Evaluation of the Use of a Semi-hyperbolic Die for Measuring Elongational Viscosity of Polymer Melts

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Abstract:
The semi-hyperbolic (SHPB) die with and possibly without wall lubrication has been proposed as a device for measuring the elongational viscosity of polymeric fluids. Using numerical simulation under the condition of complete wall slip, it was found for two polyethylenes (LDPE and LLDPE) that the calculated elongational viscosity values agreed well with strain-averaged values, $<\eta_e>$, obtained from independent measurements in stretching type rheometers. This is in agreement with the original hypothesis of Everage and Ballman (E-B). Numerical simulations showed that the Baird and Huang (B-H) approach for calculating $<\eta_e>$, which accounts for the shear stress due to geometric considerations in the presence of complete slip, agreed with data better than did the E-B approach. Numerical simulations using varying degrees of wall slip indicated that reasonable values of $<\eta_e>$ could be obtained using the B-H approach with wall slip levels which could be most likely reached using a coating such as a flouroelastomer. The numerical simulations provided an explanation as to why the elongational viscosity values determined in the SHPB die for resins such as LDPE, which are extensional-strain hardening, are less sensitive to wall slip than non-strain-hardening resins such as LLDPE.

Zusammenfassung:
Messungen mit einer semi-hyperbolischen Düse (SHPB) mit und möglicherweise ohne Wandschmierung wurden als eine Methode vorgestellt, die Dehnviskosität von Polymerflüssigkeiten zu bestimmen. Mittels numerischer Simulationen unter der Annahme vollständigen Wandgleitens wurde für zwei Polyethylene (LDPE und LLDPE) gefunden, dass die berechnete Dehnviskosität mit denen über die Dehnung gemittelten Werten gut übereinstimmt, die unabhängig bei Messungen mit Dehnrheometern bestimmt worden sind. Dies steht im Einklang mit der Hypothese von Everage and Ballman (E-B). Numerische Simulationen zeigten, dass der Ansatz von Baird und Huang (B-H) zur Berechnung der Dehnviskosität, der die Scherspannung aufgrund des vollständigen Wandgleitens berücksichtigt, mit den experimentellen Daten besser übereinstimmt als der E-B-Ansatz. Numerische Simulationen für unterschiedliche Stärken des Wandgleitens zeigten, dass adäquate Dehnviskositätswerte mit Hilfe des B-H-Ansatzes erhalten wurden für Wandgleitenstärken, die einer Oberflächenbeschichtung aus einem Fluorelastomer entsprechen. Die numerischen Simulationen geben eine Erklärung dafür, warum die Dehnviskosität, die für LDPE mittels einer SHPB-Düse bestimmt wurde, weniger von der Stärke des Wandgleitens abhängt als für das nichtdehnverfestigende LLDPE.

Résumé:
La filière semi-hyperbolique (SHPB) avec ou sans effet lubrifiant aux parois a été proposée comme un appareil pour mesurer la viscosité d'élongation de fluides de polymères. En utilisant une simulation numérique avec condition de glissement total aux parois, nous avons découvert pour deux polyéthylènes (LDPE et LLDPE) que les valeurs calculées pour les viscosités d'élongation sont en bon accord avec les valeurs moyennées en déformation, $<\eta_e>$, obtenues à partir de mesures indépendantes réalisées avec des rhéomètres d'étirement. Ceci concorde avec l'hypothèse originelle d'Everage et Ballman (E-B). Les simulations numériques montrent que l'approche de Baird et Huang (B-H) pour le calcul de $<\eta_e>$, qui tient compte de la contrainte de cisaillement associée aux considérations géométriques en présence de glissement total, est en meilleur accord avec les données que ne l'est l'approche de E-B. Les simulations numériques avec différents degrés de glissement aux parois indiquent que des valeurs raisonnables de $<\eta_e>$ peuvent être obtenues en utilisant l'approche B-H avec des niveaux de glissement aux parois qui pourraient très probablement être atteints en utilisant des revêtements tels que du fluoroelastomère. Les simulations numériques fournissent une explication à la raison pour laquelle les valeurs de viscosité d'élongation déterminées dans la filière SHPB avec des résines telles que le LDPE, qui sont rhéo-durcissantes en extension, sont moins sensibles au glissement aux parois que ne le sont les valeurs obtenues pour des résines telles que les LLDPE qui ne sont pas rhéo-durcissantes.

Key words: numerical simulation, Phan-Thien and Tanner model, semi-hyperbolic die, extensional rheometers, strain-averaged elongational viscosity, polyethylene

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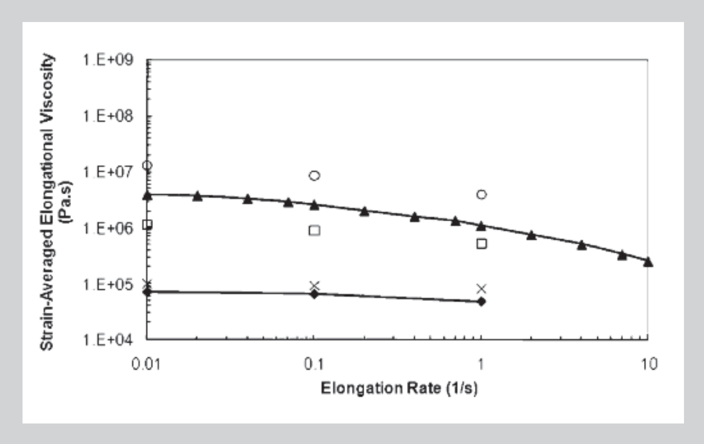

