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Viscosity of blueberry and raspberry juices for processing applications

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Abstract

Rheological behavior of blueberry and red raspberry juice concentrates were studied with the objective of defining suitable mathematical models for use in evaporation and other processing procedures. The flow properties were determined for juice with solids content of up to 65° Brix and temperatures between 20 and 60 °C. The two juice products are predominantly Newtonian over the range of temperature and solids content studied. For a given solids content, raspberry juice showed a slightly higher activation energy than blueberry juice (for example, at 65° Brix the values are 41.2 and 39.1 kJ/mol, respectively). With juices containing 10% and 55% dissolved solids, flow instability (Taylor vortices) occurred in the concentric cylinder gap when shear rates reached $180\,s^{-1}$ and $1000\,s^{-1}$, respectively. Determination of laminar flow boundaries is important for accurate characterization of flow behavior of fluid foods for processing applications. The mathematical models obtained in this study would be useful for spot determination of juice viscosity during evaporation.

Keywords: Taylor vortices; Refractance window; Evaporation; Activation energy; Viscosity model

1. Introduction

Studies on the flow behavior of juices made from small fruits such as blueberry (*Vaccinium corymbosum*) and red raspberry (*Rubus idaeus*) are scarce. Information on the viscosity of these fruit juices as influenced by concentration and temperature is of particular importance to the design and operation of evaporation processes. For example, for improving the design of the Refractance Window® (RW) evaporation system in which fluids flow by forced circulation through pipes and by gravity over an inclined evaporation surface (Nindo, Tang, Powers, & Bolland, 2004), a good understanding of how the evaporation is influenced by viscosity at different concentrations and temperatures is required. With this mixed flow system, the viscosity of the products is needed to determine the heat transfer rates, energy consumption with increases in concentration, and for controlling the temperature and flow rates of heating media to ensure continuous flow of product. The flow behavior also influences the pump performance (Telis-Romero, Telis, & Yamashita, 1999); and for a newly developed food processing system like the Refractance Window® evaporator, it is important to document the influence of product flow properties on the system's overall capacity and energy usage. For evaporators in general, these performance indicators are necessary for equipment design, saving energy in subsequent operations and for reducing handling costs (Lau, 1991).

Blueberry and raspberry juices are becoming more attractive to consumers due to their high levels of antioxidants that promote human health. Blueberry juice

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with higher amounts of anthocyanins is healthful to humans. The way these juices are processed is critical if high levels of bioactive compounds are to be retained in the product (Skrede, Wrolstad, & Durst, 2000). Temperature, oxygen concentration and exposure to light must be controlled to minimize degradation of beneficial compounds. Blueberry juice preparation can be more difficult than other berry juices due to its high level of mucilaginous material. Cold press extracted juice has a light blue color and delicate flavor, while hot press enzyme treated juice has a deep purple-blue color and stronger flavor (Bates, Morris, & Crandall, 2001). As juice processing procedures are refined or redesigned to increase retention of components that were previously discarded with the press-cake, the flow behavior of the resulting juice product is bound to change with the altered composition.

While reviewing the rheological models of fluid food products, Holdsworth (1993) underscored the importance of accurate rheological data for calculation of volumetric flow rates, selection of pumps, determination of pressure drops for pipe sizing and power consumption for pumping systems, and for prediction of heat transfer coefficients for heating, evaporation and sterilization processes. At the time when the review by Holdsworth (1993) was published, only one study by Ibarz and Pagan (1987) on the rheological behavior of raspberry juice was available. There was none for blueberry juice. Later, Rao (1999) compiled rheological data for a number of fluid foods, which included those for raspberry and clarified black currant juices. The author stated that single strength juices and concentrated clear fruit juices generally exhibit Newtonian flow behavior or close to it, and that sugar content plays a major role in the magnitude of the viscosity and the effect of temperature on viscosity. Krokida, Maroulis, and Saravacos (2001) recently assembled additional data on rheological properties of fluid fruit and vegetable puree products. They stated that fruit and vegetable juices/concentrates are assumed to behave as non-Newtonian fluids, following the power law model. If fruit juices contain considerable amounts of pulps or are very concentrated, they may show an additional resistance to flow represented by a yield stress (Hernandez, Chen, Johnson, & Carter, 1995; Telis-Romero et al., 1999). The frequently used power law model has the form:

