Relationship between In-line Viscosity and Bostwick Measurement during Ketchup Production

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ABSTRACT: The Bostwick consistometer remains an integral part of assessing the consistency of tomato products in the factory. This work addresses the blending of tomato pastes, packed at different Bostwick readings, for use in tomato ketchup production. The objective of this study was to correlate in-line viscosity measurements of 12 °Bx tomato concentrates to final product quality. Five blends of tomato concentrate were prepared by blending 2 pastes and diluting the mixture to a soluble solids level of 12 °Bx. In-line viscometry measurements at process temperature were made using magnetic resonance viscometry. The resulting Herschel–Bulkley parameters were used to evaluate an apparent viscosity at a characteristic shear rate. The apparent viscosity and Bostwick measurement for the blends were correlated based on a gravity current flow analysis, yielding a coefficient of determination of over 0.99. Ketchup was made from the tomato concentrate blends at 3 levels of natural tomato soluble solids (NTSS). The ketchup Bostwick measurement was then correlated to the ratio of $(\eta/\rho)^{-1/5}$ of the 12 °Bx tomato concentrate yielding coefficients of determination of 0.97, 0.97, and 0.91 for NTSS levels of 6%, 7%, and 7.8%, respectively. This study demonstrates that final product quality can be predicted from in-line viscosity measurements of an intermediate product.

Keywords: Bostwick consistometer, in-line viscosity, ketchup, tomato concentrate, viscosity

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Introduction

Tomato paste, in the range of 23 to 35 degrees Brix (°Bx) is used for ketchup production. These pastes are characterized by the standard method for determining the consistency, using a Bostwick consistometer (ASTM 2002), prior to packing and storing. For ketchup manufacture, the tomato paste or blends of pastes are diluted with water and pumped to cook kettles. Other ingredients are added, such as sugars, vinegar, and spices. The ketchup is cooked and then bottled at process temperature.

Marsh and others (1979a, 1979b) published work that reported the yield and quality of ketchup produced to a standard solids and consistency level. The ketchup formulations given by these researchers incorporated tomato solids, referred to as natural tomato soluble solids (NTSS), at levels of 25% and higher to meet the specifications for U.S. Grade A ketchup. These specifications, still current, are that the total solids content is not less than 33% and the flow is not less than 3 cm nor more than 7 cm in 30 s at 20 °C in the Bostwick consistometer (USDA 1992). Today the specifications are met at levels of 6% to 8% tomato solids by tomato varieties that produce much more viscous pastes.

To address continually changing raw material properties, the ketchup production process would benefit from 2 specific implementations: in-line measurement of viscosity during processing, and the relationship between the viscosity measurement and the Bostwick measurement of the final product quality. To address the relationship between the viscosity and the Bostwick measurement, researchers have developed both empirical correlations (Rao and Bourne 1977; Vercruysse and Steffe 1989; Azam and others 1995; Alamprese and others 2001; Cullen and others 2001) and theoretical relationships (McCarthy and Seymour 1993, 1994; Milczarek and McCarthy 2006; McCarthy and others 2008) between the Bostwick measurement and quantitative rheological parameters.

This study applies the approach given in McCarthy and Seymour (1993, 1994) and extends the study described in Milczarek and McCarthy (2006) and McCarthy and others (2008) to in-line viscosity measurements. The objectives of this study were (1) to blend 2 different tomato pastes, to evaluate the in-line viscosity of the blends at processing temperature and to relate the flow behavior to the Bostwick measurement, and (2) to make ketchup from the blends and to relate the in-line viscosity of the blends to the ketchup Bostwick measurement.

Materials and Methods

Dilution of blends of tomato paste

Fifty kilograms of 2 commercial tomato pastes were provided by ConAgra Foods (Helm, Calif., U.S.A.). The pastes were produced from tomatoes harvested late in the 2007 season and processed at the Helm tomato processing plant. The 1st paste was 22.8 °Bx and was packed at a Bostwick measurement of 0.7 cm. Each paste was identified by the processing location and Bostwick measurement at packing; the 1st paste was designated as H-1, "H" for Helm and "1" for a 0.7 cm Bostwick measurement (rounded for brevity). The 2nd paste, designated as H-8, was 35.1 °Bx and was packed at a Bostwick of 7.9 cm. The 2 pastes were blended to 5 H-8 : H-1 ratios: 0 : 1, 0.25 : 0.75, 0.50 : 0.50, 0.75 : 0.25, and 1 : 0. The blends were diluted with deionized water to 12 °Bx to evaluate flow behavior and to 16 °Bx to prepare ketchup.

