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Rheological properties of blueberry puree for processing applications

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Abstract

Rheological properties of purées made from small fruits like blueberries are important for application in handling and thermal processing where their physical and/or chemical attributes can be altered. Flow of purées made from highbush blueberry (*Vaccinium corymbosum* L.) was investigated in the 10–1000 s^{-1} shear rate range with the objective of determining the influence of temperature and solids content on the rheological properties. The rheological behavior was well described by the three-parameter Sisko model. The activation energy of flow (E_a) calculated with respect to apparent viscosity at 100 s^{-1} increased from 11.4 to 17.1 kJ/mol for purée with 10% and 25% total soluble solids, respectively. When evaluated in terms of consistency coefficient, the activation energy varied between 10.7 and 21.7 kJ/mol within the same range of solid contents. For the conditions investigated, a mathematical model that is suitable for describing the influence of temperature and dissolved solids on the apparent viscosity of blueberry purée was obtained. The rheological behavior of 10–20 Brix blueberry purée was well predicted ($R^2 = 0.99$). Further investigation is needed to improve the model to cover a wider Brix range.

Keywords: Evaporation; Refractance Window; Activation energy; Viscosity model

1. Introduction

Highbush blueberry (*Vaccinium corymbosum* L.) is one of the most important small fruits grown in the Pacific Northwest region of the USA. Blueberries have become very popular with consumers because of research findings that link their consumption with improvements in human health. They are one of the richest sources of antioxidant phytonutrients, containing about three times the total phenolic compounds found in red raspberry (Kalt, Forney, Martin, & Prior, 1999). Therefore, to minimize the loss of physical and chemical quality attributes of purées and juices made from blueberries, careful design of equipment for processing and handling is necessary. Although most blueberry fruits are marketed fresh, substantial quantities are processed into purées or juice to add value, extend shelf-life, and make the processed products available to consumers all year round. Typical methods for processing berries for jam and juice can affect their overall quality, including content and activity of health promoting polyphenol compounds (Skrede, Wrolsted, & Durst, 2000). Application of heat over extended periods of time coupled with continual churning during pumping can cause irreversible structural breakdown of fluid foods and make them unappealing to consumers even if the bioactive compounds may not have been affected. Therefore, besides the previously studied flow properties of blueberry juice (Nindo, Tang, Powers, & Singh, 2005), it is important to understand the rheological behavior of blueberry purées, especially for processing and handling applications involving pumping and mixing.

The effect of solid concentration on viscosity has been studied by sampling products during evaporation (Hernandez, Chen, Johnson, & Carter, 1995), dilution of the purées with de-ionized water (Perona, 2003), or by addition of glucose (Guerrero & Alzamora, 1998). The apple and pear purées investigated by Perona (2003) tended to breakdown easily during flow in pipes, particularly when flow pattern changed from laminar to turbulent. Handling

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equipment and processing conditions for concentrating fruit purées need careful selection to avoid the damage that may arise from flow transitions, application of heat, or high shear stresses (De Kee, Code, & Turcotte, 1983; Nindo et al., 2005).

New methods of handling and processing fluid foods are constantly being studied in order to improve energy efficiency and product quality. One such technology is Refractance Window® evaporation that uses a unique method to deliver thermal energy to concentrate liquid foods. In this process, a dilute liquid product with or without suspended particles can be concentrated to high solid contents by passing the product over an inclined flat plastic film heated on other side by hot water (Nindo, Tang, Powers, & Bolland, 2004). Rheological properties of fruit purées processed by this and other related methods are of considerable interest for design improvements and control of product quality. The determined rheological parameters are a powerful tool in understanding changes in food structure during processing (Guerrero & Alzamora, 1998; Holdsworth, 1993; Mizrahi, 1979). Concentration of dissolved solids, particle size distribution and shape, and mode of interaction of suspended particles can have remarkable effect on the flow behavior of fruit purées (Ditchfield, Tadini, Singh, & Toledo, 2004; Guerrero & Alzamora, 1997; Mizrahi, 1979).

Considering the consumer demand for processed foods with high quality, there is a need to define changes in rheological properties of foods in processing operations that may affect their overall acceptability. The objective of this study was to determine the rheological behavior of blueberry purée as affected by total dissolved solids and temperature, with particular reference to conditions during Refractance Window® evaporation. The models developed would be useful in the handling and evaporation of blueberry and other purées with similar rheological properties through simple measurement of Brix and product temperature.

2. Materials and methods

2.1. Sample preparation

Blueberry purée used in the study contained about 28% total dissolved soluble solids and was supplied by Overlake Foods Inc. (Olympia, WA). The purée was diluted with appropriate amounts of de-ionized water to obtain four standardized batches with 25, 20, 15 and 10 g of dissolved solids per 100 g of sample. The diluted samples were adequately mixed using a magnetic stirrer to achieve uniform consistency before loading into the rheometer.

