ADVANCES IN MULTIPHASE FLOWS Vol.1

— MEASUREMENT TECHNOLOGY

Edited by Hongjian ZHANG, Zekui ZHOU
Zhiyao HUANG, Shimin WANG

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Preface

The measurement of multiphase flows, which is very important for both of basic study of multiphase flows and its application in industry, has made much progress in recent years. To exchange academic ideas and to present new research achievement in the measurement of multiphase flows, the 1st International Symposium on Measurement Techniques of Multiphase Flows (ISMTMF) was held in 1995 in Nanjing, China. After that, the 2nd and 3rd symposiums were held in 1998 at Beijing, China and in 2001 at Fukui, Japan, respectively. This symposium, the 4th ISMTNF, is held jointly with the 2nd International Symposium on Multiphase, Non-Newtonian and Reaction Flows '04 (ISMNRF '04) in September 10-12, 2004 in Hangzhou, China.

The proceedings of the 4th ISMTMF contains 7 invited lectures and 111 papers which were contributed from authors of Belgium, China, France, Germany, Japan, UK and USA. The topics of these papers cover the measurement of gas-liquid, gas-solid and gas-liquid-liquid flows in pipe, measurement of multiphase flow in fluidized bed and combustion system. In addition, optical techniques, process tomography, devices, signal processing and other advanced methods used in multiphase flow measurement are covered as well. It is expected that these papers would be beneficial to scientific and technical exchange and also beneficial to further research work in the field of measurement of multiphase flows.

I am very grateful to the authors, chairmen, members of the 4th ISMTMF committee, the participants and all those who have contributed their time and efforts to the success of this symposium. I would like to express thanks to Zhejiang University for financial and other support to the Symposium.

Kefa Cen
Professor, Ph.D.
Academician of Chinese Academy of Engineering
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DEVELOPMENTS IN TURBULENCE MODULATION IN DISPERSED PHASE FLOWS

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EXTENDED ABSTRACT

The turbulence in the carrier, or continuous, phase of a dispersed phase flow plays a significant role in the dynamics of the flow, the heat and mass transfer (mixing) and the particle/droplet dispersion. Previous studies have shown that large particles appear to enhance carrier phase turbulence while small particles seem to attenuate the turbulence. The reasons for these trends and not fully understood but probably are attributable to wakes generated by the particles and damping by the particle surfaces.

Several models for particle generated turbulence have appeared in the literature. Some models are empirically based, others are based on point models and still others are based on averaged models. Also there has been a significant recent effort using direct numerical simulations. Some models treat the averaged equations as if they represent the conditions at a point and develop equations for turbulence in the same manner as for single-phase flows. This approach, though very common, leads to a serious fallacy.

One approach to developing multiphase flow turbulence equations is start with the mechanical energy equation. By averaging this equation, an expression for the turbulence energy ensues with the correct physics. The equation shows that the turbulence energy production derives from velocity gradients in the flow, diffusion of turbulence energy, the generation due to particle drag, the conversion from particle kinetic energy to carrier phase energy and the dissipation due to viscous effects. This equation reduces to the correct form for the simple, idealized case of particles rigidly suspended in a flow.

With experiments for turbulence generation in quiescent flows, there is no generation by velocity gradients and the diffusion and conversion are minimized so the generation of turbulence is equal to the dissipation. Expressing the dissipation in terms of the Taylor microscale yields an equation for the ratio of the microscale to the particle size. Reduction of data for quiescent flow experiments shows that the length scale ratio correlates with the particle Reynolds number.

Studies of turbulence generation in gas-particle flow behind a grid show that the turbulence length scale depends on the particle volume concentration. Obviously, the length must reduce to the single flow values as the particle volume fraction approaches zero. Some of the data also suggest that the length scale approaches an asymptotic value as the volume fraction increases. This observation suggests that there is a point where the wakes from the particles constitute the entire flow. This is referred to as the saturated condition.

For flows near boundaries, the primary turbulence generation term is the velocity gradient. If the ratio of the particle-generation term to the velocity-gradient generation term is small, the particles likely do not enhance turbulence. This trend has been observed in channel flows.

In jets flows, turbulence production is balanced by convection. On comparing water jets and air jets, the turbulence generated by particles is significantly larger for water jets than air jets. Thus the influence of particles on turbulence is larger in water jets, which have been borne out by experiment.

