MODELLING OF BREAD DOUGH AERATION DURING MIXING: EXPERIMENTAL INVESTIGATIONS USING SCALE-UP MIXERS

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ABSTRACT

Aeration of bread dough during mixing in three scales of Tweedy-type mixers was studied using a model, which defines the entrainment and disentrainment coefficients. The model describes dough aeration as a dynamic balance between the rates of entrainment and disentrainment of air during mixing. Experimental investigations were performed by measuring the change in density of dough in accounting its air content following a step change in headspace pressure in the mixer halfway through mixing. Doughs made from premium grade quality flour were mixed for two minutes in the high speed mixers; the pressure was then changed and mixing continued for a further two minutes. The density of dough samples taken following the pressure change was measured using a double-cup buoyancy technique. The effects of both a step increase and a step decrease in the headspace pressure were investigated. The value of the disentrainment coefficient was greater following a step decrease in pressure compared with a step increase for all the three mixer scales, although there was not any clear trend observed in the three mixers scales. This confirmed the earlier results of disentrainment enhancement when pressure is reduced midway through mixing despite the different mixer scales. The slight increase of entrainment ratio with mixer scale seems to agree with the excessive aeration problems in scale-up mixers used in the industry.

Keywords : *Disentrainment, Dough Aeration, Entrainment, Entrainment Ratio, Mixing, Model, Scale-Up Mixers*

INTRODUCTION

The breadmaking process consists of three major operations: mixing, during which the dough is kneaded and developed and air bubbles introduced; proving, during which the yeast produces carbon dioxide gas causing the bubbles to inflate and the dough to rise; and baking, which sets the aerated structure. In the modern no-time breadmaking processes, mixing is the stage where the baker has most control over the final bread texture. Aeration of the dough during mixing, in terms of the air content and bubble size distribution, directly determines the aerated structure and texture of the baked loaf, and hence its quality and appeal. Baker and Mize [1] observed that bread produced by mixing under very high vacuum contained few gas cells. They demonstrated that yeast was incapable of producing new gas cells during proving, and that air bubbles occluded during mixing served as nucleation sites for diffusion of carbon dioxide produced by yeast during proving. Cauvain [2] similarly concluded that the aerated dough structure created in the mixer could not be adjusted in subsequent dough processing stages.

The extent of aeration of dough during mixing depends on the dynamic balance between the entrainment and disentrainment rates of air. Air entrainment and disentrainment occur simultaneously during mixing. The actions of the mixer blade during mixing, forming and deforming new dough surfaces, results in air bubbles being entrapped and also removed. A model describing these physical processes was introduced by Campbell and Shah [3]. They measured the change in dough density following a step increase in the headspace pressure in the mixer halfway through mixing in accounting the rate of change in air content in dough to achieve steady-state. Chin and Campbell [4] later continued investigating the model by conducting mixings where a step decrease in pressure was applied. As a result, the disentrainment coefficients found were larger in the pressure step decrease mixing than in a pressure step increase mixing. They suggested that disentrainment enhancement could have occurred in the former earlier.

The pressure step decrease mixing is similar to the practise of pressure-vacuum mixing in the industrial no-time breadmaking process known as the Chorleywood Bread Process (CBP). The Chorleywood Bread Process was the first no-time dough process introduced in England and now has gained much popularity in other European countries and in Australia, New Zealand and South Africa due to its advantages in saving time and space [5-7]. In the CBP, a high pressure of 2.5 bar is introduced in the initial mixing period before pressure reduction to 0.35 bar at the end of mixing to reduce excessive air in the dough.

Process modelling of bread dough aeration during mixing is envisaged to explain the air entrainment and disentrainment processes. The question raised on whether the mixer size and volume affect the disentrainment coefficients in pressure change mixing processes, in particular in the pressure decrease direction is part of the objective in this study. This work on Tweedy scale-up mixers studies was also conducted to investigate the excessive aeration, which is disentrained by using the pressure-vacuum mixing method in the industry.

