



Measurement of dough specific volume in chemically leavened dough systems

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ABSTRACT

Gas production and gas retention properties of doughs are pivotal to the manufacture of bread of good quality, but these properties are rarely measured directly in fermenting dough due to a paucity of suitable instrumentation. A digital image analysis-based method was used to measure the dynamic specific volume (DSV) of various chemically leavened dough systems. Sodium bicarbonate (1.4–4.2 g per 100 g of flour) in combination with equivalent neutralizing amounts of the leavening acidulants glucono-delta-lactone, potassium acid tartrate, adipic acid or sodium acid pyrophosphate consistently increased the specific volume of bread dough so that void fractions in the dough spanned between 5 and 67% at ordinary fermentation temperatures. The relationship between the specific volume of dough at the end of fermentation and the actual gas evolved (measured independently) was essentially linear and was characterized by a slope that provided a good index of the actual gas-trapping properties of dough. Therefore, the use of the DSV technique in conjunction with chemical leaveners offers the possibility of obtaining quantitative, real time information on the gassing capacity of the leavening system and the gas-holding capacity of the dough.

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1. Introduction

In breadmaking, the leavening step is fundamental to creating a bread loaf that conforms to the textural requirements of its class (Bloskma, 1981). Leavening brings about changes in the cellular structure of the dough, and hence the textural properties of the bread by expanding gas cell sizes in the dough with carbon dioxide (Baker and Mize, 1941; Bloksma, 1990; Scanlon and Zghal, 2001). Though yeast is the typical source of leavening gas in breadmaking, it is by no means the only source; chemical leavening systems are bakery ingredients added to batter or dough that raise or *leaven* the volume by evolving gas, most typically carbon dioxide (Heidolph, 1996).

Chemical leavening systems can leaven bread dough faster, more consistently and often times more conveniently than yeast because they do not require lengthy activation periods or stringent environmental conditions for evolving gas (Heidolph, 1996). The chemical nature of chemical leavening systems makes them capable, once incorporated into the dough, of producing carbon dioxide in atypical processing or storage conditions such as at high extrusion temperatures, in microwave fields, and following prolonged

refrigeration or frozen storage (Atwell, 1985; Hansen et al., 2003; Heidolph, 1996; Laughlin and DeMars, 1999; Laughlin et al., 2000; Narayanaswamy and Daravingas, 2001; Perry and Colman, 2001, 2003; Yong et al., 1983). One major disadvantage of chemical leaveners, though, is that they are unable to duplicate the distinctive flavor imparted to bread by yeast (Heidolph, 1996). This undesirable effect can be mitigated by reformulation with other flavored bakery ingredients (Heidolph, 1996), or chemical leavening systems may be used in conjunction with yeast (Holmes and Hosenev, 1987b).

Gas production in chemically leavened dough closely obeys the laws of stoichiometry and reaction kinetics for a chemical neutralization reaction (Bellido et al., 2008; Hosenev, 1998). Thus, judicious selection of chemical leavening systems and fermentation temperature affords good control over the production of carbon dioxide during dough leavening (Heidolph, 1996). Better control over gas production should then translate into better control over the quality of the bread. In chemical leavening, the leavening acid (acidulant) neutralizes a bicarbonate salt in the presence of water, to produce carbonic acid that quickly decomposes into carbon dioxide and water. Sodium bicarbonate, also known as baking soda, is almost ubiquitously used as the carbon dioxide carrier because of its low cost, high purity, lack of toxicity, ease of handling, and high carbon dioxide content (Heidolph, 1996). One important property of sodium bicarbonate is that it dissolves quickly in water so that the rate of reaction is essentially governed by the speed at which the acidulant dissociates to provide H^+/H_3O^+ . Precise monitoring of

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the rate and extent of dough expansion arising from the action of a chemical or biological leavener is unfortunately not a straightforward task and requires the use of specialized equipment (Campbell et al., 2001; Chiotellis and Campbell, 2003a,b; Hibberd and Parker, 1976).

Campbell et al. (2001) introduced a dynamic dough density (DDD) apparatus which uses differences in the buoyancy of dough in xylene to monitor dough expansion as a function of time during dough fermentation. This has proven useful for monitoring the effect of ingredients (Campbell et al., 2001, 2008a,b) and processing conditions (Chiotellis and Campbell, 2003a,b) on dough expansion properties. More recently, Elmehdi et al. (2007) introduced a dynamic dough density apparatus that measures dough expansion by digital image analysis and which has also proven useful for studying aeration in yeast-leavened dough (Elmehdi et al., 2003). Because the specific volume of dough (the reciprocal of its density) is an essential quality control parameter in assessments of the efficacy of chemical leavening system products (Lonergan et al., 2003; Shoenfuss et al., 2006), the objective of this study was to monitor dynamic specific volume (DSV) in doughs where dough aeration was manipulated over a wide range of rates and extents by various chemical leavening systems and processing conditions.

2. Materials and methods

The flour employed in this study was a straight grade flour milled from number 2 grade Canada Western Red Spring wheat in the pilot mill of the Canadian International Grains Institute (Winnipeg, MB). Moisture (14.1%, wet basis), protein content (13.1%), wet gluten, dry gluten, ash content, Hagberg falling number and Farinograph absorption were determined following American Association of Cereal Chemists Approved Methods 44-15A, 46-30, 38-12A, 38-12A, 08-01, 56-81B and 54-21A, respectively (AACC, 2000). The dough formula included 100 g of flour (14% m.b.), 69.6 g deionized water (Farinograph absorption – 2%), and 0.75 g NaCl. In preliminary experiments using potassium tartrate, it was found that these levels of water and NaCl produced doughs with relatively good handling properties even at the highest amount of sodium bicarbonate.

The chemical leavening systems employed included sodium bicarbonate, as the source of carbon dioxide, plus one of four chemical leavening acids (Table 1). Three levels of sodium bicarbonate were used: 1.40, 2.80 and 4.20 g per 100 g flour, to cover the working range (1.68–2.10 g/100 g) that Heidolph (1996) suggested is appropriate for chemically leavened refrigerated dough systems. The amount of acidulant added ensured the stoichiometric neutralization of the chosen amount of sodium bicarbonate, according to the following relationship:

$$\text{Acidulant(g)} = (\text{sodium bicarbonate(g)/NV})100 \quad (1)$$

where NV is the neutralization value and is defined as the amount of sodium bicarbonate (g) that 100 g of acidulant will completely neutralize (Heidolph, 1996). The supplier provided the neutralization values for each acidulant (Table 1).