Ketchup made from blends of tomato paste

Each of the 5 blends was used to prepare ketchup at 3 levels of NTSS, 6%, 7%, and 7.8%. The recipes are given in Table 1. The 3

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ingredients for ketchup, (that is, tomato concentrate, ketchup base, and water) were weighed into a commercial mixer (Viking Professional, Viking, Greenwood, Miss., U.S.A.). The material was mixed at speed 8 for 2 min, scraped and mixed for another 2 min at speed 8. The mixture was placed in 650 mL containers and heated in a water bath to 71 °C (160 °F). Once heated, the mixture was homogenized using a single pass at 3000 psi (2 × 10^7 Pa) (Model 15MR, APV Gaulin, Inc., Wilmington, Mass., U.S.A.). The ketchup was cooled to 20 °C for physical property testing.

Physical property measurements

Soluble solids. Soluble solids of tomato concentrate blends and ketchup samples were measured by refractometry and reported in units of °Bx as described by McCarthy and others (2008).

Density. A U.S. standard weight per gallon cup (Paul N. Gardener Co., Inc., Pompano Beach, Fla., U.S.A.) with 83.2 mL volume was used for density measurements of tomato concentrate blends at process temperature (60 ± 2 °C). Measurements were accurate to 4 significant digits.

Flow behavior

In-line viscometry. The in-line viscometric technique is based on acquiring an experimental velocity profile using magnetic resonance imaging and a simultaneous pressure drop during steady pressure driven laminar flow in a pipe. The flow loop system consisted of a 19.05 mm ID plexiglass tube with a 1 m straight section upstream of the imaging plane to ensure sufficient distance for fully developed flow. Coupled with the velocity profile image, the pressure drop across the distance L of 2.0828 m was measured at 2 pressure taps on both sides of the magnet bore using a differential pressure transducer (Model PX771, Omega Engineering, Stamford, Conn., U.S.A.). A positive placement pump (Moyno pump, Model 20502, Moyno Inc., Springfield, Ohio, U.S.A.) was used to pump fluids. The fluid temperature was maintained at 60 ± 2 °C using a Haake circulator (DC10, Thermo Fisher Scientific, Inc., Waltham, Mass., U.S.A.) in an open 4 L jacketed reservoir and foam insulation on all piping. In preliminary studies, a degree of evaporation occurred and volumetric flow rates at a given pump setting varied depending on the tomato concentrate blend. To minimize evaporation, data were acquired at only 2 flow rates; the pump settings were designated "A" and "C." To ensure an independent verification of volumetric flow rate, 3 timed collections were performed for each pump setting during a trial.

Two-dimensional proton images with a field-of-view of 5.182 cm in the y-direction by 95 cm/s in the x-direction were acquired using a pulsed-gradient spin echo based sequence (echo time of 25.2 ms, acquisition sweep width of ± 20000 Hz, repetition time of 130 ms and 4 signal averages). Slice thickness was 0.01 m. The imaging was performed using an Aspect AI (Aspect Magnet Technologies, Ltd., Netanya, Israel) 1.03 Tesla permanent magnet based magnetic resonance imaging spectrometer designed for industrial process control. All velocity images were processed using zero-filling to 256 × 256 final matrices.

Shear viscosity was evaluated according to procedures given in Choi and others (2002, 2005). The force balance, which equates pressure forces to viscous forces during viscometric flow, provides the relationship between the shear stress, σ and radial position, r

$$\sigma(r) = \frac{-(\Delta P)}{2L} r \tag{1}$$

where ΔP is the pressure drop over the tube length L. The shear rate is obtained at the same radial position by differentiating the velocity data,

$$\dot{\gamma}(r) = \left| \frac{dv(r)}{dr} \right| \tag{2}$$

where v is the axial velocity. Using Eq. (1)–(2), the apparent viscosity η is determined by

$$\eta(r) = \frac{\sigma(r)}{\dot{\gamma}(r)} \tag{3}$$

The data were fit to the Herschel–Bulkley model

$$\sigma = \sigma_o + K\dot{\gamma}^n \tag{4}$$

where σ_o is the yield stress, K is the consistency coefficient, and n is the flow behavior index. Data analyses were done in Matlab® Release 2008a (The Mathworks, Natick, Mass., U.S.A.).