AERATION MODEL RECAPTURE

Following Campbell and Shah [3], the mass balance of air in the dough, based on 1 cm^3 of gas-free dough, is:

$$\frac{dm_a}{dt} = \dot{m}_i - \dot{m}_o \tag{1}$$

where m$_a$ is the mass of air in the dough (g cm$^{-3}{}_{\text{gas-free dough}}$), $\dot{m}_i$ is the air mass flow rate into the dough (g$_{\text{air}}$ s^{-1} cm$^{-3}{}_{\text{gas-free dough}}$), $\dot{m}_o$ is the air mass flow rate out the dough (g$_{\text{air}}$ s^{-1} cm$^{-3}{}_{\text{gas-free dough}}$) and t is time (s).

Using the ideal gas law, the mass of gas in the dough, m_a has a corresponding volume, V_a (cm$^3{}_{\text{air}}$ cm$^{-3}{}_{\text{gas-free dough}}$), when measured at atmospheric pressure:

$$m_a = \frac{P_{atm} V_a M_w}{RT} \tag{2}$$

where P_{atm} is the atmospheric pressure (N m^{-2}), R is the universal gas constant (J mol^{-1} K^{-1}), T is the absolute temperature (K), M_w is the molecular weight of air (g mol^{-1}) and V_a is the volumetric air content in dough (cm$^3{}_{\text{air}}$ cm$^{-3}{}_{\text{gas-free dough}}$).

Entrainment of air into the dough occurs when dough surfaces come into contact, entrapping a volume of air during mixing. The volumetric entrainment coefficient of air, v, is derived from the ideal gas law and it is proportional to the air mass flow rate into the dough:

$$\dot{m}_i = \frac{PVM_w}{RT} \tag{3}$$

where v is the volume of air entrained per unit volume of gas-free dough per second (cm$^3{}_{\text{air entrained}}$ cm$^{-3}{}_{\text{gas-free dough}}$ s^{-1}) and P is headspace pressure (Nm^{-2}).

For disentrainment, the air mass flow rate out of the dough is assumed to be proportional to the mass of air in the dough:

$$\dot{m}_o = km_a = \frac{kP_{atm} V_a M_w}{RT} \tag{4}$$

where k is the disentrainment coefficient (g$_{\text{air disentrained}}$ g$^{-1}{}_{\text{air in dough}}$ s^{-1}). Substituting Equations 3 and 4 into 1 gives Equation 5 and converting to volume basis gives Equation 6:

$$\frac{dm_a}{dt} = \frac{P_{atm} M_w}{RT}\left(\frac{P}{P_{atm}} v - kV_a\right) \tag{5}$$

$$\frac{dV_a}{dt} = \left(\frac{P}{P_{atm}} v - kV_a\right) \tag{6}$$

At steady state, $dV_a/dt = 0$ and V_a is the volumetric air content at steady-state:

$$V_a = \frac{P}{P_{atm}} \frac{v}{k} \tag{7}$$

Equation 7 indicates that the air content is proportional to the mixing pressure, relative to atmospheric pressure, and depends on the balance between the rates of entrainment and disentrainment.

When $t = 0$, $V_a = V_{a0}$ and when $t = \infty$, $V_a = V_{a\infty}$. Equation 6 is a first order differential equation with the solution:

$$V_a(t) = V_{a\infty} + (V_{a0} - V_{a\infty})\, e^{-kt} \tag{8}$$

where V_{a0} and $V_{a\infty}$ are the initial and final steady-state air contents, respectively. Following a step change in headspace pressure during dough mixing, the air volume in the dough will change exponentially from the initial steady-state air content, V_{a0} to the final steady-state air content, $V_{a\infty}$. The volumetric air content at time t, $V_a(t)$, is related to its density, $\rho(t)$, by:

$$V_a(t) = \frac{\rho_{gf}}{\rho(t)} - 1 \tag{9}$$

The disentrainment coefficient, k is therefore obtained by fitting an exponential curve in the experimental data of the graph of the inverse of dough density following a step change in headspace pressure. Knowing the steady-state air content, the entrainment coefficient, v, is then calculated from Equation 7.