Doughs were mixed at room temperature ($23 \pm 1^\circ\text{C}$) using a GRL 200 mixer (Hlynka and Anderson, 1955) at a constant speed of 165 rpm. Preliminary experimentation showed that the chemical leavening systems worked best when they were added after the formula water was fully absorbed by the flour. Otherwise, the chemical leavening systems reacted too quickly while the dough was being mixed and thus hindered dough development, resulting in doughs with reduced gas power and poor handling properties, e.g., sticky dough (Holmes and Hosenev, 1987a). A mixing time of 1 min was found to be long enough to ensure flour hydration and yet was short enough that the remaining mixing time (3 min) permitted homogeneous dispersion of chemical leaveners that were added to the dough. The sequence of steps followed to prepare the experimental doughs is shown in Fig. 1.

Immediately after mixing, the dough was removed from the mixing bowl and a sub-sample of about 4 g was excised from the dough using sharp scissors. The weight of dough was measured accurately to 0.01 g. The dough sub-sample was then placed in the apparatus (see below) used to measure specific volume of the dough as a function of fermentation time. Fermentation was carried out in a pre-heated proving cabinet set at the experimental temperature ($\pm 1^\circ\text{C}$) and at a relative humidity of 80%.

To determine the specific volume (cm^3g^{-1}) of the dough as a function of fermentation time, a modified version of the digital imaging technique described by Elmehdi et al. (2003, 2007) was used. A pair of 2.54-cm thick acrylic plates, whose temperature had been previously equilibrated to that of the experimental run in the proving cabinet, was used to gently squash the excised sub-sample of dough to a preset thickness (2.11 ± 0.01 mm). Sample thickness was maintained constant throughout the experiment by clamping the plates together (Elmehdi et al., 2003) to ensure dough expansion was restricted to the radial direction. The apparatus was then placed in the proving cabinet against a black background directly below a digital camera affixed to a tripod (Fig. 2). Calibration of pixel measurements in mm^2 was accomplished by digitizing a circular Maxwell CR 2016 battery (Hitachi Maxwell, Ltd., Japan) which had a precise diameter of 19.90 mm. The calibrant used was placed on top of the upper plate directly above the center of the dough.

Digital images of the radial expansion of the dough were taken at 3 min intervals for about 1 h, with the stopwatch zeroed immediately at the end of mixing. Measurements of the area of the dough were acquired using a digital camera (Nikon Coolpix 4500) that possessed a 4-megapixel charged-coupled device (CCD) sensor. The field of view was approximately 103×77 mm, so that with a captured image size of 640×480 pixels, the spatial resolution was approximately $(160 \mu\text{m})^2/\text{pixel}$ or ~ 39 pixels per mm^2 of the dough surface. The image analysis software used to measure the area (in pixels) of the expanding dough piece with time (and of the calibrant) was APS ASSESS[®] (Image Analysis Software for Plant Disease Quantification, The American Phytopathological Society, 2002).

The specific volume (Y) of the dough as a function of time was calculated from: $Y(t) = LA(t)/m$, where L is the sample thickness (maintained at 2.11 mm), $A(t)$ is the area of the dough as a function of time (from image analysis), and m is the dough mass.

Table 1
Chemical leavening reagents used in preparing the doughs.

Chemical reagent	Key	Chemical formula	MW ^a	NV ^b	Supplier
Sodium bicarbonate	Na bicarbonate	NaHCO ₃	84.01	–	Sigma Aldrich Co., St. Louis, MO
Sodium acid pyrophosphate 40	SAPP 40	Na ₂ H ₂ P ₂ O ₇	221.95	72	Aldrich Chemical Company Inc., Milwaukee, WI
Glucono-delta-lactone	GDL	C ₆ H ₁₀ O ₆	178.14	45	Acatris, Oakville, ON
Adipic acid	Adipic acid	HOOC(CH ₂) ₄ COOH	146.14	115	Solutia Inc., Gonzales, FL
Potassium tartrate	K tartrate	KHC ₄ H ₄ O ₆	188.18	45	Aldrich Chemical Company Inc. Milwaukee, WI

^a Molecular weight.

^b Neutralization value.

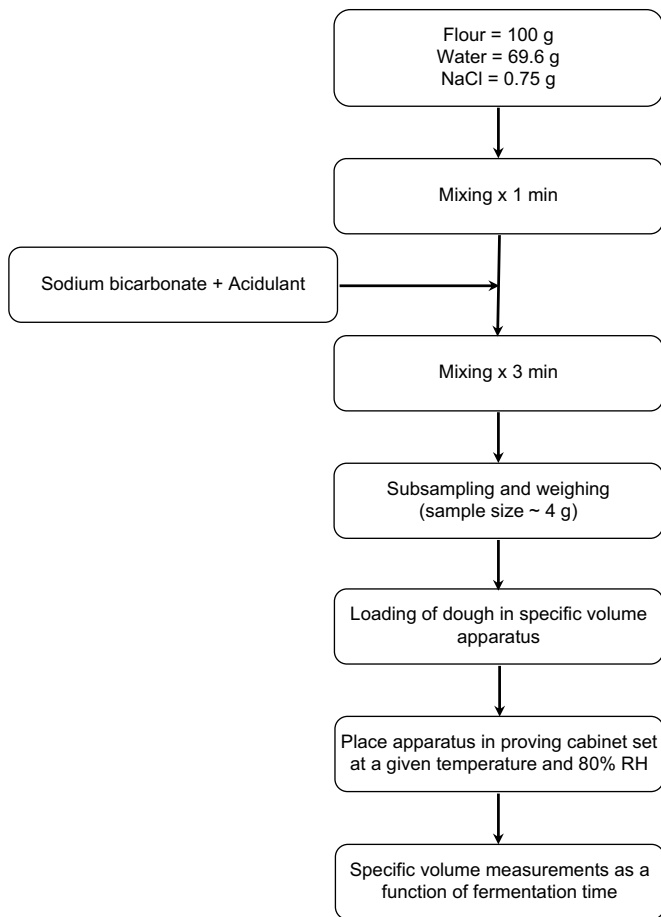


Fig. 1. Flow diagram showing the procedure followed for preparing a dough sample to measure its specific volume during fermentation.

