Application of in-line ultrasound Doppler based UVP-PD method to concentrated model and industrial suspensions

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The applicability of the non-invasive UVP-PD method (Ultrasound Velocity Profiling and Pressure Difference) to concentrated model and polydisperse industrial suspensions was investigated. The UVP-PD method was successfully applied to a large number of model and industrial suspensions containing suspended soft to hard particles of different sizes and shapes. The particle size distributions ranged from sub-microns up to large solid pieces of 3-4 cm. In addition, investigated suspensions differed in solids concentrations, particle composition and fluid matrix. Both model and food suspensions were analyzed in-line in pressure driven, steady shear flow at different volumetric flow rates in an experimental flow loop where rheological flow properties were determined, directly in-line. The ability of the UVP-PD method in combination with measurements of the sound velocity in-line to determine concentration of solids and to monitor a gradual change in rheology with structure degradation directly in the flow loop was demonstrated. A comparison with conventional off-line measurements showed that the UVP-PD method is more versatile and off-line techniques only are valid for suspensions containing particles smaller than the gap width.

Keywords: Rheology, suspensions, non-Newtonian, in-line, ultrasound

1 INTRODUCTION

Understanding the rheological behavior of concentrated suspensions is of outmost importance in the analysis and control of many industrial processing operations. With processes becoming more continuous and with rapid product changes there is an increased need to switch from conventional off-line rheometers to new in-line techniques, Roberts [1]. However, industrial concentrated suspensions often contain particles with size distributions ranging from microns up to several cm in length which show non-Newtonian behavior over wide ranges of shear rates. Commercial process rheometers generally unable to cope with large particulate suspensions and unreliable when non-Newtonian fluid systems are considered according to recent review articles, Barnes [2] and Roberts [1].

The pulsed Doppler Ultrasound Velocity Profiling (UVP) technique has become an important tool for measuring velocity profiles in research and engineering during the last decade, Takeda [3]. UVP has now been successfully applied to many industrial fluid flows ranging from environmental-, biomedical, pulp, hydraulics and food process flows.

A novel method for in-line rheometry employing the pulsed ultrasound-Doppler velocity profiling (UVP) technique combined with Pressure Difference (PD) has been developed and is described in literature, Ouriev [4] and Wiklund et al [5]. Recently, UVP has recently been successfully tested for transient flows and turbulent flows and the UVP-PD method has been extended to include determination of wall slip and yield stress in-line, Ouriev [4] and Wiklund et al. [6]. Recently, transient two-phase flows with displacement of fluids has been studied and compared with CFD simulations, Regner et al. [7].

A literature survey over existing UVP and UVP-PD studies was presented by Wiklund [8]. According to literature, all published UVP and UVP-PD studies on model and industrial suspensions have contained either small monodisperse particles or particle distributions almost exclusively in the micrometer range.

In the present study, the applicability of UVP and the UVP-PD method to concentrated model- and polydisperse industrial suspensions with size distributions ranging from microns up to cm was investigated. The suspensions contained suspended soft- to hard particles of many different concentrations, sizes and shapes. In addition, the investigated suspensions differed in solids concentrations, particle composition and fluid matrixes.

All suspensions were analyzed in-line in pressure driven, steady shear flow at different volumetric flow rates in an experimental flow loop and rheological flow properties were determined, directly in-line. Obtained rheological parameters were then compared with off-line measurements using conventional rotational rheometers. In addition, the added benefits of extending the methodology to include measurements of the sound velocity in-line and the use of flow adapter wall membranes were investigated. Detailed information about the UVP-PD method is given in Wiklund et al. [5].

2 MATERIALS

2.1 Model suspensions

The first set of model suspensions consisted of glass beads suspended in Glycerol. The average particle diameter of the smallest particles was 4µm and 15µm for the largest. The second set of model suspensions consisted of starch particles with particle size distribution of 30-300µm suspended in a syrup with viscosity ranging from 49mPas to 1.2 Pas at 20°C. The third set of model suspensions consisted of polyamide 12 (PA 12) particles suspended in rapeseed oil (η=66mPas at 20°C). The particles had a very narrow particle size distribution. The average particle diameter of the smallest particles was 11µm and 90µm for the largest.

