A Critical Look at the Electric Resistance Oven[1]

H. HE[2,3] and R. C. HOSENEY[2]

Cereal Chem. 68(2):151-155

ABSTRACT

An electric resistance oven (ERO) was used to study the properties and electric resistance of dough at increasing temperatures. In this study, a modified ERO was used to improve the flow of CO_2 released from the dough to the detector. The results showed that heating methods not only determined the profile of dough temperature but also affected the expansion, CO_2 release patterns, and electrical resistance of dough. The resistance of dough containing yeast was three times higher than that of dough without yeast. To obtain a fully baked loaf, input power needed to be sufficient to raise the dough temperature to 100°C and to compensate for the heat loss to the atmosphere. Baking with the ERO at room temperature resulted in temperature gradients from the center to the outer layer of the dough, with the greatest gradient near the top of the dough. This probably was caused by dissipation of heat to the environment and by the lack of electrical heating in the crown area of the dough.

Bread is traditionally baked in a conventional oven, in which dough is heated progressively from the outside toward the center. Marston and Wannan (1983) found that the rise in temperature below the surface of dough goes through a three-phase sequence. It begins with a slow increase up to 50°C, increases sharply from 50 to 85°C, and then gradually increases to 100°C. However, no two zones within dough undergo the same conditions at the same time (Baker and Mize, 1939a). This causes difficulties in the study of dough properties during baking. For example, it has been impossible to determine the temperature at which dough stops expanding by observing baking in a conventional oven.

Baker (1939) developed an electric resistance oven (ERO) in which heat is generated internally by using dough as a conductor with high resistivity between electrodes carrying an alternating current. Therefore, all of the dough theoretically heats uniformly. This baking method provides a useful tool for studying how dough changes with temperature during baking.

Different dough temperatures as a result of baking in an ERO have been reported in the literature. Baker and Mize (1939a) baked dough to 100°C to study the effect of temperature on dough properties. Junge and Hoseney (1981) used an updated model of an ERO to investigate the effect of shortening and surfactant on dough properties. They raised the dough temperature to 88°C; Moore and Hoseney (1986) raised it to about 86°C.

Because temperature governs the physical, chemical, and biological changes in breadmaking, different heating methods might change the baking properties of dough. However, the factors affecting dough baking properties have not been thoroughly studied. The objectives of this work were to study the effect of heating methods and conditions on dough-baking properties and the change in electrical resistance of dough during baking in an ERO.

MATERIALS AND METHODS

Preparation of Dough for Baking

A commercial bread flour containing 11.5% protein and 0.48% ash was used. The preparation of dough generally followed the AACC Method 10-10B (AACC 1983). Nonfat dry milk (4.0%) (Gallaway West, Fond du Lac, WI), instant dry yeast (0.75%) (Gist-Brocades, Charlotte, NC), and 10 ppm of $KBrO_3$ were added to the formula. Fermentation time was 180 min. Some doughs also were made without yeast.

The baking procedure before panning followed the standard method. The panning procedure consisted of molding the dough in the usual manner and then cutting it longitudinally on the top side (i.e., the side opposite the seam) to a depth of about half the diameter of the dough, so that a flat surface of dough was obtained to ensure better contact with the plates of the ERO. The dough was then placed cut-side-up on the bottom of the ERO (which was placed in a proofing cabinet) and was proofed for 55 min before baking.

Resistance Baking

The ERO used in our study is illustrated in Figure 1. Compared with the ERO presented by Junge and Hoseney (1981), some major modifications were made. Two strips (3-mm wide) were excised along the sides on each electrode plate. The gas inlet was moved to the top of the ERO and the outlets to the lower part of both side walls, 10 mm above the bottom. This ERO allowed nitrogen, as a carrier, to flow over the surface of the dough and carry the CO_2 away immediately, as it was released from dough.

Dough was placed between the two plates of the ERO, which were connected to the output of a variable transformer. The heating rate and dough temperature were controlled by adjusting the output of the variable transformer. Dough temperature was monitored by a thermocouple inserted directly into the dough through a small hole 10 mm above the bottom of the oven. The midpoint between the highest and lowest points of the dough surface was taken as dough height.

