How to Characterize Yield Stress Fluids with Capillary Breakup Extensional Rheometry (CaBER)?

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Abstract:

Filament breakup of high viscosity fluids with apparent yield stress has been investigated and strategies for an appropriate characterization of their behavior in CaBER experiments are discussed. Filament profiles of such fluids exhibit significant concave curvature. Accurate determination of filament shape is mandatory for understanding deformation behavior. Therefore, we have set up an optical train including high-speed camera, telecentric objective and telecentric back-light illumination with a blue light emitting diode (LED) providing high contrast filament shape imaging. Image analysis allows for diameter determination with an accuracy of 3.55 μm/pixel. In addition to the transient filament diameter at the neck we have extracted the curvature at this point as a function of time and the region of deformation, in order to characterize the extensional flow behavior. We have investigated the time evolution of filament shape as a function of various experimental parameters like stretching time, velocity profile during stretching, stretching ratio and initial sample volume at constant stretching ratio. Filament thinning is independent of stretching time, t_s and stretching velocity profile. But when the same stretching ratio is applied at different initial volume fraction, filament curvature increases strongly with decreasing sample volume leading to an increase of filament life time according to the negative contribution of its curvature to the Laplace pressure inside the fluid.

Zusammenfassung:

Es wurde der Fadenabriss von hochviskosen Flüssigkeiten mit scheinbarer Fließgrenze untersucht und Strategien für die Charakterisierung ihres Verhaltens in CaBER Experimenten diskutiert. Das Fadenprofil solcher Flüssigkeiten zeigt eine signifikante konkave Krümmung. Daher ist die präzise Charakterisierung der Fadenkonturen für das Verstehen des Deformationsverhaltens entscheidend. Aus diesem Grund wurde der optische Aufbau des CaBER Gerätes mit einer Hochgeschwindigkeitskamera, telezentrischen Objektiven und blauer, telezentrischer Hintergrundbeleuchtung, die eine kontrastreiche Fadenkonturabbildung ergibt, ausgestattet. Die Bildanalyse lässt eine hochauflösende Durchmesserbestimmung mit der Genauigkeit von ± 3.55 μm/pixel zu. Zusätzlich zum zeitlichen Verlauf des Durchmessers an der Fadeneinschnürung wurden auch der zeitliche Verlauf der Krümmung an dieser Stelle und der Formänderungsbereich berechnet, um das Dehnfließverhalten zu charakterisieren. Die zeitliche Entwicklung der Fadenprofile in Abhängigkeit von unterschiedlichen experimentellen Parametern wie z. B. Dehnzeit t_s, Dehngeschwindigkeitsprofil, Dehnrate and Anfangsprobenvolumen bei konstanter Dehnrate wurde untersucht. Die Fadenverdünnung ist unabhängig von t_s und dem Dehngeschwindigkeitsprofil. Wird die gleiche Dehnrate bei unterschiedlichem Anfangsprobenvolumen verwendet, steigt die Fadenkrümmung mit abnehmendem Probenvolumen stark an. Dies führt zur Erhöhung der Fadenlebensdauer entsprechend dem negativen Beitrag der Krümmung zum Laplace Druck innerhalb der Flüssigkeit.

Résumé:

La rhéologie extensionnelle de fluides de viscosité élevée ayant une contrainte seuil a été étudiée dans le but d´obtenir des connaissances déterminantes sur leur comportement lors de ce type d´écoulement. Les expériences ont été effectuées à l´aide du rhéomètre élongationel CaBER. Le profil des filaments obtenu pour de tels fluides montrent une courbure concave significative et une détermination précise de leurs formes est nécessaire pour comprendre leur comportement lors de la déformation. Pour cela nous avons équipé notre montage optique d´une caméra à haute vitesse, d´un objectif télécentrique et d´un éclairage d´arrière-plan télécentrique de couleur bleue qui permet d´obtenir un contraste élevé de l´image du filament. L´analyse des images au point de courbure du filament permet une détermination du diamètre au cours du temps avec une précision de l´ordre de 3.55 μm/pixel. En plus de la détermination du diamètre, nous avons également étudié l´évolution de la forme de la courbure du filament en fonction du temps en variant divers paramètres expérimentaux tels que : la durée de l´élongation, le profile de vitesse durant l´élongation, le taux d´élongation et le volume initiale de

ware. The time evolution of the full filament contour is detected with resolution of ± 1 pixel.

