SQUEEZING AND ELONGATIONAL FLOW

Corvalan, Carlos M.
School of Bioengineering, University of Entre Rios, Argentina

Campanella, Osvaldo H.
Agricultural and Biological Engineering Department, Purdue University, USA

Keywords: Food rheology, elongational viscosity, shear viscosity, squeezing flow, Trouton ratio, parallel plates viscometer.

Contents

Summary

Daily life provides examples of liquids and semi-liquid foods whose complex structures produce a large variety of flow patterns when processed or eaten. In order to predict and design the food operations involving the deformation and flow of liquids and semi-liquid foods, it is necessary to know the properties of materials characterizing these fluids. Rheology, the science that studies the deformation and flow of materials, is used for the determination of these material properties. From a rheological point of view, flows that are pertinent to processing and consumption of food materials can be classified as shear and elongational flows. Shear flows are commonly used to determine the rheological properties of liquid and semi-liquid foods (see *Newtonian and Non-Newtonian Flow*). However, quite often foods exhibit elongational flow behaviors that cannot be explained on the basis of properties measured by standard, shear-based viscometers. The remarkable stability of cheese strings to stretching is a striking illustration of these behaviors. Additionally, shear based viscometers may exhibit problems and artifacts when used with samples that experience slippage or have shear dependent structures.

The importance of elongational flows in the case of semi-liquid foods arises because many food operations predominantly involve an elongational mode of deformation or a combination of shear and elongational flow. Common examples include atomization of liquids during spray drying, die swelling of food materials during extrusion, rolling and sheeting of dough, flaking of cereals, and oven expansion of dough during baking, to name a few (see *Extrusion*).

Squeezing flow viscometers are inexpensive devices that enable the measurement of elongational properties of semi-liquid foods. Although several geometries can be utilized, in conventional squeezing flow viscometry, the material being tested is placed between two circular parallel plates and compressed by the vertical motion of one of the plates. With careful choice of experimental settings, the flow and resulting kinematics can be closely controlled so the material experiences only elongational flow. The evolution of the compressive stress and the separation between plates are closely monitored to provide an accurate measure of the materials behavior during the test. The measured compressive stress and the elongation of the material determined from the separation between plates are then used to evaluate the elongational properties of the material. Squeezing flow viscometers can be used as an alternative to conventional shear based viscometers, in particular, when the measurements exhibit slippage and when the structure of the food material is so weak that the material is damaged during the loading of the sample in the viscometer. Lubricated squeezing flow rheometry can get around these problems, firstly, because the slippage phenomenon is not only recognized, but also incorporated in the calculations and, secondly, because through careful setting of the test the sample is minimally disturbed during loading in the viscometer.

The last decade has seen a rapid growth in the use of squeezing flow viscometry. This review presents the basic considerations that must be taken into account in designing and interpreting squeezing flow experiments. It provides an overview of the applications of squeezing flow viscometry to characterize the elongational properties of foodstuffs and finally shows the considerable progress that has been made up to the present in the use of this technique.

1. Squeezing and Elongational Flow in Fluid Foods

Elongational flow is a phenomenon that has been extensively studied in the polymer science area, given its importance in polymer processing, notably in operations such as film blowing and plastic extrusion. Elongational flow is also present in a number of food operations, for example, in puffing, food extrusion, and baking. However, studies of this flow and how it relates to food process operations have been scarce in comparison. As an important aspect of food process engineering, in the last decade, there has been a growing interest to determine and understand the response of liquid and semi-liquid foods to elongational flow. As an answer to this necessity, lubricated squeezing flow has stood out as a useful technique. In the food rheology area, lubricated squeezing flow has been used mainly as a means to determine rheological properties of semi-liquid foods that are pertinent to this type of flow. Squeezing flow viscometry also gets around a number of problems and artifacts that traditional shear-based viscometers have when applied to food products.

