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SONIC TEMPERATURE SENSOR FOR FOOD PROCESSING

D. W. Akers
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Work Performed Under Contract No. AC07-94ID13223

For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

By
Lockheed Martin Idaho Technologies Company
Idaho Falls, ID

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ABSTRACT

The lack of adequate temperature measurement is the major barrier to the development of more efficient and better quality food processing methods. The objective of the sonic temperature sensor for food processing project is to develop a prototype sensor to noninvasively measure the interior temperature of particulate foods during processing. This, a joint project with the National Food Processors Association, utilizes the property of materials that when the temperature of a material changes, there is a corresponding change in the speed of sound. The approach taken for the sonic sensor system is to determine the speed of sound inside particulate foods using a tomographic reconstruction process. This work has shown that the speed of sound can be accurately determined to an accuracy of $\pm 0.4\%$, corresponding to a temperature uncertainty of $\pm 2^\circ\text{C}$ using tomographic reconstruction methods.

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Sonic Temperature Sensor for Food Processing

INTRODUCTION

Background

The U.S. food processing industry has invested heavily in the safe processing of canned foods. This technology has a number of safeguards to ensure that food is processed properly and efficiently because food processing is energy intensive. A key problem for the food processing industry is that accurately measuring the temperature of particulate foods during processing is difficult. Improvements in this process can result in significant improvements in both cost and quality of the processed foods. Successful development of a system that can be used to measure the temperature of particulate foods would allow a major shift to the use of an aseptic processing method that does not require the use of canning and pressure cooking methods to ensure that the food is adequately cooked. Estimated reductions in national food processing energy usage are on the order of 0.01 quads/yr.

The objective of the sonic temperature sensor for food processing project is to develop a prototype sensor to noninvasively measure the interior temperature of particulate foods during processing. This sensor utilizes the property of materials that when the temperature of a material changes, there is a corresponding change in the speed of sound. The approach taken for the sonic sensor system is to determine the speed of sound using a number of sensors and then determine the temperature inside the particulate foods using a tomographic reconstruction process.

This project began in 1991 as an initial assessment of the speed of sound in foods as a function of temperature. This initial assessment was performed primarily with potatoes and indicated that there were discernable differences in the speed of sound in a potato as a function of temperature. Following these initial tests, a collaborative effort was begun with the National Food Processors Association (NFPA) to develop the technology. The project was divided up into two phases. The first phase was to develop a stationary system that could be used on canned foods, and the second phase was to develop a sensor that could be attached to piping for use as an online system for aseptic processing. This system would be tested at the NFPA's processing test facility.

The initial prototype was completed and tests were performed with this system to assess the speed of sound in some materials. However, initial tests indicated that the original system had a number of problems that prevented accurate acquisition of the data needed for tomographic processing. Consequently, additional modeling of the process was performed, and verification measurements were performed using a state-of-the-art commercial system. Encouraging results were obtained, which suggested that although the initial schedule for the project could not be met, there was potential for completing the project. The objective of this report is to summarize the current state of the project, which includes both theoretical calculations and actual measurements of the speed of sound, and recommendations for completion of the project.

Technical Basis

The Sonic Sensor System, as visualized for an aseptic processing facility, consists of an array of transducers equally spaced around the circumference of a pipe. Figure 1 presents a schematic view of such an arrangement. The center lines of the transducers all lie in a plane that is perpendicular to the center axis of the pipe; this is referred to as the image plane.

Measurements of the time of flight (TOF) of ultrasonic pulses between pairs of transducers are obtained in order to estimate sound speed at points within the pipe. Because of ultrasonic beam width restrictions, measurements cannot be obtained between transducer pairs that are too close. In Figure 1, transducer pairs situated closer than 96 degrees cannot "see" each other. Obviously, a broad beam width is preferred over a narrow one because more measurements result in better sound speed estimates. For the geometry depicted in Figure 1, there will be a total of 225 TOF measurements.

Investigations focused on the practical aspects of obtaining TOF measurements and also on computer simulations. Laboratory TOF measurements were obtained from a variety of food samples and non-food samples using several different transducer sizes and frequencies. The measurements provided insight into the kinds of foods suitable for inspection by this method as well as an understanding of transducer limitations and requirements. Near the conclusion of the investigations, TOF measurements were obtained using a transducer geometry that mimicked a pipe array. Sound speed maps were estimated from these measurements that validated simulation results.

Computer simulations were conducted to gauge the performance of the inspection method and identify implementation issues. The sound speed estimation algorithm used for this work is based on a model of sound propagation that includes some known simplifications (i.e., approximations) for performance reasons. Simulations were employed to evaluate the effects of these simplifications. Estimates of spatial resolution and sound speed resolution resulted from the simulations.

THEORETICAL BASIS

The Estimation Process

An estimation algorithm processes TOF measurements to produce a two-dimensional map of sound speeds within the pipe. The choice of algorithms for this project was, to a significant degree, dictated by the performance requirement of generating at least one sound speed map per second. To meet this requirement, it was necessary to adopt a simplified model of sound propagation in which sound travels only along straight lines between transmitter and receiver. In other words, it was assumed that refraction (both in-plane and out-of-plane) and diffraction can be ignored.

The estimation process requires knowledge of precisely where each ultrasonic pulse originates and where it is detected. This information is not easy to determine for real transducers with finite dimensions. End-point locations vary as a function of the relative positions of the

transducers as well as the physical properties of objects in the sound field. A sound speed estimation algorithm could not include a detailed model to compute transducer origins because of the speed requirement. An approximate solution has been implemented in which the effects of finite transducer size are accounted for in a correction process that will be described later.

