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Use of an ultrasonic reflectance technique to examine bubble size changes in dough

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Abstract. Bread quality largely depends on the manner in which bubbles are created and manipulated in the dough during processing. We have developed an ultrasonic reflectance technique to monitor bubbles in dough, even at high volume fractions, where near the bubble resonances it is difficult to make measurements using transmission techniques. A broadband transducer centred at 3.5 MHz in a normal incidence wave reflection set-up is used to measure longitudinal velocity and attenuation from acoustic impedance measurements. The technique is illustrated by examining changes in bubbles in dough due to two very different physical effects. In dough made without yeast, a peak in attenuation due to bubble resonance is observed at approximately 2 MHz. This peak diminishes rapidly and shifts to lower frequencies, indicative of Ostwald ripening of bubbles within the dough. The second effect involves the growth of bubble sizes due to gas generated by yeast during fermentation. This process is experimentally challenging to investigate with ultrasound because of very high attenuation. The reflectance technique allows the changes of the velocity and attenuation during fermentation to be measured as a function of frequency and time, indicating bubble growth effects that can be monitored even at high volume fractions of bubbles.

1. Introduction

The appearance and texture of many cereal products largely depends on the manner in which bubbles are created and manipulated in the dough during processing [1,2]. Understanding the effect of bubbles on the properties of dough is critical to controlling the texture of bread and hence its quality [1,2]. However, understanding how to control bubbles in a dough system is challenging because dough is an optically opaque bubbly system and the bubble distribution changes quite rapidly with time, a phenomenon that is true due to Ostwald ripening in dough made without yeast [3] or from inflation with carbon dioxide in dough made with yeast [4]. Because ultrasound is sensitive to bubbles in dough [5], the aim of this paper was to use ultrasound to monitor time-dependent changes in the bubble size distribution in two types of dough systems – those made with and without yeast.

2. Theoretical background

2.1. Acoustic resonances in dough as an effective medium

In a bubbly system such as dough, the phase velocity (v) and attenuation coefficient (α) exhibit a strong dependence on angular frequency (ω) due to the acoustic resonance of the bubbles. This resonant behavior can be described in terms of the complex effective medium wave vector $k = \omega/v + i\alpha/2$, which deviates from the wave vector of the matrix, k_0 , by a contribution that depends on the number and sizes of the bubbles [6].

$$k^2 = k_0^2 + 4\pi \int N(r) dr \frac{r\omega^2}{\omega_M^2 - \omega^2 - i\omega\Gamma} \quad (1)$$

Comparing the predictions of this model with experimental data enables the bubble size distribution $N(r)$ to be determined, providing that we have information on the dough matrix properties, which influence the bubble resonant frequencies ω_M and the damping rate Γ (which depends on thermal, viscous, and radiative losses). We have shown in a variety of aerated soft materials that this approach is a promising line of attack [6-9].

2.2. Dough bubble size determination

It is assumed that the subdividing process occurring to air bubbles during mixing creates a log-normal distribution of bubbles in the dough [1], with median radius R , logarithmic standard deviation ε and gas volume fraction Φ . Using the above bubble resonance model [6], it can be shown that R and ε can be determined from measurements of the frequency at which the maximum in attenuation occurs f_{\max} and the height of the attenuation peak α_{\max} if the density of the dough (and hence Φ) has been determined independently, e.g., by using Archimedes principle [5].

$$\alpha_{\max} = \frac{2\sqrt{3}\Phi}{R \exp(2\varepsilon^2)} \quad (2)$$

$$(2\pi f_{\max})^2 = \frac{3\kappa P_0 + 4\mu'}{\rho_m R^2} \quad (3)$$

In these equations, κ is the polytropic index for the transformations undergone by the gas, P_0 is the pressure in the bubble, μ' is the real part of the complex shear modulus and ρ_m is the density of the dough matrix [6]. Full details of the analysis have been provided recently by Leroy et al [6].