Squeezing flow viscometry encompasses a variety of configurations, however, all share a common feature, that is, the sample is compressed vertically between two plates to induce a horizontal flow. The flow pattern during the fluid squeezing can be classified as being "frictional" or "lubricated". Frictional flow is induced when there is good contact between the sample and the plates through friction. The flow is a mix of shear and elongational flow produced by the stretching of the material when it is squeezed out of the plates due to the squeezing action. Lubricated flow is induced when the plates are lubricated intentionally or by the sample itself due to slippage. Thus, the flow patterns developed by the squeezing flow viscometry are dependent on whether there is lubrication or friction. These flow patterns are described by the so-called kinematics of the flow. Knowledge of the squeezing flow kinematics is of importance in squeezing flow viscometry because it allows one to develop the mathematical equations used for the analysis and interpretation of squeezing flow data.

Kinematics for lubricated and frictional squeezing are introduced in section 2, and the working equations used to estimate the properties of food materials in section 3. Additionally, a comprehensive list of foods for which squeezing flow viscometry has been successfully applied as well as shortcomings that arise during its application are also discussed in section 3. As a conclusion, an outline of the future of this rheological method in the food area is given.

2. Foundations of Squeezing Flow Viscometry

The mechanical properties of semi-liquid foods are very complex. The first step in characterizing these properties is to study how the material behaves in simple flows where the velocity field is precisely defined, so that the stresses resulting from the flow can be calculated. The relationship between these stresses and the velocity field or variables derived from it, notably the rate of strain, is known as the rheological constitutive model of the material (see *Rheological Constitutive Equations*). Knowledge of a material's rheological constitutive model is of relevance to processing operations associated with the flow or deformations of the material. In fact, if a rheological constitutive model is known, it can be used to predict the stresses resulting from the fluid flow. Viscometry can be regarded as a methodology to characterize the mechanical properties of materials, that is, to determine the material's rheological constitutive model. Flows used to determine the rheological constitutive model of a fluid material are known as viscometric flows. The most commonly used viscometric flow in viscometry is the shear flow, and the instruments used to produce shear flows are the capillary and rotational viscometers (see *Newtonian and Non-Newtonian Flow*). In the capillary viscometer, the pressure drop along a capillary is measured and used to calculate the shear stress at the capillary wall, whereas the other rheological variable of importance, the shear rate at the wall, is calculated from measurements of the volumetric flow rate through the capillary. Once shear stresses and shear rates are determined, they can be used to find out the rheological constitutive model for the material. In rotational viscometers, different types of geometrical surfaces are used to generate the shear flow, notably concentric cylinders, cone-and-plate, and parallel plates. The tested material is placed between the two surfaces forming the sensor. The shear flow is developed by the friction between the rotating component of the sensor and the fluid. The torque necessary to rotate the moving component at a constant rotational speed is measured and used to calculate the shear stress applied to the fluid, whereas the rotational speed is used to estimate the shear rate. As in capillary viscometry, the rheological constitutive equation of the material is found from the ratio between measured shear stresses and shear rates. Despite the wide applicability of these viscometers to the determination of rheological properties of food and non-foods fluids, they may exhibit serious shortcomings that may affect the measurements and the analysis of the data. These shortcomings are mainly related to slippage of the tested material at the sensor surfaces and the loading of the sample in the instrument.

The main hypothesis behind the utilization of viscometric shear flows is that the food sample is indeed sheared. Therefore, the application of a well-defined shear flow during the test is a necessary condition not only to perform the rheological test but also to estimate shear stresses, shear rates, and the materials rheological model. The application of shear implies there is no slippage between the sensor surfaces and the tested fluid. This assumption is satisfied for many fluid foods but there are notable exceptions, in particular, food suspensions and materials containing large amounts of fat, for which the non-slip condition cannot be taken for granted. Many semi-liquid foods materials are multi-component and multiphase concentrated suspensions, and the particles in these suspensions tend to migrate away from the wall forming a dilute layer that operates as a thin film of lubricant. The resulting flow is then shifted to a plug flow instead of the expected fully developed shear flow upon which calculations are based. A similar effect is produced when the food is self-lubricated through oil exudation, as occurs for example with butter and peanut butter. When slippage occurs the assumed shear flow is significantly altered and the application of the equations developed for shear-based viscometric flows are no longer valid. Therefore, for this type of food material, measurements based on shear flow may not reflect their true rheological properties.

