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An integrated in-line fluid characterization system for industrial applications

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1 Introduction and background

Industrial fluids are prevalent in most processing plants and are typically multiphase fluid systems. These fluids are transported in pipes between processes. Understanding their behaviour and flow dynamics is fundamental in optimizing such processes but also for improved quality control. In addition, it could provide insight into the microstructure, which would facilitate the development of new innovative materials, according to Roberts [1-2]. A few examples of industrial fluids and their flow curves are shown in **Fig. 1**.

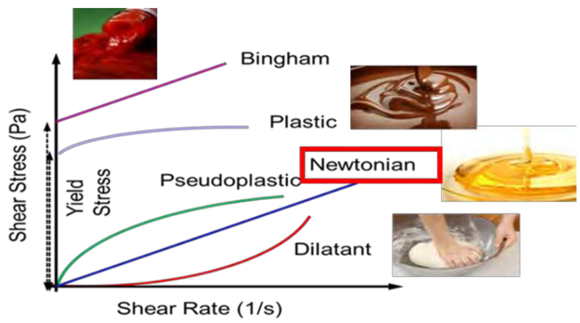

Fig. 1 Examples of industrial fluids and their flow curves

1.1 Industrial problem

Flow behaviour of liquid flows must be continuously monitored and controlled. The flow properties of industrial fluids are directly linked to product quality. Viscosity is the most important quality control parameter and available methods, such as rotational rheometers (e.g. Anton Paar, TA Instruments, Malvern) are either off-line, single point measurement or invasive. A few in-line viscometers have been tested, with limited success for industrial applications, for example the Proline Promass 83I from Endress+Hauser AG[3] and the TT-100 In-Line Viscometer from Brookfield[4]. Conventional process viscometers are in general limited to Newtonian fluids, as they provide viscosity at one shear rate at the time and are often based on intrusive techniques thus leading e.g. to cleaning problems. Currently, no practical in-line solution exists for non-Newtonian and opaque particulate fluids that meet industrial requirements[1-2].

1.2 Tube viscometry

Tube viscometers, combining flow rate and pressure difference measurements, are the most commonly used instruments for the measurement of viscosity in-line due to their relative simplicity, low cost and good accuracy [5]. A schematic of the tube viscometer concept with relevant formulae for obtaining fluid rheology is given in **Fig. 2**.

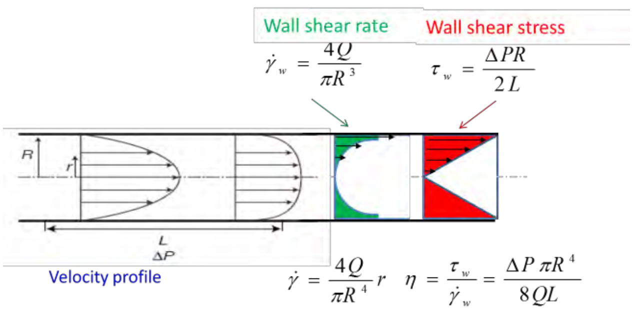

Fig. 2 Tube viscometer concept

Rheological characterization using tube viscometers in-line is however time consuming and impractical for process control as several pipes with different diameters are required. Recently, the Krohne

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Viscoline[6)] was introduced to the market. In this instrument, two static mixers are used to overcome the need for multiple pipes but the instrument cannot be used with particulate fluids and is also only applicable over a limited range of shear rates and is not possible to obtain complete flow curves.

1.3 The enhanced tube viscometer concept

The enhanced tube viscometer concept aiming to derive information on the flow behaviour of industrial fluids using the UVP+PD methodology, i.e. Ultrasound Velocity Profiling (UVP) with Pressure Difference (PD) is older than 30 years[7)]. A UVP+PD system consists of at least the following components: an instrument that can measure velocity profiles using the pulsed ultrasonic UVP technique[8)], accurate differential pressure and temperature sensors, suitable flow adaptors for installation fitted with ultrasound transducers, data acquisition systems as well as software for processing the data. More information relating to the UVP+PD methodology can be found in the literature[9-17)].

