USE OF THE CHOPIN ALVEOGRAPHE AS A RHEOLOGICAL TOOL. II. DOUGH PROPERTIES IN BIAXIAL EXTENSION[1]

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ABSTRACT

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Using the equation proposed by Bloksma for calculating dough thickness at any point of the dough bubble, which was shown to be generally valid, it is possible to evaluate stress (σ), strain (ϵ), and strain rate ($\dot{\epsilon}$) during inflation. In biaxial extension σ is shown to depend on $\dot{\epsilon}$, following a power law, and on ϵ, exhibiting ϵ-hardening behavior. A limited comparison between properties in simple shear and in biaxial extension is possible. The ϵ-hardening characteristics explain why too simple rheological models cannot account for the Alveogram's shape.

In another paper (1) we have shown that the equation proposed by Bloksma (2) for calculating dough thickness at any point of the dough bubble is generally valid; this means that the classical expressions used by Bloksma (2) for the stress (σ), strain (ϵ), and strain rate ($\dot{\epsilon}$) can be numerically evaluated. It is possible, using the experimental values obtained in that way, to examine the relation between σ, ϵ, and $\dot{\epsilon}$. The biaxial extension produced during dough bubble inflation is well-linked, from a physical viewpoint, with the process of dough rising; therefore, a better understanding of the rheological significance of the Alveograms could benefit the field of baking. Also, biaxial extension obtained by the bubble inflation technique is becoming an important method in polymer rheology (3—7).

TABLE I
Dough Protein Contents and Empirical Rheological Properties Measured with the Chopin Alveographe

Flour	Protein Content[a] Dry Matter %	Chopin Alveograms[b]		
		Toughness P mm	Extensibility G $cm^{3/2}$	Extension work at rupture W 10^3 erg/g
f00	10.2	47	23.6	150
f0	10.0	40	26.8	140
f1	13.0	75	26.1	310
f2	10.4	40	29.6	175
f3	9.5	34	31.2	120
f6	9.9	54	25.1	175

[a]Expressed as N × 5.7.
[b]Doughs containing 43.2% water and 0.83% NaCl (dough basis), mixed 6 min in the Chopin Alveographe kneader at 25°C.

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MATERIALS AND METHODS

Flours

Six industrial flours are used: a very weak flour (f3), four others rather weak but adequate for French bread-baking (f00, f0, f2, and f6), and a strong one (f1). Dough protein contents and empirical rheological properties obtained with the Chopin Alveographe are given in Table I.

Doughs

Doughs are prepared as stated in the footnote of Table I.

Rheological Measurements

The modified Alveographe, described in another paper (1), measures rheological data.

RESULTS AND DISCUSSION

σ, ϵ, and $\dot{\epsilon}$

Bloksma (2) has used the following equations giving σ, ϵ, and $\dot{\epsilon}$ at any point of the bubble:

$$\text{stress: } \sigma = \frac{pR}{2\Delta} = p \times f\,(V, s) \tag{1}$$

$$\text{strain (Cauchy definition): } \epsilon = -\frac{1}{2} \operatorname{Ln} \frac{\Delta}{\Delta_0} = g\,(V, s) \tag{2}$$

$$\text{strain rate: } \dot{\epsilon} = -\frac{1}{2}\frac{d\Delta}{dt} = Q \times \frac{dg\,(V, s)}{dV} \tag{3}$$

p is the overpressure in the bubble, R its radius, and Δ the dough thickness (initial value $\Delta_0 = 0.25$ cm) at the point characterized by the position parameter s. Using eqs. 1–3 given in another paper (1), it is easy to calculate σ, ϵ, and $\dot{\epsilon}$ for any point of the bubble at each time t and air-flow rate Q. However, Treloar (cited in 4) has stated that a uniform biaxial extension arises only in a small region around the pole if the bubble is not exactly a sphere. At high volumes, a trend toward an oblate spheroid shape has been noted; hence, σ, ϵ, and $\dot{\epsilon}$ values are calculated at the pole. Figure 1 shows that polar ϵ increases with additional bubble volume (V); from about $V = 40\ cm^3$ the following equation approximates the ϵ value:

$$\epsilon = 1.7 \log V - 2.11 \tag{4}$$

$\dot{\epsilon}$ increases rapidly with V until $V = 20.7\ cm^3$, then steadily decreases (Fig. 1).

