ON-LINE PREDICTION OF BOSTWICK CONSISTENCY FROM PRESSURE DIFFERENTIAL IN PIPE FLOW FOR KETCHUP AND RELATED TOMATO PRODUCTS

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ABSTRACT

An on-line sensor was developed by correlating pressure differential to Bostwick value for ketchup, crushed tomato and pizza sauce with Bostwick values from 4 - 12. Flow rate was varied from $6.3 \times 10^{-5}$ to $37 \times 10^{-5}$ m$^3$/s (1 to 6 gpm) and temperature from 93 to 46°C. The correlation was compared to samples measured in a factory, with mean deviations of 0.72 and 0.52 cm for ketchup and pizza sauce, respectively.

INTRODUCTION

The tomato processing industry and USDA standards of identity are based on a batch measure of consistency, the Bostwick consistometer, which does not facilitate on-line control. The Bostwick consistometer is also used to determine the consistence of baby foods, salad dressings and other tomato products. To make this measurement, a sample is removed from the product line and placed into the sample chamber. The sample flows along a channel by gravity. The distance, in cm, traveled by the sample in 30 s represents its consistency. Although it combines

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simplicity, ease of operation, and low cost, it has several disadvantages: (1) it can be a source of contamination during sample collection and cannot be automated or used for on-line control; (2) the reading is influenced by the skill of the operator, leveling, dryness of the instrument, temperature of the sample, shape of the leading edge of the flow, roughness of the bottom of the instrument, and serum separation at the edge of the flow; (3) effectiveness is compromised by operator variability. An on-line sensor would avoid the limitations of the Bostwick consistometer and also provide the advantage of a continuous and reliable signal for on-line control.

One of the first on-line sensors for ketchup was the plastometer, where product flowed through tubes of different diameters (Eokin 1956). Rao and Bourne (1997) analyzed the fundamental rheological quantities measured by this instrument, and found a linear correlation between the difference in apparent viscosity and the Bostwick readings, for fruit and vegetable purees. However, in a similar study Vercruysse and Steffe (1989) found poor correlation between the Bostwick value and apparent viscosity for baby food. Recent studies have modeled product flow in the Bostwick, producing analytical predictions of the relationship between kinematic viscosity and Bostwick readings during the gravity induced flow region (McCarthy and Seymour 1993, 1994). This model has been verified for silicone oil and tomato products.

Objectives

(1) Assessment of the feasibility of on-line sensing of Bostwick consistency via pressure differential measurements.

(2) Determination of the effect of varying flow rate, temperature and solids content on the pressure-differential-Bostwick value relationship.

MATERIALS AND METHODS

The samples tested were peeled, crushed tomato, tomato ketchup and pizza sauce (Hirzel Canning Company, Toledo, Ohio). The consistency of the crushed tomato was adjusted by adding tomato paste to thicken it to a Bostwick value of 4 cm. Ketchup was thickened with tomato paste and sugar in a 2:1 ratio. Samples with Bostwick values of 4 to 12 cm were created by diluting the thickened tomato products with water. The amount of water added was recorded so that the amount of additional water could be plotted versus the Bostwick value to determine the change in the distance of the Bostwick flow per liter of water added.

Bostwick consistency was measured in a Bostwick Consistometer (Redman Scientific Company, San Francisco, California.) For accurate results, the Bostwick consistometer was placed on a flat surface, leveled and carefully washed and dried
after every use. The small chamber of the Bostwick consistometer was filled with the sample, the sample was leveled and the gate of the chamber released. After 30 s the distance (cm) traveled by the sample was recorded. To minimize cooling, the hot sample was taken from the jacketed kettle and measured immediately by the Bostwick consistometer. Additional samples were collected and stored in screw-capped containers at room temperature for a day, then remeasured at room temperature.

The pressure differential was measured while pumping the product through a pipe. The system included a steam-jacketed kettle for controlling the temperature of the product, pump, surge tank, magnetic flowmeter (model 8711 TSA005R1, Rosemount, Inc., Eden Prairie, MN), and thermocouples at either end of the 2.3 cm interior diameter pipe (Fig. 1). The pipe was insulated to minimize temperature changes in the sample during the study. Attached to the pipe was a pressure transducer with pressure taps 265 cm apart. The pressure taps were placed 45 cm away from the ends of the pipe to avoid end effects. A datalogger was used to record the pressure differential, temperature and flow rate continuously. The temperature was varied from 93 to 46 °C. The flow rate was varied from $6.3 \times 10^{-5}$ to $37 \times 10^{-3}$ m$^3$/s (1 to 6 gpm).

FIG. 1. SCHEMATIC DIAGRAM OF THE LABORATORY TEST EQUIPMENT

The consistency coefficient was calculated from the pressure differential through the pipe. The measured pressure differential was plotted versus the six flow rates and a power law equation fit to determine the flow behavior index and consistency coefficient.

