A new fully digital UVP enabling quantitative in-line rheometry

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The performance of a newly developed fully digital UVP-PD (Ultrasonic Velocity Profiling with Pressure Drop) electronics is tested and validated with a Non-Newtonian model solution. For this purpose, a piston setup is used to create well defined flow conditions to enable a comparison of theoretical and measured velocity profile. The rheometric parameters are estimated in-line with UVP-PD by using three different approaches and compared with those obtained from off-line rotational rheometer. Considering the shear rate range available in the pipe flow, a good agreement of in- and off-line results is found.

Keywords: in-line rheometry, non-Newtonian fluids, ultrasonic velocimetry, pipe flow

1 Introduction

The idea to derive information on the flow behavior of liquids from the velocity profile measured by ultrasound — in other words, the use of Doppler velocimetry as in-line rheometer — is older than 30 years. In this period, several research groups worked on this concept: Kowalewski [9], Müller et al. [10], Ouriev and Windhab [11], Wiklund et al. [18], Wiklund and Stading [17], Birkhofer et al. [2], Fischer et al. [5], Wassell et al. [16], Dogan et al. [3, 4], Kotze et al. [8], Petit et al. [12], Birkhofer [1]. A feasibility study in highly filled adhesives presented in former work [12], proved that the UVP-DP can be used in industry for a quantitative analysis of the rheological properties of complex fluids. In order to adapt the setup to industrial requirements, a new electronic device [15], based on former work [13, 14] has been developed. The accuracy and limitations of the new UVP-PD device and technique itself are first evaluated with a well defined Non-Newtonian model liquid and flow conditions. For this purpose, a solution of polyethylene oxide polymers is pumped with a piston setup and the velocity profiles, pressure drops and temperatures are recorded. The resulting rheological parameters are then extracted, using different rheometric characterization approaches and compared with the results obtained from off-line rotatory rheometry measurements.

2 Material and methods

2.1 Polyox solution

A Solution of 2% by weight of polyethylene oxide with a molecular mass of 1 000 000 is dispersed with 0.2% of Acticide (preservative) in water to obtain a stable, shear thinning fluid.

2.2 Flow setup

The tailored flow setup has been built with a linear piston which allows to pump the fluid through a pipe of 25 mm inner diameter. A continuous flow rate ranging from 10 ml/min to 2 l/min can be obtained with this setup, allowing a well defined continuous flow of the fluid in the instrumented pipe section. This section also comprises two absolute pressure sensors and two temperature sensors.

2.3 Electronics and transducer

The electronics used in this work [15] has be developed by the University of Florence based on a previous research board [13] in collaboration with Schmid-Engineering (Münchwilen, Switzerland), Sika Technology AG and Sika Services AG. The system is connected to a custom made 5 MHz pencil transducer, excited with a 5 cycle Hanning windowed pulse of 5 MHz. The data received from the transducer in each pulse repetition interval (PRI) are sampled at 74.3 MS/s, with a 16 bit resolution. The signals are coherently demodulated, decimated to 18.6 MS/s (corresponding to a gate resolution in water (c = 1480 m/s) of 79.7 µm) by the on board FPGA and stored to a 64 MB SDRAM. The data is transferred via an ethernet connection to a PC, where it is visualized and saved in a file for further post processing. Typically 4096 PRIs are acquired for each measurement. The electronics also allows the simultaneous acquisition of pressure and temperature data. As an additional feature it is also possible to obtain the unprocessed radio frequency data, which are useful for the investigation of artifacts and the optimization of ultrasound parameters such as the amplification.

2.4 Signal processing

The velocity profile is estimated through a weighted mean of the Doppler power spectra from each depth [12]. This approach avoids the necessity of a deconvolution [7, 6]. In the model systems it is possible to obtain the full profile over the complete pipe diameter, but the second half of the profile, opposite to the transducer, is disturbed by internal reflections. For this reason, only the first half is used for the data analysis.

2.5 Rheometry

The conventional approach to extract rheometric information from the velocity profile is a nonlinear least square fitting, using equation 1. The equation describes the velocity profile for power law fluids, defined by $\eta = K\dot{\gamma}^{n-1}$, where η is the viscosity, K the power law coefficient, $\dot{\gamma}$ the shear rate and n the power law exponent.

$$v(r) = \frac{Q}{\pi R^2}\frac{3n+1}{n+1}\left(1-\left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right) \quad (1)$$

Q: flow rate, R: radius, r: radial distance from the pipe center.

