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ORIGINAL CONTRIBUTION

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Experimental and conceptual problems in the rheological characterization of wheat flour doughs

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Abstract Wheat flour dough is an industrially important material and a better understanding of its rheological behavior could have long ranging impact on the agricultural and the food processing industries. However, rheological characterization of dough is proving to be difficult due to a range of testing issues and anomalies in flow behavior. In a cone-and-plate rheometer wheat flour doughs "roll-out" of the gap before steady state viscosities can be established, as discussed by Bloksma and Nieman (1975). However, the mirror image of the transient viscosity-time plot obtained using a cone-and-plate viscometer has been used to obtain an estimate of steady shear viscosity behavior (Gleissle, 1975). To check this transient methodology for doughs, a second method, in addition to cone-and-plate transient flow, for determination of the shear viscosity, was needed. For this, capillary extrusion was chosen. Both a piston-driven and pressure driven capillary rheometer were employed. End corrections were determined to provide information on both the shear viscosity and, following Binding (1988), the extensional viscosity of the doughs. There are few data available on end corrections for doughs, though published data by Kieffer indicate that the corrections are unexpectedly very high. In this present work it was found that the end correction experiments were very difficult and imprecise in part due to the time-dependent nature of the doughs and difficulties in preparing replicate batches required to compare dies of differing *L/R* values. Further it was unexpectedly found that the samples, though prepared by normal mixing procedures to the "optimum" level, were so heterogeneous that large fluctuations in the pressure at constant output rate (in the piston-driven rheometer) and in output rate at constant pressure (in the pressure-driven instrument) were observed. These fluctuations could be eliminated by overmixing of the doughs, but overmixed doughs are of little practical interest. Although the problems encountered in this work were significant, it was encouraging that even these preliminary studies indicate that rheological measurements are effective in differentiating between spring and winter wheats. Defining a constitutive model for dough rheology still remains a major challenge, as results from one type of testing do not corroborate the findings from a different type of testing.

Key words Wheat flour doughs – shear viscosity – extensional viscosity – capillary extrusion – capillary rheometry – cone-and-plate viscometry – end corrections – rheological heterogeneity – extrusion variability – spring and winter wheats

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Introduction

Wheat flour doughs, viscoelastic materials, have attracted the attention of numerous eminent scientists over the years. In addition to the intellectual challenge of determining and understanding the complex behavior of these common materials, there are practical reasons for investigating the flow properties of doughs. In evaluating new wheat varieties it is important to measure and understand the effects of such factors as growing conditions and varietal effects on processing and final product characteristics. Our ability to develop new processing methods will benefit enormously from increased sophistication of process engineering calculations. These calculations in turn require both experimental data input and an understanding of the relevant constitutive equations applicable to describing wheat flour dough behavior. Experience gained in the polymer industry has shown the value of rheological data for quality control purposes and for evaluation of effects of other ingredients, for instance additives. In the food industry rheological information is of value in minimizing the costs associated with the use of texture panels in evaluation of food textural properties.

It has been evident from the earliest days of the scientific approach to evaluation of dough properties that wheat flour doughs were complex indeed. Schofield and Scott Blair in 1932 recognized that time during which stress was applied to dough is as important as the magnitude of the stress itself. In 1970, Tschoegl et al. noted that "Wheat flour doughs are subjected to considerable deformation during the make-up and baking process" and emphasized that "few attempts have been made to describe the large deformation behavior of doughs in terms of fundamental quantities". They found that dough properties depended on a variety of factors including rest period, mixing time, mixing atmosphere, flour variety, etc. Smith et al. (Smith, 1970) looked at dynamic methodology as a method to determine viscoelastic properties under small deformation or at short observational times, determining that the dynamic shear modulus was dependent on strain amplitude, frequency, and time.

It is not feasible here to even attempt a review of the many fine contributions made to our understanding of dough behavior. It is worth noting, with no attempt or pretense of claiming completeness, some useful reviews: Faridi and Fabion (eds.), *Fundamentals of Dough Rheology* (Faridi, 1986), and *Dough Rheology and Baked Product Texture* (Faridi, 1990), and the book by Blanshard et al., *Chemistry and Physics of Baking* (Blanshard, 1986). The importance of fundamental investigations into dough behavior has been recently emphasized by several authors, as illustrated by the article by Menjivar on "Fundamental aspects of dough rheology", a chapter in the Faridi and Faubion book previously cited (Faridi, 1990). The development of viable models for dough behavior, and the search for adequate constitutive equations to describe the behavior of these complex doughs, are engendering considerable effort by, and is of great current interest to, both theoretical and experimental rheologists and cereal chemists. For example, Nhan Phan-Thien et al. (Phan-Thien, 1997) have very recently examined a constitutive model describing the oscillatory and simple shear flows of flour – water doughs. They were able to construct a phenomenological model whose predictions compared favorably with experimental data in oscillatory and shear flows. Other approaches include Wang and Kokini (Wang, 1995) and attention can also be directed, without any attempt to be complete, to the recent work of Ramakumar et al. (Ramakumar, 1997), However, regardless of the theoretical approach or type of analysis, an essential requirement for progress in the field is a complete understanding of the significance and reliability of experimental data obtained on these difficult materials, the difficulties of which will be discussed in more detail later in this paper.

