In-Line Rheological Measurements of Complex Model Fluids using an Ultrasound UVP-PD Based Method

Johan Wiklund[1, 2], Mattias Johansson[1, 2], Jeelani Shaik[2], Peter Fischer[2], Mats Stading[3] and Anne-Marie Hermansson[1]

1 - Chalmers University of Technology / SIK, 402 29 Gothenburg, Sweden
2 - ETH Institute of Food Science / Food Process Engineering, 8092 Zurich, Switzerland
3 - SIK The Swedish Institute for Food and Biotechnology, 402 29 Gothenburg, Sweden

ABSTRACT
In this work[1], a new in-line and non-invasive rheological instrument and measurement technique was evaluated and tested in an experimental flow-loop. The concept of the new rheometer is based on the Ultrasound Doppler Velocity Profile technique (UVP), in combination with a pressure difference method, (PD). Complex model fluids such as highly shear-thinning viscoelastic surfactant solutions, and non-Newtonian suspensions containing cellulose fibres or corn starch particles in a water or water-glucose matrix, were tested in the flow-loop.

INTRODUCTION
The rheological behaviour of the in general, non-Newtonian, highly concentrated and non-transparent fluids used in industry have so far been analysed using commercially available instruments, such as conventional rotational rheometers. Most of these commercially available instruments are usually not suitable for in-line rheological measurements and quality control as they are based on invasive methods, and have geometries that can affect and disturb the flow. Real flow situations can almost never be obtained using these instruments and they may also cause severe bio-safety problems due to contamination, which also limits their applicability in many situations. The research in the present study, continued the work made by Ouriev[2] in a previous Ph.D project, using a modified experimental flow-loop at ETH – Institute of Food Science and Food Process Engineering in Zurich, Switzerland. The main objective of this research work was to expand and evaluate the UVP-PD methodology for non-invasive (no contact) rheological characterisation of non-transparent highly concentrated model fluids and shear thinning, viscoelastic, multiphase surfactant solutions. Aiming the adaptation of the UVP-PD method towards complex water-cellulose fibre suspensions introduced a new interesting field of application.

UVP-PD IN-LINE MEASURING PRINCIPLES
The principle of the Ultrasound Doppler Velocity Profile technique (UVP) is described extensively in previous work, e.g. by Takeda[3,4], and the combination with a pressure difference method, (PD) by Ouriev[2]. Only a brief description of the method is given here. The rheological flow properties were derived from the simultaneous recording of the velocity profiles and the corresponding pressure drop within the pipe, using a new flow-adaptor with housing for an ultrasonic transducer and two pressure sensors. A schematic representation of the in-line adaptor is given in figure 1.

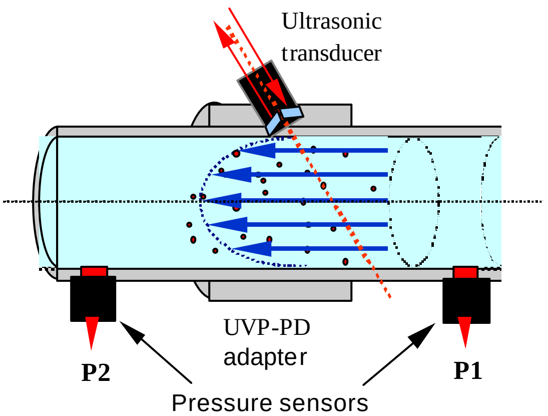

Figure 1.Schematic representation of the In-Line Adapter.

A non-linear regression of the obtained velocity profiles was performed using a power-law Eq.1 or Herschel-Bulkley model Eq.2, which enabled determination of the power-law exponent n. The parameter K was then determined using the corresponding pressure drop within the pipe. The viscosity-, and shear stress distributions in the pipe were then calculated. Conventional rotational rheometers, Bohlin CS-50, ARES and Physica MCR-300 were used for comparison of the results.

Eq.1. $$V_x(r)=\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\frac{R^{1+\frac{1}{n}}}{1+\frac{1}{n}}\left(1-\left(\frac{r}{R}\right)^{1+\frac{1}{n}}\right)$$

Eq.2. $$V_x(r)=\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\frac{1}{1+\frac{1}{n}}\left(\left(R-R^*\right)^{1+\frac{1}{n}}-\left(r-R^*\right)^{1+\frac{1}{n}}\right)$$

RESULTS

The in-line results obtained using the UVP-PD technique were found to be in very good agreement with the off-line measurements using conventional rotational rheometers. Simple power-law or Herschel-Bulkley models were found to be a good approximation of the shear-behaviour for all investigated systems.