MATERIALS AND METHODS

A. TWEEDY MIXERS

Three scales of Tweedy-type mixer were used, known as the Tweedy 1, 10 and 35 based on their approximate dough capacity in pounds, representing a range from laboratory to pilot plant scale. Figure 1 shows the top view of the Tweedy 1 mixer bowl with blade attached and Table 1 shows the dimensions of the three mixers. All mixers consist of a vertically aligned cylindrical mixing bowl, with a central anti-clockwise rotating spindle. The mixer blade is attached with the spindle and mounted on a horizontal octagonal base with two vertical helical paddles. The dough forms a single mass between the impeller

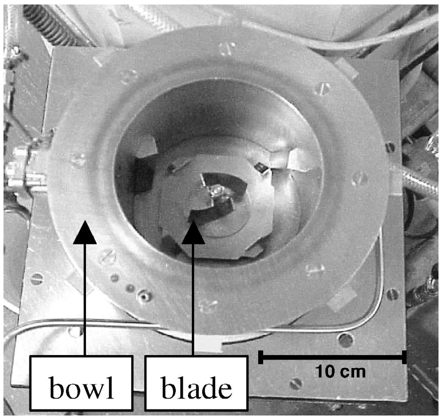

Figure 1: The Tweedy 1 mixer bowl and blade

Table 1: Dimensions of the mixing bowl of three Tweedy-type mixers

	Tweedy 1	Tweedy 10	Tweedy 35
Bowl diameter (mm)	140	306	429
Bowl height (mm)	126	296	408
Mixing volumes (g flour)	380	4000	11000
Blade Speed (rpm)			
Loaded	733	360	
Unloaded	747	383	~ 383

and the bowl wall, to which three baffles are attached. The dough mass rotates around the chamber being kneaded between the impeller and the wall in the process.

B. DOUGH FORMULATION AND MIXING CONDITIONS

Flour used was of Warbutons quality, premium grade (Warbutons DTH), priory frozen and thawed before using. The flour water absorption was characterised using Brabender/ICC Method at consistency of 584 FU. Table 2 shows the characteristics of the flour. The dough formulation is shown in Table 3.

Table 2: Characteristics of flour used

Moisture content (NIR) (%)	13.9
Protein Content (NIR) (%)	12.0
Alpha Amylase (cu/g)	0.12
FCG	-0.20
Hagberg	380
Water absorption (%)	59.1
Development time (Min)	4.2
Stability (Min)	5.4

Table 3: Dough formulation

	% based on flour weight
Flour	100
Salt	2.0
Improver	0.25
Water	59.1

The mixers were loaded with water, followed by the dry ingredients. The mixer bowl was then sealed with its lid, and the mixing commenced. Experiments were carried out in both pressure step change directions, increase and decrease. In the pressure step decrease mixing (30 to 15”Hg abs and 45 to 30”Hg abs), doughs were mixed for 120 seconds before a rapid decrease in mixing pressure for another 120 seconds. About 13 time intervals were taken within the 120 seconds and a separate dough was mixed each time. In the pressure step increase mixing (15 to 30”Hg abs and 30 to 45”Hg abs), doughs were mixed for 120 seconds before a rapid increase in mixing pressure for another 160 (or more) seconds. About 14 time intervals were taken within the 160 (or more) seconds and a separate dough was mixed each time. Only vacuum pressures could be applied to the Tweedy 35. The gas-free dough density was obtained by mixing doughs at various pressures for 120 seconds to find its gas-content.

