

IN-LINE MONITORING OF TOMATO CONCENTRATE PHYSICAL PROPERTIES DURING EVAPORATION

YOUNG JIN CHOI¹, REBECCA R. MILCZAREK¹, CHARLES E. FLECK²,
T. CASEY GARVEY², KATHRYN L. MCCARTHY^{1,3} and
MICHAEL J. MCCARTHY¹

¹*Department of Food Science and Technology
One Shields Avenue
University of California, Davis
Davis, CA 95616*

²*ConAgra Foods Research and Development
Davis, CA 95616*

Accepted for Publication July 13, 2006

ABSTRACT

This work continues the development of an ultrasonic sensor system for in-line measurement of the physical properties of fluid foods. The test system was a semi-batch evaporator in which juice from three varieties of processing tomatoes was concentrated from 5 to 24 Brix. The physical properties of the tomato concentrates were measured and correlated to ultrasound properties. Speed of sound was linearly correlated with density, soluble solids content and total solids content of the tomato concentrates. Shear viscosity of the tomato concentrates flowing in viscometric pipe flow was evaluated using ultrasonic Doppler velocimetry (UDV). The UDV technique combines a fluid velocity profile and a simultaneous pressure drop to create a rheogram. Simple shear viscosity was modeled as power law behavior for tomato concentrates as a function of solids content for the three processing varieties. Off-line measurements of apparent viscosity were well correlated to the in-line measurements.

INTRODUCTION

Over 95% of the processing tomatoes in the U.S.A. are produced in California, with industry production valued at \$719 million (USDA-NASS Agricultural Statistics 2005). The goal of U.S. processors is to remain competitive in a global economy. To do so, in-line sensor technologies are

³ Corresponding author. TEL: 530-752-1487; FAX: 530-752-4759; EMAIL: klmccarthy@ucdavis.edu

developed to provide rapid and reliable feedback for process control. This work reports the use of ultrasonic methods as a rapid and effective means to incorporate in-line measurement in a processing facility.

Acoustical properties, specifically the speed of sound and the attenuation coefficient, can be used as property indices for food systems. The speed of sound has been used as an index to characterize concentration, composition and temperature of aqueous solutions. In early work, Winder *et al.* (1970) found that the speed of sound has a linear correlation to alcohol concentration in an alcohol/water mixture. Contreras *et al.* (1992) studied the relation between speed of sound of sugar solutions with concentration and temperature and summarized the results with an empirical equation. For aqueous solutions of dextran, Akashi *et al.* (2000) found that speed of sound is linearly proportional to dextran concentration. As dextran concentration is linearly proportional to density, speed of sound has a linear correlation to density.

The attenuation coefficient, which is a measure of the energy loss of the sound waves during transmission in the fluid, is related to particle size and particle properties of the fluid. Gladwell *et al.* (1985) characterized the rheological properties of edible oil using ultrasonic attenuation behavior. In addition, the radii of the droplets in an emulsion can be measured by studying the attenuation based on ultrasonic scattering theories (McClements and Coupland 1996). This approach was applied to evaluate the milk homogenization process (Miles *et al.* 1990).

The ultrasonic Doppler velocimetry (UDV) technique, also called ultrasonic pulsed echo Doppler, was originally developed in the field of medicine mainly for measuring blood flow (Histand *et al.* 1973; Jorgensen *et al.* 1973). This technique was extended to the flow measurements in physics and engineering (Takeda 1986; Markou and Ku 1991; Takeda 1991; Hughes and How 1994). Not only can the UDV technique measure flow, but it can also be applied to evaluate rheological properties of fluids. Combining a velocity profile obtained by the UDV technique with a simultaneous pressure drop measurement allows the evaluation of various rheological properties during viscometric pipe flow. The feasibility of UDV as a rheological technique has been demonstrated for corn syrup solution and tomato juice (Choi *et al.* 2002), fat suspension (Ouriev *et al.* 2000), precrystallized fluid chocolate (Ouriev *et al.* 2003), suspensions (Ouriev and Windhab 2002, 2003) and body lotion (Brunn *et al.* 2004). The rheological properties evaluated by the UDV technique are useful for process characterization and quality control (Wunderlich and Brunn 1999; Choi *et al.* 2002).

The objective of this work was to measure tomato concentrate physical properties during evaporation and correlate these properties to ultrasound properties and to measure fluid viscosity in-line using UDV.

MATERIALS AND METHODS

Three varieties of processing tomatoes were evaluated: Orsetti 3155, Heinz 9557 and AB 2. These varieties represent raw materials that are used as a medium-viscosity peeler type (Orsetti 3155), a high-viscosity paste (Heinz 9557) and a low-viscosity peeler type (AB 2). Tomatoes were hand-harvested and transported to the processing facility. Clean mature whole fruit were ground and processed through hot break (~107C for 9–15 s, with 5 min of hold at 100C). Seeds and skin were removed with a specially designed bench-scale continuous feed finisher (designed for 1 L/min with a 6.9-cm outer diameter [OD] impeller operating at 1,750 rpm and 7.7-cm OD screen with 1.14-mm openings) (American International Manufacturing, Woodland, CA). Juice was immediately deaerated in a 20-L glass-walled vacuum vessel operating at 26.7 kPa (constructed at ConAgra Foods Research and Development, Davis, CA). The total volume of juice was approximately 120 L; initial soluble solids content ranged from 5.2 to 6.5 Brix. The juice was held in cold storage at 4C until processing. The custom-built semi-batch evaporation unit was charged with 35 L of juice. The sequence of the start-up procedure was: (1) circulate the fluid using a gear pump (Model 024, Wakkasha Pump, Cherry-Burrell, Delavar, WI); (2) provide the steam heating medium at 130C to the tube and shell heat exchanger (56 4.76-mm tubes in a 38.1-mm OD stainless steel sanitary pipe); and (3) start the vacuum pump (Model TRSC 40-100/C/F, Coker Pump and Equipment Co., Salida, CA) to maintain system pressure at 9.9 kPa within the vapor-concentrate separator.