Bostwick measurement. Flow lengths of the tomato concentrate blends and ketchup samples were measured using a standard Bostwick consistometer (CSC Scientific Co., Inc., Fairfax, Va., U.S.A.). The sample compartment dimensions were 4, 5, and 5 cm for the height, length, and width, respectively. For each fluid, a sample at 20 ± 1 °C was loaded into the compartment. The gate was opened, and the distance traveled by the leading edge of the concentrate after 30 s was recorded to the nearest 0.1 cm. Three measurements were performed and averaged.

Relationship between apparent viscosity and Bostwick measurement. Previous work from the laboratory has focused on the relationship between the Bostwick consistometer measurement and physical properties of the fluid (McCarthy and Seymour 1993, 1994; Milczarek and McCarthy 2006; McCarthy and others 2008). The flow in a Bostwick consistometer was treated as a gravity current. Gravity currents occur when a fluid flows primarily horizontally due to gravitational forces. The gravitational force acting on fluid in a Bostwick consistometer is opposed by viscous forces, limiting the distance the fluid front travels during the measurement time. Generalizing the analysis developed for Newtonian fluids to non-Newtonian fluids yielded a relationship between L' and the apparent viscosity (McCarthy and Seymour 1994)

$$L' = c\left(\frac{\eta}{\rho}\right)^{-1/5} \tag{5}$$

where L', which is the total length of the gravity current and corresponds to Bostwick measurement plus 5 cm (adding the length of the sample compartment), ρ is the fluid density, and c is a constant.

Table 1 – Ketchup recipe for 3 levels of NTSS.

Ketchup recipe for 1000 g: percent NTSS	6.0% Mass (g)	7.0% Mass (g)	7.8% Mass (g)
Tomato concentrate at 16 °Bx	375	437	488
Ketchup base at 51 °Bx	510	510	510
Water	115	53	5

Ketchup base recipe for 1000 g	Mass (g)
Sugar blend	589
82% (w/w) 63/43 corn syrup, Cargill Inc. Minneapolis, Minn., U.S.A.	
18% (w/w) IsoClear 42% High Fructose Corn Syrup, Cargill Inc.	
Nonionized salt	58
120 Grain vinegar	185
Water	168

The apparent viscosity, η, is evaluated at a characteristic shear rate,

$$\dot{\gamma} = \frac{(L')^2}{qt} \tag{6}$$

where q is the volume/width of the sample compartment and t is the measurement time of 30 s.

The linear relationship between L' and $(\eta/\rho)^{-1/5}$ has been established for a number of Newtonian and homogeneous power law fluids (McCarthy and Seymour 1994) and extended to tomato concentrates in the range of 5 to 24 °Bx (Milczarek and McCarthy 2006), and blends of 12 °Bx tomato concentrates (McCarthy and others 2008).

Results and Discussion

Figure 1 illustrates the relationship between the Bostwick measurement, taken at 12 °Bx, and mass fraction of H-8 paste. The linear relationship indicates that the Bostwick measurement is additive for the pastes used in this study. The trend is noteworthy because the contribution of the solids of the H-8 paste to the blends differs due to the different Brix levels of the original H-1 and H-8 pastes. For example, H-8 contributes 35.4% of the solids to the 0.25 H-8 blend.

During the process, a 12 °Bx blend in the Bostwick range of 2 to 4 cm is preferred for ketchup production. For these H-8:H-1 blends, mass fractions from 0.23 to 0.51 H-8 were anticipated to produce good quality ketchup that falls in the range of 3 to 7 cm Bostwick for final product quality. The intent of this study was to verify the range and to examine other blends for acceptability. In-line viscosity measurements are a means to provide real-time measurements of the consistency of concentrates for use in the production of good quality ketchup.

Figure 2A illustrates a representative magnetic resonance (MR) phase encoded velocity profile for the 0.75 H-8 blend flowing at a volumetric flow rate of 62.4 mL/s. The maximum velocity is at the center of the pipe (pixel 131 on the y-axis) and decreases toward the pipe wall at pixels 84 and 178. Significant wall slip was observed for all blends. Zero velocity was at pixel 129 on the x-axis in Figure 2A. Within the resolution of the imaging process, wall slip for this blend and flow rate was 14.2 cm/s and is observable in Figure 2B, the velocity profile extracted from the image. Though the total volumetric flow rate is considered the sum of the contribution from the slip velocity and the volumetric flow rate without slip, rheological parameters were determined from the volumetric flow rate without slip (as given by Steffe 1996). This volumetric flow rate without slip is the shearing and plug region of the velocity profile. Flow measurements for the 5 tomato concentrate blends at 2 pump settings are given in Table 2. Each entry is the average of 3 measurements and ±1 standard deviation.