Quantification of CO_2

CO_2 was measured by a Beckman model 865 Infrared Analyzer with Range 1, which could detect a CO_2 concentration of 0–500 ppm. The flow diagram for measuring the rate of CO_2 released

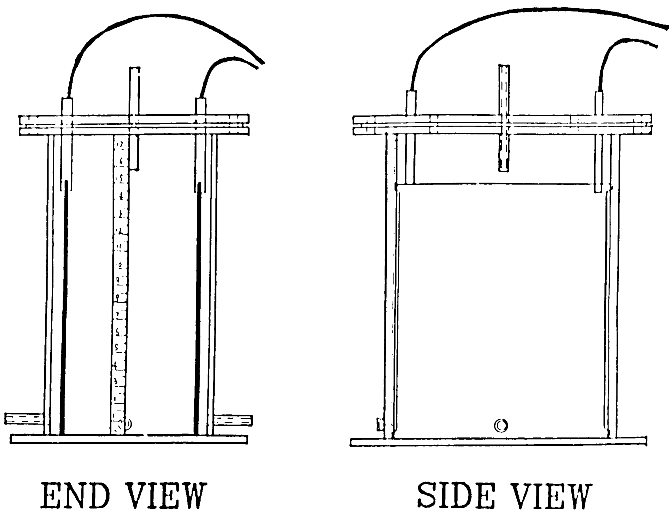

Fig. 1. Electric resistance oven.

[1]Contribution 90-364J. Kansas Agricultural Experiment Station, Manhattan, KS 66506.

[2]Graduate research assistant and professor, Department of Grain Science and Industry, Kansas State University, Manhattan, KS 66506.

[3]Present address: Anheuser-Busch Companies, Inc., St. Louis, MO 63118-1852.

from the dough is shown in Figure 2. Nitrogen, as a carrier, flowed into the ERO at a rate of 4,500 cm^3/min. The gases coming out of the ERO were dried by three flasks of concentrated sulfuric acid, in series, to remove water and minimize its interference with infrared analysis of CO_2. Silica gel was used to check the dryness of the gas. The gas was then split into a smaller flow suitable for the detector. The magnitude of CO_2 released from dough during baking was recorded. A baseline was established with nitrogen as a blank gas.

The CO_2 detection of the infrared detector was linear within the range of 0–70 units on the scale, with a slope of 3.6 ppm of CO_2/unit, which corresponds to the upper limit of 252 ppm of CO_2. The maximum rate of CO_2 released from bread dough during baking is about 1,150 ppm/min. Therefore, only one fifth of the gas produced entered the infrared detector at a flow rate of 900 cm^3/min. Standard gas contained 306 ppm of CO_2 in nitrogen. Therefore, the instrument was calibrated to indicate 17 units (306 ppm of CO_2 divided by 3.6 ppm of CO_2 per unit divided by 5) on the scale with the standard gas. Each unit on the chart represents the flow rate of CO_2 at 25°C:

$$\frac{3.6 \text{ ppm} \times 900 \text{ cm}^3/\text{min}}{2.4451 \times \text{cm}^3/\text{mol}}$$

The maximum rate of CO_2 that could be detected in the linear range was 46.4×10^{-6} mol/min.

Measurement of Dough Resistance

A Simpson 462 Autoranging Digital Multimeter (Simpson Electric Co., Elgin, IL) was connected in series with the ERO to measure the AC current passing through the dough. According to Ohm's law, $V = R \times I$, where V is the voltage (volts) applied to dough, R is the resistance (ohms) of dough, and I is the current (amps). Thus, the resistance of the dough can be calculated by the known voltage divided by the measured AC current.

Measurement of Dough Temperature Gradient

During baking in the ERO, dough temperature was monitored with a thermocouple. When the dough at the center of the loaf 10 mm above the bottom (Fig. 3, side view A) reached 70, 80, or 90°C, voltage was reduced to maintain the temperature for 30 sec. During this holding period, additional temperature measurements were taken at various points from the center on the top of dough, as follows: 1) at increasing depths within the dough mass (2.5, 12.5, 22.5, 42.5, and 62.5 mm, Fig. 3, side view A), 2) from the end of the dough (i.e., the oven wall) (62.5, 42.5, 22.5, 12.5, and 2.5 mm, Fig. 3, top view B), or 3) from the side of dough (32.5, 22.5, 12.5, and 2.5 mm, Fig. 3, also top view B).