In recent years it has been recognized that for complete characterization of a rheologically complex material testing in more than one deformational mode is required. Measurement in simple shear is perhaps the most commonly used rheological testing mode, but extensional flows have attracted a great deal of interest in polymer work since extensional or elongational flows are basic to such processes as spinning as discussed by Petrie (Petrie, 1979). Thus, in addition to a shear viscosity it would be most useful to have information on the extensional viscosity of dough. The chain of events reported in this manuscript started with the recognition that uniaxial compression of dough discs in an Instron Universal Testing Machine was imposing on the sample a biaxial deformation in the two directions perpendicular to the applied force. This is the same type of deformation that is generated in a Chopin Alveograph and the same as that imposed during bubble expansion, which occurs during the baking of doughs.

As normally operated, however, the Chopin Alveograph does not yield rheological data which can be converted to absolute units of stress (force per unit area) and strain. In contrast, the Instron compressional data can be quantified so that the stresses and strains can be determined during the compressional experiment. From such data an extensional, as opposed to a shear, viscosity can be determined. Such absolute data can then be examined in detail and fitted to appropriate constitutive relationships. Actual compressional data obtained on doughs have been examined in this way and were found to be quite well represented by the Upper Convected Maxwell Model (UCMM)' yielding two parameters, a viscosity and a relaxation time.

Figure 1, taken from Bagley et al. (Bagley, 1988) shows the biaxial extensional viscosity of a hard wheat

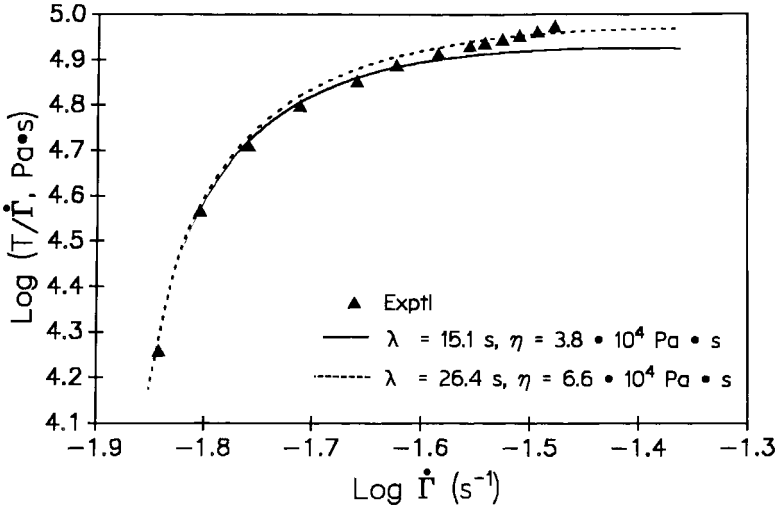

Fig. 1 Logarithmic plot of the biaxial extensional viscosity versus strain rate for a hard wheat flour dough. The experimental points were obtained by uniaxial compression of the dough and the solid and dotted lines were computed using the Upper Convected Maxwell Model with parameters as shown (Bagley, 1988)

