Behavior of Surface Membrane of Yeasted Dough during Expansion in a Cylinder

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Expansion of yeasted dough in a glass cylinder with time was followed by measuring the dough height with a cathetometer. The gassing power of the dough was estimated by collecting the expelled air and the released carbon dioxide. The volume of dough at which CO₂ began to escape from the dough, estimated from the gassing power and dough expansion curves, was higher for rapidly-expanding and oxidized doughs than for slowly-expanding, reduced and control doughs. The doughs which showed higher volumes at the point of CO₂ leakage had higher tension of the surface membrane. The top surface of yeasted doughs in the glass cylinder, determined from the measured volume of the dough meniscus, appeared to have the shape of a revolving parabola rather than that of a revolving ellipsoid. In the comparison of these results obtained from the behavior of the dough surface membrane with the results of test baking the former data were found to be applicable to the basic research on baking properties of dough.

In basic studies of breadmaking, loaf volume is the main index used to evaluate flour strength, gassing power of yeasted doughs, and adequacy of breadmaking processes such as dough mixing, fermentation, rounding, moulding, proofing, and baking. Volume of the loaf is attained by expansion of the dough during proofing and baking. The behavior of yeasted dough in a glass cylinder can be used as a model of expanding dough in a baking pan. Yeasted dough comprises a large number of gas cells. The cells in a dough which is confined in a baking pan or a glass cylinder are presumed to expand by elongation of the cell wall parallel to the wall of the container. Much of the pressure in the cell is in equilibrium with the tension of the membrane of each cell. Only the tension of the membrane on the top of the dough exerts a pressure downward into the dough. Estimation of the pressures involved in a expanding dough requires information on the shape of the expanding dough membrane.

The present study is part of a series of our studies on the relationship between the surface tension of dough membranes and the ability of the dough to retain CO₂ during expansion under fermentation. The study was carried out using a simple experimental assembly wherein measurements were made on various expanding doughs in a glass cylinder.
Materials and Methods

Materials

The flour used was a commercially milled hard wheat flour provided by Nisshin Flour Milling Company (Kobe). Its protein and ash contents were 12.1% and 0.33%, respectively, expressed on a 14% moisture basis. The yeast was of the commercial compressed type provided by Nitten Yeast company. Salt (NaCl) and cane sugar were commercial products of reagent grade.

Doughs (Table 1) were mixed in a vertical screw pin mixer (Kanto Mixer Company, type 151) for 5 min at 100 rpm followed by 2 min at 190 rpm. The temperature of the dough when taken out of the mixer was controlled at 25°C. After bulk fermentation for 20 min at 30°C, the dough was divided into three parts as follows: (1) 100 g for gassing power and expansion tests or for the determination of meniscus volume; (2) 45 g for the measurement of tension of the surface membrane; and (3) 160 g for the baking test.

The estimations were made with a vertical glass cylinder (50 mm inside diameter and 350 mm high) in which 100 g of dough was allowed to expand from the bottom toward the top. The details were described by Hosomi et al.1). The increasing height of dough in the cylinder was measured with a cathetometer every 10 min during fermentation. The volume of expansion was obtained from the height increment of the dough and the inside area of the horizontal section of the cylinder, assuming that the shape of the top of the dough did not change. This assumption was confirmed as described herein after.

Air displaced by the expanding dough and released carbon dioxide were collected, recorded every 10 min, and used to determine the gassing power. Dough pieces to be tested were rounded, sheeted, and molded according to the AACC baking test3). Cylindrical pieces were folded into a U shape, inserted into the cylinder, rounded end first, and pushed up into position by a rubber stopper.