A simplified technique is the use of the relation of the maximum velocity and n as shown in equations 2 and 3.

$$v_{\max} = \frac{Q}{\pi R^2}\frac{3n+1}{n+1} \tag{2}$$

which can be transformed to:

$$n = \frac{v_{\max} - a}{3a - v_{\max}};\ a = \frac{Q}{\pi R^2} \tag{3}$$

Compared to the fitting approach, the complexity and computational weight of the maximum velocity based approach is extremely reduced, which makes it interesting for the implementation in an embedded system.

For both approaches the power law coefficient K can be calculated in a second step, using equation 4, which requires a pressure drop (ΔP) measurement over a certain length (L).

$$K = \frac{\Delta P}{2L}\left(\frac{Q}{\pi}\frac{3n}{n}R^{\frac{-3n-1}{n}}\right)^n \tag{4}$$

Compared to the classic technique, where n and K are fitted simultaneously [2] this two-step approach allows to clearly distinguish problems originating from the profile shape and the pressure drop measurement.

The wall shear rate, used as maximum shear rate of the in-line measurements in the comparison with the off-line rheometry, is calculated using equation 5.

$$\dot{\gamma}_{\mathrm{w}} = \frac{3n+1}{4n}\frac{4Q}{\pi R^3} \tag{5}$$

Finally, a third approach, the so called gradient method [10], is used. For this method the local shear stress τ is $\Delta Pr/2L\dot{\gamma}$ and $\dot{\gamma}$ simply the first derivation of the velocity profile, thus $\dot{\gamma} = \mathrm{d}v/\mathrm{d}r$.

3 Results and discussion

3.1 Rotational rheometry

The off-line rheometry measurements are made as triple determination with an Anton Paar Physica MRC301 rheometer, using a cone/plate geometry with a 2° angle and 25 mm diameter. The Polyox solution shows a shear thinning behaviour (fig. 1), which can be approximated with the power law model. The corresponding fits are also shown in figure 1 in dashed and dotted lines. The plot shows that the shear thinning is more pronounced at higher shear rates. The temperature influence between 20 and 25 °C is rather insignificant and nearly in the precision of the measurement.

3.2 In-line rheometry

The presented results are based on 56 measurements made with flow rates varying from 100 to 3000 ml/min at fluid temperatures between 23.5 and 24.5 °C. For the measurements only the pulse repetition frequency is adjusted to the flow rate, all other measurement and processing parameters are identical over all measurements.

Figure 2 shows the intensities of the power spectra for a representative example, where the black line is the estimated profile. This profile, also shown in thin line in figure 3, is then used for the fitting (thick line in the same figure), the estimation of the maximum velocity and the determination of the first derivative for the gradient method.

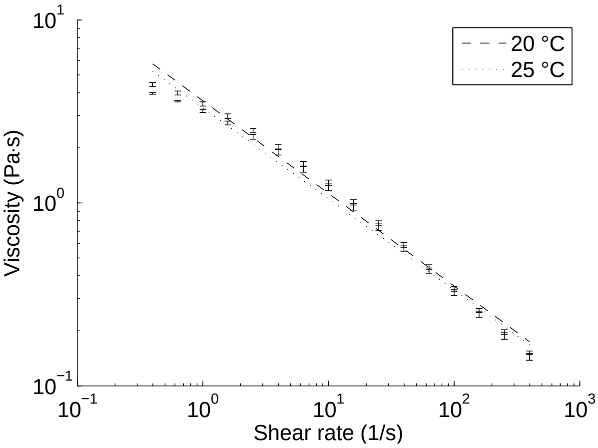

Figure 1: Viscosity of Polyox (0.125%) as function of the shear rate at 20 °C and 25 °C measured with a rotational rheometer. Error bars indicate the $\pm 2\sigma$ range from the triple determination.

