Rheological characterisation of almost intact and stirred yogurt by imperfect squeezing flow viscometry

Thongchai Suwonsichon and Micha Peleg*

Department of Food Science, Chenoweth Laboratory, University of Massachusetts, Amherst, MA 01003, USA

Abstract: Samples of plain yogurt of two national brands, almost intact and after stirring for 1 min by hand and with a domestic blender, were placed in a wide shallow Teflon^{R} container. They were subsequently compressed with a wide Teflon^{R} plate to induce imperfect lubricated 'squeezing flow'. The recorded force versus height relationships were plotted on logarithmic co-ordinates. The resulting curves all had a clear linear part indicating the region where squeezing flow was dominant. Its slope was on the order of −1.2 to −1.3 in the almost intact specimens and −0.5 to −0.9 in the stirred samples. The test reproducibility, expressed in terms of the coefficient of variation ($100\sigma/\bar{x}$) was on the order of about 15% more than sufficient to detect textural differences between the two brands and to monitor textural changes caused by stirring. These were expressed in terms of the apparent compressive stress at two preselected heights (1 and 2 mm) and the residual stress after relaxation for two preselected times (60 and 120 s). The flowability of the stirred samples was also expressed in terms of apparent elongational viscosity versus biaxial elongational strain rate relationships. All these mechanical parameters had a modest dependence on the upper plate diameter but the latter had no effect on their sensitivity as measures of yogurt consistency.

Keywords: yogurt; squeezing flow; extensional viscosity

INTRODUCTION

The rheological properties of yogurt have received considerable attention in the food literature. [1–3] They were primarily evaluated by testing the gel's strength (eg Modler *et al*,[4] and Mottar *et al*[5]), coaxial viscometry (eg Labropoulos *et al*,[6,7] Parnell-Clunies *et al*,[8] Mottar *et al*,[5] Ramaswamy and Basak[9,10] and Skriver *et al*,[11]) or dynamic testing (eg, Keogh and O'Kennedy[12] and Ozer *et al*[13]). In both coaxial viscometry and dynamic testing the specimen is pressed into the narrow gap of the sensor and is subsequently subjected to a steady, increasing, decreasing or oscillatory shear. The resulting flow curves, that is the shear stress versus shear rate or the complex shear viscosity versus frequency relationships are then used to calculate the rheological constants of the sample.

It has long been established that the consistency of yogurt depends, among other things, on the integrity of a relatively weak casein gel network. Consequently, any disruption of the latter will result in alteration of the yogurt texture. Insertion of a yogurt specimen into the narrow gap of a viscometer can produce enough shear to cause such a disruption, and since its extent is usually unknown, let alone controlled, the relationship between the measured properties and those of the original yogurt is also largely unknown. This may not be a problem in stirred yogurt testing where the gel has already been destroyed, but it can be a very serious problem in testing the original product, since the gel disruption is an irreversible process.

Another problem that can adversely affect viscometric measurements of yogurt by traditional methods is slip. The calculation of rheological constants from experimentally recorded flow curves, or frequency sweeps, is based on several conditions. Among them is the requirement that there is a good contact between the tested fluid and the sensor surfaces. This requires that the fluid's edge in contact with the moving part of the sensor has the same velocity as the latter, and that the fluid's edge in contact with the stationary part of the sensor has a zero velocity. This condition is not satisfied if the specimen separates and produces fluid layers that act as a lubricant. In such cases the flow pattern, and the velocities profile within the specimen, can change dramatically, thus undermining the validity of the whole measurement. Published results of stirred or partially disrupted yogurt suggest that slip

* Correspondence to: Micha Peleg, Department of Food Science, Chenoweth Laboratory, University of Massachusetts, Amherst, MA 01003, USA
E-mail: micha.peleg@foodsci.umass.edu
Contract/grant sponsor: USDA-NRICG-P; contract/grant number: 9502429
(*Received 15 May 1998; revised version 17 September 1998; accepted 9 November 1998*)

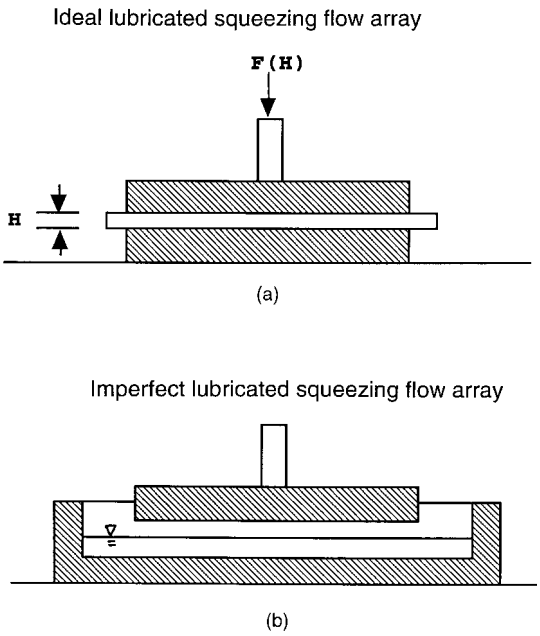

Figure 1. Schematic view of (a) perfect and (b) imperfect lubricated squeezing flow geometries.

may not be only a potential problem. Reported values of the flow index of yogurt, *n,* rarely exceeded 0.5 and in certain cases they were as low as 0.2–0.3. Although such a degree of pseudo-plasticity is not theoretically impossible, the alternative explanation, ie, that the low *n* values reflect slip, should at least be considered.

Lubricated squeezing flow viscometry (Fig 1 (a)) offers a way to avoid, or considerably reduce, the problems posed by both structural disruption and slip. The method is based on compression, ie squeezing of a thin layer of fluid between lubricated plates[14,15] to produce what is known as a plug flow (see below). It has been introduced to food rheology by Dr Edward Bagley of the USDA-NRRC of Peoria, IL[16] and has been applied to other dairy products (eg Campanella *et al*[17] and Ak and Gunasekaran[18]), as well as other foods (eg Campanella and Peleg,[19] Huang and Kokini[20] and Ramirez-Wong *et al*[21]). Since the specimen is loaded when the plates are widely separated, the specimen is spared much of the disruption that occurs in conventional viscometry, where it is forced into the narrow space of the sensor. Because the plates are also lubricated, or made of Teflon^R, slip is intentionally induced. Thus instead of being an artifact, slip in this method is a prerequisite for a proper test. The difficulty with the method is that preparation and mounting of the specimen can be somewhat inconvenient. For this reason it has recently been proposed to use what has been called 'imperfect lubricated squeezing flow viscometry' (Fig 1 (b)), where the bottom plate is replaced by a shallow container. At least in principle a specimen like yogurt can actually be formed in the container and hence be tested virtually intact. Because of the imperfect geometry, the measured forces are influenced by entry effect, annular flow and buoyancy (see below). It has been demonstrated though that the method, despite its imperfections, can be remarkably sensitive and useful for rheological characterisation of foods whose slip and/or uncontrolled structural disruption are acute problems when tested by conventional methods.[22–25]

The objectives of this work are to present the imperfect squeezing flow method and to evaluate its potential use as a tool to assess the rheological properties of yogurt, almost intact and after stirring.

