The Back Extrusion Test as a Technique for Determining the Rheological and Tribological Behaviour of Yield Stress Fluids at Low Shear Rates

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Abstract:

A new method is developed to determine the rheological and tribological behaviour of viscoplastic fluids using a back extrusion test. In back extrusion geometry, the material is forced to flow in the gap between the inner and the outer cylinder. Such a flow is modelled by a Bingham constitutive law under different wall boundary conditions (stick, slip with friction and perfect slip). When steady-state flow is reached, an apparent shear rate is computed. The analysis of the inner cylinder penetration force versus the penetration depth helps us to develop a method to identify the fluid rheological and tribological properties. This method is based on an inverse analysis to identify the fluid behaviour parameters from experiments performed at different ram velocities and with different apparatus geometries. In order to study more complex fluids (Herschell-bulkley rheological behaviour, for example), an equivalent flow curve is plotted from tests characterized by different average shear rates. The tribological behaviour is identified using different wall boundary conditions, varying the surface roughness of the cylinders. The method is applied to oil/sugar suspension and plasticine. Rheological and tribological behaviours are identified and results are compared with those obtained under steady state shear flow. The obtained rheological parameters are close to those provided by the common rheological methods (difference lower than 15 %).

Zusammenfassung:

Eine neue Methode wird vorgestellt, um das rheologische und tribologische Verhalten von viskoplastischen Flüssigkeiten mit Hilfe des sogenannten „Rückflußextrusion“-Tests zu bestimmen. Bei dieser Geometrie fließt das Material in dem Spalt zwischen dem inneren und dem äußeren Zylinder. Diese Strömungssituation wird durch die Konstitutivgleichung für eine Bingham-Flüssigkeit bei verschiedenen Randbedingungen an der Wand (Wandhaften, Wandgleiten mit Reibung und vollständiges Wandgleiten) modelliert. Wenn eine stationäre Strömung erzielt wird, wird die scheinbare Schergeschwindigkeit berechnet. Die Berechnung der Penetrationskraft beim inneren Zylinder als Funktion der Eindringtiefe hilft eine Methode zu entwickeln, um die rheologischen und tribologischen Eigenschaften zu identifizieren. Diese Methode basiert auf einer inversen Analyse, um die Parameter für die Flüssigkeit aus den Experimenten zu ermitteln, die bei unterschiedlichen Kolbengeschwindigkeiten und bei unterschiedlichen Apparaturgeometrien gewonnen wurden. Um komplexere Flüssigkeiten zu analysieren (z. B. Herschell-Bulkley-Fluide), wird eine äquivalente Fließkurve aufgetragen, die aus Versuchen bei verschiedenen Schergeschwindigkeiten gewonnen wurde. Das tribologische Verhalten wurde bei verschiedenen Randbedingungen an der Wand untersucht, wobei die Oberflächenrauhigkeit des Zylinders variiert wurde. Die Methode wird auf Öl/Zucker-Suspensionen und Knete angewandt. Das rheologische und tribologische Verhalten wurde untersucht, und die Ergebnisse mit denen der stationären Scherströmung verglichen. Die rheologischen Größen sind sehr ähnlich zu denen, die durch die üblichen rheologischen Methoden erhalten werden (der Unterschied beträgt weniger als 15 %).

Résumé:

Une nouvelle méthode d’analyse rhéologique et tribologique est développée en exploitant l’écoulement de back extrusion. L’utilisation des courbes « effort d’extrusion en fonction du déplacement du cylindre intérieur » permet d’identifier les caractéristiques rhéologiques et tribologiques du fluide testé à partir des résultats de tests réalisés avec différents vitesses de pénétration du cylindre intérieur et différentes configurations géométriques. Dans le cadre de l’étude de fluides complexes incompressibles tels que les fluides d’Herschell-Bulkley frottant, la méthode permet d’aboutir à la construction d’un rhéogramme équivalent tracé à partir d’essais caractérisés par différents taux de déformation moyen. Le comportement tribologique peut être identifié en modifiant les conditions de frottement à la paroi en variant la rugosité des surfaces. La méthode est appliquée aux cas de suspensions concentrées huile/sucre et plasticine. Les comportements rhéologiques et tribologiques sont identifiés et comparés aux résultats obtenus avec la rhéométrie traditionnelle. Les paramètres rhéologiques obtenus sont proches de ceux obtenus par rhéometrie traditionnelle (différence toujours inférieure à 15%).