To ensure precise quantification of the area of the dough, the calibration procedure was carried out in exactly the same way as the fermentation experiments, but, instead of using a fermenting dough, a 60×60 -mm piece of graph paper was placed on top of the bottom acrylic plate (plates maintained at their preset thickness of 2.11 mm) (Fig. 2). The number of pixels corresponding to the imaged area of the battery (I_{battery}) and those of the image of the graph paper ($I_{\text{graph-paper}}$) were extracted from the acquired images at seven increasingly higher magnification steps using the zoom-in button in the digital camera (Fig. 3).

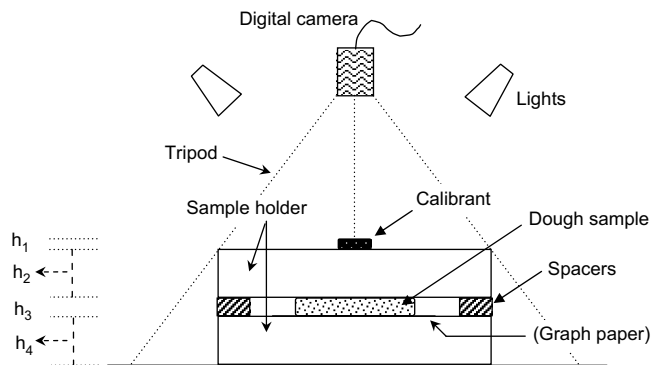


Fig. 2. Schematic diagram of the apparatus used for specific volume measurements. Actual heights are shown on the left-hand side: $h_1 = 1.60$ mm; $h_2 = 25.0$ mm; $h_3 = 2.11$ mm; $h_4 = 25.0$ mm. Distance between camera and top of sample holder = 260 mm. Graph paper only used during calibration steps (see text).

By geometrical comparison, the slope of the plot I_{battery} versus $I_{\text{graph-paper}}$ (Fig. 3) is proportional to the ratio of the actual area of the battery ($A_{\text{battery}} = \pi D^2/4 = 311.0 \text{ mm}^2$) to that of the graph paper ($A_{\text{graph-paper}} = L^2 = 3600 \text{ mm}^2$), as follows:

$$\frac{I_{\text{battery}}}{I_{\text{graph-paper}}} = \frac{A_{\text{battery}}}{A_{\text{graph-paper}}} f = \frac{\pi D^2}{4L^2} f \quad (2)$$

where f is a correction factor (dimensionless) associated with using image analysis to calculate the area of the graph paper using a calibrant located on a slightly different focal plane. Replacing values in Eq. (2), including the slope value for I_{battery} versus $I_{\text{graph-paper}}$, f was found to be 1.083. Therefore, the area of the expanding dough during fermentation was calculated from:

$$A_{\text{dough}}(t) = \frac{I_{\text{dough}}(t)}{I_{\text{battery}}} A_{\text{battery}} f \quad (3)$$

The density of the gas-free doughs was determined using a combination of X-ray microtomography and density measurements with a gravimetric bottle (Bellido et al., 2006). To prevent carbon dioxide evolution from interfering with acquisitions of the X-ray microtomograph, chemical leavening systems were reacted separately with a portion of the formula water. This solution was then added to the dough formula along with the remaining formula water, and followed by standard mixing. Sample preparation and X-ray image reconstruction techniques as well as the methodology for void fraction determination have been described by Bellido et al. (2006).

To examine the effect of chemical leavening systems on the specific volume of wheat flour doughs, a full factorial design, with triplicates of each treatment, was used. Four leavening acids (adipic acid, glucono-delta-lactone, potassium acid tartrate and sodium acid pyrophosphate 40), three concentrations of sodium bicarbonate (based on 1.4, 2.8 and 4.2 g per 100 g of flour), and three fermentation temperatures (27, 33 and 39 °C) were the experimental treatments. Experimental treatments were assigned according to three randomized complete block designs where the blocks represented each fermentation temperature.

3. Results

3.1. Effect of the type of chemical leavening system on dough specific volume

Curves of dough specific volume (DSV) as a function of fermentation time for various chemical leavening systems are

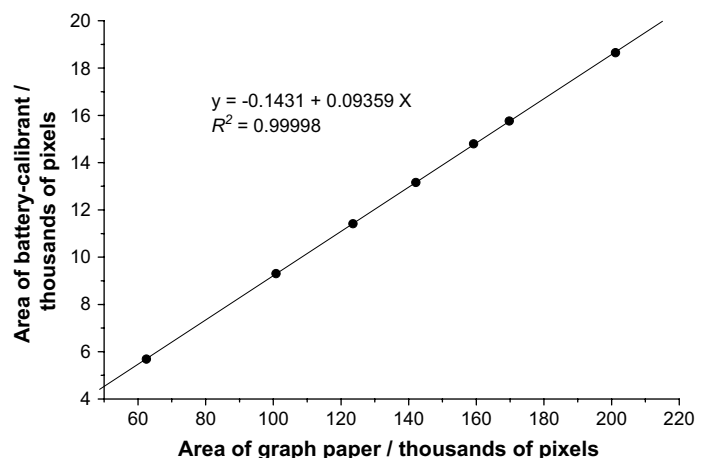


Fig. 3. Calibration curve for correcting measured areas by an image analysis technique. The solid line is a linear fit to the data.

shown in Fig. 4 for one sodium bicarbonate concentration and one fermentation temperature. It can be seen that the ability of a chemical leavening system to evolve carbon dioxide depends strongly on the leavening acid used. Regardless of the fermentation temperature or the amount of baking soda, the DSV technique was found to yield specific volume values whose coefficient of variation was better than 5% for triplicate determinations, except for the leavening system containing GDL where the repeatability was within 7%. The precision of the DSV technique was indicative of its potential to ascertain the leavening capacity of a wide range of chemical leavening systems.