THEORETICAL BACKGROUND

The force exerted by a power law fluid squeezed between parallel frictionless plates at a constant displacement rate is given by[17,26]

$$F(H) = \pi R^2\ K3^{(n+1)/2}(V/H)^n \qquad (1)$$

where F is the momentary force, H the specimen's momentary height, R the plate radius, V the displacement rate and K and n the fluid's consistency and flow index, respectively. Thus when the force versus height relationship is plotted in logarithmic co-ordinates the result is a straight line with a slope of -n. Once n has been determined, K, the consistency coefficient, can be calculated with eqn 1.

In frictional flow, that is when the plates are not lubricated, the force versus height relationship is given by Scott's equation,[27–29] ie

$$F(H) = [2\pi KR^{n+3}/(n+3)][(2n+1)/n]^n V^n/H^{2n+1} \qquad (2)$$

The theoretical slope of the log $F(H)$ versus log H plot in this case is therefore -$(2n+1)$.

Since the absolute value of the flow index of a shear thinning fluid, n, must be between zero and one, $0 < n < 1$, the absolute magnitude of the slope of the log $F(H)$ versus log H plot in frictional flow must also be bigger than one. Thus an experimentally determined slope with an absolute magnitude smaller than one is a strong evidence of a lubricated squeezing flow. In an ideal experiment this can also be confirmed visually. If the exiting liquid's front has a rectangular shape (Fig 1(a)), which is a characteristic of a plug flow, the flow

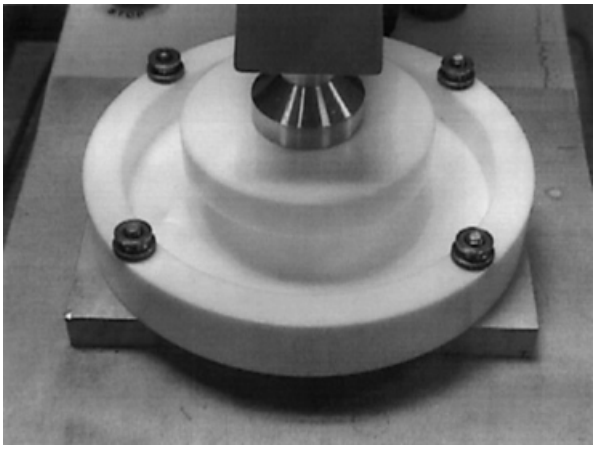

Figure 2. The all Teflon^R sensor used in this work.

is indeed of the 'lubricated' type. (Had the plates provided considerable friction the profile of the exiting fluid would have a parabolic shape). In the case of a plug flow the squeezed specimen remains unsheared, which allows for the calculation of its elongational biaxial viscosity, μ_b, as a function of the elongational strain rate, $\dot{\varepsilon}_b$, ie[16]

$$\mu_b = 2F(H)H/\pi R^2 V \quad (3)$$

and

$$\dot{\varepsilon}_b = V/(2H) \quad (4)$$

If the absolute magnitude of the slope of the log $F(H)$ versus log H plot is small but larger than one, 1.2, say, its interpretation is more difficult. It can indicate frictional flow with a partial slip, a high degree of plasticity, or that Scott's equation is inappropriate for reasons that have to do with the material properties rather than the presence or absence of friction at the plates surfaces (see below). In the case of imperfect squeezing flow (Fig 1 (b)), the measured momentary force, $F(H)$, contains other components which reflect the contribution of buoyancy, annular flow and entry and end effects.[30] If, however, the sensor is sufficiently large and has a wide gap, then disregarding these effects can be justified. In other words, with a sensor geometry of the kind used in this work (see below) eqns1, 3 and 4 can be used to estimate the rheological constants of the tested fluid.[23] The consistency of the estimates can be tested by using upper plates of different diameters. It has been demonstrated in other foods that the rheological constants calculated from tests performed with such sensors indeed had only a weak dependence on the upper plate diameter.[23,25] The validity of the K and n calculation using eqn 1 (or 2) rests on the assumption that the power law model is an appropriate constitutive equation of the tested fluid. This may not be the case if the material has a high yield stress which can affect the stress distribution within the sample.[31] In such a case (see below) the consistency of different samples can be compared in terms of their apparent stress at a given height, eg

$$\sigma_{@1or2mm} = F_{@1or2mm}/(\pi R^2) \quad (5)$$

with or without correction for the buoyancy effect.[24,25] Obviously such a parameter has arbitrary elements, that is the displacement rate at which the test is performed and the height, or heights, selected for the comparison. The parameter's calculated magnitude, however, is not based on any assumed rheological model which may or may not be applicable. The apparent stress so determined has a significant advantage over purely empirical measures of consistency. Being measured in specimens having a high diameter to height ratio and expressed in force per area units, the apparent stress magnitude is much less affected by artifacts than measures based on other test geometries. Also, the validity of the apparent stress as a consistency measure can be verified experimentally by comparing results of tests performed with upper plates of different diameters.

Yield stress

It is difficult to determine the yield stress of a semi-liquid food by squeezing flow viscosimetry performed at a constant displacement rate. (It can be done in a creep array[19] where the specimen height is monitored under a constant load. Standard commercial creep testers however, are not readily available and therefore it is doubtful that this method will gain popularity in food research in the near future.) Nevertheless an estimate of the yield stress can be obtained by determining the residual apparent stress of the specimen after it has been allowed to relax at a given height for a given time, eg

$$\sigma_{app\,@\,60\,or\,120s} = F_{@60\,or\,120s}/(\pi R^2) \quad (6)$$

In imperfect squeezing flow, the force of fluids without a yield stress decays to the buoyancy force almost instantaneously. The higher the yield stress, and more solid-like the specimen's structure, the higher is the absolute magnitude of the residual force, and the apparent stress after relaxation. The latter therefore can serve as a measure of solidity (on the pertinent time scale) and hence as an indicator of the yield stress magnitude.

EXPERIMENTAL

Materials

Large jars of fresh plain yogurt (16 oz), of two national brands were ordered and purchased at a local supermarket. Since we are not equipped to test specimens at a controlled low temperature the yogurt jars were left in the laboratory for approximately 4 h until their temperature reached the ambient temperature of about 23 °C. Their contents were tested soon after to avoid additional changes and spoilage. Because no attempt has been made to establish how representative the samples were of their respective manufactures, the latter are not identified by name.