The equations utilized to calculate the shear stress and shear rates in shear flows impose several geometrical restrictions on the sensor system utilized. One is that the gap in which the material is sheared needs to be small. This creates practical problems when semi-liquid food materials are tested. In many cases, semi-liquid foods contain particles and the size of these particles are of the same order of magnitude as the gaps used, rendering the assumption of shear flow and the rheological measurement inadequate. Additionally, to load the specimen into the measuring system, almost without exception, it must be pressed into small capillary tubes or the narrow gap between concentric cylinders, parallel plates, or cone and plate geometries. Thus, the application of capillary or rotational viscometry to fragile food structures or food materials whose structure are shear dependent, such as yogurt or tomato paste, to name a few, is, to say the least, troublesome. Merely mounting the specimen may destroy its original internal structure and modify its rheological properties even before tested.

In addition, there are large qualitative differences between the mode in which foods containing long molecules behave in flows (where the molecules are strongly stretched) and the mode in which those foods behave in shear flows. Hence, it is worthwhile to search for practical methods that measure these stretching or elongational properties. Naturally, elongational properties cannot be measured by shear-based viscometers.

A way to avoid slippage and sample loading problems, along with the added benefit of measuring elongational properties, is to use squeezing flow viscometry. In squeezing flow viscometers, the food sample is placed in the gap formed between two plates and a vertical force is applied to cause the fluid in the gap to be horizontally squeezed out. Experiments are mainly performed at either constant squeezing speed or constant squeezing load. When the fluid fills the space between the two plates, the test can be considered as one with a constant compression area (constant area). Conversely, if the tested fluid occupies only a portion of the space between the plates, the experiment is one in which the volume is kept constant during the test (constant volume). Typical testing configurations are illustrated in Figure 1, which shows the sample confined between two large coaxial plates and subjected to a prescribed vertical motion of the plates (velocity *V*) or to a prescribed load (F).