3.2. Fermentation temperature

Increasing fermentation temperature in yeasted dough increases the rate of carbon dioxide evolution (Chiotellis and Campbell, 2003a,b), an effect also observed in chemically leavened dough (Bellido et al., 2008). This occurs because, as temperature is increased, the solubility of carbon dioxide in the liquid (continuous) phase of dough decreases whereas the rate of carbon dioxide production increases (Campbell and Mougeot, 1999; Chiotellis and Campbell, 2003a,b). However, increasing fermentation temperature did not necessarily increase specific volume (Fig. 5). In fact, results suggested that the level of sodium bicarbonate in the dough was much more influential than fermentation temperature in bringing about changes in the volume of dough. A possible explanation for the subtle specific volume changes brought about by temperature is that while an increase in fermentation temperature is expected to increase gas production, it also decreases gas retention. It has been reported that decreased gas retention in the temperature range 25–40 °C arose from changes in the mechanical properties of dough, attributed either to decreased strain hardening (Dobraszczyk et al., 2003) or reduced apparent viscosity (Blokksma, 1990).

3.3. Amount of sodium bicarbonate

The influence of the level of sodium bicarbonate on the specific volume of dough was more pronounced than that of fermentation temperature as illustrated in Fig. 5 for dough chemically leavened with adipic acid. However, there was not a one-to-one correspondence between amount of sodium bicarbonate and the expected change in specific volume associated with release of its carbon dioxide during fermentation. For example, at 27 °C, doubling and then tripling the lowest level (1.40 g/100 g) of sodium bicarbonate in dough leavened with adipic acid increased its specific volume from 1.1 cm³ g⁻¹ to only 1.4 cm³ g⁻¹ and 1.6 cm³ g⁻¹, respectively. A

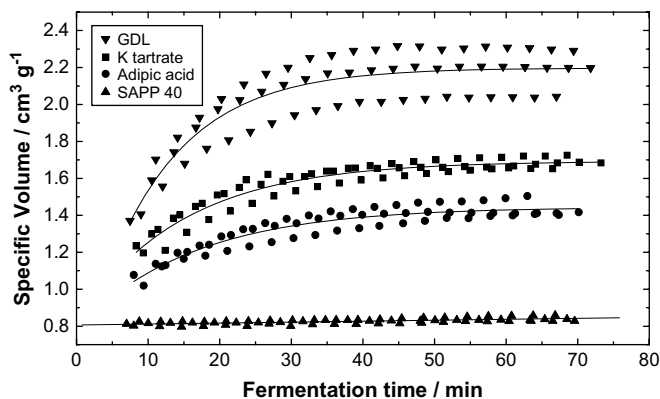


Fig. 4. Specific volume changes during fermentation at 27 °C for dough prepared with 2.80 g sodium bicarbonate and 6.22 g GDL, 2.43 g adipic acid, 6.22 g potassium tartrate or 3.89 g SAPP 40.

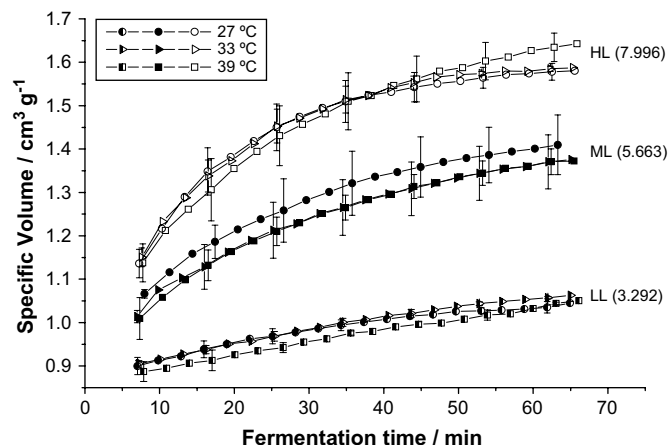


Fig. 5. Effect of fermentation temperature and level of the chemical leavener adipic acid on the specific volume of fermenting dough. LL, ML, and HL denote addition of adipic acid in sufficient amounts so as to completely neutralize 1.40 g (low level), 2.80 g (medium level), and 4.20 g (high level) of sodium bicarbonate, respectively, in a base dough formula. Values in parentheses represent theoretical maximum specific volumes (cm³ g⁻¹) assuming 100% evolution and 100% retention of CO₂ (based on ideal gas law at 27 °C).

less than expected increase in dough specific volume with amount of sodium bicarbonate was true for other fermentation systems and temperatures as well.

3.4. Dynamics of dough specific volume

In the temperature range from 27 to 39 °C the time-dependent behavior of the specific volume of dough could be described (Fig. 6) by a first-grade exponential growth fit of the form:

$$Y = Y_0 - A_1 e^{-t/\tau} \quad (4)$$

where Y is the specific volume of dough, Y_0 the maximum specific volume attained by the dough for a given leavening system at a given temperature, A_1 a scaling parameter, and τ a time constant. Goodness of fit, estimated using the coefficient of determination, was calculated using the chi-square test. Error terms in the fitted functions represented the amount by which observed values differed from those predicted by the model (Tables 2–4). Data on dough that had been chemically leavened with SAPP did not exhibit

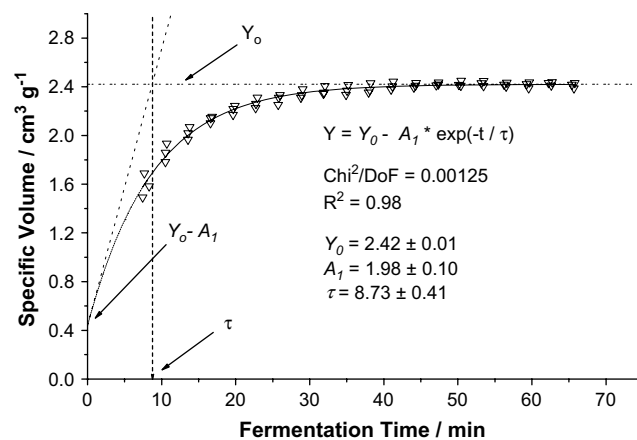


Fig. 6. Mathematical characterization of the exponential growth function used for describing changes in specific volume with fermentation time for three replicates of a selected dough sample. Sample corresponds to dough prepared with GDL and sodium bicarbonate at a level of 9.33 g and 4.2 g, respectively, per 100 g flour, and fermented at 33 °C.