Direct numerical simulations are playing a more significant role in turbulence modeling and the results are yielding useful information. It is important that the effect of the particle surface be included to have a meaningful simulation.

There is still considerable effort needed to understand turbulence modification by particles. Also there is a need to develop reliable models for practical LES simulations.

Rheo-optics as a probing technique for multiphase systems

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ABSTRACT

Multiphase materials can be encountered in applications ranging from commodity household products to high-tech applications such as in the automotive, electronic and medical industries. Despite their widespread occurrence, the processing of such materials is not yet fully understood. The microstructure of the final products – e.g. the phase-morphology in a multiphase material – depends not only on the material properties but also on the details of the processing. A fundamental understanding of these relations is essential in the rational design of products with well-defined final properties and in the optimization of their processing. Developing and applying such understanding is, to a large extent, based on in-situ monitoring of the morphology during processing, i.e. during flow. Here, the applicability of rheo-optical methods for this purpose will be discussed.

Keywords: processing, dispersions, emulsions, blends, rheo-optics, rheology

1. INTRODUCTION

Rheo-optical methods have a long tradition in the study of flowing systems. Initially, the term *rheo-optics* referred to the measurement of the components of the deviatoric stress tensor by optical means, see e.g. the review by Peterlin [1] or the book by Janeschitz-Kriegl [2] for an overview of earlier work. Such methods have been applied successfully to single-phase polymer liquids to characterize changes in the molecular deformation during flow, even very rapid ones [3]. From these data also the corresponding full stress tensor can be calculated [4,5]. Similar techniques have been used to spatially resolve the stresses in complex flow fields [6,7]. More recently, the term rheo-optics has been used in a broader sense. It now applies to an ensemble of optical methods and approaches with which can be probed, both qualitatively and quantitatively, the changes induced by flow in structured fluids. The results provide insight in the effect of processing on microstructure. They also make it possible to study the effect of the flow history on the rheology of complex systems [8], as the rheological response of such systems is often governed by the evolving microstructure. Rheo-optical methods have been successfully applied to a number of materials, including emulsions of low viscosity fluids or very viscous polymers [9], suspensions with flow-dependent microstructures, e.g. those containing non-spherical particles [10], phase separating polymeric systems [11,12] and even crystallizing polymers [13,14]. In this paper we will review some activities in the field of two-phase fluids.

2. METHODS

In order to investigate the flow-induced structures of complex fluids, a wide variety of techniques is available. A common procedure is to detect the results of superimposing an external field on the flowing material. Such an external field could be a mechanical one (superposition rheometry), an electric one (dielectric spectroscopy during flow) or the superposition of electromagnetic radiation. Depending on the wavelength used (visible light, UV, infrared, X-rays or neutrons), a wide variety of length scales can be probed with the latter. Here, using the superposition of visible light on a flowing system will be discussed.

When light interacts with matter, different phenomena can arise. The radiation can propagate through the material with a change in its state of polarization or intensity. This forms the basis for polarimetric techniques such as linear

conservative dichroism and birefringence. Secondly, the energy can be absorbed with possible subsequent emission of some or of all the energy. This forms the basis for absorption and emission spectroscopic techniques such as infra-red dichroism and Raman scattering. These methods are frequently used for chemical analysis but can also be applied under flow to investigate miscible multi-component materials (e.g. [10]). By using appropriate labeling methods such as deuteration of certain groups, these techniques can track the orientation dynamics of the deuterated species. Thirdly, the angular dependence of scattered radiation can be studied. In this manner information is obtained about the spatial organization of scatterers, such as particles or fluctuations in density or concentration. Reviews on these optical techniques can be found in Fuller [10] and Sondergaard [11]. Most of the optical techniques require the sample to be sufficiently transparent, although a few techniques can be applied to turbid samples. The angular dependence of the light scattered by turbid media can no longer be used, but there is temporal information in the intensity of the scattered light that may be used to characterize dynamical processes in the media. The corresponding technique has been called diffusing wave spectroscopy (DWS) [15,16,17]

In this contribution, the main focus will be on two complementary methods being the linear conservative dichroism and small angle light scattering (SALS). When light passes through matter, the electric vector can be attenuated. If the dielectric properties of the material are anisotropic, this attenuation becomes anisotropic as well, leading to a difference in principal eigenvalues of the imaginary part of the refractive index tensor. This anisotropy, i.e. the 'dichroism' [10], can be caused by two contributions: by intrinsic interactions originating from the absorption of light in the molecules, or by form contributions caused by the scattering of light from larger scale structures in the material. In the case of dichroism, these two effects can be separated since the intrinsic contribution is a strong function of the wavelength of the light. Hence, by selecting a light source with a proper wavelength in order to reduce absorption, the scattering contribution will dominate. Due to this ability of separating intrinsic and scattering effects, the so-called linear conservative dichroism is an interesting tool to study flow-induced structures on the micron length scale.