C. DOUGH DENSITY MEASUREMENT

Dough density was measured as described by Campbell et al. [8] using a double cup system placed on a Precisa Electronic Balance 125A (Precise Balances Ltd., UK). For each mixing trial, six samples of dough, each of about 10 g, were weighed in air and then immersed in xylene; from the difference in weights and knowing the density of the xylene, the density was calculated as:

$$\rho = \frac{m_{air}}{m_{air} - m_{xylene}} \rho_{xylene} \qquad (10)$$

The standard deviations of mean from six dough density measurements per mixing were not shown in the graphs because they are smaller than the symbols (<0.0001 g cm^{-3}), and that it suggested sufficient samples used.

The gas-free dough density was determined by mixing doughs at various headspace pressures and extrapolating to zero absolute pressure [9].

RESULTS AND DISCUSSION

A. DOUGH DENSITY FOLLOWING PRESSURE CHANGES AND DISENTRAINMENT COEFFICIENTS

Figure 2 shows the inverse dough density versus time following pressure step change at time, $t = 0$ for the Tweedy 1, 10 and 35 mixers. Each experiment showed a clear exponential curve as the inverse dough density attained a new steady-state. As expected, the inverse density changes more rapidly to steady-state in a pressure step decrease mixing for all the mixers. The dotted lines show the critical and final inverse densities expected from the single pressure experiments illustrated in Figure 4. The expected final densities agree well with the final densities of the pressure step change experiments except for the 15-30”Hg abs in the Tweedy 35 which was significantly lower.

The experimental data was fitted with exponential curves to find the disentrainment coefficient, k, (following Equations 8 and 9) which was defined to indicate the air mass flow rate out

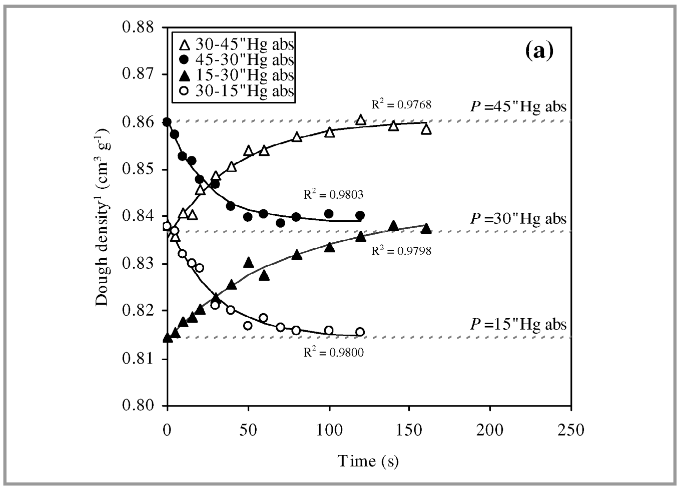

Figure 2(a)

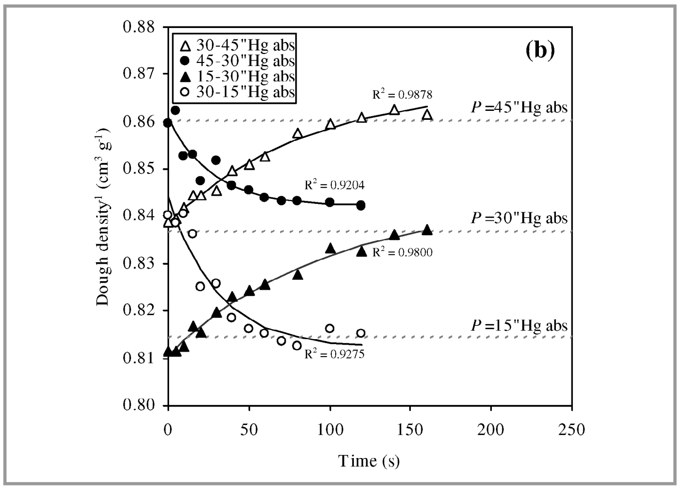

Figure 2(b)