2.2 Industrial suspensions

Several industrial suspensions were investigated in-line using the UVP-PD method ranging from cellulose pulp to slurries and several kinds of foods. They differed in solids concentrations, particle composition and fluid matrix. Soft and hard particles with size distributions from submicron, microns to large solid pieces of up to 3-4 cm in length were used, e.g. aggregating clay particles, spherical glass beads, rod-like pulp and fruit fibers, kidney shaped seeds, odd shaped herb-, fish-, and vegetable pieces. In addition, the investigated industrial suspensions differed significantly in flow behavior from strictly Newtonian to shear-thinning and slightly shear-thickening. A summary of the investigated fluid systems' approximate concentrations and particle sizes/distributions is given in Table 1.

3 EXPERIMENTAL METHODS, SET-UP AND INSTRUMENTATION

3.1 Off-line viscometry

The flow behavior of the model suspensions and industrial suspensions were analyzed off-line using conventional rheometers, Bohlin VOR and Rheologica Stresstech. Concentric cylinder geometries with a bob diameter of 20-25 millimeters were used. The viscosity was measured at several temperatures and shear rates corresponding to those in the experimental flow loop. Particles larger than a mm were removed prior to measurements due to gap restrictions.

3.2 Flow loop and experimental equipment

The flow loop is shown in Figure 1 and is described in detail together with the methodology elsewhere, [5]. It consists of a closed stainless steel piping circulation system with an inner pipe diameter of 35.5 mm. A positive displacement pump, On-line OL2/0025/10, Johnson Pump, UK was used to re-circulate the sample fluids through the piping from a stainless steel product tank with an agitator. Several temperature transmitters, mass and volumetric flow meters were installed in order to accurately monitor and characterize the flow. Two pressure sensors, ABB ETP80, Sweden, separated 2.42m apart, were used to measure the pressure difference. Four ultrasound transducers, 2-4 MHz, TX-line, Imasonic, France were installed in a novel flow adapter cell, described in section 3.4.

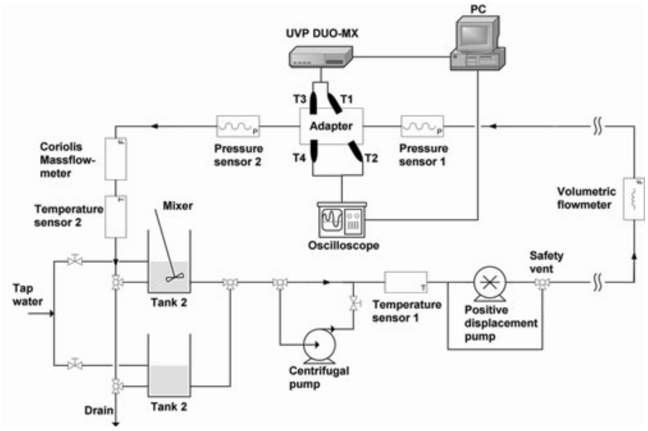

Figure 1: Schematic of the experimental flow loop and instrumentation.

3.3 Data acquisition and UVP-PD software

Velocity profiling was performed using the latest available UVP-Duo-MX model with a Multiplexer, Met-Flow SA, Switzerland, [9]. The UVP-Duo instrument and all hardware devices are connected to a master PC for data acquisition, data processing and analysis using novel Matlab-GUI based software developed within this project. Communication with UVP hardware is implemented with an Active X library supplied by Met-Flow SA. All ultrasound signals are continuously monitored using a 4-channel digital oscilloscope, Agilent Technologies, model 54624A, USA. Velocity profiles, pressure difference, mass or volumetric flow rates, temperature and velocity of sound as function of e.g. time, temperature were recorded and processed in-line.