Under normal concentrating conditions, the evaporator system temperature was 60C, controlled by steam flow rate to the heat exchanger. The tomato concentrate circulated at a flow rate in the range of 3,800–7,600 mL/min. Fresh feed was added at a rate of 150 mL/min until the entire batch of juice was incorporated into the system. No product was drawn off, with the exception of sampling for off-line physical property testing. Concentration over a period of 10–12 h continued to a soluble solids content of 20–24 Brix. Two trials were performed with each of the three varieties.

To incorporate a test section for the ultrasound measurements, a section of U-shaped piping was connected between the heat exchanger and the vacuum separator. A schematic diagram of the experimental flow system is shown in Fig. 1. The flow section for the ultrasound measurements consisted of 3.81-mm OD stainless steel sanitary piping. The straight section upstream of ultrasound transducers ensured sufficient distance for fully developed flow for viscometric measurements.

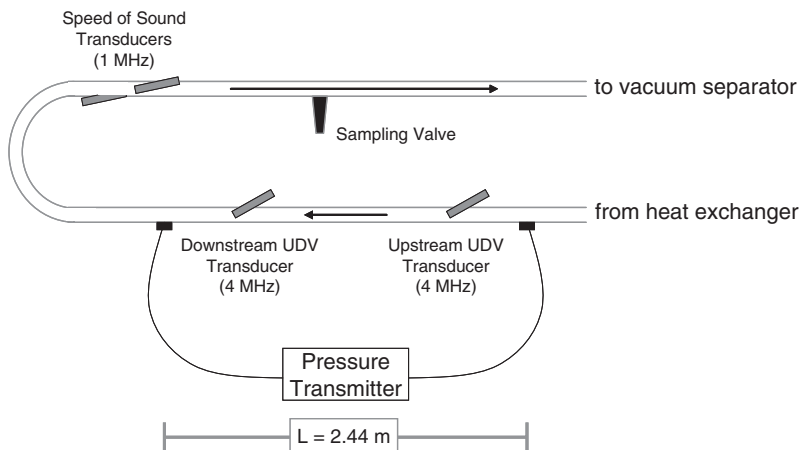


FIG. 1. SCHEMATIC OF THE TEST SECTION OF THE EVAPORATOR SYSTEM

Physical Property Measurement

Total Solids. Total solids content of the sample was determined by vacuum oven method (Isotemp Vacuum Oven, Model 280A, Fisher Scientific, Hampton, NH). A sample of approximately 1 g was put into an aluminum-weighing dish and weighed. The sample was then dried at 70–72°C for a minimum of 12 h at a pressure of 16.6 kPa. After drying, the sample was removed from the oven and weighed. The fraction of total solids was calculated as the ratio of the dried sample mass to the raw sample mass. The test was performed in triplicate; the mass fraction of the replicates was averaged.

Soluble Solids. Soluble solids were measured by a refractometer (RFM 320 Refractometer, Bellingham & Stanley, Ltd., Tunbridge Wells, Kent, U.K.) at 20°C. Approximately 0.5 mL of tomato concentrate was placed directly on the refractometer glass surface for the reading in Brix. The soluble solids reading was a sucrose scale and temperature compensated.

Density. A U.S. standard weight per gallon cup (Paul N. Gardener Co., Inc., Pompano Beach, FL) with 83.2-mL volume was used for density measurements of tomato concentrate samples at process temperature ($50 \pm 5^\circ\text{C}$). Measurements were accurate to four significant digits.

Rheology: Off-line Apparent Viscosity. The off-line apparent viscosity of the tomato concentrates was measured by rotational viscometry (Viscotester

VT24, Haake, Saddle Brook, NJ) using the infinite cup geometry. The bob dimensions were 25 mm in diameter and 50 mm high; cup dimensions were 86 mm in diameter and 112 mm high. The bob was immersed in the tomato concentrate to a depth of 64 mm and rotated at 27.1 rpm. Using a Newtonian approximation for the shear rate at the bob, this geometry corresponds to a characteristic shear rate of 6.2/s (Steffe 1996). The tomato concentrates were evaluated at process temperature ($50 \pm 5^\circ\text{C}$).

Ultrasound Properties

Speed of Sound. The Ritec ultrasonic system (Ritec, Inc., Warwick, RI) consists of a square wave pulser, a broadband receiver and a diplexer. The system is especially suitable for speed of sound and attenuation coefficient measurements and was used for both off-line and in-line measurements.

Off-line speed-of-sound measurements were made in a 30-mL sample cell. Tomato concentrate was loaded into this specially designed measurement cell. Ultrasound signals at 5 MHz were sent and echoes from the reflection surface were received. The speed of sound through the sample, c , was determined by the ratio of $2D$ to t , where D was the distance between the ultrasound transducer surface and the reflection surface (1.00 cm) and t was the time of flight of the ultrasound between the two surfaces. Echo spectrum construction and analyses were performed using MatLab7.0.0 (R14) software (The MathWorks Inc., Natick, MA). The MatLab program identified the peak value of two continuous echoes for calculating the time of flight.