The UVP+PD methodology theoretically allows rheological characterization of opaque non-Newtonian fluids inline and in real-time which makes it ideal for industrial applications. Despite this, no in-line fluids characterization instrument based on Doppler velocimetry except for the Flow-Viz system meeting industrial requirements has been made commercially available. The system is presented below. This is mainly due to the many problems associated with the existing transducer technology, electronics and complex signal processing required for the measurements as well as very difficult software algorithms that are required for determining rheological parameters from the measured data[18, 24-25)].

2 Development of the Flow-Viz methodology and system

The Flow-Viz methodology and system is the result of several research groups that have systematically worked on this concept over a period of more than 14 years to ensure that the system can be used in industry for a quantitative analysis of the rheological properties of complex industrial fluids, see [24)].

2.1 Industrial requirements

In order for industry to use a measuring system it needs to comply with the following:

- Applicable to industrial fluids (high concentration of solids, opaque, non-Newtonian)
- Measurements under realistic processing conditions (same geometry and shearing conditions, comply with pressure and temperature levels)
- Easy installation with clamp-on sensors or spool pieces that allows for non-invasive measurements directly in the process line. (Must meet hygienic design and CIP criteria)
- Real-time and continuous measurements of fluid rheology. Data output that can be linked to existing process control systems
- Robust, non-model based, signal processing that requires no a priori knowledge and can cover complex flow behaviour (e.g. Newtonian plateau)
- Accurate yield stress determination
- Process monitoring & control applications

2.2 Development of new transducers

Commercially available transducers are typically immersion type pencil transducers[22-24)]. They must be installed in a spool piece with a cavity in front of the transducer in order to avoid measurements within the near field zone. The cavities influence the measurement of the velocity profile due to the increase of velocity at the actual pipe wall as well as problems with attenuation of the ultrasound signal. These problems were eliminated by the introduction of new ultrasound transducers incorporating a delay line[22-24)]. The delay line incorporates material that is fixed ahead of the transducer and flush with the pipe wall. It is used for beamforming and beam focusing, thus making it possible to have the focal point of the ultrasound beam at the wall interface. This allows for accurate measurements directly from the liquid wall interface and a well-defined and focused beam. The delay line transducer technology is presented in **Fig. 3**.

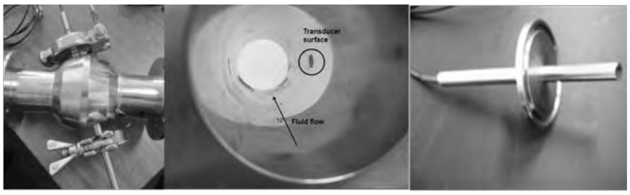

Fig. 3 Delay line pencil type transducer

2.3 Non-invasive transducer technology

Despite the success of the delay line concept, further development of the transducer technology was needed for industrial applications. In industrial processes it is an absolute requirement to measure non-invasively through stainless steel pipes but no such transducer technology has been commercially available [22-24)]. To overcome this limitation, new non-invasive sensor technology has been developed, optimized and validated for SS316L stainless steel process pipes of different diameters (12-150 mm) and wall thicknesses. The unique 0.2-10 MHz non-invasive sensor, shown in **Fig. 4** and **8**, consists of a transducer, wedge, attenuator and acoustic coupling media. Currently it is the only sensor solution that allows for true non-invasive Doppler velocity profile measurements in highly attenuating suspensions through stainless steel wall materials [22-24].

