IN-LINE MONITORING OF TOMATO CONCENTRATE PHYSICAL PROPERTIES DURING EVAPORATION

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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...
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 (~107°C for 9–15 s, with 5 min of hold at 100°C). 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 4°C 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, Wakkesha Pump, Cherry-Burrell, Delavar, WI); (2) provide the steam heating medium at 130°C 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 60°C, 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.
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 ± 5°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 ± 5C).

**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 deter-
mined by the ratio of \( 2D/t \), 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 Math-
Works 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 oppo-
site 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 \( d/t \), 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 \( \alpha \), defined by:

\[
I = A \exp(-\alpha D)
\]  

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 $\alpha$. 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 $\theta$, 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:

$$v = \frac{c f_D}{2 f_0 \cos \theta}$$  \hspace{1cm} (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:

$$r = x \cdot \sin \theta = \frac{c \tau}{2} \sin \theta$$  \hspace{1cm} (3)

where $\tau$ 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, $\sigma$, and the tube radius, $r$:

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

where $\Delta P$ is the pressure drop over the tube length $L$. The shear rate is obtained at the same radial position by differentiating the velocity data:

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

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

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

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

$$\sigma = K\dot{\gamma}^n$$

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
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

![Graph showing the relationship between speed of sound and tomato solids density](a)

![Graph showing the relationship between speed of sound and soluble solids concentration](b)

**FIG. 2. RELATIONSHIP BETWEEN IN-LINE SPEED OF SOUND (T = 60°C) AND (A) TOTAL SOLIDS AND (B) SOLUBLE SOLIDS BY VARIETY**

- •, Orsetti 3155; ▲, Heinz 9557; ×, AB2.
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.
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

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 (—)
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 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**

<table>
<thead>
<tr>
<th>Brix</th>
<th>(K) (Pa·s(n))</th>
<th>(R^2)</th>
<th>(n)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>5.0</td>
<td>0.315</td>
<td>0.998</td>
<td>5.8</td>
</tr>
<tr>
<td>6.8</td>
<td>9.8</td>
<td>0.257</td>
<td>0.986</td>
<td>7.1</td>
</tr>
<tr>
<td>7.7</td>
<td>13.3</td>
<td>0.249</td>
<td>0.977</td>
<td>8.0</td>
</tr>
<tr>
<td>8.9</td>
<td>19.1</td>
<td>0.256</td>
<td>0.987</td>
<td>9.4</td>
</tr>
<tr>
<td>10.7</td>
<td>28.2</td>
<td>0.239</td>
<td>0.987</td>
<td>10.8</td>
</tr>
<tr>
<td>11.9</td>
<td>38.0</td>
<td>0.249</td>
<td>0.963</td>
<td>12.6</td>
</tr>
<tr>
<td>14.6</td>
<td>46.6</td>
<td>0.214</td>
<td>0.965</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20.4</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Brix</th>
<th>(K) (Pa·s(n))</th>
<th>(R^2)</th>
<th>(n)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>3.0</td>
<td>0.372</td>
<td>0.998</td>
<td>5.2</td>
</tr>
<tr>
<td>6.8</td>
<td>4.7</td>
<td>0.394</td>
<td>0.997</td>
<td>7.1</td>
</tr>
<tr>
<td>7.7</td>
<td>6.2</td>
<td>0.380</td>
<td>0.996</td>
<td>8.2</td>
</tr>
<tr>
<td>9.0</td>
<td>9.4</td>
<td>0.368</td>
<td>0.994</td>
<td>9.2</td>
</tr>
<tr>
<td>10.5</td>
<td>18.6</td>
<td>0.275</td>
<td>0.981</td>
<td>10.7</td>
</tr>
<tr>
<td>13.0</td>
<td>33.1</td>
<td>0.223</td>
<td>0.993</td>
<td>13.1</td>
</tr>
<tr>
<td>15.3</td>
<td>43.3</td>
<td>0.210</td>
<td>0.990</td>
<td>15.6</td>
</tr>
<tr>
<td>18.6</td>
<td>61.8</td>
<td>0.181</td>
<td>0.997</td>
<td>20.0</td>
</tr>
<tr>
<td>19.6</td>
<td>83.9</td>
<td>0.146</td>
<td>0.997</td>
<td>21.8</td>
</tr>
<tr>
<td>23.6</td>
<td>84.6</td>
<td>0.179</td>
<td>0.986</td>
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</table>

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 15°C from the process temperature of 60°C. 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.

### Table 3.

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

<table>
<thead>
<tr>
<th>Trial 1</th>
<th></th>
<th></th>
<th></th>
<th>Trial 2</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Brix</td>
<td>$K$ (Pa·s$^n$)</td>
<td>$n$</td>
<td>$R^2$</td>
<td>Brix</td>
<td>$K$ (Pa·s$^n$)</td>
<td>$n$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>6.2</td>
<td>4.3</td>
<td>0.239</td>
<td>0.854</td>
<td>6.5</td>
<td>2.6</td>
<td>0.357</td>
<td>0.999</td>
</tr>
<tr>
<td>7.4</td>
<td>5.7</td>
<td>0.317</td>
<td>0.973</td>
<td>7.4</td>
<td>3.5</td>
<td>0.340</td>
<td>0.999</td>
</tr>
<tr>
<td>8.1</td>
<td>7.6</td>
<td>0.237</td>
<td>0.999</td>
<td>8.3</td>
<td>5.2</td>
<td>0.290</td>
<td>0.998</td>
</tr>
<tr>
<td>9.1</td>
<td>8.7</td>
<td>0.304</td>
<td>0.957</td>
<td>9.2</td>
<td>7.2</td>
<td>0.254</td>
<td>0.980</td>
</tr>
<tr>
<td>10.9</td>
<td>14.5</td>
<td>0.253</td>
<td>0.995</td>
<td>10.9</td>
<td>10.3</td>
<td>0.260</td>
<td>0.993</td>
</tr>
<tr>
<td>12.5</td>
<td>22.1</td>
<td>0.185</td>
<td>0.999</td>
<td>12.6</td>
<td>20.2</td>
<td>0.183</td>
<td>0.988</td>
</tr>
<tr>
<td>14.4</td>
<td>28.7</td>
<td>0.202</td>
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<td>27.8</td>
<td>0.151</td>
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<td>16.3</td>
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<td>0.990</td>
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<td>39.3</td>
<td>0.169</td>
<td>0.969</td>
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<td></td>
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<td></td>
<td>20.1</td>
<td>52.4</td>
<td>0.180</td>
<td>0.988</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>22.3</td>
<td>55.3</td>
<td>0.201</td>
<td>0.990</td>
</tr>
</tbody>
</table>

The parameters are averaged over two to four replicates.
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.

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