Using eq. 4 it is possible to write:

$$\dot{\epsilon} = \frac{0.74\ Q}{V}\ (V \geqslant 40\ cm^3) \tag{5}$$

With the air-flow rate varying from 2.78 $cm^3 \cdot sec^{-1}$ to 33.33 $cm^3 \cdot sec^{-1}$, $\dot{\epsilon}$ at the pole goes approximately from 4×10^{-3} sec^{-1} ($V = 500\ cm^3$) to 0.67 sec^{-1} ($V \simeq 25\ cm^3$); the measurements on flour f0 are realized between 0.5 $cm^3 \cdot sec^{-1}$ and 44.44 $cm^3 \cdot sec^{-1}$, which extends the $\dot{\epsilon}$ limits to 0.7×10^{-3} sec^{-1} and 0.89 sec^{-1}.

Dough Behavior in Biaxial Extension

The biaxial extension viscosity η^E is defined as the σ over $\dot{\epsilon}$ ratio:

$$\eta^E = \frac{\sigma}{\dot{\epsilon}} = \frac{p}{Q} \times f\ (V, s) \times \frac{dV}{dg\ (V, s)} \tag{6}$$

At the pole ($s = 0$), for a fixed value of V, η^E remains proportional to p/Q when the air-flow rate and, hence, $\dot{\epsilon}$ vary. Figure 2 shows that the biaxial extension viscosity decreases when $\dot{\epsilon}$ increases and that it follows a power law; the power law exponent α is almost independent of the volume, *i.e.*, of ϵ. This result confirms previous work (8) and generally has been found to be valid; however, at volumes equal to or less than 50 cm^3, or higher than 350 cm^3, the value of α may be slightly different. The power law exponent does not seem to change very much from flour to flour, but there is a definite trend toward smaller values of α for

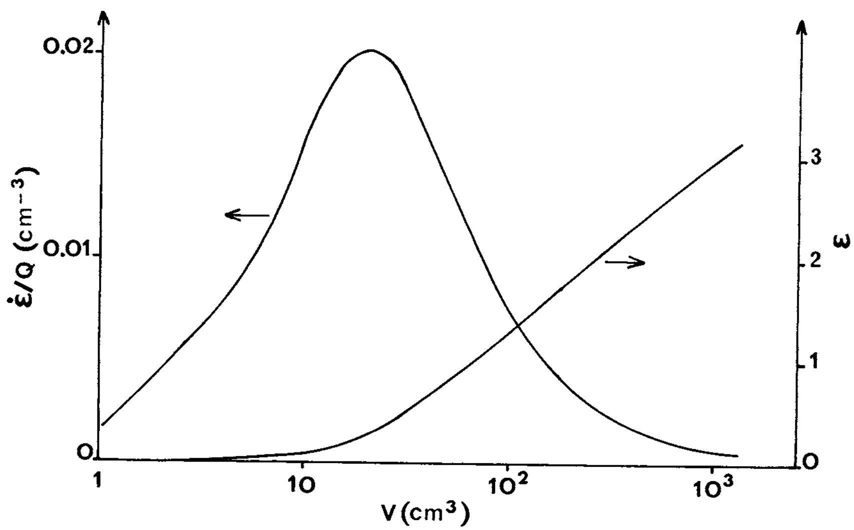

Fig. 1. ϵ and $\dot{\epsilon}$ at the pole *vs.* bubble volume.

