Newtonian fluid systems, but UVP has only been used in few studies on pulp suspension flow,) [3-5]. The pulp consistencies were however below 2% (w/w). In a previous comparative study between UVP and LDA, velocity profiles were successfully measured with good agreement between the two techniques in pipe flow of pulp suspensions with consistencies as high 7.8% (w/w), see [6]. Recent studies, e.g. [7] have also indicated a concentration gradient within the pulp suspension flow in pipes in the near wall region. In recent publications, [8, 9] it is shown that direct access to Demodulated Echo Amplitude (DMEA) data from a customized UVP instrument provides information on the quality of acquired data but also that new information can be extracted from spectral analysis. Ultrasound echo energy dependence can e.g. be used to measure the variation in bulk concentration of solids in fluid systems.

1.1 Aim of the study

Velocity profile and demodulated echo amplitude measurements were performed at four different bulk velocities and for two pulp consistencies. By investigation of the variations in echo amplitude and velocity gradient in the near wall layer related the demodulated echo amplitude to a concentration gradient or profile.

2 MATERIALS

A fully bleached kraft pulp from Södra Cell Värö was used in this study. The pulp had an average fibre length of 2.65 mm and an average diameter of 30 µm. The pulp was diluted from the original concentration, around 20 % (w/w), to two consistencies, 1.9 and 4.8 % (w/w). Approximately 150 L of pulp suspension was used in each test.

3 EXPERIMENTAL SET- UP & EQUIPMENT

3.1 Experimental flow loop

The experiments were carried out in a specific test facility at Chalmers University of Technology. A schematic view of the experimental flow loop is shown in Figure 1.

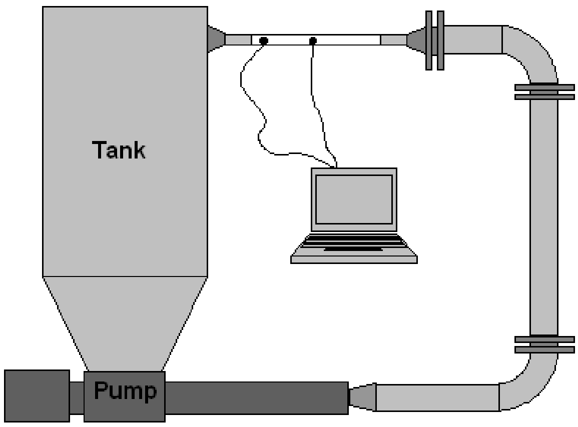

Figure 1: Experimental pulp flow loop.

The set-up consists of a 300 L open tank that supplies pulp suspension to a progressive cavity pump, which produces a maximum bulk velocity of 180 L/min. The pump is connected to a stainless steel pipe of a larger diameter than the downstream test section in order to reduce the pressure load on the pump. The pulp flows from the larger cylindrical pipe 100 mm in diameter through a contraction, designed for pulp suspensions, into a smaller cylindrical pipe 40 mm in diameter and then into the UVP test section. The test section, shown in Figure 2, is a 40 mm square Plexiglas conduit. The velocity profiles were measured at the location shown in Figure 2 using two 4 MHz TX-TN type transducers (Imasonic, Bensancon, France). The wall thickness was optimized for maximum transmission of ultrasound energy and transducers were installed at a distance from the wall interface to avoid measurements within the near-field. More details are given in [11].

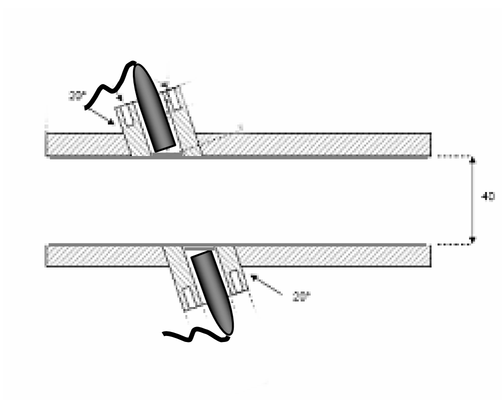

Figure 2: Experimental transducer set-up.