2.2. Rheological measurements

Rheological measurements were carried out using an AR2000 rheometer (TA Instruments, New Castle, DE) controlled with commercial computer software (Rheology Advantage Data Analysis Software v4.1.2, TA Instruments, New Castle, DE). The experiments were carried out in the controlled stress mode using a concentric cylinder geometry consisting of a rotating inner cylinder with an outer radius of 14 and 42 mm immersed height. The outer stationary cup had an inner radius of 15 mm giving a gap of 1.0 mm. The concentric cylinder fixture was preferred over the cone and plate setup because the pulp in the purée tends to separate easily when tested with the latter configuration. The instrument was calibrated with standard oil # S60 (Cannon Instruments Co., State College, PA) following the procedure recommended by the manufacturer. Viscosity of blueberry purées with 10%, 15%, 20% and 25% total soluble solids was measured at 25, 40, 50 and 60 °C (±0.1 °C). This temperature range was chosen for investigation because fluid foods experience similar temperatures during processing in the newly developed Refractance Window® evaporator that we used as a model system. The data obtained are expected to be equally applicable to other unit operations such as mixing, filling, and emptying that usually take place near these temperatures. Three experimental replications were conducted for each Brix number, and every time a new sample was loaded into the measuring cylinder system. A $100\,\mathrm{s}^{-1}$ conditioning step that lasted 2 min was applied to the purée. The instrument was programmed to allow equilibration of the sample to a set temperature before starting the data collection. During pumping, in-pipe flow, mixing and stirring of liquid-like foods, shear rates in the range of $10\text{–}1000\,\mathrm{s}^{-1}$ may be experienced. Therefore, rheological experiments should preferably be done within the shear rate range that encompasses most applications (Steffe, 1996).

3. Selection of rheology models

The choice of an appropriate model to relate product viscosity to Brix number and shear rate depends essentially on the intended application and use of a suitable instrument to determine the model parameters. During experiments, laminar flow conditions are necessary for accurate measurements; and for fruit purées containing particles with nonuniform sizes and shapes, stability may sometimes be difficult to achieve at either very low or high shear rates. At high shear rates, turbulent flow conditions are likely to be induced by the dispersed particles, resulting in structural breakdown of the sample. Even with these complexities, most purées generally exhibit non-Newtonian flow patterns. Therefore, the non-Newtonian models in Eqs. (1)–(3) were considered for their suitability in describing the flow of blueberry purées.

The Ostwald de Waelle model, commonly referred to as the Power Law model [Eq. (1)], has been used extensively in studies on handling and heating/cooling of foods because it gives good description of fluid flow behavior in the shear rate range that is easily measured by most rheological instruments. However, it exhibits poor fitting for data obtained at a wide range of shear rates. This model is in the form

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

where σ (Pa) is shear stress, K (Pa s^n) is consistency index, $\dot{\gamma}$ is shear rate (s^{-1}) and n is the dimensionless flow behavior index. Most fruit purées show shear-thinning behavior ($0<n<1$), a situation that may be regarded as an indication of breakdown of structural units in a food due to the hydrodynamic forces generated during shear (Rao, 1999). Quantification of flow parameters within some defined shear rate ranges may be a good way of studying these changes in product structure. If the foodstuff has a finite yield stress, the yield term can be included in the Power Law model to yield the Herschel-Bulkley (HB) model:

$$\sigma = \sigma_0 + K_{\mathrm{H}}(\dot{\gamma})^{n_{\mathrm{H}}}, \tag{2a}$$

where σ is shear stress (Pa), σ_0 is yield stress (Pa), K_{H} is consistency index (Pa $s^{n_{\mathrm{H}}}$), $\dot{\gamma}$ is shear rate (s^{-1}), and n_{H} is a dimensionless flow behavior index. The yield stress can be determined experimentally, graphically as explained by Steffe (1996), or calculated by a separate model. The Casson model [Eq. (2b)] gives the yield stress (as square of the intercept, $K_{0\mathrm{c}}$) when the square roots of σ and $\dot{\gamma}$ are plotted against each other on linear coordinates (Rao, 1999):

$$\sigma^{0.5} = K_{0\mathrm{c}} + K_{\mathrm{c}}(\dot{\gamma})^{0.5}. \tag{2b}$$

The HB model is convenient because Newtonian, Power law and Bingham Fluids can be considered as special cases obeying this generalized model (Ditchfield et al., 2004). However, the yield stress obtained by fitting the three-parameter HB model is strongly dependent on the selected shear rate range (Steffe, 1996).

For high shear rates, the three-parameter Sisko model, which explicitly relates the apparent viscosity with shear rate, has been used (Holdsworth, 1993; Rao, 1999). It gives the infinite-shear rate viscosity η_∞, consistency coefficient K_{s}, and flow behavior index n_{s} for shear-thinning fluid (when $n<1$):

$$\eta_{\mathrm{a}} = \eta_\infty + K_{\mathrm{s}}\dot{\gamma}^{n_{\mathrm{s}}-1}, \tag{3}$$

where $\eta_{\mathrm{a}} = (\sigma/\dot{\gamma})$ is the apparent viscosity (Pa s).

This model may be applied to pumping of fluid foods and mixing processes involving high shear rates. The Sisko model can be considered as a generalized Power Law model that includes a Newtonian component. A fluid that obeys the Sisko model will approach Newtonian behavior if either $n_{\mathrm{s}} = 1$ or $K_{\mathrm{s}} = 0$. Since fruit purée is made up of serum (which is usually more Newtonian) and particles of various sizes and shapes dispersed within it, then the pulp with associated pectin may be the component contributing to nonNewtonian behavior (Hernandez et al., 1995).

