Rheological Characterization of Highly Concentrated Mineral Suspensions Using Ultrasound Velocity Profiling with Combined Pressure Difference Method

Reinhardt Kotzé*, Rainer Haldenwang and Paul Slatter

Institute of Material Science and Technology, Cape Peninsula University of Technology,
P.O. Box 652, Cape Town, South Africa

* Email: reinhardtkotze@yahoo.com
Fax: x27.21.4603990

Received: 18.2.2008, Final version: 25.6.2008

Abstract:

The rheological behaviour of non-Newtonian, highly concentrated and non-transparent fluids used in industry have so far been analysed using commercially available instruments, such as conventional rotational rheometers and tube viscometers. When dealing with the prediction of non-Newtonian flows in pipes, pipe fittings and open channels, most of the models used are empirical in nature. The fact that the fluids or slurries that are used normally are opaque, effectively narrows down the variety of applicable in-line rheometers even further, as these instruments are normally based on laser or visible light techniques, such as Laser Doppler Anemometry. In this research, an Ultrasonic Velocity Profiling technique (UVP), in combination with a pressure difference (PD) measurement, was tested to provide in-line measurement of rheological parameters. The main objective of this research was to evaluate the capabilities of the UVP-PD technique for rheological characterisation of different concentrations of non-transparent non-Newtonian slurries. Kaolin, bentonite, Carboxymethyl Cellulose (CMC) and water solutions were used as model non-Newtonian mining slurries. Results determined by the UVP-PD method were compared with results obtained by off-line rheometry and in-line tube viscometry. The agreement between the UVP-PD method, tube viscometry and conventional rheometry was found to be within 15 % for all of the highly concentrated mineral suspensions investigated over a given range of shear rates. This method, if used in combination with a pressure difference technique (PD), has been found to have a significant potential in the development process of new in-line rheometers for process control within the mining industry.

Zusammenfassung:

Das rheologische Verhalten nichtnewtonscher hochkonzentrierter und nichttransparenter Fluide in der industriellen Produktion wurde bisher mit handelsüblichen Instrumenten wie Rotationsrheometern und Schlauchviskosimetern analysiert. Bei der Vorhersage nichtnewtonscher Strömungen in Rohren, Rohranschlüssen und offenen Kanälen sind die meisten angewendeten Modelle empirischer Art. Da die normalerweise verarbeiteten Fluide oder Schlämme trüb sind, wird die Bandbreite anwendbarer Rheometer im Produktstrom (In-Line-Rheometer) noch weiter eingeschränkt, denn diese Instrumente bauen meist auf optischen Techniken auf, die mit Laser- oder sichtbarem Licht arbeiten, wie beispielsweise die Laser-Doppler-Anemometrie. In dieser Forschungsarbeit wurde eine Ultraschall-Doppler-Methode (Ultrasonic Velocity Profiling – UVP) in Kombination mit einer Druckdifferenzbestimmung (Pressure Difference – PD) getestet, um eine Messung rheologischer Parameter im Produktstrom zu ermöglichen. Hauptziel dieser Forschungsarbeit war die Bewertung der Fähigkeiten der UVP-PD-Technik für die rheologische Bestimmung verschiedener Konzentrationen nichttransparenter nichtnewtonscher Schlämme. Dabei wurden Kaolin, Bentonit, Carboxymethylcellulose (CMC) und wässrige Lösungen als Modell-Suspensionen für nichtnewtonsche Bergbauschlämme verwendet. Die mit dem UVP-PD-Verfahren ermittelten Ergebnisse wurden mit Ergebnissen der Off-Line-Rheometrie und In-Line-Viskosimetrie verglichen. Die festgestellte Übereinstimmung zwischen dem UVP-PD-Verfahren, der Schlauchviskosimetrie und der herkömmlichen Rheometrie lag innerhalb von 15 % bei allen hochkonzentrierten Mineralsuspensionen, die über einen bestimmten Bereich von Scherraten untersucht wurden. Diese Methode, wenn sie in Kombination mit einem Druckdifferenzbestimmungsverfahren (PD) eingesetzt wird, hat ein erhebliches Potenzial im Entwicklungsprozess neuer In-Line-Rheometer für die Prozesssteuerung in der Bergbauindustrie gezeigt.

