Dielectric Monitoring of Gas Production in Fermenting Bread Dough

MAKOTO ITO,[1] SHIGENORI YOSHIKAWA,[1] KOJI ASAMI,[2] and TETSUYA HANAI[2]

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ABSTRACT

We developed a dielectric method to monitor the volume fraction (Φ) of CO_2 gas in bread dough during fermentation. Capacitance (C) and conductance (G) of bread dough were measured at 0.32, 3.2, and 32 MHz using disc-type and needle-type electrodes. The value of Φ was calculated from the observed values of C and G using simple dielectric mixture equations. The results agreed well with those obtained by an ordinary volumetrical method. The dielectric method is very useful for quality control in the production of bread because the gas production or expansion of dough can be automatically monitored without special containers.

One of the important stages in fermenting bread dough is CO_2 gas production, which depends on the conditions of the dough, such as flour quality and yeast activity. Monitoring the CO_2 gas production is, therefore, necessary to control product quality. Although many devices have been developed for this purpose (Markley and Bailey 1932, Sherwood et al 1940, Hullet 1941, Glabe 1942, Working and Swanson 1946, Sutton 1950, Rubenthaler et al 1980), most of them are only for laboratory use, and they need closed chambers or containers because their measurement parameters are volume and pressure.

In this study, we tested a dielectric method for measuring gas production in bread dough. The principle of this method is completely different from those of other methods. The measurement parameters are capacitance (C) and conductance (G) (or permittivity and conductivity, respectively) of the dough. Because the gas phase has different permittivity and conductivity from the rest of the dough, C and G are a function of the volume fraction (Φ) of the gas phase in the dough. The value of Φ is, thus, calculated from the measured values of C and G using simple dielectric mixture equations. This method has a great advantage over other methods, especially for monitoring product quality in factories, because it does not need a special container, only a pair of simple electrodes.

MATERIALS AND METHODS

Preparation of Bread Dough

The formula for the bread dough consisted of 100 parts wheat flour (Nisshin Flour Milling Corporation, Tokyo, Japan), 2.4 parts compressed yeast (Oriental Yeast Co., Ltd., Tokyo, Japan), 0.2 parts salt, and 57 parts water. The dough was mixed in a mixer (model N-50G, Hobart Co., Troy, OH) at 60 rpm for 3 min and then 120 rpm for 3 min.

Dielectric Measurement

A pair of electrodes were placed in contact with a piece of bread dough, and its capacitance and conductance were measured with an Impedance/Gain Phase Analyzer (model 4194A, Yokogawa-Hewlett Packard Ltd., Tokyo, Japan) at three frequency points, 0.32, 3.2, and 32 MHz. The stray capacitance and residual inductance arising from the electrodes were compensated for using an internal function of the analyzer. We tested two types of electrode systems, disc-type and needle-type, as shown in Figure 1. In the disc-type electrode system, a pair of platinum (Pt) discs 40 mm in diameter were used, and the distance between them was variable from 0 to 50 mm. In the needle-type electrode system, a pair of stainless-steel needles 0.8 mm in diameter and 25 mm long were fixed to a lucite plate 15 mm apart.

Calculation of Volume Fraction of Gas

We consider fermenting bread dough to be represented by an electrical model, in which bubbles (of relative permittivity ϵ_g and conductivity κ_g) are dispersed in a continuous phase (of ϵ_m and κ_m) with a volume fraction Φ, as shown in Figure 2. Using a dielectric theory for the heterogeneous system (Hanai 1968), we obtained the relative permittivity ϵ and conductivity κ of the system on the assumptions of $\epsilon_g \ll \epsilon_m$ and $\kappa_g \ll \kappa_m$:

$$\epsilon/\epsilon_m = (1-\Phi)^{3/2}, \tag{1}$$

$$\kappa/\kappa_m = (1-\Phi)^{3/2}. \tag{2}$$

If ϵ_m and κ_m remain constant during fermentation, the permittivity ϵ_0 and conductivity κ_0 of the dough measured at the initial stage (where $\Phi = 0$) may be substituted for ϵ_m and κ_m. Thus, instead of equations 1 and 2, we can use the following equations:

