Ultrasonic Velocity in Cheddar Cheese as Affected by Temperature

A. Mulet, J. Benedito, J. Bon, and C. Rossello

ABSTRACT

The ultrasonic velocity in Cheddar cheese is temperature dependent. This relationship can be used to make corrections when determining ultrasonic texture or to determine mean temperatures in cooling/heating processes. At 0 < T < 35 °C ultrasonic velocity was 1590 to 1696 m/s, at 0 and 35 °C, respectively. Differential Scanning Calorimetry thermograms linked the temperature dependence of ultrasonic velocity to fat melting. Three parts are distinguished in the curve as a consequence of the fat melting and the appearance of free oil. The most reliable temperature interval to carry out ultrasonic measurements in Cheddar cheese is identified as 0 to 17 °C.

Key Words: Cheddar cheese, DSC, fat melting, ultrasonic velocity

INTRODUCTION

ULTRASONIC TECHNIQUES HAVE BEEN USED IN MEDICINE (Wells, 1977), metal testing (Papadakis, 1976), and recently in the food industry. Ultrasonics provide a non-destructive, rapid, automated, and low cost technique for quality evaluation (Povey and McClements, 1988).

Ultrasonic techniques have been used in the beef industry to quantitatively determine carcass value and predict heritable muscling and quality attributes (Miles et al., 1990; Whittaker et al., 1992; Cross and Belk, 1994). Velocity, attenuation, and frequency spectrum composition are the commonly measured acoustical parameters (Povey and McClements, 1988; Povey, 1989, 1998). The frequency spectrum composition has been used to detect hollow hearts in potatoes (Cheng and Haugh, 1994) and intramuscular fat (Whittaker et al., 1992). Ultrasound velocity measurement has been carried out to determine meat quality (Cross and Belk, 1994); to estimate the solid/liquid ratio in fats, oils, and adipose tissue (Miles et al., 1985); to measure the quality of fruits (Mizrach et al., 1991); or to estimate cod fillet moisture (Ghaedian et al., 1997).

Structural defects may be determined in Parmesan cheese (Orlandini and Annibaldi, 1983), cut-time in cheese making (Gunasekaran and Ay, 1996), rheological properties of cheese (Lee et al., 1992), and cheese maturity (Benedito et al., 1998), all using variations in ultrasound technique. The ultrasonic velocity through cheese increased with increasing firmness during maturation (Benedito et al., 1998), and ultrasound velocity has been found related to bulk modulus or shear modulus. These properties are temperature dependent (Povey and McClements, 1988). Therefore, temperature must be known to relate velocity to physical properties. The influence of temperature on velocity was studied as related to oils, adipose tissue (Miles et al., 1985), and cod fillets (Ghaedian et al., 1997).

Velocity becomes more temperature dependent when phase changes occur. Differential Scanning Calorimetry (DSC) studies showed that dried cheese underwent a phase transition from about –30 to 38 °C, primarily due to changes in fat crystallinity (Tunick, 1994).

Cooling of Cheddar cheese blocks is the primary means of controlling microbial activity to promote homofermentative metabolism (Fryer, 1982). Cooling rate is a very important factor affecting flavor development during aging (Miah et al., 1974; Grazier et al., 1993). A non-invasive method for monitoring internal temperature would be advantageous.

Ultrasonic temperature determinations are performed by measuring ultrasonic velocity through a material at different temperatures and establishing a temperature-velocity relationship (Lynnworth, 1992). The study of the temperature-velocity relationship has been used to determine the composition of food products, such as fish (Ghaedian et al., 1998).

Our objective was to quantify the relationship between ultrasonic velocity and sample temperature in Cheddar cheese. This relationship was tested by using an unsteady heating experiment to determine the accuracy of the procedure.

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MATERIALS & METHODS

Raw material

Cheddar cheese (Kerrygold, Irish Dairy Board, Dublin, Ireland) purchased from a local supermarket was used. The cheese was kept refrigerated at 1 °C in a sealed plastic bag to avoid water loss, and all tests were performed within 7 d of purchase.

Proximate analysis of cheese

Protein was determined by a Kjeldahl method (Method 991.22. AOAC. 1996), fat by solvent extraction (Method 933.05. AOAC. 1996), ash by overnight heating at 550 °C (Method. 935.42. AOAC. 1995), and moisture by oven drying (Method. 24003. AOAC, 1984).