Mechanical testing

Specimens of the yogurt were tested in three forms; almost undisturbed; after stirring by hand for 1 min, and after stirring in a domestic blender for 1 min. The almost undisturbed yogurt samples were specimens gently transferred from their original container into the all Teflon^R container shown in Fig 2, using a very large spoon to minimise breakage of the gel. The container's diameter was 140 mm and the yogurt depth in it about 6–7 mm. Subsequently the yogurt samples were compressed by a Teflon^R upper plate 100 or 120 mm in diameter (Fig 2) as described by Hoffner *et al*[23] (The reader should notice that since only data at high compression ratios were used for the yogurt consistency evaluation – see below – an initially uneven specimen height has hardly any effect on the measure-

ments, theoretically and in practice). The stirred samples were prepared by stirring the plain yogurt manually with a spoon or by a domestic Osterizer® blender for 1 min. They were then poured into the same sensor's 140 mm Teflon^{R} container to occupy a height of about 6–7 mm, and were subsequently compressed in the same way as the almost undisturbed samples.

The compression tests were performed with a TA.TX2 Texture Analyzer (Texture Technologies Corp, Scarsdale, NY) equipped with a 25 kg load cell and interfaced with a Gateway 2000 microcomputer. The specimens were compressed to a final height of 0.7 mm at a speed of 0.1 mm s^{-1}. In some experiments the crosshead was stopped at the end of the run and the decaying force recorded for about 3 min before the crosshead was withdrawn. The raw data files were imported to and processed by the Systat 5.0 package (Systat Inc. Envanston, IL).

Each test was performed in four replicates.

Data processing

The recorded raw data were converted into force–height relationships plotted in linear and logarithmic co-ordinates (see below). The linear part of the logarithmic plot was considered as representing the region of dominant squeezing flow [23,24] and its slope was determined by linear regression. The initial part of the force–height relationships (corresponding to specimen heights down to about 4–7 mm) was considered as reflecting entry effects and therefore discarded. The slope of the linear part was used to estimate the value of n eqn1 without taking into account buoyancy, secondary flows and end effects (see below). The apparent stress at a specimen height of 1 or 2 mm, $\sigma_{app@H=1 \text{ or } 2\,mm}$, was calculated by eqn5 and was used as a semi-empirical consistency measure. The force decay data recorded at a fixed specimen height were used to calculate an apparent residual stress after 60 and 120 s using eqn 6.

RESULTS AND DISCUSSION

The shape of the force–height curve and the products consistency

Typical $F(H)$ versus H relationships of the three kinds of yogurt plotted on linear and logarithmic co-ordinates are shown in Figs 3 and 4. The curves were remarkably reproducible (see below) and enabled characterisation of the products in terms of the various mechanical parameters listed in Tables 1 and 2. The logarithmic plots had the expected characteristic shape, and its linear part allowed for a clear identification of the region where squeezing flow had been dominant. Consequently, all the data points outside this region (corresponding to a specimen height above 4 mm) could safely be discarded. The absolute magnitudes of the slopes of the linear parts of the log $F(H)$ versus log H curves of the different yogurts are also listed in Tables 1 and 2. The typical values of the hand and blender stirred products of manufacturers A and B were about 0.7–0.8 and 0.6–0.7, respectively. If these values indeed correspond to the flow index, n, then the latter is appreciably higher than the values 0.3–0.5 previously published. Similar observations have been reported with other foods, eg peanut butter, tomato products, mayonnaise and mustard[19,23,24] where the n values determined by squeezing flow viscometry were higher than those obtained with coaxial viscometers. This suggests that the rheology of stirred yogurt products can be analysed in the same way as that of other power law liquids through lubricated squeezing flow viscometry.

The absolute magnitude of the slope of the log $F(H)$ versus log H relationship of the unstirred samples, of both manufacturers, was higher than one, the highest theoretical possible value in lubricated squeezing flow. It is highly doubtful that yogurt can develop a fully frictional squeezing flow pattern when compressed between smooth Teflon^{R} plates. It is more reasonable to assume that the flow of these yogurts was governed by their gel's deformability and relatively high yield stress. If this is indeed the case, then the power law model is probably inadequate to describe the rheology of undisturbed yogurt. To calculate rheological parameters from such data will require different models and additional research to test them. Nevertheless, the magnitude of the apparent stress at a given specimen height can still be used as a legitimate measure of the yogurt consistency; this is because it is determined directly and its value is not contingent on the validity of any rhelogical constitutive equation (see below).

The tests' reproducibility

Despite the crudeness of the experimental array, the sample preparation and the specimen loading procedure, the measurements, and the rheological parameters which they provided, were remarkably reproducible (Tables 1 and 2). This was irrespective of the yogurt brand, its pretreatment and the diameter of the upper plate used for its compression. Thus the measurements were not only sensitive enough to detect the large textural changes induced by stirring, but also to distinguish, clearly and consistently, between the products of the two manufacturers (see below). A similar degree of reproducibility has been observed in other products evaluated by this method.[23–25] This suggests that since the plates are wide, and the specimen height very small in comparison, any irregularity in the initial specimen's height had only a very minor effect on the results. That there was a certain degree of textural variability within and among the samples also cannot be ruled out, but since the observed scatter was not much larger than that found in Newtonian fluids[30] one can conclude that the yogurts tested in this work had a fairly uniform texture.