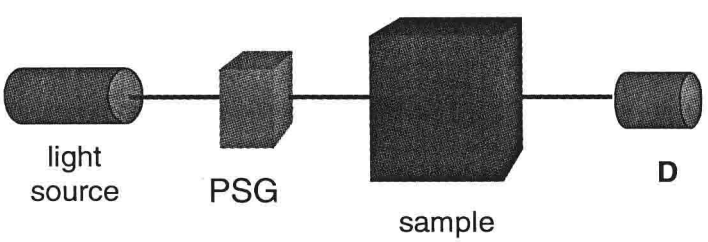

Figure 1: Schematic representation of the experimental setup for dichroism experiments.

An experimental polarimetric set-up to measure dichroism is schematically depicted in figure 1. A laser is used as light source. The emitted light passes through a polarization state generator (PSG) to achieve the desired polarization condition. After passing through the sample the resulting polarization state is analyzed (D). In order to measure the dichroism, a variety of combinations of optical components can be used (see [11] for a detailed overview). In our experimental setups, the PSG consists either of a combination of a polarizer and a half wave plate rotating at a frequency of 2 kHz or a combination of a polarizer, a photo-elastic modulator and a quarter wave plate. The latter set-up considerably enhances the time resolution. After the modulation, light reaches the sample that is contained in a flow cell that can either be a parallel plate geometry (experiments in the gradient plane) or a Couette cell (experiments in the vorticity plane). The light leaving the sample at zero angle (transmitted light) is detected (D) and demodulated by phase-locking amplifiers that determine the desired components from the AC part of the transmitted light, from which the dichroism can be calculated.

The experimental set-ups discussed above can be modified to perform time-dependent small angle light scattering (SALS) experiments during flow. The light scattered by the sample is then collected on a semi-transparent screen, positioned after the sample. A high-resolution camera records the scattering images on the screen, it digitizes the images and stores them on a computer for further analysis.

3. ILLUSTRATIVE CASE STUDIES

3.1 Droplet morphology in liquid/liquid systems

Firstly, an application to an emulsion-type material is demonstrated. In the processing of emulsions the evolution of size, shape and orientation of the dispersed phase is normally very important. In the area of materials processing this can be illustrated by the processing of immiscible polymer blends. During the past decade, such systems have been the subject of many theoretical and experimental studies (see e.g. Tucker and Moldenaers [18] for a recent review). The kinematic conditions during the processing of two-phase polymer blends can be quite complex, because morphological changes such as deformation, break-up and coalescence of the droplets all occur simultaneously. Using rheo-optical techniques, the time evolution of the structure of the droplets can be probed in-situ, at least on transparent or dilute systems. Using simple flow histories the basic laws of flow-induced structure development can be established. This has also been used successfully to analyse the complex rheological behaviour of two-phase polymer blends.

Small angle light scattering measurements are very suitable to study the mechanism of droplet break-up. The blends consist of 1 wt% of polydimethylsiloxane dispersed in polyisoprene. The flow history contains two parts: first, the blend is presheared at a relatively low shear rate in order to generate a reproducible initial droplet morphology. Next, the shear rate is suddenly increased. This results in droplet break-up, which is tracked by the time evolution of the SALS-patterns. Such a flow history mimics sudden changes in flow conditions in real processing operations such as injection moulding. An example of the evolution of the SALS patterns in the gradient plane is shown in figure 2.

0 s 5.5 s 6 s 6.5 s

Figure 2: SALS patterns resulting from droplet break-up during flow in a dilute immiscible polymer blend (adapted from Van Hemelrijck et al. [14]).

