DEVELOPMENT OF AN INDUSTRIAL UVP+PD BASED RHEOMETER - OPTIMISATION OF UVP SYSTEM AND TRANSDUCER TECHNOLOGY

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A complete UVP+PD system and methodology that meets the industrial requirements has recently been developed at SIK in collaboration with CPUT and industrial partners. The updated UVP+PD methodology and system has now been successfully installed in industry for different industrial applications including; fat crystallization, heat treatment, fiber flows, injection grouting, CIP cleaning and in-line mixing. The new industrial version of the UVP+PD system features new transducer technology, electronics, new signal processing techniques featuring multiple velocity estimation algorithms and deconvolution and also a complete UVP+PD software known as RheoFlow™. It is currently the only system capable of true non-invasive in-line flow visualization and rheometry measurements in real-time through stainless steel.

Keywords: Ultrasonic Velocity Profiling, in-line rheometry, industrial applications, ultrasonic transducer

1 INTRODUCTION AND HISTORY

Understanding the rheological behavior of industrial fluids such as concentrated suspensions is important in the analysis and control of many industrial processes. More than 95% of the fluids used in industry are structured fluids i.e. non-Newtonian fluids that exhibit complex flow behavior over wide ranges of shear rates. In addition, these fluids are almost exclusively opaque and contain a high concentration of solids/particles with size distributions ranging from microns up to several cm in length. The trend within the fluid industry is towards continuous production, leading to an increasing demand for new and improved methods that allow real-time monitoring of quality parameters and fast process control [1]. The consistency and viscosity can be described by fluid rheology and are frequently used as quality control parameters. Rheological properties can be correlated with product microstructure, they govern the performance of unit operations and detailed knowledge is fundamental for the design of new process equipment and for predicting e.g. heat transfer. The determination of rheological properties in-line, in real time, thus has a great economic impact and is important from a quality perspective for the development of innovative and competitive products. This is also a prerequisite for efficient process control.

The most promising in-line viscometer concept is based on the combination of volumetric flow rate measurements in combination with pressure difference measurements and this concept has been known for more than 100 years [1-3]. However, since instruments using this concept are based on the measurement of the average volumetric flow rate, they only provide viscosity at one shear rate, or at most, a few shear rates. The current in-line and on-line techniques available for industrial applications are generally unable to cope with large particulate suspensions and are unreliable when non-Newtonian fluid systems are considered, according to recent reviews [1–3]. Moreover, commercial process rheometers are often based on intrusive techniques that disturb the flow, which also results in cleaning problems.

In the mid 1990's several research groups proposed to use a multi-shear rate method based on measurements of velocity profiles in combination with a pressure difference (PD) in order to estimate rheological flow properties directly in-line. Both optical techniques such as laser Doppler anemometry (LDA) and magnetic resonance imaging (MRI) were proposed, but found impractical for industrial applications due to several limitations such as; high cost, requiring transparent fluids, long acquisition times etc. The Ultrasonic Velocity Profiling (UVP) or Pulsed Ultrasound Velocimetry technique was first introduced and adapted for measurements in opaque, general fluids, in the 1980's [4]. UVP has since then been accepted as an important tool for measuring flow profiles in opaque liquids in research and engineering. The UVP technique has now been expanded to include e.g. 2D/3D-flow mapping as well as in-line tube viscometry.

The in-line concept for enhanced tube viscometry combining the UVP technique with simultaneous Pressure Difference (PD) measurements is now known as the UVP+PD method. The UVP+PD in-line rheometer concept was proposed in the literature for the first time over 15 years ago and has been investigated by many authors [5–9]. Although the initial results demonstrated that the UVP+PD method had the potential to become an important industrial tool for flow visualization, process monitoring and control, there still exists no commercial UVP+PD system on the market. This is due to the complexity of real industrial fluids and the harsh conditions within the fluids industry. The system must e.g. be designed to operate over wide temperatures and pressure ranges and the measurements must be non-invasive, real-time, robust and user friendly. It is thus very difficult to meet all of these industrial requirements at the same time.

A scientific collaboration was initiated in the year 2000 between SIK-The Swedish Institute for Food and Biotechnology, ETH-Zurich, Switzerland and Met-Flow SA, Lausanne, Switzerland with the aim to develop and improve a complete UVP+PD and system method for improved measurement accuracy in industrial applications. Starting in 2008, SIK found a new scientific partner in Cape Peninsula University of Technology (CPUT), Cape Town, South Africa. The projects have been very successful with several outputs: 3 PhD's, several MSc's, a large number of journal and conference articles as well as patents [10-14].

2 CURRENT LIMITATIONS WITH THE UVP+PD METHOD

2.1 Transducer technology and interfaces

According to the literature [1,5-7,10-11], the UVP+PD systems used so far were all based on traditional and simple components, such as, commercially available submersion type transducers, simple pipe flow adapter cells for housing the transducers and pulser-receivers with simple velocity estimation algorithms. The UVP+PD systems used therefore have several limitations in measurement accuracy, mainly due to the high uncertainty in the near wall region owing to the ultrasonic near field. This leads to poor accuracy of the measured velocity gradient close to pipe walls. For volumetric flow rate measurements this is not critical, but for in-line rheometry the velocity gradient in the high shear region near the walls combined with the pressure difference over a fixed distance of pipe length is used to determine the shear dependent viscosity. The measured velocity gradient must thus be correct in order to obtain the true flow curve.