From each dough, temperature measurements were taken of only one dimension—depth, length, or width. Duplicate temperature measurements were made in each dimension.

To examine the effects of various heating methods on baking properties, different voltage potentials, obtained by adjusting the output of a variable transformer, were applied to the ERO to bake dough. Temperatures were measured periodically at the center of the dough 10 mm above the bottom and were plotted against time. Methods A and B used constant potentials of 75 and 120 V, respectively. Method C used variable voltage potentials during different periods of baking: 50 V (0–8 min), 90 V (9–10 min), 100 V (11–12 min), and 120 V (13–22 min).

RESULTS AND DISCUSSION

Dough Temperature

Three temperature-time profiles are shown in Figure 4. When a constant 75-V potential was applied (method A), dough temperature increased linearly to 66°C. Above 66°C, it rose at a decreasing rate to 86°C. When dough was baked with a constant 120-V potential (method B), the heating rate was so fast that dough temperature reached 100°C in only about 5 min.

With method C, dough temperature slowly reached 50°C

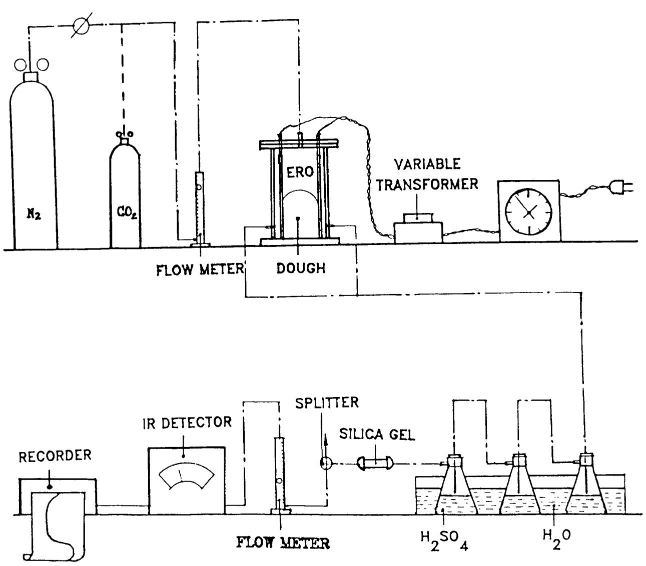

Fig. 2. Electric resistance oven system to detect rate of CO_2 loss.