The following standard error (SE) formula was used to determine how good the models fit the data:

$$\mathrm{SE} = \left(\frac{\sum(y_{\mathrm{m}} - y_{\mathrm{c}})^2}{n-1}\right)^{1/2}, \tag{4a}$$

where y_{m} is the measured value, y_{c} is calculated value for each data point, and n is the number of observations. The bias factor (B_{f}) formula in Eq. (4b) was used to further evaluate the overall agreement between predicted and observed values, and whether such predictions lie above or below the line of equivalence. A perfect agreement between observed and predicted values would give a B_{f} of 1.0 (Betts & Walker, 2004):

$$B_{\mathrm{f}} = 10^{\left[\sum \log(y_{\mathrm{c}}/y_{\mathrm{m}})/n\right]}. \tag{4b}$$

Based on statistical evaluation and overall suitability of the models considered, the Sisko model was selected to describe the rheological behavior of blueberry purées.

4. Results and discussion

4.1. Comparison of selected rheological models

Shear stress and shear rate data were collected for blueberry purée with 10, 15, 20 and 25 g of dissolved solids per 100 g of sample at temperatures between 25 and 60 °C. The three models, namely, Power Law [Eq. (1)], HB [Eq. (2), and Sisko [Eq. (3)] were used to fit the measured data to determine the one that best described the flow behavior of blueberry purée over the studied temperature and concentration ranges. The most appropriate mathematical model for describing the flow characteristics of blueberry purées was selected based on the coefficient of determination (R^2), SEs, the existence of yield stress, and overall bias factors obtained by fitting the measured viscosity data using Eqs. (1)–(3). Even though the R^2 values for the three models are all close to one when the apparent viscosity is fitted for all combinations of Brix number and temperature treatments, the SE tabulation and bias factor curves show that HB and Sisko models perform better than the Power Law model (Figs. 1(a) and (b)). The flow curves for blueberry purée all showed yield stress, indicating that the Power Law model is not suitable for describing their rheological behavior. The inadequacy of the Power Law model to describe the rheological behavior of these purées is further shown by the much lower bias factor at low dissolved solids concentration (10 Brix) where flow instabilities are likely and be more pronounced (Nindo et al., 2005).

4.2. Effect of temperature and solids content on yield stress (σ_0)

Representative curves of shear stress versus shear rate for blueberry purée at 25–60 °C and 10–25 Brix all indicate shear-thinning behavior (Figs. 2(a)–(d)). The continuous

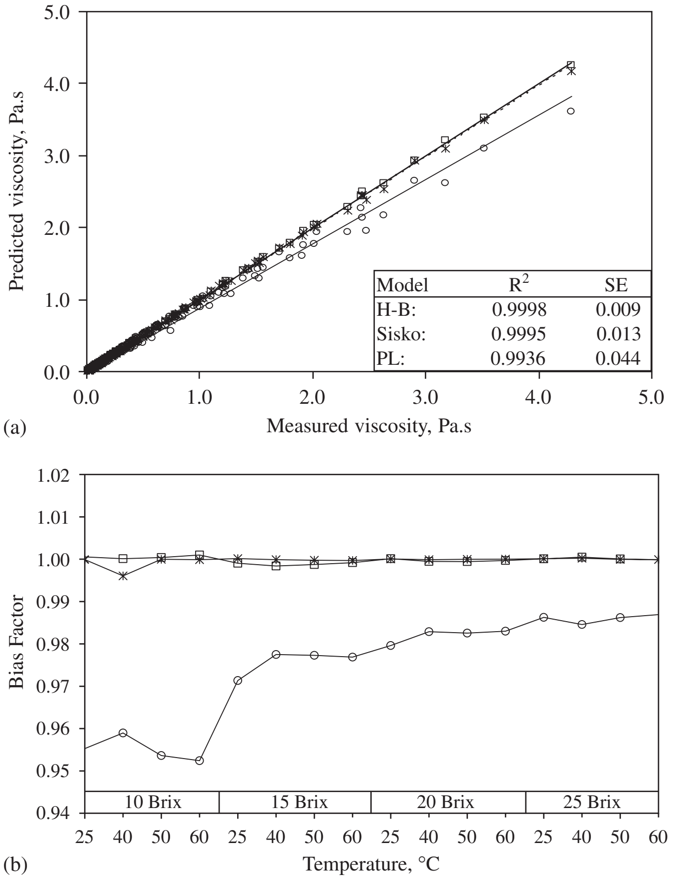

Fig. 1. (a) Comparison of HB (□), Sisko (✻), and Power Law (○) models for predicting the viscosity of blueberry purée. (b) Bias factor comparison of HB (□), Sisko (✻), and Power Law (○) models.

curves in these figures represent the Sisko model fitted to the measured data. For the 0–1000 s^{-1} shear rate range investigated, the maximum shear stress imposed on the blueberry purée at 25 °C increased from about 12 Pa for 10 Brix to almost 165 Pa for the 25 Brix. For all the concentrations of solids investigated, there is also evidence of finite yield stress (σ_0), which can be estimated at flow conditions with the shear rate close to zero (that is, as viscosity approaches infinity in the case a shear-thinning fluid). The blueberry juices investigated previously did not show any detectable yield stress (Nindo et al., 2005).