In-line speed-of-sound measurements were made using a 1-MHz pitch-and-catch system. A pair of 1-MHz ultrasonic transducers were inserted opposite one another in the upper section of the test portion of the flow loop. One transducer transmitted an ultrasonic pulse through the flowing fluid and the other transducer received the ultrasonic signal. Unlike off-line speed-of-sound measurement, the transmitted ultrasonic pulse was not reflected and traveled only the distance d across the pipe. Therefore, the speed of sound through the sample c was evaluated by the ratio of d to t , where t was the time of flight of the ultrasound between the two transducers. Analyses were performed with MatLab7.0.0.

Attenuation Coefficient. The off-line echo spectrum was also used to determine the attenuation coefficient α , defined by:

$$I = A\exp(-\alpha D) \quad (1)$$

where I is the normalized echo amplitude (echo amplitude/full scale of the analog-to-digital board) and D is the flight distance of ultrasound. The flight

distance between any continuous two echoes was 1 cm. Regression on seven continuous echoes yielded two parameters, A and α . It should be pointed out that the decay coefficient measured in the ultrasound measurement cell was not only a fluid-dependent parameter, but related to the reflector surface property as well.

UDV. UDV is based on the response of ultrasonic energy as it is reflected from the fluid sample. The UDV transducer, in contact with the fluid sample at a given angle θ , emits a pulse train through the sample and receives echoes from the sample, whose frequency is shifted because of Doppler effect. The velocity at that position, v , is a function of the Doppler shift frequency f_D and speed of sound in the sample c through the relationship:

$$v = \frac{cf_D}{2f_0 \cos \theta} \quad (2)$$

where f_0 is the ultrasound frequency.

The radial position r of this velocity component is evaluated by identifying the radial component of the distance x traveled by the sound wave. The value of r is related to the speed of the reflected wave and the distance traveled by:

$$r = x \cdot \sin \theta = \frac{c\tau}{2} \sin \theta \quad (3)$$

where τ is the time interval between transmitting and receiving the signal (Takeda 1986, 1991).

The ultrasonic velocity profile monitor was a Met-flow unit (UVP-DUO MX, Met-flow SA, Lausanne, Switzerland). Two 4-MHz ultrasound transducers (IM-HP-1/4-2 Xactex, Pasco, WA) were inserted into the pipe wall at a 45° angle to contact the fluid. The basic ultrasound frequency f_0 was set to 4 MHz with a pulse cycle of 5–20 and repetition number of 200. The pulse repetition frequency was adjusted in the range of 1–3 kHz by changing the maximum depth of the profile. The number of channels was 64 or 128. These parameters provided a velocity resolution and a radial resolution of less than 3 mm/s and 1 mm, respectively. In order to improve the accuracy of the velocity measurement, 256 consecutive velocity profiles were averaged to generate one velocity profile.

Coupled with the velocity profile image, a pressure drop across the distance L of 2.44 m was measured using a differential pressure transducer (Model PX771, Omega Engineering, Stamford, CT).

Shear viscosity was evaluated according to procedures given in Choi *et al.* (2002). The force balance, which equates pressure forces to viscous forces during viscometric flow, provides the relationship between the shear stress, σ , and the tube radius, r :

$$\sigma(r) = \frac{-(\Delta P)}{2L}r \quad (4)$$

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:

$$\dot{\gamma}(r) = \left| \frac{dv(r)}{dr} \right| \quad (5)$$

where v is the axial velocity. Using Eqs. (4) and (5), the apparent viscosity η is determined by:

$$\eta(r) = \frac{\sigma(r)}{\dot{\gamma}(r)} \quad (6)$$

The flow behavior of the tomato concentrates was best modeled by the power law model:

$$\sigma = K\dot{\gamma}^n \quad (7)$$

where K is the consistency index and n is the flow behavior index.

All the rheological calculations were performed using a MatLab graphical user interface program. The detailed data-processing protocol is given in Choi *et al.* (2005).

RESULTS AND DISCUSSION

Ultrasonic Characterization of Physical Properties

Speed of Sound. For all three tomato varieties, in-line speed-of-sound measurements correlated linearly with both total solids content (Fig. 2a) and soluble solids content in Brix (Fig. 2b). This result is in agreement with previous findings that, at a given temperature, speed of sound increased with sucrose concentration (Contreras *et al.* 1992; Saggin and Coupland 2001) and

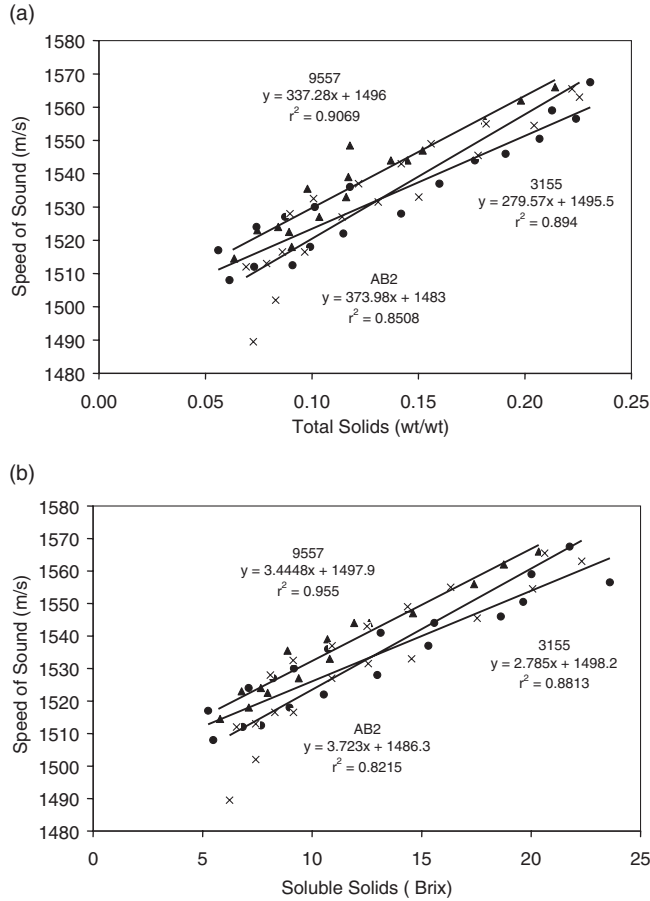


FIG. 2. RELATIONSHIP BETWEEN IN-LINE SPEED OF SOUND ($T = 60^{\circ}\text{C}$) AND (A) TOTAL SOLIDS AND (B) SOLUBLE SOLIDS BY VARIETY
●, Orsetti 3155; ▲, Heinz 9557; ×, AB 2.