3. Materials and methods

To investigate the dynamics of air bubbles introduced into the dough during mixing, doughs were made without yeast, from 100 g of hard red spring wheat flour, 57 g of water (for ease of sample preparation) and 2.4 g of salt. Dough was mechanically developed as previously described [5] by mixing for 4 minutes.

To investigate bubble expansion due to the addition of yeast, samples were prepared using a sponge and dough procedure [10] using 69.2 g of hard red spring wheat flour and 41 g of water for sponge and 29.7 g of flour and 4.8 g of water for dough (optimized water absorption).

Dough density was measured to ascertain the amount of air incorporated into the dough using 25 mL gravimetric bottles (Kimble Glass Inc., Vineland NJ) using 5 g sub-samples of dough.

Experiments were performed in a normal incidence wave reflection set-up using a transducer with a central frequency of 3.5 MHz, an acrylic delay line, to which the transducer was bonded, and a pulser. Reflected signals were detected by the same transducer, amplified and recorded on a digital oscilloscope.

A very sharp razor blade, lightly greased with mineral oil, was used to cut a disc approximately 9 mm thick from the centre of the dough sample. The cut surface was also lightly greased with mineral oil and placed greased side down on the acrylic delay line (so as to establish good acoustic contact). A metal weight was placed on top of the dough to improve contact.

The reflection set-up was used either at room temperature, but covered (to prevent moisture loss) for doughs made without yeast, or placed inside a proofing cabinet at normal proofing conditions (37°C, 83% relative humidity). In the latter case the set-up had been placed in the proofing cabinet for at least one hour prior to experiments to allow acclimatization to the proofing cabinet's temperature.

A reference signal (the reflected ultrasonic pulse with no dough on delay line) was measured at the beginning of all experiments. Acquisitions were then performed every minute after sample mounting. From the ratio of the Fourier transforms of dough and reference signals, the complex impedance of the dough was determined [6]. From the real and imaginary parts of the complex impedance, the longitudinal phase velocity and attenuation coefficient as a function of frequency were calculated over a broad frequency range.

4. Results and Discussion

4.1. Monitoring Ostwald ripening in unyeasted dough

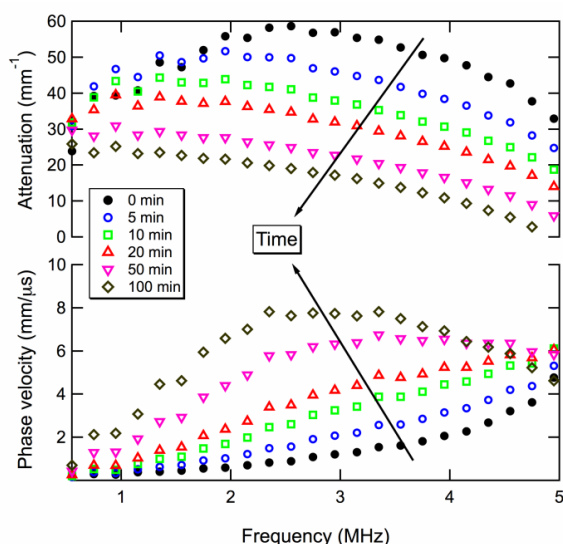


Figure 1. Changes in ultrasonic phase velocity and attenuation coefficient vs frequency for unyeasted dough.

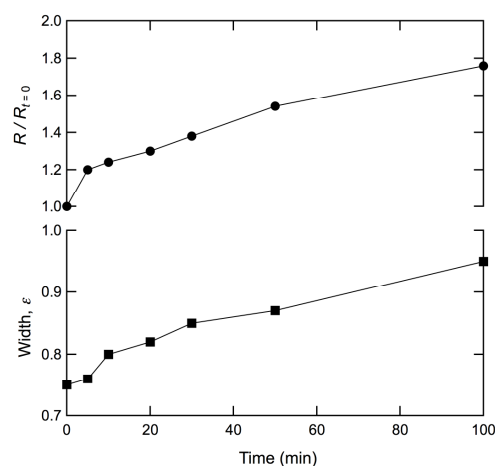


Figure 2. Increase in median bubble size and width of bubble distribution with time (determined from data in figure 1).