The initial scattering pattern is elliptic. It provides information about the deformation of the droplets, which in this case results from the preshearing. Upon inception of the higher shear rate, the scattering pattern becomes rapidly more anisotropic, reflecting the stronger deformation of the droplets by the higher shear rate. With time, secondary and even tertiary maxima develop in the scattering pattern. These multi-streak patterns can be associated with droplet break-up by Rayleigh instabilities [19]. Indeed, when subjected to a sufficiently high shear rate, droplets will be stretched continuously into long fibrils. During the deformation, the cross section of the fibrils decreases, reducing the radius of curvature and increasing the interfacial stress accordingly. This will ultimately result in the appearance of interfacial instabilities, so-called Rayleigh instabilities, consisting of growing periodic variations in fibril width, which will cause the filaments to break up in an array of individual droplets. The periodic pattern of the fibril surface during the growth of the instabilities causes the secondary streaks in the scattering patterns of figure 2. The wavelength of the instabilities can be derived from the position of these peaks (see [20] for a detailed analysis). The periodicity is still present after the filament is broken up in a series of droplets and hence the secondary strings remain present. In the course of time (not shown in figure 2) the periodic structure of the droplet array will be destroyed during flow. As a result the multi-streak pattern will gradually disappear, leading again to an elliptic scattering pattern.

Information about the morphology development during flow can also be deduced from the linear conservative dichroism. This method is particularly suitable to determine the time-scales of the various morphological processes. Figure 3 shows the typical evolution of the dichroism after two different start-up experiments for a blend consisting of 3 wt% polybutadiene in polyisobutylene, starting from a microstructure generated at 1 s^{-1}. For a small step-up ratio in

shear rates (i.e. 3), the dichroism continuously increases towards a steady state value, i.e. the flow is not strong enough to cause rupture of the droplets but will lead to a mere deformation of the dispersed droplets. For larger step-up ratios (e.g. 7), droplet break-up will occur as discussed above, resulting in a more complex dichroism curves. The stronger droplet deformation will initially cause a larger anisotropy and hence a larger dichroism. The subsequent droplet break-up, with or without the periodic interfacial instabilities, leads to the formation of smaller and therefore less deformed droplets, this will again reduce the anisotropy, explaining the maximum in the dichroism curve of figure 3. It has been shown by Vermant et al. [21] that the time scale associated with the break-up process of the droplets can be quantified by a value t_B (figure 3), which is located in the decreasing part of the dichroism curve. This has been used used to develop scaling relations for the break-up time [22]. When working in the vorticity plane the time evolution of the orientation angle of the droplets can also be measured [21].

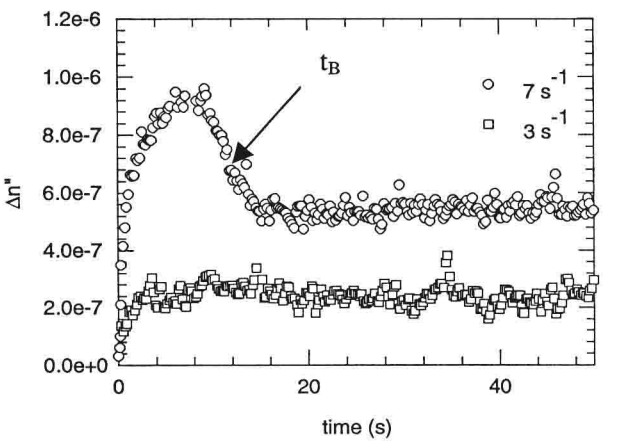

Figure 3: Dichroism evolution after two different step-up experiments.

3.2 Flow-induced particle structures

In stable colloidal dispersions, the particle structure is defined by the distribution of the distances between particles, expressed by the radial distribution function. During the flow this function can become distorted and can even loose its spherical symmetry. More dramatic effects occur when flow either induces the formation of aggregates, as in flow-induced flocculation, or breaks the previously existing flocs. Such processes can also be followed rheo-optically. Dichoism and turbity measurements have for instance been used to demonstrate that shear thickening in colloidally stable dispersions was caused by a flow-induced hydrodynamically controlled aggregation of particles [23].