$$\tau = K\dot{\gamma}^n \tag{1}$$

where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), K is the consistency index (Pa s^n), which is the shear stress at a shear rate of 1.0 s^{-1}, and the exponent n, called the flow behavior index (–), reflects the closeness to Newtonian flow (Rao, 1999). When $n = 1$, the fluid is Newtonian and hence K becomes the viscosity η(Pa s). It is very important to know the values of the rheological parameters K and n, which once determined, can be used to show the influence of temperature and solids content (Saravacos & Maroulis, 2001). Krokida et al. (2001) indicated that an Arrhenius relationship (Eq. (2)) can be used to describe the effect of temperature and concentration on K values:

$$K = K_0 \exp\left(\frac{E_a}{RT} + BC\right) \tag{2}$$

where K_0 is the frequency factor (Pa s^n), E_a activation energy (kJ/mol), $R = 8.314$ kJ/mol K is the gas constant, T is temperature (K), C is solids content (%), and B is a constant. Ibarz and Pagan (1987) presented a combined model (Eq. (3)) for raspberry juice covering the concentration and temperature ranges between 15 and 41° Brix, and 5–60 °C, respectively. Eq. (3) was first used by Holdsworth (1971) for Newtonian fluid foods and the same model was later modified by Speers and Tung (1986) in their study of the flow behavior of xanthan gum dispersions.

$$K = K_0 \exp\left(\frac{E_a}{RT}\right), \quad \text{where } E_a = 37.9 \text{ kJ/mol} \tag{3}$$

and $K_0 = AC^b$; $A = 2.076 \times 10^{-15}$; C is concentration in %, and $b = 5.018$.

Cepeda, Hermosa, Llorens, and Villaran (2002) studied the rheology of freshly pressed, cloudy blueberry juice with 24.9–60.7% solids content. The activation energy obtained was from 4.6 to 24.0 kJ/mol. Commercial processing of berry juices usually includes a stage where the juice is treated with pectolytic enzymes to increase the yield. When berry juices are crushed without using these enzymes, the soluble pectin causes gelling of the mash before the juice can run off the press. Hence, the juice yield would be very low if a non-enzymatic process is adopted (Höhn, 1996). Depending on the efficiency of filtration and enzyme treatment processes, existence of residual particles in the juice can lead to complex flow patterns within the processing equipment. In the present study, commercial berry juice concentrates were used to study the flow behavior for applications in RW evaporation and other related fluid food heating processes (Nindo et al., 2004). During RW evaporation, the product temperature may rise to about 60 °C. This product temperature is dependent on heating medium temperature (usually 95–97 °C) and fluid flow rates. Compared to total solids concentration of 60–65° Brix that is attainable with existing commercial falling film evaporators, the Refractance Window evaporation process can achieve Brix levels similar to scrapped surface evaporators (up to 85° Brix was obtained in a preliminary experiment).

The objective of this research was to determine the rheological properties of blueberry and raspberry juices as representative small fruit products that can be processed in Refractance Window® or other evaporators over a wide range of temperatures and solids contents.

2. Materials and methods

2.1. Preparation of juice products

Commercial juice concentrates at 65° Brix, processed from cultivated varieties of Highbush blueberry (*Vaccinium corymbosum* L.) and red raspberry (*Rubus idaeus*), were used in the study. The blueberry juice concentrate (pH 2.55–2.80 and acidity 4.55–4.90% as citric) was obtained from Valley Processing Inc. (Sunnyside, WA) courtesy of Overlake Foods Corp. (Olympia, WA), while the raspberry juice concentrate (pH 3.0–3.3 and acidity 8.2–12.0% as citric) was supplied by Milne Fruit Products Inc. (Prosser, WA). The juice concentrates were diluted with de-ionized water to obtain Brix levels between 10% and 65% for the rheology experiments. The Brix number was measured using automatic temperature compensating type hand refractometers (Atago ATC-1E and ATC-2E for Brix ranges 0–32% and 28–62%, respectively). For the higher total solids content (65° Brix), the concentrates were diluted before taking the Brix reading. The Brix number of the concentrates was calculated from the dilution factor and the measured Brix of the diluted sample. Before conducting the tests, the prepared samples were stirred for about 2–3 min to ensure uniformity.