The estimation algorithm assumes that the two-dimensional sound speed map can be accurately represented as a series expansion of the form

$$s(x,y) = \sum_{i=1}^N a_i b_i(x,y) \quad (1)$$

where $s(x,y)$ is the value of the sound speed at location (x,y) , b_i are two-dimensional local basis functions arranged on a square grid, and a_i are coefficients of the basis functions. The local basis functions used in this application are overlapping cubic B-splines. The linear process resulting in TOF measurements can then be represented as

$$\mathbf{y} = \mathbf{H}\mathbf{a} + \mathbf{v} \quad (2)$$

where $\mathbf{y}$ is the TOF measurement vector, $\mathbf{H}$ is the constant matrix relating TOF measurements to basis function coefficients, $\mathbf{a}$ is the vector of basis function coefficients (to be estimated), and $\mathbf{v}$ is the measurement noise vector. The matrix $\mathbf{H}$ depends only on the relative positions of the transducers and is computed just once for a given transducer arrangement. With prior statistical knowledge of $\mathbf{v}$ and $\mathbf{a}$ and the assumption of gaussian statistics, the maximum a posteriori estimate of $\mathbf{a}$ is

$$\hat{\mathbf{a}}_{\text{MAP}} = (\mathbf{V}_a^{-1} + \mathbf{H}^T \mathbf{V}_v^{-1} \mathbf{H})^{-1} (\mathbf{H}^T \mathbf{V}_v^{-1} \mathbf{y} + \mathbf{V}_a^{-1} \boldsymbol{\mu}_a) \quad (3)$$

where noise, $\mathbf{v}$, is assumed to be zero mean with variance $\mathbf{V}_v$ and the coefficients, $\mathbf{a}$, are assumed to have mean $\boldsymbol{\mu}_a$ and variance $\mathbf{V}_a$. The error variance of the estimate can be expressed as

$$\mathbf{V}_i = \mathbf{V}_a - \mathbf{V}_a \mathbf{H}^T (\mathbf{V}_v + \mathbf{H} \mathbf{V}_a \mathbf{H}^T)^{-1} \mathbf{H} \mathbf{V}_a \quad (4)$$

For this study, it was assumed that noise, $\mathbf{v}$, is uncorrelated ($\mathbf{V}_v$ is diagonal), and the coefficients of variance $\mathbf{V}_a$ decrease linearly to zero as distance between basis functions increase. The signal-to-noise ratio (SNR) is defined as the ratio of the diagonal components of $\mathbf{V}_a$ to the diagonal components of $\mathbf{V}_v$. The assumed SNR of an estimator (estimation matrix) is a design parameter. For this work, SNRs of 100, 1000, and 10,000 were assumed.

The basis functions $[b_i(x,y)]$ in Equation (1) are assumed to be arranged on a square grid. The spacing of the basis functions affects the spatial resolution of the sound speed maps and the sensitivity of the estimation process to measurement noise and modelling noise. As the spacing between basis functions decreases, it is possible to produce more detailed images using those basis functions; that is, spatial resolution increases. On the other hand, when the number of basis functions increases, the number of coefficients to be estimated in Equation (2) also increases. Without a corresponding increase in the number of TOF measurements, the solution to

Equation (2) becomes more sensitive to noise. Equation (2) will become underdetermined if the basis functions become dense enough, and a solution will not be obtainable.

A 20-by-20 basis function grid was used in this study. This basis function density was determined by experiment to represent a reasonable trade-off between spatial resolution and noise immunity.

Ideally, it should be possible to precisely reproduce any sound speed pattern that may occur in the image plane by using a linear combination of basis functions. In reality, this is not the case. Some patterns, especially ones containing discontinuities, cannot be matched exactly. The inaccuracies occurring in the calculated sound speed maps are said to result from modelling noise. As an example, Figure 2 shows the locations of three circular regions within a circular pipe where the sound speed is 5% greater than in the surrounding medium. Figure 3 is a surface plot showing a least-mean-squared-error approximation to the sound speed map depicted in Figure 2, assuming a 20-by-20 basis function grid. If the basis functions were capable of duplicating the sound speed distribution exactly, three cylinders of equal height would appear in Figure 3.

Practical Aspects of Measuring Time of Flight Through Food

Ultrasound transmission through canned corn, peas, and diced carrots was studied. The vegetables were placed in a rectangular plastic container with just enough water to fill the gaps. A few different transmitters were studied: four 0.5-in. transducers were used with center frequencies in the 1 to 15 MHz range; a 0.054-in. pinducer was also used. Measurements were acquired using a Matec Explorer 9000 ultrasonic instrument and two different pulsers: a square wave pulser and a spike pulser. The attenuation in db/in. was determined by comparing the water-filled container to the vegetable-filled container. Conclusions are as follows:

- Corn and peas are very attenuative compared to the diced carrots and may be difficult to work with above 5 MHz.
- In all cases, transit time was less through vegetables than through water, indicating the higher velocity of the subject vegetables.
- The vegetables generally act as a lowpass filter (<3 MHz).
- Pinducers do not have adequate power to penetrate 2.65 in. of dense food particles, indicating that the use of point source transmitters may be ineffective in some situations.
- The square wave pulser provides far better penetration than a spike pulser, indicating that narrow band transducers and narrow band excitation is preferable.