DSC

Thermal transitions of Cheddar cheese were determined by DSC (DSC5200C0, Seiko Instruments, Torrance, Calif., U.S.A.). The instrument was calibrated with indium at 5 °C/min from 25 to 250 °C. Cheese (30 mg) was introduced into an aluminum crucible (Seiko Instruments ∅5), dried at 130 °C in a forced-draft oven for 20 min (Tunick, 1994), and analyzed by DSC. Thermograms of oven dried and lyophilized samples were coincident. Water removal avoided interference with fat melting in the DSC curve. An empty crucible was used as a reference. Preliminary steps carried out before obtaining the DSC curves were as reported by Tunick (1994), the samples being tempered at 60 °C for 5 min, cooled to –50 °C at 5 °C/min and held at –50 °C for 5 min. A DSC curve was then obtained by heating the sample to 50 °C at 5 °C/min.

Ultrasonic measurements

The experimental setup for velocity measurements consisted of two narrow-band ultrasonic transducers (1 MHz, 0.75″ crystal diameter, A314S-SU Model, Panametrics, Waltham, Mass., U.S.A.), a pulser-receiver (Toneburst Computer Controlled, Model

PR5000-HP,Matec Instruments, Northborough, Mass., U.S.A.), a digital storage oscilloscope (Tektronix TM TDS 420, Tektronix Inc. Wilsonville, Oreg., U.S.A.) linked to a personal computer using a GPIB interface. A special software was developed in Visual Basic to receive the signal from the oscilloscope by the computer and calculate the velocity. A cheese cube was placed between the transducers.

For each velocity measurement, 5 signal acquisitions were taken and averaged, and the time of flight was computed from the average. These velocity measurements were replicated 5 times (using a different cube each time) and averaged. Distance between transducers was measured with a digital height gage (Electronic Height Gage, Model 752A, Athol, Mass., U.S.A.) and relayed to the computer through a RS232 interface. In order to calculate the system delay, pulse transit time measurements were performed on a set of calibration cylinders (aluminum) of different thickness. The delay time was determined from a plot of time vs thickness and used in the velocity computation.

Measurements at uniform temperature

To measure the velocity at different mean temperatures, 2-cm cube samples were cut and placed in controlled temperature (± 0.1 °C) chambers for ≥ 4 h, at which time cheese cubes had reached the expected uniform temperature. The contact fluid used at the transducer-sample interface was olive oil.

Unsteady state heating measurements

A 2-cm cube sample was placed between the transducers at an initially uniform temperature of 12 ± 0.1 °C and allowed to warm for 33 min. The top and bottom of the cube was in contact with the transducers, while remaining sides were isolated. The only heat entering the sample came from the transducer surfaces making heat transfer unidimensional although uneven due to the heat source from the emitter. Because of the changing boundary conditions, a numerical procedure was employed to produce the temperature change. The temperature on the top and bottom faces was measured using two small thermocouples. Temperature profile was calculated by finite difference (Arpaci, 1966), using 20 intervals of 1 mm. Temperature at the nodal points (T(i,n)) was computed from the initial temperature and the changing boundary conditions.

The temperature at the nodal points was calculated as follows.

$$T(i,n+1) - T(i,n) = \alpha[\Delta t/(\Delta x)^2] \times [T(i+1,n) + T(i-1,n) - 2 \times T(i,n)] \quad (1)$$

where α is the thermal diffusivity, Δt the integration time interval, Δx the interval length, and $\alpha(\Delta t)/(\Delta x)^2$ is the Fourier's modulus (F_o). To avoid solution instability, the values of Δt and Δx must be chosen to make the Fourier's modulus < 0.5 (Arpaci, 1966). The nodal point temperature was considered the average for each of the intervals. Velocity within the cube at a given time was calculated from relationships between the mean temperature and the velocity. The mean ultrasonic velocity through the sample was obtained by dividing the sample length by the time of flight (computed from the velocity at each interval) using:

$$V_{mean} = N\Delta x / \sum_{i=1}^{N} (\Delta x / V_i) \quad (2)$$

All computations were carried out using the EXCEL™ spreadsheet.