Mizrahi (1979) observed that fruit purées are frequently classified erroneously as shear thinning with zero yield stress purely from observations made when a straight line results from the fitting of shear stress versus shear rate data on log–log coordinates. Apart from the HB model, the other model that has been used to obtain the yield stress is the Casson model which produces a straight line when the square root of shear rate is plotted against the square root of shear stress (Rao, 1999). Table 1 shows yield stress values obtained when the HB and Casson models were fitted to the measured data. In all cases, yield stress decreases with temperature. As demonstrated by Steffe (1996) and Mizrahi (1979), the yield stress values are strongly dependent on the shear rate range, type of model, and shape and size of particles forming the purées. The dependency of σ_0 on model type is noticeable from values calculated using the HB and Casson models, both of which indicate that σ_0 increased with solids content (Table 1). The yield stress σ_0 versus concentration of dissolved solids generally followed an exponential relationship with R^2 values between 0.960 and 0.998, while there appears to be no simple mathematical expression that can describe the temperature dependence of yield stress. This was not the case with the infinite-shear rate viscosity η_∞ in the Sisko model which fitted the data well over the entire range of solids content and temperatures investigated.

Plotting apparent viscosities versus shear stress and noting the shear stress value at infinite viscosity is a good alternative if σ_0 is not obtained experimentally (Steffe, 1996). The infinite viscosity corresponds to zero-shear rate. This method is illustrated in Figs. 3(a) and (b) for 10 and 25 Brix purées at different temperatures. Although the extrapolation method merely gives an approximation of the yield stress, it provides a means of knowing the influence of solids and temperature on the shear stress that must be overcome before the purée starts to flow. For the range of temperatures investigated, the 25 Brix blueberry purée showed yield stress values that are 18–20 times more than the 10 Brix purée. Again as temperature of purée was changed from 25 to 60 °C, the yield stress decreased by nearly 50%. These observations have practical implications in the selection of pumps that can provide the necessary initial torque to cause flow of purée, especially those with high concentration of total solids.

4.3. Influence of temperature and solids content on viscosity

The influence of dissolved solids concentration on viscosity of purée at two temperatures, 25 and 60 °C, is illustrated in Fig. 4 for a shear rate of 100 s^{-1}. At 25 °C, the viscosity of blueberry purée at 100 s^{-1} increased by about 0.62 Pa s as the dissolved solids content was increased from 15 to 25 Brix (Fig. 4(a)). For the process occurring at 60 °C with the same increase in Brix number, the viscosity increased by 0.29 Pa s (Fig. 4(b)), which is nearly half of what is observed at 25 °C. Therefore, it is expected that the load on pumping and shear stresses imposed on blueberry purée will be reduced at the higher process temperature of 60 °C. However, the interaction of other factors, such as changes in particle-to-particle proximity with temperature and Brix number, must not be overlooked. For low-temperature concentration processes, the viscosity will change by a larger margin before the desired Brix is reached. These considerations help in the selection of pumps that will keep the fluid flowing throughout the entire viscosity range.

At infinite shear rate, the shear-thinning purée became more Newtonian with a viscosity represented by η_∞ in the Sisko model [Eq. (3)]. This viscosity at infinite shear rate varied with both the concentration of dissolved solids