3.4 Flow adapter and in-line sound velocity measurements

A novel ultrasound transducer flow adapter cell, shown in Figure 2, was developed and fitted with two transducer pairs. All transducers were installed with a membrane in front of the transducers in order to eliminate the near field problem, increase the signal quality close to the wall and to enable true non-invasive measurements. The membranes were made of aluminium, steel or Plexiglas and the thickness were optimized for maximum transmission of ultrasound. The first transducer pair was used for in-line signal amplitude measurements and sound velocity determination based on time-of-flight method (Δt), between transducer T1 and T2. The second transducer pair was used for non-invasive measurements of velocity profiles. Detailed information is given in Wiklund et al. [5]. The methodology for in-line sound velocity determination was developed together with Birkhofer et al. [10].

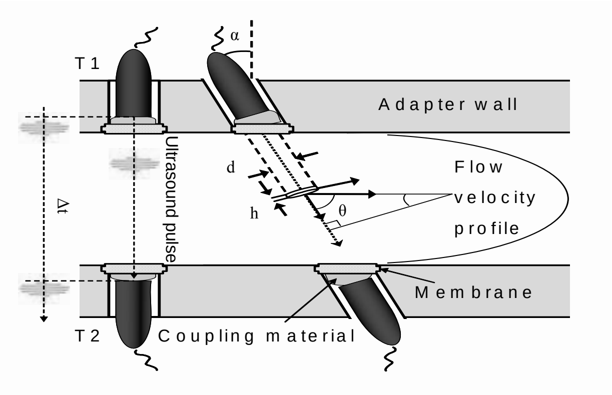

Figure 2: Schematic of the flow adapter fitted with two transducer pairs for non-invasive measurements of velocity profiles and principle of in-line sound velocity determination based on time-of-flight measurements.

4 RESULTS AND DISCUSSION

4.1 Velocity profiles and effects of particle size, shape and concentration

The results show that UVP could successfully be applied to a large number of highly concentrated bimodal and polydisperse model and industrial suspensions. In this study, we have covered a much wider range of suspension characteristics than what has so far been reported in literature.

Results further showed that instantaneous and complete velocity profiles could be obtained in all investigated suspensions after optimization. It was concluded that polydisperse suspensions containing large amounts of small particles up to approximately 10µm have the strongest influence on the signal quality, discussed in section 4.3. It was shown that UVP can be used for particle concentrations up to approximately 45% by weight for more or less spherical particles in suspensions where hydrodynamic forces dominate. In addition, UVP technique can be used for particle concentrations up to at least 8% by weight for suspensions containing network-building rod-like fibers, Wiklund et al. [6].

4.2 UVP-PD In-line viscometry

Experimental results show that a rapid or gradual change in both rheology and shape of the velocity profiles over time, e.g. from pronounced flat plug-flow non-Newtonian behavior into more Newtonian behavior can be monitored. Results from our work on seafood chowder and vegetable soup have also shown the UVP-PD method capable of monitoring a gradual change in rheological behavior with structure degradation directly in the process line.

An example of UVP-PD in-line monitoring of structure degradation in a vegetable sauce containing large solid particles of up to 3-4 cm is shown in Figure 3. It is shown how the power-law flow exponent n and consistency index K changes with increasing shear rates and thus increasing structure degradation in the flow loop.

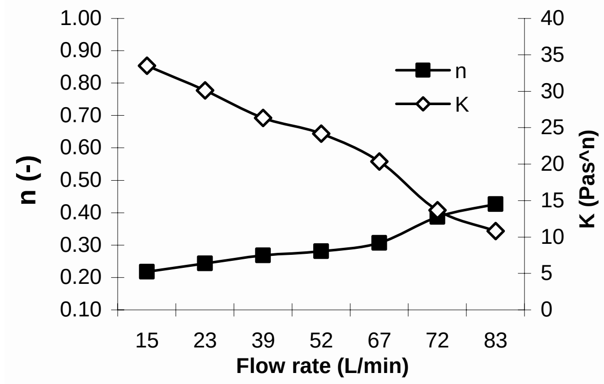

Figure 3: UVP-PD in-line monitoring of structure degradation in a vegetable sauce with increasing shear rates in the flow loop.

Figure 4 shows a comparison example between shear viscosities for two food suspensions, a low-fat strawberry yoghurt and a cheese sauce measured in-line using UVP-PD with off-line measurements using a Bohlin VOR rheometer.

