In-Line Rheometry of Particulate Suspensions by Pulsed Ultrasound Velocimetry Combined with Pressure Difference Method

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Abstract :
The in-line rheometer concept based on the combination of the ultrasonic velocity profiling (UVP) technique and pressure difference (PD) measurements was utilized for investigating the influence of particle concentration and size distribution on the rheology of particulate suspensions in pipe flow under realistic industrial process conditions. Well defined model suspensions were used, consisting of 11 μm and 90 μm diameter polyamide particles suspended in rapeseed oil at concentrations ranging from 1 to 25 % by volume. The variation of concentration and particle size distribution had the expected effects on the shear viscositiy of the investigated unimodal and bimodal suspensions. The in-line results showed that the investigated suspensions exhibit Sisko flow behavior and demonstrated that the UVP+PD method can be used to determine the flow behavior of complex fluids and suspensions, even at high solid concentrations, under industrial conditions in-line. The obtained in-line results were in good agreement with measurement data obtained using a conventional rotational controlled-stress rheometer. Limitations of commercially available transducer technology were identified and other possible sources of inaccuracy of the UVP+PD method were investigated. Several improvements of the UVP+PD measurement method were proposed.

Zusammenfassung:
Das In-Line-Rheometer Konzept, das auf die Kombination von Ultraschall-Strömungsprofilmessung (UVP) und Druckdifferenz (PD) basiert, wurde für die Untersuchung des Einflusses der Partikelkonzentration und Größenverteilung auf die Rheologie von Suspensionen in Rohrströmungen unter realistischern industriellen Prozessbedingungen verwendet. Es wurden wohldefinierte Modell-Suspensionen verwendet, welche aus Polyamid Partikeln von 11 µm und 90 µm Durchmesser in Rapsöl in Konzentrationen von 1 bis 25 Vol.% bestanden. Die Variation der Konzentration und Teilchengrößenverteilung hatte die erwarteten Auswirkungen auf die Scher-Viskosität der untersuchten bimodalen und unimodal Suspensionen. Die In-Line-Ergebnisse zeigten, dass das Fliessverhalten der untersuchten Suspensionen mit dem Sisko Modell beschrieben werden kann und dass die UVP + PD-Methode geeignet ist, das Fließverhalten von komplexen Fluiden und Suspensionen zu messen, auch bei hohen Feststoffkonzentrationen. Die erhaltenen in-line Ergebnisse weisen eine gute Übereinstimmung mit der off-line Messung mit einem herkömmlichen Rotations-Rheometer auf. Es wurden gewisse Einschränkungen bei Verwendung der kommerziell erhältlichen Ultraschall-Technologie identifiziert und andere mögliche Ursachen von Ungenauigkeiten der UVP + PD-Methode untersucht. Basierend darauf, werden mehrere Verbesserungsmöglichkeiten der Technologie vorgeschlagen.

Résumé:
Le concept du rhéomètre utilisé “en ligne” est basé sur : la technique de vélocimétrie ultrasonore (VU) combinée avec lamesure de perte de charge (PC). Des mesures ont été réalisées afin d´étudier l´influence de la concentration et de la taille des particules sur les paramètres rhéologiques de particules en suspension, s´écoulant dans des tuyaux, sous des conditions réelles de production industrielle. Les échantillons utilisés sontconstitués de particules de polyamide de 11 µm et 90 µm de diamètre, suspendues dans une solution d´huile de colza dont la concentration varie de 1 à 25%. Les variations de la concentration en particules et de la taille de ces dernières, ont crée les effets escontés sur la viscosité des suspensions unimodales et bimodales étudiées. Les résultats obte-

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increase accuracy and precision of the UVP+PD method further, improvements of the transducer technology and its fixation in the flow adapter are necessary. Also the effect of the numerous measurement parameters on the rheometric results has been investigated systematically. To increase the available shear rate range towards the wall, thus the high shear region, a deconvolution of the velocity profile is necessary. New transducer technology and a non-invasive sensor set-up, currently under development, in combination with new improved pulser/receiver electronics will eliminate many of the current limitations of the UVP+PD method discussed in this work.

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REFERENCES

[1] Kowalewski TA: Velocity profiles of suspension flowing through a tube. Arch. Mech. 32 (1980) 857–865.

