EVALUATION OF SLIP EFFECTS IN THE CAPILLARY FLOW OF FOAMS

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Foams have been prepared from water added with a surfactant (Sodium-Dodecyl-Sulfate, SDS) and a polymer (Poly-Ethylene-Oxide, PEO) at different concentrations. This work was devoted to a study of the flow properties of the foams. The pressure drops were measured during flow in capillary tubes (2.5, 3.5 and 4 mm) in laminar regime. It was found a strong dependence of the flow curves on capillary diameter showing that pronounced wall slip effects exist. Two known approaches were applied to quantify the slip velocity: (a) the Mooney method, in which the key assumption is that the slip velocity depends only on the wall shear stress, was not applicable and (b) the Oldroyd-Jastrzebski method, in which the assumption is that the slip velocity depends not only on the wall shear stress but also on the flow geometry, yielded satisfactory results. The determination of the pressure drop coefficient showed that the Metzner and Reed correlation, *i.e.*, the Reynolds analogy based on the generalised Reynolds number, could be applied if the data are corrected for slip effects.

Key-words:
foams, rheology, capillary flow, Reynolds number, friction factor, slip velocity, slip correction methods.

Des mousses préparées en utilisant comme tensio-actif du SDS (Sodium-Dodecyl-Sulfate) et un polymère (Poly-Ethylene-Oxyde) ont été étudiées. L'objectif de ce travail était l'étude des propriétés de ces mousses en écoulement dans des conduites capillaires en régime laminaire. Les courbes d'écoulement obtenues dépendent du diamètre des tubes capillaires, ce qui est significatif de la présence d'effets de glissement à la paroi. Des méthodes de correction de glissement ont été appliquées. Alors que la méthode de Mooney ne semble pas être applicable, celle de Oldroyd-Jastrzebski donne des résultats satisfaisants. On montre que la corrélation de Metzner et Reed peut être utilisée avec succès si on utilise les résultats obtenus après correction des effets de glissement.

Mots-clés:
Mousses, rhéologie, écoulement en conduite capillaire, nombre de Reynolds, coefficient de perte de charge, vitesse de glissement, méthodes de correction du glissement.

Durch Beimengung eines Tensids (Sodium-Dodecyl-Sulfat, SDS) und eines Polymers (Poly-Ethylene-Oxid, PEO) zu Wasser wurden Schäume bei verschiedenen Konzentrationen hergestellt. In dieser Arbeit werden Fließeigenschaften dieser Schäume studiert. Im laminaren Regime wurde der Druckabfall während des Durchflusses durch verschiedene Kapillaren (2,5, 3,5 und 4 mm) gemessen. Die gefundene starke Abhängigkeit der Fließkurven vom Kapillardurchmesser zeigt, daß an der Wand ausgeprägte Schlupfeffekte auftreten. Es wurden zwei bekannte Ansätze verwendet, um die Schlupfgeschwindigkeit zu messen: (a) die Mooney-Methode, und (b) die Oldroyd-Jastrzebski-Methode, bei der angenommen wird, daß die Schlupfgeschwindigkeit nicht nur von der Scherspannung an der Wand, sondern auch von der Strömungsgeometrie abhängt; damit ergaben sich befriedigende Resultate. Die Bestimmung des Druckabfall-Koeffizienten zeigte, daß die Metzner und Reed-Korrelation, d. h. die Reynolds-Analogie basierend auf einer generalisierten Reynoldszahl angewendet werden kann, sofern in den Daten eine Schlupfkorrektur berücksichtigt wird.

Schlagworte:
Schäume, Rheologie, Kapillarströmung, Reynoldszahl, Reibung, Schlupfgeschwindigkeit, Schlupfkorrekturen.