In some cases flow causes a specific ordering. This could be the formation of layers containing hexagonally packed particles. Such a structure will give rise to a characteristic diffraction pattern [24]. In other cases strings or bundles of particles seem to develop under flow [25]. String formation is known to happen a.o. with particles suspended in viscoelastic media [26 27]. Rheo-optical methods can be used to investigate the nature of this flow-induced alignment. Scirrocco et al. [28] recently presented a rheo-optical study of the effect of the rheological properties of the suspending medium on flow-induced alignment of particles. Alignment was studied by means of video microscopy and with small angle light scattering as shown in figure 4. The onset of string formation was shown not to be generally governed by a critical Weissenberg number as assumed earlier. More specifically, particle alignment could not be induced at all in Boger fluids, even at elevated Weissenberg numbers. In a modified Boger fluid the critical Weissenberg number was found to be an order of magnitude larger than in some other polymer solutions. In some cases, SALS could be used to calculate interparticle distances within the strings. In this manner it could be proven that particles in strings did not touch each other.

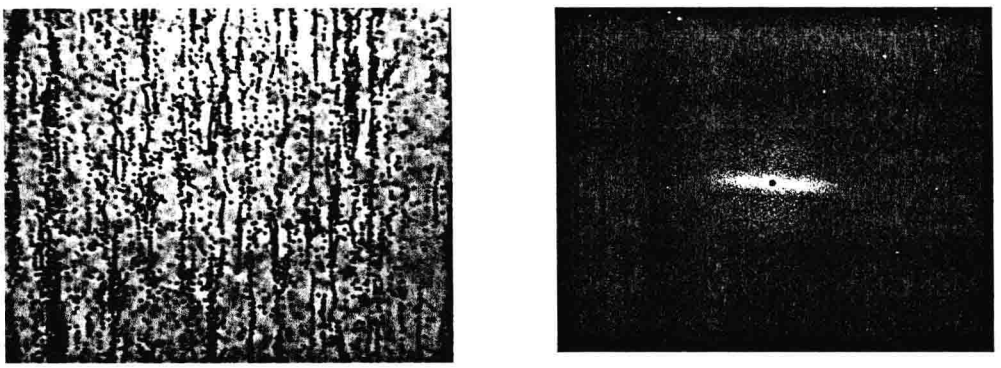

Figure 4: (a) Micoscopic image of a flowing suspension of 3 micrometer polystyrene beads in a solution of hydroxypropylcellulose in water, showing the formation of particle strings when sheared at a rate of 50 s^{-1}; (b) corresponding SALS image.

From the two-dimensional SALS pattern quantitative information about the asymmetry of the suspension microstructure can be deduced. For this purpose, the measured scattered intensity $I(\mathbf{q},\phi)$, with $\mathbf{q}$ being the scattering vector and ϕ the azimuthal angle, is weighed by a spherical harmonic. The asymmetry in the pattern is then captured by defining an alignment factor $A_f(q)$:

$$A_f(q) = \frac{\int_0^{2\pi} I(q,\phi)\cdot\cos(2\phi)\cdot d\phi}{\int_0^{2\pi} I(q,\phi)\cdot d\phi}$$

With the SALS experiments it also becomes possible to investigate whether the observed phenomena are induced by the walls or whether they are produced in the bulk of the liquid. Also the temporal evolution of the alignment can now be studied in a quantitative manner. This is illustrated in figure 5, where the evolution of the alignment factor is plotted for a suspension of 1.2% (v/v) polystyrene particles in HPC. Data for different shear rates are presented, the anisotropy is plotted versus strain, i.e. the time has been multiplied by the shear rate. String formation turns out to be very slow and seems, to a first approximation, to be strain-controlled, as the data for different shear rates can be superimposed rather when plotted versus strain..

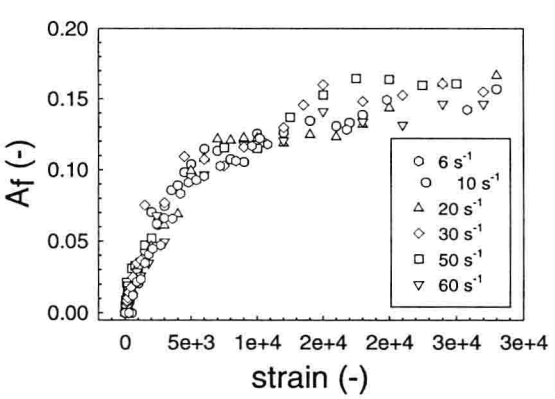

Figure 5. Evolution of the alignment factor for suspensions of PS (1.2%, v/v) in a HPC solution at different shear rates: as function of strain [20].