concentration of tomato solids in the form of ketchup (Saggin and Coupland 2001). While the correlations in Fig. 2 are identified by tomato variety, the three varieties can be examined together, as for density in Fig. 3.

Figure 3 shows the linear relationship between speed of sound and tomato concentrate density for both in-line (Fig. 3a) and off-line (Fig. 3b) measurement techniques. All three tomato varieties are represented together in these correlations. When all other variables are held constant, increasing the density of a fluid is expected to decrease the speed of sound. However, in the tomato concentrate system, as in simple solutions of sucrose in water, the effect of the

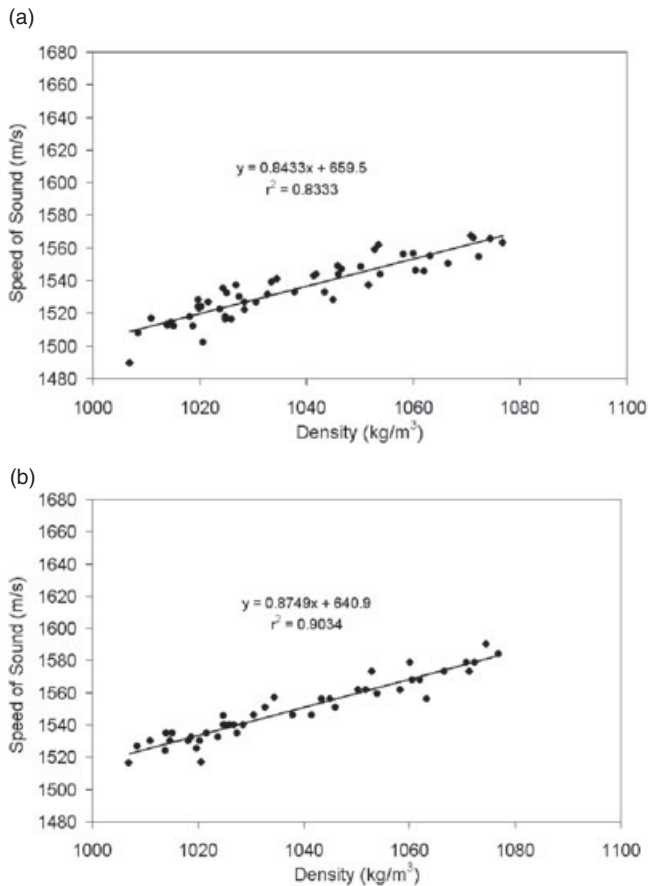


FIG. 3. RELATIONSHIP BETWEEN SPEED OF SOUND AND DENSITY OF TOMATO CONCENTRATES AT PROCESS TEMPERATURE, ALL VARIETIES

Speed of sound was measured (a) in-line with a pitch-catch regime using 1-MHz ultrasonic transducers and (b) off-line with a pulse-echo regime using a 5-MHz ultrasonic transducer.

increase in soluble and total solids dominates the change in sound velocity. This results in a directly proportional relationship between speed of sound and density (Kress-Rogers 2001). In this study, density was highly correlated with both soluble solids content and total solids content (data not shown). Thus, a strong linear correlation was found between speed of sound and density. The relationship holds for both the in-line pitch-catch regime and the off-line pulse-echo regimen, documenting consistency between the two methods of measurement.

Attenuation Coefficient. The attenuation measurement was determined from multiple echoes in the off-line testing cell. Although the attenuation coefficient would be expected to increase with increasing total solids content, soluble solids content and density, no clear relationship among these variables was found in this study. As shown in Fig. 4, plots of attenuation coefficient versus the three physical parameters illustrate only general trends. Within a run for one variety, some structure may be observed, but no relationship can be applied to the results of all six trials taken as a whole.

UDV Characterization of Apparent Viscosity

A representative mean velocity profile is shown in Fig. 5a for Orsetti 3155 at 5.5 Brix. The radial distance is given in distance from the pipe wall. Velocity profiles were taken under steady and fully developed flow condition in the straight section of pipe. The velocity profiles showed non-Newtonian behavior as illustrated by the blunted flow region in the center of the pipe. This flow behavior is typical of suspensions and fluids with particulates. As the concentration of tomato solids increased, the plug flow region increased in radial dimension. The fluids did not exhibit slip at the pipe wall. However, far-field artifacts are seen at the far side of the pipe (at a radial distance of 3 cm). These far-field artifacts are typical in UDV applications and are due to alteration of the acoustic field by multiple echoes of the ultrasonic pulses (Eckert and Gerbeth 2002; Bachelet *et al.* 2003).

