Combined Method for Quantitative Characterisation of Fluid Flow

Yatchko Ivanov, Vasil Kavardjikov*, Dessislava Pashkuleva*

Bulgarian Academy of Sciences, Central Laboratory of Physico-Chemical Mechanics
1 Acad. G. Bonchev str., 1113 Sofia, Bulgaria

E-mail: yaiv@bgcict.acad.bg

*Bulgarian Academy of Sciences, Institute of Mechanics,
4 Acad. G. Bonchev str., 1113 Sofia, Bulgaria

Received: 16.3.2001, Final version: 2.10.2001

Abstract:
A method has been proposed for quantitative characterization of the flow behaviour of fluids, which is an important problem of applied rheology. Particle Image Velocimetry technique has been used for visualization and measurement of the velocity field. The rheometric study of the fluid is aimed at determining the character of the flow and its dynamic viscosity. It is shown that the experimental data obtained for the velocity field and the viscosity are necessary and sufficient for determining the shear stress field at each point of the flow bulk. The major part of the investigations are performed using a Newtonian fluid (epoxy resin), but some data for the non-Newtonian fluid (solution of xantan) are shown too. The flow is produced by gravity in a system of tubes (a barrel and a capillary) with different round crossections. The possibility of further improvement of the combined rheo-optical method is shown.

Zusammenfassung:
Eine Methode zur quantitativen Charakterisierung des Fliessverhaltens von Flüssigkeiten, eine wichtiges Problem in der angewandten Rheologie, wird vorgestellt. Hierbei wird die "Particle Image Velocimetry" zur Visualisierung und Vermessung des Geschwindigkeitsfeldes verwendet. Die rheometrische Untersuchung der Flüssigkeit hat zum Ziel, die Strömungsart und die dynamische Viskosität zu bestimmen. Es konnte gezeigt werden, dass das experimentell bestimmte Geschwindigkeitsfeld und die Viskosität zur Bestimmung des Scherspannungsfeldes an jedem Punkt im Inneren der Strömung ausreichen. Der grösste Teil der Untersuchungen wurde an newtonischen Flüssigkeiten (Epoxydharz) vorgenommen, aber einige Daten einer nicht-newtonischen Flüssigkeit (Xantanlösung) werden auch gezeigt. In einem schwerkraftgetriebenen Versuchsaufbau (Vorratsgefäss und einer Kapillare) werden die untersuchten Strömungsprofile mit verschiedenen runden Querschnitten erzeugt. Die Möglichkeit zur weiteren Verbesserung der kombinierten rheo-optischen Methode wird aufgezeigt.

Resumée:
Une méthode a été proposée pour une caractérisation quantitative du comportement en écoulement des fluides, ce qui est un important problème de la rhéologie appliquée. La technique de velocimétrie par image de particules a été utilisée afin de visualiser et de mesurer le champ de vitesse. L'étude rhéometrique du fluide a pour but de déterminer le caractère de l'écoulement et sa viscosité dynamique. Il est montré que les données expérimentales obtenues pour le champ de vitesse et la viscosité sont nécessaires et suffisantes pour la détermination du champ de contrainte de cisaillement à chaque point du volume en écoulement. La majeure partie des investigations a été menée avec un fluide Newtonien (résine d'Epoxy) mais des données obtenues avec un fluide non Newtonien (solution de Xantham) sont également présentées. L'écoulement est produit par la gravité dans un système de tubes (un tonneau et un capillaire) de differéntes sections. La possibilité d'amélioration de la technique combinée de rhéo-optique est présentée.

Key Words: fluid flow characterization, Particle Image Velocimetry, rheological measurement, velocity profile, shear stress profile.