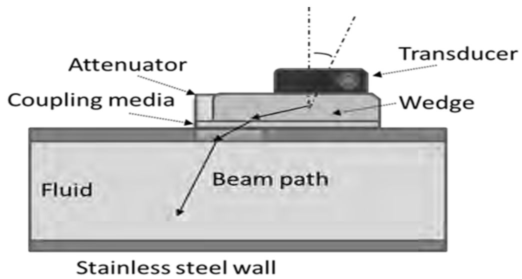

Fig. 4 Schematic of the developed non-invasive sensor technology

2.4 Optimization of Doppler velocity estimation

One problem with commercially available pulser-receivers is that they often rely on simple and single velocity estimation algorithms that require a low degree of signal processing in order to save time and cost. However, for attenuating industrial fluids this often leads to inaccurate results and a more sophisticated velocity estimation procedure is thus required. Within the Flow-Viz project, new firmware and software have been developed that allows velocity estimation using several different algorithms, for example FFT, time-domain, spectral, etc. Several algorithms can be used simultaneously to improve the measurement accuracy under real industrial process conditions. Using FFT, the velocity profile is typically estimated through a weighted mean of the Doppler power spectra from each depth and with a high sampling frequency, thus avoiding also the necessity of a deconvolution. **Fig. 5** shows an example of velocity estimation using different algorithms.

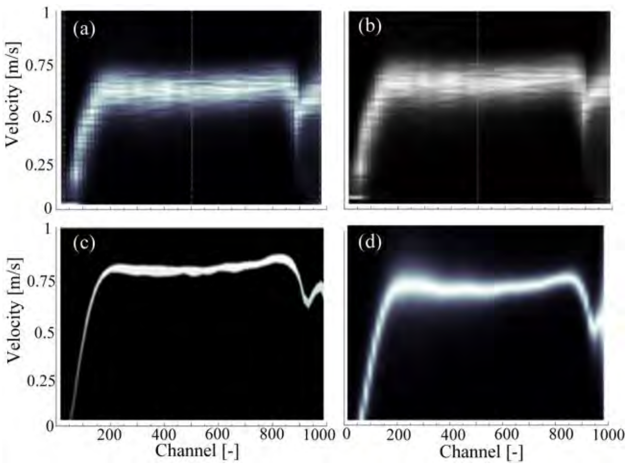

Fig. 5 Velocity estimation using (a) FFT, (b) Real-Time FFT, (c) time-domain and (d) spectral algorithms.

2.5 Conventional methods for obtaining fluid rheology

The most challenging aspect of the UVP+PD methodology is how to accurately obtain the fluid rheology. The most common method is to use a model-fitting approach involving constitutional rheological models, such as Bingham, power-law and Herschel-Bulkley. The main disadvantages with this approach are that it requires a priori knowledge of which model to use and the applicability of these models to complex fluids and the shear rate range[11-12,18]. Moreover, the Non-singleton mathematical fitting solution and the yield stress determination is difficult as even a small uncertainty in the determination of the wall position leads to inaccurate rheology results[11-12,18].

The second approach is to use non-rheological mathematical model approximations, such as polynomials or irrational powers[11,16]. Although this method does not require a priori knowledge about fluid rheology there are many problems associated with this approach. For example, polynomials are prone to fluctuations thus resulting in inaccurate shear rates. Secondly, the acoustic properties are not constant along the beam axis and there is often non-uniform flow behaviour over a wide range of shear rates, which cannot be handled by approximations using polynomials or irrational powers as discussed in the literature by[9,11,16].

2.6 Non-model based signal processing

As the traditional application of a model-fitting approach for the rheological characterization produces unrealistic results an alternative method has been developed within the Flow-Viz project. In this case, the slope of the measured velocity gradient is used to obtain the shear rates and the pressure drop data is used to determine the shear stress at the wall. The shear viscosities as function of shear rates are thus determined directly from the measured data. The yield stress is automatically determined from the measured plug radius. An absolute requirement for this method is the ability to obtain the full profile over the complete pipe diameter with high spatial resolution and non-invasive measurements of velocity data close to the pipe walls. This direct non-model approach has been verified to be both more robust and accurate as it can capture e.g. the transition from a Newtonian plateau to shear thinning behaviour[2]. The range of shear rates and viscosity that can typically be measured is shown in **Fig. 6**.