The influence of the stretching parameters of the CaBER device on capillary thinning of fluids with an apparent yield stress was discussed. Neither stretching time nor stretching velocity profile has significant influence on the capillary thinning of those fluids. Suggested initial set-up parameters are cushioned stretching profile, which provides the best reproducible results and optimal stretching time is in the range between 35 ms and 50 ms. Variation of Hencky strain, results in a decrease of initial diameter and filament life time with increasing ϵ, but it has no influence on the initial curvature. Moreover, diameter and curvature at the neck, measured for different ϵ show similar time evolution. Lastly, if plate separation is varied in a way that keeps Hencky strain unchanged, the initial value of diameter remains constant but the curvature increases with decreasing initial gap separation and results in a deceleration of the thinning process according to the corresponding drop of the Laplace pressure inside the filament.

Although further efforts are required for a determination of physical quantities like elongational viscosity, the CaBER technique can be successfully applied to investigate elongational flow properties of yield stress fluids. The time- and space- evolution of the fluid filament can be quantified. The measurement technique gives well reproducible results, variation in the characteristic parameters extracted from the filament profiles do not exceed 10 %. Thus, future work will address influence of fluid properties, e.g. volume fraction of disperse phase and droplet size for the emulsions or polymer concentration and pH value for the thickener solutions, on capillary thinning. The determination of an elongational yield stress and the identification of rheological parameters characterizing the transient extensional properties of such fluids which can be correlated to processing and application properties will be of particular interest.

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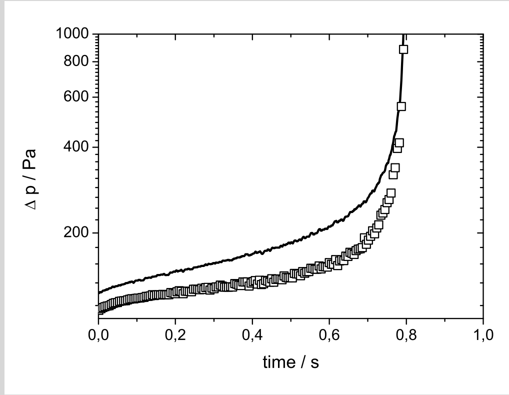

Figure 12: Influence of filament curvature on Laplace pressure. The open symbols show the Laplace pressure calculated from Eq. 4 using the data from Figure 11 (a) and (b). The initial plate distance was h_0 = 1.5 mm, and end plate distance, h_f = 16.64 mm. Solid line was calculated neglecting the filament curvature, i.e. R_2 = 0.

REFERENCES

[1] Plateau J: Experimental and theoretical researches on the figures of equilibrium of a liquid mass withdrawn from the action of gravity, Annu. Rep. Smithsonian Inst. (1863) 207–285.
[2] Lord Rayleigh: On the stability of jets, Proc. London Math. Soc. 10 (1879) 4–13.
[3] Sridhar T, Tirtaatmadja V, et al.: Measurement of extensional viscosity of polymer solutions, J. Non-Newtonian Fluid Mech. 40 (1991) 271–280.
[4] Tirtaatmadja V, Sridhar T: A filament stretching device for measurement of extensional viscosity, J. Rheol. 37 (1993) 1081–1102.
[5] Entov VM, Hinch EJ: Effect of a spectrum of relaxation times on the capillary thinning of a filament of elastic liquid, J. Non-Newtonian Fluid Mech. 72 (1997) 1081–1102.
[6] Rodd LE, Scott TP, et at.: Capillary break-up rheometry of low-viscosity elastic fluids, Appl. Rheol. 15 (2004) 12–27.
[7] Basilevskii AV, Entov VM, et al.: Failure of Polymer Solution Filaments, Polym. Sci. A 39 (1997) 316–324.
[8] Basilevskii AV, Entov VM, et al.: Failure of an Oldroyd Liquid Bridge as a Method for Testing the Rheological Properties of Polymer Solutions, Polym. Sci. A 43 (2001) 1161–1172.
[9] Clasen C, Plog JP, et al.: How dilute are dilute solutions in extensional flows?, J. Rheol. 50 (2006) 849–881.
[10] Solomon MJ, Muller SJ: The transient extensional behavior of polystyrene-based Boger fluids of varying solvent quality and molecular weight, J. Rheol. 40 (1996) 837–856.
[11] Rothstein JP: Strong flows of viscoelastic wormlike micelle solutions, Rheol. Rev. (2008) 1–42.
[12] Bhardwaj A, Miller E, et al.: Filament stretching and capillary breakup extensional rheometry measurements of viscoelastic wormlike micelle solutions, J. Rheol. 51 (2007) 693–719.
[13] McKinley GH: Visco-elasto-capillary thinning and break-up of complex fluids, Rheol. Rev. (2005) 1–48.
[14] Kheirandish S, Guybaidullin I, et at.: Shear and elongational flow behavior of acrylic thickener