Table 2

Parameters for exponential growth fits of specific volume ($\text{cm}^3 \text{g}^{-1}$) versus fermentation time (min) data ($n=3$; 20 data points per replicate) for doughs prepared with one of three levels of GDL^a and fermented at 27, 33 or 39 °C.

GDL ^a	Equation ^b : $Y = Y_0 - A_1 \exp(-t/\tau)$			
	$Y_0 \pm \text{error}$	$A_1 \pm \text{error}$	$\tau \pm \text{error}$	R^2
27 °C				
LL	1.55 ± 0.01	0.785 ± 0.003	15.83 ± 0.82	0.978**
ML	2.14 ± 0.02	1.516 ± 0.159	11.39 ± 1.21	0.884*
HL	2.11 ± 0.01	1.31 ± 0.06	12.49 ± 0.85	0.953*
33 °C				
LL	1.62 ± 0.00	0.929 ± 0.021	13.53 ± 0.39	0.993**
ML	2.16 ± 0.03	1.502 ± 0.210	11.59 ± 1.85	0.965**
HL	2.42 ± 0.01	1.981 ± 0.105	8.73 ± 0.41	0.976*
39 °C				
LL	1.57 ± 0.02	0.784 ± 0.091	13.55 ± 2.13	0.808*
ML	2.00 ± 0.01	1.237 ± 0.175	10.33 ± 1.37	0.836*
HL	2.22 ± 0.01	1.275 ± 0.129	9.43 ± 0.98	0.890*

* $p < 0.01$; ** $p < 0.001$.

^a LL = 3.11 g GDL + 1.40 g sodium bicarbonate; ML = 6.22 g GDL + 2.80 g sodium bicarbonate; HL = 9.33 g GDL + 4.20 g sodium bicarbonate.

^b Y = specific volume ($\text{cm}^3 \text{g}^{-1}$); t = fermentation time (min); τ = fermentation time constant.

exponential growth behavior but linear (Fig. 4) and so the fitting function reflected this relationship (Table 5).

As illustrated in Fig. 6, the changes in specific volume with fermentation time (except for leavening systems containing SAPP 40 where only one linear region was present) can be delineated into three regions: (1) an initial region, where leavening systems brought about the most rapid change in dough specific volume with time; (2) a transitional region where reactant availability began limiting the evolution of carbon dioxide; and (3) a plateau region where the amount of carbon dioxide entering into solution and into the gas bubbles was offset by that lost to the atmosphere. The time constant (τ) in Tables 2–4 – the time required to change the specific volume by a set amount – decreased with increased sodium bicarbonate concentration and also (though slightly) with fermentation temperature. Overall, the time constants were the smallest for doughs prepared with GDL and the largest for those prepared with adipic acid. The results for SAPP 40, modeled using linear functions, showed that the rate of change in dough specific

Table 3

Parameters for exponential growth fits of specific volume ($\text{cm}^3 \text{g}^{-1}$) versus fermentation time (min) data ($n=3$; 20 data points per replicate) for doughs prepared with one of three levels of potassium tartrate^a and fermented at 27, 33 or 39 °C.

K tartrate ^a	Equation ^b : $Y = Y_0 - A_1 \exp(-t/\tau)$			
	$Y_0 \pm \text{error}$	$A_1 \pm \text{error}$	$\tau \pm \text{error}$	R^2
27 °C				
LL	1.08 ± 0.01	0.233 ± 0.035	18.65 ± 5.52	0.614*
ML	1.69 ± 0.01	0.874 ± 0.069	14.58 ± 1.47	0.914*
HL	2.11 ± 0.01	1.31 ± 0.06	12.49 ± 0.85	0.953*
33 °C				
LL	1.16 ± 0.01	0.263 ± 0.023	15.38 ± 2.38	0.843**
ML	1.85 ± 0.01	0.850 ± 0.034	14.72 ± 0.97	0.965**
HL	2.10 ± 0.01	1.59 ± 0.11	7.80 ± 0.47	0.954*
39 °C				
LL	1.17 ± 0.03	0.268 ± 0.028	23.36 ± 7.84	0.648*
ML	1.85 ± 0.03	0.852 ± 0.090	15.20 ± 2.70	0.794*
HL	1.99 ± 0.00	1.09 ± 0.71	4.48 ± 1.12	0.618*

* $p < 0.01$; ** $p < 0.001$.

^a LL = 3.11 g potassium tartrate + 1.40 g sodium bicarbonate; ML = 6.22 g potassium tartrate + 2.80 g sodium bicarbonate; HL = 9.33 g potassium tartrate + 4.20 g sodium bicarbonate.

^b Y = specific volume ($\text{cm}^3 \text{g}^{-1}$); t = fermentation time (min); τ = fermentation time constant.

Table 4

Parameters for exponential growth fits of specific volume ($\text{cm}^3 \text{g}^{-1}$) versus fermentation time (min) data ($n=3$; 20 data points per replicate) for doughs prepared with one of three levels of adipic acid^a and fermented at 27, 33 or 39 °C.

Adipic acid ^a	Equation ^b : $Y = Y_0 - A_1 \exp(-t/\tau)$			
	$Y_0 \pm \text{error}$	$A_1 \pm \text{error}$	$\tau \pm \text{error}$	R^2
27 °C				
LL	1.08 ± 0.02	0.217 ± 0.013	39.58 ± 7.83	0.926**
ML	1.44 ± 0.05	0.515 ± 0.055	24.89 ± 8.40	0.665*
HL	1.65 ± 0.03	0.735 ± 0.054	19.58 ± 3.31	0.897*
33 °C				
LL	1.16 ± 0.03	0.295 ± 0.022	60.20 ± 9.36	0.978**
ML	1.43 ± 0.05	0.501 ± 0.037	31.09 ± 9.20	0.788*
HL	1.61 ± 0.01	0.681 ± 0.022	17.86 ± 1.19	0.971**
39 °C				
LL	1.49 ± 0.67	0.637 ± 0.662	196.46 ± 25.0	0.871**
ML	1.43 ± 0.02	0.534 ± 0.015	28.32 ± 3.12	0.959**
HL	1.70 ± 0.04	0.726 ± 0.037	26.32 ± 4.87	0.876*

* $p < 0.01$; ** $p < 0.001$.

