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:

$$V/V_0 = 1/(1-\Phi), \quad (7)$$

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

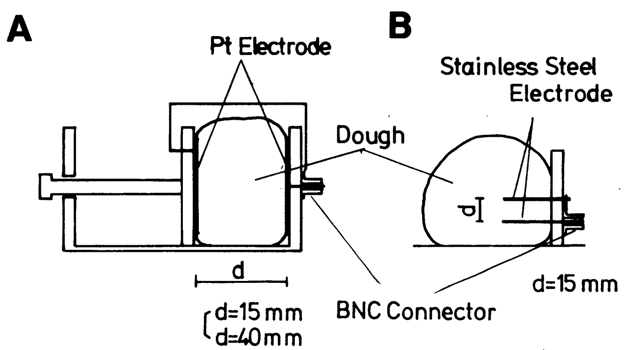

Fig. 1. Two types of electrode systems used in dielectric measurements of bread dough. **A,** Disc-type electrode system with a variable distance. **B,** Needle-type electrode system. d = the distance between electrodes. BNC connector = connectors for coaxial cables.

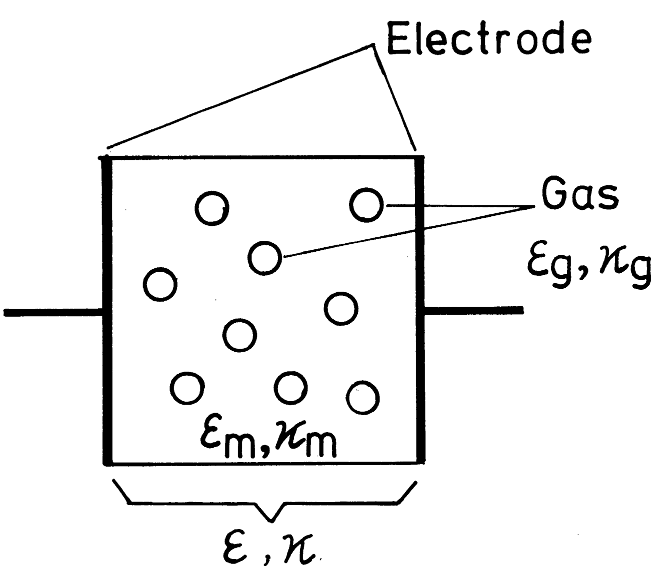

Fig. 2. An electrical model of fermenting bread dough. Bubbles of relative permittivity $\epsilon_g(\approx 1)$ and conductivity $\kappa_g(\approx 0)$ are dispersed in a continuous phase of ϵ_m and κ_m.