strong flours. The constancy of α when the strain increases means that it is possible to separate the effect on σ of ϵ and $\dot{\epsilon}$, and eq. 6 can be written in the following form:

$$\sigma = \dot{\epsilon}^{\alpha} \times f(\alpha, \epsilon) \tag{7}$$

The same result has been displayed by Tschoegl *et al.* (9) in uniaxial extension experiments. The slope of each straight line of Fig. 2 gives the value of $\alpha - 1$ at the corresponding ϵ; using eqs. 1 and 3, the value of $f(\alpha, \epsilon)$ at this ϵ can be obtained. The results are plotted on Fig. 3: $f(\alpha, \epsilon)$, which is also the biaxial extension viscosity at $\dot{\epsilon} = 1\ \text{sec}^{-1}$, increases rapidly with ϵ. The viscosity seems to approach a constant value at very low ϵ, and is an exponential function of ϵ at higher ϵ:

$$\sigma = \eta_{1\ \text{sec}^{-1}}^{E} \cdot \dot{\epsilon}^{\alpha} = K_{\epsilon = 0} \cdot 10^{\beta\epsilon} \cdot \dot{\epsilon}^{\alpha} \tag{8}$$

The value of β is generally smaller than one; the results of Fig. 3 correspond to a value of β close to 1. The main difference between the three flours appears to lie in $K\epsilon = 0$.

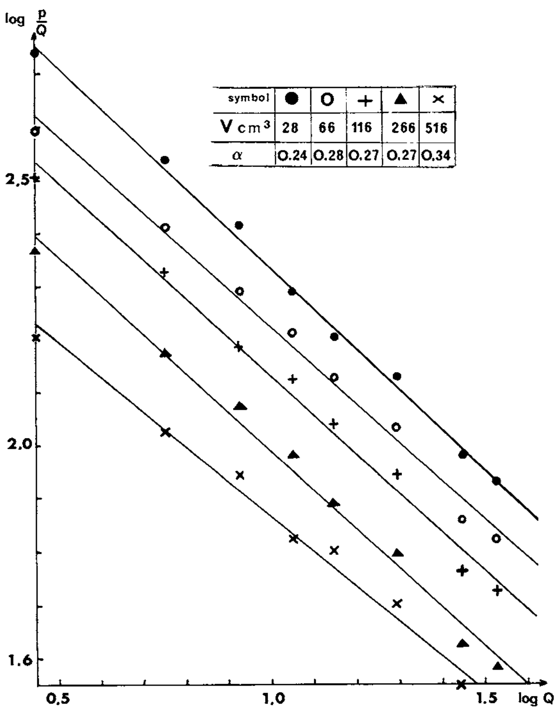

Fig. 2. Biaxial extension viscosity *vs.* extension rate (arbitrary units). Flour f00 dough containing 44.6% water, 0.83% NaCl, mixed 6 min in the Alveographe kneader.

The power-law relation between p and Q does not depend on the point chosen on the dough shell; hence, eqs. 7 and 8 are applicable to the nonpolar points but f (α, ϵ) and K will have values different from those obtained at the pole.

Simple Shear and Biaxial Extension

We have shown (10,11) that the rheological properties of wheat-flour dough in simple shear can be studied with a cone-plate viscometer and that they are comparable with those of some molten plastics: for example, a σ overshoot phenomenon is evident. In simple shear, a power-law relation between σ and shear rate can also be used, at least between 10^{-2} and 1 sec^{-1} (10). It is then possible to compare, for the same doughs, the power law exponents and the apparent viscosity at 1 sec^{-1} in simple shear and biaxial extension; such a comparison is done in Table II using Fig. 3 to obtain a rough estimate of the biaxial-extension viscosity at zero ϵ.

Despite the limited number of results, some preliminary conclusions can be drawn. It appears that the values of α corresponding to the biaxial extension are always smaller than those obtained in simple shear. As α would be zero for a purely elastic solid (σ independent on $\dot{\epsilon}$) and one for a Newtonian liquid (σ proportional to $\dot{\epsilon}$), it means that the non-Newtonian characteristics are more prominent in biaxial extension than in simple shear. However, the viscosities in biaxial extension and simple shear are of the same order of magnitude; their ratio at 1 sec^{-1} is smaller than 6, the Trouton ratio, and increases when the ϵ rate (or the shear rate) decreases: a qualitatively similar result has been obtained by Maerker and Schowalter with polyisobutylene (6).

