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Online Viscosity Measurement of Complex Solutions Using Ultrasound Doppler Velocimetry

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A new method to measure the viscosity of non-Newtonian fluids over a wide range of shear rates in a short period of time is presented. The technique is based on the measurement of the velocity profile in a pipe flow using ultrasound Doppler velocimetry (UDV), which is a non-invasive method, and simultaneously determining the pressure drop. The velocity profile is used to obtain shear rate distribution, while the pressure drop is used to calculate the shear stress distribution. By taking the ratio of these quantities at a radial position, local viscosity can be obtained within the shear rate range in the flow, zero at the center, and maximum at the wall, within minutes. For comparison purposes, viscosity of xanthan gum solutions with concentrations of 0.6 and 1.0 kg/m^3 are also measured using a conventional technique and the agreement between the results is satisfactory. Therefore, this technique shows promise for use as an online viscosity sensor for production processes.

Key Words: Viscosity, ultrasound Doppler, non-Newtonian, polymer, pipe flow.

Introduction

Rheological properties of industrial materials are one of the most important indicators of their quality. Furthermore, rheological or flow properties of process streams directly affect the design and operation of processes. Therefore, rheological characterization of samples, taken in some critical steps in production, provides crucial insight into product quality control and process economics. However, there are some difficulties in taking samples one by one out of the process and examining them. For example, viscosity, which is the most important rheological property, must be determined in a range of shear rate as most of the fluids in industry are non-Newtonian. Moreover, rheological properties of many samples are closely related to the flow conditions in the process. That is why the measurements in laboratory conditions may lead to inaccurate results. Another alternative for determining viscosity characterization is to carry out the measurement on the process itself. A method that can provide viscosities over a wide range of shear rate regions rather than one shear rate in a short time period can potentially be used as a process monitoring and control tool.

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Various online viscosity measurement methods are currently used in industry due to their important roles in process economy and product quality[1]. However, the viscosity measurement instruments currently implemented on processes in various fields can only operate at a single or in a limited range of shear rate[2]. Useful rheological characterization of materials, however, requires a wide range of shear rate measurements.

The present method is based on the simultaneous velocity profile and pressure drop measurements in a fully developed circular pipe flow under steady and laminar conditions. Flow of liquids through pipes occurs with a velocity distribution over the pipe cross-section. With their shear rate-dependent viscosities, non-Newtonian liquids exhibit different velocity profiles than that of the typical parabolic distribution of Newtonian liquids. Hence, a range of shear rates is observed in the flow, being zero at the pipe center and maximum at the wall. Therefore, it is possible to obtain shear rate distribution in the tube from the velocity profile, and it should be measured by a technique. In the present study, ultrasound Doppler velocimetry (UDV) is employed since it can enable non-invasive, non-disturbing, quick, and accurate measurements. The distribution of shear-stress, on the other hand, can be determined by using pressure drop. At a radial position, the ratio of shear-stress to shear rate, by definition, yields the viscosity at that point. As a result, for the shear rate range in the flow, viscosity values can be obtained by means of only one online experiment. This is a method known in the literature as pointwise rheological measurement[3–6].

Viscosity measurements of various polymer solutions and suspensions were accomplished successfully using this method in earlier studies[7,8] in which magnetic resonance imaging (MRI) was used to obtain laminar velocity profiles. MRI is highly sensitive, non-invasive, and applicable to both transparent and opaque fluids. However, it is a very expensive and complicated method[9]. In addition, the presence and effect of a strong magnetic field on some processes may not be desirable.

UDV is also employed to obtain velocity distributions. It is based on the frequency shift of sound waves scattered by moving particles in the flow. In a typical UDV measurement, an ultrasound probe is installed on the conduit wall with an angle, θ. The probe is used both as a transducer and receiver of the ultrasound at frequencies in MHz ranges. Following transmission of an ultrasound pulse to the flow, echo, which is sound reflected back by the moving tiny particles in the flow, is recorded. The position of any measurement point can be calculated by using the time delay between emission and reception of sound, t_f.

$$d = \frac{c\,t_f}{2}.$$

Here d is the distance between the probe tip and the measurement point, and c is the sound velocity in the medium. The local velocity is encoded in terms of the frequency shift of the signal originating from the point. The axial velocity, V, is obtained by using the frequency shift, f_d, of the signal reflected back from the point as

$$V = \frac{c f_d}{2 f_0 \cos\theta}$$

where f_0 is the ultrasound emission frequency. Generally, velocities around 1 m/s cause Doppler frequency shifts of less than 10 kHz. Since the ultrasound pulse traverses the entire pipe radius, the signal contains axial velocity versus position data for the entire cross-section. Therefore, in a single measurement, the velocity profile can be determined.