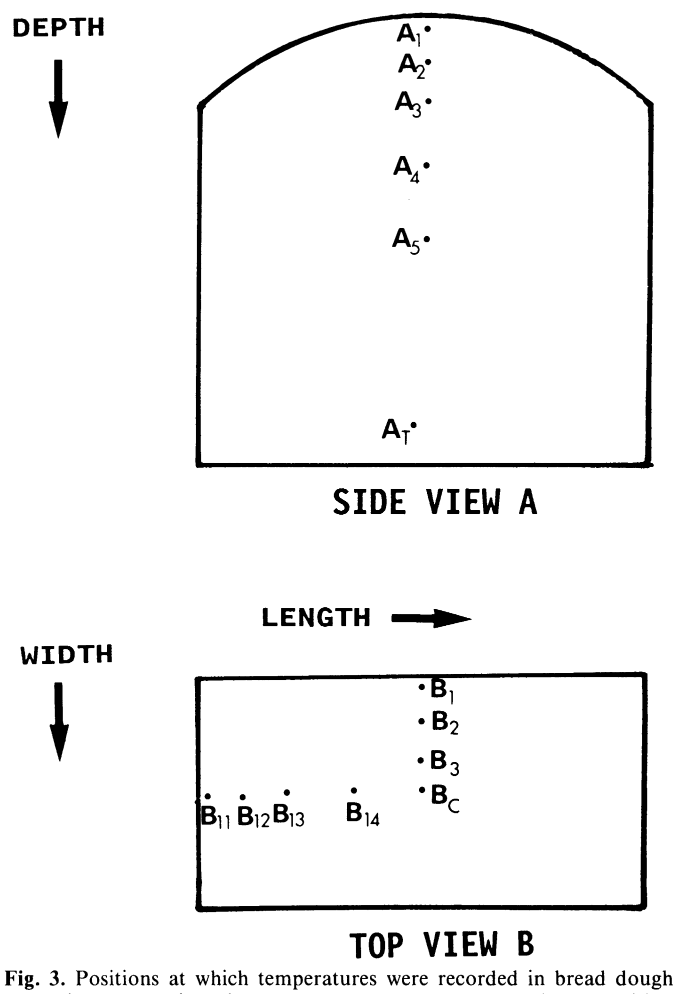

Fig. 3. Positions at which temperatures were recorded in bread dough baked in the electric resistance oven. In **side view A,** A_T is the position where the thermocouple was located at the center, 10 mm above the bottom of the dough. A_1, A_2, A_3, A_4, and A_5 are positions in the center of the dough at depths of 2.5, 12.5, 22.5, 42.5, and 62.5 mm from the top, respectively. In **top view B,** B_1, B_2, B_3, and B_C are positions 2.5, 12.5, 22.5, and 32.5 mm from the side of the dough toward the center, at a depth of 22.5 mm. B_{11}, B_{12}, B_{13}, B_{14}, and B_C were 2.5, 12.5, 22.5, 42.5, and 62.5 mm, respectively, from the end of the dough (the oven wall) toward the center, at a depth of 22.5 mm.

(within 8 min) and then greatly increased from 50 to 85°C, with a maximum dough temperature of 100°C. Method C gave the closest profile to that reported by Marston and Wannan (1983) of temperature versus time for the center of dough baked in a conventional oven.

Dough Properties

Heating methods affected final loaf height (Fig. 5). When baked by method C, dough did not stop expanding until the temperature reached about 97°C, whereas with method A, because dough temperature reached only 86°C, dough stopped expanding at 86°C. As a result, method C resulted in a loaf about 15 mm greater in height.

Heating methods also affected the profiles of CO_2 release during baking (Fig. 6). In the early stages of baking, the rate of CO_2 loss was about 5 μmol/min from the doughs baked with methods A and C. Also, both doughs started to lose more CO_2 at about 72°C. However, with method A, the rate of CO_2 loss gradually increased, with rather large fluctuation, to about 25 μmol/min at the end of baking. With method C, the rate of CO_2 loss sharply increased to a maximum of 43 μmol/min at 88°C and then decreased slowly before a sharp decrease occurred at about 97°C. The total amount of CO_2 released from the dough was considerably more with method C than with method A during 22 min of baking time.

Dough Resistance

Figure 7 shows the changes in dough resistance during baking of yeasted doughs with methods A and C and nonyeasted dough with method A. The fully proofed yeasted doughs had 145 Ω of resistance, which was much higher than that of nonyeasted dough. As the temperature rose, the yeasted dough resistance decreased slightly (which might be attributed mainly to thermal effects on ionic conductivity) and then, at about 65°C, started to increase gradually. The increase may be related to the fact that less free water was available to the ionic solution as the starch started to gelatinize. When the temperature reached 78°C, dough resistance increased faster with method A than with method C. This occurred because with method A, the dough temperature slowly increased from 78 to 86°C; therefore, more water evaporated during this period. The final resistance reached 170 Ω.

The resistance of dough baked with method C started to increase sharply when the temperature reached 95°C and reached 325 Ω at 100°C. This is in agreement with the findings of Baker and Mize (1939a). The sharp increase in dough resistance might be attributed to rapid water vaporization.

The resistance of nonyeasted dough was 50 Ω. Upon heating, it decreased slightly. When the temperature reached 78°C, the resistance started to increase slowly. Above 95°C, it increased markedly and reached 100 Ω at 100°C.

According to Ohm's law, the resistance of a conductor is in direct proportion to resistivity and length and in inverse proportion to the cross-section area. If the entire piece of dough, including gas cells, is considered a conductor, the length of dough is constant. The cross-section areas of yeasted doughs are larger than those of nonyeasted doughs. Therefore, yeasted doughs must have greater resistivity than nonyeasted doughs.