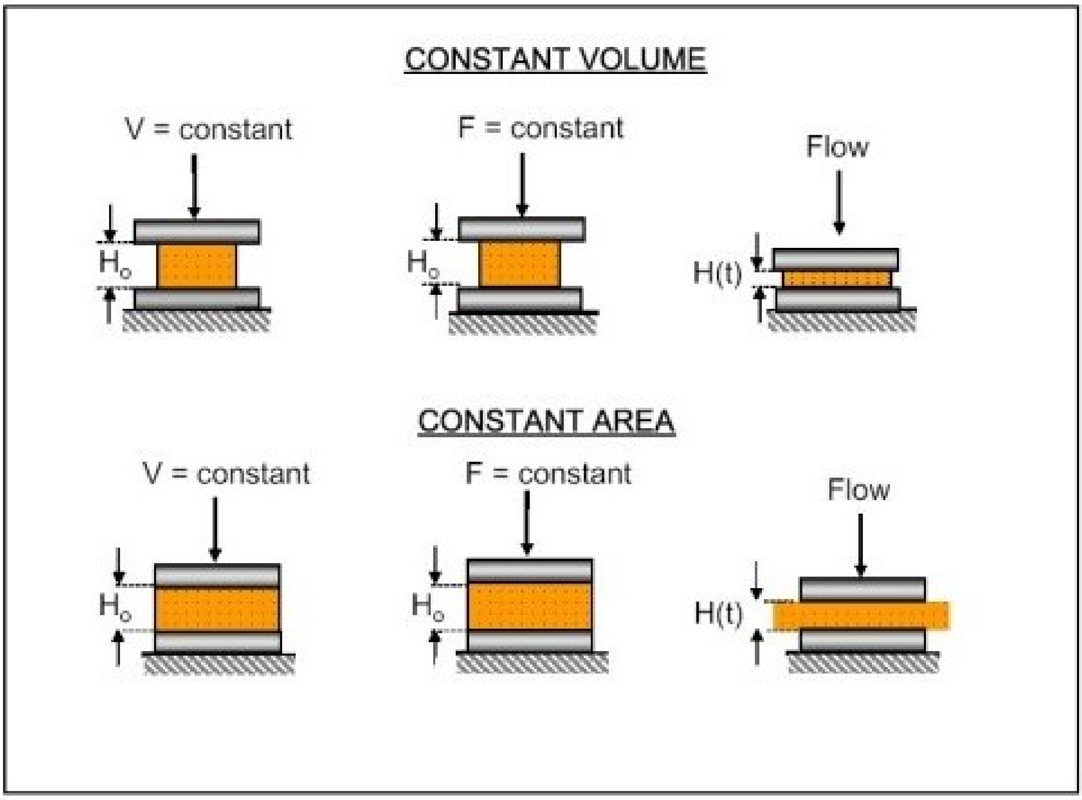

Figure 1. The basic test configurations utilized in squeezing flow viscometry with parallel plates as a sensor.

Figure 1 clearly shows that if the sample is gently transferred to the bottom surface and the upper plate is slowly moved until it touches the sample, the sample will be subjected to very little damage and can be tested practically intact. An additional advantage of squeezing flow viscometry over coaxial or capillary methods is that it allows testing of foods that contain large particles, provided the particles are no larger than the final height of the specimen. Mustard with seeds and refried beans are examples of such foods, which were tested using lubricated squeezing flow viscometry.

For food materials that exhibit slippage, the use of squeezing flow viscometry with lubricated plates is a good alternative, because the existence of slip or self-lubrication is not only acknowledged, it is also incorporated in the calculation of the properties.

Hence, squeezing flow viscometry is a rheological technique based on either pure elongational flow or a mixed shear and elongational flow. If the food sample slips at the solid surfaces due to the presence of a lubricating layer, the kinematics of the test will be governed by an elongational flow. Conversely, if the material sticks to the surfaces, the presence of friction will induce a shear flow, which is analyzed considering a balance between the squeezing force and the forces that oppose the flow due to the sample shear viscosity.

-
-
-

Bibliography

Ak M.M. and Gunasekaran S. (1996). Evaluating rheological properties of mozzarella cheese by the squeezing flow method. *Journal of Texture Studies* **26**, 695-711. [This article presents an application of the lubricated squeezing method to evaluate the rheological properties of mozzarella cheese.]

Barnes H.A. and Walters K. (1985). The yield stress myth. *Rheologica Acta* **24**, 323-326. [This article discusses the existence of the rheological property known as yield stress.]

Bhattacharya S., Bhattacharya S., and Narasimha H.V. (1999). Uniaxial compressibility of blackgram doughs blended with cereal flours. *Journal of Texture Studies* **30**, 659-675. [This article describes the use of a compressive test to determine the rheological properties of dough products.]

Campanella O.H. (1987). Rheological Behavior of Semi-Liquid Foods. PhD Thesis. University of Massachusetts. [This thesis introduces the concept of squeezing flow viscometry to test the rheological properties of semi-liquid foods.]

Campanella O.H. and Peleg M. (1987). Squeezing flow viscometry of peanut butter. *Journal of Food Science* **52**, 180-184. [This article describes the application of lubricated squeezing flow to the determination of the rheological properties of a self-lubricated semi-liquid such as peanut putter.]

Campanella O.H. and Peleg M. (1987). Determination of the yield stress of semi-liquid foods from squeezing flow data. *Journal of Food Science* **52**, 214-217. [This article introduces the non-lubricated squeezing flow method under constant load to determine the yield stress of a variety of semi liquid food products.]

Campanella O.H., Popplewell L.M., Rosenau J.R., and Peleg, M. (1987). Elongational viscosity measurements of melting American process cheese. *Journal of Food Science* **52**, 1249-1251. [This article describes the use of lubricated squeezing flow to measure the rheological properties of melted American cheese.]