The pressure differential of pizza sauce and tomato ketchup was measured during an actual production run in a commercial plant (Hirzel Canning Company, Toledo, Ohio). The same piping used in the laboratory was installed in the factory, attached to the filling tank, where the finished products are stored for a short time before canning. The sample collection outlet was placed close to the pressure taps, so that the sample collected for Bostwick measurements was the same fluid as in the pressure transducer at that time. In the factory the flow rate through the pipe
was $22 \times 10^{-5}$ m³/s (3.5 gpm) and the temperature was 46C. The mean deviation was calculated as the average of the absolute difference between measured and predicted values.

The apparent viscosity was calculated at the average shear rate of the sample, determined from:

$$\dot{\gamma}_m = \frac{1}{R} \int_0^R \frac{dv}{dr} 2\pi rdr$$

where the velocity profile is that of a power law fluid in steady, fully-developed tube flow:

$$v = \left( \frac{3n+1}{n+1} \right) \frac{\nu}{1 - \left( \frac{r}{R} \right)^{n+1}}$$

Substituting Eq. 2 into Eq. 1, integrating, and taking the absolute value

$$|\dot{\gamma}_m| = \frac{2\nu}{R} \sqrt{\frac{3n+1}{2n+1}}$$

Apparent viscosities were calculated using the above mean shear rate for a power law fluid

$$\mu = K\dot{\gamma}_m$$

RESULTS AND DISCUSSION

A correlation was developed between pressure differential and Bostwick values. The effect of varying solids content, flow rate and temperature was determined, and on-line use was tested in a commercial factory.
Determination of Bostwick Value — Pressure Differential Relationship

The Bostwick value was plotted versus the inverse of the pressure differential, for a range of solid contents. The solids content was varied to cover the range from hot break juice to beyond a reasonable ketchup solids content, so that the plot could be used for an on-line prediction of Bostwick measurements during ketchup manufacture. The pressure differential can be converted to viscosity, however this does not improve the correlation. Therefore the plot is left as pressure differential for ease of use in an on-line sensor. For ketchup and crushed tomato, the results of flow rates from $6.3 \times 10^{-5}$ to $37 \times 10^{-5}$ m$^3$/s (1 to 6 gmp) is seen in Fig. 2 and 3, respectively. As expected, the pressure differential is greater at faster flow rates due to increasing frictional losses. The slopes of the lines increase with increasing flow rate, since ketchup and crushed tomato are shear thinning fluids which respond to the changing shear rate.

![Graph showing the relationship between Bostwick value and pressure differential for ketchup](image)

FIG. 2. EFFECT OF FLOW RATE ON THE RELATIONSHIP BETWEEN BOSTWICK VALUE AND PRESSURE DIFFERENTIAL FOR KETCHUP

There is a linear correlation between the Bostwick value and inverse of pressure differential between a Bostwick value of 14 and 6. At a given flow rate and fixed conditions, the pressure differential times a constant equals the viscosity, therefore there is also a linear correlation between the Bostwick value and viscosity. For product thicker than 6 cm, the linear relationship no longer holds. McCarthy and Seymour (1994) determined that after the initial 1 s of flow, the Bostwick distance is linearly related to the kinematic viscosity to the power -0.2. The data for ketchup was plotted in a similar manner, using Eq. 4 (Fig.4). The
result, Bostwick value versus (kinematic viscosity)$^{-0.2}$ was linear across the entire range, thus confirming their results.

![Graph showing Bostwick value versus (kinematic viscosity)$^{-0.2}$ for ketchup and crushed tomato.]

**Fig. 3.** Effect of flow rate on the relationship between Bostwick value and pressure differential for crushed tomato.

**Fig. 4.** Bostwick value versus (kinematic viscosity)$^{-0.2}$ for ketchup.

At selected Bostwick values the consistency coefficients for both ketchup and crushed tomato are presented in Table 1. The consistency coefficients were calculated from the pressure differential along the pipe at different flow rates, shown in Fig. 2 and 3.
TABLE 1.
CONSISTENCY INDEX FOR KETCHUP AND CRUSHED TOMATO