Unlike actual processing condition, the flow loop was used to bring the 12 °Bx blends to the 60 °C processing temperature prior to MR imaging and a certain amount of evaporation took place from the open 4 L fluid reservoir. Soluble solids and Bostwick measurements were performed both before and after MR imaging on representative samples taken from the flow loop. The values are given in Table 3. Since the pump setting was changed from A to C for each trial, the before MR imaging values best reflect flow at the pump setting A and the after MR imaging values best reflect flow at pump setting C. The changes in soluble solids levels decreased as MR imaging trials progressed. For instance, 0.5 H-8 was the first blend run and showed a 0.8 °Bx change in soluble solids; 0.75 H-8 was the last blend run and showed a 0.0 °Bx change in soluble solids. For a given blend, Bostwick measurements decreased with increasing soluble solids level due to a higher viscosity. One density measurement was made midway through each trial and is also given in Table 3. The density was not a strong function of the blend or soluble solids level and averaged 1019 kg/m^3.

Although 3 MR images were acquired for each pump setting in each trial, the 1st image for pump setting A and the 3rd image for pump setting C were analyzed for rheological parameters. These images best correspond to the physical properties reported in Table 3. For each image, the radial dimension of the plug region,

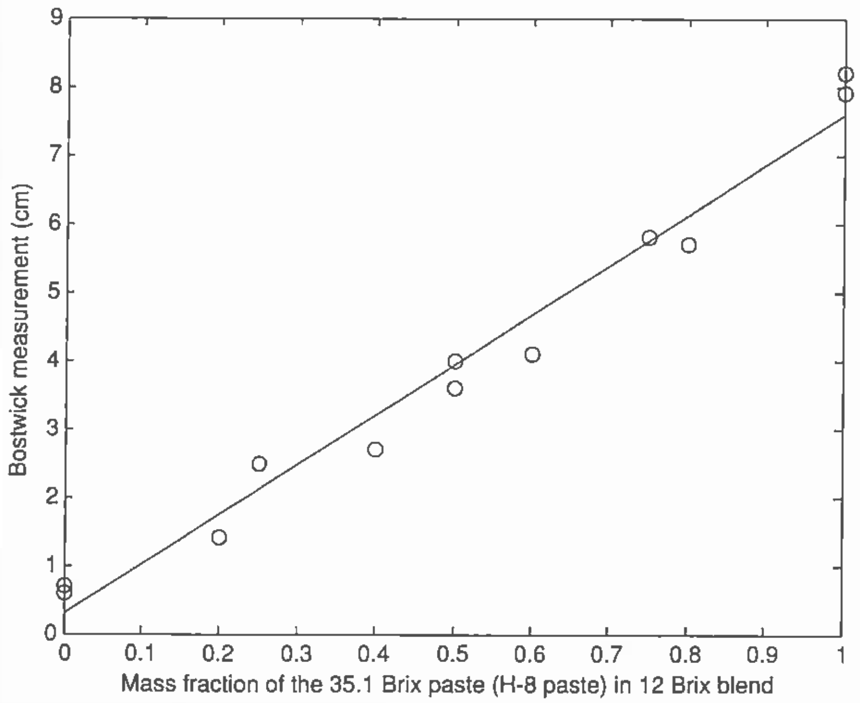

Figure 1 – Bostwick measurement for a range of tomato concentrate blends, the slope of the best fit linear regression is 7.29 with an R^2 = 0.968 (intercept of 0.290).