3 The Flow-Viz in-line fluids characterization system

Flow-Viz is a new fully integrated ultrasound based

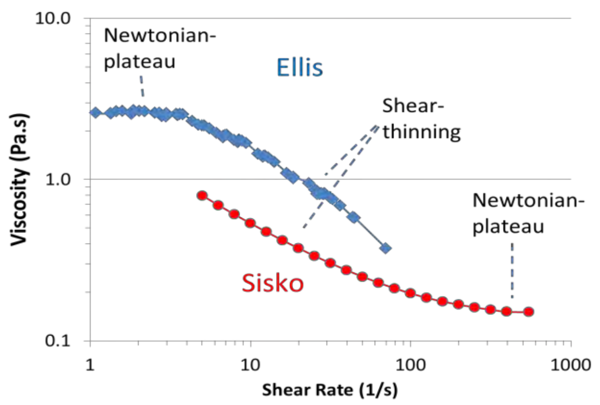

Fig. 6 Flow curve – shear thinning fluids with Newtonian plateaus.

in-line fluid characterization system that has been developed especially for opaque, non-Newtonian industrial fluids and it is designed to meet industrial requirements. The platform consists of an operator's panel housing the electronics, a sensor unit housing all sensors and the user interface (software). The system is presented in more detail in the following sections.

The industrial grade sensor unit is installed in the process network and makes up the measuring section. The measuring section is equipped with at least one pair of unique custom made non-invasive ultrasound transducer assemblies (Flow-Viz, Sweden), a differential pressure sensor with remote seals (ABB Automation Technology Products AB, Sollentuna, Sweden) and a non-invasive PT-100 sensor (Pentronic, Gunnebo, Sweden). The sensor unit further comprises a stainless steel cabinet protecting the heat-jacketed stainless steel pipe with diameters ranging from 10 mm ID up to DN150 (or larger). The sensor unit and the non-invasive transducer assembly are shown in **Fig. 7**.

New electronics has been developed to overcome

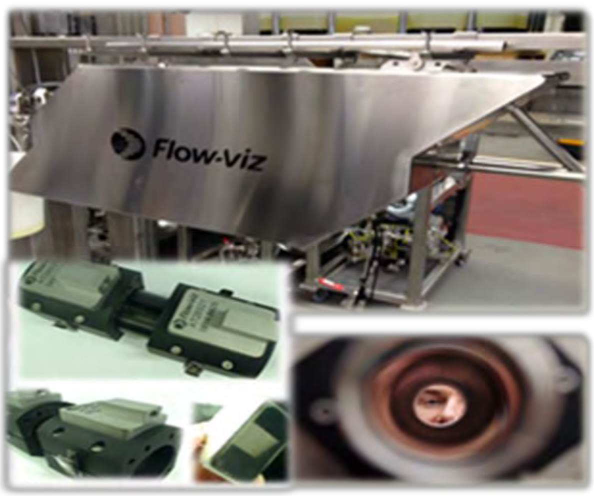

Fig. 7 The industrially approved sensor unit featuring the unique custom made non-invasive transducer assembly.

the main limitations with commercially available pulser-receivers, for example temporal and spatial resolution. The integrated hardware platform comprising a total of four analog and digital electronics boards and has been developed in collaboration with University of Florence, Schmid Elektronik AG (Münchwilen, Switzerland), Sika Technology AG and Sika Services AG Zurich, Switzerland)[19-21,24).

4 Examples of industrial applications

The following section provides three examples of industrial applications in different industries which have been investigated using the Flow-Viz system. The number of potential applications is increasing rapidly.

4.1 Ketchup

The Bostwick consistometer (**Fig. 8**) is a very simple instrument and has been used for more than 40 years in industry. It is a single point measurement device that requires sample removal. The desired sample is poured into the sample reservoir up to the top of the product gate. The product is released by pressing down on the lever arm and the product is allowed to run along the slope for 30 seconds. The value is interpreted as the consistency of the product but it cannot accurately describe the true flow properties of non-Newtonian fluids such as ketchup. Therefore process monitoring and control is not possible. **Fig. 9** shows the single point measurement results using the Bostwick at different viscosities and flow rates.