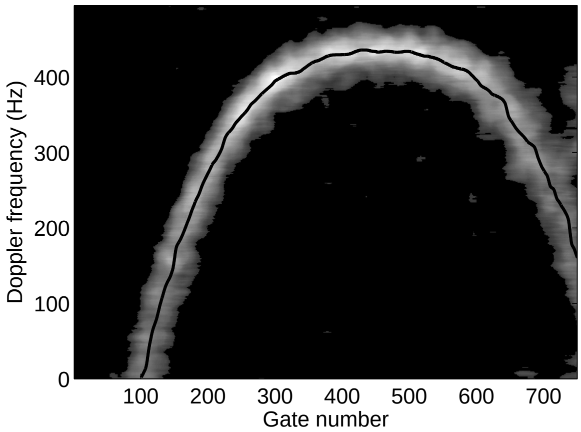

Figure 2: Spectral intensities represented as surface plot and the estimated profile in black line. The flow rate is 2500 ml/min.

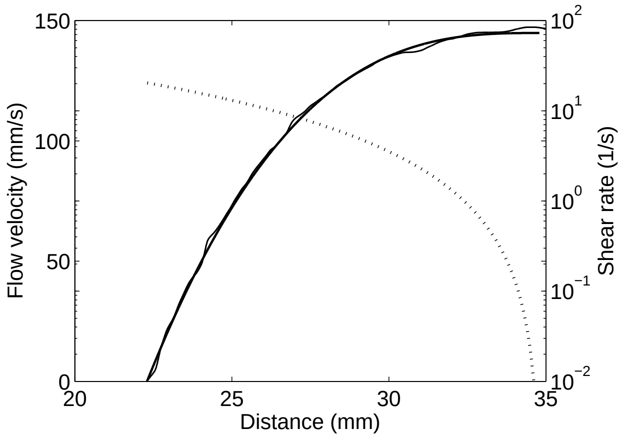

Figure 3: The estimated flow velocity profile from figure 2 in thin line, the fitted power law profile in thick line and the local shear rate in dotted line.

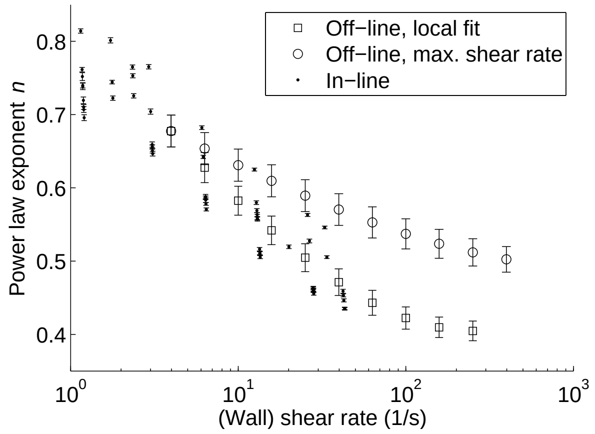

Figure 4: A comparison of the power law exponent *n* determined by two different approaches from the off-line rheometer data and the in-line measurements. The error bars indicate the 95 % confidence interval from the fitting.

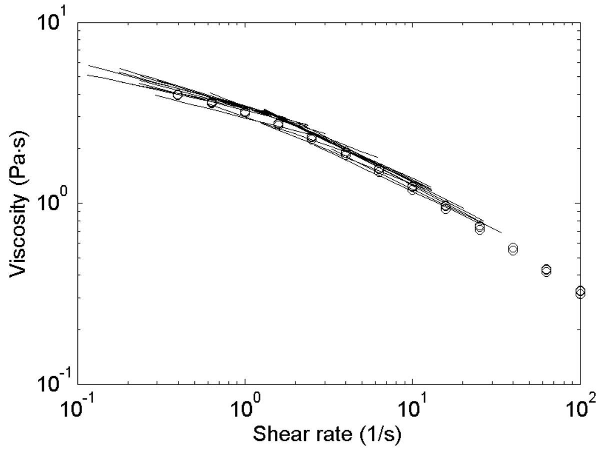

Figure 5: Viscosity as function of shear rate measured by the rotational rheometer shown in circles. The lines are based on the power law parameters *n* and *K* determined in-line.