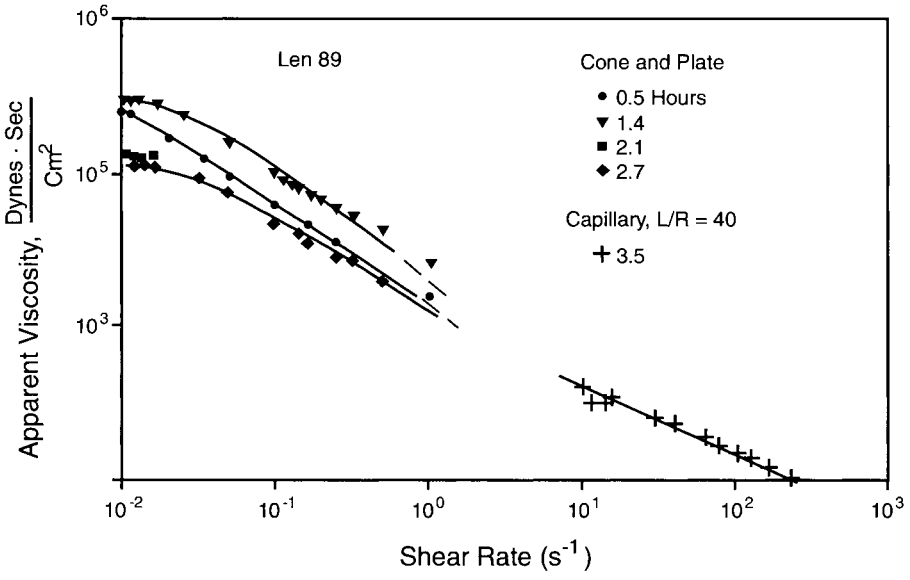

Fig. 2 Apparent viscosity of a dough prepared from a wheat flour (Len 89) versus shear rate. Cone-and-plate data shown are the mirror images of the logarithmic plots of transient viscosity versus time measurements (Gleissle, 1988). Capillary data were obtained using a pressure driven capillary rheometer

flour dough plotted against extensional rate. The lines are computed from the UCMM for two choices of the parameters, shear viscosity and relaxation time.

An obvious question was whether or not the shear viscosity evaluated in fitting this compressional data agreed with an actual direct measurement of a viscosity in shear. The clear need was to determine a shear viscosity for the dough independently and to compare with the one computed from the UCMM. This would provide independent confirmation of the value of the model. A second question was why only one single relaxation time did such a good job in fitting the compressional data since doughs are known to have a broad distribution of relaxation times. The work below addresses these questions in more detail.

Determination of the shear viscosity of doughs

Attempts to determine shear viscosity directly in a cone-and-plate rheometer failed because the sample rolled out of the gap before a steady-state condition was reached. Bloksma and Nieman (Bloksma, 1975) maintain this occurs at a total applied shear strain of about 20 units. The problem can be avoided by measuring the transient build-up of viscosity at various shear rates. The mirror image of the viscosity/time plots yields the steady-state values for viscosity/shear rate plots (Gleissle, 1986).

Figure 2 shows the mirror image of the transient viscosity/time plot determined using a Mechanical Spectrometer in the cone-and-plate mode. The viscosity values

are shear rate dependent but appear to be approaching a constant viscosity level, the Newtonian viscosity, at the lowest shear rates. However, for the same flour, viscosity values for preparations of different ages were found to vary by as much as half a decade. In addition to this difficulty there was also the uncertainty as to whether or not the "mirror method" did, in fact, give the "correct" shear viscosity values for these doughs. An additional independent determination of the shear viscosity was needed.

The tried and true extrusion methodology was adopted to provide an alternate approach to the measurement of the shear viscosity. In this method nitrogen pressure is applied to force material to flow from a reservoir through a capillary die of length L and radius R. The value of L/R chosen was large in the hope of minimizing effects of pressure losses in the barrel of the viscometer in calculating the viscosity. For a given applied nitrogen pressure P the output rate, Q, in cc/sec is determined. Values of Q for a range of applied pressures are found and the results converted to shear stress/shear rate or viscosity/shear rate plots. As can be seen from Fig. 2, there is a gap between the cone-and-plate and the extrusion data. Further, the slope of the extrusion plot is different from that of the other data.

Data such as that shown in Fig. 2 left unanswered a number of questions including the critical one as to whether or not the L/R value is high enough to mask the effects of flow within the barrel. Such effects within the barrel are accounted for by the "end corrections" which describe quantitatively the pressure drops within the barrel as material accelerates towards the die (capillary). The end correction time, e, gives the effective length of the capillary as $(L+eR)$.

The shear stress, τ, corrected for pressure losses within the barrel, is given by

$$\tau = PR/2\,(L + eR) \tag{1}$$

The apparent shear rate, τ is computed as

$$\gamma = 4Q/\pi R^3 \tag{2}$$

and then the apparent viscosity is

$$\eta_a = \pi PR^4/8Q\,(L + eR) \tag{3}$$

If e is small enough, or the length of the capillary large enough, then eR can be neglected and the expression for viscosity reduces to $\pi PR^4/8LQ$, the well-known Poiseuille relation. (The correction to the computation of shear rate for the non-Newtonian character of the material, the Rabinowitsch correction, is readily made but need not concern us here.)