The texture of almost intact yogurt and the effect of stirring

As could be expected, the almost intact yogurt

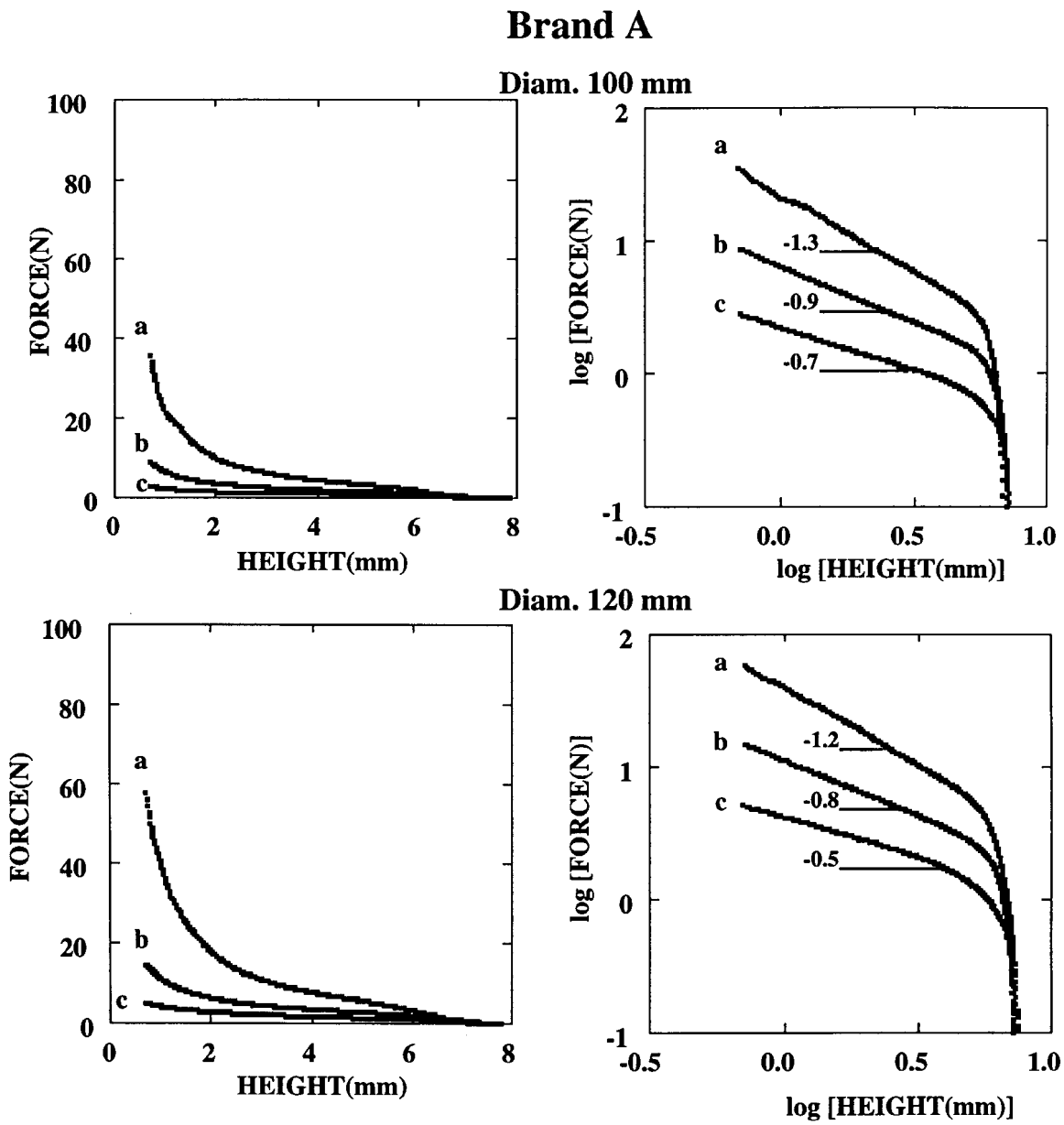

Figure 3. Typical flow curves of almost intact and stirred plain yogurt of brand A: a, almost undisturbed; b, stirred by hand for 1 min; c, stirred in a domestic blender for 1 min.

samples, in which the original gel structure was hardly disrupted, had a stronger consistency than that of the stirred samples. This was evident, and could be quantified, in terms of the apparent stress at 1 or 2 mm (Table 1 and 2). The same was also observed in the relaxation pattern (Fig 5). The almost intact specimens maintained a considerable amount of residual stress even after 2 min (Tables 1 and 2) which was higher than the initial stress that the stirred samples developed at the same height, ie 0.6–1.0 versus 0.15–0.3 kPa and 2.1–2.7 versus 0.4–1.0 kPa in the yogurts of brands A and B, respectively. Although the procedures employed to stir the samples were arbitrary, their outcome could be compared using the same mechanical parameters. That the domestic blender had a more disruptive effect on the yogurt consistency in comparison with hand stirring is clearly evident in the magnitude of the stresses at a specimen height of either 1 or 2 mm (Tables 1 and 2). This can also be assessed visually from the of the shape of the $F(H)$ versus H and relaxation curves (Figs 3–5). Both stirring procedures resulted in products having only a small or non-existent yield stress. This was evident from the relaxation curves, where the force dropped to approximately the buoyancy level. Unlike the undisturbed yogurt, the stirred samples flowed under their own weight when their container was tilted. Consequently the stirred product could be considered as being power law fluids at least as a first-order approximation. This allowed presentation of their flowability in terms of an elongational viscosity versus elongational strain rate plots using eqns 4 and 5 to convert the data. Examples of such plots are given in Figs 6 and 7. They too demonstrate that the more