3.2.1 Power law model fitting

As shown in section 3.1, the Polyox solution is not a perfect power law fluid: the shear thinning behaviour, characterized by the power law exponent *n*, increases with shear rate. Nevertheless, a meaningful fit is possible because the relevant shear rate range over the pipe radius, with its maximum at the pipe wall, is limited to one or two decades (fig. 3, dotted line). The coefficient of determination (R^2) for the fit with equation 1 is at least 0.9932. Figure 4 shows the power law exponent *n* extracted in 3 different ways as a function of the shear rate: (1) from the rotational rheometer data using 6 consecutive measurement points («local fit»), corresponding approximately to one decade, (2) also from the off-line rheometer, using the data from the minimum shear rate to the shear rate on the x-axis («max. shear rate»), also with a minimum of 6 points, and (3) the in-line data with the points shown on the x-axis at their wall shear rate.

An alternative comparison of the in- and off-line data is shown in figure 5 where the in-line results are represented with the shear rate dependent viscosity determined over one decade based on the fitted power law parameter *n* and *K*. The agreement observed is good and the in-line data also shows the increase of the shear thinning behaviour with increasing shear rate.

3.2.2 Maximum velocity based analysis

Equation 3 can be used to calculate the power law exponent *n* directly from the maximum velocity of the flow velocity profile. Figure 6 shows the correlation of the two different calculation methods. The fitted line has a slope of 0.94 and an offset of 0.0063. The *n* determined from the maximum velocity is always larger than the *n* determined from the fitting. This can easily be explained with the stronger influence of the behaviour at low shear rates in the pipe center.

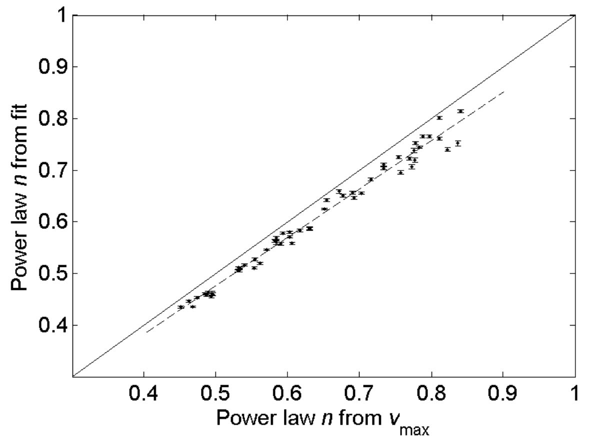

Figure 6: Comparison of the power law exponent *n* determined by two different methods: fitting and extraction from the maximum flow velocity. The solid line shows the 1:1 correlation, the dashed line the linear approximation of the points.

3.2.3 Gradient method

The results of the gradient method are shown in figure 7. Applying more smoothing and filtering it would be possible to achieve better result, but then the degree of complexity increases with-

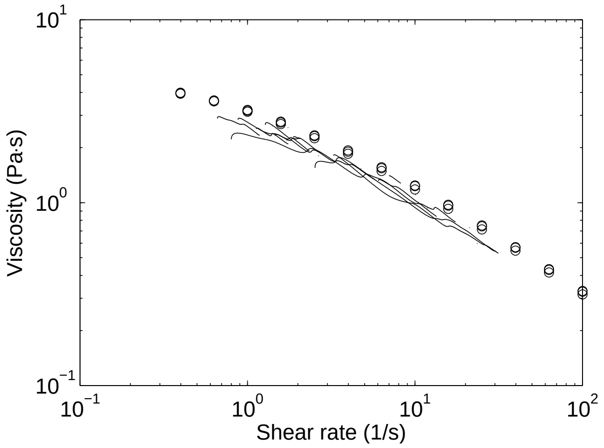

Figure 7: Viscosity as a function of the shear rate determined by the off-line rotational rheometer (circles) and the gradient method (one curve per measurement).

out additional information compared to the power law fitting approach. The main problem of this method is the strong impact of minor artifacts in the shape of the measured velocity profile on the derived local shear rate.

4 Summary and conclusions

The presented first series of measurements made on a simple Non-Newtonian fluid prove, that UVP-PD can be used to obtain accurate and quantitative measurement of the flow properties. It is important to consider the shear rate range in the pipe flow. As it is usually limited to one or two decades, it is possible to use the power law fluid model as an approximation for a fluid, which is not perfectly described by the power law model. It is also possible to use simply the maximum velocity for the rheological characterization. The gradient method also gave an acceptable agreement between in- and off-line measurements, but it showed no advantages compared to the power law model approach.

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