CONCLUSIONS

Various rheo-optical techniques can be used to obtain structural information of flowing multiphasic systems. Measurements of turbidity, linear dichroism and scattering patterns are commonly used for that purpose. Recent

advances in instrumentation and analysis have led to the use of time-resolved, in-situ measurements. Light scattering is suitable for studying rather slow phenomena, such as droplet break-up or some types of structure development in suspensions such as particle alignment in filled polymers. Linear conservative dichroism is well suited for faster phenomena; an example being the way concentration fluctuations are enhanced by flow []. The methods presented here are also applicable in more complex flow geometries and have a potential for on-line measurements.

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REFERENCES

1. Peterlin A, Optical effects in flow, Ann. Review of Fluid Mech, Vol 8, pp 35-55, 1976
2. Janeschiz Kriegl H, *Polymer melt rheology and flow birefringence*, Berlin : Springer, 1983.
3. Zebrowski BE and Fuller GG, Rheo-optical studies of concentrated polystyrene solutions subjected to transient simple shear flow. J Polym. Sci Pol. Phys Vol 23 (3): pp 575-589, 1985
4. Brown EF, Burghardt WR, Kahvand , Venerus DC Comparison of optical and mechanical measurements of 2nd normal stress difference relaxation following step strain, Rheol. Acta Vol 34 (3): 221-234, 1995
5. Kalogrianitis SG, vanEgmond JW, Full tensor optical rheometry of polymer fluids J RHEOL Vol 41 (2): 343-364, 1997
6. Baaijens FPT, Selen SHA, Baaijens HPW, Peters GWM, Meijer HEH Viscoelastic flow past a confined cylinder of a low density polyethylene melt J. Non-Newt. Fluid Mech Vol 68 (2-3): pp 173-203, 1997
7. Li JM, Burghardt WR, Yang B, Khomami B Birefringence and computational studies of a polystyrene Boger fluid in axisymmetric stagnation flow J. Non-Newt. Fluid Mech Vol 91 (2-3): pp189-220 (2000)
8. Fuller G .G. , *Optical Rheometry of Complex Fluids : Theory and Practice of Optical Rheometry (Topics in Chemical Engineering),* Oxford Univ Press; 1997
9. Sondergaard K., *Rheo-Physics of Multiphase Polymer Systems: Characterization by Rheo-Optical Techniques,* Technomic Pub Co, 1995.
10. Vermant J, Yang H, Fuller GG, Rheooptical determination of aspect ratio and polydispersity of nonspherical particles AICHE J Vol 47 (4): pp 790-798 (2001)
11. Yanase H., Moldenaers P, Mewis J, Abetz V, Van Egmond J and Fuller GG, Structure and dynamics of a polymer-solution subject to flow-induced phase-separation, Rheol. Acta, Vol 30 (1): pp 89-97, 1991
12. Vanegmond JW, Wwerner DE, Fuller GG, Time-dependent small-angle light-scattering of shear-induced concentration fluctuations in polymer-solutions , J Chem Phys Vol 96 (10): pp 7742-7757, 1992.
13. Kumaraswamy G, Issaian AM, Kornfield JA Shear-enhanced crystallization in isotactic polypropylene. 1. Correspondence between in situ rheo-optics and ex situ structure determination Macromolecules Vol 32 (22): 7537-7547, 1999
14. Devaux N, B. Monasse, JM Haudin, P. Moldenaers, J. Vermant Rheo-optical study of the early stages of flow-enhanced nucleation in isotactic polypropylene Rheol. Acta, Vol **43**, 210-222, 2004
15. Maret G. and P.E. Wolf , Multiple light scattering from disordered media. The effect of Brownian motion of scatterers. Zeitschrift fur Physik Vol B 65, pp. 409–413, 1987
16. Pine D.J., D.A. Weitz, P.M. Chaikin and E. Herbolzheimer , Diffusing-wave spectroscopy. *Phys Rev Lett Vol* **60**, pp. 1134–1137 (1988)
17. Maret G, Diffusing-wave spectroscopy. Curr Opin Colloid Interface Sci Vol 2, pp. 251–257, 1997
18. Tucker C.L.and P. Moldenaers, Microstructural evolution in polymer blends, Ann. Rev. Fluid Mech., Vol. 34, pp. 177-210, 2002.