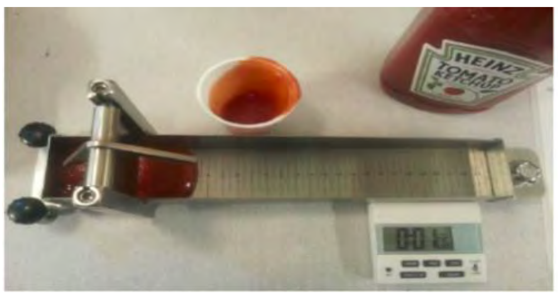

Fig. 8 Bostwick Consistometer

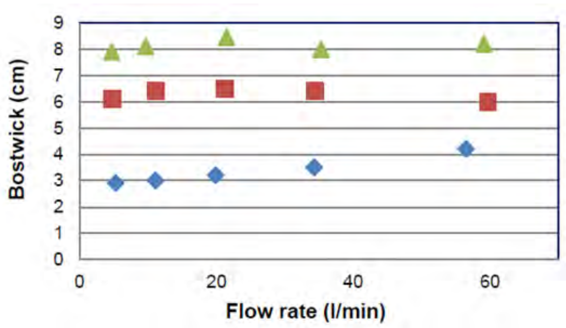

Fig. 9 Single point measurements of ketchup with Bostwick consistometer at different flow rates

The Flow-Viz system is capable of measuring an instantaneous velocity profile and to determine the fluid rheology in real-time and directly in the process line, thus eliminating the need for sample removal. **Fig. 10** shows a typical example of a velocity profile of an industrial fluid, Heinz ketchup, measured non-invasively through an SS316L stainless steel pipe with an inner diameter of 51 mm. The pipe wall can be clearly seen and the spatial resolution is here in the order of a few micrometres compared to, at best, one or several millimetres using other pulser-receivers.

The corresponding measured complete flow curves for three concentrations Heinz ketchup at different flow rates is shown in **Fig. 11**. The off-line measurement data from a rotary viscometer shows excellent agreement with the Flow-Viz system. This is an immense improvement on single point measurements and if this data is measured in real-time it can be used for quality control which will reduce waste with significant financial benefits.

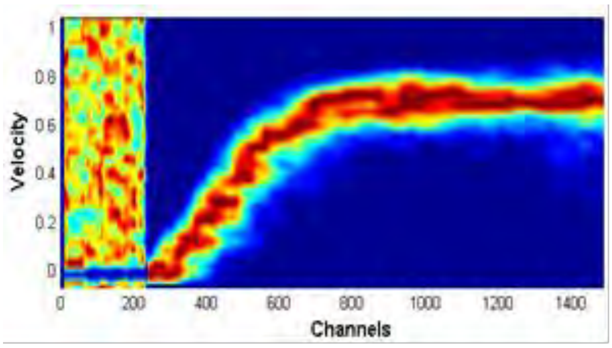

Fig. 10 Velocity profile of Heinz ketchup, (flow rate of 56 L/min)