From figure 1, it can be seen that there are pronounced changes in phase velocity (bottom) and a peak in attenuation (top) due to the resonance of bubbles in the dough [11]. This peak in attenuation, which occurs at approximately 2 MHz, diminishes rapidly with time and shifts to lower frequencies.

By fitting the model described in section 2 [6-8] to the phase velocity and attenuation data in figure 1, we determined how the median bubble size and the width of the bubble distribution of the bubbles in the dough changes as a function of time (figure 2). It can be seen that both the median radius and the width of the distribution increase with time. Both these changes are characteristic features of Laplace-pressure driven growth of large bubbles at the expense of smaller ones, indicative of Ostwald ripening of bubbles within the dough [3].

4.2. Monitoring the effects of carbon dioxide on dough properties

The fermentation process is experimentally challenging to investigate with ultrasound because very high attenuation limits propagation of the ultrasonic signal, particularly at long proofing times [4]. With our reflection setup, signals with excellent signal to noise ratio can be detected throughout the entire proofing process, enabling the frequency dependence of the attenuation and velocity to be determined, and f_{\max} and α_{\max} to be measured. It can be seen from figure 3 that both f_{\max} and α_{\max} change in a non-linear manner as fermentation progresses.

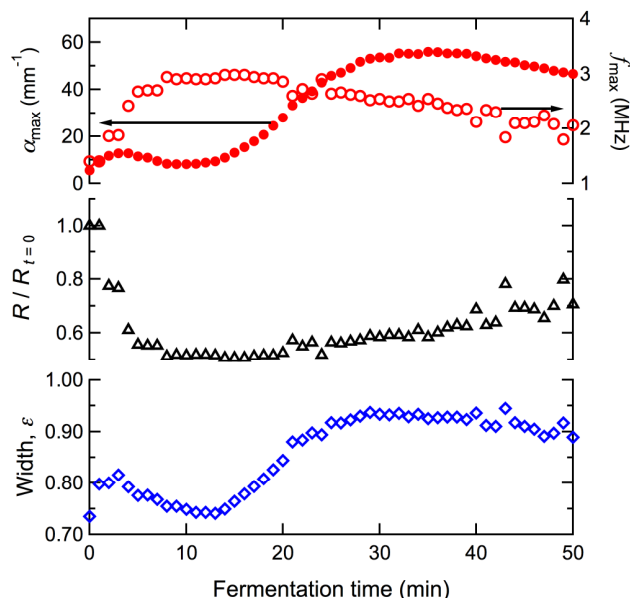


Figure 3. Changes in ultrasonic attenuation parameters that translate into changes in median bubble size and width of bubble distribution with proofing time.

An interesting phenomenon occurs for $5 < t < 10$ mins, where α_{\max} decreases and the frequency at which the peak in attenuation occurs shifts to higher frequency (essentially a shorter wavelength). Lower attenuation at short fermentation times has previously been reported in low frequency experiments [12]. This is consistent with yeast being a facultative anaerobe, preferentially consuming oxygen when available. The air bubble volume will then shrink by ~20% (an effect also confirmed by initial increases in dough density).

At longer times, the yeast cells start to generate carbon dioxide as a result of fermentation activities. Attenuation is increased by the growth of bubble sizes due to inflation with CO_2 , and the increase in bubble distribution width (observed up to 30 min fermentation) is monitored from ultrasonic reflection measurements.

5. Conclusions

Ultrasonic velocity and attenuation (as measured by a novel reflection technique) are sensitive to the size of bubbles in bread dough. It is shown that for unyeasted dough the median radius and the width of the bubble log-normal distribution increase with time due to Ostwald ripening. The reflectance technique allows changes due to bubble growth effects during fermentation to be measured as a function of time, even at high volume fractions of bubbles, where it is difficult to make ultrasonic measurements using transmission techniques.

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