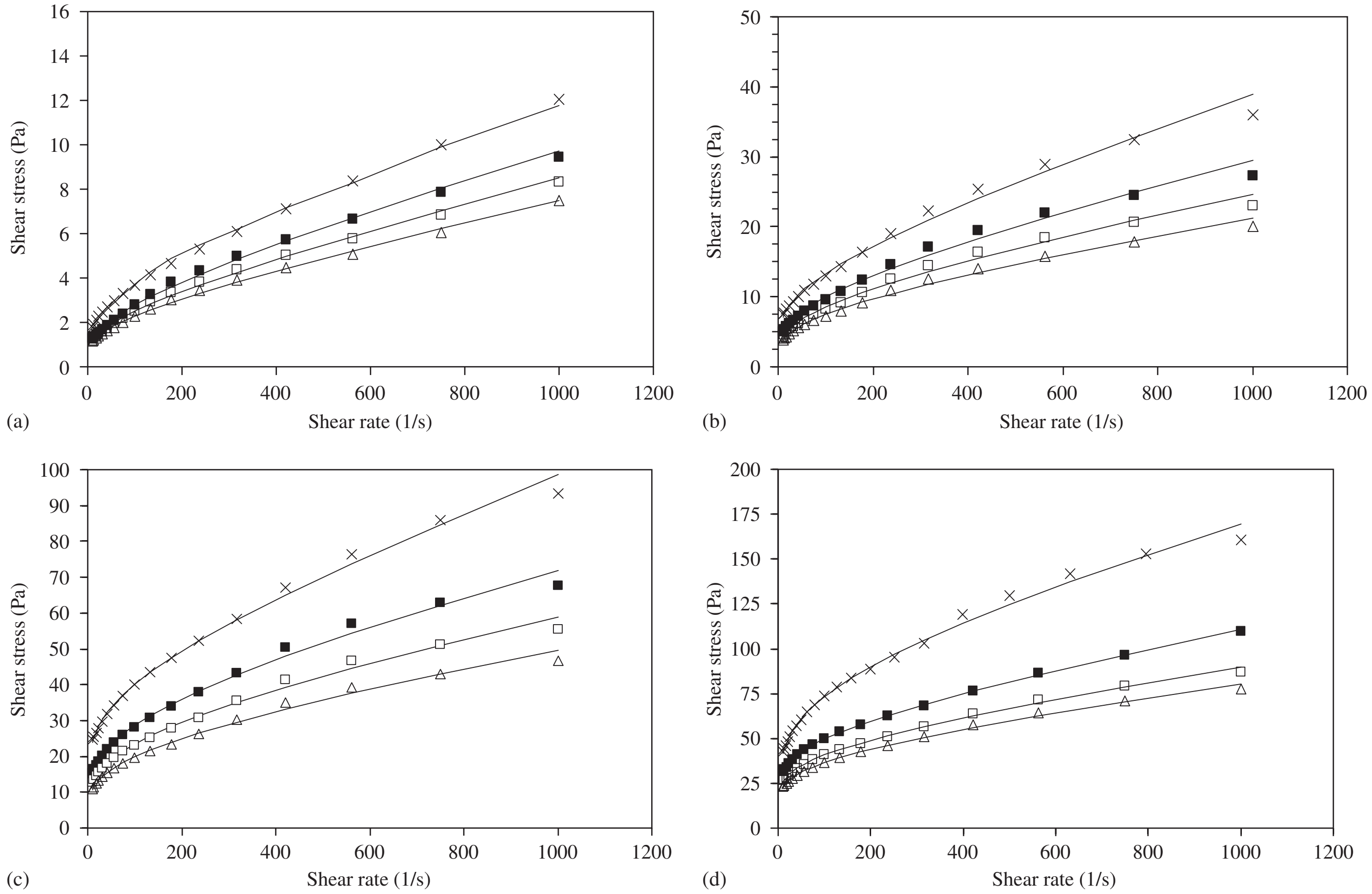

Fig. 2. Shear stress versus shear rate for (a) 10 Brix blueberry purée at 25 °C (×), 40 °C (■), 50 °C (□), 60 °C (△) with respective standard errors (SE) of 0.12, 0.12, 0.11, and 0.09; (b) 15 Brix blueberry purée at 25 °C (×), 40 °C (■), 50 °C (□), 60 °C (△) with respective SE of 1.0, 0.8, 0.6, and 0.5; (c) 20 Brix blueberry purée at 25 °C (×), 40 °C (■), 50 °C(□), 60 °C (△) with respective SE of 1.6, 1.5, 1.2, and 1.0. (d) 25 Brix blueberry purée at 25 °C (×), 40 °C (■), 50 °C (□), and 60 °C (△) with respective SE of 2.9, 0.5, 1.1, and 1.0.

Table 1
Yield stress (Pa) of blueberry purée estimated from HB, Casson and graphical methods

Method	Temperature (°C)	Brix			
		10	15	20	25
HB model	25	1.32	4.53	18.03	27.45
	40	0.72	2.31	8.83	25.62
	50	0.83	2.21	7.57	19.48
	60	0.85	2.08	6.41	16.53
Casson model	25	1.41	6.02	20.98	38.87
	40	0.95	4.25	13.92	27.92
	50	0.92	3.70	11.54	23.18
	60	0.86	3.30	9.86	20.65
Graphical method	25	1.94	7.50	24.50	41.25
	40	1.25	4.80	15.20	30.00
	50	1.19	4.10	13.00	24.00
	60	1.13	3.70	11.00	21.50

(C, g/100 g) and temperature (T, K), and was modeled using the relationship

$$\eta_\infty = \{(54 - 0.1496\,T)C^2 \times 10^{-5}\}, \quad R^2 = 0.978. \tag{5}$$

The influence of dissolved solids on apparent viscosity (η_a) at 100 s^{-1} and consistency index K_s was also described by a power model (Holdsworth, 1993; Marcotte, Taherian Hoshahili, & Ramaswamy, 2001):

$$\eta_a \text{ or } K_s = \alpha C^\beta, \tag{6}$$

where α and β are constants. For η_a at 100 s^{-1} the magnitude of parameter α averaged 1.87×10^{-5}, while β decreased slightly from 3.3 to 3.1 (mean value: 3.2±0.1) as temperature was increased from 25 to 60 °C. The corresponding values of α and β for the relationship between consistency index K_s and solids content were 2.65×10^{-4} Pa s and 3.7–3.3 (mean value: 3.4±0.2), respectively.

An Arrhenius relationship [Eq. (7)] was used to describe the influence of temperature on apparent viscosity η_a (Pa.s) at a shear rate of 100 s^{-1}:

$$\eta_a = A \exp\left(\frac{E_a}{RT}\right), \tag{7}$$

where A is the pre-exponential or frequency factor associated with collision rates, E_a is the activation energy (kJ/mol), R is gas constant (8.314 kJ/mol K) and T is temperature (K). The activation energy (E_a) for viscous