Casiraghi E.M., Bagley, E.B., and Christianson D.D. (1985). Behavior of mozzarella, cheddar and process cheese spread in lubricated and bonded uniaxial compression. *Journal of Texture Studies* **16**, 281-301. [This article is the first application of squeezing flow viscometry in food rheology.]

Chatraei S.H., Macosko C.W., and Winter H.H. (1981). Lubricated Squeezing Flow: a new biaxial extensional rheometer. *Journal of Rheolog* **25**, 433-443. [This articles introduces lubricated squeezing flow viscometry under constant load.]

Chen X.D. (1993). Slip and no-slip squeezing flow of liquid food in a wedge. *Rheologica Acta* **32**, 477-482. [This articles analyses squeezing flow in a wedge.]

Corradini M.G. and Peleg M. (2000). Lubricated squeezing flow viscosimetry for dulce de leche ("milk sweet"). *Food Science and Technology International* **6**, 339-344. [This article describes the application of lubricated squeezing flow to determine the rheological properties of a very viscous semi-liquid dessert].

Corradini, M.G., Stern V., Suwonsichon T., and Peleg, M. (2000). Squeezing flow of semi-liquid foods between parallel Teflon coated plates. *Rheologica Acta* **39**, 444-451. [This article introduces the use of Teflon coated plates to achieve a better lubrication and thus determine the elongational properties of semi-liquid foods.]

Corradini M.G., Engel R., and Peleg M. (2000). Assessment of the consistency loss in semi liquid foods by compression and shear. *Journal of Texture Studie* **31**, 363-379. [This article describes how the elongational properties of semi-liquid foods are modified by shear as determined by squeezing flow viscometry.]

Covey G.H. and Stanmore B.R. (1981). Use of the parallel plate plastometer for the characterization of viscous fluids with a yield stress. *Journal of Non-Newtonian Fluid Mechanics* **8**, 249-260. [This articles develops the main theoretical equations describing the flow of viscous fluid with yield stress.]

Damrau E. and Peleg M. (1997). Imperfect squeezing flow viscometry of Newtonian liquids. Theoretical and practical considerations. *Journal of Texture Studies* **28**, 187-204. [This paper describes the imperfect squeezing flow configuration.]

Dealy J.M. (1971). Extensional flow of Non-Newtonian fluids. A Review. *Polymer Engineering Science* **11**, 433-445. [This is a review article describing different types of extensional flows found in polymer processing. The kinematics of each flow is presented as well as a number of rheological constitutive equations.]

Hoffner B., Gerhards C., and Peleg M. (1997). Imperfect lubricated squeezing flow viscosimetry for foods. *Rheologica Acta* **36**, 686-693. [This article describes the application of imperfect squeezing flow configuration to test the properties of semi-liquid foods.]

Huang H. and Kokini J.J. (1993). Measurement of biaxial extensional viscosity of wheat flour dough. *Journal of Rheology* **37**, 879-891. [This article describes the application of squeezing flow viscometry to determine the elongational properties of dough.]

Hoffner B., Gerhards C., and Peleg M. (1998). A method to assess the ability of rough surfaces to eliminate slip in food viscosimetry. *Journal of Texture Studies* **29**,. 527-536. [This article describes methods to improve friction in squeezing flow viscometry so the test can be performed as non-lubricated squeezing flow.]

Hoffner B., Campanella O.H., Corradini M.G., and Peleg M. (2001). Squeezing flow of a highly viscous incompressible liquid pressed between slightly inclined lubricated plates. *Rheologica Acta* **40**, 289-295. [This article describes the effect of tilt on lubricated squeezing flow results.]

Kokini J. L. (1992). Rheological properties of foods. In *Handbook of food engineering* (eds. D.R. Heldman. and D.B. Lund). New York: Marcel Dekker. [This chapter describes rheological methods utilized to characterize food materials.]

Lee S.S. and Peleg M. (1992). Imperfect squeezing flow viscometry with a wide and a shallow container. *Journal of Texture Studies* **23**, 267-278. [This article gives the basic fundamentals to describe the imperfect squeezing flow test.]