2.2 Attenuation, wall effects, sound velocity etc.

Other problems include, depending on the installation method, attenuation, wall effects and the finite size of the measuring volume which partially extends over the wall interface and refraction of the ultrasonic wave (Doppler angle changes). For invasive set-up's distortion caused by cavities situated in front of ultrasonic transducers, measurement volumes overlapping wall interfaces and sound velocity variations as well as physical changes of the ultrasonic beam shape and intensity, are also important factors leading to poor measurement accuracy [10-12].

2.3 Non-linear model fitting approach

To date, the shear viscosity and rheological parameters have been calculated from a non-linear fit of the measured velocity profiles and pressure drop data to e.g. the integrated form of the power law model. However, a model-fitting approach requires detailed knowledge about the wall positions as well as a-priori knowledge about the rheology of the fluid under investigation in order to provide realistic initial estimates. The application of a model-fitting approach for rheological characterization produces unrealistic results, as the fitted parameters are sensitive to the position of the pipe wall and vary significantly even over the minimum channel distance or i.e. the distance between the velocity sampling points [10-11]. Moreover, industrial fluids rarely exhibit single model flow behavior over a wide range of shear rates.

3 DEVELOPMENT OF AN INDUSTRIAL UVP+PD BASED RHEOMETER

3.1 The new delay line transducer concept

The near field problem was solved by the introduction of new transducers featuring a delay line. The delay line in this case is a material or several materials, attached to the front of the transducers, which are optimized for beam forming and contain the near field, thus focusing the beam on the liquid wall interface. The transducer has a curved front with angle compensation, thus perfectly matching the radius of the pipe. Experimental set-up's at SIK comprising Doppler string and needle phantoms and a robot for mechanical X,Y,Z scanning of the acoustic pressure field in front of the transducers and for estimating the physical dimensions of the sample volume along the measuring line were used to optimize the transducer performance. Fig. 1 shows the new delay line transducer and a schematic diagram of the flow adapters with delay line transducers installed. More information on the delay line transducers and the improved accuracy in the near wall region can be found in [14].

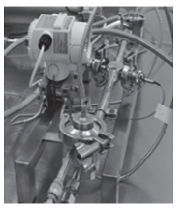

Figure 1: New delay line transducer (left) and complete UVP+PD test section with delay line transducers installed.

3.2 The new non-invasive sensor concept

Industrial unit operations often involve high temperatures and pressure levels as well as abrasive materials or corrosive fluids. Consequently, there is a large interest from industry to obtain a complete sensor unit that can be used to measure non-invasively through stainless steel pipes. Several ultrasonic time-of-flight or Doppler based flow meters of the clamp-on type have appeared on the market, but it has been shown to be very difficult to accurately measure the complete velocity profile and gradient near the wall using this set-up in combination with stainless steel pipes due to several reasons; impedance matching, attenuation, beam split modes, internal reverberation and beam refraction. To overcome previously mentioned problems, a new non-invasive sensor unit has been developed and optimized for stainless steel pipes. The sensor unit consists of a transducer, delay line, wedge, attenuators and acoustic couplants. The configuration provides optimum acoustic beam properties, such as, beam forming, focusing and coupling and impedance matching. It further provides an optimum beam path through material layers and into the fluid medium as well as sensor protection. The configuration is designed to generate or eliminate different types of waves in any solid or semi-solid materials that could be used for non-invasive measurements. The sensor “block” can either be an integral part of the material wall layer (e.g. pipe wall) or used as a clamp-on device. Fig. 2 shows a 3D-model of the non-invasive sensor unit with mounting device.

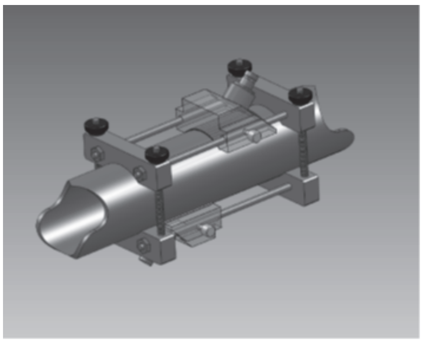

Figure 2: 3D-model of the non-invasive sensor unit with mounting device.

Fig. 3 demonstrates that it is possible to obtain accurate and identical velocity profiles in a moderately shear-thinning industrial fluid using both the new delay line transducers with a flush mounted configuration non-invasively through Plexiglas and stainless steel using the non-invasive sensor unit. Fig. 4 shows a spectral plot of a single velocity profile for an industrial detergent measured under true industrial conditions through a 51mm stainless steel (316L) pipe using the novel non-invasive sensor unit.