Input Power

Input power was calculated by $W = I \times V$ and plotted against dough temperature (Fig. 8). With method A, the change of input power to yeasted dough was small, as would be expected from

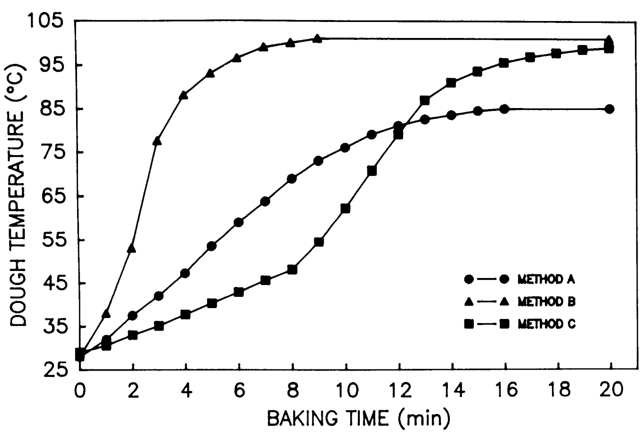

Fig. 4. Comparison of heating methods in temperature-time profile. Method A, 75 V (0–22 min); method B, 120 V (0–22 min); method C, 50 V (0–8 min), 90 V (9–10 min), 100 V (11–12 min), and 120 V (13–22 min).

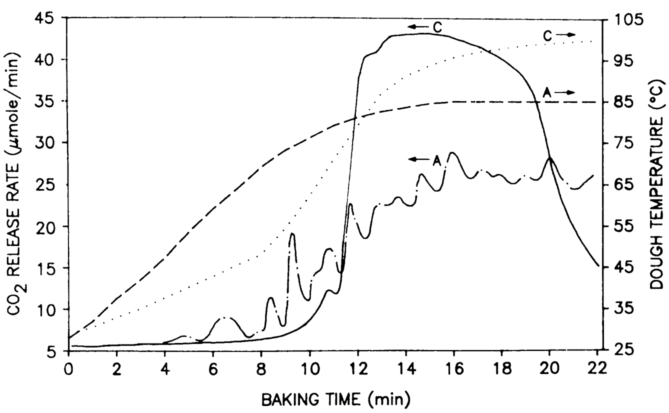

Fig. 6. Effect of heating method on CO_2 loss from dough during baking in an electric resistance oven.

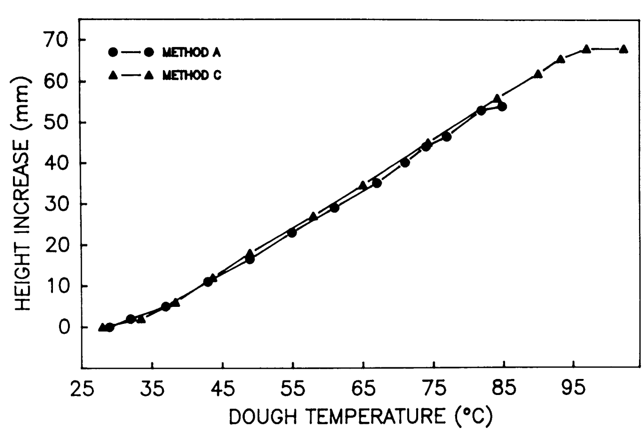

Fig. 5. Effect of heating method on increased loaf height.

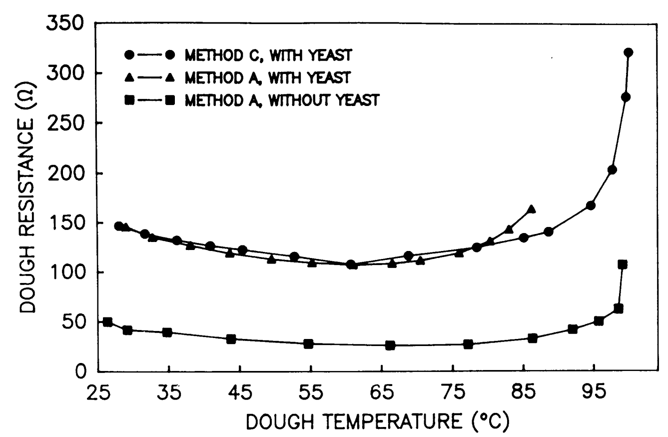

Fig. 7. Electrical resistances in doughs containing yeast during baking with methods A and C compared with those of unyeasted doughs during baking with method A.

the change in dough resistance. As the input power decreased to a minimum, it just compensated for the heat lost to the environment; therefore, the dough temperature stopped rising. This explains why the maximum temperature of yeasted dough baked with method A only reached about 86°C. Method C, by increasing voltage potentials, provided sufficient input power to overcome heat dissipation and raise the dough temperature to 100°C.