1 *INTRODUCTION*

A foam forms when a gas is intimately mixed with a liquid containing one or more surface active agents. Foams are structured two-phase gas-liquid dispersions with the liquid as the continuous phase and the gas as the dispersed phase. Gas bubbles are separated by interconnecting thin liquid films, and the volume fraction of the continuous liquid phase is small. One of the more important properties of a foam is the relative gas content which can be characterised by the quality, Γ, defined as the ratio of the volume of gas to the sum of gas and liquid volumes, respectively V_g and V_l, i.e., $\Gamma = V_g/(V_g+V_l)$. The quality is between zero and unity. Foam behaviour is of great interest due to numerous applcations in many industrial sec-

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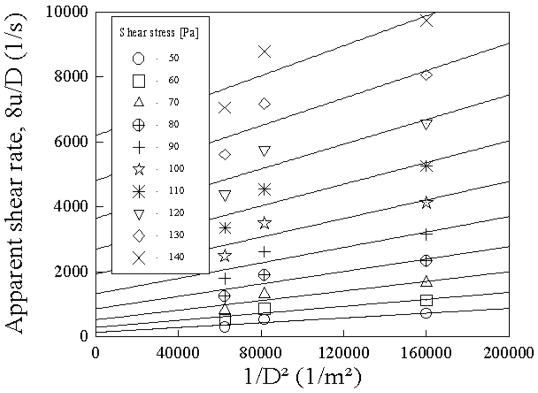

Figure 8 (left): Application of the Oldroyd-Jastrzebski method for a 0.3%PEO foam (shear rate as function of 1/D²at given shear stress). A straight line was fit to the experimental data points for each wall stress using the least squares method.

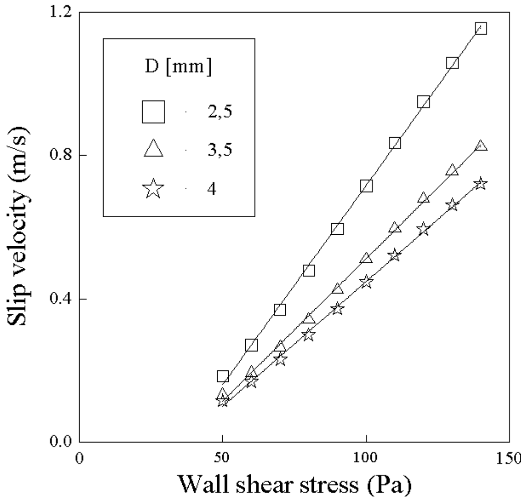

Figure 10 (right): Slip velocities as a function of wall shear stress for a 0.3% PEO foam.

$$\left(\frac{8u}{D}\right)_c = \frac{8}{D}\left(u - \frac{S(\tau_w,D)}{D}\right) \tag{10}$$

which is used for true shear rate calculation.

This method was applied to the same data as previously and the results are presented in Fig. 8. It can be observed that, with this method, the intercepts of the straight lines with the apparent shear rate axis are all positive and vary consistently with the wall stress. Clearly, this shows that the correcting method of Oldroyd-Jastrzebski can be applied successfully to our foamed polymer solutions. This validation of the correcting method brought us to determine $S(\tau_w, D)$ for each value of the shear stress.

In Fig. 9, $S(\tau_w, D)$ is plotted against the wall shear stress τ_w. The best fit curve of $S(\tau_w, D)$ vs. τ_w suggests that a simple linear model is adequate to describe the relationship. Introducing the equation of the straight lines in Eq. 10 yields the corrected shear rate

$$\left(\frac{8u}{D}\right)_c = \frac{8}{D}\left(u - \frac{a\tau_w + b}{D}\right) \tag{11}$$

where the parameters a and b are shown in Fig. 9.

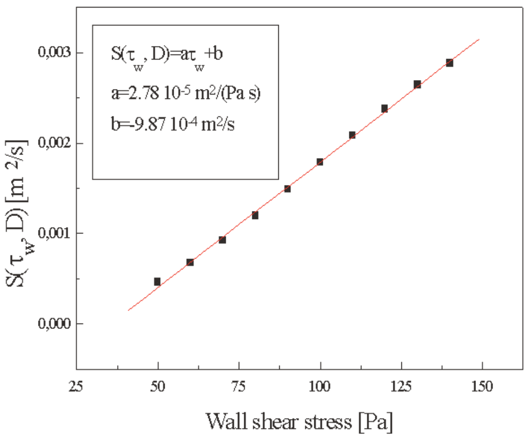

Figure 9 (left): Slip coefficient against wall shear stress for a 0.3% PEO foam.