Thermal diffusivity measurements

The thermal diffusivity was determined by an unsteady state experiment (Sweat, 1986). Cubes of cheese (4 cm) were cut and placed into a thermostatic bath filled with olive oil at 38 ± 0.5 °C. The temperature was measured at the center of the cube with a thin thermocouple every 30 s, thus providing a set of experimental temperatures. The oil was vigorously stirred to assure a negligible external heat transfer resistance.

Diffusivity was determined by an iterative procedure by substituting one diffusivity into Eq (3) and minimizing differences between experimental and theoretical temperatures. To solve the optimization problem the tool SOLVER from the spreadsheet EXCEL™ was used.

$$[T(t) - T_\infty]/[T_0 - T_\infty] = 4 \times \sum_{n=0}^{\infty} \times [(-1)^n]/[(2n+1) \times \pi] \times e^{-\alpha\{[(2n+1) \times \pi]/2L\}^2 t} \quad (3)$$

Where T(t) is the temperature at time t, T_∞ is the oil temperature, T_0 the initial cheese temperature, α is the thermal diffusivity and 2 L is the cube side length. The series was evaluated to twenty terms.

RESULTS & DISCUSSION

THE RAW MATERIAL WAS 30.4% FAT, 37.9 % MOISTURE, 23.9% protein, and 4.3% ash, and the rest (3.5%) corresponded to carbohydrates and other components. These proximate composition values were similar to those reported in databases (USDA Database, 1997). The experimental temperature values were compared with calculated temperatures using Eq (3) (Fig. 1). The explained variance (V) was 99.75% calculated using Eq (4) (Lipson and Sheth, 1973).

$$V = [1 - S^2_{yx} / S^2_y] \times 100 \quad (4)$$

S_y is the standard deviation of the experimental data and S_{yx} the corresponding estimation. The thermal diffusivity was $0.81 \cdot 10^{-7}$ m^2/s ($\pm$ $0.06 \cdot 10^{-7}$).

Ultrasonic velocity decreased (Fig. 2) with increasing temperature. Velocity ranged from 1590 m/s to 1696 m/s (mean s.d. 2.83). Temperature influenced velocity in three segments 0 to 17 °C; 17 to 25 °C; and 25 to 35 °C. The limits of the segments could only be approximated from the velocity–temperature curve and were refined using the DSC curves (Fig. 3). Two regions of moderate melting were separated by a region with high melting rate. The ultrasonic velocity in liquid oil was lower than in solid fat (Miles et al., 1985; McClements, 1997). In segment "a" (Fig. 2), velocity decreased moderately with an increase of temperature due to the

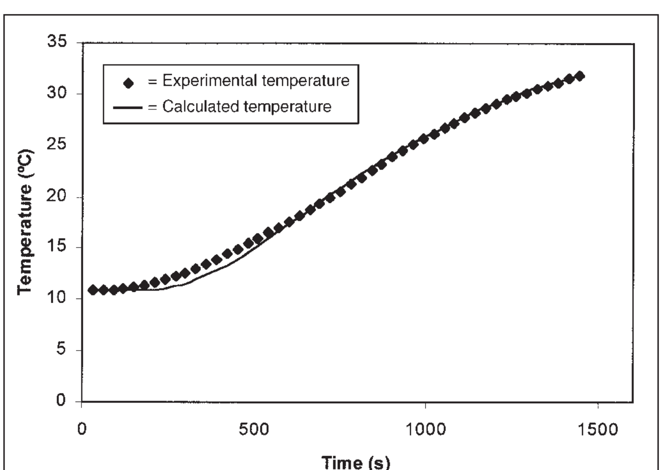

Fig. 1—Comparison of the experimental temperature measured in the center of a cheese cube submerged in an oil bath and the calculated temperature using a thermal diffusivity of 0.81×10^{-7} m^2/s.

negative temperature coefficient of the ultrasonic velocity of the solid fat (McClements, 1997) and the increase in liquid content. This was similar to Miles' et al. (1985) observation of velocity decrease with increasing temperature during fat melting and solidification on adipose tissue.