Equation (1) can be rearranged to give

$$P = 2\tau\,(L/R) + 2\tau e \tag{4}$$

Table 1 End corrections for a dough and for the corresponding gluten, calculated from data given by Kieffer et al. (Kieffer, 1982)

Dough (no additives)		Gluten
Shear rate (s^{-1})	End correction	
3.6	138	63.7
7	129	51.3
18	123	52.7
36	166	69.3
71	170	71.2
175	206	109.5

so that at constant shear rate a plot of pressure needed to attain that shear rate against the length to radius ratio of the die should be linear. From such plots the end correction e can be determined.

These end corrections can be very large indeed for wheat flour doughs and even for gluten alone as is illustrated in Table 1.

These values of e were computed from data published by Kieffer et al. (Kieffer, 1982) and indicate that the die lengths used in obtaining Fig. 2 were not long enough. Clearly, a more detailed investigation of these end corrections for wheat flour dough systems was needed.

An additional and quite fascinating feature of the Kieffer data given in Table 1 is the absolute size of the end corrections. For many synthetic high polymers and for polymer solutions values of e above the range 10 to 15 are rare. Kieffer's high values of e for doughs are not unique; similar high values have been reported by others, including ourselves. Note, however, that for Kieffer's experiments the value of eR is 206×38 mm or 78 mm, more than half the length of the viscometer barrel, which is 150 mm! The physical significance of such large values needs to be carefully considered, particularly with regards to the reliability and significance of data obtained when more than half of the barrel charge has been extruded.

Extensional viscosities from capillary flow experiments

Another reason for such capillary end correction studies was that from the end correction data information on extensional flow properties of the dough could be determined. This was first proposed by Cogswell some years ago and a more recent theoretical analysis by Binding (Binding, 1988) has revived interest in the approach.

Figure 3 illustrates the physical processes going on during extrusion from a reservoir through a capillary die. A pressure is applied at the top of the reservoir and material is forced through the tube at the bottom. Along the center line material is being subjected to an exten-

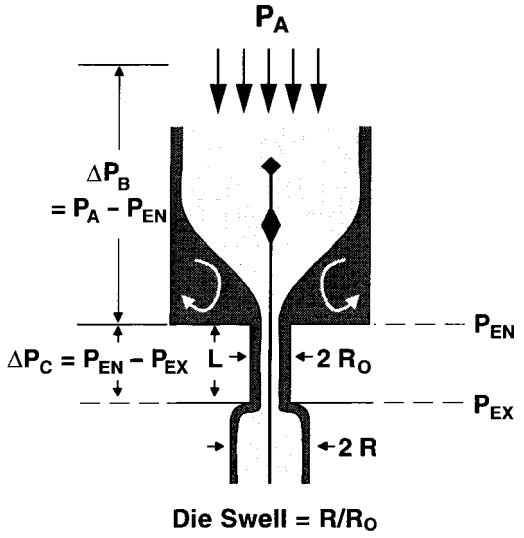

Fig. 3 Diagrammatic illustration of flow of a viscoelastic fluid from a reservoir (barrel) through a capillary or die of radius R_0 and length L. The total applied pressure is P_A and the pressure at the die exit is P_{ex}, usually atmospheric pressure. From pressure drops in the barrel and capillary the extensional and shear viscosities, respectively, can be evaluated

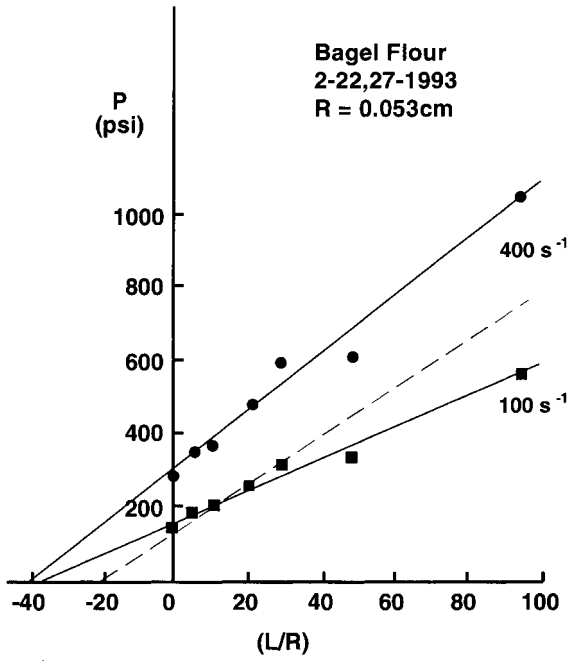

Fig. 4 Pressure versus capillary (L/R) for a bagel dough (no yeast) for two shear rates. The potential data variability is indicated by the two lines fitted to the lower shear rate line, this variability leading to significant uncertainty in intercepts at both $L/R=0$ and $P=0$

sional deformation. Material off the center line undergoes increasing proportion of shear deformation as the distance from the center line is increased. Pressure in this flow process drops from P to atmospheric in passing down through the barrel and the capillary. From the pressure drop in the barrel an extensional viscosity is computed following Binding. From the pressure drop in the capillary the shear viscosity is determined. This extrusion experiment, in principle, completely characterizes the shear and extensional rheological behavior of a material.