Leider P.L. and Bird R.B. (1974). Squeezing flow between parallel plates. I. Theoretical analysis. *Industrial and Engineering Chemical Fundamentals*. **13**, 336-341. [This article introduces the fluid mechanics pertinent to the non-lubricated squeezing flow test under constant load and a power-law fluid.]

Leider P.L. and Bird E.B. (1974). Squeezing flow between parallel plates. II. Experimental results. *Industrial and Engineering Chemical Fundamentals* **13**, 342-346. [This article presents experimental results to validate a theoretical model describing non-lubricated squeezing flow of a power-law fluid].

Limanond B., Castell-Perez E., and Moreira R.G. (1999). Effect of time and storage conditions on the rheological properties of masa for corn tortillas. *Food Science and Technology-Lebensmittel-Wissenschaft & Technologie* **32**,344-348. [This article describes the application of the squeezing flow test to determine the rheological properties of dough.]

Lo T., Moreira R.G., and Castell-Perez E. (1999). Rheological properties of corn meal dough. *Food Science and Technology International* **5**, 59-65. [This article describes the application of the squeezing flow test to determine the rheological properties of corn products.]

Lorenzo M.A., Gerhards C., and Peleg M. (1997). Imperfect squeezing flow viscometry of selected tomato products. *Journal of Texture Studies* **28**, 543-567. [This article describes the application of imperfect lubricated squeezing flow to determine the rheological properties of tomato products.]

Ma L. and Barbosa-Cánovas G.V. (1995). Rheological characterization of mayonnaise. I. Slippage at different oil and xanthan gum concentrations. *Journal of Food Engineering* **25**, 397-408. [This article illustrates the presence of slippage during rheological testing of mayonnaise using a shear-based test.]

Meeten G.H. (2000). Yield stress of structured fluids measured by squeeze flow. *Rheologica Acta* **39**, 399-408. [This article introduces the measurement of yield stress of structured fluids by squeezing flow viscometry.]

Meeten G.H. (2001). Squeeze flow between plane and spherical surfaces. *Rheologica Acta* **40**, 279-288. [This article introduces the plate and lens squeezing flow configuration.]

Moskowitz H. R. Ed. (1988). *Applied Sensory Analysis of Foods*. Boca Raton: CRC Press. [This book introduces sensory methods to characterize the properties of foods.]

Ramirez-Wong B., Sweat V.E., Torres P.I., and Rooney L.W. (1996). Evaluation of the rheological properties of fresh corn masa using squeezing flow viscometry: Biaxial extensional viscosity. *Journal of Texture Studies* **27**, 185-198. [This article describes the application of lubricated squeezing flow to measure elongational properties of corn dough product.]

Rao M.A. (1999). *Rheology of Fluid and Semisolid Foods*. Gaithersburg, Maryland: Aspen Publishers, Inc. [This book describes rheological methods that use both shear and elongational flow to characterize foods.]

Sherwood J.D. and Durban D. (1996). Squeeze flow of a power law viscoplastic solid. *Journal of Non-Newtonian Fluid Mechanics* **62**, 35-45. [This article describes the application of squeezing flow viscometry to a power-law fluid with yield stress.]

Schowalter W.R. (1978). *Mechanics of Non-Newtonian Fluids*. New York: Pergamon Press. [This is a general book on rheology; it describes methods and models to characterize the rheology of complex fluid materials.]

Shukla A., Rizvi S.S.H., and Bartsch, J.A. (1995). Rheological characterization of butter using lubricated squeezing flow. *Journal of Texture Studies* **26**, 313-323.

Shukla A. and Rizvi S.S.H. (1997). Comparative evaluation of three fundamental techniques for measurement of butter rheology. *Milchwissenschaft-Milk Science International* **52**, 25-28. [This article compares the rheology of butter obtained by lubricated squeezing flow and other two rheological methods.]

