Interpretation of T-Bar Tool Measurements for Yield Stress Materials

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Abstract:
The T-bar rheometrical tool (Brookfield Engineering Laboratories, Inc.) is a slender rod which is placed in a material and rotated horizontally about its short axis by a vertical shaft. The torque on the shaft from laminar flow of material around the rod is determined by the material's rheological properties. T-bar experiments for a Newtonian liquid are shown to agree closely with existing theory. For yield stress materials an approximation is derived for the torque on a rotating T-bar which is supported by experiments on a range of materials. The torque for very slow rotational speed is insensitive to boundaries beyond a few T-bar diameters and is shown to correlate with the material's yield stress and other non-Newtonian parameters. A step-decrease in torque for each half-revolution of the T-bar was shown by some materials and possible origins of this effect are discussed.

Zusammenfassung:
Das sogenannte T-Stück-Werkzeug (Brookfield Engineering Laboratories, Inc.) ist ein schlanker Stab, der in die Testflüssigkeit geführt wird und horizontal entlang seiner kurzen Achse mittels eines kurzen Schaftes rotiert. Das auf den Schaft aufgrund der laminaren Strömung um den Stab wirkende Drehmoment wird von den rheologischen Eigenschaften der Testflüssigkeit beeinflusst. Experimente mit einer Newtonschen Flüssigkeit in dieser Geometrie sind mit der existierenden Theorie in guter Übereinstimmung. Für Materialien mit einer Fließspannung wird eine Näherung für das Drehmoment, das auf den rotierenden Stab wirkt, hergeleitet, die für eine große Materialklasse mit den experimentellen Resultaten übereinstimmt. Das Drehmoment bei sehr kleinen Drehgeschwindigkeiten wird nur wenig von den Randbedingungen bei kleinen Durchmessern der T-Stückgeometrie beeinflusst und korreliert mit der Fließpannung und weiteren nicht-Newtonschen Parametern der Testflüssigkeit. Eine stufenweise Abnahme des Drehmoments bei jeder halben Umdrehung des T-Stücks wurde bei einigen Materialien festgestellt. Die möglichen Ursachen dieses Effekts werden diskutiert.

Résumé:
L'outil rhéométrique T-bar (Brookfield Engineering Laboratories, Inc.) est un barreau fin et allongé qui est inséré dans un matériau et est mis en rotation horizontalement autour de son axe court au moyen d'un arbre vertical. Le couple exercé sur l'arbre par l'écoulement laminaire du matériau autour du barreau dépend des propriétés rhéologiques du matériau. Les expériences de T-bar avec un liquide Newtonien sont en accord avec les théories existantes. Pour les matériaux à contrainte seuil, une approximation est dérivée pour le couple exercé sur le T-bar en rotation, qui est supportée par des expériences menées pour une série de matériaux. Pour des vitesses de rotation très lentes, le couple est insensible aux zones de matériaux situées au-dessus de quelques diamètres de T-bar, et est corrélé avec la contrainte seuil du matériau, ainsi qu'avec d'autres paramètres non Newtonien. Une chute soudaine du couple pour chaque révolution du T-Bar est mise en évidence pour certains matériaux, et des origines possibles pour cet effet sont discutées.

Key words: rheometry, T-bar, vane, yield stress, thixotropy, viscoplasticity

1 INTRODUCTION

Shear during sample manipulation can disturb a subsequent rheological measurement, e.g. when a gelled material in a container is transferred to a rheometer. One well-known non-disturbing tool is a thin-bladed vane which can be lowered into the gelled material. The torque to rotate the vane gives the material's yield stress and its linear viscoelastic parameters [1–3]. The T-bar (Brookfield Engineering Laboratories, Inc.) as shown in Figure 1 is also a non-disturbing tool. Additionally it can measure vertical rheological gradients in a material [4], either by making torque measurements at vertical intervals, or by making continuous torque

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ments were made of the torque M and angle θ using tools of different bar-length L, rotated at an angular speed ω. For small angles M increased with θ, followed by a plateau region where $M = M_1$ was largely θ-independent. This suggested a pre- and post-yield behavior separated by a yield angle θ_Y. The near-constancy of $\frac{1}{2}L\theta_Y$ showed the T-bar displacement was approximately 1½ diameters at full yield. The dependence on L of the post-yield torque M_1 supported a model of the tool in which the torques from the bar and the shaft were added to obtain M_1.

Two kinds of fluctuations were found in the torque of the T-bar rotated at constant speed in a yield stress fluid. Minor fluctuations of a few percent were ascribed to spatial fluctuations in rheology that remained despite pre-measurement homogenization. Similar fluctuations were found by Tokpavi et al. [27] in yield stress materials and attributed to unrelaxed localized stresses. Some yield stress materials revealed much larger fluctuations which varied systematically with the angle of rotation. Thus after a whole number of half-rotations the T-bar sensed a rheology disturbed by the previous half-rotation. These fluctuations were absent for non-thixotropic materials, in accord with the distinction made by Fall et al. [30]. Although thixotropy can explain this memory effect, it could also originate from unrelaxed localized stresses as suggested by Tokpavi et al. [27], or because the bar created a channel that separated the sample, or from a combination of all these. To avoid the torque measured in one plane being affected by the shear in the previous plane, a vertical distance of more than about three bar-diameters was required between successive horizontal planes.

An approximate theoretical expression was derived for the yielding torque M of a T-bar rotating slowly with angular speed ω in a yield stress fluid in terms of plastic and viscous drag parameters α_R and β_R. These parameters are analogous to α and β of Tokpavi et al. [26, 27], and Jossic and Magnin [28]. They describe the force on a straight wire moved normally to its length, and are independent of L, D, and the parameters of the Herschel-Bulkley rheological model. Our derivation gave $M(\omega) = M_Y + A\omega^m$, where for a given material and T-bar, the yield torque M_Y and the parameters A and m are constants. This relation was validated by experiment, which gave parameters α_R and β_R in fair agreement with α and β, respectively. For a number of different materials and T-bar geometries we found $\alpha_R = 9.9 \pm 1.3$. Some of the standard deviation may be owing to friction variations at the material-bar surface noted by Tokpavi et al. [27]. The term $M_Y \propto \alpha_R \tau_o$, hence the yield stress τ_o may be obtained from T-bar measurements of M_Y if α_R is known or assumed. The fairly weak dependence of $M_1(\omega)$ on ω allows a good precision of M_Y, and thus if ω is sufficiently small single-speed measurements suffice. Thus for yield-stress materials the T-bar tool can measure τ_o in samples of limited height and for inhomogeneous samples it can measure the vertical gradient of τ_o.

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