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

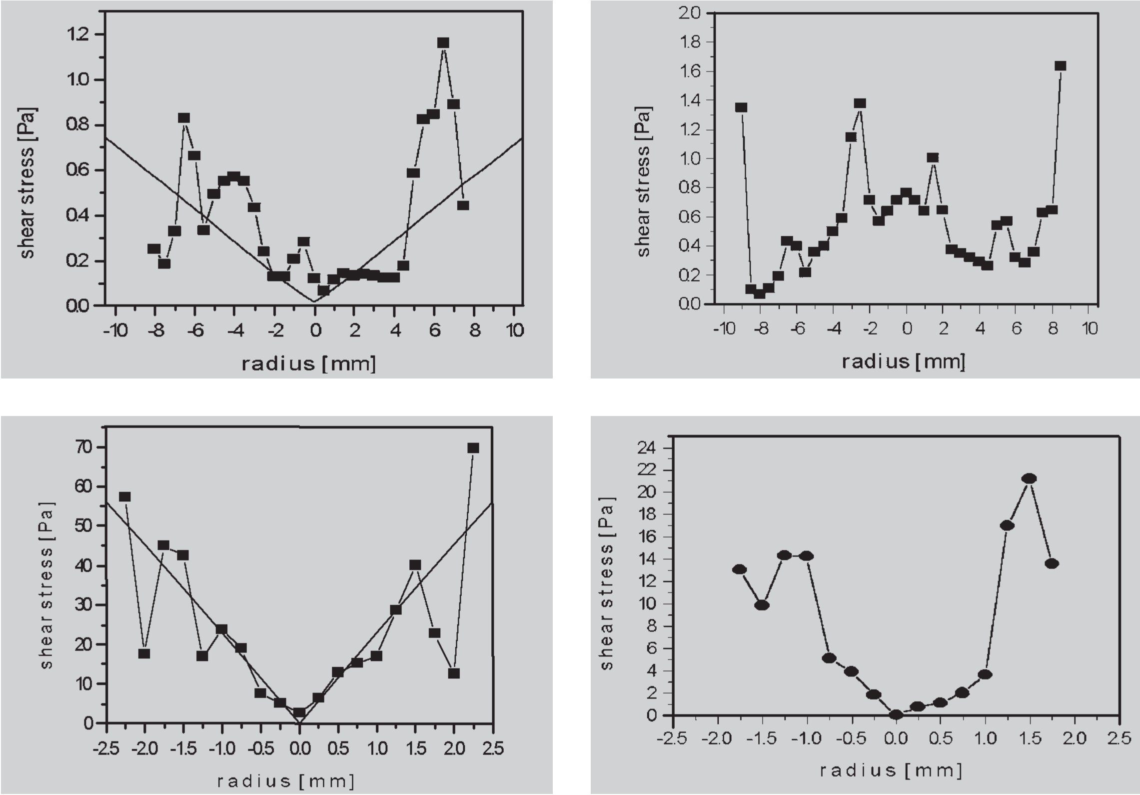


Figure 4: Shear stress profiles as a function of the glass body radius:
a) (left above): crossection A,
b) (right above): crossection B,
c) (left below): crossection C,
d) (right below): crossection D
(calculated curves (■); analytical curves (lines)).

the flow can be approximated by the Poisoil's law:

$$V = V_{\max}\left(1 - \frac{r^2}{R^2}\right) \qquad (2)$$

where V_{max} is the maximum flow velocity at the glass body axis of symmetry, R is the tube radius at the respective crossection, and r is the distance between the axis of symmetry and a point along the radius.

The velocity profiles A and C are calculated using relation (2) and presented in Fig.2. The V_{max} values are equal to the measured maximal values. In the laminar zone of the capillary flow, where the velocity profile C is measured, very good coincidence between calculated and measured profiles exists. A significant deviation of the experimental from the analytical results is observed close to the tube walls where $R - r < 1$mm. A similar deviation is also observed at the crossection A. The velocity profile B cannot be approximated by the Poisoil's law (2). It presents the converging flow at the barrel to capillary transitional zone. Because of the complicated flow behaviour in the vicinity of crossections B and D, no theoretical flow profiles are presented at this stage of our work. The important rheological property of a flow, the shear rate, can be determined after differentiation of the velocity profiles along the tube radius:

$$\dot{\gamma} = -\frac{dV}{dr} \qquad (3)$$

The fluid viscosity value and the flow curve are obtained experimentally by the rotational viscometer (see the flow curve in Fig. 3). These data are enough for determination of the shear stress function, τ (r), at all crossections of the flow:

$$\tau = \eta\dot{\gamma} \qquad (4)$$

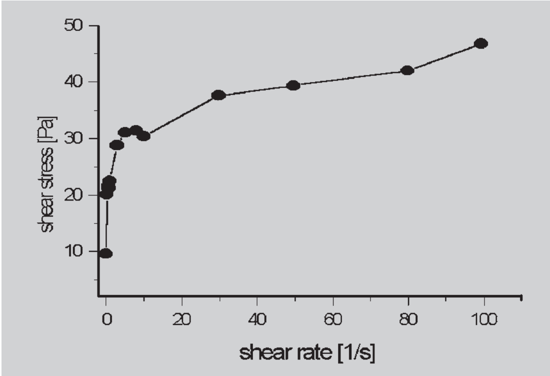
The profiles of shear stress, calculated by Eq. 3 and Eq. 4 from the respective flow velocity profiles (Fig. 2) are shown in Fig. 4. The function τ (r) determined using the Eq.2 at the crossections A and C is linear, but the functions, obtained from the measured velocity profiles at the same crossections are non-linear. This is a result of deviations of the measured velocity values from the respective calculated values. The experiments show that these deviation increase when the difference $R - r$ decreases. Due to the absence of theoretical shear stress functions at this stage, only the shear stress functions, calculated from the measured velocity profiles at crossection B and D are presented in Fig. 4b and Fig. 4d.