While transmission of an ultrasonic pulse is detectable through canned corn and peas when the transmitting and receiving transducers share the same axis, attenuation is probably too high for these vegetables to be inspected using a pipe array sensor. In the pipe array sensor, most TOF measurements will be made between off-axis transducer pairs. The ultrasonic signal emitted in the direction of an off-axis transducer is generally weaker than in the on-axis direction, and

grows weaker as the off-axis angle increases. Corn and peas are both surrounded by a semi-rigid shell, which might explain the difference in attenuation when compared with diced carrots. As will be discussed in a later section, spatial resolution is too poor to inspect objects the size of corn, peas, or diced carrots anyway.

In some experiments with canned corn and peas, the transmitted ultrasonic pulse appears delayed by the vegetables; that is, sound speed in water appears greater than that propagating through the vegetables. This suggests that the transmitted ultrasonic signal propagates around the vegetable particles by scattering and/or diffraction. The signal penetrating the vegetables apparently suffers so much attenuation that it becomes undetectable. The scattered and diffracted signals are of no use for sound speed estimation because the interior of the food particles are not sampled.

Ultrasonic pulses propagating through corn, peas, and diced carrots appeared to undergo lowpass filtering. It is not known whether this filtering is due to particle size or material properties. If due to material, it would be appropriate to use the lowest frequency possible with adequate measurement accuracy. The trade-off between penetration and measurement accuracy is a design consideration that will have to be addressed for each different geometry and food type.

Some problems are encountered when attempting to conduct well-controlled laboratory experiments with food samples. The sound speed of food samples varies between samples and is nonuniform within a sample. In addition, it is difficult to create a food sample with a precise cylindrical shape, and food samples deteriorate with use. Because of these problems, a search was conducted for suitable phantoms to use instead of food. An ideal phantom would have a sound speed approximately 5% greater than water (approximately 1.55 mm/ μ s), would have uniform material properties, and would be cylindrical in shape. No solid material could be identified that met these requirements. Therefore, a thin-walled plastic tube filled with castor oil (with a sound speed of 1.55 mm/ μ s) was tested with a through-transmission yoke. Under these conditions, the castor oil phantom produced acceptable results. However, in the NFPA scanning system (used to mimic a pipe transducer array), the phantom produced results that were discontinuous with the water. The plastic shell apparently had a greater effect than expected at grazing angles.

Transducer Beam Width Considerations

A real transducer has a beam width that is something smaller than 180 degrees. For the Sonic Sensor System, transducer beam width determines the number of TOF measurements that will be available for sound speed estimation. In general, better sound speed estimates will result from more measurements. However, estimation errors due to restricted beam width exhibit a spatial dependence; as beam width decreases, sound speed estimates near the pipe wall deteriorate much more rapidly than near the center of the pipe. Equation (4) is useful for investigating the spatial dependence of estimation error on beam width. The error variance was calculated for the case of 45 equally spaced transducers. The calculations were done for three different beam widths and three measurement noise levels for each beam width. For the highest level of measurement noise, the standard deviation of added noise was 0.1% of the average TOF along a central chord. Noise levels of 0.03% and 0.01% were also used. The results appear in Figure 4. The standard deviation of estimation error is presented in temperature units because there is a direct correlation between changes in sound speed and temperature variations.

Experiments with cooked potatoes at 120°C have shown that the speed of sound decreases 0.2% for each increase in temperature of 1°C. For this application (aseptic processing), temperature changes are more meaningful than changes in the speed of sound.

In Figure 4, the standard deviation of estimation error is displayed as a function of position along a central chord of the circular pipe. Pipe radius is normalized to 0.5. Transducers are point sources and point detectors. Refraction is not considered. It is clear that beam width has a much larger effect on temperature estimates near the pipe wall than near the center. The estimation error is essentially unchanged in the center half of the pipe as the beam width shrinks from 172 to 92 degrees. As the beam width shrinks farther to 28 degrees, estimation error is significantly larger everywhere except for a small area near the center.

The beam width of a typical unfocused transducer is a function of diameter and frequency. Beam width (or beam spread) is given by

$$\theta/2 = \sin^{-1} k\lambda/d$$

where $\theta/2$ is the half-angle of beam spread, k is a constant representing drop in beam intensity, λ is the wavelength, and d is the diameter of the active element. Using the -6 db points, ($k=0.72$), the beam spread ($\theta/2$) is calculated to be 11 degrees for a pinducer with an active element diameter of 0.054 in. (1.3 mm). Empirically, it was determined that the useful beam spread for these transducers was approximately 14 degrees (at approximately -12 db). Referring to Figure 4, this beam spread (28 degrees full width) would result in a very small region of acceptable accuracy near the center of the pipe. A wider beam spread is required, but transducers with smaller diameters do not produce enough power to penetrate typical food densities; the pinducers used here, though adequate for one or two small cooked potato pieces, do not produce enough power for realistic food densities. An alternative solution is to use a shaped transducer (i.e., convex) to produce a higher-energy, spherical wave front. This option may provide the desired wave front, but cost of building these customized transducers would be higher. Attenuation and field of view are both affected by transducer characteristics; therefore, transducer design is an important issue that must be addressed during future work.

MEASUREMENT RESULTS

Effects of Refraction

Refraction affects the trajectory of an ultrasonic pulse as it travels between a pair of transducers. In general, the pulse does not travel along a straight line. However, the straight line approximation is valid when variations in sound speed are small. Investigations were conducted to determine if the straight line approximation is valid for sound speed variations typical of aseptically processed foods. These investigations consisted of laboratory measurements and computer simulations.