2.2. Measurement of rheological properties

Rheological measurements were carried out using AR2000 rheometer (TA Instruments, New Castle, DE) with commercial computer software (Rheology Advantage Analysis Software Version. 4.1, TA Instruments). The experiments were carried out in the controlled stress mode. A concentric cylinder geometry (stator inner radius 15 mm, rotor outer radius 14 mm, cylinder immersed height 42 mm, gap 5920 μm) was used to measure the viscosity of the juices at different dilutions. About 19 ml of juice was put into the stationary rheometer cup. The AR2000 is equipped with a Peltier plate for accurate control of temperature within the gap. Viscosity standards for low and high viscosity ranges, namely, S60 and S600 (Cannon Instrument Co., State College, PA), were used to calibrate the instrument before running the experiments with the juices. The viscosities of the juice products were measured at temperatures between 20 and 60 °C (±0.1 °C) since this is the range of temperature that the fluid products experienced in a previous evaporation study (Nindo et al., 2004).

Flow instabilities or Taylor vortices frequently occur during rheological tests with concentric cylinder geometries. Laminar flow is usually much more stable when the inner cylinder is stationary and the outer cylinder is rotating (Ferguson & Kemblowski, 1991; Steffe, 1996; Yim, Lo, Titchener-Hooker, & Shamlou, 1998). Ferguson and Kemblowski (1991) indicated that formation of Taylor vortices is possible only in fluids of low viscosity. However, for more concentrated viscoelastic fluids that are likely to show time-dependent behavior, a different type of instability may occur when the characteristic deformation time is of the same order of magnitude as the characteristic observation time. If this happens, the fluid loses its ability to respond to high rates of deformation. The instabilities occurring at low and high concentrations can lead to serious errors being reported if measurements are conducted over a wide range of shear rates. Therefore, the instrument was set to apply shear rates from 1 to 500 s^{-1} where secondary flows or Taylor vortices were not expected to develop for the juice concentrations studied (Steffe, 1996; Nickerson et al., 2003). Since most fluid foods are viscoelastic in nature, care was taken during the tests to eliminate any time-dependent behavior by pre-shearing the samples at 100 s^{-1} for 10 min (Cepeda et al., 2002). Prior to this the rheometer was calibrated following the procedure outlined by the manufacturer to ensure that measurements were made within the linear viscoelastic range.

3. Results and discussion

3.1. Effect of flow instabilities on viscosity measurement

Figs. 1 and 2 show the viscosity versus shear rate curves for blueberry and raspberry juice with 10% solids content at temperatures between 20 and 60 °C. The rheometer used in this study has torque sensitivity of between 0.1 and 200 m Nm. When we plotted flow data corresponding to shear rates below 10 s^{-1} for low viscosity juices, there was much scatter. Therefore, for juice with less 10% solids, shear rate readings below 10 s^{-1} (corresponding to the lower torque limit) were considered as artifacts. At low solids concentration, it was consistently observed that viscosity of the juices starts to increase after reaching a certain shear rate (Figs. 1 and

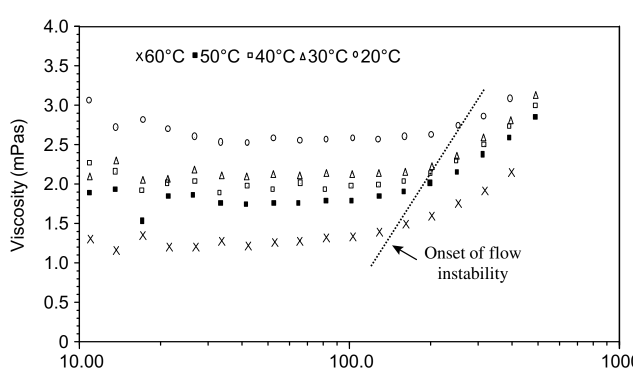

Fig. 1. Viscosity of 10° Brix blueberry juice showing onset of flow instabilities with increasing temperature.

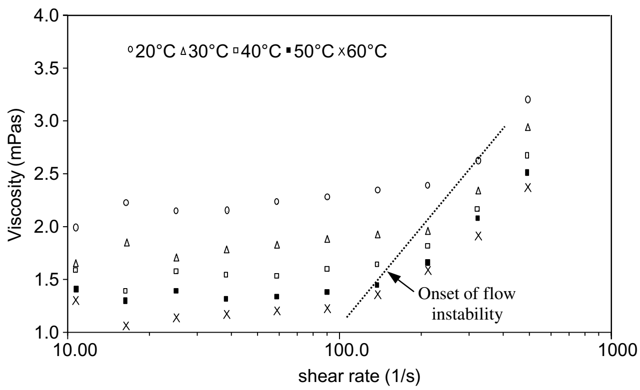

Fig. 2. Viscosity of 10° Brix raspberry juice showing onset of flow instabilities with increasing temperature.