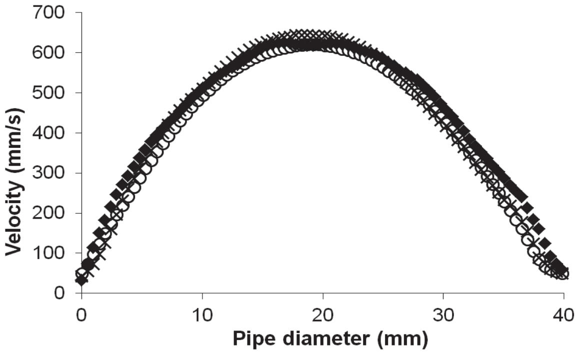

Figure 3: Velocity profiles measured using a flush mounted configuration with delay line transducers (open circles) and non-invasively through Stainless steel (crosses) and Plexiglas (filled diamonds) using the non-invasive sensor unit with mounting device.

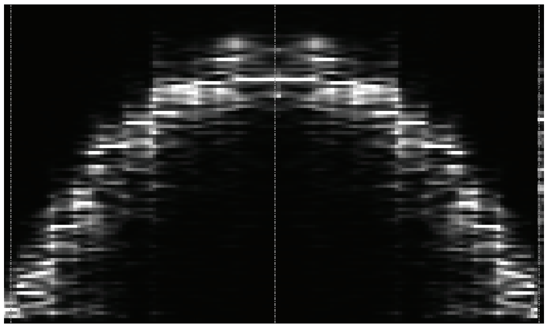

Figure 4: Spectral plot of a single velocity profile measured through 51mm stainless steel 316L pipe using novel non-invasive sensor unit.

3.3 Deconvolution & velocity estimation algorithms

The new UVP-DAQ system and software has been upgraded to include several new velocity estimation algorithms (FFT, time-domain, PBurg spectral etc.) that can be used simultaneously to improve the measurement accuracy under real industrial process conditions. Velocity data close to pipe walls, which is critical for accurate fluid characterization, are further corrected for by implementing a deconvolution procedure. More information is presented in detail in [10-14].

3.4 The non-model approach for obtaining the true shear viscosity distribution

As mentioned in Sec. 2.3 the application of a model-fitting approach for the rheological characterization produces unrealistic results due to several reasons. Therefore, an alternative method was developed in which the shear viscosities as function of shear rates are determined directly from the measured velocity profile and pressure drop data. The yield stress can be obtained once the plug radius has been automatically determined from the deconvolved velocity profile(s). Fig. 5 shows the true shear viscosity distribution of four industrial products obtained under realistic processing conditions using the direct non-model approach/method, which was found to be both more robust and accurate as it can capture e.g. a Newtonian plateau.

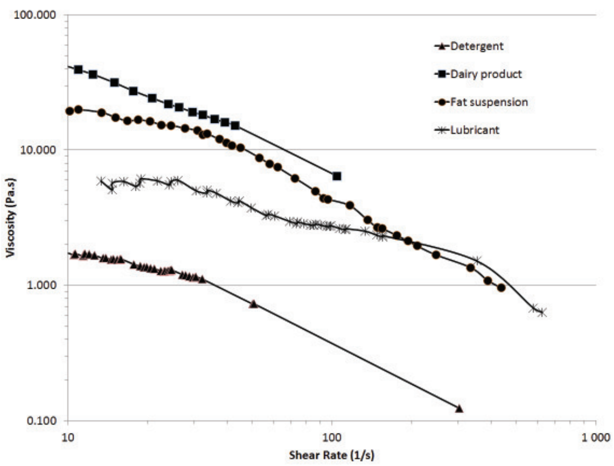

Figure 5: Shear viscosities as function of shear rates for four industrial products obtained using the non-model approach.

4 STAGE OF DEVELOPMENT

A few prototype systems have been developed and successfully installed by SIK in Europe under industrial conditions with large international companies, Additional systems have been developed and successfully used e.g. in an EU-project Healthy Structuring FOOD-CT-2006-023115. New complete sensor systems and a new integrated UVP-DAQ electronics are being developed and finalized. Both are in the final stage of development and are ready for final laboratory testing before customization. New software is currently being tested for industrial applications to be fully compatible with existing commercial systems for integrated process control.

5 SUMMARY

A new complete UVP-DAQ in-line rheometry system and methodology including unique software algorithms, together with novel sensor technology has been developed over the past 10 years and validated under real industrial process conditions. This inventive system and method can be applied to a wide range of fluids and industrial applications, e.g. oil, petroleum, food, minerals, chocolate, explosive emulsions, pharmaceutical industry and more. Our final industrial system and method will be able to accurately visualise the flow, determine the flow-rate, rheological properties and concentration of solids. Shear viscosity as a function of shear rate is determined directly from the measured data without using any model fitting procedure. The industrial system and method will be a unique product thus not directly competing with any other product on the market. It is currently the only system capable of true non-invasive in-line flow visualization and rheometry measurements in real-time through stainless steel.

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