Temperature Gradient

In the ERO, heat is generated internally by using the dough as the resistance between electrodes carrying an alternating current. With this method, the temperature within the entire mass of dough theoretically should be the same at any time. To examine the uniformity in temperature within the dough baked in the ERO, temperature was measured from the top center of the loaf to various depths (Fig. 3) when the dough at the center of the loaf 10 mm above the bottom reached 70, 80, and 90°C. The temperatures at the depth of 62.5 mm (about the center of the baked loaf) were 72, 81, and 92°C, respectively. Figure 9 shows that the dough temperature decreased with an increase in distance from the center of the loaf. A large temperature gradient was noted near the top of dough. The difference in temperature between the center of the dough and at a depth of 2.5 mm was about 33°C.

Figure 10 shows dough temperature 22.5 mm from the top of the dough along its length and width (Fig. 3). Temperatures were also taken when the center of the dough at 10 mm above the bottom reached 70, 80, and 90°C. Dough temperatures decreased slightly from the center of dough to its side, which contacted the oven wall or electrode plate. However, the temperature gradients along the length and width of dough were much smaller than those in the depth of dough. The difference in temperature between the center of the dough and at 2.5 mm from the side was about 10°C.

Therefore, our data clearly show that the temperature within the dough baked in the ERO was not uniform. A possible explanation is that the baking was not conducted under conditions of heat insulation, but rather at 23°C, 55% RH. Under such conditions, heat was transported or dissipated to the environment through the electrode plates, oven walls, and top of the dough. The large temperature gradient near the top of the dough was probably caused by two factors: heat dissipation (mainly by vapor) and no electricity flowing through the crown at the top of the dough.

The mechanism of heat transport in dough mainly follows the principle of Watt; i.e., water vapor flows and condenses at relatively colder surfaces. In a conventional oven, water vapor is generated near the crust layer and condenses at the center of the loaf (Sluimer and Krist-Spit 1987). Therefore, the moisture of the loaf increases from the outside toward the center. Measurements showed that the moisture of the crust was about 11% and of the center crumb about 47%, while moisture in the dough before baking was about 43%. However, when dough is baked in an ERO, water vapor from the center of the loaf condenses at the outer surfaces, resulting in a wet surface and water distribution opposite to that of a conventional loaf. The moisture at the sides and top of the loaf baked in the ERO was about 43%, considerably higher than at the center of the loaf (about 35%).

Problems Associated with the ERO

Because of the large temperature gradient in the loaf baked in the ERO, observations on dough expansion and CO_2 released from dough as a function of temperature may be misleading. The profile of gas loss from dough baked with method C (Fig. 6) shows not only that a broad temperature range was present from the start of increasing CO_2 loss to the start of the decrease in gas, but also that some CO_2 was left in the ERO loaf. At the end of baking, the rate of CO_2 loss was about 15 μmol/

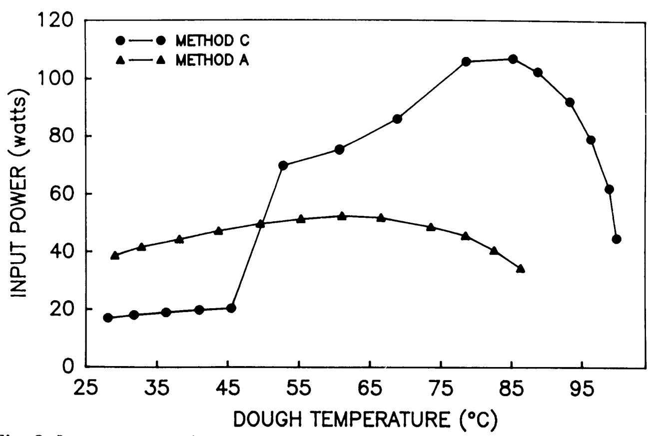

Fig. 8. Input power with methods A and C.