Figure 4 indicates how the separation between pressure drop in the barrel and pressure drop in the capillary is made experimentally. Pressure/shear rate plots are obtained for a number of dies of different L/R values. From these plots, the pressure required to give a given shear rate is determined for each L/R value and the results are plotted as P versus L/R as in Fig. 4. The value of the end correction e is determined from the intercept of these linear L/R plots on the $P=0$ axis. The pressure drop in the barrel is the pressure at $L/R=0$. Knowing this value the pressure drop in the capillary can be determined. Following Binding's analysis then both the extensional and shear viscosities can be found.

Preliminary experiments with a number of different spring and winter varieties gave results shown in Table 2. It appears that the ratio of extensional to shear viscosity is high for the spring and low for the winter varieties.

However, in attempting to replicate data, experimental problems became very evident. Specifically, as illustrated in Fig. 4, it can be hard to get data to the precision needed to obtain good values either of the intercept at $L/R=0$ or of the slope of the plot (which gives the true shear stress at the capillary wall and hence the shear viscosity). It is not enough to simply fit the data statistically; one needs good straight line plots of high precision and accuracy such as can often be obtained with synthetic polymers. For doughs, however, two

Table 2 Values of the ratio of l and k, the parameters computed from experimentally determined shear and elongational viscosities, obtained for a number of spring and winter wheat varieties. Protein levels for the particular samples are also tabulated

	$\eta_S = k\dot{\gamma}^{n-1}$		$\eta_E = l\dot{\varepsilon}^{t-1}$		
	Spring wheats				
	Marshall (#354)	Guard (#318)	Stoa (#304)	Butte (#350)	Len (#315)
Protein %	14.9	16.5	17.1	15.5	19.5
l/k	109	157	215	231	417
	Winter wheats				
	Rocky (#403)	Newton (#446)	Yolo (#411)	Arkan (#433)	Chisholm (#421)
Protein %	17.6	13.4	7.8	14.5	12.7
l/k	30	32	36	80	161

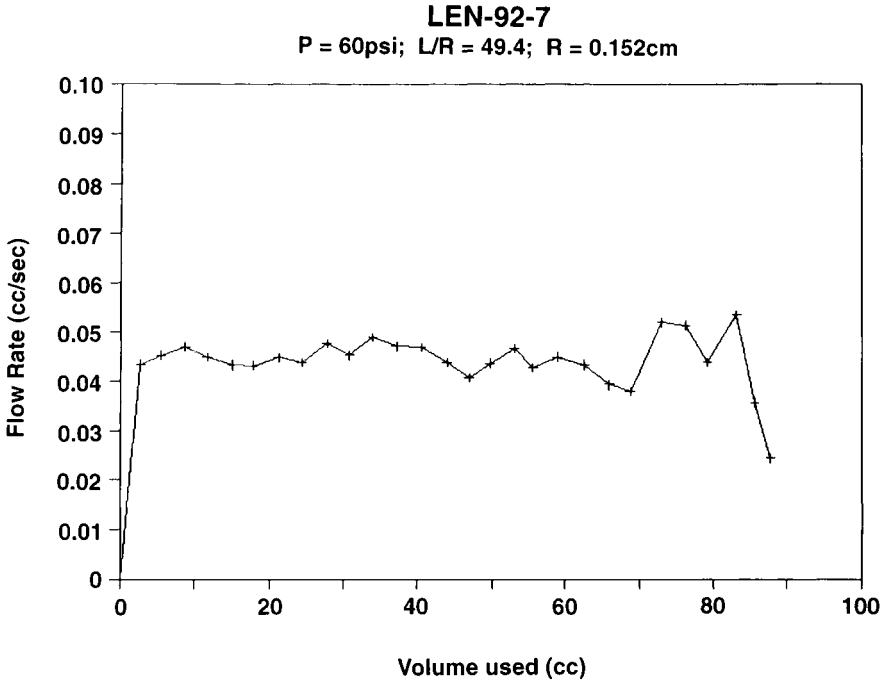

Fig. 5 Variations in flow rate during capillary extrusion at constant applied pressure plotted against total volume of sample extruded from the barrel (which is equivalent to time). Flour used is a LEN mixed to 500 BU

problems exist that are normally absent in synthetic polymer systems. First, dough samples change properties significantly as they age so the effects of sample age are of major concern. In consequence of this aging effect, it becomes necessary that each set of points at a given L/R is obtained with one batch of dough. A fresh batch is made up (and appropriately aged) for the next set of points at a new L/R. It is extremely difficult to prepare the replicate batches to the desired level of precision to yield acceptable values of either the slopes of the plots (which give the true shear stress) or the intercept at L/R (from which the calculation of extensional viscosity is made).