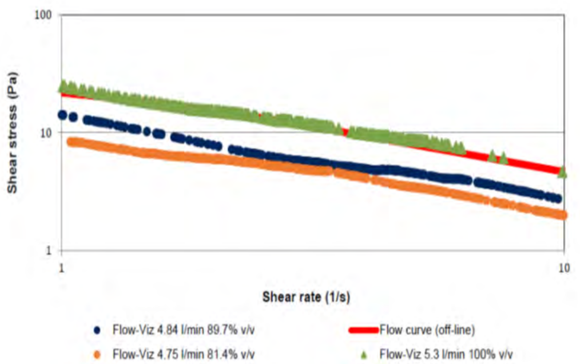

Fig. 11 Complete flow curves for different concentrations Heinz ketchup

4.2 Cement grouts

Cement grout is a construction material used to embed rebar in masonry walls, connect sections of pre-cast concrete, fill voids, and seal joints and prevent water ingress from the surroundings in tunnels. Grout is generally a mixture of water, cement, sand, often colour tint, and sometimes fine gravel. Grout is injected as a thick emulsion and hardens over time. A commercial grouting system with mixer, agitated storage tank, piston pumps and is shown in **Fig. 12**. The problem within the grouting industry today is quality control of the grout. The flow properties must be adjusted according to the rock conditions but even today, simple empirical devices are used in the field after a sample has been removed.

Although flow rate and pressure is constantly monitored, research conducted in the last 20 years have demonstrated that the piston pumps used produce pulsation flows which are difficult to measure with existing control instruments such as the commercial Logac system. The lack of accurate in-line measurements currently makes it difficult to obtain good grouting results and new inline and real-time instruments are needed[26]. Research conducted by KTH Royal Institute of Technology and SP-Technical Research Institute of Sweden using the Flow-Viz system has shown that much more accurate flow-rate measurement can be obtained with the new system. This is shown in **Fig. 12** above. Moreover, the project objective was also to measure the rheology in-line to enhance and maintain the quality of the grout during grouting operations. A secondary objective was to characterize different grout recipes and to investigate the effect of different additives, such as set control agents. This has already been shown to be feasible in a pilot plant study[27] and will now be tested in actual field conditions. An example of velocity profiles measured using the Flow-Viz system in cement grouts with different water/cement ratios is shown in **Fig. 13**.

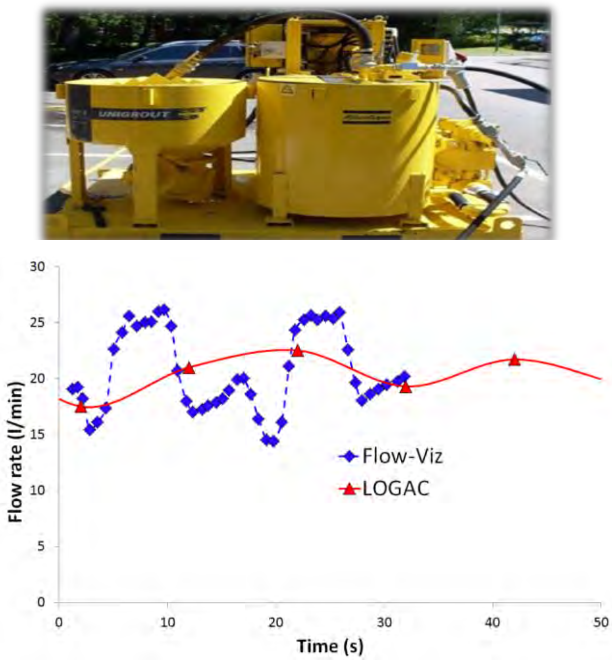

Fig. 12 Grouting application with mixer setup Variation in flow rate measured with Flow-Viz and Logac systems