19. Van Hemelrijck E., P. Van Puyvelde and P. Moldenaers, Direct evidence for breakup of liquid fibrils via Rayleigh instabilities in model polymer blends in step-up experiments, Langmuir, Vol. 20, pp. 3498-3500, 2004.
20. Mewis J, H. Yang, P. Van Puyvelde, P. Moldenaers, L. Walker, Small angle light scattering study of droplet break-up in emulsions and polymer blends, Chem. Eng. Sci., Vol. 53, pp. 2231-2239, 1998.
21. Vermant J, P. Van Puyvelde, P. Moldenaers, J. Mewis and G.G. Fuller, Anisotropy and orientation of the microstructure in viscous emulsions during flow, Langmuir, Vol. 14, pp. 1612-1617, 1998.
22. Van Puyvelde P, H. Yang, J. Mewis and P. Moldenaers, Breakup of filaments in blends during simple shear flow, J. Rheol., Vol. 44, pp. 1401-1415, 2000.
23. D'Haene P, J. Mewis and G.G. Fuller, Scattering dichroism measurements of flow-induced structure of a shear thickening suspension, J Colloid Interf. Sci., Vol. 156, pp. 350-358, 1993.
24. Ackerson B.J., Pusey PN, Shear induced order in suspensions of hard spheres, Phys. Rev. Lett., Vol 61 (8): pp 1033-1036,1988
25. Vermant J., L. Raynaud, J. Mewis, B. Ernst. and G.G. Fuller, Large scale bundle ordering in Sterically stabilized latices. J. Colloid and Interface Sci, Vol 211, pp 221-229, 1999
26. Michele J, R. Pätzold, R. Donis, Alignment and aggregation effect in suspensions of spheres in non-Newtonian media, Rheol. Acta Vol. 16 pp 317-321 (1977) .
27. Lyon M.K., D.W. Mead, R.E. Elliott, L.G. Leal, Structure formation in moderately concentrated viscoelastic suspensions in simple shear flow, J. Rheol. Vol. 45, pp 881-890, 2001.
28. Scirocco R, Vermant J, Mewis J Effect of the viscoelasticity of the suspending fluid on structure formation in suspensions J Non Newt Fluid Mech Vol 117 (2-3): pp 183-192, 2004

OPTICAL MEASUREMENT TECHNIQUES FOR MULTIPHASE FLOWS

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ABSTRACT

In this contribution two novel techniques for particle characterisation in dispersed, multiphase flows will be discussed: cross-sectional area difference method and the time-shift technique. Both methods are rather new and each offers some very distinct advantages for specific applications. The purpose of this contribution is to briefly outline the physical working principles of each technique and to outline their specific features. This information is meant to stimulate use of these techniques for hitherto inaccessible applications and measurement quantities.

1. INTRODUCTION

In dispersed multi-phase flow systems it is of primary importance to be able to experimentally characterise the dispersed phase in terms of size, velocity, and local concentration, whereby the dispersed phase can be solid particles, bubbles or droplets. Such information is essential to capture not only the hydrodynamic behaviour of the dispersed phase but also the transport phenomena, i.e. evaporation, drying, chemical reactions. Existing optical methods to obtain at least some of the above quantities include direct image processing, laser diffraction, photon correlation spectroscopy, phase Doppler techniques and a number of more specialized techniques for particular applications [1, 2, 3]. Generally non-intrusive techniques are not acceptable in multi-phase flows and will not be considered further. Some non-optical, non-intrusive techniques, in particular various tomographic methods have also become quite advanced during recent years; however the present contribution be restricted to new optical techniques which offer some additional advantages over existing techniques.

Two techniques will be briefly described, both rather new and exhibiting unique features which are beneficial for particular applications. The techniques are the cross-sectional area difference method and the time-shift technique. Their working principles will be introduced and reference will be made to existing literature about each technique. However, the main purpose of this survey is to clearly point out which new features are available with each technique and how these features may be used to improve measurements in multi-phase flows.

2. CROSS-SECTIONAL AREA DIFFERENCE METHOD (CSAM)

The cross-sectional area difference method was first introduced in [4] and later analysed in more detail in [5]. A more complete description of the technique is given in [1] and recent measurement results have been reported in [6]. In a laser Doppler system the ellipsoidal measurement volume is defined by the e^{-2} decay of the modulated part of the signal in relation to the modulated signal amplitude at the crossing point of the two laser beams. Because of the