$$\epsilon/\epsilon_0 = (1-\Phi)^{3/2}, \tag{3}$$

$$\kappa/\kappa_0 = (1-\Phi)^{3/2}. \tag{4}$$

Because the permittivity ratio ϵ/ϵ_0 and conductivity ratio κ/κ_0 are equal to the capacitance ratio C/C_0 and conductance ratio G/G_0, respectively, where the subscript 0 refers to the value at the initial stage, the volume fraction is calculated from

$$\Phi_c = 1-(C/C_0)^{2/3}, \tag{5}$$

$$\Phi_g = 1-(G/G_0)^{2/3}, \tag{6}$$

[1]Applied Microbiology Laboratory, Yamazaki Baking Co., Ltd., Kumegawacho, Higashimurayama, Tokyo 189, Japan.
[2]Institute for Chemical Research, Kyoto University, Uji, Kyoto 611, Japan.

where Φ_c and Φ_g refer to the volume fractions calculated from C/C_0 and G/G_0, respectively. The volume fraction is easily converted into the volume ratio V/V_0 of the dough as:

$$V/V_0 = 1/(1 - \Phi), \tag{7}$$

where V_0 is the initial volume.

Measurement of Dough Volume

The volume of dough was measured with a graduated cylinder 60 mm in diameter and 300 mm high. A piece of dough was placed at the bottom of the cylinder, and its volume was measured every 30 min at 27°C.

RESULTS AND DISCUSSION

The C and G of fermenting dough at 27°C were measured every 10 min at three frequency points, 0.32, 3.2, and 32 MHz. Figure 3 shows the results obtained with a disc-type electrode system at 15-mm distance. The data are represented by the capacitance ratio C/C_0 and conductance ratio G/G_0, where C_0 and G_0 are the capacitance and conductance at the initial stage. The value of C/C_0 decreases with time and attains a steady level within 90 min, the change being in accord with that of G/G_0. These changes are independent of frequency, at least between 0.32 and 32 MHz.

Using the electrical model shown in Figure 2, we calculated the volume fraction Φ of gas in the dough from the measured values of C/C_0 and G/G_0 (Fig. 4). The values of Φ_c calculated from C/C_0 are in close agreement with those of Φ_g calculated from G/G_0. These values were reproduced within ±5% (at the final steady stage) for three different samples. Excellent agreement was also obtained between the values of Φ estimated by the dielectric and volumetric methods. These results suggest that the dielectric method provides accurate and reliable measurements of gas production in fermenting dough.

Although accurate values of Φ are obtained with the disc-type electrode system at a 15-mm distance, this is not a convenient method for monitoring product quality in factories because the narrow electrode distance causes serious deformation of the

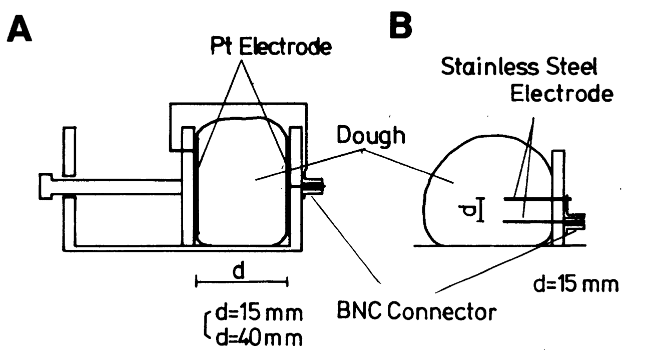

Fig. 1. Two types of electrode systems used in dielectric measurements of bread dough. **A,** Disc-type electrode system with a variable distance. **B,** Needle-type electrode system. d = the distance between electrodes. BNC connector = connectors for coaxial cables.