A pair of transducers was mounted in a yoke, as pictured in Figure 5, so that the transducers faced each other and shared the same center axis. The yoke was translated so that cylindrical samples of potato and PVC plastic passed between the transducers. The axis of each cylindrical sample was perpendicular to both the transducer axis and the direction of motion of the yoke-

mounted transducers. Sound speed in the samples was greater than sound speed in water. Figure 6 depicts the general shape to be expected from a plot of TOF versus transducer position (yoke position) obtained in this manner. The receiving transducer was a pinducer in all tests. The transmitting transducer was a pinducer in the refraction experiments described here.

The food samples used in the experiments were cooked potatoes. The samples were cut, using a coring tool, into cylindrical pieces about 2 in. long with a diameter of 0.75 in. Samples cut from PVC plastic rods were also used. The PVC rods also had a diameter of 0.75 in.

Knowing the size of the sample, the distance between the transducers, and the sound speed in water, it was possible to determine the average sound speed in the samples from TOF measurements. The sound speed in the cooked potato samples was found to be 1.54 mm/ μ s, about 5% greater than the sound speed in water. Sound speed in the PVC samples was 2.31 mm/ μ s.

From sample size and sound speed, theoretical TOF values were calculated for two different models of sound propagation. The simplest model assumed no refraction or diffraction. A more complicated model assumed refraction but no diffraction. Measured TOF values were compared with TOF values calculated from these models.

Figure 7 shows the results of measurements from a potato sample and a PVC sample. A pinducer transmitter was used for these measurements. Also displayed are the TOF values calculated using the two models described above. Refraction effects are clearly evident. It is also apparent that the simple refraction model does a fairly good job of predicting TOF values.

TOF values were computed using a realistic model of sound propagation that incorporated effects due to refraction and transducer size. The TOF values were then processed by the estimation algorithm to yield sound speed maps. The results of these simulations will be presented after the discussion of transducer size effects.

Transducer Size Effects

A model was developed to account for transducer size effects. It assumes that a finite-size transducer can be modelled as a dense linear array of point transducers. To calculate the TOF between a pair of transducers, the TOF is first calculated for all combinations of point transmitter-point receiver pairs from the linear arrays constituting the two transducers. The smallest calculated value is accepted as the TOF between the finite-size transducer pair. The top graph in Figure 8 shows TOF measurements obtained from a potato sample using two different transmitter sizes: a pinducer and a 0.5-in. transducer. The bottom graph shows TOF measurements obtained using four different transmitter sizes. The apparent width of the sample increases as the transmitter diameter increases for both potato and PVC samples.

TOF values computed using this model appear in Figure 9. Two simulated TOF curves are shown, one that includes refraction effects alone, and one that includes both refraction and transducer size effects. The sample is assumed to be a cylinder of diameter 0.75 in. with sound speed 1.54 mm/ μ s, the same as the potato samples. Computed transducer size effects are similar in magnitude to measured effects evident in the top graph in Figure 8.

Transducer size has an enormous effect on sound speed maps estimated from TOF measurements, but the effect can be reduced significantly through the use of a simple correction scheme. The sound speed map appearing at the top of Figure 10 was computed from simulated TOF values that include both refraction and transducer size effects. These TOF values were calculated for the case of 45 evenly spaced transducers. Pipe diameter was assumed to be 6 in., and transducer diameter was 0.25 in. It was assumed that transducers closer than 96 degrees could not detect each other. A single cylinder, with diameter 1.2 in. and sound speed 5% greater than the surrounding fluid, was placed at the center of the pipe. It is apparent from the figure that transducer size effects are overwhelming. However, the bottom graph in Figure 10 shows that a simple correction scheme is capable of removing most of the effects due to transducer size. The TOF values used to generate the bottom graph were corrected by subtracting from them the TOF values for an empty field; that is, the TOF values for a constant-valued temperature field with sound speed equal to the surrounding fluid.

Monte Carlo Experiments to Evaluate Effects of Refraction and Transducer Size

Computer simulations were conducted to evaluate the effects of refraction and transducer size on sound speed maps. TOF measurements were calculated for numerous cases in which cylinders were randomly positioned within the center region of a 6-in. pipe. The diameter of the center region was 3 in. A cylinder was considered within the center region if its center lay within 1.5 in. of the pipe center. Forty-five 0.25-in. transducers were assumed to be evenly spaced around the circumference of the pipe. The diameters of the cylinders were 1.2 in. The sound speed of the cylinders was 5% greater than the surrounding fluid.

Noise was added to the simulated TOF measurements. Sound speed maps were estimated for three different signal-to-noise ratios: 100, 1000, and 10,000. For SNR = 100, the standard deviation of additive measurement noise was 0.1% of the mean TOF along a central chord. For SNR = 1000, the value was 0.0316%; for SNR = 10,000, the value was 0.01%. For a 60-in. pipe, these values correspond to measurement error standard deviations of approximately 103, 33, and 10 ns, respectively.

Sound speed maps were analyzed by computing the statistics of pixels inside and outside the randomly positioned cylinders. A pixel was considered inside a cylinder if its center lay within 0.3 in. of the actual center of the cylinder. A pixel was outside if its center lay more than 0.9 in. from the center of all cylinders. Pixels were square with dimension 0.12 in. The following statistics are reported here: the mean value within all cylinders, the standard deviation of that mean, the mean of the peak (maximum) values within all cylinders, and the standard deviation of that mean.

Experiments were first conducted with ideal TOF values; that is, TOF values computed with no refraction or transducer size effects. Table 1 summarizes the results of these experiments. Estimation error is presented in temperature units as described above. A 0.2% change in sound speed translates to a temperature decrease of 1°C.

Experiments were next conducted with refraction and transducer size effects included. TOF values were used that were calculated with these effects. The correction for transducer size effects described earlier was then applied to the TOF values. Table 2 summarizes the results of these experiments.