^a LL = 1.22 g adipic acid + 1.40 g sodium bicarbonate; ML = 2.43 g adipic acid + 2.80 g sodium bicarbonate; HL = 3.65 g adipic acid + 4.20 g sodium bicarbonate.

^b Y = specific volume ($\text{cm}^3 \text{g}^{-1}$); t = fermentation time (min); τ = fermentation time constant.

volume also increased with both sodium bicarbonate level and fermentation temperature (Table 5).

The maximum specific volume, Y_0 , gave an indication of the final degree of aeration achievable in the dough at the end of fermentation. As discussed previously, Y_0 increased, though not proportionally, with the amount of sodium bicarbonate in the formula (Tables 2–4). No clear relationship could be established between fermentation temperature and Y_0 . The difference $Y_0 - A_1$ was expected to theoretically yield the specific volume of dough at the end of mixing because it was equivalent to extrapolating the specific volume of dough to zero fermentation time (immediately after mixing). However, the uncertainty associated with the specific volume of dough immediately after mixing, $Y_0 - A_1$, was relatively high so an alternative means of measuring it was required (see Section 4).

4. Discussion

4.1. Void fraction created by leavening system

The relationship between the final void fractions in chemically leavened dough and the amount of sodium bicarbonate in the

Table 5

Parameters for linear fits of specific volume ($\text{cm}^3 \text{g}^{-1}$) versus fermentation time (min) data ($n=3$; 20 data points per replicate) for doughs prepared with one of three levels of SAPP 40^a and fermented at 27, 33 or 39 °C.

SAPP 40 ^a	Equation ^b : $Y = A + Bt$		
	$A \pm \text{error}$	$B \pm \text{error}$	R^2
27 °C			
LL	0.825 ± 0.002	$5.83 \times 10^{-5} \pm 3.14 \times 10^{-5}$	0.153
ML	0.807 ± 0.003	$50.9 \times 10^{-5} \pm 7.6 \times 10^{-5}$	0.653**
HL	0.813 ± 0.008	$89.2 \times 10^{-5} \pm 18.5 \times 10^{-5}$	0.532*
33 °C			
LL	0.815 ± 0.003	$20.0 \times 10^{-5} \pm 7.9 \times 10^{-5}$	0.317*
ML	0.798 ± 0.005	$110 \times 10^{-5} \pm 14 \times 10^{-5}$	0.709**
HL	0.787 ± 0.004	$195 \times 10^{-5} \pm 11 \times 10^{-5}$	0.919**
39 °C			
LL	0.801 ± 0.002	$51.6 \times 10^{-5} \pm 5.2 \times 10^{-5}$	0.795**
ML	0.789 ± 0.003	$126 \times 10^{-5} \pm 7 \times 10^{-5}$	0.914**
HL	0.811 ± 0.013	$316 \times 10^{-5} \pm 31 \times 10^{-5}$	0.876**

* $p < 0.01$; ** $p < 0.001$.

^a LL = 1.94 g SAPP 40 + 1.40 g sodium bicarbonate; ML = 3.89 g SAPP 40 + 2.80 g sodium bicarbonate; HL = 5.81 g SAPP 40 + 4.20 g sodium bicarbonate.

^b Y = specific volume ($\text{cm}^3 \text{g}^{-1}$); t = fermentation time (min).

formula is shown in Fig. 7. The specific volume of the gas-free dough (Y_{gf}) was obtained via X-ray tomography in doughs in which the reacted chemical leaveners were added. The final void fraction, ϕ_f , of the doughs was derived from the specific volume of the dough at long fermentation time (Y_f) (i.e., final specific volume data in Tables 2–5) using:

$$\phi_f = 1 - \frac{Y_{gf}}{Y_f} \quad (5)$$

Fig. 7 indicates that for the same amount of sodium bicarbonate in the formula, which theoretically should lead to equivalent levels of gas production, the final void fraction in the dough samples depended strongly on the type of acidulant employed. Although the different gas production capacities of the various chemical leavening systems may have played a role in determining the final void fraction in the dough (as will be discussed in the following section), an alternate hypothesis is that acidulants affected the development of the gas-trapping gluten network of the dough during mixing and/or fermentation, so that gas retention properties in the dough were the basis for differences in the final void fractions.

Gas retention properties of the dough are expected to be altered by various interactions between water, gluten proteins and chemical leavening ions as well as by the drop in pH brought about by fermentation. For example, increasing the level of sodium bicarbonate beyond 2.8 g per 100 g flour did not have a major impact on dough specific volume as the dough appeared to become more permeable to carbon dioxide. This may explain why Heidolph (1996) recommended that bread be leavened using sodium bicarbonate at a level between 1.68 and 2.10 g per 100 g flour. Changes in gas retention properties at high levels of chemical leavening systems may have arisen due to competition between chemical leaveners and gluten proteins for the available water (constant water absorption was employed), and this may have affected dough development. Regardless of the gas-trapping properties of dough developed during mixing, these properties will also be affected by the by-products arising from the chemical leavening reaction. By-products such as phosphate and tartrate salts are known to affect dough rheology due to their associated lyotropic effect on gluten proteins (He et al., 1992; Holmes and Hosney, 1987a; Kinsella and Hale, 1984; Wellner et al., 2003). Thus, it is the combined effects of

chemical leaveners during both mixing and leavening that are expected to dictate the overall gas retention of the dough by the end of the leavening operation. However, because the leavening agents employed did not decompose completely at conventional fermentation temperatures (<39 °C) (Bellido et al., 2008), and because the extent to which they do decompose has a bearing on both the amount of gas evolved and the by-product species liberated during leavening, gas evolution must also be considered in assessments of the effects of dough rheology on gas retention properties.

4.2. Gas retention versus gas evolution

Knowing actual carbon dioxide production in the dough enables one to determine the relative proportion of carbon dioxide retained versus that evolved, providing a good index of gas retention properties in the dough (Chiotellis and Campbell, 2003b). The total amount of carbon dioxide produced by the four chemical leavening systems has been measured using a pressuremeter in a previous study (Bellido et al., 2008). Accordingly, results from the DSV technique and the pressuremeter study were consolidated to determine actual values for carbon dioxide retention as a function of gas production in these chemically leavened doughs. [Gas production data at a fermentation temperature of 33 °C were interpolated from measurements at 27 and 39 °C (Bellido et al., 2008)]. Though an unaccounted amount of carbon dioxide was lost in the mixer, gas loss differences among chemical leavening systems may be considered negligible since this step followed standard protocol and its duration was short compared to fermentation times.