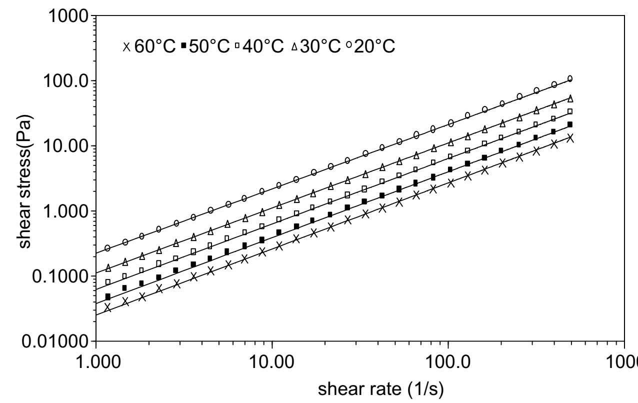

Fig. 4. Shear stress versus shear rate curves for 65° Brix raspberry juice.

2). At higher solids content, apparent deviations in the flow pattern were not observed (Figs. 3 and 4). Previous studies on the rheology of raspberry juice (Ibarz & Pagan, 1987) and cloudy blueberry juice (Cepeda et al., 2002) did not show any shear-thickening behavior that may explain the observed deviation in flow and viscosity. The influence of concentration-dependent flow instabilities (Taylor vortices) in the narrow gap of the concentric cylinder measuring system is considered a possible explanation for the observed deviations at higher shear rates.

In a concentric cylinder geometry, increased flow resistance can occur due to hydrodynamic instabilities which lead to secondary flow effects and even to turbulent flow behavior with vortices at high shear rates (Mezger, 2002). Both flow and viscosity curves show higher slopes compared to what would be expected at laminar flow conditions and, therefore, at first glance, may give the impression of shear thickening behavior as shown by the viscosity values corresponding to shear rates greater than $100\,\mathrm{s}^{-1}$ (Figs. 1 and 2). The stability criterion for the critical angular velocity ω_c where Taylor vortices occur in the narrow gap of concentric cylinder geometry is given by (Ferguson & Kemblowski, 1991; Steffe, 1996):

$$\frac{\omega_c R_i^2 (\delta_{cc} - 1)^{1.5} \rho}{\eta} \geqslant 41.2 \tag{4}$$

where ρ is juice density, η is its viscosity, R_i radius of inner rotating cylinder, R_0 is radius of cup, and $\delta_{cc} = R_0/R_i$. The left side of the expression is the Taylor Number, Ta. For the AR2000 concentric cylinder geometry used in this study, $R_0 = 15\,\mathrm{mm}$ and $R_i = 14\,\mathrm{mm}$. It is noted that DIN 53019 standard for the determination of viscosities and flow curves using standard design rotary viscometers with a standard geometry measuring system gives the ratio δ_{cc} for this particular geometry as 1.0847, and not the absolute values of cylinder and cup radii. Smaller gaps are necessary to ensure that deformation and velocity gradient are constant throughout the gap. Taylor vortex flow will occur in the fluid under test when Ta is greater than 41.2 (Mezger, 2002; Walkenström et al., 1999). From the literature on juice density (Rao & Vitali, 1999; Cepeda et al., 2002; Ramos & Ibarz, 1998), the Taylor number was calculated and the critical shear rate ($\dot{\gamma}_c$) determined from the stability criterion (Eq. (4)). Taking the DIN 53019 standard for $\delta_{cc} \leqslant 1.2$, the critical shear rate $\dot{\gamma}_c$ was determined [i.e. $\dot{\gamma}_c = 12.33 \times \omega_c$]. This critical shear rate is a function of solids content and temperature, changing positively with ° Brix and inversely with juice temperature. For the 10° Brix blueberry juice at 60 °C, Taylor vortices are likely to occur after a shear rate of $180\,\mathrm{s}^{-1}$ is reached (Fig. 5). At 20 °C, the critical shear rate increases to about $350\,\mathrm{s}^{-1}$. The corresponding limit at 60 °C at a higher concentration (55° Brix) is $1000\,\mathrm{s}^{-1}$, almost six times the shear rate at 10° Brix (Fig. 6). Vortex development was not observed in the juices with 65% solids content. The actual viscosity curves in Figs. 1 and 2 indicate early onset of instabilities compared to the predictions. The possible explanation for this may be because of gradual transition from laminar to turbulent conditions