The mean error and the mean peak error represent estimator biases that can be corrected for. The important quantities are the standard deviations of those means. When the data from all the simulated cases are combined, we find that refraction and transducer size effects cause the standard deviation of the inside mean to increase from 0.84 to 1.49 degrees. The standard deviation of the mean peak value increases from 0.5 to 1.5 degrees. The number of cylinders positioned in the image plane of the pipe does not have a significant effect on the accuracy of the calculated sound speed maps.

Figures 11 through 15 show sound maps computed for a variety of SNR levels and containing from one to three cylinders. The maps on the left in each figure are generated from simulated TOF measurements that do not include the effects of refraction or transducer size, and contain no measurement noise. The center maps are generated from simulated TOF measurements that include the effects of refraction and transducer size, but contain no measurement noise. The maps on the right were generated from simulated TOF measurements that include the effects of refraction and transducer size as well as measurement noise. The parameters (number of transducers, transducer diameters, sound speeds, etc.) used to simulate TOF measurements and compute the sound speed maps are the same as those used for the Monte Carlo experiments discussed above. In the figures, the sound speed maps are normalized so that the pipe diameter is 1 in., cylinder diameters are 0.2 in., and transducer diameters are 1/24th the diameter of the pipe. The normalized dimensions are equivalent to a pipe diameter of 6 in., cylinder diameters of 1.2 in., and transducer diameters of 0.25 in.

Spatial Resolution for the Sound Speed Map Estimation Process

A series of experiments was conducted to determine the spatial resolution of sound speed maps estimated from TOF measurements. TOF measurements were simulated for several different cylinder diameters. Refraction effects, transducer size effects, and measurement noise were included in the TOF calculations. In all cases, the sound speed in the cylinders was 5% greater than the sound speed in the surrounding fluid. The TOF measurements were simulated for 45 transducers and for 30 transducers. Beam width restrictions were similar for both transducer arrangements. Other parameters used to simulate the TOF measurements and compute the sound speed maps were the same as described earlier. Figure 16 summarizes the results of the experiments for an SNR level of 1000; the peak (maximum) sound speed value of a cylinder is plotted as a function of cylinder diameter. It is evident that the peak value is an accurate estimation of the actual cylinder sound speed as long as the cylinder diameter is larger than some threshold value. For a 6-in. pipe with 45 transducers, this threshold is approximately 0.9 in. For a 6-in. pipe with 30 transducers, this threshold is approximately 1.2 in. For a 3-in. pipe, the threshold values will be 0.45 and 0.6 in. for 45 and 30 transducers, respectively. This information implies that, for a 6-in. pipe, the spatial resolution of the sound speed map estimation process is around 0.9 in. when 45 transducers are employed, and around 1.2 in. for 30 transducers. For a 3-in. pipe, the resolution will be 0.45 and 0.6 in. for 45 and 30 transducers, respectively.

Results From Actual Ultrasonic TOF Measurements

Actual TOF measurements were obtained using a circular scanning system, and these measurements were used to estimate sound speed maps. The scanning system was configured to simulate a 45-transducer pipe array. Pinducers were used for both transmission and reception. The effective beam width of the pinducers was 28 degrees (56 degrees of arc). With this narrow field of view, only points near the center of the pipe were sampled by all 45 transducers.

Figure 17 depicts the experimental setup. Dimensions in Figure 17 are normalized to a pipe diameter of 1 in. The actual diameter of the "pipe" was 3.67 in. The diameter of the potato cylinders was 0.55 in. TOF measurements were collected with a single potato sample at the center, and again with the sample offset. Measurements were then obtained with potatoes occupying both center and offset positions. As is evident in Figure 17, only the center potato sample is in the field of view of all transducers. The temperature of the water bath was also varied during the experiments. Equilibrium between the potato samples and the water bath was apparently achieved at all temperature levels before TOF measurements were made.

TOF measurements were made using the Sonix ultrasonic inspection system. The data collected were TOF measurements to the first zero crossing of the first arrival signal. Measurement resolution was 16 ns. Wave forms were averaged 16 times before zero crossings were determined to minimize the error caused by baseline noise. With this level of averaging, the standard deviation of measurement noise was less than 8 ns for on-axis transducer pairs, and less than 15 ns for transducer pairs oriented 36 degrees off-axis. This level of measurement noise is insignificant compared to other noise sources.

Figure 18 shows sound speed maps generated from TOF measurements. An SNR level of 1000 was assumed. Figure 19 shows a sound speed map generated from simulated TOF measurements calculated to approximate the two-potato geometry displayed in Figure 17. The appearance of the offset potato varies somewhat between maps generated with real data and maps generated with simulated data. This could be due to an inaccurate value for the sound speed for the offset potato and/or to density variations within the potato sample.

Figure 20 shows a sound speed map generated from actual measurements with the water bath temperature raised to 40°C. The surface plot appears essentially the same as that obtained at room temperature, but the whole plot is elevated because the average sound speed is increased. In all, TOF measurements were obtained with the water bath at 20, 40, 50, 60, 70, 80, and 90°C. At all elevated temperature levels, the sound speed maps appeared to be elevated versions of the maps obtained at 20°C.

Figure 21 illustrates how sound speed varies with water bath temperature. One curve shows the sound speed within the potato, as determined from the sound speed maps. Another curve shows measurements obtained in pressure cooker experiments that were performed several years ago. A third curve shows the sound speed in the water bath. Obviously, the pressure cooker sound speeds are significantly different from those obtained in this latest set of experiments. The reasons are unknown. The potato sound speeds obtained in the recent experiments increase at a rate slower than the sound speed in the water bath. This is due in part to deterioration of the

potato samples at higher temperatures as the potato began to cook and the composition of the potato began to change. It was necessary to replace the potato samples at 90°C.