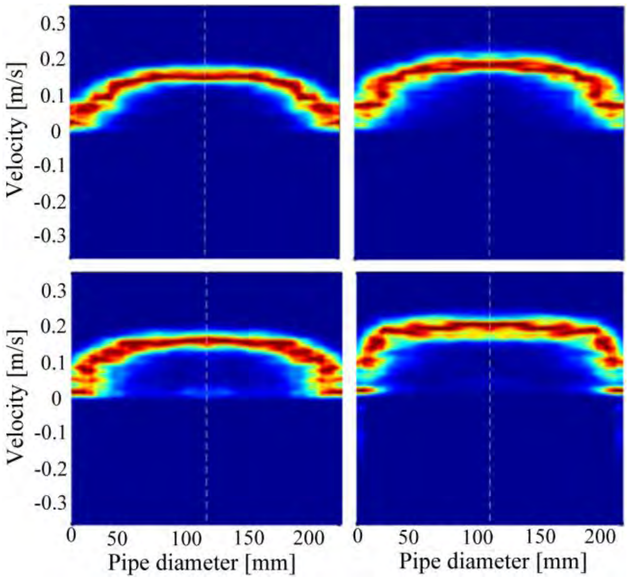

Fig. 13 Velocity profiles of different cement grout concentrations

4.3 Waste water – filter belt press flocculation control

Many WWT plants have sludge dewatering installations where treated waste water sludge is dewatered for final disposal using land applications. The objective is to produce a filter cake with the highest total solids content. To achieve this, the plant needs to be controlled optimally. One of the most expensive inputs in these plants is the polymers used as flocculants. Controlling the optimum dosing cannot currently be done in the process in real-time. It has been shown that huge savings can be made by optimizing the dosing rates using rheology [28-29]).

Tests have been done with a tube viscometer fitted with the UVP-PD system at a WWTP using secondary sludges feeding a filter belt press. The measured and calculated velocity profiles of 4.6% sludge are shown in **Fig. 14** and show an excellent fit. Rheological characterization of the sludges were compared using the two systems and results (**Fig. 15-Fig. 14**) indicates the result for the 4.6% sludge showing that sludge can be measured successfully opening up the possibility to link the rheological parameters to optimum polymer dosing. This is currently being investigated.

5 Summary

In this work we have presented the world's first commercially available embedded in-line fluids characterization system, "Flow-Viz". It has been specifically designed for the non-invasive, in-line, continuous, real-time velocity profile and rheological assessment of opaque, non-Newtonian industrial fluids.

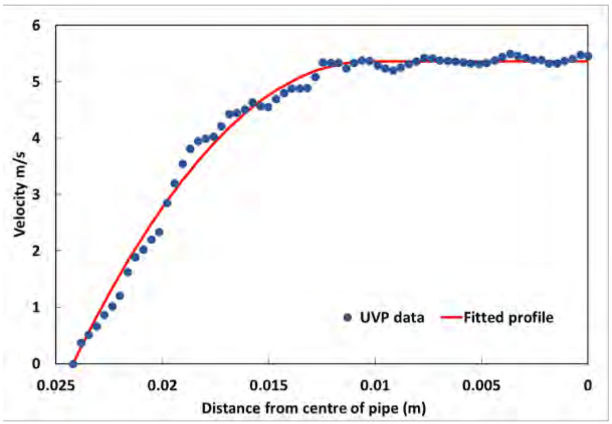

Fig. 14 Measured and fitted velocity profiles for a 4.6% waste water sludge

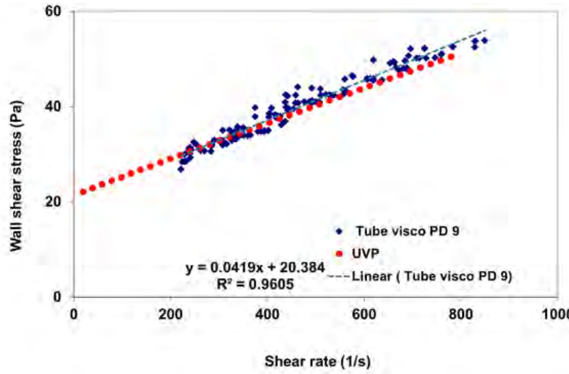

Fig. 15 Sludge rheology comparison between tube viscometry and UVP+PD for 4.6% w/w wastewater

The Flow-Viz system has been successfully installed in pilot plants of international companies and used also for academic research. The technology has been applied to a wide range of fluids and industrial applications, e.g. oil, petroleum, food, minerals, chocolate, explosive emulsions, pharmaceutical industry and more. An international patent has been filed. The main limitations of the system include: multiphase flows containing gas, need for reflectors and maximum particle concentration. The challenge is also to convince industry to replace current standard methods.

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