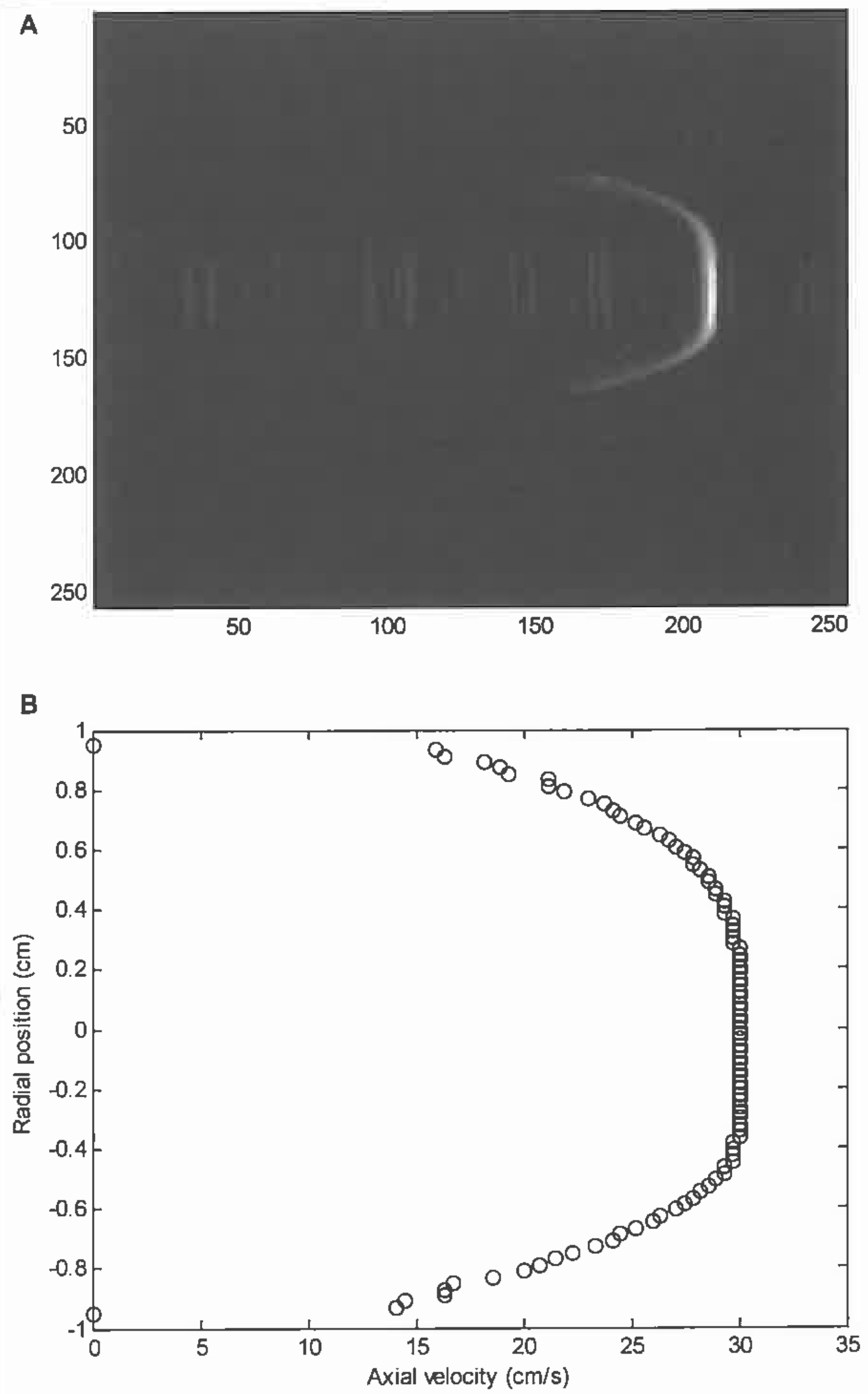

Figure 2—(A) Representative MR image of 12 Brix tomato concentrate flowing at 62.4 mL/s and (B) the extracted velocity profile.

Table 2—Flow measurements for the 5 tomato concentrate blends at 2 pump settings. Each entry is the average of 3 measurements and ± 1 standard deviation.

	Pump setting A			Pump setting C		
Mass fraction of paste H-8	Average velocity (cm/s)	Pressure drop (kPa)	Slip velocity (cm/s)	Average velocity (cm/s)	Pressure drop (kPa)	Slip velocity (cm/s)
0.00	7.1 ± 0.2	43.8 ± 0.3	7.4 ± 0.1	8.5 ± 0.6	47.6 ± 0.6	9.3 ± 0.2
0.25	10.3 ± 0.1	35.2 ± 0.1	9.6 ± 0.5	14.4 ± 0.3	38.4 ± 0.2	13.2 ± 0.4
0.50	13.7 ± 0.3	22.7 ± 1.1	10.2 ± 0.6	18.9 ± 0.2	25.2 ± 1.2	14.3 ± 0.4
0.75	15.8 ± 0.3	16.9 ± 1.0	10.4 ± 0.6	22.0 ± 0.2	17.8 ± 1.0	14.2 ± 1.0
1.00	17.8 ± 0.2	12.3 ± 1.1	9.1 ± 1.0	24.9 ± 0.2	13.5 ± 0.9	13.3 ± 0.4

Table 3 — Soluble solids levels and Bostwick measurements of the 5 tomato concentrate blends before and after MR imaging.