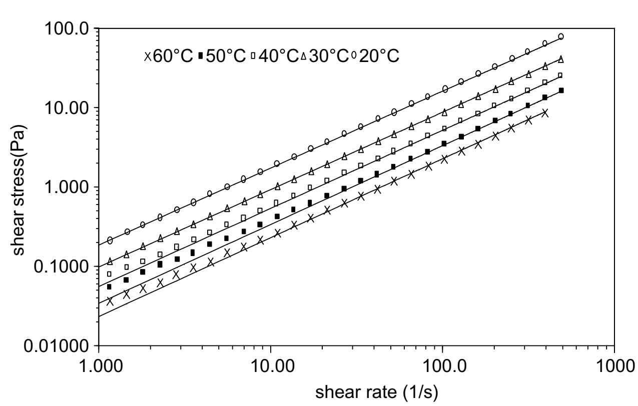

Fig. 3. Shear stress versus shear rate curves for 65° Brix blueberry juice.

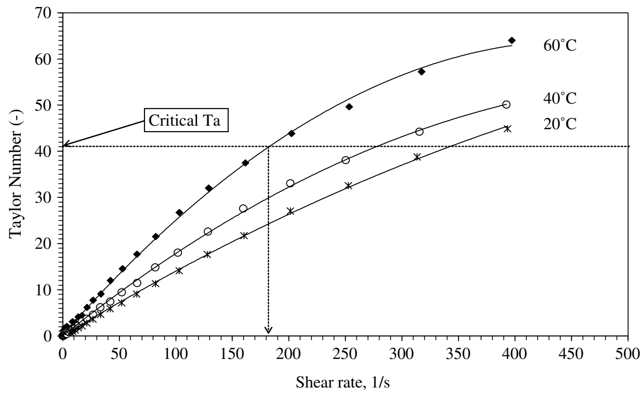

Fig. 5. Taylor Number (*Ta*) versus shear rate for 10° Brix blueberry juice.

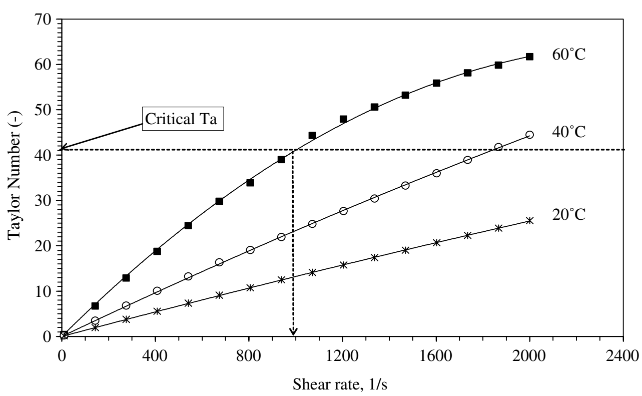

Fig. 6. Taylor Number (*Ta*) versus shear rate for 55° Brix blueberry juice.

in the gap. Therefore, for juice with more than 10% solids content and at temperatures up to 60 °C, it is unlikely that errors would occur due to hydrodynamic instabilities in the narrow gap. Therefore, when conducting rheological tests using the concentric cylinder geometry, it is important to define the laminar flow boundary and ensure that measurements are taken where Taylor vortices would not compromise the usefulness of data collected. The viscosity data for all samples were collected below the shear rate corresponding to the *Ta* value of 41.2.

3.2. Comparison of viscosities of blueberry and raspberry juices

The flow and viscosity curves appeared much closer together at lower solids content than at a higher Brix number (65° Brix) for the juice temperatures (20–60 °C) used in the study, indicating a greater influence of concentration on viscosity (Figs. 7 and 8). As solids content increases from 10% to 65% at a constant temperature of 20 °C, the viscosity of red raspberry juice increased from 1.8 to 224.0 mPa s compared to that of

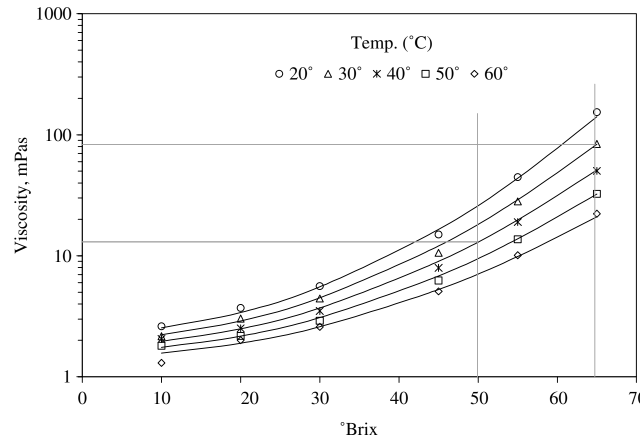

Fig. 7. Measured data and prediction curves (continuous lines) for blueberry juice viscosity. Scattered data are means of three replicates.