UDV has some advantages similar to MRI. It is a non-invasive method and applicable to both transparent and opaque liquids in contrast to Laser Doppler Velocimetry (LDV), in which point velocity per

measurement is obtained. Hence, constructing a velocity distribution with LDV requires many successive measurements. UDV is a less costly and easier method when compared to MRI. Therefore, it has been employed in different areas with an increasing number of uses. UDV was first used to study blood flow in humans[10,11] and was later successfully applied to other flow media and geometries[12−14]. Measurements can be taken in less than 1 s and with position and velocity resolutions of 1 mm and 1 mm/s, respectively. It is also possible to increase resolutions by increasing measurement duration. It has been shown that UDV can be used for velocity measurements in multi-phase flows[15,16] as well. In another study, the fluid shear rate at the pipe wall (wall slip) in a multi-phase flow was determined by this method[17]. Moreover, particle size distributions and concentrations of emulsions or suspensions can be determined based on different propagation and reflection properties of ultrasound in different phases[18,19].

It was shown in recent studies that UDV can also be used for rheological measurements. Viscosity measurements of single-phase[20] or multi-phase[21] viscoelastic fluids were made in these studies and the results indicated that UDV is a promising technique for determining the viscosity of complex fluids on the production line. Therefore, the aim of the present study was to exploit the characteristics of UDV to develop an online viscosity sensor.

Experimental

Experiments were carried out by simultaneously measuring the velocity profile and pressure drop in a circulating flow system (Figure 1). The flow system is composed of 2 tanks, a test section in the form of a rigid polypropylene pipe, connection hoses, a pump, a rotameter, and a control valve. Constant liquid head was maintained by overflowing the upper tank as the solution was continuously circulated between the tanks using the pump and a drain line as shown in Figure 1. Part of the solution in the upper tank was returned to the lower one after flowing through the rigid pipe, which had an inner diameter of 2 cm. The first pressure tap was placed 1 m away from the entrance, while the UDV transducer was installed 2.5 m away. Those distances were sufficient to ensure measurements of the fully developed section of the flow at a Reynolds number (Re) of approximately 1000.

A UDV system (model DOP 2125, Signal-Processing, Switzerland) was used to obtain the velocity profile. The software implemented on the UDV enables one to also obtain raw velocity profile data to process elsewhere. Aqueous Xanthan gum solutions at concentrations of 0.6 and 1.0 kg/m^3 were used in the experiments. The solutions exhibited shear-thinning behavior under the experimental conditions. Viscosity of the solutions was also determined using a conventional viscometer (Fann Viscometer Model 35SA, Houston, USA) for comparison purposes.

The parameters in the experiments were solution concentration, flow rate, and ultrasound emitting frequency. Flow rate of the solution was either 3 or 4 L/min. Further increasing the flow rate makes it possible to obtain measurements at wider shear rates. On the other hand, this method entails a steady, smooth, unidirectional, and hence laminar velocity field. The flow rates used were satisfactory from these perspectives. The ultrasound emitting frequencies in the measurements were 2 and 4 MHz. Higher frequencies result in increased spatial and velocity resolutions. Low frequency ultrasound, however, is less prone to signal attenuation due to scattering.