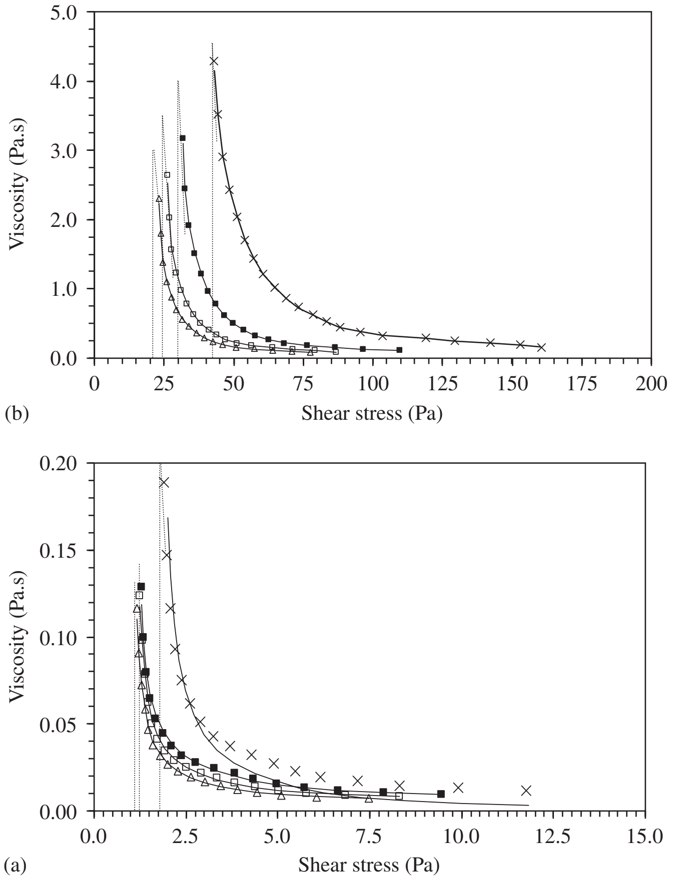

Fig. 3. Approximation of yield stress by extrapolation of viscosity versus shear stress curves for (a) 10 Brix, and (b) 25 Brix blueberry purées at 25 °C (×), 40 °C (■), 50 °C (□), 60 °C (△).

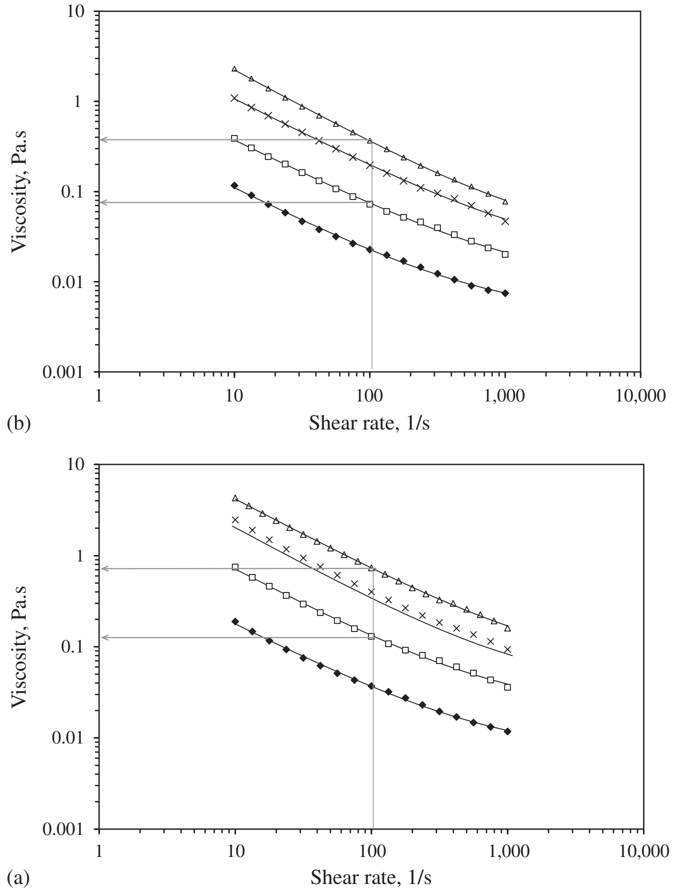

Fig. 4. Influence of dissolved solids content on viscosity of blueberry purée at (a) 25 °C, and (b) 60 °C. Brix levels: 10 Brix (◆), 15 Brix (□), 20 Brix (×), 25 Brix (△).

flow, based on the apparent viscosity at 100 s^{-1} shear rate (Krokida, Maroulis, & Saravacos, 2001; Rao, 1999), was then calculated for blueberry purée with 10, 15, 20 and 25 Brix. The E_a values corresponding to these Brix numbers were 11.3, 13.7, 16.6, and 17.0 kJ/mol, respectively. The frequency factor A also increased with the concentration of dissolved solids from 3.69×10^{-4} to 7.35×10^{-4} Pa s for 10 and 25 Brix purées, respectively. The E_a value for the 25 Brix purée differed from that of the 20 Brix purée by 0.4 kJ/mol. Since the pulp particles within the purée are much closer at higher Brix, it is likely that in addition to the effect of dissolved solids on flow, some irreversible structural breakdown occurred in the purée matrix.