Considering the symmetry of velocity profile under isothermal, fully developed laminar flow condition, half of the velocity profile provides sufficient information to evaluate rheological properties of the fluid. Therefore, the near-half of the velocity profile from the transducer was used for further data analysis. In Fig. 5b, the truncated velocity profile is shown with power law fit. Even though a small deviation at the near pipe wall was present, the velocity profile generally obeyed power law fluid behavior. As the tomato concentration increased, the shearing region decreased regardless of the variety. Tables 1–3 give the power law parameters for each trial of all three varieties. The shear rate range was typically from 0.15 to 60/s. For each variety, the consistency index increased with increasing Brix. Heinz 9557 has the highest values, followed by Orsetti 3155. Both those varieties have exponential trends in the increasing value of K . In contrast, the AB 2 values of the consistency index are lower and have a more linear trend with increasing Brix. The flow behavior index, n , ranges from approximately 0.40 to 0.13 with a general downward trend as the solids content increases.

Visually, log-log plots of apparent viscosity versus shear rate (Fig. 6) provide direct comparison of the varieties as they were sampled at approximately the same solids content. Even though the shear rate range was

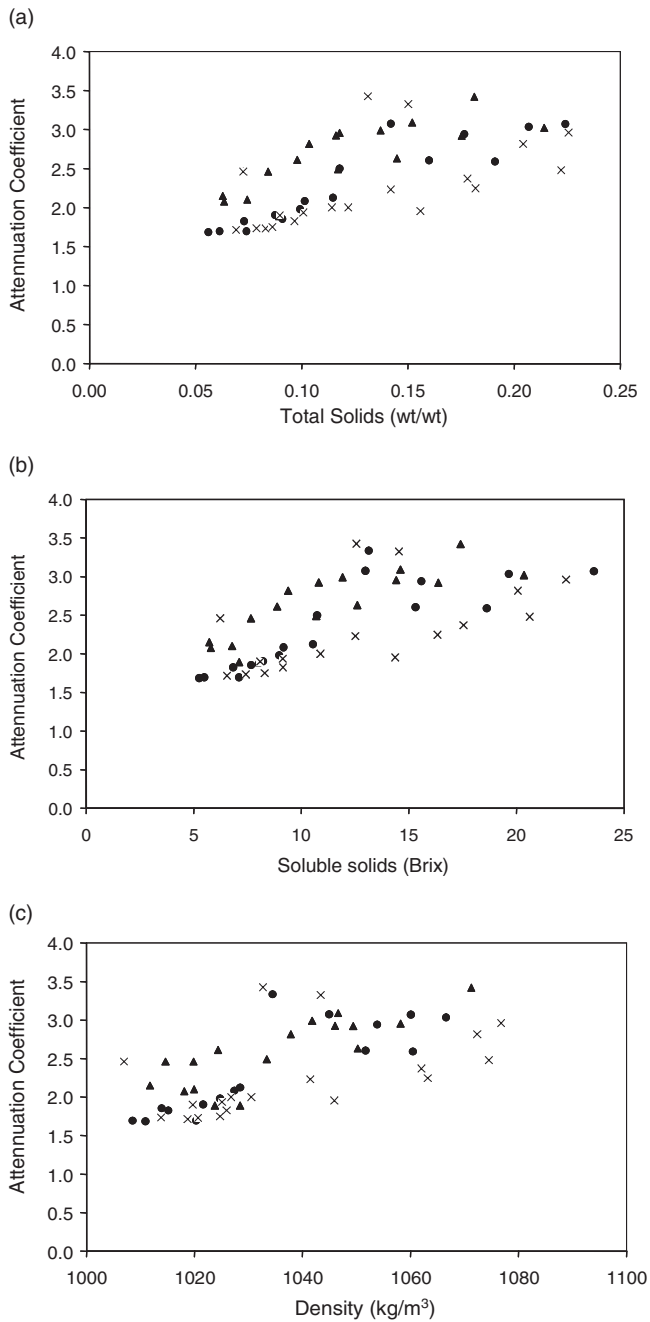


FIG. 4. RELATIONSHIP BETWEEN ATTENUATION AND (A) TOTAL SOLIDS, (B) SOLUBLE SOLIDS AND (C) DENSITY BY VARIETY

●, Orsetti 3155; ▲, Heinz 9557; ×, AB 2.