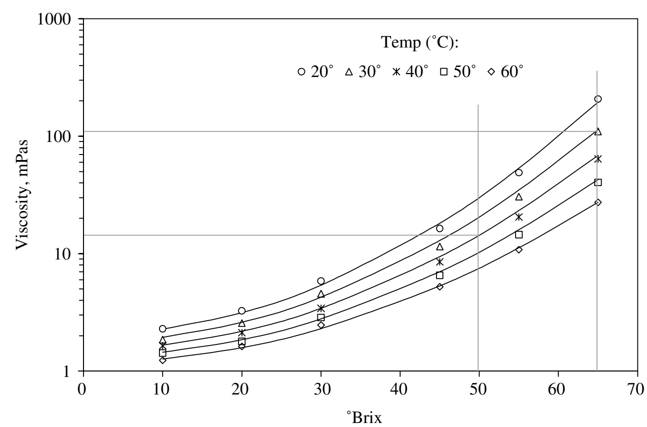

Fig. 8. Measured data and prediction curves (continuous lines) for raspberry juice viscosity. Scattered data are means of three replicates.

blueberry juice which increased from 2.9 to 184.0 mPa s. A 10° change in temperature at higher solids contents (for example, from 50° to 65° Brix) caused a 99.2 mPa s change in the viscosity of raspberry juice compared to 70 mPa s for blueberry juice. The sugar composition and processing procedures for the two juices are likely factors that can explain the differences in rheological properties. Whereas glucose and fructose are present in almost equal proportion in the two berries (Mathews, Pehrsson, & Farhat-Sabat, 1987; USDA, 2003), red raspberry (*Rubus idaeus*) juice contains more sucrose and total sugars than blueberry (*Vaccinium corymbosum*) juice (Table 2). Solute type, size, shape, and state of hydration all have an effect on viscosity (Fennema, 1996). Chirife and Buera (1997) showed that sucrose, with a higher molecular weight than either glucose or fructose, has a higher viscosity for a solution of the same concentration. Since raspberry juice contains more sucrose than blueberry juice, it was observed that for the same solids content and temperature, raspberry juice became more viscous at higher concentrations than

Table 1
Flow behavior index (n) for blueberry and raspberry juices at 10°, 30° and 65° Brix

Temp. (°C)	Blueberry juice			Raspberry juice		
	10° Brix	30° Brix	65° Brix	10° Brix	30° Brix	65° Brix
20	0.97	1.02	0.97	1.05	1.04	0.99
30	1.00	1.03	0.98	1.06	1.05	1.00
40	0.99	1.03	0.99	1.04	1.06	1.01
50	1.03	1.04	0.99	1.01	1.06	1.01
60	1.05	1.04	0.99	1.04	1.07	1.02
Mean	1.01 ± 0.02	1.03 ± 0.01	0.98 ± 0.01	1.04 ± 0.01	1.05 ± 0.01	1.00 ± 0.01

Table 2
Sugar composition per 100 g of fresh blueberry and raspberry juice

	Moisture content (%)	Glucose	Fructose	Sucrose	Maltose	Total sugars
Blueberries	85.6	3.1	4.1	0.4	0.5	7.9
Raspberries	86.6	3.5	3.2	2.8	–	9.5

Source: Mathews et al., 1987; USDA, 2003.

blueberry juice. Apart from the differences in sugar contents, suspended particles remaining in the juice after depectinization and filtration processes may influence the viscosity of the juices (Hernandez et al., 1995). During evaporation, raspberry juice will become more viscous faster than blueberry juice. Therefore, the concentrate can be kept flowing through evaporators by a slight increase in temperature to avoid clogging of flow channels and pipes.

3.3. Viscosity models for the two berry juices

Starting with the assumption that the rheological behavior of the berry juices follows the power law, the parameters K and n were calculated for each concentration and temperature. Typical values of n for the two juices at 10°, 30°, and 65° Brix and at temperatures between 20 and 60 °C are shown in Table 1. The flow behavior index n is between 0.98 and 1.03 for blueberry juices, and 1.00–1.05 for raspberry juice. Therefore, for the two juices, n is nearly 1 at both low and high solids content (Table 1). This shows that for the temperature, concentration, and shear rate conditions studied, the two juices have similar rheological behavior. When the viscosities of the two juices are compared at the same temperature and solids content as illustrated in Figs. 7 and 8, the rheological similarity is again evident in the plot of such data (Fig. 9). We conclude that both blueberry and raspberry juices are predominantly Newtonian in nature, and the K-parameter in Eq. (1) then refers to juice viscosity η(Pa s).