Sample heterogeneity

In establishing our ability to replicate data, to determine variability from laboratory to laboratory and to explore for time variations, extrusion experiments were conducted using both a gas pressure driven rheometer and a Rosand piston driven rheometer. For both instruments large and unexpected data fluctuations were observed. In the case of the Rosand piston-driven rheometer data were obtained in the form of pressure versus time at constant output rate. In the gas-driven rheometer, output rate was monitored as a function of time at constant applied gas pressure.

Surprisingly large fluctuations in output rate at constant pressure were observed as illustrated in Fig. 5 where output rate is plotted against volume of sample in the barrel used. (Using this volume measure is equivalent to using time as the abscissa.) Such large fluctuations make it impossible to obtain end corrections or barrel pressure drops to the precision needed for adequate characterization of dough properties for applications such as quality control. Equivalent variations in pressure at constant output rate were found with the Rosand viscometer. For a given flour and a given mix the fluctuations appear to be quite random and the magnitude of the fluctuations seems to be approximately the same for replicate mixes. However, a detailed and careful statistical study of the fluctuations has not at this time been carried out.

That these variations are associated with sample heterogeneity was confirmed by direct visual observation of the actual dough filament extrudates. One could see significant fluctuations in extrudate diameter as the filaments emerged from the dies.

An obvious way to make the samples less heterogeneous is to overmix them. In preparing dough samples the usual standard mixing procedure were employed in which water levels were adjusted and samples mixed to a peak in the Brabender mixing unit of 500 Brabender Units. When samples were deliberately overmixed the output rate fluctuations seen in Fig. 5 disappeared, and output rates which varied little with time (or volume extruded) were observed (Fig. 6).

Thus with overmixing, the output rate at constant pressure is constant, during the time that the barrel is being emptied, to within about 1% as is seen on Fig. 6. Such experimental precision is needed to obtain adequately precise end correction results and to reduce the variability of P versus L/R plots illustrated in Fig. 4. Such im-

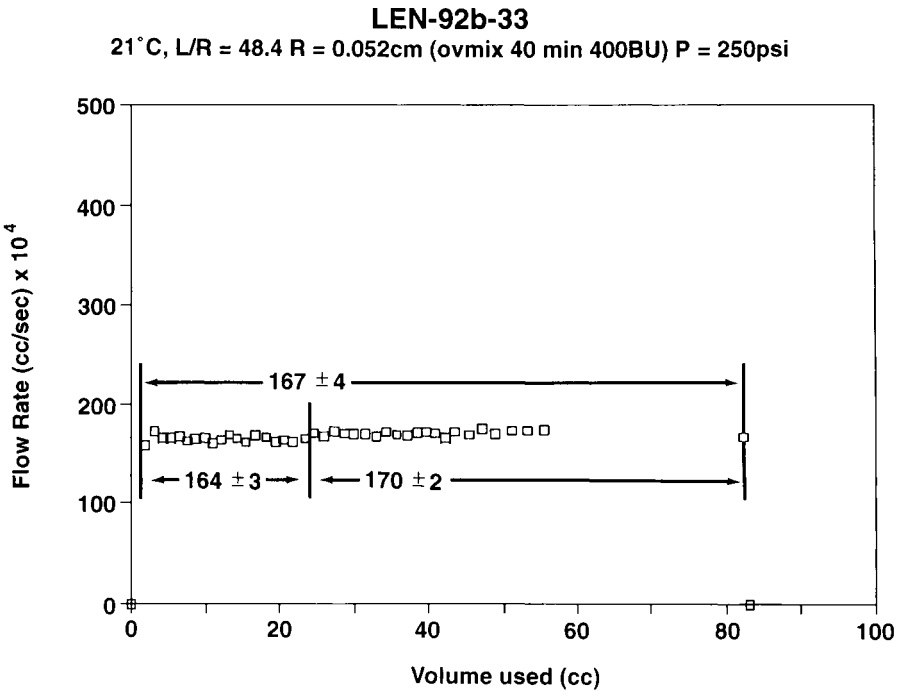

Fig. 6 Variations in flow rate during capillary extrusion of a LEN dough that has been overmixed (compare with Fig. 5). The variations in output rate are shown for the initial portion, last portion and total curve and it is evident that overmixing has reduced the fluctuations to something of the order of 1%

proved data precision is absolutely essential to obtain data good enough to differentiate among varieties and to compute "good" extensional and shear viscosities.