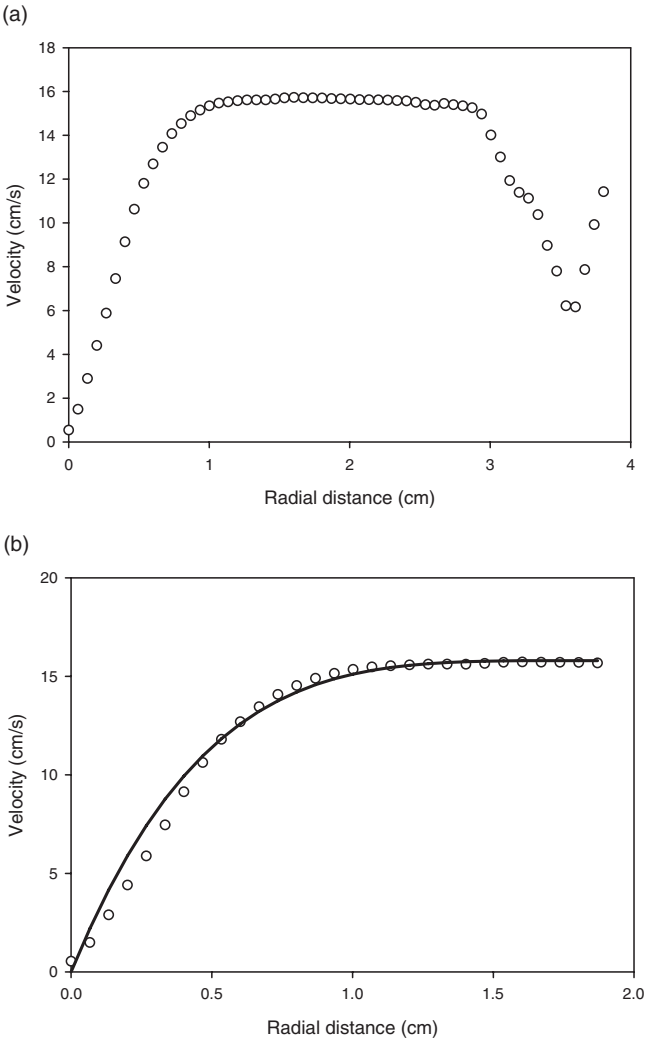


FIG. 5. REPRESENTATIVE ULTRASONIC DOPPLER VELOCIMETRY DATA OF Orsetti 3155 AT 5.5 Brix

(a) Velocity profile, (b) data analysis using the near-half of the ultrasonic Doppler velocity profile (○) with a power law model fit (—)

dependent on the flow rate, it ranged from 0.2/s to a minimum of 30/s under the experimental conditions. In Fig. 6a, the apparent viscosities of each variety prior to evaporation are given. The soluble solids contents of all the varieties were approximately 5 Brix. Prior to evaporation, the viscosity of

TABLE 1.
POWER LAW PARAMETERS FOR VARIETY HEINZ 9557 AT T = 60°C, AS A FUNCTION OF
CONCENTRATION OVER A SHEAR RATE RANGE OF 0.15–66/s

Trial 1				Trial 2			
Brix	K (Pa·s ^{<i>n</i>})	<i>n</i>	R^2	Brix	K (Pa·s ^{<i>n</i>})	<i>n</i>	R^2
5.7	5.0	0.315	0.998	5.8	5.4	0.281	0.998
6.8	9.8	0.257	0.986	7.1	8.7	0.274	0.992
7.7	13.3	0.249	0.977	8.0	11.8	0.268	0.978
8.9	19.1	0.256	0.987	9.4	16.7	0.263	0.993
10.7	28.2	0.239	0.987	10.8	25.8	0.223	0.984
11.9	38.0	0.249	0.963	12.6	40.8	0.190	0.996
14.6	46.6	0.214	0.965	14.4	54.3	0.177	0.986
				17.4	65.9	0.175	0.984
				20.4	94.3	0.131	0.998

The parameters are averaged over two to four replicates.

TABLE 2.
POWER LAW PARAMETERS FOR VARIETY ORSETTI 3155 AT T = 60°C, AS A FUNCTION
OF CONCENTRATION OVER A SHEAR RATE RANGE OF 0.12–58/s

Trial 1				Trial 2			
Brix	K (Pa·s ^{<i>n</i>})	<i>n</i>	R^2	Brix	K (Pa·s ^{<i>n</i>})	<i>n</i>	R^2
5.5	3.0	0.372	0.998	5.2	2.4	0.308	0.999
6.8	4.7	0.394	0.997	7.1	5.4	0.332	0.999
7.7	6.2	0.380	0.996	8.2	7.6	0.352	0.995
9.0	9.4	0.368	0.994	9.2	11.7	0.314	0.978
10.5	18.6	0.275	0.981	10.7	17.0	0.301	0.985
13.0	33.1	0.223	0.993	13.1	27.5	0.260	0.997
15.3	43.3	0.210	0.990	15.6	45.1	0.209	0.998
18.6	61.8	0.181	0.997	20.0	81.1	0.149	0.993
19.6	83.9	0.146	0.997	21.8	99.5	0.149	0.990
23.6	84.6	0.179	0.986				

The parameters are averaged over two to four replicates.

Heinz 9557 was the highest, Orsetti 3155 was somewhat lower and AB 2 was the lowest. At this concentration, as well as when evaporation progressed, the varieties show a strong shear thinning behavior. The slope of the plots is ($n - 1$). The same general trend, with respect to varieties, continued as the solids content increased (Fig. 6b–d), with the apparent viscosity of Orsetti 3155 approaching the apparent viscosity of Heinz 9557 at a given shear rate.

TABLE 3.
POWER LAW PARAMETERS FOR VARIETY AB 2 AT T = 60C, AS A FUNCTION OF
CONCENTRATION OVER A SHEAR RATE RANGE OF 0.10–61/s

Trial 1				Trial 2			
Brix	$K \text{ (Pa}\cdot\text{s}^n)$	n	R^2	Brix	$K \text{ (Pa}\cdot\text{s}^n)$	n	R^2
6.2	4.3	0.239	0.854	6.5	2.6	0.357	0.999
7.4	5.7	0.317	0.973	7.4	3.5	0.340	0.999
8.1	7.6	0.237	0.999	8.3	5.2	0.290	0.998
9.1	8.7	0.304	0.957	9.2	7.2	0.254	0.980
10.9	14.5	0.253	0.995	10.9	10.3	0.260	0.993
12.5	22.1	0.185	0.999	12.6	20.2	0.183	0.988
14.4	28.7	0.202	0.996	14.5	27.8	0.151	0.992
16.3	37.2	0.147	0.990	17.5	39.3	0.169	0.969
				20.1	52.4	0.180	0.988
				22.3	55.3	0.201	0.990

The parameters are averaged over two to four replicates.