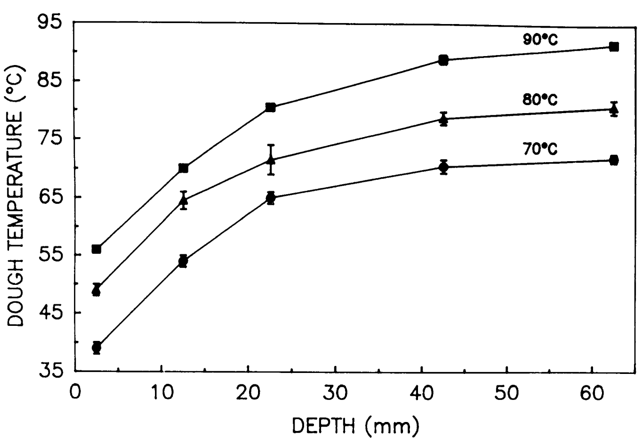

Fig. 9. Temperature gradients at different depths of dough, when the temperature at the bottom of the dough reached 70, 80, and 90°C.

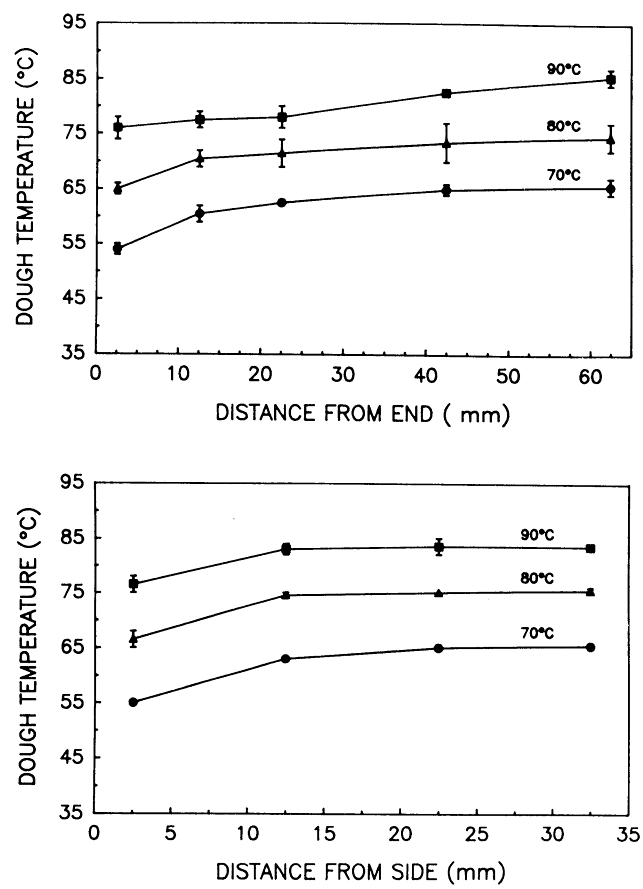

Fig. 10. Temperature gradients along the length and width of dough at a depth of 22.5 mm, when the temperature at the dough 10 mm above the bottom reached 70, 80, and 90°C.

min. If N_2 was passed over the ERO bread (without heating) for 2 hr, the CO_2 left in the ERO bread decreased but still was not totally depleted. The residual CO_2 in the loaf could have been retained in the top or crown of the loaf. When the temperature at the center of the loaf 10 mm above the bottom reached 100°C, the temperature near the top was only about 67°C. At that temperature, dough still has the ability to retain gas.

While the ERO provides a useful tool to study breadmaking, one must be aware that large temperature gradients can occur throughout the dough mass if baking is not conducted under conditions of heat insulation.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS 1983. Approved Methods of the AACC. Method 10-10B, approved January 1983, revised September 1985. The Association, St. Paul, MN.

BAKER, J. C. 1939. A method and apparatus for testing dough. Cereal Chem. 16:513.

BAKER, J. C., and MIZE, M. C. 1939. The effect of temperature on dough properties. I. Cereal Chem. 16:517.

JUNGE, R. C., and HOSENEY, R. C. 1981. A mechanism by which shortening and certain surfactants improve loaf volume in bread. Cereal Chem. 58:408.

MARSTON, P. E., and WANNAN, T. L. 1983. Bread baking: The transformation from dough to bread. Baker's Dig. 57(4):59.

MOORE, W. R., and HOSENEY, R. C. 1986. Influence of shortening and surfactants on retention of carbon dioxide in bread dough. Cereal Chem. 63:67.

SLUIMER, P., and KRIST-SPIT, C. E. 1987. Heat transport in dough during the baking of bread. Pages 355-363 in: Cereals in a European Context. D. Morton, ed. Ellis Horwood Ltd.: Chichester, England.

[Received April 18, 1990. Accepted August 31, 1990.]