It was shown that the UVP-PD technique could be applied for measurements of complex, non-transparent and highly concentrated fluids that exhibit a non-Newtonian behaviour. The results of the non-linear fit for a shear-thinning surfactant solution are illustrated in Fig.2.

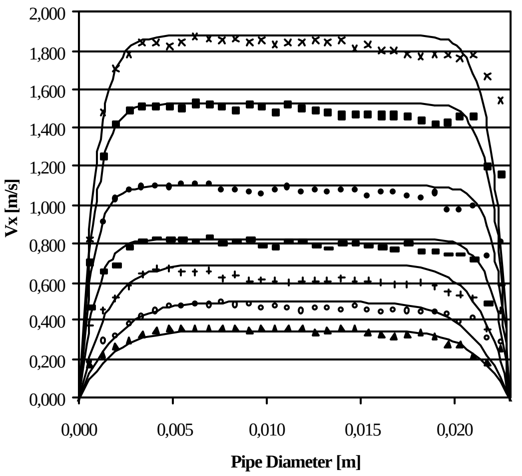

Figure 2.Velocity Profiles (symbols) and Non-linear Fit (line) at different volumetric flow rates for a viscoelastic surfactant solution.

The technique was applicable to cellulose fibre in water systems with a yield stress that could not be measured off-line using conventional rotational rheometers, due to compression and drainage of the sample. The results of the non-linear fit are illustrated in Fig.3.

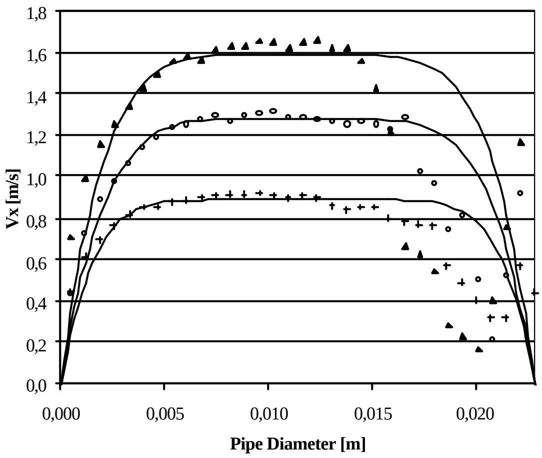

Figure 3.Velocity Profiles (symbols) and Non-linear Fit (line) at different volumetric flow rates for 1.0%-wt Cellulose Fibres in a water

More rheological information about the sample such as the shear stress and shear rate distributions in the pipe could be obtained using this new in-line technique as illustrated in Fig. 4.

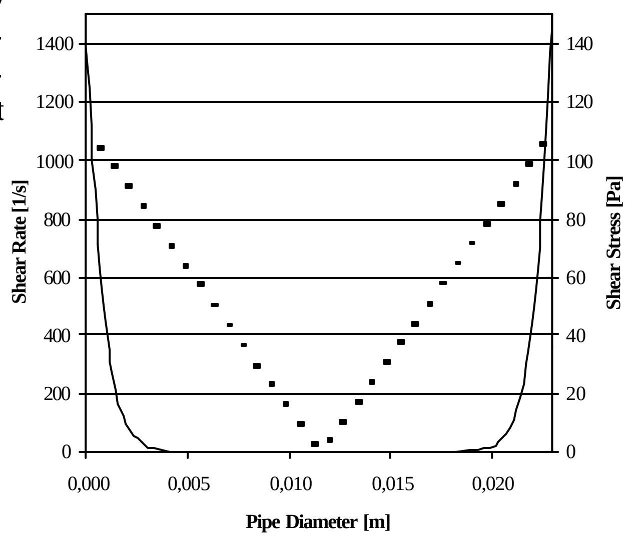

Figure 4.Shear Stress (dotted line) and Shear Rate (line) Distribution for a viscoelastic surfactant solution.

CONCLUSIONS

The UVP-PD technique was found to have a large potential for non-invasive, in-line measurements of complex and opaque fluids. The results obtained using the UVP-PD technique were found to be in very good agreement with the off-line measurements using conventional rotational rheometers and can easily be improved with minor modifications of the UVP-PD instruments and the set-up of the experimental flow-loop. Statistical data treatment of the recorded velocity profiles was found to be necessary in order to reduce the effects of e.g. scattering air bubbles and external sources of disturbance. The technique is expected to find several applications in many different branches of industry.

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email: johan.wiklund@privat.utfors.se
johan_anders_wiklund@hotmail.com