The slope of the DSC curve (Fig. 3) from 0 to 17 °C was moderate and quite uniform, indicating a moderate rate but continuous melting of fat. Segment "b" (Fig. 2) had a steeper slope than segment "a." This effect was due to the high increase in the liquid content that was superimposed on the negative temperature coefficient of the solid and liquid fat. From the DSC curve (Fig. 3) segment "b" coincided with a peak, indicating high melting. The increased liquid was accompanied by the change known as "oiling off" or "fat leakage." The oiling off occurs when the casein matrix collapses with heating, allowing fat globules to coalesce and flow to the surface (Tunick, 1994). This collapse of the matrix produced a change in the microstructure, one of the main factors affecting velocity of a material. At T > 25 °C (segment "c"), velocity decreased slightly with temperature because most of the low melting point fat had already melted. A similar pattern for Mozzarella fat melting was reported by Tunick (1994).

Each segment (Fig. 2) was represented by regression equations 5, 6, and 7 for the different temperature ranges. T > 35 °C were not considered because cheese started to flow and deformed excessively at such high temperatures.

$$v = -3.3T + 1695 \quad r^2 = 0.997 \quad 0 - 17\ °C \qquad (5)$$

$$v = -5.3T + 1729.3 \quad r^2 = 0.999 \quad 17 - 25\ °C \qquad (6)$$

$$v = -0.9T + 1618.7 \quad r^2 = 0.912 \quad 25 - 35\ °C \qquad (7)$$

From 0 to 17 °C, a change of 1 °C changed velocity by ± 3.3 m/s. The temperature coefficient for water is 3 $ms^{-1}\,°C^{-1}$ except that the sign is reversed. Thus, ± 0.1 °C corresponds to velocity fluctuation of ± 0.33 ms^{-1} between 0 to 17 °C. From 17 to 25 °C, ± 0.1 °C would change velocity at a rate of 0.53 m/s, and between 25 to 35 °C the velocity change would be 0.09 m/s. The accuracy of velocity measurement in cheese was highly dependent on temperature control. The most reliable range of temperatures to perform ultrasonic velocity measurements on this type of cheese should be from 0 to 17 °C. At 17 to 20 °C, greatest errors in velocity measurements occur when temperature was not controlled, and at T > 25 °C the cheese structure would irreversibly change with loss of oil, making measurements unreliable.

Equations (5) to (7) could be used to determine the mean temperature of cheese from the ultrasonic velocity. These equations are valid only for this type of cheese with this specific composition and solid fat content. For other types, although the same pattern would be expected (three regions), new relationships would need to be determinated on representative samples.

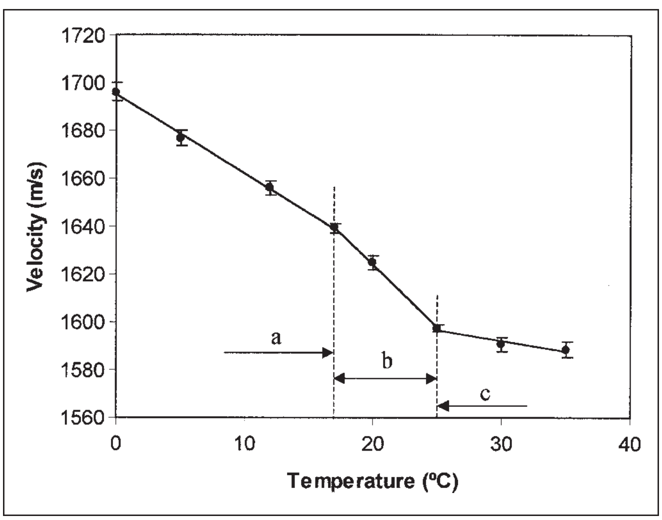

Fig. 2—Variation of ultrasonic velocity with temperature.

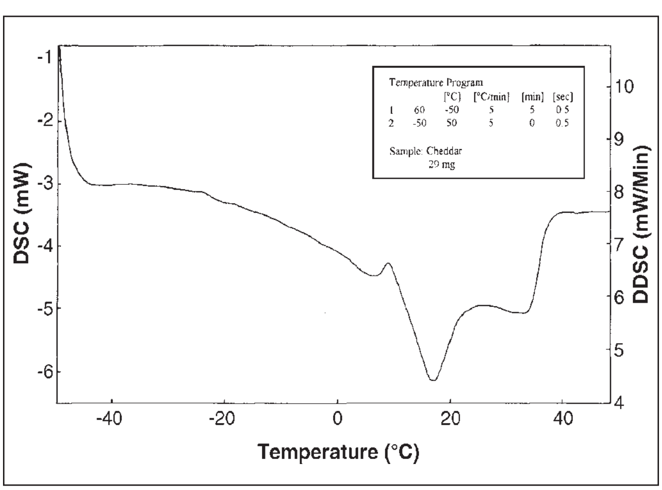

Fig. 3—Melting profile of fat from a Cheddar Cheese sample.