The problem is that it is not the overmixed doughs we really want to characterize. There are two obvious ways to proceed. If the objective is shifted to answering the question concerning the degree of heterogeneity of a dough mixed to the "optimum" level of 500 BU, then the fluctuations observed in these extrusion studies could be used to evaluate quantitatively the degree of sample heterogeneity. One could also use other methods involving very small samples of the dough, for instance cone-and-plate viscometry, and running a number of different samples. The results from a series of samples would, no doubt, fluctuate and these fluctuations could again be analyzed to provide a quantitative measure of sample heterogeneity.

On the other hand, if the objective remains characterization of the shear and extensional viscosities through the capillary viscometer approach, then larger samples need to be used. If samples are large enough, a better approximation to the "true" output rate at constant pressure for the sample could be obtained. This would lead to end correction plots with less variability and hence more data precision. Larger samples would, for capillary viscometry, mean larger radii dies and this in turn means larger reservoirs and the approach could rapidly become unwieldy.

An alternate approach to using a "batch" type rheometer, where the dies or capillaries are being fed from a reservoir of limited capacity, is to feed the dies continuously from an extruder. This approach has been successfully applied by, for example, Senouci and Smith (Senouci, 1988) and Seethamraju and coworkers (Seethamraju, 1994).

There are, naturally, problems with the use of extruders, particularly if large radius dies are used. Operation at high shear rate can be very profligate of material and the method is obviously unsuited to experiments where only small quantities of material are available. Further, output rate has to be controlled and monitored. The control of output rate can be done in various ways, for example, by changing the rate of rotation of the screw. This will affect the amount of work and the rate of work input into the dough and thus alter the properties of the material being investigated. One can operate with a starved screw (Senouci, 1988) or control output through the die by taking material off a side stream (Seethamraju, 1994).

For an extrusion process measurements of the type discussed above may be very useful for process control or for monitoring of product properties. However, it is not clear whether or not the extrusion data (say through a slit die) can be obtained with the precision and accuracy desirable for a scientific investigation of such issues as how best to evaluate protein quality and how protein quality relates to varietal and/or environmental effects, etc. Some of the factors affecting extrusion studies and some aspects of experimental errors involved in such studies have been discussed by Padmanabhan and Bhattacharya (Padmanabhan, 1991). Frequently in published work general trends can be readily seen but often the data are plotted on log-log scales and scatter on such scales, and the corresponding variations

in the absolute values of the quantities being measured can be for many purposes unacceptably large.

Relaxation times

The measurement and interpretation of relaxation times in wheat flour doughs represent another area of challenge. The two relaxation times chosen for fitting the data for the dough of Fig. 1 are 15.1 and 26.4 s. Percentagewise, of course, this is a wide variation. Further, even a cursory look at dough behavior reveals that much longer relaxation effects can be present indicating relaxation processes occupying hundreds or even thousands of seconds (Bagley, 1987). Nevertheless, the values from Fig. 1 (20 s) were not out of line with values, which were in the range 12–50 s, reported by Frazier et al. (Frazier, 1975). This later reference is of especial interest because some effects of protein level, whear variety, and work input during dough preparation are described though it should be remarked that the method used by Frazier et al. to evaluate relaxation time is arbitrary, yet nevertheless effective for their needs.

One approach to measuring the distribution of relaxation times for polymers is to measure dynamic properties over a decade or two of frequency and to do this at a variety of temperatures. Master curves can then be drawn using the Williams-Landel-Ferry shift factor. These master curves extend over numerous decades of time and thus a picture of the relaxation times and relaxation time distribution can be obtained.

For doughs, as for most biopolymers, the concept of measuring over a range of temperatures just is not workable, since the properties of doughs change irreversibly with temperature. Dough heated to 80 °C is quite a different substance than dough at room temperature (Schofield, 1983). The fact remains, though, that there is sufficient evidence in the literature to conclude that it would be valuable to have a better insight into the relaxtion times, and hence relaxation processes, of doughs. More detailed investigations of, and theoretical and molecular analyses of, relaxation behavior of doughs could be most informative.

Concluding comments

In spite of excellent contributions from many cereal scientists over the years, the problems associated with determination of the rheological properties of wheat flour doughs continue to provide ongoing challenges. Theoretical considerations make it clear that testing of such complex materials as wheat flour dough requires application of a variety of testing modes, two common testing modes being extension and simple shear. Having obtained the rheological data, a critical subsequent step is to describe the material behavior mathematically through the use of an appropriate constitutive equation or model. Such a model can be used in a variety of ways, for example in engineering calculations or to provide parameters that can be checked through independent experimental measurements to confirm both the value of the model and the validity of the experimental data.