Résumé:

Le comportement rhéologique des fluides non-newtoniens, à forte concentration et non transparents utilisé dans l'industrie a jusqu'à présent été analysé en utilisant des instruments disponibles dans le commerce, comme des rhéomètres conventionnels à rotation et des viscosimètres à tubes. Lorsqu'il s'agit de la prédiction des flux non-newtoniens dans des tubes, des raccords et des canaux ouverts, la pluparts des modèles utilisés est de nature empirique. Le fait que les fluides ou les liquides utilisés sont normalement opaques, de fait restreint enco-

© Appl. Rheol. 18 (2008) 62114-1 – 62114-10

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

5 CONCLUSIONS

The capabilities of the UVP-PD technique for the rheological characterisation of different concentrations of non-Newtonian slurries have been evaluated. Results were compared with those obtained by off-line rheometry and in-line tube viscometry. Concentrated Carboxymethyl Cellulose (CMC) solution have been tested and rheological results determined by the UVP-PD method agreed well within 15 % with results measured by the tube viscometer and conventional rheometer. A viscous bentonite mineral suspension has been rheologically characterised, using two in-line methods and one off-line method. Results obtained from all three methods showed a 15 % agreement when compared over the total shear rate range. The degree of time dependence of the concentrated bentonite mineral suspension influenced the off-line rheometric results. Rheological results obtained from all three methods for the kaolin mineral suspension agreed well over the shear rate range. In comparison ultrasonic energy was seen to have attenuated significantly more than the attenuation in bentonite suspensions and CMC solutions. However, velocity profiles required for calculation of rheological parameters could still be measured in the highest concentration of kaolin (12 %v/v). The UVP-PD rheometric method can be used effectively for in-line rheological characterisation of highly concentrated mineral suspensions and has been found to have significant potential for the development of new in-line rheometers for process control within the mining and minerals industry.

6 RECOMMENDATIONS FOR FUTURE WORK

Birkhofer [10], Wiklund [11] and Wiklund et al. [12] optimised the UVP-PD method and contributed significantly to the methodology for using the in-line rheometric technique. These techniques can be applied to improve the accuracy and quality of results obtained when determining in-line rheological results of mining slurries.

Flow adapter and ultrasound transducer design

As mentioned in Section 3.1, the cavity in front of the transducer (Figure 2) influences the measurement of the velocity profile due to the increase of velocity before the actual pipe wall interface. This problem could be reduced by the introduction of new ultrasound transducers incorporating a delay line. The delay line should be fixed ahead of the transducer and in flush with the pipe wall, thus making it possible to have the focal point of the ultrasound beam at the wall interface. A transducer of this kind is currently under development [10, 11].

Demodulated Echo Amplitude (DMEA) monitoring

As explained by Birkhofer [10] and Wiklund [11], the direct access to demodulated echo amplitude (DMEA) data or 'raw data' allows for several advantages during velocity profile measurements.

Pipe wall detection

As shown by Wiklund et al. [12] and Birkhofer et al. [31], the power-law fitted rheological parameters are sensitive to the estimated pipe wall position measured from the front of the ultrasound transducer. Methods for wall detection based on cross-correlation and singular value decomposition (SVD) were successfully developed and implemented by Wiklund et al. [12]. This problem can also be reduced by the introduction of new ultrasound transducers, as described earlier [10, 11].

Data enhancement and analysis

Smoothing filters and methods for data enhancement were implemented by Wiklund et al. [12] in order to reduce the effects of correlated and uncorrelated noise. Results show that UVP data can be significantly improved by the implementation of different kinds of filters. However, one must be prudent when applying filters as they can introduce artifacts and modify the original data [11, 12].

REFERENCES

[1] Ouriev B, Windhab EJ: Rheological study of concentrated suspensions in pressure-driven shear flow using a novel in-line ultrasound Doppler method, Exp. Fluids 32 (2002) 204–211.

[2] Lazarus JH, Slatter PT: A method for the rheological characterisation of tube viscometer data, J. Pipelines 7 (1988) 165–176.

[3] Haldenwang R, Slatter P, Alderman N, Kotzé R, Sery G, George N: Balanced Beam Tube Viscometry vs Rotary Viscometry: A Comparison, 13th International Conference on Transport and Sedimentation of Solid Particles, Tbilisi, Georgia (2006) 145–156.