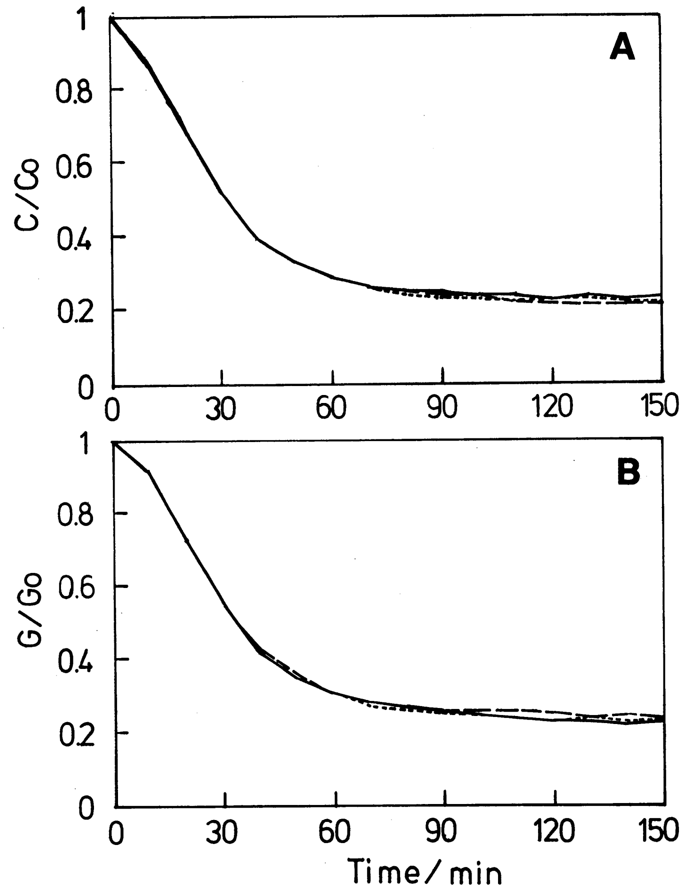

Fig. 3. Change in C/C_0 (**A**) and G/G_0 (**B**) of fermenting dough measured with the disc-type electrode system at different frequencies. d = 15 mm. Solid line represents data obtained at 0.32 MHz. Dashed line represents data obtained at 3.2 MHz. Dotted line represents data obtained at 32 MHz.

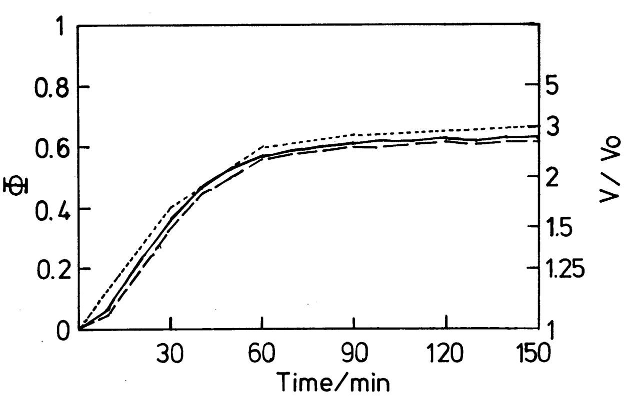

Fig. 4. Change in the volume fraction of gas in fermenting dough. Solid line represents data calculated from the values of G/G_0 in Figure 3. Dashed line represents data calculated from the values of C/C_0 in Figure 3. Dotted line represents data obtained by the volumetric method.

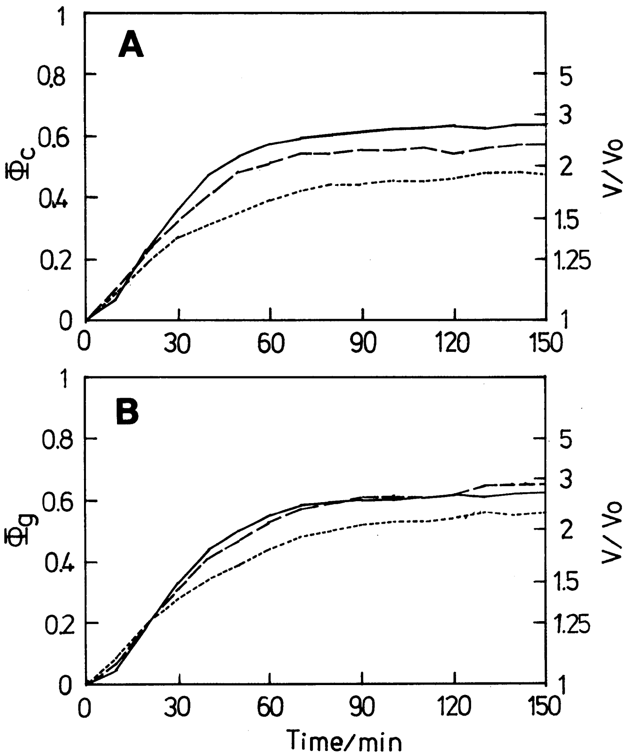

Fig. 5. Comparison of volume fractions calculated from the data measured with different types of electrodes. **A,** the volume fraction Φ_c calculated from C/C_0. **B,** Φ_g calculated from G/G_0. Solid line represents data from the disc-type electrodes (d = 15 mm). Dashed line represents data from the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

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