The dependence of dough properties on such factors as time, work input, and rate of work input coupled with the extreme sensitivity of dough properties to water level and biological activity (e.g., activity due to the presence of specific enzymes) complicate the task of obtaining reliable and meaningful data. The difference between “reliable” and “meaningful” can be illustrated with reference to the heterogeneity of whear flour doughs mixed to the normal level of 500 BU. The data obtained on such a mixture fluctuates over a range determined by the degree of heterogeneity and the sample size. These fluctuations can be minimized by overmixing the sample, but while the data so produced are reliable they are not particularly meaningful because the market for overmixed dough is pretty limited though interest in the mixing process is high (Danno, 1982; Okada, 1987)!

This paper was to describe the experimental and conceptual problems arising in the rheological characterization of wheat flour doughs. It is essential to recognize first of all that any experimental method chosen (say to measure a shear viscosity) will yield numbers of some sort. It is necessary somehow to obtain independent checks of these numbers. To obtain these independent checks is not easy. The experimental problems can be very frustrating, as in the case of sample “roll-out” from a cone-and-plate viscometer. Methods developed with materials other than doughs, for example the Gleissle mirror image methodology, may or may not be valid for doughs. The applicability of a particular methodology needs to be confirmed. Other problems may arise unexpectedly, as for instance the effect of sample heterogeneity arising with doughs mixed to an “optimum” level.

Since this work was presented orally at Reading (UK, 1995), Phan-Thien and Safardi-Ardi have published some extremely relevant material addressing many of the same issues and concepts we are discussing here (Phan-Thien, 1998). We cannot do better to illustrate the tenor of their remarks than by quoting from their paper:

“The repeatability of data, which was a major problem with dough, was confirmed with different samples…A variation in the data of the order of 10%…was found…The shear deformation induced by the testing may lead to further development of dough thereby changing dough properties”.

Too little attention has been given in the literature to such factors and we hope that such careful analyses and discusson of data such as given by Phan-Thien and Safardi-Ardi will become the rule, rather than the exception, in future dough investigations. While we are in complete agreement with the philosophy implicit in the work of Phan-Thien and Safardi-Ardi, we (not unexpectedely, perhaps) have occasional reservations with some of the specific remarks made in their paper. They comment, referring to problems of data repeatability, moisture and shear effects that: "The variation is judged to be acceptable, considering the time dependent nature of the material".

The question of acceptability certainly depends on the use to which the data is put. In some cases as discussed above (e.g., in connection with evaluation of end effects) some data variations are unacceptable. Much more work is warranted on these time-dependent, concentration and temperature sensitive, and generally difficult materials to determine how best one should investigate, characterize and process them.

These authors have made very clear the difficulties of measuring steady state viscosity but while their conclusion that dough is a "solid" rather than a "fluid" may lie at the root of the experimental and theoretical problems of measuring and modeling viscosity of doughs, how do we account for the observations that fluid models seem to fit dough "flow" data reasonably well (Ramakumar, 1997; Wang, 1995)?"

We thus have a series of problems related to both the experimental and theoretical treatment of dough behavior. Heterogeneity can be overcome by making measurements on samples large enough so the heterogeneity is not observable, for instance by continuous extrusion using large dies. But how are the effects of extrusion processing on dough properties to be taken into account for a material so sensitive to moisture level, time, and shear history? How should we treat the question of relaxation times of doughs when certain data are well fitted with a single relaxation time when we know that there is a very broad distribution of relaxation times (from tenths of seconds to thousands of seconds) that can be significant as seen in stress relaxation experiments? What molecular and structural features exist in doughs to give rise to this broad distribution of relaxation times? How do we obtain a broad spectrum of modulus/time plots when time-temperature superposition methods cannot be used with a temperature sensitive material such as dough?

These and numerous other questions remain to provide opportunities for advances both in our understanding of dough behavior and protein quality and in our ability to apply our knowledge to improve processing procedures and final product quality. Among ways available for the cereal scientist to exploit these opportunities one can include the application of the sophisticated computational methodology currently available today. These methods can be used to examine rheological data in the light of a variety of constitutive equations and rheological models. There also seem to be opportunities to apply some of the newer concepts of fractals, chaos and advances in treatment of non-linear systems in general, to examine in detail such effects as the output rate fluctuations observed during dough extrusion at constant pressure. Not least among the opportunities is the chance and need to obtain more experimental rheological information on well characterized flour systems to more fully delineate the behavior of wheat flour-doughs.

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