Soskey P.R. and Winter H.H. (1985). Equibiaxial extension of two polymer melts. Polystyrene and low density polyethylene. *Journal of Rheology* **20**, 493-517. [This article describes a technique to achieve lubricated squeezing flow with a constant rate of strain.]

Steffe J.F. (1996). *Rheological Methods in Food Process Engineering*. 2nd Edition. East Lansing, MI: Freeman Press. [This book on food rheology describes rheological methods, using both shear and elongational flows to characterize foods.]

Suwonsichon T. and Peleg M. (1998). Imperfect squeezing flow viscosimetry of mustard with suspended particulates. *Journal of Food Engineering* **39**, 217-226. [This article describes the application of imperfect squeezing flow to characterize semi-liquid foods with particles.]

Suwonsichon T. and Peleg M. (1999). Imperfect squeezing flow viscosimetry for commercial refried beans. *Food Science and Technology International* **5**, 159-166. [This article describes the application of imperfect squeezing flow to characterize the rheological properties of semi-liquid foods with particles.]

Suwonsichon T. and Peleg M. (1999). Rheological characterization of ricotta cheeses by imperfect squeezing flow viscosimetry. *Journal of Texture Studies* **30**, 89-103. [This article describes the application of imperfect squeezing flow to the characterization of the rheological properties of semi-liquid foods with particles.]

Suwonsichon T. and Peleg M. (1999). Rheological characterization of almost intact and stirred yogurt by imperfect squeezing flow viscosimetry. *Journal of the Science of Food & Agriculture* **79**, 911-921. [This article describes the application of imperfect squeezing flow viscometry to characterize the properties of yogurt and how they are affected by shear.]

Wang Y.C., Muthukumarappan K., Ak M.M., and Gunasekaran S. (1998). A device for evaluating melt/flow characteristics of cheeses. *Journal of Texture Studies* **29**, 43-55. [This article describes the application of squeezing flow viscometry to evaluate the melting characteristics of cheeses.]

Wikstrom K. and Bohlin L. (1999). Extensional flow studies of wheat flour dough. II. Experimental method for measurements in constant extension rate squeezing flow and application to flours varying in breadmaking performance. *Journal of Cereal Science* **29**, 227-234. [This article describes the application for characterizing wheat flour dough.]

Wilson S.D.R. (1993). Squeezing flow of a Bingham material. *Journal of Non-Newtonian Fluid Mechanics* **47**, 211-219. [This article describes the squeezing flow of a material with yield stress.]

Wise G.M., Denn M.M., and Bell A.T. (2000). Surface mobility and slip of polybutadiene melts in shear flow. *Journal of Rheology* **44**, 549-567. [This article describes the slippage phenomenon observed during the testing of a polymeric material in shear flow.]

Yoshimura A.S. and Prud'homme R.K. (1988). Wall slip corrections for Couette and parallel disks viscometers. *Journal of Rheology* **32**, 53-67. [This article describes the corrections needed when testing materials that may exhibit slippage in shear-based viscometers.]

Biographical Sketches

Osvaldo H. Campanella is Associate Professor at Purdue University. He earned a B.S. degree in chemical engineering from the University of Buenos Aires, Argentina and a Ph.D. degree in food engineering from the University of Massachusetts. He was a senior lecturer in the Department of Food Technology, Massey University, New Zealand, from 1990 to 1998, where he taught and investigated the areas related to food engineering, rheology and extrusion. At Purdue University, Campanella has focused his research on computer-aided design of food processes and rheology. He is a member of the Whistler Carbohydrate Center at Purdue University.

Carlos M. Corvalan is Associate Professor in the School of Bioengineering at the University of Entre Rios, Argentina. In March 2000, he joined the Agricultural and Biological Engineering Department at Purdue University as a visiting scholar. He earned a B.S. degree in chemical engineering from the Argentina National University of Technology and a Ph.D. degree in chemical engineering from the University of Litoral, Argentina. His research interests include computational fluid dynamics of food and biological processes and free surface flows. He is a member of the Whistler Carbohydrate Center at Purdue University.