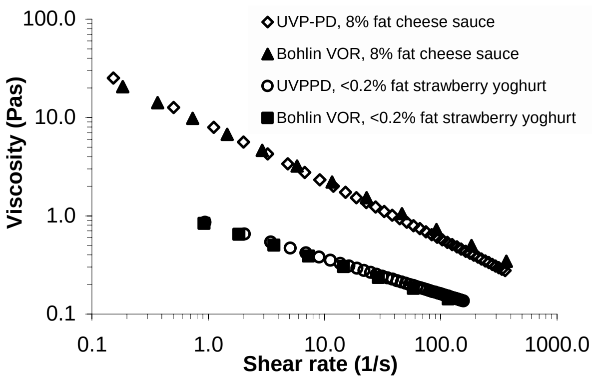

Figure 4: Comparison between shear viscosities for two food suspensions measured in-line using UVP-PD with off-line measurements using a Bohlin VOR rheometer.

As shown in Figure 4, good agreement between the methods is generally found for suspensions containing particles smaller than the gap width, in the concentric cylinder geometries. These experimental results are consistent for all investigated highly concentrated bimodal and polydisperse model- and industrial suspensions.

In addition, results further showed that off-line measurements using conventional rotational rheometers produce unrealistic results for suspensions containing larger particles since the standard measurements are performed on rheologically different systems containing no large particles and under different flow conditions.

4.3 Flow adapter and in-line sound velocity measurements

An extension of the UVP-PD method to involve in-line sound velocity measurements and attenuation was shown to be beneficial. The sound velocity is generally found to be a linear function of concentration of solids and temperature. Attenuation was found to be stronger in hydrophobic continuous phases compared to hydrophilic, aqueous phases.

Experimental results on model and industrial suspensions showed that polydisperse suspensions containing large amounts of small particles up to approximately 10µm have the strongest influence on the signal attenuation probably due to signal deletion caused by multiple scattering. Recently, it was shown that microscopic (crystal size/shape) information in cocoa butter, Birkhofer et al. [10]. In this work, we have shown that also structure degradation can be monitored using in-line sound velocity measurements. In addition, macroscopic information (concentration of solids) information can also be obtained, e.g. in pulp, Wiklund et al. [6].

In addition, it was showed that the signal quality close to the pipe walls can be significantly improved by using novel flow adapters with membranes in front of the transducer.

Table 1: Summary of investigated fluid systems with particle shapes and sizes.

Investigated systems	Particle shape	C_{Max} %(w/w)	Particle sizes
Glycerol+ glass beads	spherical		4-15 µm
Rapeseed oil+ nylon particles	spherical	~ 45	8–90 µm
Syrup + starch particles	~spherical	~ 40	30–300 µm
Slurries	agglomerates	~ 40	100nm –1 mm
Tomato sauce	rodlike fibers	~ 30	~1 mm
Strawberry Yoghurt	seeds,kidney shaped	~ 8	1-1.2 mm
Fruit jams, marmalades	rodlike fibers		0.2–2 mm
Pasta sauce	mixture		~1-4 mm
Cellulose pulp	rodlike fibers	~8	2-2.4 mm
Cheese sauce + vegetables	cubic		0.5-1 cm
Seafood Chowder	mixture		-> 2-3 cm
Vegetable sauces	mixture		-> 3-4 cm

6 SUMMARY

UVP and the UVP-PD method were successfully applied for non-invasive in-line measurements of velocity profiles and rheology of both model and industrial suspensions. Results were consistent for highly concentrated bimodal and polydisperse model and industrial suspensions containing particles ranging from soft to hard. A much wider range of particle sizes, distributions, shapes and suspension characteristics was covered compared to what has so far been reported in literature.

UVP-PD method in combination with in-line sound velocity measurements enabled determination of concentration of solids and the possibility to of monitor a gradual change in rheological behavior with structure degradation directly in the process line. Comparison with off-line measurements using conventional rotational rheometers revealed that off-line measurements often produce unrealistic results since they are performed on rheologically different systems containing no solid particles larger than a few millimeters and under different flow conditions.

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