		Before MR imaging		After MR imaging	
Mass fraction of paste H-8	Density (kg/m³)	Soluble solids (°Bx)	Bostwick (cm)	Soluble solids (°Bx)	Bostwick (cm)
0.00	1032	12.3 ± 0.0	0.6 ± 0.0	12.8 ± 0.0	0.4 ± 0.0
0.25	1031	12.0 ± 0.0	2.5 ± 0.1	12.5 ± 0.1	1.9 ± 0.1
0.50	1009	12.2 ± 0.0	3.6 ± 0.1	13.0 ± 0.1	3.5 ± 0.1
0.75	1013	12.1 ± 0.0	6.8 ± 0.1	12.1 ± 0.0	6.0 ± 0.1
1.00	1008	12.1 ± 0.1	8.2 ± 0.1	12.3 ± 0.1	8.4 ± 0.2

Table 4 — Herschel–Bulkley parameters for the 5 blends.

	Herschel–Bulkley parameters			
Mass fraction of paste H-8	Yield stress (Pa)	Flow behavior index	Consistency index (Pa sⁿ)	Valid to shear rate (1/s)
0.00	63.76	0.264	21.85	16
0.25	34.68	0.264	20.15	40
0.50	19.44	0.264	11.6	90
0.75	14.75	0.264	7.2	125
1.00	9.8	0.264	5.3	190

R_o, characteristic of fluids that have a yield stress, was used to evaluate the yield stress

$$\sigma_o = \frac{-(\Delta P)}{2L} R_o \tag{7}$$

The data were then fit stepwise for the flow behavior index and the consistency index. The nonlinear relationship between shear stress (Eq. 1) and shear rate (Eq. 2) gave the flow behavior index, n. Finally, the consistency index, K, was determined using the volumetric flow rate for a Herschel–Bulkley fluid (Q_{H-B}) in a circular tube was given by Holdsworth (1993)

$$Q_{H-B} = \left(\frac{\pi R^3(\sigma_w - \sigma_0)^{s+1}}{K^s \sigma_w^3}\right)\left(\frac{n}{3n+1}\sigma_w^2 + \frac{2n^2}{(2n+1)(3n+1)}\sigma_w \sigma_0 + \frac{2n^3}{(n+1)(2n+1)(3n+1)}\sigma_0^2\right) \tag{8}$$

where s is $1/n$ and σ_w is the shear stress evaluated at R. The value of K was iterated on to approach the experimental volumetric flow rate. This approach was developed to address the concerns raised by Mullineux and Simmons (2008) when fitting rheological models for several parameters simultaneously.

The Herschel–Bulkley parameters were determined for the 5 blends at the 2 flow rates. A 2-way analysis of variance (ANOVA) was performed for each of the parameters with blend and flow rate as factors. A significant difference in means was observed for the yield stress with respect to blend but not flow rate. No significant difference in means was observed for the flow behavior index, n, with respect to either factor. The consistency index was then iterated on with the appropriate averages for the yield stress and flow behavior index. The values for the 3 parameters are given in Table 4. In addition, the shear rate range is given for each blend (Table 4). The maximum shear rate is at the tube wall and the minimum shear rate is at R_o and reflects the resolution of the MR image. Figure 3 illustrates the apparent viscosity for blends over the shear rate range from 5 1/s to the maximum shear rate for the blend.

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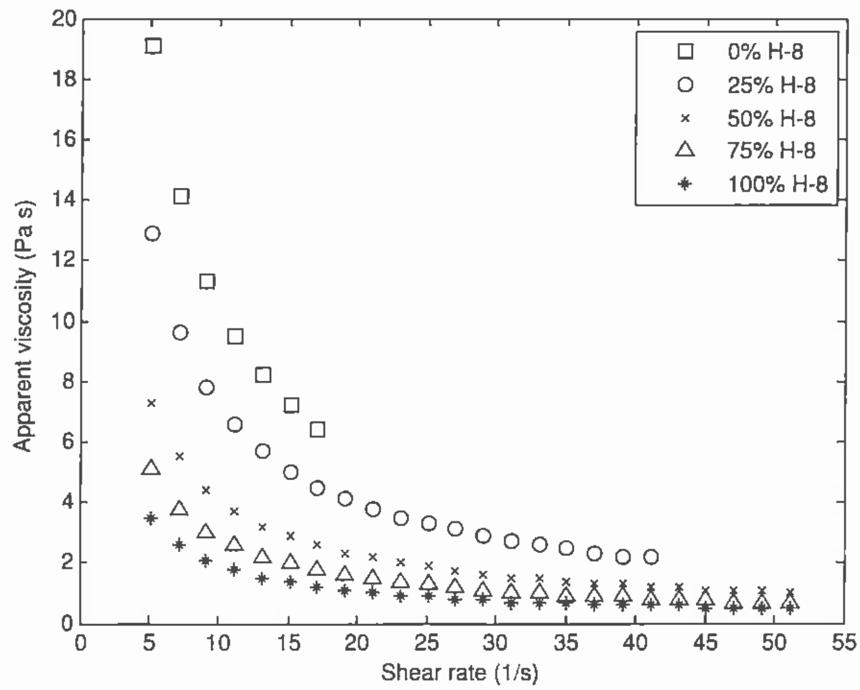