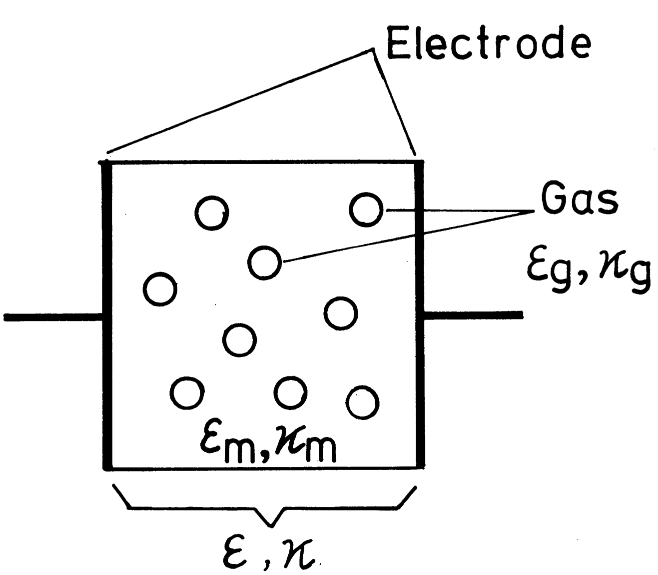

Fig. 2. An electrical model of fermenting bread dough. Bubbles of relative permittivity $\epsilon_g(\approx 1)$ and conductivity $\kappa_g(\approx 0)$ are dispersed in a continuous phase of ϵ_m and κ_m.

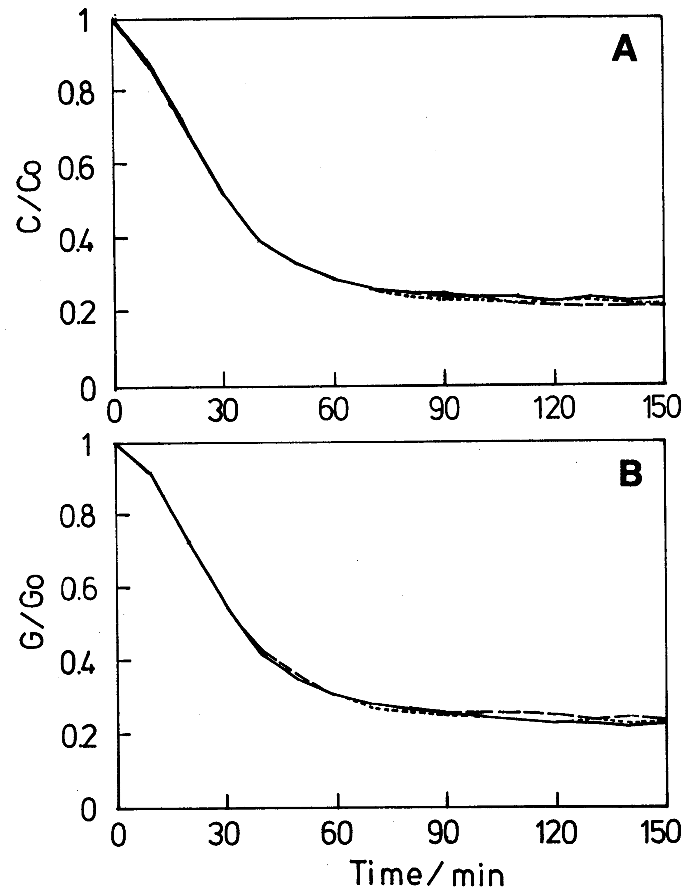

Fig. 3. Change in C/C_0 (**A**) and G/G_0 (**B**) of fermenting dough measured with the disc-type electrode system at different frequencies. d = 15 mm. Solid line represents data obtained at 0.32 MHz. Dashed line represents data obtained at 3.2 MHz. Dotted line represents data obtained at 32 MHz.