Key words: tribology, yield stress fluids, back extrusion, flow curve

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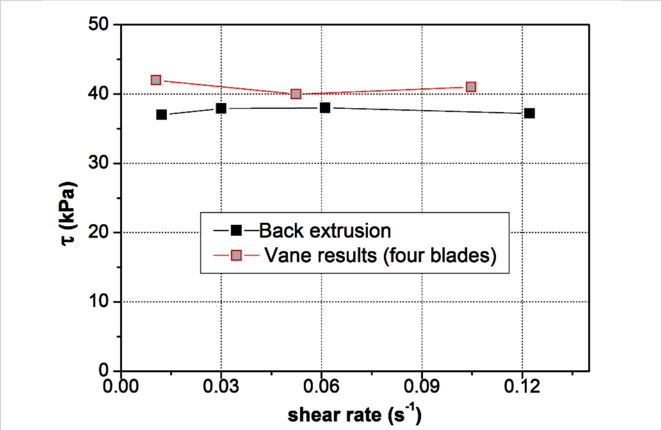

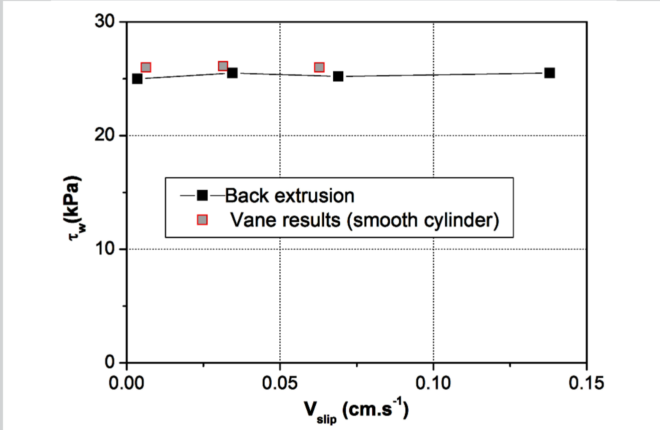

Figure 9 (left): Plastic behaviour of plasticine described by vane tests and back extrusion tests.

Figure 10: Tribological behaviour of plasticine described by vane tests and back extrusion tests.

As slipping flow is obtained with the smooth surface, the tribological behaviour of the sugar dispersion can be studied. From the procedure described in section 4.2, we use the rheological parameters obtained with roughened surfaces in the data analysis of the tests performed with smooth surfaces. This makes it possible to plot a curve which links the slip velocity to the wall shear stress (Figure 8). The result shows an increase of wall shear stress with the slip velocity increasing. As the material is sheared near the wall, we note here that the computed wall shear stress τ_w is higher than the material yield stress. This means that the wall friction is sufficient to shear the material.

4.2 PLASTICINE

Plasticine is known to be a mainly plastic material after short compression [18]. Four tests are carried out with smooth and roughened surfaces at different inner cylinder velocities ranging from 0.1 to 1 mm/s. Results are compared with shear flow measurement under constant controlled velocity obtained with a four-bladed vane of 8 mm in both height and diameter and friction measurement obtained with smooth cylinder of 8 mm in both height and diameter. This leads to independently identify the yield stress and the wall friction stress of plasticine. BET with roughened surface tests allow to plot the equivalent flow curve. The previously proposed methods are used to study the plasticine behaviour. As expected for plastic material, the shear stress is not influenced by shear rate in the range of tested velocities (Figure 9). The back extrusion test and vane test results are also shown to be in accordance. Vane tests provide a yield stress average value of 41 kPa with the Estellé et al. procedure and 40 kPa with the stress growth test while BET provides a value of 37.5 kPa. The relative deviation is less than 5 %.

With a smooth surface and at the tested penetration velocities, the material is not sheared and a plug flow appears in the gap. Equation 24 makes it possible to compute the , parameter for a given slip velocity defined by Equation 23. The β parameter enables the determining of a new tribological law that is reinserted into the analytical model. The results plotted in Figure 10 show that plasticine exhibits a constant wall friction stress in the range of used slip velocities (0.14 mm/s to 1.4 mm/s). Tests performed with a rotating smooth cylindrical tool confirm this value as shown by Figure 10. The rotating tool is immersed in the paste. Then, a grid is drawn on the plasticine surface to check if shearing occurs. After the test, at a constant angular velocity, the grid is checked. If the grid has not changed, we conclude that only slippage at the tool surface occurs. The tool radius and the angular velocity allow us to compute the slip velocity at the material/device interface. Those tests provide an average friction stress value of 26 kPa while BET provides a value of 25.5 kPa. Here, the relative deviation is less than 3 %.

5 CONCLUSIONS

The developed back extrusion rheometer allows for behaviour characterization of highly viscous pastes in good correlation with conventional techniques. Tests performed with an oil/sugar suspension and plasticine highlight the ability of back extrusion to be used as a polyvalent tribometer/rheometer. Back extrusion tests provide a useful and simple technique to evaluate the yield stress of viscoplastic materials and to both estimate equivalent flow curve and slip velocity/ wall stress curve. The developed technique is validated using a sugar-oil suspension and plasticine. The presented results shows the ability of the BET to characterizate the rheological and tribological properties of viscoplastic fluids. Wall friction stress and yield stress values of plasticine have been estimated from back extrusion geometry. All obtained values are in agreement with the values obtained by conventional measurements.

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