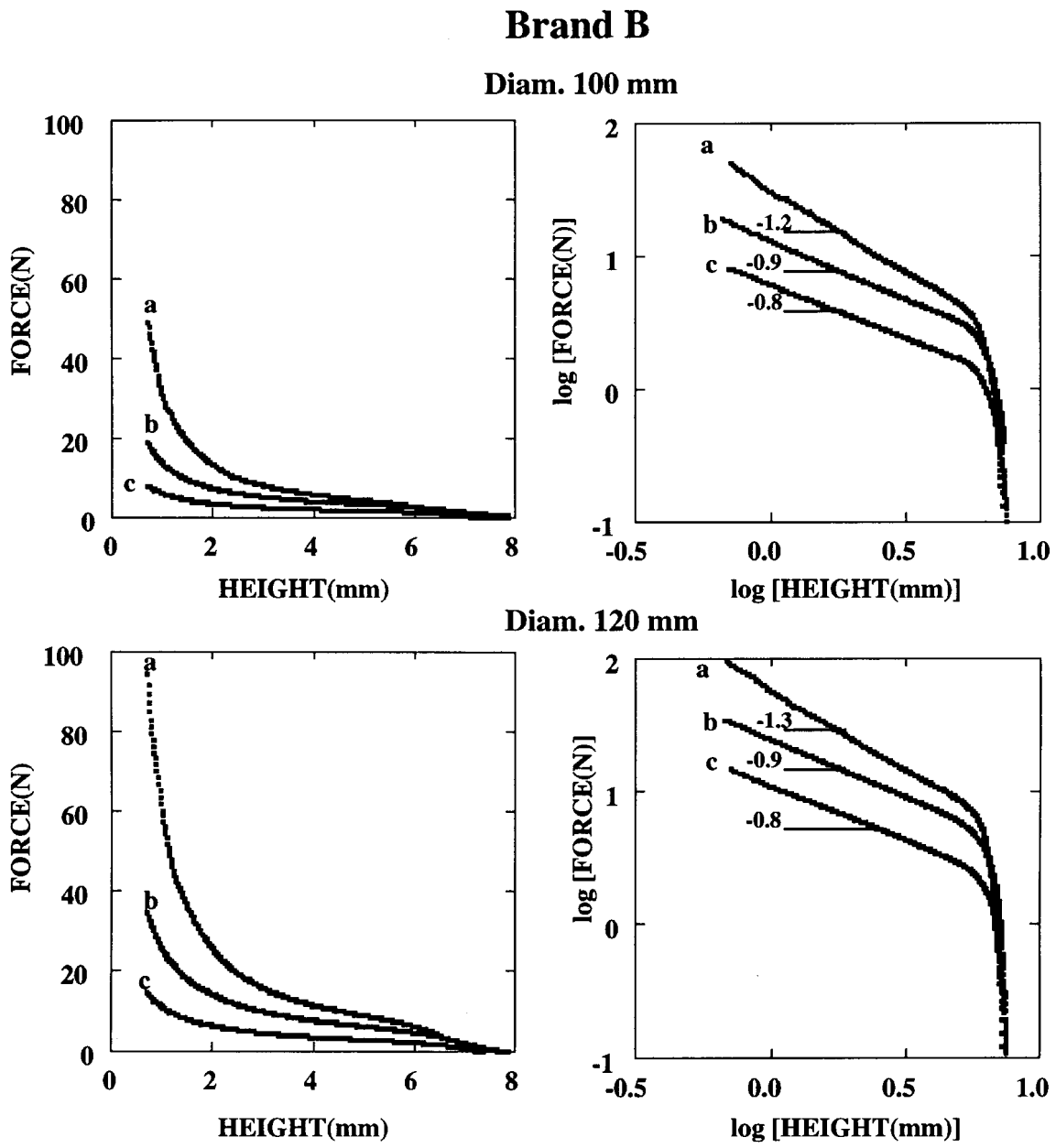

Figure 4. Typical flow curves of almost undisturbed and stirred plain yogurt of brand B: a, almost undisturbed; b, stirred by hand for 1 min; c, stirred in a domestic blender for 1 min.

extensive structural disruption which was produced by the domestic blender resulted in a fluid of weaker consistency, ie having a lower biaxial elongational viscosity at a comparable strain rate. It should be added here that the elongational viscosity is determined directly from the data without the use of any rheological constitutive equation or model. All that is needed to assure meaningful results is that the flow is

Table 1. Rheological parameters of plain yogurt of Brand A determined by lubricated imperfect squeezing flow viscosimetry

Sample	*Diam. (mm)*	*|Slope|*	*σ@H=2mm (kPa)*	*σ@H=1mm (kPa)*	*σ@t=0s (kPa)*	*σ@t=60s (kPa)*	*σ@t=120s (kPa)*
Almost intact	100	1.3±0.1	1.14±0.07	2.95±0.12	5.85±0.96	0.98±0.24	0.64±0.13
	120	1.2±0.0	1.37±0.14	3.18±0.3	5.58±0.52	1.44±0.20	1.00±0.14
Hand-stirred	100	0.9±0.0	0.45±0.01	0.83±0.04	1.76±0.14	0.35±0.0	0.21±0.02
	120	0.8±0.0	0.57±0.01	1.01±0.03	1.87±0.04	0.49±0.03	0.33±0.02
Blender-stirred	100	0.7±0.1	0.18±0.00	0.28±0.00	0.50±0.02	0.17±0.01	0.15±0.01
	120	0.5±0.1	0.23±0.02	0.33±0.03	0.47±0.07	0.22±0.02	0.21±0.01

Table 2. Rheological parameters of plain yogurt of Brand B determined by lubricated imperfect squeezing flow viscosimetry

Sample	*Diam. (mm)*	*|Slope|*	*σ@H=2mm (kPa)*	*σ@H=1mm (kPa)*	*σ@t=0s (kPa)*	*σ@t=60s (kPa)*	*σ@t=120s (kPa)*
Almost intact	100	1.2±0.1	1.89±0.22	4.37±0.47	8.64±0.79	2.91±0.44	2.09±0.35
	120	1.3±0.1	2.24±0.34	5.37±0.89	8.60±0.47	3.54±0.33	2.76±0.34
Hand-stirred	100	0.9±0.0	0.92±0.02	1.72±0.03	3.34±0.10	0.73±0.04	0.42±0.02
	120	0.9±0.0	1.21±0.04	2.22±0.07	3.81±0.10	1.47±0.09	1.01±0.07
Blender-stirred	100	0.8±0.0	0.44±0.01	0.76±0.02	1.47±0.07	0.49±0.03	0.36±0.03
	120	0.8±0.0	0.56±0.0	0.95±0.1	1.7±0.10	0.7±0.06	0.6±0.05

practically frictionless, and hence shear free. The flow of the stirred samples, as the slopes of their log $F(H)$ versus log H relationships indicate, appears to have been such a case. It is not clear whether this was true with the almost undisturbed samples. Since, as already stated, the absolute magnitude of the slope of their log $F(H)$ versus log H relationship was bigger than one, their flow data were not converted into μ_b versus $\dot{\varepsilon}_b$ relationships.