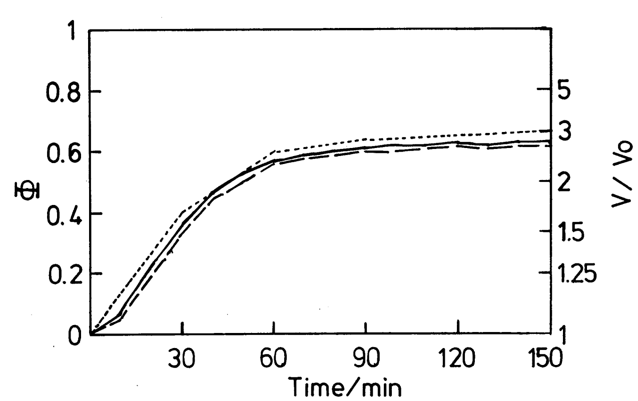

Fig. 4. Change in the volume fraction of gas in fermenting dough. Solid line represents data calculated from the values of G/G_0 in Figure 3. Dashed line represents data calculated from the values of C/C_0 in Figure 3. Dotted line represents data obtained by the volumetric method.

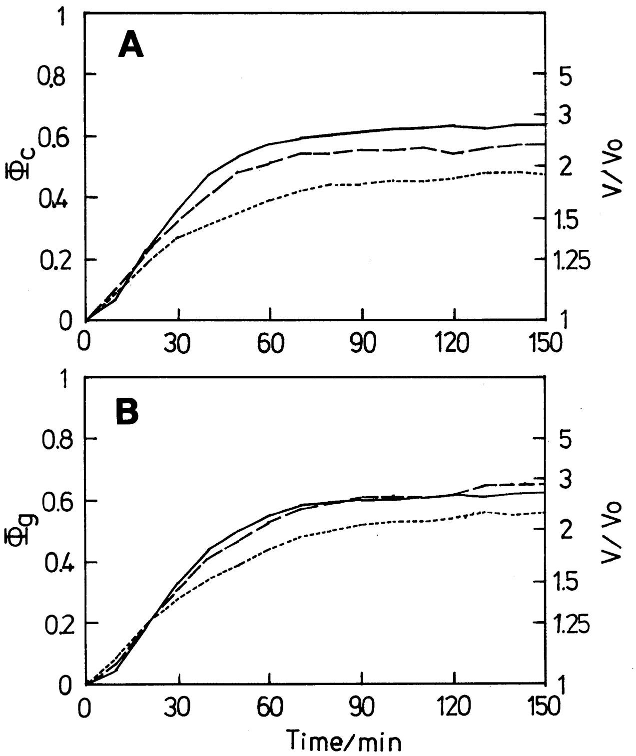

Fig. 5. Comparison of volume fractions calculated from the data measured with different types of electrodes. **A,** the volume fraction Φ_c calculated from C/C_0. **B,** Φ_g calculated from G/G_0. Solid line represents data from the disc-type electrodes (d = 15 mm). Dashed line represents data from the disc-type electrodes (d = 40 mm). Dotted line represents data from the needle-type electrodes (d = 15 mm).

dough. Therefore, we tested a disc-type electrode system with a wider gap (40 mm) and a needle-type electrode system. The results are shown in Figure 5. With the disc-type electrode system, there was little difference in the values of Φ_g regardless of the electrode distance, whereas the values of Φ_c at a 40-mm distance included some errors, probably because of uncorrected stray capacitance. With the needle-type electrode system, there was some reduction of the values of Φ_c and Φ_g compared with those obtained with the disc-type electrode system at a 15-mm distance. However, this is not a serious problem for practical use because we can correct the data using a prepared calibration table.

CONCLUSION

The volume fraction of gas in fermenting dough can be monitored by the dielectric method. The disc-type electrode system provides an accurate value of the volume fraction, which can be calculated from either the capacitance or the conductance measurements on the dough. Although measurements with the needle-type electrode system require calibrations, they are quite useful for monitoring product quality in factories because the method does not deform the dough or require a closed chamber. We used an expensive impedance analyzer in this study; however, inexpensive conductivity meters are available and can be used just as effectively.

ACKNOWLEDGMENT

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