Fig. 10 shows the plot of the slip velocity V_s as a function of the wall shear stress τ_w for each capillary diameter It may be observed that the slip velocity decreases as the capillary diameter increases. Also, the slip velocity increases linearly as τ_w increases for any diameter in the range of shear stresses studied. Therefore, it may be concluded that the slip velocity determined by the Oldroyd-Jastrzebski method is a function of both the wall shear stress and the capillary diameter, as expected.

3.5 CORRECTED FLOW CURVE

Fig. 11 shows a plot of the wall shear stress as a function of the shear rate corrected for slip. It can be seen that the corrected measurements obtained with different capillaries are fitted by an unique master curve which can be considered as the true flow curve. In comparison, it was observed previously that the flow curves constructed before slip correction exhibited a marked dependence on the pipe diameter (see Fig. 6). A best fit analysis of the corrected data brought us to the conclusion that the rheological behaviour of our foams can be modelized by a power law constitution model $\tau = k\gamma^n$.

The values of the flow index *n* and the consistency *k* derived from this curve were used to calculate the corrected generalised Reynolds number. Fig. 12 shows the results obtained. It appears that, compared to non-corrected data (see also Fig. 4), the corrected data are closer to the Poiseuille curve for Reynolds numbers ranging between 0.1 and 100. On the opposite, for Reynolds numbers lower than 0.1 the correlation seems to be better when non-corrected data are used. These results indicate that within the low velocities range, the slip effects are negligible.

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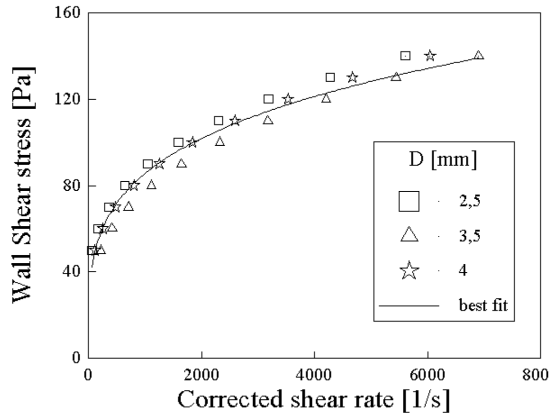

Figure 11 (left): Corrected flow curves for a 0.3% PEO foam.

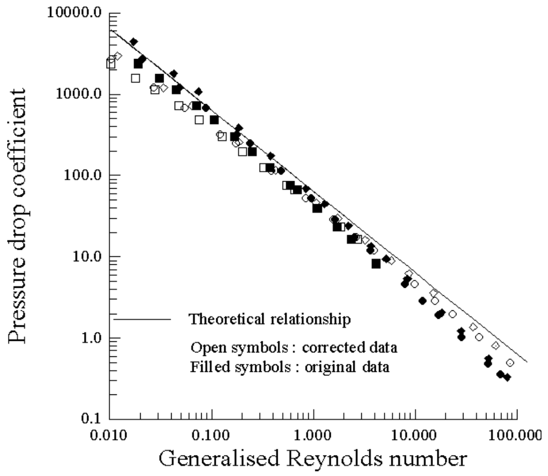

Figure 12 (right): Pressure drop coefficient, λ, (Fanning friction factor) as a function of corrected generalised Reynolds number for a 0,3% PEO foam and different pipes (◆, ✧: 4 mm; ●, ○: 3.5 mm; ■, □: 2.5 mm) and comparison with non-corrected data.

4 CONCLUSION

The flow curves measured by use of a capillary tube rheometer were found to be highly diameter dependent. A master flow curve, independent from the tube diameter, was obtained by applying slip velocity corrections. Application of the Oldroyd-Jastrzebski correction method yields more satisfactory results than the Mooney method. From the unique flow curve it was observed that the foam behaves like a power-law fluid. A good agreement was also found with the generalised Reynolds number correlation proposed by Metzner and Reed when the corrected data are used.

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