Figure 22 shows that the sound speeds estimated from TOF measurements for the water bath region match closely the values obtained from simple pitch-catch measurements. This information provides some validation of the estimation process. Figure 23 compares the measured water bath sound speeds with published values for water.

CONCLUSIONS AND RECOMMENDATIONS

The objective of the sonic temperature sensor for food processing project is to develop a prototype sensor to noninvasively measure the interior temperature of particulate foods during processing. An initial prototype was completed and tests were performed with a variety of food materials to assess the capability of the sensor to measure the temperature of particulate foods in a processing environment. These initial tests indicated that the original prototype had a number of problems that prevented accurate acquisition of the data needed for accurate temperature measurements. Consequently, additional modeling was performed and verification measurements were performed using a state-of-the-art commercial time of flight (TOF) sonic measurement system. The objective of this report is to document the results of these additional modeling and verification measurements.

The theoretical evaluation of the sonic sensor process focused on the development of a two-dimensional map of sound speeds within a measurement can or pipe section. Following the development of this model using a 20 x 20 grid of transmitters and receivers, various objects were placed in the mode, and the effects of various effects such as refraction were evaluated. This assessment showed that sound speed can be determined, using a 45-transducer pipe array, to an accuracy of approximately $\pm 0.4\%$, corresponding to a temperature uncertainty of approximately $\pm 2^\circ\text{C}$ using the conversion factor discussed earlier. This accuracy is achieved in the central region of the pipe. The size of the central region is determined by the transducer beam width. Analysis of the estimation process indicates that TOF measurement noise will not be a limiting factor.

A simplified linear estimator was used to compute cross-sectional sound speed maps from TOF measurements. This work showed that the simplifications, made for performance reasons, were justified; refraction effects are small and a simple correction is capable of nearly nullifying the effects of transducer size. These conclusions are valid for sound speed variations in the 5% range. For larger variations, these conclusions may not be valid. These simulations have shown that, for a 6-in. pipe, spatial resolution of approximately 1 in. is achievable using a transducer pipe array. For a 3-in. pipe, resolution will be approximately 0.5 in. These theoretical resolution results are slightly larger than the requirements identified by the National Food Processors Association (NFPA), which had requested a resolution on the order of 0.25 inches. These results indicate that although the NFPA temperature measurement requirement ($\pm 2^\circ\text{C}$) is feasible, using current technology, it would be impossible to meet the spatial resolution requirement of 0.25 in.

Laboratory measurements using food samples were also performed for comparison with the theoretical studies. These results indicated that the sound speed maps obtained from actual TOF measurements compare favorably with maps obtained from simulated TOF values. These results provide validation of the estimation algorithm.

It was determined from the laboratory measurements that variations in the material properties of the processed foods may present problems for the implementation of temperature measurements in particulate foods using the sonic sensor technique. If the sound speed in a certain type of food varies significantly between samples at canning temperatures ($>120^{\circ}\text{C}$), then it may be difficult to inspect that food type using this technology. It has been noticed during this work that the sound speed in potato samples varies by $\pm 1.2\%$ at room temperature. This error is three times larger than the estimation error reported above. However, some preliminary work performed at higher temperatures suggested that at canning temperatures, variations between same-type food samples becomes negligible.

Primary conclusions of the theoretical and laboratory studies are that the temperature estimation accuracy may meet the NFPA requirement of being able to measure temperatures within $\pm 2^{\circ}\text{C}$; however, it may be difficult to meet the spatial resolution requirement of 0.25 in. Additional work may be needed to confirm these conclusions at temperatures near those used for food processing where it has been suggested that some of the identified limitations of the sonic sensor technique may have a lesser effect.

Recommendations for completion of this project are summarized below:

- Better develop the relationship between temperature and the speed of sound for a number of foods that are of interest to the NFPA.
- Perform a series of measurements using the redesigned system on specific food types and use these data to benchmark the tomography calculations so that the uncertainties associated with measurements are adequately defined. Parameters to be addressed include food temperature, differences in food consistency, and measurements at canning temperatures.
- Based on the previous measurements and calculations, in conjunction with the NFPA, assemble a fixed array pipe prototype using transducers in a configuration that can be used at the NFPA test facility.
- Perform sonic sensor measurements at the NFPA facility to assess the effects of an actual industrial environment on the system.

Following completion of this series of measurements and calculations, it should be possible to define the uncertainties and determine whether a production system is possible. Use of aseptic processing techniques with adequate temperature measurement can be expected to be valuable to many parts of the food industry with considerable cost savings and increases in food quality.

Figure 1 - The Sonic Sensor System consists of an array of transducers mounted around the circumference of a pipe, as diagramed here. Thirty transducers appear in these drawings. Because of beam width restrictions, the nearest receiving transducer is separated by 96° from the transmitting transducer. The sequence of drawings shows how the transmitter position shifts between sets of measurements.

Figure 2 - The locations of three circular region with sound speed 5% greater than the surrounding fluid are shown. This geometry is assumed for several of the simulation results discussed in this report.

Minimum norm fit to three cylinders

Figure 3 - The closest approximation possible to three cylinders using a 20 by 20 grid of cubic B-splines is shown. The inaccuracies are said to result from modelling noise.