From Fig. 8 it is clear that the volume of carbon dioxide retained per unit of carbon dioxide evolved is still a strong function of the acidulant in the leavening system. Lines in Fig. 8 represent linear fits to the experimental data using data pooled for the various fermentation temperatures since a clear relationship with fermentation temperature was absent. Although the planar configuration of the DSV technique shortens the diffusion path length for carbon dioxide to the external surfaces of the dough, thus reducing the slopes of the lines compared to a buoyancy technique

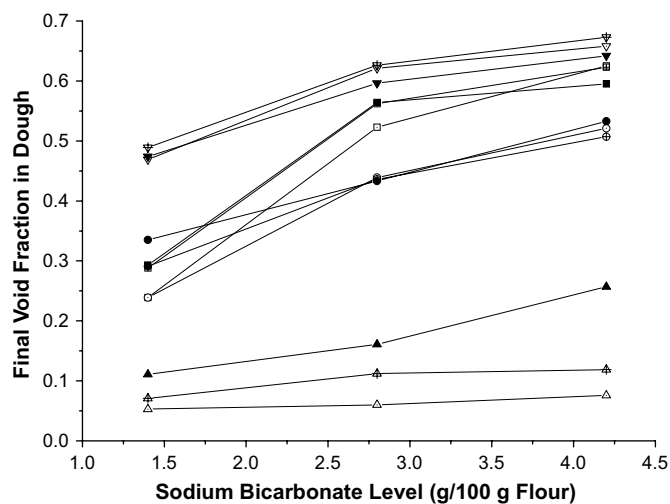


Fig. 7. The final void fraction of doughs that had been proved at 27 °C (solid symbols), 33 °C (dotted (.) symbols) and 39 °C (vertically crossed (+) symbols) for 1 h and formulated with 1.40 g, 2.80 g, or 4.20 g of sodium bicarbonate per 100 g flour (14% m.b.) and one of four acidulants, GDL (downward triangles), K tartrate (squares), adipic acid (circles) and SAPP 40 (upward triangles), each at a level determined by their neutralization value. See text for details on void fraction calculations.

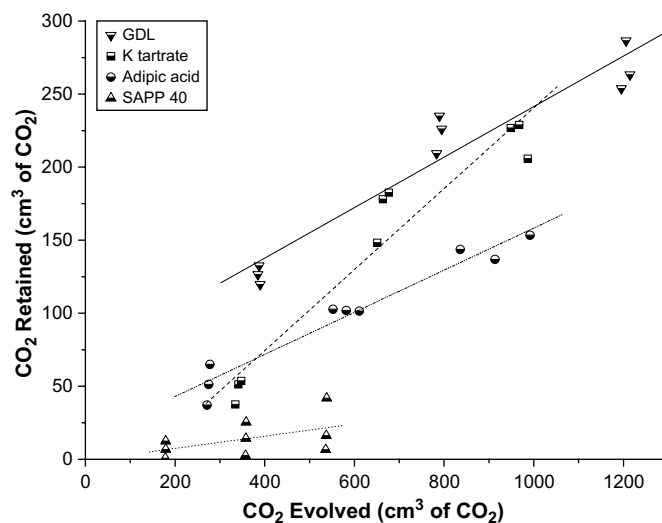


Fig. 8. Relationship between the amount of carbon dioxide retained to that evolved during fermentation of dough prepared with various chemical leavening systems. Data pooled for various fermentation temperatures. Lines represent the fit given by a linear regression (see text). Chemical leavening systems were composed of sodium bicarbonate (1.40 g, 2.80 g, or 4.20 g) and leavening acid at a level given by its neutralization value.

using a spherical dough specimen, the ranking of chemical leavening systems is not expected to be altered. The slopes of these lines could be interpreted as the effectiveness of the chemical leavening system to leaven the dough with rankings (in decreasing order) as: K tartrate (0.306 cm³ of CO₂ retained per cubic centimeter of CO₂ evolved), GDL (0.143), adipic acid (0.110) and SAPP 40 (0.039). As well, the linear fits of Fig. 8 were associated with reasonably good coefficients of determination (R^2): 0.96, 0.81, 0.96 and 0.47 for K tartrate, GDL, adipic acid and SAPP 40, respectively (statistically, the R^2 for all systems but SAPP 40 were highly significant based on the chi-squared test). Although gas losses at high void fractions may have occurred due to coalescence of the gas bubbles in the dough (Babin et al., 2005), this study indicates that the permeability of the dough to carbon dioxide gas is a factor in maximizing specific volume in the dough. From a food engineering point of view, gas transport phenomena are associated with the diffusion of carbon dioxide across the gas–dough interface and this is the subject of an upcoming research work.

5. Conclusions

The accuracy of measurements of the dynamic specific volume (DSV) of chemically leavened dough using a technique based on digital image analysis was improved with a novel calibration step. Using chemical leavening systems consisting of sodium bicarbonate and one of the leavening acidulants GDL, potassium tartrate, adipic acid or SAPP 40, raised the specific volume of bread dough so that the final void fractions spanned between 5 and 67% at fermentation temperatures. It was found that the relationship between the specific volume of dough at the end of fermentation and the actual gas evolved (measured independently using the Gassmart) was fairly linear and was characterized by a slope that provided a good index of the gas-trapping properties of dough. It was surmised that doughs with better gas-trapping networks had more positive slopes because leavening system ions disrupted network formation to a lesser extent.