Estimation of the tension of surface membrane

The tension of the surface membrane was determined as described by Hosomi et al.1) using a principle of estimating the surface tension of mercury. The horizontal ring plunger was forced into the dough at a speed of 1 mm/sec to a depth of 10 mm. Stress equilibrated after 5 minutes was determined and recorded with a Rheoner (RE-3305 Yamaden Co. Tokyo). The tension of the surface membrane was derived from the total stress divided by the total circumference of inner and outer as shown in Fig. 1. The stress to the plunger was assumed to be caused by two elements, one was the tension of surface membrane as shown in Fig. 1, and the other was inside pressure of the dough. The calculation shown above should be calibrated using the latter element. In the case of estimating the surface tension of mercury, calibration was done using buoyancy of the ring in the mercury pool.

Matsumoto2) showed that the latter stress, which was caused by inside pressure, was only 1/20 of the former stress caused by tension when the horizontal ring plunger was smaller in cross section. Thus no calibration was done

<table>
<thead>
<tr>
<th>Table 1 Ingredients of dough</th>
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<tbody>
<tr>
<td>(A) Control dough</td>
</tr>
<tr>
<td>Flour</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>(B) Reduced dough</td>
</tr>
<tr>
<td>Flour</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>(C) Oxidized dough</td>
</tr>
<tr>
<td>Flour</td>
</tr>
<tr>
<td>100</td>
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Shown as ratio to 100 parts of flour
Amounts of yeast are shown under each figure or Table 2.
Fig. 1 Estimation of tension of dough surface membrane

\[
T = \frac{Stress}{2\pi r + 2\pi R}
\]

\[r = 1.04 \text{ inner radius (cm)}
\]
\[R = 1.10 \text{ outer radius (cm)}
\]

Fig. 2 Estimation of meniscus volume

\[V_1 = h_2 \pi r^2 - 50 \text{ ml}
\]

in this experiment.

**Estimation of meniscus volume of dough in glass cylinder**

The volume of the spindle-like meniscus of the dough in the glass cylinder was determined by pouring 50 ml of water over the top of the dough and measuring the water level \(h_2\) with a cathetometer. The volume \(V_1\) was calculated as shown in Fig. 2.

**Baking tests**

Baking tests were carried out according to the AACC straight dough test baking method\(^{13}\). The loaves were baked for 20 min at 200°C. The height of the loaf was measured and the oven spring calculated by subtracting the depth of the pan from the loaf height\(^{11}\). Loaf volume was determined by sesame seed displacement.

**Results and Discussion**

**Expansion of dough in a glass cylinder**

Fig. 3 shows the gassing power and expansion of yeasted doughs containing 1%, 2% and 3% yeast as a function of time. Initially, when all of the \(\text{CO}_2\) produced is retained by the dough, the two curves, the solid line and the broken line, coincide. However, at a critical (indicated by the arrow), the two curves separate; the gassing power continues to increase at approximately the same rate but the expansion slows down dramatically due to the loss of the gas-retaining ability of the dough. The results showed that in a rapidly expanding dough (e.g. at 3% yeast), total gas retention is maintained to a higher dough volume than in a slowly-expanding dough (e.g. at 1% yeast). This observation is fundamental to the ex-
planation of the effect of various ingredient and processing factors on loaf volume.

Figure 4 shows that the dough which had been oxidized with potassium bromate (C) reaches a higher expansion volume than that of the control (A) through better ability to retain the fermentation gas. When this dough was baked, the combined effects produced a higher oven spring and hence a larger loaf volume as shown in Table 2. Addition of cysteine produced a slightly negative effect on the oven spring but no significant effect on loaf volume.

Tension of membrane

The membrane tension of expanding doughs decreased with time (Fig. 5). The tension values for doughs with 3% yeast or doughs treated with potassium bromate were higher than those for doughs with 1% yeast, doughs with reducing agent, and control doughs. The tension values decreased sharply at the point in time where gas leakage occurred especially in case of 3% yeast. This might depend on higher initial tension which was broken by gas leakage. These results suggest a meaningful relationship between the gas retaining capacity and the tension of dough membranes. The ability of oxidizing agents, such as potassium bromate, to increase loaf volume shown in Table 2 can be explained on the basis of their ability to increase membrane tension and thereby increase the dough volume at which gas-retaining ability is kept. Usually oxidative improvers are known to increase resistance for extension estimated with an extensigraph. Increased net works in wheat protein with the bromate are also assumed to increase membrane tension.