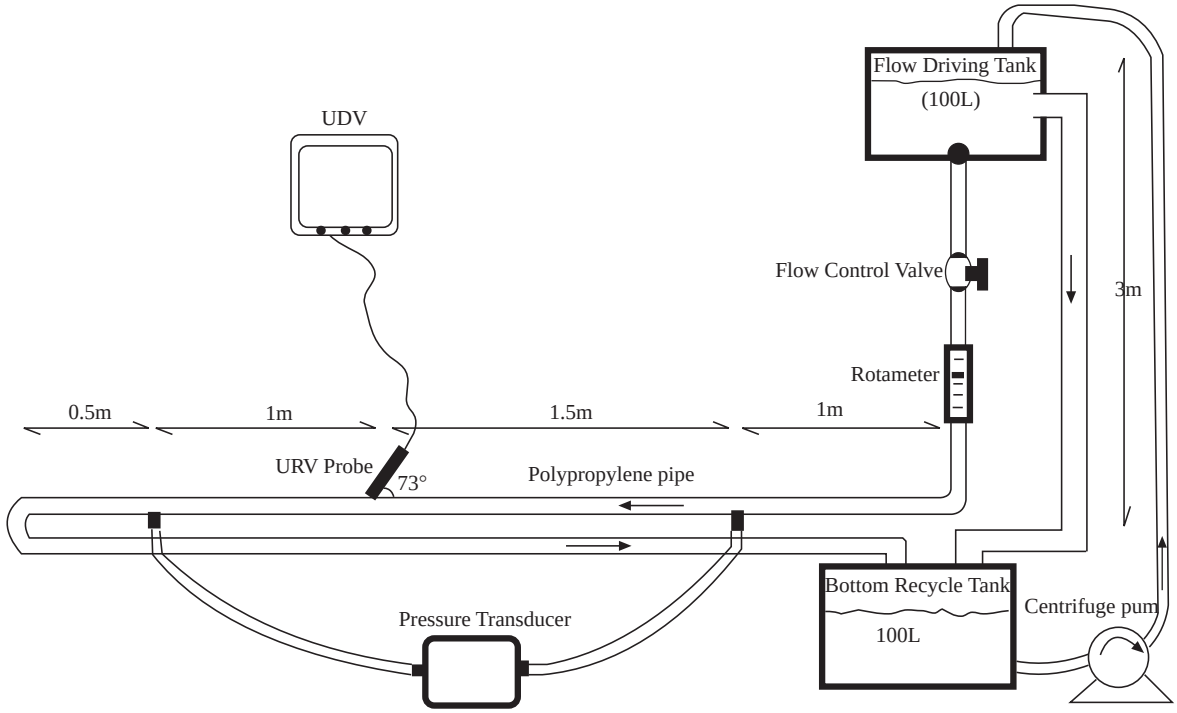

Figure 1. Experimental flow system.

Results and Discussion

A typical velocity distribution in the flow of the 0.6 kg/m^3 polymer solution is depicted in Figure 2. Volume flow rate and ultrasound frequency are 3 L/min and 2 MHz, respectively. In this figure and all subsequent velocity profiles, the vertical axis corresponds to the radial distance in the pipe and the horizontal axis is velocity. Measured velocity values are shown by points. Origin of the vertical axis corresponds to the center of the pipe where maximum velocity is observed. Similarly, velocity becomes zero at the pipe wall, as expected. Due to the shear-thinning behavior, a non-parabolic velocity profile is observed in the flow. Velocity data are smoothed by using even polynomial expressions, which are represented by solid lines in the velocity profile figures. The gradient of this function, with respect to radial position, yields an analytical expression for the shear rate distribution. It should be noted that obtaining the velocity profile took approximately 1 s and did not disturb the flow field since the UDV probe does not make contact with the solution.

In Figure 3, the velocity profile of the polymer with a concentration of 1.0 kg/m^3, flow rate of 3 L/min, and frequency of 4 MHz is shown. Since the profile does not follow a smooth pattern, the quality of the data can be considered of lower quality than that of Figure 2. Higher ultrasound frequency increases the scattering of the sound in the solution, which in turn results in smaller signal to noise ratio, S/N. In this case, a smaller S/N seems to outweigh the improved resolutions at the higher frequency of 4 MHz. In addition, a flat velocity profile near the pipe center in Figure 3 might occur due to a higher polymer concentration in the solution than in the experiment of Figure 2. As concentration increases, one may expect higher viscosities so that low shear rates around the pipe center might not be sufficient to induce a deformation detectable within the velocity resolution of the measurement.