Comparison of the two brands

Figs 3–5 and Tables 1 and 2 show clearly, that the

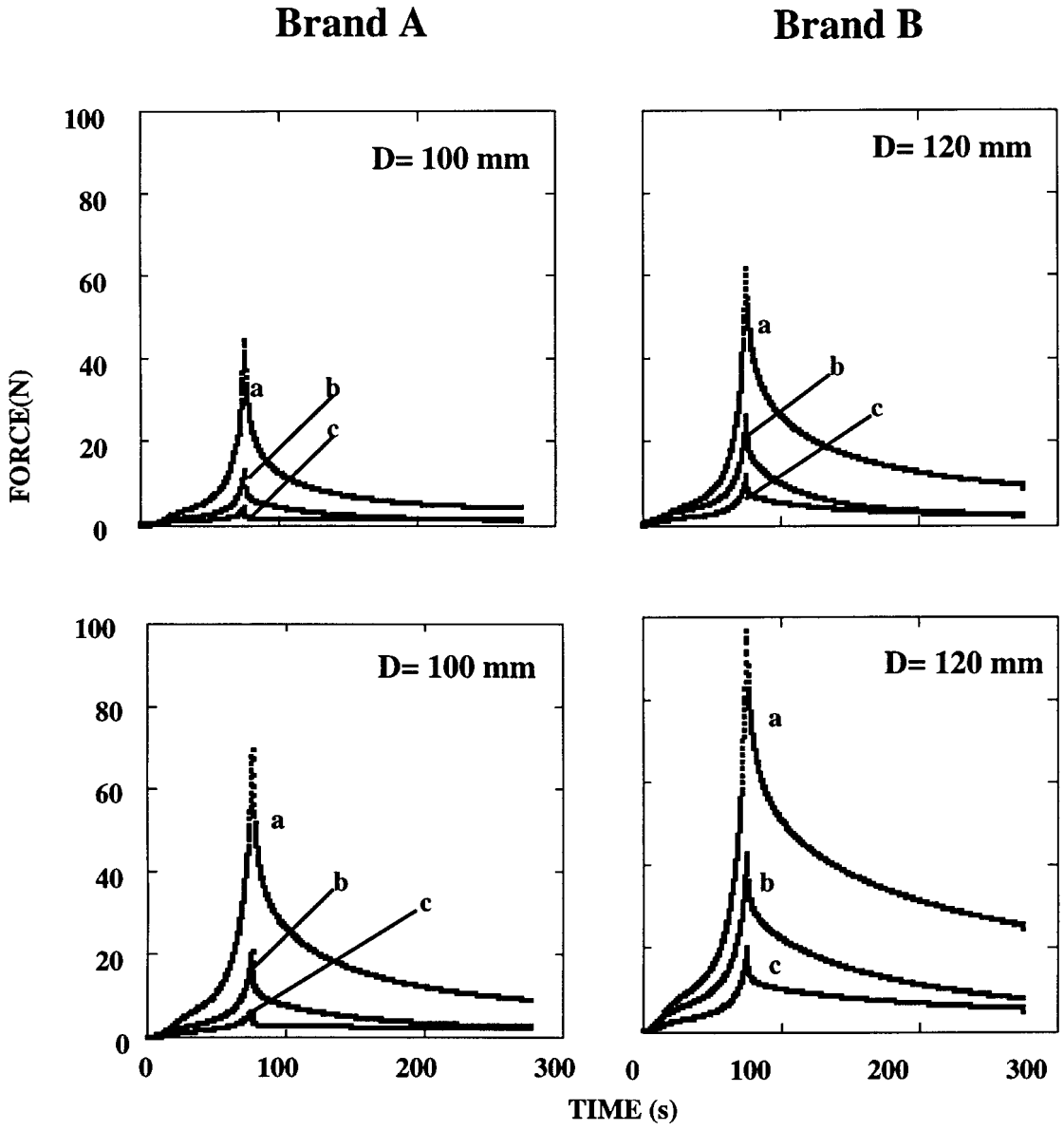

Figure 5. Typical relaxation curves of squeezed almost undisturbed and stirred yogurts of brands A and B: a, almost undisturbed; b, stirred by hand for 1 min; c, stirred in a domestic blender for 1 min.

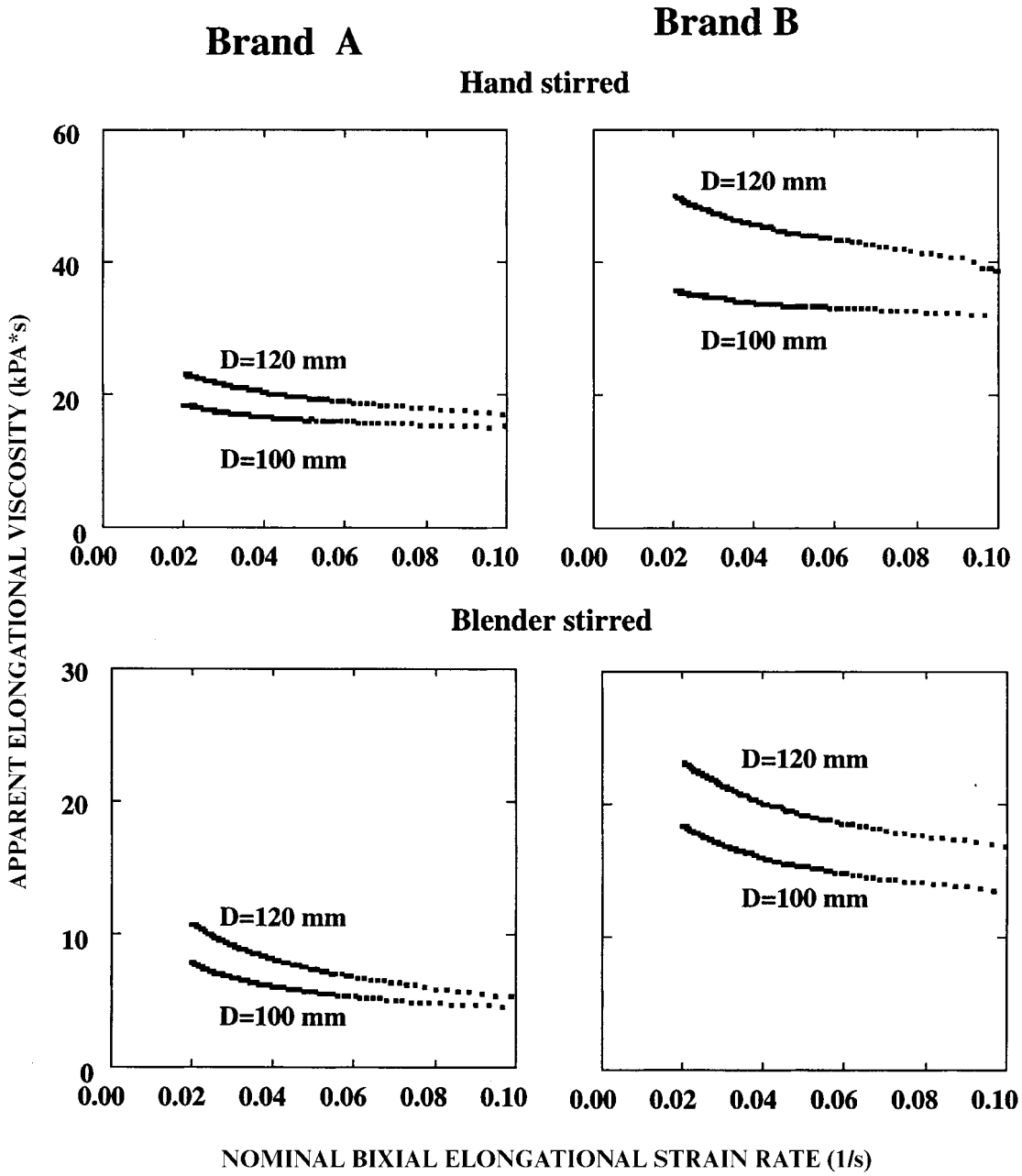

Figure 6. Apparent biaxial elongational viscosity versus elongational strain rate relationships of stirred yogurts of brands A and B on linear co-ordinates.

plain yogurt of brands A and B have a similar kind of rheological characteristics. The slope of the log $F(H)$ versus log H flow curves was practically identical and they shared a very similar relaxation pattern. The difference between them was in their overall consistency. The yogurt of brand B had the stronger consistency and this was manifested simultaneously in the magnitude of the recorded forces at any given specimen height and after relaxation at any given time. Thus at 1 mm height the apparent stress of the yogurt of brand A was on the order of 1.1–1.4 kPa as compared to 1.9–2.2 of the brand B. This is clearly a statistically significant difference. What is not clear is whether this difference is also perceived sensorily by humans, and if so, if it is also assessed as being of such magnitude. To resolve the issue one must conduct a series of sensory analyses, which was clearly outside the scope of this particular study. Hence the issue is only briefly mentioned here, and its implications will not be further discussed. The specimens of brand B maintained a higher consistency after stirring by a factor of about two as judged by the apparent stress at either 1 or 2 mm height. This observation was not unexpected and it suggests that stirred yogurt consistency may be associated with the initial gel strength. At a comparable height the ratio of the apparent stresses of the yogurt of both brands was about 4 (almost intact): 2 (hand stirred): 1 (blender stirred) although, theoretically at least, each could have exhibited a different ratio. What controls yogurt texture before and after stirring has been a topic of extensive research and it should not concern us here.