Figure 3 — Apparent viscosity of the 5 blends, designated by percent of 35.1 Brix paste (H-8) in the blend.

The gravity current model (Eq. 5) required density (Table 3) and apparent viscosity evaluated at the characteristic shear rate given in Eq. (6), along with the Bostwick measurement (Table 3). Figure 4 illustrates the linear relationship between L' (Bostwick measurement +5 cm) and the ratio $(\eta/\rho)^{-1/5}$. The regression line has a coefficient of determination of 0.994 with a slope of 0.0861 and intercept of −0.269. This relationship addressed the 1st objective of the study and established that the off-line Bostwick measurement for these blends can be predicted from the in-line apparent viscosity value.

Ketchups at 3 levels of NTSS were prepared from the 5 blends. Table 5 gives the soluble solids content and the Bostwick measurements for the ketchups. Each Bostwick entry is the average of 3 measurements and ± 1 standard deviation. The soluble solids entry is the average of 2 measurements. All formulations meet the requirement of 33% or more total solids; however, several have Bostwick measurements outside the 3 to 7 cm range specified by USDA (1992). Figure 5 addresses the 2nd objective of the study which was the relationship of the in-line viscosity of the blend to ketchups made from that blend. Linear correlations between

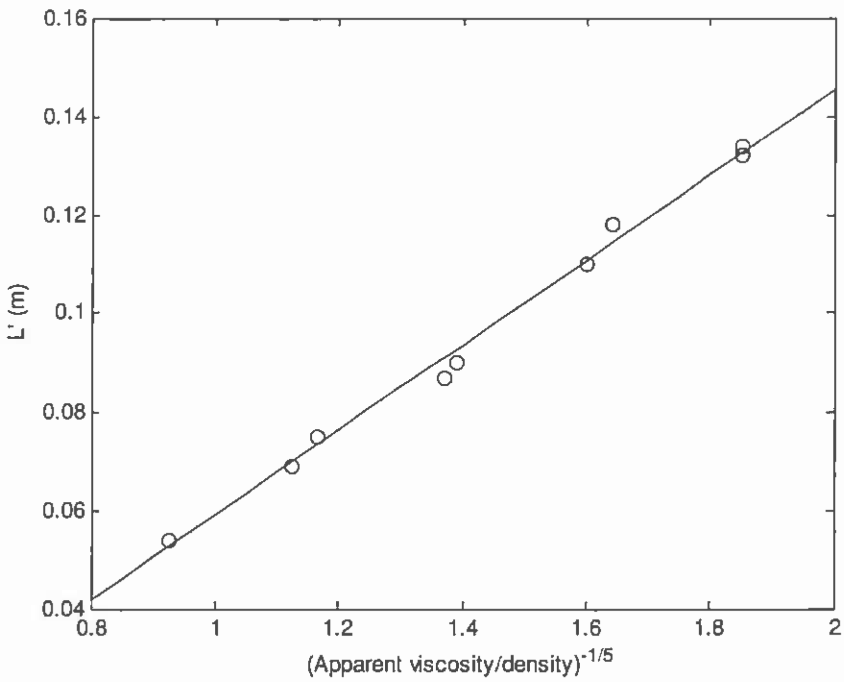

Figure 4—Relationship between apparent viscosity and L' (Bostwick measurement +5 cm). The regression line has a slope of 0.0861 and intercept of −0.0269 (R^2 = 0.994).