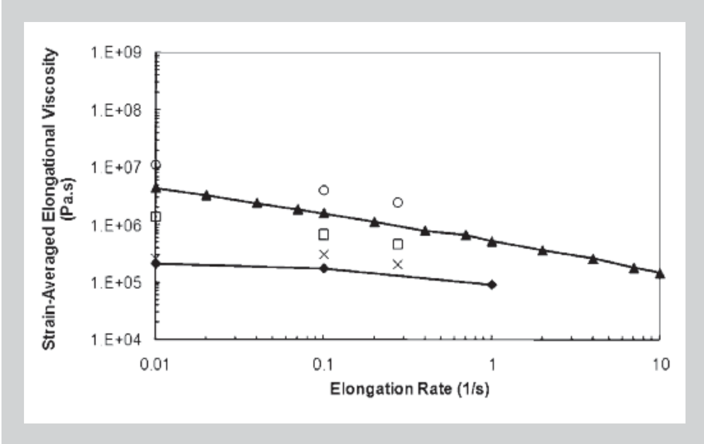

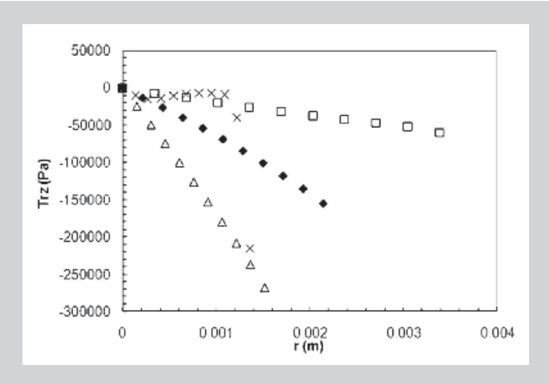

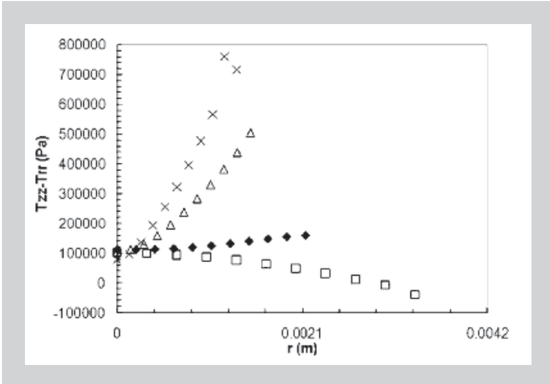

Figure 15 (left above): Strain-averaged elongational viscosity versus elongation rate for NTX101. No wall slip condition was used in numerical simulation of flow in SHPB die. RER, ϵ = 3: (♦); SHPB measured, no lubrication, ϵ = 4: (▲); SHPB calculated, ϵ = 3: (x); Baird & Huang, ϵ = 3: (□); Everage & Ballman, ϵ = 4: (○).

Figure 16 (right above): Strain-averaged elongational viscosity versus elongation rate for NA952. No wall slip condition was used in numerical simulation of flow in SHPB die. RER, ϵ = 3: (♦); SHPB measured, no lubrication, ϵ = 4: (▲); SHPB calculated, ϵ = 3: (x); Baird & Huang, ϵ = 3: (□); Everage & Ballman, ϵ = 4: (○).

Figure 17 (left below): Calculated values of shear stress τ_{rz} versus radial distance, r, for NTX101 at an extension rate of 1 s^{-1} for different axial distances z from the die entrance in a SHPB die designed to produce a maximum Hencky strain of 4 with no wall slip.
z = 0.004 m, ϵ = 2.2: (□);
z = 0.01 m, ϵ = 3.1: (♦);
z = 0.02 m, ϵ = 3.8: (△);
z = 0.025 m, ϵ = 4: (x).

Figure 18 (right below): Calculated values of tensile stress τ_{zz} - τ_{rr} versus radial distance, r, for NTX101 at an extension rate of 1 s^{-1} for different axial distances z from the die entrance in a SHPB die designed to produce a maximum Hencky strain of 4 with no wall slip.
z = 0.004 m, ϵ = 2.2: (□);
z = 0.01 m, ϵ = 3.1: (♦);
z = 0.02 m, ϵ = 3.8: (△);
z = 0.025 m, ϵ = 4: (x).

measured in the RER and SER than do the values obtained from the method of Everage et al. For both LDPE and LLDPE, the predictions of Baird et al. [9] agree with measurements from the RER and SER provided there is a sufficient degree of slip at the wall, but perfect slip does not seem to be required based on the numerical simulations. In fact, it is proposed that a surface coating applied to the die walls such as a flouroelastomer could provide sufficient slip. With increasing wall resistance to the flow, the effect of shear stress on wall pressure measurements becomes increasingly dominant, making the predictions of Baird et al. [9] too high but approaching those determined from the SHPB die and the method proposed by Collier and coworkers. The effect of shear stress on the elongational viscosity measurements in a SHPB die is smaller for LDPE which exhibits extensional strain-hardening than for LLDPE which does not exhibit strain-hardening.

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