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

[4] Takeda Y: Velocity Profile Measurement by Ultrasound Doppler Shift Method, Int. J. Heat Fluid Flow 7 (1986) 313–318.
[5] Takeda Y: Velocity Profile Measurement by Ultrasonic Doppler Method, Exp. Therm. Fluid Sci. 10 (1995) 444–453.
[6] Takeda Y: Ultrasonic Doppler Method for Velocity Profile Measurement in Fluid Dynamics and Fluid Engineering, Exp. Fluids 26 (1999) 177–178.
[7] Steger R, Vorwerk J, Brunn PO: Geschwindigkeitsmessungen mit einem On-Line-Ultraschallsensor zur kontinuerlichen Prozesskontrolle komplexer Fluide (z. B. Lebensmittel), Chem. Ing. Tech. 65 (1993) 1087.
[8] Müller M, Brunn PO, Wunderlich T: New Rheometric Technique: the Gradient-Ultrasound Pulse Doppler Method, Appl. Rheol. 7 (1997) 204–210.
[9] Ouriev B: Ultrasound Doppler Based In-Line Rheometry of Highly Concentrated Suspensions, Ph.D. Thesis, Swiss Federal Institute of Technology Zurich, Switzerland (2000).
[10] Birkhofer BH: Ultrasonic In-Line Characterization of Suspensions, Laboratory of Food Process Engineering, Institute of Food Science and Nutrition, Ph.D. Thesis, Swiss Federal Institute of Technology Zurich, Switzerland (2007).
[11] Wiklund J: Ultrasound Doppler Based In-Line Rheometry: Development, Validation and Application, Ph.D. Thesis, SIK – The Swedish Institute for Food and Biotechnology, Lund University, Sweden (2007).
[12] Wiklund J, Shahram I, Stading M: Methodology for in-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques, Chem. Eng. Sci. 62 (2007) 4159–4500.
[13] Ouriev B, Windhab EJ: Rheological Study of Concentrated Suspensions in Pressure-Driven Shear Flow Using a Novel in-Line Ultrasound Doppler Method, Exp. Fluids 32 (2002) 204–211.
[14] Wiklund J, Johansson M, Shaik J, Fischer P, Windhab E, Stading M, Hermansson AM: In-Line Rheological measurements of Complex Model Fluids using an Ultrasound UVP-PD based method, Annual Transactions – The Nordic Rheology Society 8/9 (2001) 128–130.
[15] Wiklund J, Stading M, Trägårdh C: Monitoring liquid displacement of model and industrial fluids in pipes by in-line ultrasonic rheometry, J. Food Eng. (2008) accepted.
[16] Wiklund J, Stading M: Application of in-line ultrasound Doppler based UVP-PD method to concentrated model and industrial suspensions, Flow Meas. Instr. 19 (2008) 171–179.
[17] Urick RJ: A Sound Velocity Method for Determining the Compressibility of Finely Divided Substances, J. Appl. Phys. 18 (1947) 983–987.
[18] Brunton GD: Density and compressibility of Wyoming bentonite particles, Clays and Clay Minerals 36 (1988) 94–95.
[19] Chen AQ, Freear S, Cowell DMJ: Measurement of Solid in Liquid Content Using Ultrasound Attenuation, 5th World Congress on Industrial Process Tomography, Bergen, Norway (2007) 820–826.
[20] Kuttruff H: Ultrasonics: Fundamentals and Applications, London and New York: Elsevier Applied Science (1991).
[21] Jensen JA: Estimation of Blood Velocities Using Ultrasound: A Signal Processing Approach, Great Britain: Cambridge University Press (1996).
[22] Met-Flow SA: UVP Monitor – Model UVP-DUO User's Guide. Software version 3. Met-Flow SA, Lausanne, Switzerland, (2002).
[23] Chhabra RP, Richardson JF: Non-Newtonian Flow in the Process Industries, Oxford, Great Britain: Butterworth-Heinemann (1999).
[24] Björkman U: The Nonlinear History of Fibre Flow Research: Part 1. Background and Beginning, Appl. Rheol. 18 (2008) 23974.
[25] Bjorkman U: The Nonlinear History of Fibre Flow Research: Part 2. Continuation, Reflections and Suggestion, Appl. Rheol. 18 (2008) 34694.
[26] Lazarus JH, Slatter PT: Comparative rheological characterisation using a balanced beam tube viscometer and rotary viscometer, Hydrotransport 10 (1986) 291–232.
[27] Kwon KC, Park YK, Floyd T, Vahdat N, Jackson E, Jones P: Rheological Characterization of Shear-Thinning Fluids with a Novel Viscosity Equation of a Tank-tube Viscometer Appl. Rheol. 17 (2007) 51413.
[28] Shekarriz A, Sheen DM: Slurry Pipe Flow Measurements using Tomographic Ultrasonic Velocimetry and Densitometry, Proceedings of FEDSM, ASME Fluids Engineering Division Summer Meeting, Washington, USA (1998) 98–5076.
[29] Goldstein RJ: Fluid Mechanics Measurements, Hemisphere Publishing Corporation, Washington, USA (1983).
[30] Wiklund JA, Stading M, Petterson AJ, Rasmuson A: A comparative study of UVP and LDA techniques for pulp suspensions in pipe flow, AIChe J. 52 (2005) 484–495.
[31] Birkhofer BH, Jeelani SAK, Windhab EJ, Ouriev B. Lisne, KJ, Braun P, Zeng Y: Monitoring of fat crystallization process using UVP-PD technique. Flow Measurement and Instrumentation 19 (2008) 163–169.

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