Varying temperature

Equations (5), (6), and (7) were further tested in unsteady state experiments with temperature measured at both transducers as the time dependent varying boundary condition. The temperature profile was then computed (Eq 1) and mean velocity changes were calculated (Eq 2). A thermal diffusivity 8.1×10^{-8} m^2/s, $\Delta t = 5$ s, and $\Delta x = 1 \times 10^{-3}$m was used to satisfy $F_0 = 0.4$.

Temperature profiles were calculated at different times (Fig. 4), and the corresponding experimental and calculated velocities vs time were compared (Fig. 5). The calculated velocities agreed well with the experimental values ($r^2 = 0.99$).

Equations (5), (6), and (7) could be used to calculate the ultrasonic velocity for this type of cheese at any given uniform temper-

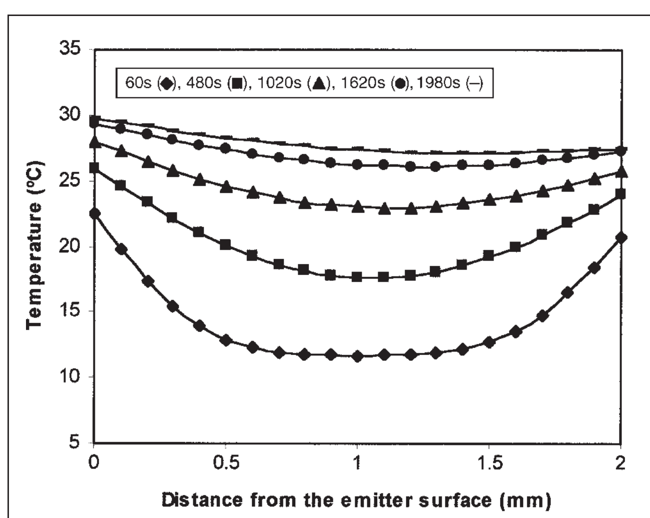

Fig. 4—Temperature profiles for a cheese cube placed between a pair of transducers atdifferent times. The sides of the cube were isolated and the length origin corresponds to the emitter face.

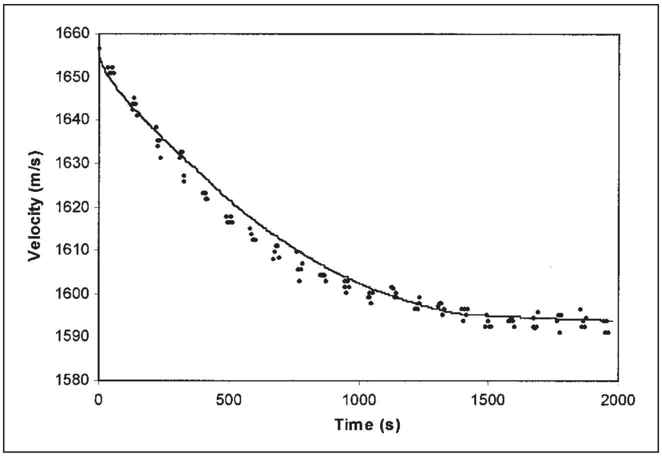

Fig. 5—Comparison of the experimental and calculated ultrasonic velocities in cheese.

ature or when a temperature profile is known. They also demonstrate the feasibility of using ultrasonic measurements to determine temperatures in Cheddar cheese. The system used was suitable for measurements on thicknesses > 25cm.

CONCLUSIONS

ULTRASONIC VELOCITY AT 1 MHZ CORRELATED HIGHLY WITH temperature of Cheddar cheese. The change in ultrasonic velocity with temperature reflected thermal transitions of fat within the cheese structure. The most convenient temperature span to determine velocity was 0 to 17 °C. Velocities measured near 7 °C would be suitable as well for studies of structural changes since that is a common curing temperature.

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