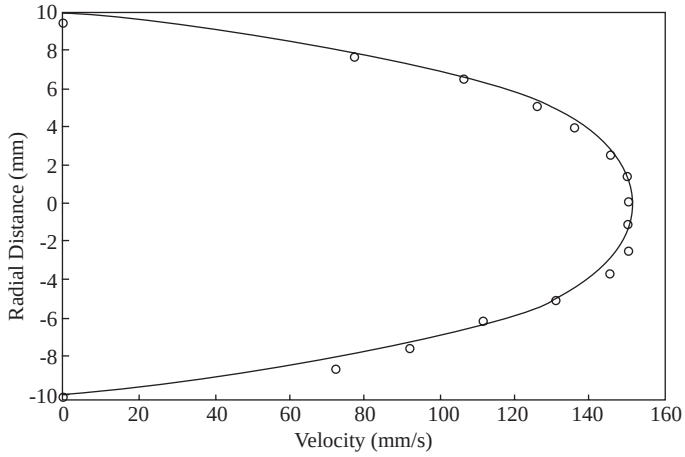

Figure 2. Velocity distribution of xanthan gum solution obtained by UDV under the following conditions: Polymer concentration = 0.6 kg/m^3, flow rate = 3 L/min, ultrasound frequency = 2 MHz. Solid line is given by V (mm/s) = –0.0093.r^4– 0.6243.r^2+ 151.30, where r is in mm.

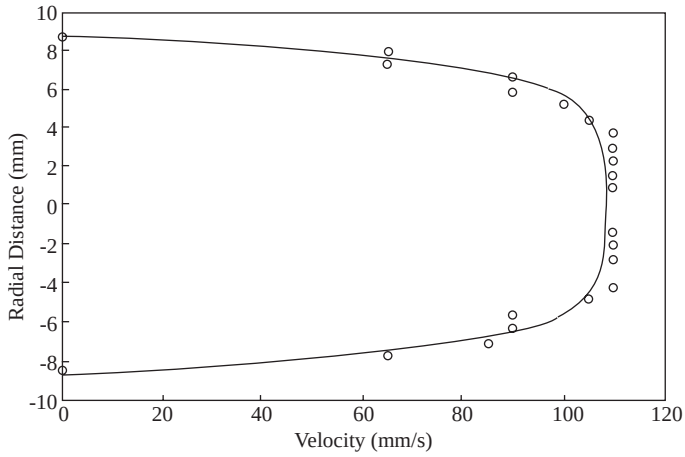

Figure 3. Velocity distribution of xanthan gum solution obtained by UDV under the following conditions: Polymer concentration = 1.0 kg/m^3, flow rate = 3 L/min, ultrasound frequency = 4 MHz. Solid line is given by V (mm/s) = –0.0003 r^6+ 0.0067 r^4– 0.1749 r^2 +108.26, where r is in mm.

Viscosity versus shear rate curves are calculated using the velocity profiles in Figures 2 and 3, and the corresponding pressure drops (78.7 and 132.0 Pa/m, respectively) as shown in Figure 4. A logarithmic scale is used for the vertical axis in order to make a visual observation of shear-thinning behavior, at both concentrations, easier than with a linear scale. Viscosities of the higher concentration solution are greater than those of the lower concentration solution. They were also determined using a Fann Viscometer at various shear-rate points. They agree well with those of the UDV technique, especially at both polymer concentrations. Hence, the presented method seems to capture the viscosities by the conventional method reasonably well.

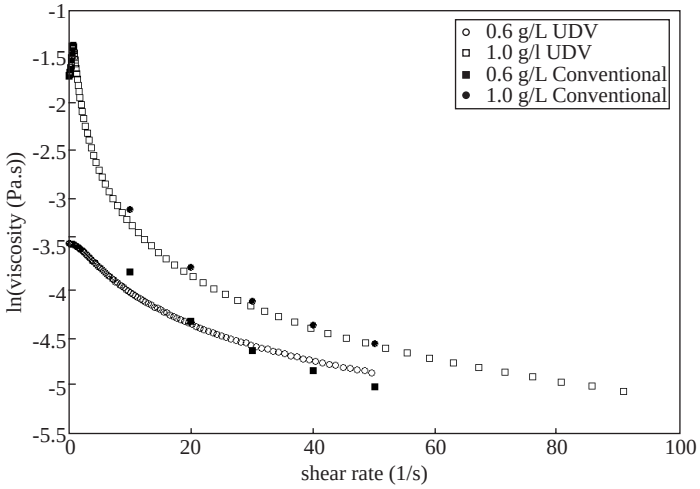

Figure 4. Viscosity versus shear rate obtained by using velocity distributions in Figures 2 and 3, and by the conventional viscometer.