Volume of dough meniscus in a glass cylinder

Preliminary measurements showed that the height of the meniscus, $h_1$ (Fig. 2) was greater than that of the control (A) through better ability to retain the fermentation gas. When this dough was baked, the combined effects produced a higher oven spring and hence a larger loaf volume as shown in Table 2. Addition of cysteine produced a slightly negative effect on the oven spring but no significant effect on loaf volume.

<table>
<thead>
<tr>
<th>Table 2 Results of baking test</th>
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<tr>
<td></td>
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<tr>
<td>Yeast 1%</td>
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<tr>
<td>Yeast 2%</td>
</tr>
<tr>
<td>Yeast 3%</td>
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</table>

|                             | Oven spring (mm) | Loaf volume (ml) |
| (A)                         | 19±1             | 373±6            |
| (B)                         | 18±2             | 381±9            |
| (C)                         | 23±1             | 396±8            |

(A) Control Dough  (B) Reduced Dough  (C) Oxidized Dough  ± indicated standard deviation  Amount of yeast, 3 parts to 100 parts of flour

Fig. 4 Expansion of 100 g of dough containing 3% yeast  A, control; B, reduced dough; C, oxidized dough
Fig. 5 Expansion (D, control dough) and tension of surface membrane (A–C) of doughs containing 1% and 3% yeast
A, control; B, reduced dough; C, oxidized dough

Calculation of meniscus volume $V_1$
Assumed as a revolving parabola

$$y = ax^2 + h - (2) \quad a = -\frac{h}{r^2}$$

$$x^2 = \frac{y - h}{a} = -\frac{r^2(y - h)}{h}$$

$$V_1 = \pi \int_{-r}^{r} x^2 \, dy$$

$$= \frac{\pi r^4 h}{2}$$

$$= 0.5 \pi r^4 h$$

$$\frac{V_1}{\pi r^4 h} = 0.5$$

Assumed as a revolving ellipsoid

$$\frac{x^2}{r^2} + \frac{y^2}{h^2} = 1 -(3)$$

$$x^2 = r^2 \left(1 - \frac{y^2}{h^2}\right)$$

$$V_1 = \pi \int_{-r}^{r} x^2 \, dy$$

$$= \frac{2}{3} \pi r^3 h$$

$$= 0.66 \pi r^3 h$$

Fig. 6 Calculation of meniscus volume
r : radius of cylinder
h : height of head from contacting point of dough and cylinder
a : constant
(2) (3) equation of parabola and ellipsoid respectively shown by x and y axis

than r, the radius of the cylinder, and accordingly the shape of the meniscus was not spherical. Therefore the possibility of it being parabolic or ellipsoid was examined.

The ratios of $V_1$, the volume, over $\pi r^4 h$ for the parabolic and ellipsoid surfaces were derived as shown in Fig. 6. For a revolving parabola, this ratio has a value of 0.5, and for a revolving ellipsoid the ratio is 0.666. The values obtained from measurements of various expanding doughs (Table 3) are close to 0.5.

Therefore, it was concluded that the shape of the meniscus of expanding dough in a glass cylinder is close to that of a revolving parabola. Furthermore there was no significant difference between the values obtained for the various doughs that were investigated as long as the measurements were made in the range of dough volume where all of the gas produced was retained by the dough.

Finally, it is worth noting that under conditions where dough expansion and gassing power
Table 3 Calculated values K from Meniscus volume $V_1$

<table>
<thead>
<tr>
<th>Proofing time (min)</th>
<th>Calculated values (K)</th>
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<tbody>
<tr>
<td></td>
<td>(A)</td>
</tr>
<tr>
<td>Yeast 1%</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Yeast 3%</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
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</table>

(A) Control dough  (B) Reduced dough  (C) Oxidized dough

No value for 90 min for 3% yeast since that is over the critical volume.