Figure 4 - The standard deviation of temperature estimation error is displayed as a function of position along a central chord of a circular pipe for the case of 45 equally spaced transducers. Calculations were done for three beam widths and for three levels of measurement noise for each beam width. For the highest level of measurement noise, the standard deviation of added noise is .1% of the average time of flight along a central chord. Values of .03% and .01% are also used. Beam width has a much larger effect on estimation accuracy near the pipe wall than at the center.

Figure 5 - A pair of transducers was mounted in a yoke, as displayed here, for laboratory time-of-flight measurements. The transducers face each other and share the same center axis. The yoke was translated so that cylindrical samples of potato and PVC plastic passed between the transducers. The axis of each cylindrical sample was perpendicular to both the transducer axis and the direction of motion of the yoke-mounted transducers.

Figure 6 - The general shape of a plot of time-of-flight versus transducer position, obtained using the arrangement depicted in Figure 5, is shown.

Figure 7 - Time-of-flight measurements from a potato sample (top) and a PVC plastic sample (bottom) are shown. Simulated results also appear. Simulations including the effects of refraction are clearly more accurate. Refraction effects cause the cylinder samples to appear noticeably wider.

Figure 8 - The effects of transducer size are illustrated. The top graph shows time-of-flight measurements obtained from a cylindrical potato sample using a pinducer and a half inch transducer. The bottom graph shows measurements obtained from a PVC plastic cylinder sample using four different transducer sizes. The wider transducers cause the cylinder samples to appear noticeably wider.

Figure 9 - A model was developed to simulate the effects of finite transducer size. Using that model, time-of-flight measurements for two different transducer diameters were computed and are displayed here.

45 transducers, nearest transducer= 96°
SNR=1 000, 20x20 basis fn. grid
.25" transducer, 6" pipe, includes refraction

45 transducers, nearest transducer= 96°
SNR=1 000, 20x20 basis fn. grid
.25" transducer, 6" pipe, includes refraction

Figure 10 - The top graph illustrates the effects of transducer size on sound speed map estimation. The bottom graph shows the improvement achieved through the use of a simple correction scheme.

Number of cylinders simulated	SNR	Mean error inside	SD of mean error	Mean peak error inside	SD of peak error	Number of experiments
1	100	-1.1°	1.1°	-2.5°	.7°	1000
2	1000	-1.1°	.7°	-2.1°	.3°	1000
3	10000	-1.1°	.6°	-2.0°	.3°	1000
1	100	-1.0°	1.1°	-2.5°	.8°	1000
2	1000	-1.1°	.7°	-2.1°	.4°	1000
3	10000	-1.1°	.7°	-2.1°	.3°	1000
1	100	-1.0°	1.2°	-2.5°	.9°	1000
2	1000	-1.0°	.8°	-2.1°	.4°	1000
3	10000	-1.0°	.7°	-2.1°	.4°	1000

Table 1 - A statistical summary of the results of computer simulations is presented. Refraction and transducer size effects were ignored.

Number of cylinders simulated	SNR	Mean error inside	SD of mean error	Mean peak error inside	SD of peak error	Number of experiments
1	100	1.9°	1.6°	.1°	1.6°	100
2	1000	1.8°	1.4°	.4°	1.6°	100
3	10000	1.7°	1.4°	.2°	1.8°	100
1	100	1.9°	1.6°	.1°	1.6°	100
2	1000	1.9°	1.3°	.5°	1.4°	100
3	10000	1.9°	1.3°	.6°	1.4°	100
1	100	1.8°	1.6°	.1°	1.5°	100
2	1000	1.8°	1.6°	.5°	1.3°	100
3	10000	1.8°	1.6°	.5°	1.3°	100

Table 2 - A statistical summary of the results of computer simulations is presented. The effects of refraction and transducer size are included.

Figure 11 - Sound speed maps computed from simulated time-of-flight (TOF) data are shown. The diameter of the pipe is assumed to be 1. A single cylinder, with diameter .2, is positioned at the center of the pipe. The sound speed within the cylinder is 1.05, 5% greater than the sound speed of the surrounding fluid. Forty-five equally spaced transducers are assumed. Transducer diameters are assumed to be 1/24th the diameter of the pipe. Transducers nearer than 96° cannot detect each other. The sound speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 100. A SNR of 1000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For this normalized system, with pipe diameter of 1 and sound speed of 1 in the surrounding fluid, a SNR of 100 corresponds to measurement noise with standard deviation of .001. A SNR of 1000 corresponds to measurement noise with standard deviation of .00316.

Figure 12 - Sound speed maps computed from simulated time-of-flight (TOF) data are shown. The diameter of the pipe is assumed to be 1. A cylinder with diameter .2 is positioned at the center of the pipe. In the bottom row a second cylinder, identical to the first, is positioned at $x=-.3, y=0$. The sound speed within the cylinders is 1.05, 5% greater than the sound speed of the surrounding fluid. Forty-five equally spaced transducers are assumed. Transducer diameters are assumed to be 1/24th the diameter of the pipe. Transducers nearer than 96° cannot detect each other. The sound speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 10000. A SNR of 100 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For this normalized system, with pipe diameter of 1 and sound speed of 1 in the surrounding fluid, a SNR of 10000 corresponds to measurement noise with standard deviation of .0001. A SNR of 100 corresponds to measurement noise with standard deviation of .001.

Figure 13 - Sound speed maps computed from simulated time-of-flight (TOF) data are shown. The diameter of the pipe is assumed to be 1. A cylinder with diameter .2 is positioned at the center of the pipe. A second cylinder, identical to the first, is positioned at $x=-.3, y=0$. The sound speed within the cylinders is 1.05, 5% greater than the sound speed of the surrounding fluid. Forty-five equally spaced transducers are assumed. Transducer diameters are assumed to be 1/24th the diameter of the pipe. Transducers nearer than 96° cannot detect each other. The sound speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 1000. A SNR of 10000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For this normalized system, with pipe diameter of 1 and sound speed of 1 in the surrounding fluid, a SNR of 1000 corresponds to measurement noise with standard deviation of .00316. A SNR of 10000 corresponds to measurement noise with standard deviation of .0001.