3.1 UVP-PD method and data acquisition system

The UVP-PD method and data acquisition system for in-line viscometry, developed at SIK, has been presented in e.g. [8, 9]. A customized Doppler-based ultrasound velocity profiling instrument equipped with a Multiplexer and modified firmware that allowed direct access to the demodulated echo amplitude (DMEA) was used for data acquisition (UVP-Duo-MX, Met-Flow SA, Lausanne, Switzerland). The instrument was connected to a master PC and communication was implemented with an Active X library, supplied by Met-Flow SA Lausanne, Switzerland. Versatile Matlab (Math Works, Natick, MA, USA) based software with a user-friendly GUI was developed and used to control data acquisition, for real-time data processing of DMEA raw data, visualization and analysis. The Doppler shift frequency and velocity profiles were determined using time-domain or frequency domain based signal processing, [8, 9, and 10]. A digital oscilloscope, Agilent Technologies, model 54624A, USA was an integral part of the set-up and was used for measuring the acoustic properties of the suspensions. Experimental UVP parameters are given in Table 1.

Table 1: Experimental UVP parameters

Frequency	4 MHz
Cycles per pulse	2-4
Repetitions	256 and 512
No. profiles	50
Sound velocity	~1490 (1.9 %) ~1505 (4.8 %) m/s
Doppler angle	70±0.5°
Spatial resolution	~0.37-0.74 mm
Time resolution (single profile)	55 ms/profile
Velocity resolution	6.5-22 mm/s

4 RESULTS & DISCUSSION

4.1 Measured velocity profiles and gradient

Figures 4 and 5 show the measured arithmetic mean velocity profiles, averaged over 30 profiles, from both transducers (TX and TN) for the two pulp suspensions of consistencies 1.9 and 4.8 %(w/w) respectively. Figures 4 and 5 shows a distinct plug region at the centre of the pipe that was found to stay intact and move as a solid body. The size of the plug was found to decrease with an increasing bulk velocity but also to increase with increasing consistency. A small difference in measured plug velocity was observed, at the right and the left side of the profile respectively, which can be seen in Figures 4 and 5. The measurements were made sequentially in different directions relative to the flow direction and started with the TX-transducer followed by the TN- transducer for each bulk velocity. The temperature of the pulp suspension increased during the run of the flow loop but the sound velocity was only measured and updated at the beginning of the measurements of each bulk velocity. However, the most likely explanation for the small difference in measured velocities is that the pump has a tendency to loose effect after a while, thus giving lower flow velocities at the same frequency setting. Both effects were found to be more pronounced when the consistency was increased. A stationary echo is visible in Figure 4 for the highest and lowest bulk velocity at the 1.9 % consistency. This is indicated by local dips in velocity, in the plug flow area, and was most likely caused by multiple reflections in the pipe interface wall material. Measured velocity profiles are in good agreement with previous studies [4, 6].

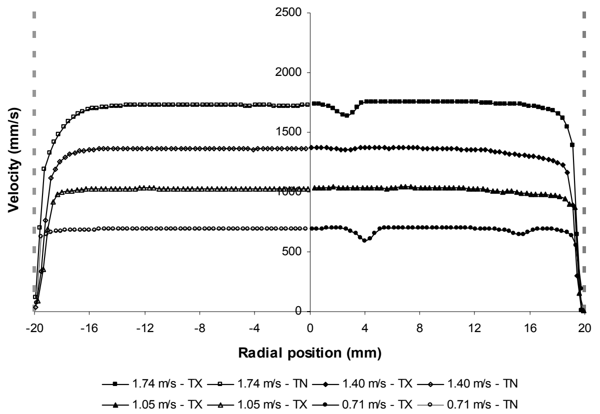

Figure 4: Measured velocity profiles at 4 different bulk velocities for a 1.9% (w/w) pulp suspension.