In Figure 4, unexpected behavior of the viscosity versus shear rate at small shear rates occurs due to the finite value of the UDV resolution. Near the pipe center, the shear rate gets smaller and eventually becomes zero at the center. Those small differences in the velocity then become smaller than the velocity resolution and make it harder to detect the deformation in this region. Therefore, viscosity results corresponding to the shear rates at this region are unreliable. One way to overcome this problem is to operate at higher velocities so that viscosity uncertainties are confined to the smaller shear rates.

In order to investigate the effects of flow rate, experiments at 4 L/min were also conducted and the results are depicted in Figures 5 and 6. Polymer concentrations of the solutions were 0.6 and 1.0 kg/m^3, respectively. Similar to the lower flow rate results (Figures 2 and 3), in this case, higher solution viscosity associated with higher concentration results in an increased flat velocity region around the pipe center. The advantages of faster flow are two-fold. Larger deformations in the flow result in more accurate velocity measurement within the resolved space. Furthermore, the viscosity can be determined at a wider shear rate region than lower flow rate.

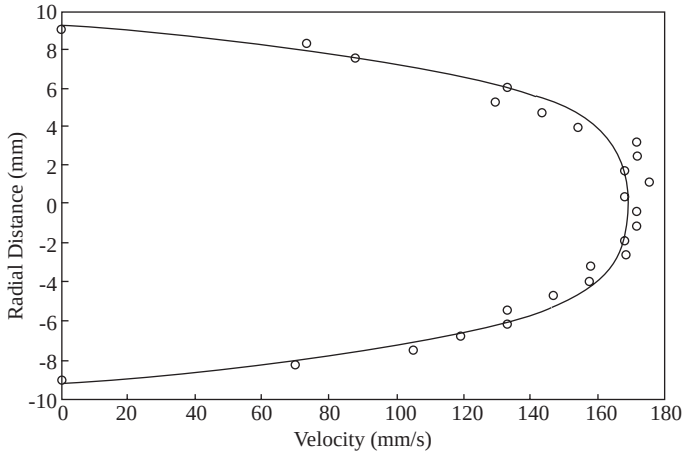

Figure 5. Velocity distribution of xanthan gum solution obtained by UDV under the following conditions: Polymer concentration = 0.6 kg/m^3, flow rate = 4 L/min, ultrasound frequency = 4 MHz. Solid line is given by V (mm/s) = –0.0205 r^4– 0.2523 r^2 + 168.46, where r is in mm.

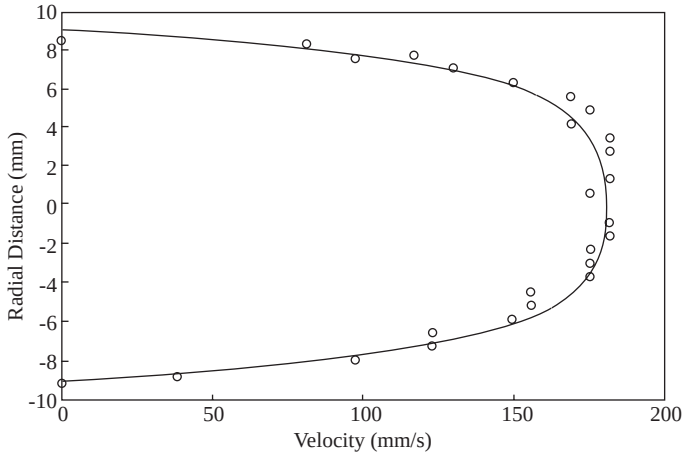

Figure 6. Velocity distribution of xanthan gum solution obtained by UDV under the following conditions: Polymer concentration = 1.0 kg/m^3, flow rate = 4 L/min, ultrasound frequency = 4 MHz. Solid line is given by V (mm/s) = –0.0003 r^6 + 0.0008 r^4 – 0.4713 r^2 + 180.48, where r is in mm.

Viscosities, which are calculated using the velocity profiles given in Figures 5 and 6, as well as the pressure drops (88.0 and 150.5 Pa/m, respectively) are shown in Figure 7 along with the conventional viscosity measurements. The viscosity values at the shear rates used in the conventional techniques are also listed in the Table. Ideally, the same viscosity versus shear rate behavior should be observed for a given solution regardless of the flow rate. The Table and the comparison between Figures 4 and 7 show that this technique is robust and is not affected by the flow rate, as long as flow remains laminar.