Comparison of Off-line and In-line Apparent Viscosity Measurements

Figure 7 illustrates the linear correlation between off-line and in-line apparent viscosity measurements evaluated at 6.2/s. This correlation, with a coefficient of determination of $r^2 = 0.99$, indicates good agreement between the infinite cup geometry of the Haake VT24 and the in-line UDV shear viscosity measurement. However, the slope of the curve in Fig. 7 is 0.67, not a slope value of 1. This discrepancy is likely caused by two factors: the temperature dependence of the viscosity and the assumptions used for determining apparent viscosity from the infinite cup geometry. The off-line measurement of apparent viscosity was performed approximately 2 min after sample material was taken from the processing line. In this time interval, the tomato concentrate cooled as much as 15C from the process temperature of 60C. At the same solids content, the apparent viscosity of tomato concentrate is expected to decrease exponentially with temperature (Lee *et al.* 2002). Therefore, the apparent viscosity of a cooler, off-line sample would be expected to be higher than its in-line counterpart. In addition, a major assumption used for the conversion of the Haake VT24 reading to an apparent viscosity value is that the fluid at the bob/fluid interface exhibits Newtonian behavior. Although this assumption is appropriate for a first approximation of apparent viscosity, the tomato concentrates analyzed in this experiment were clearly non-Newtonian. Thus, in this experiment, deviation of the in-line and off-line values of apparent viscosity was expected. The correlation is strong enough that the UDV system could replace a single point reading off-line viscometer in a production setting.

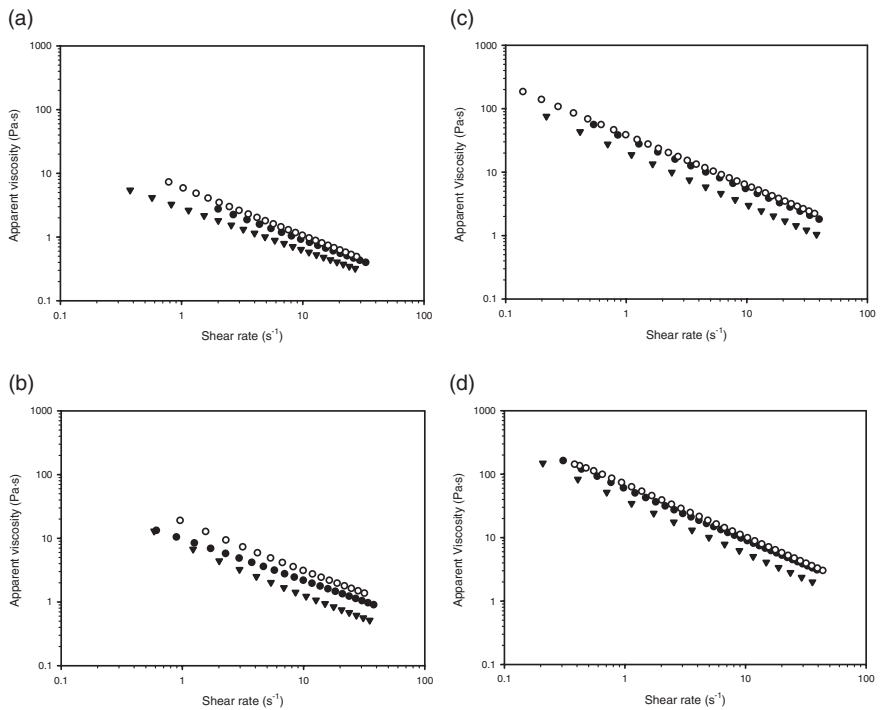


FIG. 6. APPARENT VISCOSITIES AS A FUNCTION OF VARIETY AT SOLUBLE SOLIDS OF APPROXIMATELY (A) 5 Brix, (●) ORSETTI 3155 AT 5.5 Brix, (○) HEINZ 9557 AT 5.8 Brix AND (▼) AB 2 AT 6.5 Brix; (B) 9 Brix, (●) ORSETTI 3155 AT 9.0 Brix, (○) HEINZ 9557 AT 9.4 Brix AND (▼) AB 2 AT 9.2 Brix; (C) 12 Brix, (●) ORSETTI 3155 AT 13.0 Brix, (○) HEINZ 9557 AT 12.6 Brix AND (▼) AB 2 AT 12.6 Brix; (D) 17 Brix, (●) ORSETTI 3155 AT 18.6 Brix, (○) HEINZ 9557 AT 17.4 Brix AND (▼) AB 2 AT 17.5 Brix

In summary, ultrasound technologies show good promise as in-line sensors for fluid tomato products. Speed of sound correlates with tomato solids content and density. UDV provides an in-line means to measure shear viscosity. In-line measurements were successful over a wider Brix range than previously reported and the measurements are robust with respect to tomato variety.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of the summer processing crew at the ConAgra facility: Megan Caulder, Christine Danbom, Nina Ghamrawi, Casey Schroeder, Davy Seng, Lea Shell and Alison Wohlgemuth.