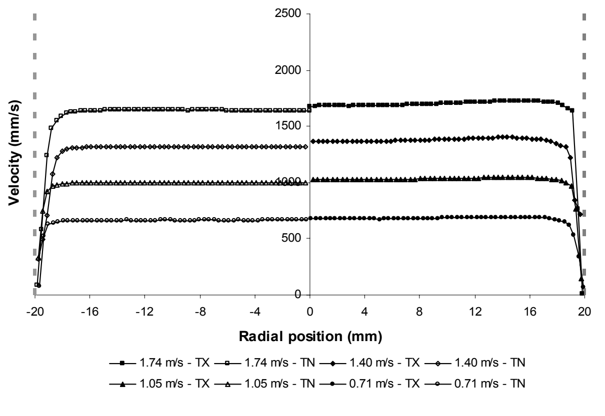

Figure 4b: Measured velocity profiles at 4 different bulk velocities for a 4.8% (w/w) pulp suspension.

Obtained results indicate an area close to the wall with a shear layer with a velocity gradient, thus indicating also a possible fibre concentration gradient. This is in accordance with previous studies by [4, 6, and 7]. Even though the trends are the same in the different studies the width of the gradient layer differs between the studies. These differences could originate from the different measurement techniques used, e.g. if comparing for example LDA and UVP measurements. The gradient layer measured with LDA is reported to be around 0.2 mm, which is much thinner compared to the ones measured with UVP (around 2 mm). The difference in the measured width of the gradient layer between the UVP based studies in literature is probably due different experimental UVP parameter settings. However, the velocity resolution along the measurement axis in the near wall region was significantly higher in this study, 0.37mm.

4.2 Relating demodulated echo amplitude and fibre concentration

In this study, an attempt was made to relate the demodulated echo amplitude to a concentration gradient or profile. The general trend for the echo amplitude curve is to have low amplitude close to the wall interface and to slowly rise to a maximum due to the migration of particles from the wall area towards the centre of the pipe. The echo amplitude then decreases with increasing distance from the transducer due to attenuation of ultrasound energy. This trend can be seen, e.g. in water seeded with a small amount of particles. The shape of the demodulated echo amplitude curve can thus be used to indicate the width of a concentration gradient layer.

Figures 4 and 5 shows a distinct plug region at the centre of the pipe that was found to stay intact and move as a solid body. An increase in echo amplitude closer to the plug front indicates an increase in concentration of fibres (since more fibres give a stronger echo). Theoretically, the location of the maximum received demodulated echo amplitude in the radial direction thus indicates the point at which the plug starts since the plug front generates the strongest echo. This is since the maximum received echo amplitude in the radial direction theoretically occurs at the position where the difference in acoustic impedance is the largest. Two examples of measured DMEA vs. radial position are presented in Figures 6 and 7.

When compared to the demodulated echo amplitude curve for water we observe that the echo amplitude peak is very sharp for the pulp suspensions and then quickly drops due to the attenuation of ultrasound energy, as shown in Figure 6 and 7. It also clearly indicates a decrease in plug size when bulk velocity is increased. This is in agreement with previous studies for softwood pulp suspension flow at lower consistencies, 2.0-3.1% (w/w), 7].

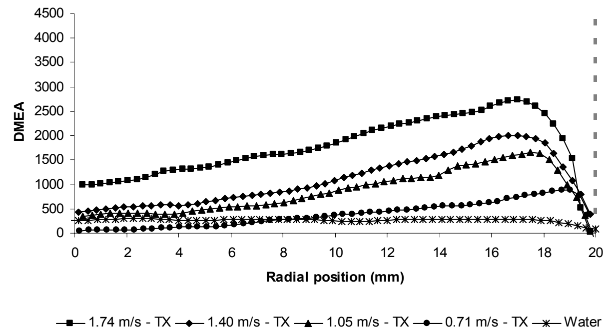

Figure 6: DMEA profiles for water and a 1.9 % (w/w) pulp suspension measured at 4 different bulk velocities.

Another interesting observation for the 1.9 % consistency is that the size of the plug for velocity profiles and thickness of the concentration gradient seems to more or less the same. This contradicts the results from a previous study where the width of the concentration gradient was larger than the width of the velocity gradient, [7].