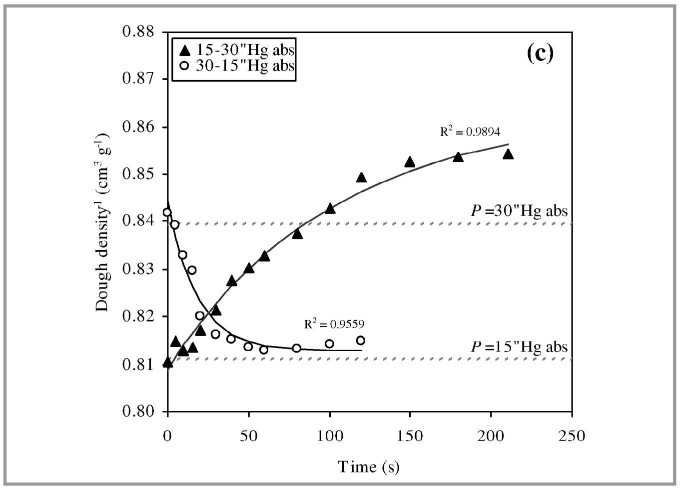

Figure 2(c)

Figure 2: Inverse dough density change following step change in pressure at t = 0 for the (a) Tweedy 1, (b) Tweedy 10 and (c) Tweedy 35. Dotted lines show the critical and final inverse densities expected from the single pressure experiments

of the dough during the mixing process [4]. A software package called GraphPad Prism 3.0 (GraphPad Software, Inc., U.S.A.) was used. The disentrainment coefficients found are illustrated in Figure 3 and tabulated in Table 4. The disentrainment coefficients for the pressure step decrease is significantly higher than the step increase as discovered previously [4]. The disentrainment coefficients also seem to decrease for the step increase but increase for the step decrease with increasing mixer scale.

B. GAS-FREE DOUGH DENSITY

Figure 4 shows the dough density mixed at various pressures for the three Tweedy mixers. The gas-free dough density was determined by extrapolating the density-pressure linear relationship to zero absolute pressure. The Tweedy 1 and 10 gave almost identical regression, with ρ_{gf} of 1.2603 g cm^{-3}. The Tweedy 35, unexpectedly gave a higher ρ_{gf} of 1.2742 g cm^{-3}. The most likely explanations for the anomalous Tweedy 35 result is that steady-state was not achieved in the 120 s mixing. This is suggested by the deviation of this inverse density calculated at relevant mixing pressures from Figure 4 with the inverse final density for the 15-30"Hg abs in Figure 2(c).

C. ENTRAINMENT COEFFICIENTS AND RATIO

Following Equation 7, Figure 5 shows a plotted Figure 4 with V_a as the *y*-axis and P/P_{atm} as the *x*-axis. The slope, *v/k*, is perceived as the volume of entrained air at steady-state mixing which can be physically labelled as the entrainment ratio. The entrainment ratios observed increased with mixer scale and this is in agreement with the application of vacuum mixing at the end of mixing to reduce the excessive aeration problems in larger mixers. The entrainment ratio and coefficients for all three mixers at both directions of pressure step change during mixing are also presented in Table 4.

Table 4: The disentrainment and entrainment coefficients, and the entrainment ratios

	Tweedy 1	**Tweedy 10**	**Tweedy 35**
Disentrainment Coefficients, *k* (s^{-1})			
Step decrease			
30 – 15"Hg abs	0.03494	0.04233	0.05164
45 – 30"Hg abs	0.03079	0.04388	
Step increase			
15 – 30"Hg abs	0.01293	0.00886	0.00968
30 – 45"Hg abs	0.02179	0.01123	
Entrainment Ratio (cm$^3_{air}$ cm$^{-3}_{gas\text{-}free\ dough}$)	0.0561	0.0575	0.0692
Entrainment Coefficients, *v* (s^{-1})			
Step decrease			
30 – 15"Hg abs	0.00196	0.00177	0.00357
45 – 30"Hg abs	0.00237	0.00252	
Step decrease			
15 – 30"Hg abs	0.00073	0.00051	0.00067
30 – 45"Hg abs	0.00122	0.00065	