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References

- AACC, 2000. Approved Methods of the American Association of Cereal Chemists, 10th ed. AACC International, St. Paul, MN.
- Atwell, W.A., 1985. Refrigerated dough. U.S. Patent 4,526,801.
- Babin, P., Della Valle, G., Dendievel, R., Lassoued, N., Salvo, L., 2005. Mechanical properties of bread crumbs from tomography based finite element simulations. *Journal of Materials Science* 40, 5867–5873.
- Bellido, G.G., Scanlon, M.G., Page, J.H., Hallgrímsson, B., 2006. The bubble size distribution in wheat flour dough. *Food Research International* 39, 1058–1066.
- Bellido, G.G., Scanlon, M.G., Sapirstein, H.D., Page, J.H., 2008. The use of a pressuremeter to measure the kinetics of carbon dioxide evolution in chemically leavened wheat flour dough. *Journal of Agricultural and Food Chemistry* 56, 9855–9861.
- Baker, J.C., Mize, M.D., 1941. The origin of the gas cell in bread dough. *Cereal Chemistry* 18, 19–34.
- Bloskma, A.H., 1981. Effect of surface tension in the gas–dough interface on the rheological behaviour of dough. *Cereal Chemistry* 58, 481–486.
- Bloskma, A.H., 1990. Rheology of the breadmaking process. *Cereal Foods World* 35, 228–236.
- Campbell, G.M., Mougeot, E., 1999. Creation and characterisation of aerated food products. *Trends in Food Science & Technology* 10, 283–296.
- Campbell, G.M., Herrero-Sanchez, R., Payo-Rodriguez, R., Merchan, M.L., 2001. Measurement of dynamic dough density and effect of surfactants and flour type on aeration during mixing and gas retention during proofing. *Cereal Chemistry* 78, 272–277.
- Campbell, G.M., Ross, M., Motoi, L., 2008a. Bran in bread: effects of particle size and level of wheat and oat bran on mixing, proving and baking. In: Campbell, G.M., Scanlon, M.G., Pyle, D.L. (Eds.), *Bubbles in Food 2: Novelty, Health and Luxury*. Eagan Press, St Paul, MN, pp. 337–354.
- Campbell, G.M., Koh, K.-C., Keung, Y.-M., Morgenstern, M., 2008b. Effect of wheat bran particle size on aeration of bread dough during mixing. In: Campbell, G.M., Scanlon, M.G., Pyle, D.L. (Eds.), *Bubbles in Food 2: Novelty, Health and Luxury*. Eagan Press, St Paul, MN, pp. 355–368.
- Chiotellis, E., Campbell, G.M., 2003a. Proving of bread dough I – modelling the evolution of the bubble size distribution. *Transactions of the Institution of Chemical Engineers, Part C, Food and Bioproducts Processing* 81, 194–206.
- Chiotellis, E., Campbell, G.M., 2003b. Proving of bread dough II – measurement of gas production and retention. *Transactions of the Institution of Chemical Engineers, Part C, Food and Bioproducts Processing* 81, 207–216.
- Dobraszczyk, B.J., Smewing, J., Albertini, M., Maesmans, G., Schofield, J.D., 2003. Extensional rheology and stability of gas cell walls in bread doughs at elevated temperatures in relation to breadmaking performance. *Cereal Chemistry* 80, 218–224.
- Elmehdi, H.M., Page, J.H., Scanlon, M.G., 2003. Monitoring dough fermentation using acoustic waves. *Transactions of the Institution of Chemical Engineers, Part C, Food and Bioproducts Processing* 81, 217–223.
- Elmehdi, H.M., Page, J.H., Scanlon, M.G., 2007. Evaluating dough density changes during fermentation by different techniques. *Cereal Chemistry* 84, 250–252.
- Hansen, L.M., Anderson, B.R., Lorence, M.W., Reinke, J.D., 2003. Freezer to oven dough products. U.S. Patent 6,589,583.
- He, H., Roach, R.R., Hoseney, R.C., 1992. Effect of nonchaotropic salts on flour bread-making properties. *Cereal Chemistry* 69, 366–371.
- Heidolph, B.B., 1996. Designing chemical leavening systems. *Cereal Foods World* 41, 118–126.
- Hibberd, G.E., Parker, N.S., 1976. Gas–pressure–volume–time relationships in fermenting doughs. I. Rate of production and solubility of carbon dioxide in dough. *Cereal Chemistry* 53, 338–346.
- Hlynka, I., Anderson, J.A., 1955. Laboratory dough mixer with an air-tight bowl. *Cereal Chemistry* 32, 83–87.
- Holmes, J.T., Hoseney, R.C., 1987a. Chemical leavening: effect of pH and certain ions on breadmaking properties. *Cereal Chemistry* 64, 343–348.
- Holmes, J.T., Hoseney, R.C., 1987b. Frozen doughs: freezing and thawing rates and the potential of using a combination of yeast and chemical leavening. *Cereal Chemistry* 64, 348–351.
- Hoseney, R.C., 1998. Principles of Cereal Science and Technology, second ed. American Association of Cereal Chemists, Inc., St. Paul, MN, pp. 29–64, pp. 275–305.
- Kinsella, J.E., Hale, M.L., 1984. Hydrophobic associations and gluten consistency: effects of specific ions. *Journal of Agricultural and Food Chemistry* 32, 1054–1056.
- Laughlin, D.L., DeMars, J.A., 1999. Method of preparing dough. U.S. Patent 5,858,440.
- Laughlin, D.L., DeMars, J.A., Vargas, G.C., 2000. Method of preparing dough. U.S. Patent 6,165,533.
- Loneragan, D.A., Perry, M.R., McIntyre, T.L., 2003. High raw specific volume dough in a chub. U.S. Patent 6,602,529.
- Narayanaswamy, V., Daravingas, G.V., 2001. Refrigerated and shelf-stable bakery dough products. U.S. Patent 6,261,613.
- Perry, M.R., Colman, M.A., 2001. Packaged dough product. U.S. Patent 6,242,024.
- Perry, M.R., Colman, M.A., 2003. Leavened dough or batter packaging system. U.S. Patent 6,635,291.
- Scanlon, M.G., Zghal, M.C., 2001. Bread properties and crumb structure. *Food Research International* 34, 841–864.
- Shoenfuss, T.C., Levin, L.B., Casper, J.L., Oppenheimer, A.A., 2006. Refrigerated, developed, chemically leavened dough compositions comprising concentrated protein ingredient. International Patent PCT/US2005/029895.
- Wellner, N., Bianchini, D., Mills, E.N.C., Belton, P.S., 2003. Effect of selected Hofmeister anions on the secondary structure and dynamics of wheat prolamins in gluten. *Cereal Chemistry* 80, 596–600.
- Yong, S.H., Anderson, G.R., Levin, L., 1983. Dough product containing an organic acid leavener. U.S. Patent 4,388,336.