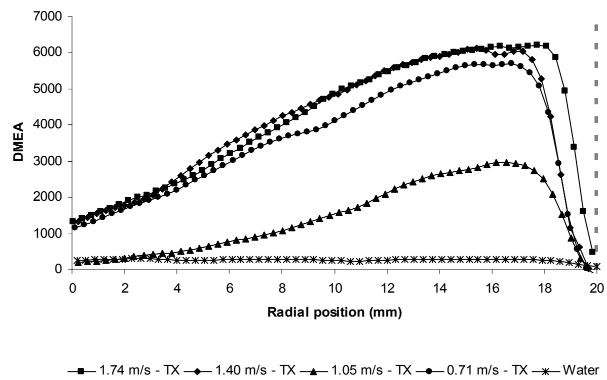

Figure 7: DMEA profiles for water and a 4.8 % (w/w) pulp suspension measured at 4 different bulk velocities.

For the 4.8 % consistency, shown in Figure 7, the trends are not as clear as in the 1.9 % case. Here, it appears that the size plug increases when the bulk velocity increases. The width of the concentration gradient also seems to be larger than the size of the velocity gradient. This can be explained by the fact that the DMEA profiles for the 4.8 % consistency were most likely affected by the flow situation. The measurements were performed in the so called rolling friction regime for all the bulk velocities at the 4.8 % consistency. In the rolling friction regime there are flocs present between the plug and the pipe wall and the size of the flocs reduces with an increase in velocity, [4]. This could explain why the width of the velocity gradient increases with decreasing bulk velocity.

5 CONCLUSIONS

(1) Velocity profiles were successfully obtained in pipe flow of pulp suspensions at four different bulk velocities and at two different consistencies. The obtained mean velocity profiles are in good agreement with results from previous studies, both in terms of profile shape and in width of the velocity gradient.

(3) Higher spatial and velocity resolution in the near wall region was achieved compared to previous studies presented in the literature.

(4) The demodulated echo amplitude curve can be used to indicate the start of a moving fiber plug as well as the width of a concentration gradient layer.

ACKNOWLEDGEMENT

The financial support of Södra Cell is gratefully acknowledged. A G. Gogniat and O. Mariette at Met-Flow SA, Switzerland are acknowledged for their support. Beat Birkhofer from ETH, Switzerland is acknowledged for fruitful discussions.

REFERENCES

[1] Duffy G, Titchener, A, Lee, P, Moller K: The mechanisms of flow of pulp suspensions in pipes, APPITA J. 29 (1976) 363-370.
[2] Duffy G: The significance of Mechanistic-Based Models in Fibre Suspension Flow, Nord. Pulp Paper Res. Jour. 18(2003) 74-80
[3] Hirsimaki, O: Determination of radial velocity profile and flow disturbance of pulp suspensions by ultrasonic echo correlation, Paperi ja Puu 60 (1978) 95-97.
[4] Dietemann P, Rueff M: A study of fibre suspension flow by means of Doppler ultrasound velocimetry and image analysis, in PAPTAC 90th Annual Meeting, Montreal, Que., Canada (2004).
[5] Hanjiang X, Aidun C: Characteristics of fiber suspension flow in a rectangular channel, Int. journ. of multiphase flow. 31(2005) 318-336.
[6] Wiklund J, Pettersson J, Rasmuson A, Stading M: A Comparative Study of UVP and LDA Techniques for Highly Concentrated Pulp Fibre Suspensions in Pipe Flow, AIChE J. 52 (2006) 484-495.
[7] Pettersson J. Wikström T, Rasmuson A: Near Wall Studies of Pulp Suspension Flow Using LDA, Can. Jour. Chem. Eng. 84 (2006) 422-430.
[8] Wiklund J "Ultrasound Doppler Based In-Line Rheometry – Development, Validation and Application", Ph.D. Thesis, Lund University, Lund, Sweden, 2007.
[9] Wiklund J, Sharam I, Stading M: Methodology for In-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques, Chem. Eng. Sci. 62 (2007) 4277-4293.
[10] Wiklund J, Stading M: Application of in-line ultrasound Doppler-based UVP-PD rheometry method to model and industrial suspensions, Flow Meas & Instr. 19 (2008) 171-179.
[11] Fock H. et al.: Ultrasound Velocity Profile (UVP) Measurements of Pulp Suspension Flow near the Wall, J. Pulp & Paper Sci. XX (2008), in press.