The influence of temperature on consistency coefficient K was also determined. Based on the consistency index K_s calculated using Eq. (3), the activation energy (E_{ak}) values of 10.7, 17.5, 21.7 kJ/mol were obtained for 10, 15 and 20 Brix, respectively. Its value then dropped suddenly to 13.3 kJ/mol for the 25 Brix. As noted by Guerrero and Alzamora (1997), there are probably some interactions promoted by high temperatures that could affect the temperature dependence of the consistency index. Table 2 summarizes literature values of rheological properties of several selected fruit purées. For peach, mango, and banana purées with 26–51 Brix, Guerrero and Alzamora (1998) obtained activation energy values between 16 and 27 kJ/mol. The high concentration of dissolved solids for those purées they investigated was achieved by addition of glucose. In a previous study (Rao, 1999), the activation energy of guava purée was found to be 15.2 kJ/mol. The activation energy values of 10.7–21.7 kJ/mol that we obtained for blueberry purée are consistent with values reported for other fruit purées. However, it is important to note that most authors used either the Power Law or HB models to determine the rheological parameters. No mathematical information was found in the literature that describes the flow behavior of purées made from small fruits such as blueberry. In the present study, we show the magnitude of these parameters for blueberry purée using the Sisko model which resembles the HB model in form but explicitly defines the apparent viscosity as a function of shear rate.

From Eq. (3), a model describing the consistency index K_s as a function of temperature (25–60 °C) and dissolved solids concentration (10–20 Brix) was obtained [Eq. (8a)]. The activation energy E_{ak} (kJ/mol) varied linearly with the concentration of dissolved solids C (g/100 g) as in Eq. (8b):

$$K_s = K_0 \exp\left(\frac{E_{ak}}{RT} - 0.164C\right), \tag{8a}$$

Table 2
Literature values of consistency coefficient, flow behavior index, and activation energy of selected fruit purées

Purée	Brix	Temp (°C)	Shear rate (s^{-1})	K (Pa s^n)	n	E_a (kJ/mol)	Ref.
Guava	7.2–7.4	24	10^2–10^4	0.26	0.68	15.2	Rao, 1999[§]
Pear	16	30–82		5.6–4.6	0.27–0.35	7.95	Holdsworth, 1993[‡]
Peach	11.7	30–82.2	5–50	7.2–5.8	0.28	7.11	Holdsworth, 1993[‡]
	26–51	25–55	0–300	0.06–0.75	0.5–0.7	13–16	Guerrero & Alzamora, 1998[†]
Mango	28–51	10–55	0–300	0.3–3.4	0.46–0.78	24–30	Guerrero & Alzamora, 1998[†]
Papaya	12–51	25–55	0–300	0.7–15.3	0.32–0.67	62	Guerrero & Alzamora, 1998[†]
Banana	21–51	10–55	0–300	0.3–9.2	0.41–0.64	18.4–26.8	Guerrero & Alzamora, 1997[†]
	22.1	30–120	0–1000	0.03–4.92	0.41–0.97		Ditchfield et al., 2004[†]
Blueberry	10–25	25–60	0–1000	0.07–7.2[†] 0.6–20.5[*]	0.64–0.49[†] 0.26–0.19[*]	10.7–21.7	This study

Data based on: [§]Power Law; [‡]Variation of overall heat transfer coefficient and K; [†]Herschel-Bulkley model; [*]Sisko model.

$$E_{ak} = 1.1C + 0.11, \quad R^2 = 0.98, \tag{8b}$$

where $K_0 = 0.053$ (Pa s^n); $R = 8.314\,\text{J/mol K}$, and T is temperature (K). The mathematical model in Eq. (8a) predicted the consistency index K_s for 10–20 Brix purées with an R^2 value of 0.99.

The flow behavior index n_s [Eq. (3)] decreased linearly with the concentration of dissolved solids in blueberry purée as given in Eq. (9), while its magnitude was little affected by temperature:

$$n_s = -0.0048\,C + 0.313, \quad R^2 = 0.96. \tag{9}$$

By substituting Eqs. (4b), (8), and (9) into Eq. (3), the apparent viscosity of blueberry purée was predicted and compared with the measured values for all temperatures and solids content investigated (Fig. 5). It is observed that the apparent viscosity of blueberry purée with 10–20% dissolved solids is well described by the developed mathematical models that account for the effect of temperature and solids content. The model predicted the viscosity of blueberry purée in that Brix range with R^2 value of 0.995. Data for purée with 25% dissolved solids were not included in the prediction of apparent viscosity because of the deviation in activation energy that was noticed. It is possible that some structural transformation occurred in the purée with high total solids content during the flow tests, hence giving the variation in consistency coefficient that cannot be explained solely by the influence of temperature and solids content. Some changes in matrix structure likely occur in purées with higher solids content where particles are closer together, especially when they are agitated at elevated temperatures. The particles can separate and agglomerate on the geometry walls. This behavior was not observed at low concentrations where particle-to-particle interaction is very weak, and so there is no indication of structural units being disrupted. It is important to differentiate between this structural breakdown and instabilities due to Taylor vortices. Since Taylor vortices can be a major problem for experiments conducted using a coaxial viscometer with rotating inner cylinder, precaution was taken to ensure that measurement was done within a shear rate range that did not cause flow instabilities in the cylinder gap (Mizrahi, 1979; Nindo et al., 2005; Steffe, 1996).