[2] Müller M, Brunn P, Harder C: New rheometric technique: The gradient-ultrasound pulse Doppler method. Appl. Rheol. 7 (1997) 204-210.

[3] Wunderlich T, Brunn PO: Ultrasound pulse Doppler method as a viscometer for process monitoring. Flow Measurement and Instrumentation 10 (1999) 201-205.

[4] Brunn PO, Wunderlich T, Müller M: Ultrasonic rheological studies of a body lotion. Flow Measurement and Instrumentation 15 (2004) 139–144.

[5] 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.

[6] Birkhofer BH, Jeelani SAK, Windhab EJ, Ouriev B, Lisner KJ, Braun P, Zeng Y: Monitoring of fat crystallization process using UVP+PD technique. Flow Measurement and Instrumentation 19 (2008) 163-169.

[7] Wiklund J, Johansson M, Shaik J, Fischer P, Windhab EJ, Stading M, Hermansson A-M: In-Line Ultrasound based Rheometry of industrial and model suspensions flowing through pipes. Proceedings of the 3rd ISUD, Lausanne, Switzerland (2002) 69-76.

[8] Wiklund J, Shahram I, Stading M: Methodology for in-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques. Chem. Eng. Sci. 2 (2007) 4277-4293.

[9] Wiklund J, Stading M: Application of in-line ultrasound Doppler-based UVP+PD rheometry method to concentrated model and industrial suspensions. Flow Measurement and Instrumentation 19 (2008) 171-179.

[10] Dogan N, McCarthy MJ, Powell RL: Application of an in-line rheological characterization method to chemically modified and native corn starch. J. Texture Stud. 36 (2005) 237-254.

[11] Dogan N, McCarthy MJ, Powell RL: Measurement of polymer melt rheology using ultrasonics based in-line rheometry. Measurement Science and Technology 16 (2005)1684-1690.

[12] Kotze R, Haldenwang R, and Slatter P: Rheological characterisation of highly concentrated mineral suspensions using an ultrasonic velocity profiling with combined pressure difference method. Appl. Rheol. 18(2008) 62114.

[13] Kotze R, Wiklund J, Haldenwang R, Fester V: Measurement and Analysis of Flow Behavior in Complex Geometries using Ultrasonic Velocity Profiling (UVP) Technique. Flow Measurement and Science Journal 22 (2011) 110-119.

[14] Kotze R, Wiklund J, Haldenwang R: Optimization of the UVP+PD Rheometric method for flow behavior monitoring of industrial fluid suspensions. Appl. Rheol. 22 (2012) 42760.

[15] Ricci S, Liard M, Birkhofer B, Lootens D, Brühwiler A, Tortoli P: Embedded Doppler System for Industrial In-Line Rheometry. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 59 (2012) 1395-1401.

[16] Birkhofer B, Debacker A, Russo S, Ricci S. Lootens D: In-line rheometry based on ultrasonic velocity profiles: comparison of data processing methods. Appl. Rheol. 22 (2012) 44701.

[17] Stickel JJ, Powell RL: Fluid mechanics and rheology of dense suspensions. Ann. Rev. Fluid Mech. 37 (2005) 129-149.

[18] Krieger IM: Rheology of monodisperse latices. Adv. Colloid Interface Sci. 3 (1972) 111-136.

[19] Völtz C, Nitschke M, Heymann L, Rehberg I: Thixotropy in macroscopic suspensions of spheres. Phys. Rev. E 65 (2000) 051402.

[20] Hoffmann RL: Discontinuous and dilatant viscosity behavior in concentrated suspensions. I.