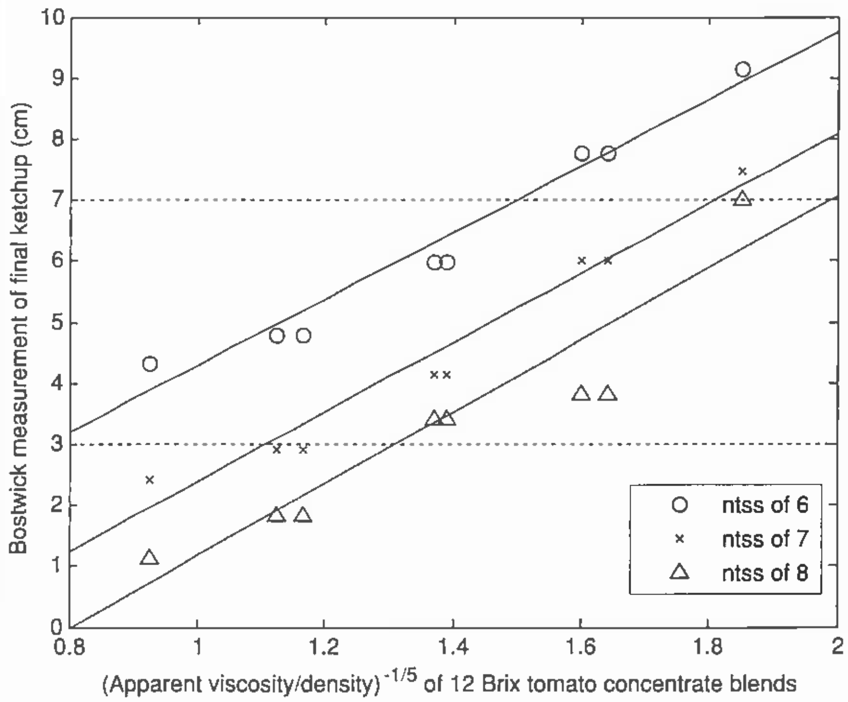

Figure 5—Correlation between apparent viscosity of the intermediate product tomato concentrate blends and the Bostwick length of ketchups made to different NTSS. The slopes are 5.447 (R^2 = 0.970), 5.691 (R^2 = 0.970), and 5.896 (R^2 = 0.910) for 6%, 7%, and 7.8% NTSS, respectively.

Table 5—Soluble solids and Bostwick measurements of the ketchups made from the 5 tomato concentrate blends.

Mass fraction of paste H-8	% NTSS	Soluble solids (°Bx)	Bostwick (cm)
0.00	6.0	32.4	4.3 ± 0.1
0.25		32.8	4.8 ± 0.1
0.50		32.6	6.0 ± 0.1
0.75		32.4	7.8 ± 0.1
1.00		32.4	9.1 ± 0.1
0.00	7.0	33.6	2.4 ± 0.1
0.25		33.8	2.9 ± 0.1
0.50		34.4	4.1 ± 0.1
0.75		33.1	6.0 ± 0.0
1.00		33.6	7.5 ± 0.1
0.00	7.8	34.6	1.1 ± 0.1
0.25		34.5	1.8 ± 0.1
0.50		34.2	3.4 ± 0.1
0.75		34.3	3.8 ± 0.1
1.00		33.9	7.0 ± 0.2

the ketchup Bostwick measurement for each NTSS is illustrated in Figure 5, as well as the desired 3 to 7 cm Bostwick range. As stated previously, 12 °Bx blends in the Bostwick range of 2 to 4 cm (mass fractions from 0.23 to 0.51 H-8) were expected to yield good quality ketchup, as characterized by ketchup Bostwick measurements between 3 and 7 cm. The 0.50 H-8 blend, at $(\eta/\rho)^{-1/5}$ value of 1.4, yielded ketchup Bostwick measurements in this range for all 3 NTSS. The 0.25 H-8 blend yielded acceptable ketchup Bostwick values between 6% and 7% NTSS $[(\eta/\rho)^{-1/5} = 1.1]$. In addition, the 0.75 H-8 blend produced acceptable ketchup in the range of 7% to 8% NTSS $[(\eta/\rho)^{-1/5} = 1.6]$, and the 0.0 H-8 blend produced an acceptable ketchup at 6% NTSS $[(\eta/\rho)^{-1/5} = 0.9]$.

Conclusions

Twelve °Bx tomato concentrate blends were prepared from 2 different tomato pastes. The blends were characterized as Herschel–Bulkley fluids by in-line MR-based viscometry. The in-line viscosities of the intermediate product (the blends) were correlated to final product Bostwick measurements. With this approach, a range of blends were identified that yielded the consistency required for Grade A ketchup. The application is an in-line viscosity measurement that predicts the Bostwick measurement of the final product.

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