Shear stress versus shear rate data for both blueberry and raspberry juices were modeled by expressing the viscosity η_0 as an exponential function of solids concentration. The model form is similar to those reported by

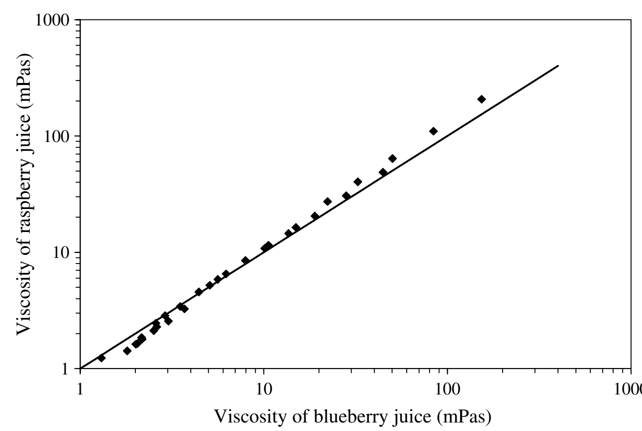

Fig. 9. Raspberry and blueberry juice viscosities at same temperature and solids content.

Cepeda et al. (2002); Krokida et al. (2001) and Rao (1999). However, the activation energy E_a is now uniquely expressed as a function of juice concentration. Eqs. (5) and (7) show the influence of solids content (10–65° Brix) and temperatures from 20 to 60 °C on viscosity of blueberry juice:

$$\eta_0 = 0.056\exp(-0.0019C^2)\ (\text{mPa s}), \quad R^2 = 0.991 \tag{5}$$

$$E_a = 0.007C^2 + 9.055\ \text{kJ/mol K}, \quad R^2 = 0.994 \tag{6}$$

Hence,

$$\eta = 0.056\exp\left\{\frac{[7C^2 + 9055]}{8.314 \times T} - 0.0019C^2\right\}\ (\text{mPa s}) \tag{7}$$

The corresponding relationships for raspberry juice within the same range of solids content and temperature are:

$$\eta_0 = 0.0206\exp(-0.0017C^2)\ (\text{mPa s}),\quad R^2 = 0.980 \tag{8}$$

$$E_a = 0.0068C^2 + 11.196\ \ \text{kJ/mol K},\quad R^2 = 0.990 \tag{9}$$

Hence,

$$\eta = 0.0206\exp\left\{\frac{[6.8C^2 + 11196]}{8.314\times T} - 0.0017C^2\right\}\ (\text{mPa s}) \tag{10}$$

Eqs. (6) and (9) indicate the influence of Brix on activation energy for the two fruit juice concentrates. As the solids content increased from 10° to 65° Brix, the activation energy for blueberry juice increased from 9.14 to 39.15 kJ/mol; while that of raspberry juice increased from 12.2 to 41.2 kJ/mol. Therefore, at a given solids content the activation energy of raspberry juice is slightly higher than that of blueberry juice. Krokida et al. (2001) reported that the energy of activation (E_a) in Newtonian fluid foods increases from 14.4 kJ/mol for water to more than 60 kJ/mol for concentrated clear juices and sugar solutions. The results we have obtained for blueberry and raspberry juices are within the range of activation energy values reported by Krokida et al. (2001). These equations would be suitable for predicting the rheological properties of these juices over a wider range of solids content.

The fitting of the of the mathematical models to the measured data was very good, with R^2 values of more 0.90. Recently, Bui and Nguyen (2004) reported an exponential model of the same form for viscosity of glucose as a function of temperature and mole fraction of the solute. Ibarz and Pagan (1987) also used an exponential relationship to explain the rheology of raspberry juice. However, explicit models showing the variation of activation energy with Brix number for blueberry and raspberry juice has not been presented before. The models relating the viscosity and activation energy to percent solids have been combined into a global model for predicting the viscosity of the juices (Eqs. (7) and (10)). As evidenced by the steep rise in the curves of viscosity versus solids content (Figs. 7 and 8), the percent dissolved solids (C) has stronger influence on viscosity of the two juices when compared to temperature change (Figs. 10 and 11).