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http://www.appliedrheology.org

Observation of a flow instability. Trans. Soc. Rheol./J. Rheol. 16 (1972) 155-173.
[21] Ferrini F, Ercolani D, de Cindio B, Nicodemo L, Nicolais L, Ranaudo S: Shear viscosity of settling suspensions. Rheol. Acta 18 (1979) 289-296.
[22] Krieger IM, Dougherty TJ: Mechanism for non-Newtonian flow in suspensions of rigid spheres. Trans. Soc. Rheol./J. Rheol. 3 (1959) 137-152.
[23] Farris RJ: Prediction of the viscosity of multimodal suspensions from unimodal viscosity data. Trans. Soc. Rheol./J. Rheol. 12 (1968) 281-301.
[24] Chang C, Powell RL: Effect of particle size distributions on the rheology of concentrated bimodal suspensions. J. Rheol. 38 (1994) 85-98.
[25] Chang C, Powell RL: The rheology of bimodal hard-sphere dispersions. Phys. Fluids 6 (1994) 1628-1636.
[26] Probstein RF, Sengun MZ, Tseng TC: Bimodal model of concentrated suspension viscosity for distributed particle sizes. J. Rheol. 38 (1994) 811-829.
[27] Greenwood R, Luckham PF, Gregory T: The Effect of Diameter Ratio and Volume Ratio on the Viscosity of Bimodal Suspensions of Polymer Latices. J. Colloid Interface Sci. 191 (1997) 11-21.
[28] Chong JS, Christiansen EB, Baer AD: Rheology of concentrated suspensions. J. Appl. Polymer Sci. 15 (1971) 2007-2021.
[30] Barnes HA, Hutton JF, Walters K: An Introduction to Rheology. Elsevier, Amsterdam (1989).
[31] Marti I, Höfler O, Fischer P, Windhab EJ: Rheology of concentrated suspensions containing mixtures of spheres and fibres. Rheol. Acta 44 (2005) 502-512.
[32] Barnes HA: Measuring the viscosity of large-particle (and flocculated) suspensions - a note on the necessary gap size of rotational viscometers. J. Non-Newtonian Fluid Mech. 94 (2000) 213-217.
[33] Lemmin U, Rolland T: Acoustic velocity profiler for laboratory and field studies. J. Hydraulic Eng. 123 (1997) 1089-1098.
[34] Rittgers SE, Putney WW, Barnes RW: Real-time spectrum analysis and display of directional Doppler ultrasound blood velocity signals. IEEE Transactions on Biomedical Engineering 27 (1980) 723-728.
[35] Tortoli P, Guidi F, Guidi G, Atzeni C: Spectral velocity profiles for detailed ultrasound flow analysis. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 43 (1996) 654-659.
[36] Sisko AW: The flow of lubricating greases. Ind. Eng. Chem. 50 (1958) 1789.
[37] Moallemi N,. Shafieenejad, I, Novinzadeh, AB: Exact solutions for flow of a sisko fluid. Special Issue of the Bulletin of the Iranian Mathematical Society 37 (2011) 49-60.
[38] Jones SA: Fundamental sources of error and spectral broadening in Doppler ultrasound signals. Crit. Rev. Biomed. Eng. 21(1993) 399-483.
[39] Markou CP, Ku DN: Accuracy of velocity and shear rate measurements using pulsed Doppler ultrasound: A comparison of signal analysis techniques. Ultrasound in Medicine & Biology 17 (1991) 803-814.
[40] Jorgensen JE, Garbini JL: An analytical procedure of calibration for the pulsed ultrasonic Doppler Flow meter. Transactions of the ASME/Journal of Fluids Engineering 96 (1974) 158-167.
[41] Jorgensen JE, Campau DN, Baker DW: Physical characteristics and mathematical modeling of pulsed ultrasonic flowmeter. Med. Biol. Eng. 11(1973) 404-421.
[42] Hughes PE, How TV: Quantitative measurement of wall shear rate by pulsed Doppler ultrasound. J. Med. Eng. Techno. 17 (1993) 58-64.
[43] Tortoli P, Morganti T, Bambi G, Palombo C, Ramnarine KV: Noninvasive simultaneous assessment of wall shear rate and wall distension in carotid arteries. Ultrasound in Medicine & Biology 32 (2006) 1661–1670.
[44] Matas JP, Glezer V, Guazzelli E: Trains of particles in finite-Reynolds-number pipe flow. Phys. Fluids 16 (2004) 4192-4195.
[45] Butler JE, Bonnecaze RT: Imaging of particle shear migration with electrical impedance tomography. Phys. Fluids 11 (1999) 1982-1994.
[46] Birkhofer BH: Ultrasonic in-line characterization of suspensions. PhD thesis, ETH Zurich (2007).

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