It must also be pointed out that the viscosity is calculated using total ϵ.

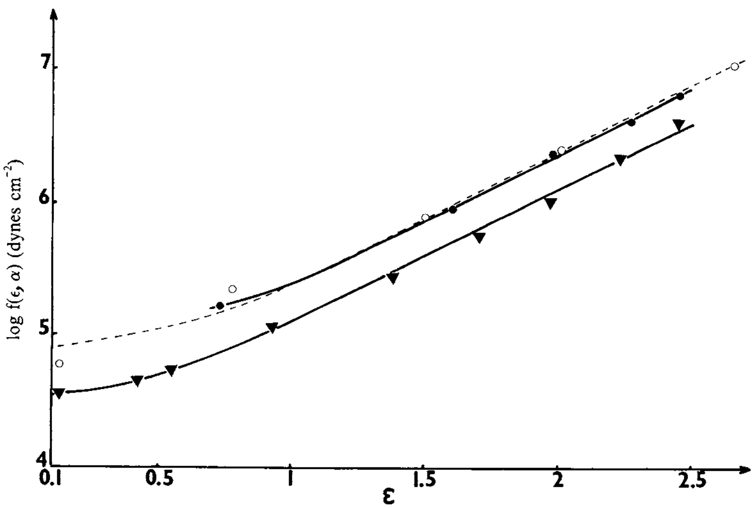

Fig. 3. Biaxial extension viscosity *vs.* ϵ. ●:flour f0; o:f2;▼:f3; doughs prepared as indicated in the footnote of Table I.

TABLE II
Rheological Parameters in Equal Biaxial Extension and Simple Shear[a]

Flour	Simple Shear		Biaxial Extension	
	α	η^S (in 10^4 poises) at 1 sec^{-1}	α	η^E (in 10^4 poises) at 1 sec^{-1}
f0			0.29	7.5
f1	0.32	5.3	0.22	
f2	0.37	4.1	0.31	7.5
f3	0.35	2.8	0.28	3.4
f6	0.36	3.2	0.24	

[a]Doughs containing 43.2% water and 0.83% NaCl (dough basis), mixed 6 min in the Chopin Alveographe kneader at 25°C.

However, owing to the viscoelastic behavior of wheat-flour doughs, ϵ has to be divided in recoverable (or elastic) ϵ and irrecoverable (or viscous) ϵ. The first one increases rapidly at the beginning of the extension and, consequently, viscous $\dot{\epsilon}$ is smaller than total ϵ when total ϵ is close to zero; the use of viscous $\dot{\epsilon}$, instead of total ϵ, would give a higher biaxial-extension viscosity at zero ϵ and it would then be possible to obtain a Trouton ratio closer to six.

CONCLUSION

The rheological behavior of wheat-flour dough in equal biaxial extension follows a power law at least with $\dot{\epsilon}$ between 10^{-2} and 1 sec^{-1}. Besides this σ-softening effect, an ϵ-hardening phenomenon is evident from the beginning of the extension, as pointed out a long time ago by Schofield and Scott Blair (12), and it becomes very important beyond $\epsilon = 1$, which corresponds to a 170% extension. This result, consistent with Tschoegl's results (9), is obtained in uniaxial extension. The ϵ-hardening phenomenon explains why Bloksma (13) was unable to calculate the Alveogram's shape, even though he used an equation describing dough pseudoplastic behavior.

There is still a problem about the exact meaning of the biaxial-extension viscosities if we consider our method of measurements: it is apparent on Fig. 1 that a permanent-flow regime is never established and the equilibrium viscosities (σ and $\dot{\epsilon}$ constant) may be different from the transitory values. A constant-ϵ rate would imply a decreasing gas-flow rate during the course of inflation, as shown by eq. 5. However, a steady state may never be obtained, due to the ϵ-hardening properties. Taking into account the dough-leavening process, the biaxial extension possesses a basic advantage compared with the other types of deformation: the new values derived from the Alveograms could have interesting practical applications.

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