<table>
<thead>
<tr>
<th>Bostwick</th>
<th>crushed tomato</th>
<th>ketchup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k, Pa-s^n</td>
<td>n</td>
</tr>
<tr>
<td>5.1</td>
<td>274</td>
<td>0.29</td>
</tr>
<tr>
<td>5.8</td>
<td>272</td>
<td>0.32</td>
</tr>
<tr>
<td>6.2</td>
<td>218</td>
<td>0.28</td>
</tr>
<tr>
<td>7.3</td>
<td>214</td>
<td>0.31</td>
</tr>
<tr>
<td>7.9</td>
<td>194</td>
<td>0.32</td>
</tr>
<tr>
<td>9.1</td>
<td>157</td>
<td>0.30</td>
</tr>
<tr>
<td>9.6</td>
<td>143</td>
<td>0.30</td>
</tr>
<tr>
<td>10.7</td>
<td>126</td>
<td>0.30</td>
</tr>
<tr>
<td>12.4</td>
<td>112</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The correlation between Bostwick value and pressure differential is product dependent, as can be seen by comparing ketchup and crushed tomato (Fig. 2 and 3). These two tomato products differ compositionally in the amount of vinegar and sugar present, which affects the gel structure formed. For a given Bostwick value, the pressure differential for ketchup is 21-52% higher than for crushed. However, the consistency coefficients for ketchup and crushed tomato are not different (Table 1). Thus the stronger gel structure of the ketchup results in a greater apparent viscosity for a given Bostwick value, but its shear thinning curve is the same as for crushed tomato, as indicated by the consistency index.

The addition of water to change the Bostwick value of the sample also reflects the stronger gel structure present in ketchup. The amount of water added to the tomato products was plotted versus the Bostwick value to determine the change in the distance of the Bostwick flow per liter of water added (graph not shown). There was a linear correlation of 0.12 cm/1000 mL water added for ketchup and 0.22 cm/1000 mL water added for crushed tomato, in a 30 gallon sample (R^2>0.99). Twice as much water is required to change the Bostwick value of ketchup, as is required for crushed tomato.

The temperature dependence of the Bostwick distance also reflects the difference between ketchup and the other products. Comparing the Bostwick values at processing and room temperature, the average differences between the hot and cold values were 1.6 cm (27%) for ketchup, 2.2 cm (33%) for pizza sauce and 2.4 cm (32%) for crushed tomato. The value for ketchup was significantly different from pizza sauce or crushed tomato. Thus ketchup is more stable to
The effect of temperature on the Bostwick value was reported by Davis et al. (1954) for tomato puree. They found a linear dependence of approximately 0.09 cm/C. The repeatability of samples in the Bostwick value vary by up to 0.5 cm, therefore the Bostwick value is not sensitive to a change of less than 6°C. Contrary to reports by some processors, the temperature does not have to be tightly controlled during measurement.

The effect of temperature on the Bostwick value-pressure differential relationship was also tested. Over the processing temperature range of 93-85°C, the results were not significantly different (Fig. 5). At 46°C there was a significantly different curve. The activation energy for the consistency coefficient of ketchup is 1.99-4.88 kcal/mole (Rani and Bains 1987) and for tomato concentrates is 1.62-3.34 kcal/mole, for products with 5 to 36% solids (Rao et al. 1981). Thus with activation energies this small for small temperature changes, little change in viscosity, and hence pressure differential, would be expected.

Using the data collected in the laboratory, a prediction line was created for the correlation between Bostwick values and inverse of pressure differential, for the temperature and flow rate present in the factory. This on-line sensor prediction curve is shown for two different products: ketchup (Fig. 6 top) and pizza sauce (Fig. 6 bottom). Samples of ketchup and pizza sauce were collected over four days during a production run in a commercial factory, and compared to the
predicted lines (Fig. 6). Note that the line was predicted from the laboratory results and thus is not a regression line for the data points presented. The data points are to determine how accurate the prediction line is, under factory conditions. The samples were of finished product, so the measured points are clustered together. Comparing the ketchup measurement to its predicted line, and the pizza sauce to its predicted line, the mean deviation is 0.72 and 0.52 cm, respectively. In some commercial situations, this is less deviation than occurs due to operator error.

FIG. 6. FACTORY ON-LINE APPLICATION FOR KETCHUP (TOP) AND PIZZA SAUCE (BOTTOM): COMPARISON OF FACTORY RESULTS TO LABORATORY BASED PREDICTION LINES
CONCLUSIONS

Pressure differential measurement appears to be useful for on-line monitoring of Bostwick consistency of tomato products, although further in-plant data are necessary to extend the sensor's capabilities. Except for the 46C measurement, temperature effects appear to be minor over the processing temperature range. Bostwick value appears to be related to \((\text{kinematic viscosity})^{-0.2}\), confirming research findings of other investigators.

NOMENCLATURE

\begin{align*}
\gamma_m & \quad \text{mean shear rate (s}^{-1}\text{)} \\
\mu & \quad \text{apparent viscosity (Pa s)} \\
\rho & \quad \text{density (kg/m}^3\text{)} \\
K & \quad \text{consistency coefficient (Pa s}^n\text{)} \\
n & \quad \text{flow behavior index} \\
r & \quad \text{radial coordinate (m)} \\
R & \quad \text{tube inside radius (m)} \\
v & \quad \text{velocity (m/s)} \\
v_{\text{avg}} & \quad \text{average velocity (m/s)}
\end{align*}

REFERENCES