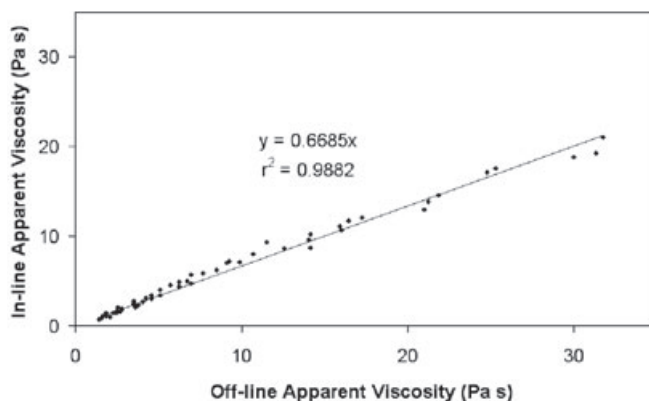


FIG. 7. RELATIONSHIP BETWEEN OFF-LINE APPARENT VISCOSITY AND IN-LINE APPARENT VISCOSITY, EVALUATED AT 6.24/s

REFERENCES

- AKASHI, N., KUSHIBIKI, J. and DUNN, F. 2000. Measurements of acoustic properties of aqueous dextran solutions in the VHF/UHF range. *Ultrasonics* 38, 915–919.
- BACHELET, C., DANTAN, P.H. and FLAUD, P. 2003. Indirect on-line determination of Newtonian fluid viscosity based on numerical flow simulations. *Eur. Phys. J. AP* 21, 67–73.
- BRUNN, P.O., WUNDERLICH, T. and MULLER, M. 2004. Ultrasonic rheological studies of a body lotion. *Flow Meas. Instrum.* 15, 139–144.
- CHOI, Y.J., MCCARTHY, K.L. and MCCARTHY, M.J. 2002. Tomographic techniques for measuring fluid flow properties. *J. Food Sci.* 67, 2718–2724.
- CHOI, Y.J., MCCARTHY, K.L. and MCCARTHY, M.J. 2005. A MATLAB user interface program for tomographic viscometer data processing. *Comput. Electron. Agric.* 47, 59–67.
- CONTRERAS, N.I., FAIRLEY, P., MCCLEMENTS, D.J. and POVEY, M.J.W. 1992. Analysis of the sugar content of fruit juice and drinks using ultrasonic velocity measurements. *Int. J. Food Sci. Technol.* 27, 515–529.
- ECKERT, S. and GERBETH, G. 2002. Velocity measurements in liquid sodium by means of ultrasound Doppler velocimetry. *Exp. Fluid* 32, 542–546.
- GLADWELL, N., JAVANAUD, C., PETER, K.E. and RAHALKAR, R.R. 1985. Ultrasonic behaviour of edible oils: Correction with rheology. *J. Am. Oil Chem. Soc.* 62, 1231–1236.

- HISTAND, B.M., MILLER, C.W. and MCLEOD, F.D. 1973. Transcutaneous measurement of blood velocity profiles and flow. *Cardiovasc. Res.* 7, 703–712.
- HUGHES, P.E. and HOW, T.V. 1994. Pulsatile velocity distribution and wall shear rate measurement using pulsed Doppler ultrasound. *J. Biomech.* 27, 103–110.
- JORGENSEN, J.E., CAMPAU, D.N. and BAKER, D.W. 1973. Physical characteristics and mathematical modeling of the pulsed ultrasonic flowmeter. *Med. Biol. Eng.* 11, 404–420.
- KRESS-ROGERS, E. 2001. Ultrasound propagation in foods and ambient gases: Principles and applications. In *Instrumentation and Sensors for the Food Industry*, 2nd Ed. (E. Kress-Rogers and C.J.B. Brimelow, eds.), CRC Press, New York, NY.
- LEE, Y., BOBROFF, S. and MCCARTHY, K.L. 2002. Rheological characterization of tomato concentrates and the effect on uniformity of processing. *Chem. Eng. Commun.* 189, 339–351.
- MARKOU, C.P. and KU, D.N. 1991. Accuracy of velocity and shear rate measurements using pulsed Doppler ultrasound: A comparison of signal analysis techniques. *Ultrasound Med. Biol.* 17, 803–814.
- MCCLEMENTS, D.J. and COUPLAND, J.N. 1996. Theory of droplet size distribution measurements in emulsions using ultrasonic spectroscopy. *Colloids Surf. A* 117, 161–170.
- MILES, C.A., SHORE, D. and LANGLEY, K.R. 1990. Attenuation of ultrasound in milks and cream. *Ultrasonics* 28, 394–400.
- OURIEV, B., BREITSCHUH, B. and WINDHAB, E.J. 2000. Rheological investigation of concentrated suspensions using a novel in-line ultrasound Doppler method. *Colloid J.* 62, 234–237.
- OURIEV, B. and WINDHAB, E.J. 2002. Rheological study of concentrated suspensions in pressure-driven shear flow using a novel in-line ultrasound Doppler method. *Exp. Fluids* 32, 204–211.
- OURIEV, B. and WINDHAB, E.J. 2003. Transient flow of highly concentrated suspensions investigated using the ultrasound velocity profiler-pressure difference method. *Meas. Sci. Technol.* 14, 1963–1972.
- OURIEV, B., WINDHAB, E.J., BRAUN, P., ZENG, Y. and BIRKHOFER, B. 2003. Industrial application of ultrasound based in-line rheometry: Visualization of steady shear pipe flow of chocolate suspension in pre-crystallization process. *Rev. Sci. Instrum.* 74, 5255–5259.
- SAGGIN, R. and COUPLAND, J.N. 2001. Concentration measurement by acoustic reflectance. *J. Food Sci.* 66, 681–685.
- STEFFE, J.F. 1996. *Rheological Methods in Food Process Engineering*, 2nd Ed., Freeman Press, East Lansing, MI.

- TAKEDA, Y. 1986. Velocity profile measurement by ultrasound Doppler shift method. *Int. J. Heat Fluid Flow* 7, 313–318.
- TAKEDA, Y. 1991. Development of an ultrasound velocity profile monitor. *Nucl. Eng. Des.* 126, 277–284.
- USDA-NASS Agricultural Statistics. 2005. United States Department of Agriculture. <http://www.usda.gov/nass/pubs/agr05/acro05.htm> (accessed December 1, 2005).
- WINDER, W.C., AULIK, D.J. and RICE, A.C. 1970. An ultrasonic method for direct and simultaneous determination of alcohol and extract content of wines. *Am. J. Enol. Vitic.* 21, 1–11.
- WUNDERLICH, T.H. and BRUNN, P.O. 1999. Ultrasound pulse Doppler method as a viscometer for process monitoring. *Flow Meas. Instrum.* 10, 201–205.