Extensional rheology of biopolymer systems

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ABSTRACT

Experimentally rheology has to date mainly dealt with shear flow and the majority of rheological experiments have been performed in shear. Recently there has been an increased interest in experimental extensional rheology, but there are still few experimental techniques available. Hyperbolic Contraction Flow is a suitable method for medium viscosity fluids.

INTRODUCTION AND THEORY

Any change in geometry during flow or processing of a non-Newtonian, viscoelastic liquid generates an extensional flow component. The response to the extensional flow is described by the extensional viscosity, η_E, which may be significantly higher than the shear viscosity, η and can behave in a completely different manner. A shear-thinning polymer solution e.g. often exhibits a tension-thickening extensional viscosity[1].

The uniaxial extensional viscosity, η_E, is in the limit

$$\eta_{e(\dot{\varepsilon})}\Big|_{\dot{\varepsilon}\to 0} = 3\eta_{shear(\dot{\gamma})}\Big|_{\dot{\gamma}\to 0} \qquad (1)$$

and a more general expression, the "Trouton ratio" T_R is defined as

$$T_R = \frac{\eta_E(\varepsilon)}{\eta(\gamma)} \qquad (2)$$

where γ is the shear rate and ε is the extension rate. Elastic liquids, such as polymer systems, are noted for having high Trouton ratios, much higher than 3, which emphasizes the importance of the extensional viscosity. Experimentally, it is often not possible to reach a steady state for η_E and instead the transient extensional viscosity, $\eta_E(t,\varepsilon)$ is measured. A steady state would often require $\varepsilon_H \approx 7$ which is irrelevant for most practical applications and $\eta_E(t,\varepsilon)$ is therefore sufficient[2, 3].

Extensional rheology is well studied theoretically, mainly by the use of fluid dynamics. Experimentally, extensional rheology is far less studied due to substantial experimental difficulties. There is a number of measuring techniques described in literature and some of them have also at times been commercialised. Almost the only method suitable for medium-viscosity fluids ($\eta \approx 1$-50 Pas) is the Hyperbolic Contraction Flow method (HCF).

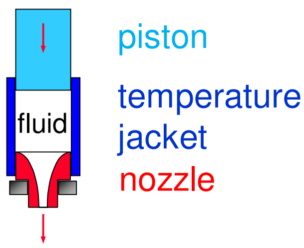

Figure 1. Schematic representation of the Hyperbolic Contraction Flow method

A fluid is forced through a hyperbolic nozzle and the force on the nozzle is monitored. The nozzle is designed to give a constant extension rate by applying the theoretical work by Binding[4] and was first utilized by Wikström and Bohlin[5]. The method has been further refined and applied to medium and high viscosity systems[6-10], and verified by other methods[11] and by using flow mapping[12] and simulations[13].

Extensional rheology is a determining factor for foaming. A suitable level of extensional viscosity together with strain hardening balances the bubble growth during foaming. Cereal proteins form thermoplastic melts[14, 15] suitable for both technical foams and for edible foams (bread)[6-8].

RESULTS AND DISCUSSION

Technical foams were formed in a hot mould by mixing the maize prolamin protein zein with starch, plasticizer and a foaming agent[9]. Figure 2 shows the extensional viscosity of two different zein based melts before foaming. The percentage expresses the ratio of protein to starch, 40% and 60% respectively. For hot mould foaming at the present temperature these compositions determined the limits. The higher protein concentration produced small pores and the lower formed bubbles that grew until they collapsed.

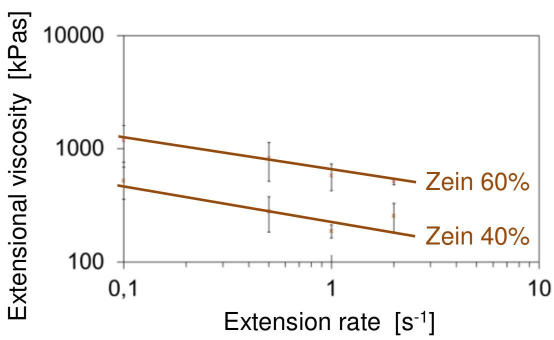

Figure 2. Extensional viscosity measured by the HCF method for zein protein melts intended for technical foams[9].

Melts, or dough, of similar composition were used to bake gluten-free bread[10]. The melts of zein and starch were supplemented with either the hydrocolloid HPMC (hydroxypropylmethylcellulose) or ß-glucan rich oat bran (Oatwell, Swedish Oat Fiber, Bua, Sweden). The resulting dough formed was compared to wheat dough. Zein has higher glasstransition temperature than wheat gluten and mixing of the zein dough was therefore performed at 40°C. The extensional viscosity was measured at both 20° and 40°C for the wheat dough as it is normally mixed at room temperature. Figure 3 shows that the zein based dough had similar extensional viscosity to wheat dough at 20°C. The extensional viscosity predicts foaming behaviour well and both zein based doughs formed porous bread.

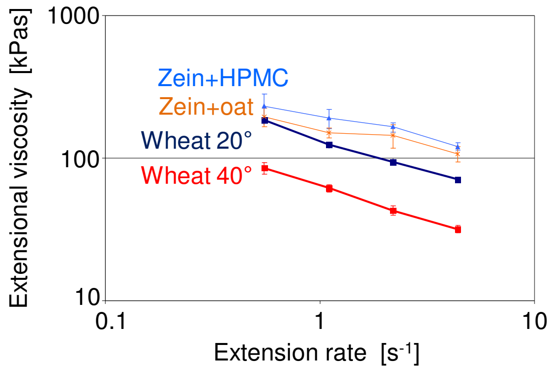

Figure 3. Extensional viscosity measured by the HCF method for dough. The wheat dough was prepared at 20° and 40°C and the zein dough at 40°C with added HPMC or oat bran[10].

Figure 4. Example of a small loaf baked from a zein based dough.

CONCLUSIONS

- Hyperbolic Contraction Flow is a suitable method to measure the extensional viscosity of medium to high viscosity fluids.
- Extensional viscosity predicts foaming behaviour well.
- Cereal proteins form melts with the necessary properties for foaming.

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