Calculated Values K for Revolving Parabola = 0.50
Revolving Ellipsoid = 0.666

$K = \frac{V_1}{\pi r^2 h}$
($V_1$, $r$, $h$ are shown in Fig. 2)

curves coincide, the flow of dough toward the top of the cylinder is essentially Newtonian in a range of extremely low rates of shear. This is rather surprising since the dough consists of multiple gas cells and is not homogeneous.

**General Discussion**

The observation that the tension of the dough membrane decreased as dough expansion progressed will be discussed first. In an earlier paper, MATSUMOTO\(^2\) showed that the downward pressure in a dough confined to a pan (or a glass cylinder) was higher in the early stages of expansion than in the later stages. The higher pressure probably corresponds to the higher membrane tension. For spherical gas bubbles the relationship between pressure ($P$) and membrane tension is given by the equation,

$$P = \frac{2 T}{R}$$

where $P$ is the pressure, $T$ the tension, and $R$ the radius of the gas bubble. It is assumed that this equation is approximately applicable to bubble shapes that deviate slightly from the spherical shape, e.g. revolving parabolas and ellipsoids.

The higher membrane tension values obtained for the 3%-yeasted dough compared with that of the 1% dough can be explained by the following equation derived by MATSUMOTO\(^3\) on the assumption that the Maxwell rheological model (elastic and viscous elements joined in series) applies to the dough system under conditions used in this study.

$$T = \eta c + (T_0 - \eta c) \exp\left(-\frac{t}{\tau}\right)$$

to

where $T$ = membrane tension at time $t$
$\eta$ = coefficient of viscosity
$c$ = rate of expansion
$T_0$ = tension at zero time
$t$ = expansion time
$\tau$ = relaxation time ($= \eta/G$ where $G$ is the elastic modulus)

According to the above rheological equation, when the rate of extension ($c$) increases the value ($T_0 - \eta c$) decreases and $\eta c$ increases, assuming that $T_0$, $\eta$ and $\tau$ are constant (which may not be strictly applicable). Accordingly, $T$ can have higher values for doughs subjected to higher $c$ values (e.g. faster dough expansion) if the relative contribution of $\eta c$ is greater than that of $T_0 - \eta c$.

The positive effect of oxidation on tension values can also be explained. Compared with untreated control doughs, oxidized doughs have a longer relaxation time if the Maxwell model applies.

Additionally, HALTON\(^5\) showed that the elastic modulus ($G$) of fermenting dough did
not change with fermentation time and/or rate. Accordingly the increase in membrane tension (T) with oxidation appears to follow the change in viscosity (η) which increases under the same conditions. This explanation was made by assuming the Maxwell model. Various models have been proposed, such as multi Maxwell models with various relaxation times arranged in parallel\(^5\) or the Maxwell and Voigt model arranged in series including yield values\(^7\). Also nonlinear behavior has been shown. However, under limited conditions, the behavior of dough could be found to be explained with the Maxwell model\(^8\).

The relationship between the tension of dough membrane and loaf volume can be tentatively explained on the assumption that the same rheological phenomena apply to membrane tension as to resistance and extensibility as measured with the extensigraph or the alveograph. It is well known that doughs which show higher resistance and extensibility produce loaves of larger volume. Similarly, the present study has shown that doughs with higher tension of surface membrane produced larger loaves. Accordingly, in this content, it would be interesting to study further the relationship between the gas retension properties of the dough membrane and the higher values of tension of rapidly expanding or oxidized doughs in a troughs or in a baking pan.

Acknowledgement
The authors wish to express their appreciation to Professor W. BUSHUK, University of Manitoba Canada, for reviewing this paper.

References

(Received Jun. 19, 1992)