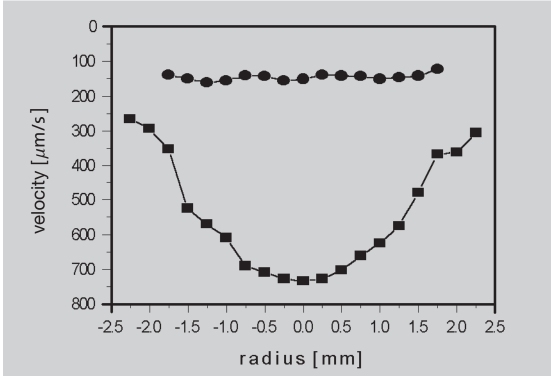
Our approach to the determination of the shear stress field in the volume of a flow can also be applied to Non-Newtonian fluids. For example, this technique has been applied to an aqueous solution of the biopolymer xantan (5 wt%). The experimentally obtained data are: a flow curve (Fig. 5), measured by a rotational viscometer and a flow velocity profile (Fig. 6), measured by speckle photography. The velocity pro-

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

Figure 5 (left): The flow curve for a xantan solution (Non-Newtonian fluid).

Figure 6 (right): The flow velocity profiles at cross section C for a xantan solution (•) and for epoxy resin (■).





file of epoxy resin, measured at the same crossection, is presented in Fig. 6 at the same scale of the velocities. As can be seen, the velocity profile of the xantan solution flow is typical of Non-Newtonian fluids. Its shape is very different from the shape of the epoxy resin profile.

4 CONCLUSION AND OUTLOOK

The Particle Image Velocimetry technique permits detailed measurements of vector Fluid Velocity Fields. The combination of this technique with rheometric measurements permits obtaining, on the basis of the measured velocity field, the shear stress field. The experimental device can be used for measuring the size of velocity vectors in the range of 15 μm/s - 800 μm/s with an accuracy of 1 μm. A 250 μm minimum distance between neighbouring measured vectors in the velocity field is attained. The combined rheo-optical method is applicable to both Newtonian and non-Newtonian fluids. On the basis of obtained data, a quantitative estimation of the shear stresses in different zones of the convergent flow is made.

The measurements show significant deviations of the theoretically obtained velocity profiles near the tube walls as compared to the experimentally measured profiles. This phenomenon is an object of the future investigations. Using this method, it is possible to determine the shear stress vector field of fluids with a high Reynolds number, the light source being an appropriate laser. Utilization of a photographic film for registration of the particle image patterns is in principle not a disadvantage of the method. It is possible to replace the photographic films by CCD cameras. Digital image recording and processing devices with a CCD matrix sensitive to visible or X-ray radiation and having an effective area and spatial resolution comparable with these parameters of the photographic films will be commercially available in the nearest future. Taking into account this possibility we have arrived at the conclusion that the combined use of Digital Particle Image Velocimetry and usual rheometry is a promising approach to complex quantitative analysis of the properties of a large class of fluid flows which are of interest for applied rheology and chemical engineering.

ACKNOWLEDGMENT

This work was partially supported by the Bulgarian Ministry of Education and Science under the Grant No. TN - 332/93.

REFERENCES

[1] Ouriev B: Ultrasound Doppler based in-line rheometry of highly concentrated suspensions, Appl. Rheol. 10 (2000) 148-150.

[2] Gijsen FJ, Goijaerts HA et al.: A new method to determine wall shear stress distribution, J. Rheol. 41 (1997) 995-1006.

[3] Gibbs StJ, James KL et al.: Rheometry and detection of apparent wall slip for Poiseuille flow of polymer solutions and particulate dispersions by nuclear magnetic resonance velocimetry, J. Rheol. 40 (1996) 425-439.

[4] Altobelli SA, Fukushima E: Nuclear magnetic resonance imaging of particle migration in suspensions undergoing extrusion, J. Rheol. 41 (1997) 1105-1115.

[5] Park H et al.: Laser photochromic velocimetry of vorticity and pressure field - two-dimensional flow in a curved wessel, Exp. Fluids 26 (1999) 55-58.

[6] Adrian RJ: Particle-Imaging Techniques for Experimental Fluid Mechanics, Annu. Rev. Fluid Mech. 23 (1991) 261-304.

[7] Sjodahl M: Accuracy in electronic speckle photography, Appl. Optics 13 (1997) 2875-2885.

[8] Ivanov Ya, Kavardjikov V et al.: The use of speckle photography in composite material rheology, J. Theoretical Appl. Mech. 1 (1998) 63-78.

[9] Shapiro V, Kavardjikov V et al.: Approach to automatic analysis of Young's fringes in speckle photography, Appl. Optics 23 (1993) 4378-4387

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org