Statistical correlation curves between the predicted and measured viscosity for blueberry and raspberry juices show a reasonable agreement, with R^2-values of nearly 1 (Fig. 12). Therefore, the mathematical models obtained would be very useful for fast determination of berry juice viscosity during evaporation. As a unit operation in food processing, evaporation is usually a vital step for improving the energy efficiency of a subsequent process such as drying. This is particularly relevant in the Refractance Window® drying process

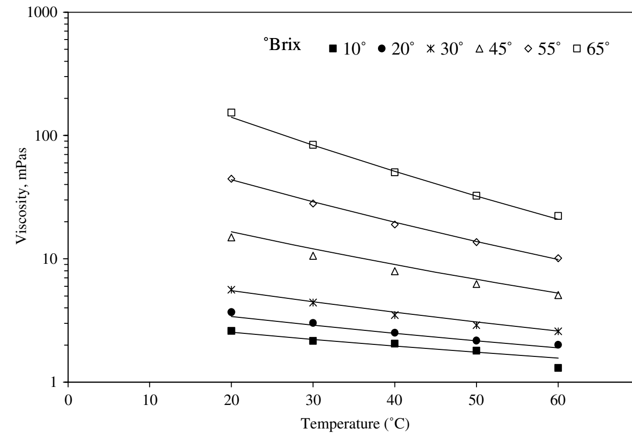

Fig. 10. Viscosity model curves for blueberry juice as a function of temperature.

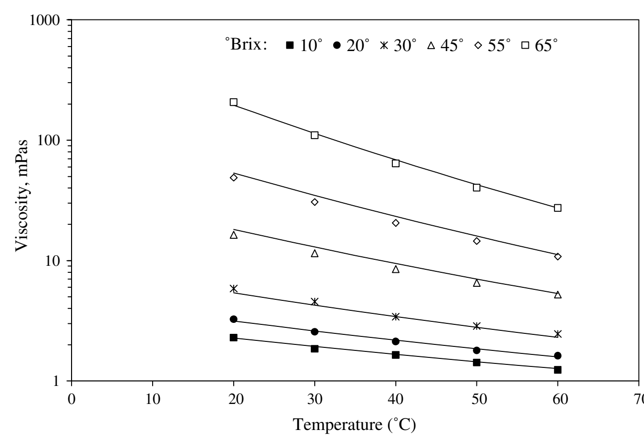

Fig. 11. Viscosity model curves for raspberry juice as a function of temperature.

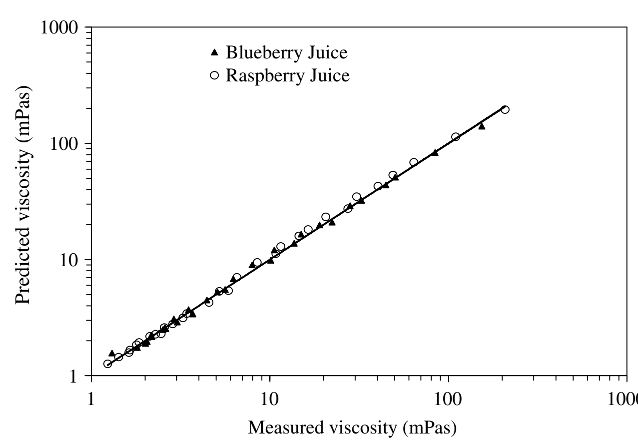

Fig. 12. Predicted versus measured viscosity of blueberry and raspberry juices.

where the consistency of dried product and energy efficiency would be greatly improved if the starting fluid product has the right viscosity and solids content.

4. Conclusions

Mathematical models that are suitable for describing the rheological behavior of blueberry and raspberry juices in terms of solids content and temperature are presented. Juice rheological properties are determined for solids contents up to 65° Brix and temperatures between 20 and 60 °C. Though significant overlap of rheological properties of the two juices was noted, raspberry juice showed a slightly higher activation energy at a given solids content. At the highest solids content studied (65° Brix), the activation energy of blueberry and raspberry juices was 39.1 and 41.2 kJ/mol, respectively. While the two berry juices showed a predominantly Newtonian behavior over the range of temperature and solids content studied, raspberry juice had slightly higher viscosity than blueberry juice at high solids content. At 60 °C, Taylor vortices started to occur when the shear rate in 10° Brix juice reached $180\,s^{-1}$, increasing to $1000\,s^{-1}$ for 55° Brix. Reporting of such laminar flow boundaries for different measuring geometries is important for accurate characterization of flow behavior of fluid foods. The mathematical models obtained would be useful for one spot determining of juice viscosity during evaporation and processing of other related fluid foods.

Acknowledgments

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