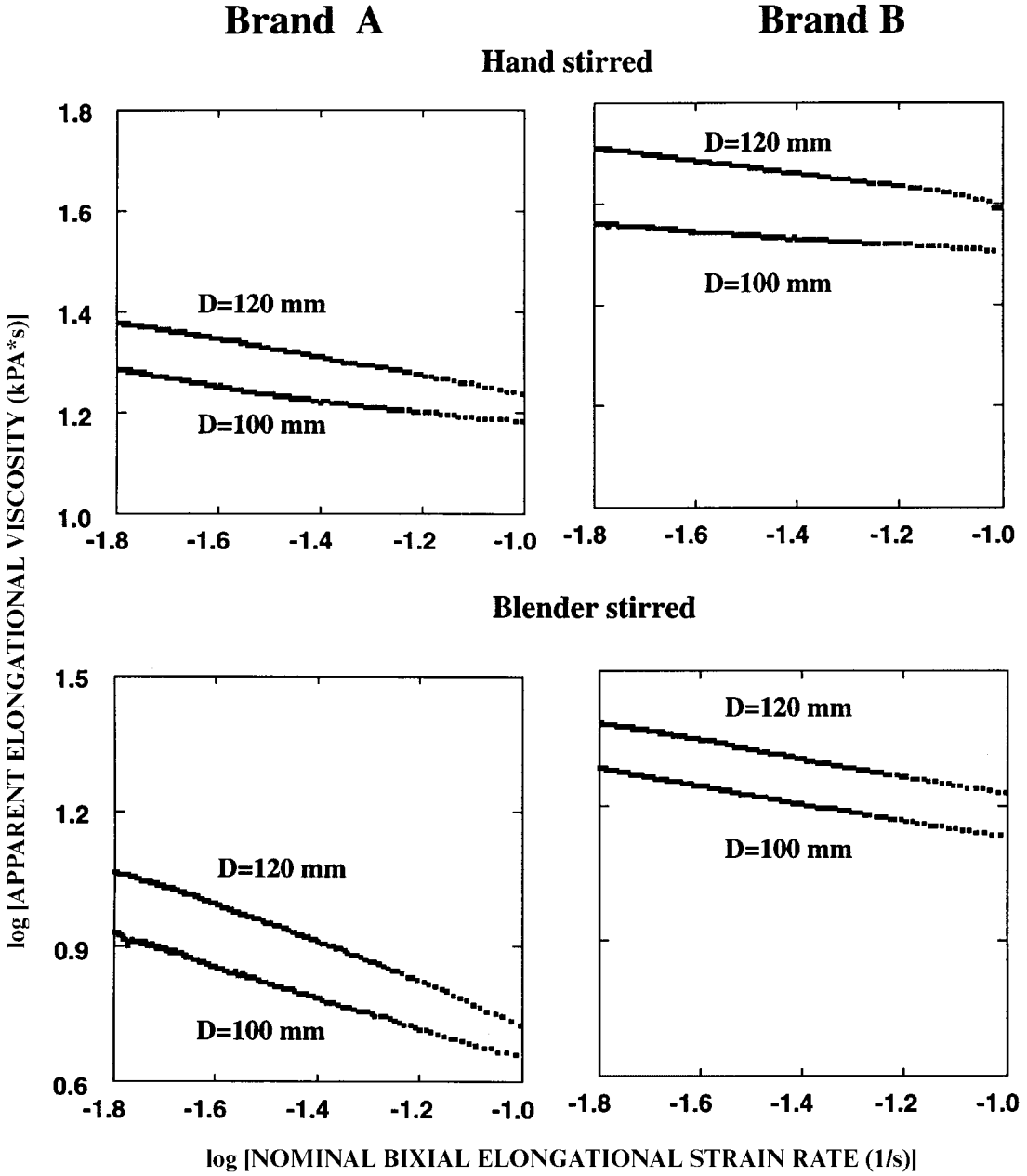

Figure 7. Apparent biaxial elongational viscosity versus elongational strain rate relationships of stirred yogurts of brands A and B on logarithmic co-ordinates.

The described method is only a tool to monitor and quantify differences or changes in textural properties. Its advantage over many previously used methods is that both the almost intact and stirred products can be evaluated by the same procedure and their properties expressed in the same mechanical terms (see below).

Effect of the upper plate diameter

In an ideal lubricated squeezing flow analysis (Fig 1 (a)) the stress, $F(H)/(\pi R^2)$, at any given height, H, is expected to be independent of the plates diameter (eqn 1). In reality end effects are inevitable and hence a high diameter-to-height ratio ought to be maintained in order for the results to be meaningful. In imperfect lubricated squeezing flow viscometry the situation is further complicated by buoyancy, annular flow and entry effects as previously stated. It can be shown though, that as the upper plate's radius increases, the relative weight of these factors can be considerably reduced, provided that the gap between the upper plate and the container wall remains sufficiently large.[30] The option of increasing the sensor's diameter, however, has its limitations. The main one, apart from the obvious limit on the physical size of any sensor mounted on a testing machine, is that the larger the upper plate the more difficult it is to assure that it has no tilt. It can be shown that even a slight tilt can have a dramatic effect on the measurements. The sensor dimensions selected for this work are a result of a compromise–trying to accommodate the conflicting requirements of a test accuracy with an attempt to avoid experimental errors caused by a slight plate inclination. Tables 1 and 2 show that the apparent stresses determined with the larger upper plate

(120 mm diameter) were consistently about 20–25% higher than those determined with the smaller plate (100 mm). A similar observation was reported in other food products tested with the same instrument.[23] The data recorded with the larger upper plate are probably closer to what would be recorded in an ideal test, but because of the test's imperfect geometry, the results obtained with either sensor could only provide an estimate of the true rheological properties of the yogurts. As shown in the tables and figures, the method using either upper plate was sufficiently sensitive to monitor differences and changes despite this shortcoming.