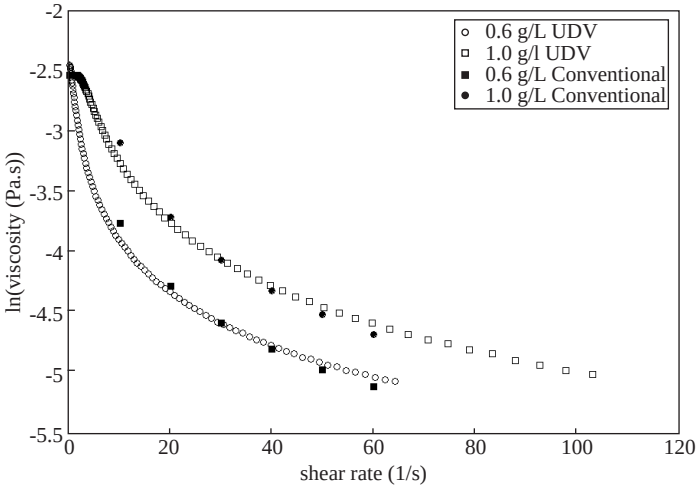

Figure 7. Viscosity versus shear rate obtained by using velocity distributions in Figures 5 and 6, and by the conventional viscometer.

In spite of the general similarities between the results in Figures 4 and 7, some crucial differences are also observed. It was possible to determine the viscosities at wider shear rates (up to 103.3 s^{-1}), in the case of 4 L/min flow rate, than the lower flow rate (up to 90.7 s^{-1}). The other difference is observed in the low shear rates. As pointed out above, higher velocities reduce negative effects of resolution limits in this region so that quality of the viscosity versus shear rate curve increases at low shear rates as shown in Figure 7.

Table. Viscosities at different shear rates. μ_H is the viscosity obtained using UDV at high (4 L/min) flow rate; $\mu_L$is the viscosity obtained using UDV at low (3 L/min) flow rate, $\mu_{conv.}$ is the viscosity measured using a conventional viscometer (Fann Viscometer), and $\dot{\gamma}$ is the shear rate.

	Viscosities at 0.6 kg/m^3 polymer, Pa.s			Viscosities at 1.0 kg/m^3 polymer, Pa.s		
$\dot{\gamma}$, s^{-1}	μ_H	μ_L	μ_{conv}	μ_H	μ_L	μ_{conv}
10	19.9×10^{-3}	18.7×10^{-3}	23.3×10^{-3}	38.2×10^{-3}	39.4×10^{-3}	45.4×10^{-3}
20	12.9×10^{-3}	13.3×10^{-3}	13.7×10^{-3}	23.3×10^{-3}	22.2×10^{-3}	24.5×10^{-3}
30	10.1×10^{-3}	10.7×10^{-3}	10.1×10^{-3}	17.4×10^{-3}	16.2×10^{-3}	17.1×10^{-3}
40	8.4×10^{-3}	9.0×10^{-3}	8.1×10^{-3}	13.7×10^{-3}	12.7×10^{-3}	13.2×10^{-3}
50	7.2×10^{-3}	7.9×10^{-3}	6.9×10^{-3}	11.6×10^{-3}	10.4×10^{-3}	10.8×10^{-3}
60	6.4×10^{-3}		6.0×10^{-3}	10.1×10^{-3}	9.2×10^{-3}	9.2×10^{-3}

It should be noted that data acquisition by UDV was completed within 1 s and processing the data was carried out in a matter of minutes, so that measurement of the viscosity of non-Newtonian liquids was accomplished at a wide shear rate region (0 to 100 s^{-1}) in a short time; whereas characterization of the viscosity within such a shear rate region would have required much longer measurement time by means of a conventional viscometer. Therefore, the presented technique shows promise as an online viscosity sensor for production lines.

Conclusions

The presented results allow one to draw the following conclusions:

Steady velocity profiles can be determined in 1 s using the UDV technique.

Velocity distributions become more flat near the pipe center with increasing polymer concentrations due to more pronounced non-Newtonian effects.

Better experimental results were obtained at higher flow rates due to a decrease in the negative impact of the velocity resolution. Further, higher flow rates make it possible to operate at wider shear rate ranges.

The viscosities obtained by UDV and the conventional technique agree well with each other at the polymer concentrations and flow rates used in the experiments

It has been shown that the viscosity of non-Newtonian fluids can be obtained in a wide range of shear rates and in a matter of a few minutes using the presented technique. Therefore, the method can be used as an online viscometer for process control purposes.

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