Figure 14 - Sound speed maps computed from simulated time-of-flight (TOF) data are shown. The diameter of the pipe is assumed to be 1. Three cylinder, with diameter .2, are positioned in the image plane of the pipe. One cylinder is located at the center of the pipe. A second cylinder is positioned at $x=-.3, y=0$. A third cylinder is positioned at $x=.25, y=-.25$. The sound speed within the cylinders is 1.05, 5% greater than the sound speed of the surrounding fluid. Forty-five equally spaced transducers are assumed. Transducer diameters are assumed to be 1/24th the diameter of the pipe. Transducers nearer than 96° cannot detect each other. The sound speed maps in the top row are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 100. A SNR of 1000 is assumed for the maps in the bottom row. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For this normalized system, with pipe diameter of 1 and sound speed of 1 in the surrounding fluid, a SNR of 100 corresponds to measurement noise with standard deviation of .001. A SNR of 1000 corresponds to measurement noise with standard deviation of .00316.

Figure 15 - Sound speed maps computed from simulated time-of-flight (TOF) data are shown. The diameter of the pipe is assumed to be 1. Three cylinder, with diameter .2, are positioned in the image plane of the pipe. One cylinder is located at the center of the pipe. A second cylinder is positioned at $x=-.3, y=0$. A third cylinder is positioned at $x=.25, y=-.25$. The sound speed within the cylinders is 1.05, 5% greater than the sound speed of the surrounding fluid. Forty-five equally spaced transducers are assumed. Transducer diameters are assumed to be 1/24th the diameter of the pipe. Transducers nearer than 96° cannot detect each other. The sound speed maps are generated with an estimator that assumes a signal-to-noise ratio (SNR) of 10000. Simulated TOF measurements used to generate the maps in the left column do not include the effects of refraction or transducer size, or measurement noise. Simulated TOF measurements used to generate the maps in the center column include the effects of refraction and transducer size, but contain no measurement noise. Simulated TOF measurements used to generate the maps in the right column include the effects of refraction and transducer size as well as measurement noise. For this normalized system, with pipe diameter of 1 and sound speed of 1 in the surrounding fluid, a SNR of 10000 corresponds to measurement noise with standard deviation of .0001.

Figure 16 - The peak sound speed values estimated for several cylindrical sample are displayed as a function of sample diameter. Simulated time-of-flight measurements were used to obtain these results. In all cases, the sound speed in the sample was 5% greater than the sound speed of the surrounding fluid.

Figure 17 - The experimental setup used to obtain time-of-flight measurements for sound speed map estimation is shown. One or two cylindrical potato samples were placed inside the "pipe." This 45-transducer pipe array geometry was actually achieved using a 2-transducer circular scanning system.

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., potato at center with normalized diameter .17, peak=1.0319

1

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., potato off-centered with normalized diameter .17, peak=1.0204

2

45 transducers, 20x20 grid, transducer view=28 degrees, filter SNR=1000
Room temp., two potatoes with normalized diameter .17, peak=1.0292

3

Figure 18 - Sound speed maps generated from actual time-of-flight measurements are shown. The geometry shown in Figure 17 is used. For the first surface plot the potato was located at the center. For the second the potato was offset. In the third plot potato samples occupied both positions.

Simulated data, includes refraction and transducer size effects
Cylinders at (0,0) and (.27,0), cylinder diameters=.15, sound speed=1.028
45 transducers, 28° beam width, 20x20 basis fn. grid, SNR=1000
Measurement noise added ($\sigma=20$ ns)

Figure 19 - A sound speed map generated from simulated time-of-flight measurements is shown. The simulated measurements were calculated to approximate the two-potato geometry displayed in Figure 17.

40° C, two potatoes, normalized diameter=.15, peak=1.0592
45 transducers, 28° beam width, 20x20 basis fn. grid, SNR=1000

Figure 20 - A sound speed map generated from actual time-of-flight measurements is shown. The water bath temperature has been raised to 40°C.

Figure 21 - The variation of sound speed with temperature is illustrated. One curve shows the sound speed within the potato sample, as determined from estimated sound speed maps. Another curve shows the sound speed variation within the surrounding water. A third curve shows measurements obtained in pressure cooker experiments.

Pedestal and Measured Sound Speeds

Figure 22 - Water bath sound speeds, determined from estimated sound speed maps, are compared with direct pitch-catch measurements of the water bath sound speed. The close correlation provides some validation of the estimation process.

Sound Speed of Water vs Temp.

Figure 23 - Measured water bath sound speeds are compared with published values.

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FACILITY NAME: Idaho National Engineering Laboratory

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ACTIVITY	PAST FY 1996	CURRENT FY 1997	PLAN FY 1998	OUT-YEARS	
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Scientific and Technical	353	325	300	300	280
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Schedule 5-8
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FACILITY NAME: Idaho National Engineering Laboratory

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	<u>Past Year</u> <u>FY 1996</u>	<u>Current Year</u> <u>FY 1997</u>	<u>Plan Year</u> <u>FY 1998</u>	<u>Outyear 1</u> <u>FY 1999</u>	<u>Outyear 2</u> <u>FY 2000</u>
Number of Articles	76	70	65	60	60
Cost (in thousands)	25	27	25	27	30