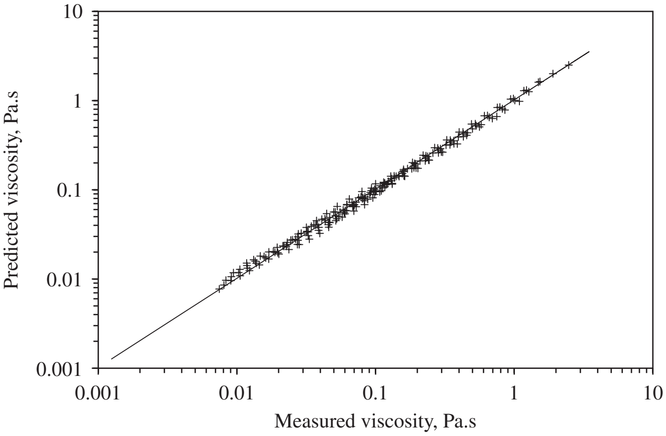

Fig. 5. Predicted versus measured viscosities for 10–20 Brix blueberry purée ($R^2 = 0.995$).

5. Conclusion

The rheological behavior of blueberry purées with solids content ranging from 10 to 25 Brix was investigated. As opposed to blueberry juice, which is more Newtonian in nature, the purées showed shear-thinning behavior. The Sisko model, which is a combination of Newtonian and Power Law models, fitted the data very well with an overall R^2 of more than 0.99, and, therefore, used to describe the apparent viscosity of purées at 25, 40, 50 and 60 °C. The activation energy E_a increased with total solids content except for 25 Brix when it suddenly decreased. With respect to apparent viscosity determined at a shear rate of $100\,s^{-1}$, E_a increased from 11.4 to 17.1 kJ/mol for purée with 10% and 25% total soluble solids, respectively. The apparent viscosity was also expressed as a function of solids content, a relationship that is important for monitoring of viscosity changes during evaporation processes. For a shear rate range of 10–1000 s^{-1} tested in this study, a useful mathematical model expressing the viscosity coefficient as a function of solids content and temperature was obtained for blueberry purée with 10–20 Brix. Further investigation is needed to widen the applicability of the mathematical model for purées with consistency coefficient above 20 Pa s^n where some unexplained variation was observed.

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References

Betts, G. D., & Walker, S. J. (2004). Verification and validation of food spoilage models. In R. Steele (Ed.), *Understanding and measuring shelf life of food* (pp. 184–217). Boca Raton, FL: CRC Press.

De Kee, D., Code, R. K., & Turcotte, G. (1983). Flow properties of time-dependent foodstuffs. *Journal of Rheology*, *27*, 581–604.

Ditchfield, C., Tadini, C. C., Singh, R., & Toledo, R. T. (2004). Rheological properties of banana purée at high temperatures. *International Journal of Food Properties*, *7*, 571–584.

Guerrero, S. N., & Alzamora, S. M. (1997). Effect of pH, temperature and glucose addition on flow behavior of fruit purées: I. Banana purée. *Journal of Food Engineering*, *37*, 77–101.

Guerrero, S. N., & Alzamora, S. M. (1998). Effect of pH, temperature and glucose addition on flow behavior of fruit purées: II. Peach, papaya, and mango purées. *Journal of Food Engineering*, *33*, 239–256.

Hernandez, E., Chen, C. S., Johnson, J., & Carter, R. D. (1995). Viscosity changes in orange juice after ultrafiltration and evaporation. *Journal of Food Engineering*, *25*, 387–396.

Holdsworth, S. D. (1993). Rheological models used for the prediction of the flow properties of food products: A literature review. *Transactions of the Institution of Chemical Engineers*, *71C*, 139–179.

Kalt, W., Forney, C. F., Martin, A., & Prior, R. L. (1999). Antioxidant capacity, vitamin C, phenolics, and anthocyanins after fresh storage of small fruits. *Journal of Agricultural Food Chemistry*, *47*, 4638–4644.

Krokida, M. K., Maroulis, Z. B., & Saravacos, G. D. (2001). Rheological properties of fluid fruit and vegetable purée products: Compilation of literature data. *International Journal of Food Properties*, *4*, 179–200.

Marcotte, M., Taherian Hoshahili, A. R., & Ramaswamy, H. S. (2001). Rheological properties of selected hydrocolloids as a function of concentration and temperature. *Food Research International*, *34*, 695–703.

Mizrahi, S. (1979). A review of the physicochemical approach to the analysis of the structural viscosity of fluid fruit products. *Journal of Texture Studies*, *10*, 67–82.

Nindo, C. I., Tang, J., Powers, J. R., & Bolland, K. (2004). Energy consumption during Refractance Window evaporation of selected berry juices. *International Journal of Energy Research*, *28*, 1089–1100.

Nindo, C. I., Tang, J., Powers, J. R., & Singh, P. (2005). Viscosity of blueberry and raspberry juices for processing applications. *Journal of Food Engineering*, *69*, 343–350.

Perona, P. (2003). An experimental investigation of laminar–turbulent transition in complex fluids. *Journal of Food Engineering*, *60*, 137–145.

Rao, M. A. (1999). *Rheology of fluids and semi-solid foods*. Gaithersburg: Aspen publishers.

Skrede, G., Wrolsted, R. E., & Durst, R. W. (2000). Changes in anthocyanins and polyphenolics during juice processing of Highbush blueberries *(Vaccinium corymbosum* L.). *Journal of Food Science*, *65*, 357–364.

Steffe, J. F. (1996). *Rheological methods in food process engineering*. East Lansing: Freeman Press.