Potential advantages and limitations

The main advantage of the described method is that it allows for the testing of almost undisturbed yogurt samples. Even the crude loading procedure was quite reproducible as could be judged from the results scatter. The coefficient of variance of the apparent stress (at either 1 or 2 mm height) was on the order of 1–10% in the products of brand A and 11–17% of brand B. It shows that the results scatter was by far smaller than the effect of stirring and the difference between the two brands. Obviously, if the specimen is actually formed in a wide container whose bottom is lubricated, or Teflon^{R} coated, the test can be performed on a *totally* intact yogurt specimen. (The construction of a set of such containers need not be too difficult a task.) In principle the method can also be applied to yogurt that contains dispersed solids or soft fruit particles provided that the latter are not too large and numerous. (In fact the method has been found suitable to assess and compare the texture of commercial refried beans products which have suspended particles.[25]) The possibility of testing stirred and unstirred products by the same method should also be considered an advantage as already stated. The apparent stresses at a given height, or apparent biaxial elongational viscosity versus extensional strain rate relationships, are expressed in universally accepted rheological terms and units. They can therefore be clearly interpreted and meaningfully compared. The results of the imperfect squeezing flow viscometry as shown have weak but inevitable dependence of the sensor dimensions. Therefore a valid comparison between results requires that they have been obtained with sensors of at least similar dimensions. In principle the problem can be avoided by testing the same samples with several sensors and extrapolating the results to those of a sensor with an infinite diameter. This, however, is not a practical option especially in routine testing. One also has to make sure that the machine used has a good crosshead location and speed controls, and that the whole array is very stiff; because of the relatively small displacements involved, any inaccuracy in the speed or the height measurement, or even a slight compliance of the instrument or sensor themselves, can become a source of a considerable error. With the proper machine, however, the method is simple and straightforward. It requires neither an elaborate data processing, nor the application of a complicated correction procedure to account for the slip.

ACKNOWLEDGEMENTS

The contribution of the Massachusetts Agricultural Experiment Station at Amherst, and the support of the work by the USDA-NRICGP (under contract No 9502429) is gratefully acknowledged. The authors also express their thanks to the Royal Thai Government for the graduate training scholarship granted to TS.

REFERENCES

1 Velez-Ruiz JJ and Barbosa-Canovas GG, Rheological properties of selected dairy products. *Crit Rev Fd Sci Nut* **37**:311–359 (1997).
2 Benezech T and Manigonant JJ, Characterization of the rheological properties of yogurt-a review. *J Food Eng* **21**:447–472 (1994).
3 Prentice JJ, *Dairy Rheology: A Concise Guide*, VCH Publishers, New York (1992).
4 Modler HH, Larmond MM, Lin CC, Froehlich D and Emmons DB, Physical and sensory properties of yogurt stabilized with milk proteins. *J Dairy Sci* **66**:422–429 (1983).
5 Mottar J, Bassier A, Joniau M and Baert J, Effect of heat-induced associated of whey proteins and casein micelles on yogurt texture. *J Diary Sci* **72**:2247–2256 (1989).
6 Labropoulos AA, Collins WW and Stone WW, Effects of ultra-high temperature and vat processes on heat-induced rheological properties of yogurt. *J Dairy Sci* **67**:405–409 (1984).
7 Labropoulos AA, Palmer JJ and Lopez A, Whey protein denaturation of UHT processed milk and its effect on the rheological properties of yogurt. *J Texture Studies* **12**:365–374 (1981).
8 Parnell-Clunies EE, Kakuda Y, Mullen K, Arnott DD and deMann JJ, Influence of heat treatment of milk on the flow properties of yogurt. *J Food Sci* **51**:1459–1462 (1986).
9 Ramaswamy HH and Basak S, Rheology of stirred yogurts. *J Texture Studies* **22**:231–241 (1991).
10 Basak S and Ramaswamy HH, Simultaneous evaluation of shear rate and time dependency of stirred yogurt rheology as influence by added pectin and strawberry concentrate. *J Food Eng* **21**:385–393 (1994).
11 Skriver A, Roemer H and Qvist KK, Rheological characterization of stirred yogurt: viscometry. *J Texture Studies* **24**:185–198 (1993).
12 Keogh MM and O'Kennedy BB, Rheology of stirred yogurt as affected by added milk fat, protein and hydrocolloids. *J Food Sci* **63**:108–112 (1998).
13 Ozer BB, Bell AA, Grandison AA and Robinson RR, Rheological properties of concentrated yogurt (labneh.) *J Texture Studies* **29**:67–79 (1998).
14 Chatraei SS, Macosko CC and Winter HH, Lubricated squeezing flow. A new biaxial extension rheometer. *J Rheol* **25**:433–443 (1981).
15 Soskey PP and Winter HH, Equibiaxial extension of two polymer melts: polystyrene and low density polyethylene. *J Rheol* **29**:493–517 (1985).
16 Casiraghi EE, Bagley EE and Christianson DD, Behavior of mozzarella cheddar and processed cheese spread in lubricated and bonded uniaxial compression. *J Texture Studies* **16**:281–301 (1985).
17 Campanella OO, Peleg M, Popplewell LL and Rosenau JJ,

Elongational viscosity measurements of melting American processed cheese. *J Food Sci* **52**:1249–1251 (1987).
18 Ak MM and Gunasekaran S, Evaluating rheological properties of mozzarella cheese by squeezing flow method. *J Texture Studies* **26**:695–711 (1996).
19 Campanella OO and Peleg M, Squeezing flow viscosimetry of peanut butter. *J Food Sci* **52**:180–184 (1987).
20 Huang H and Kokini JJ, Measurement of biaxial extensional viscosity of wheat flour doughs. *J Rheol* **37**:879–891 (1993).
21 Ramirez-Wong B, Sweat VV, Torres PP and Rooney LL, Evaluation of rheological properties of fresh corn masa using squeezing flow viscometry: biaxial extension viscosity. *J Texture Studies* **27**:185–198 (1996).
22 Lee SS and Peleg M, Imperfect squeezing flow viscosimetry with a wide plate and a shallow container. *J Texture Studies* **23**:267–278 (1992).
23 Hoffner B, Gerhards C and Peleg M, Imperfect lubrication squeezing flow viscometry for foods. *Rheol Acta* **36**:686–693 (1997).
24 Lorenzo MM, Gerhards C and Peleg M, Imperfect squeezing flow viscosimetry of selected tomato products. *J Texture Studies* **28**:543–567 (1997).
25 Suwonsichon T and Peleg M, Imperfect squeezing flow viscometry for commercial refried beans. *Food Sci Technol Intnl* **5**:159–166 (1999).
26 Lee SS and Peleg M, Lubricated and nonlubricated squeezing flow of a double layered array of two power law liquids. *Rheol Acta* **29**:360–365 (1990).
27 Leider PP, Squeezing flow between parallel disks. II. Experimental results. *Ind Eng Chem Fundament* **13**:342–346 (1974).
28 Leider PP and Bird RR, Squeezing flow between parallel disks. I. Theoretical analysis. *Ind Eng Chem Fundament* **13**:336–341 (1974).
29 Avila F and Binding DD, Normal and reverse squeezing flow. *J Non-Newtonian Fluid Mech* **11**:111–126 (1982).
30 Damrau E and Peleg M, Imperfect squeezing flow viscosimetry of Newtonian liquids-theoretical and practical considerations. *J Texture Studies* **28**:187–204 (1997).
31 Campanella OO, Rheological properties of semi-liquid foods. PhD thesis, University of Massachusetts, Amherst (1987).
32 Labropoulos AA, Lopez A and Palmer JJ, Apparent viscosity of milk and cultured yogurt thermally treated by UHT and vat systems. *J Food Prot* **44**: 874–876 (1984).