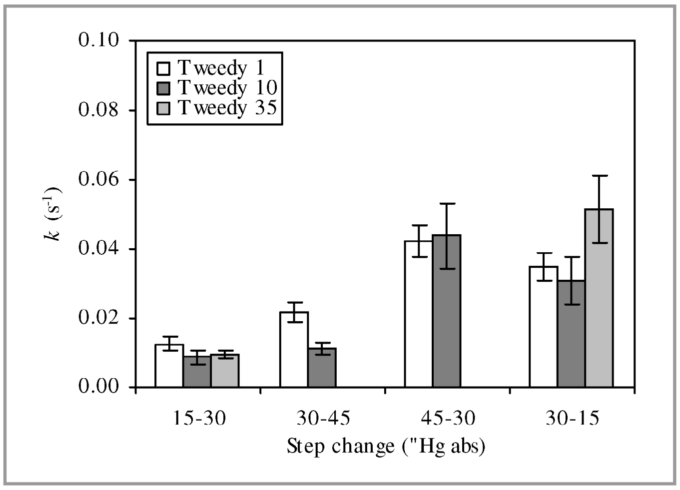

Figure 3: Disentrainment coefficients, k following step changes in pressure for Tweedy 1, 10 and 35

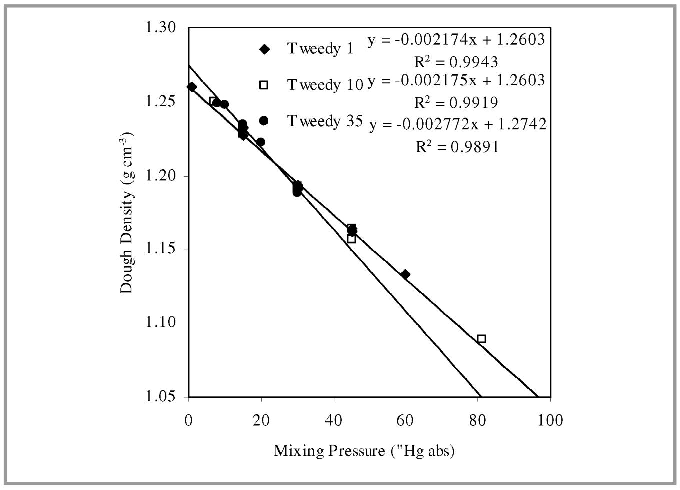

Figure 4: The disentrainment and entrainment coefficients, and the entrainment ratios

CONCLUSIONS

The results of the investigation of bread dough aeration model during mixing in scale-up mixers confirmed that the process of

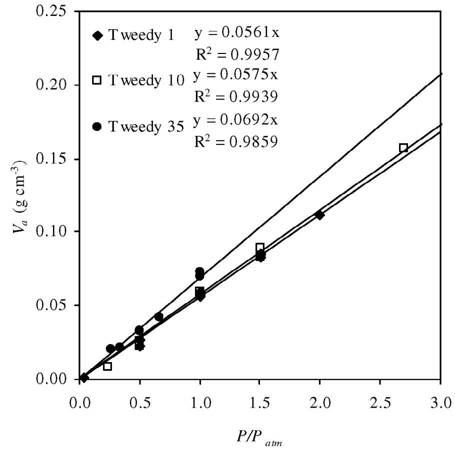

Figure 5: Plot of V_a versus P/P_{atm} to find the entrainment ratio, v/k

bread dough aeration during mixing could be modelled in terms of the dynamic balance between the rates of entrainment and disentrainment of air. The mixer scale does not affect the disentrainment coefficients greatly but they were higher following a pressure step decrease during mixing compared with a step increase. This suggests that reducing the pressure during mixing enhances the disentrainment mechanism and gives implications of shorter residence time or higher air turnover rate in dough during such mixings. This also gives a plausible explanation of a lower air content in doughs mixed with the application of a pressure reduction. The slight increase of entrainment ratios with mixer scale provides explanation to the currently observed excessive aeration in large mixers which is resolved by drawing partial vacuum at the end of dough mixing.

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