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solutions, Part I: Effect of intermolecular aggregation, Rheol. Acta 47 (2008) 999–1013.
[15] Kheirandish S, Guybaidullin I, et al.: Shear and elongational flow behavior of acrylic thickener solutions, Part II: effect of gel content, Rheol. Acta 48 (2009) 397–407.
[16] Renardy M, Renardy Y: Similarity solution for breakup of jets of power law fluids, J. Non-Newtonian Fluid Mech. 122 (2004) 303–312.
[17] Renardy M: Similarity solution for jet breakup for various models of viscoelastic fluids, J. Non-Newtonian Fluid Mech. 104 (2002) 65–74.
[18] Renardy M: Self-similar breakup of Giesekus jet, J. Non-Newtonian Fluid Mech. 97 (2001) 261–293.
[19] Renardy M: Self-similar jet breakup for generalized PPT model, J. Non-Newtonian Fluid Mech. 103 (2002) 261–269.
[20] Yildirim OE, Basaran OA: Deformation and breakup of stretching bridges of Newtonian and shear-thinning liquids: comparison of one- and two-dimensional models, Chem. Eng. Sci. 56 (2001) 211–233.
[21] Ambravaneswaran B, Basaran OA: Effect of insoluble surfactants on the nonlinear deformation and breakup of stretching liquid bridges,Phys. Fluids 11 (1999) 997–1015.
[22] Webster MF, Matallah H, et al.: Numerical modeling of step-strain for stretched filaments, J. Non-Newtonian Fluid Mech. 151 (2008) 38–58.
[23] Oliveira MSN, Yeh R, et al.: Extensional Rheology and Formation of Beads-on-a-String Structures in Polymer Solutions, J. Non-Newtonian Fluid Mech. 137 (2006) 137–148.
[24] Stelter M, Brenn G, et al.: Validation and application of a novel elongational device for polymer solutions J. Rheol. 44 (2000) 595–616.
[25] McKinley GH, Tripathi A: How to extract the Newtonian viscosity from capillary breakup measurements in a filament rheometer, J. Rheol. 44 (2000) 653–670.
[26] Lowry BJ, Steen PH: Capillary Surfaces: Stability from Families of Equilibria with Application to the Liquid Bridge, Proc. R. Soc. London, A 449 (1995) 411–439.
[27] Mahajan MP, Tsige M, et al.: Stability of liquid crystalline bridges, Phys. Fluids 11 (1999) 491–493.
[28] Goldin M, Pfeffer R, et al.: Break-up of a capillary jet of a non-Newtonian fluid having a yield stress, Chem. Eng. J. 4 (1972) 8–20.
[29] Rothstein JP, Miller E, et al.: The Effect of Step-Stretch Parameters on Capillary Breakup Extensional Rheology (CaBER) Measurements, Proc. Int. Cong. Rheol. (2008).
[30] Sattler R, Wagner C, et al.: Blistering Pattern and Formation of Nanofibers in Capillary Thinning of Polymer Solutions, Phys. Rev. Lett. 100 (2008) 164502.
[31] Smith WJ: Modern optical engineering, 3rd Edition, McGraw-Hill, New York (2000).
[32] Bowman AW, Azzalini A: Applied Smoothing Techniques for Data Analysis: the Kernel Approach with S-Plus Illustrations, Oxford University Press (1997).

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