

Chapter 3

Bubbles interaction modelling in doughs

3.1 Introduction

To obtain a bread crumb with a light and even texture after mixing, a sufficient number of gas cells has to be incorporated in the dough [Bloska A.H. et al., 1990a]. This is due to fermentation reactions that produce the gas. As the fermentation proceeds, the gas cells become larger and the distance between them decreases, consequently there is small thickness to the dough membrane.

The types of physical instabilities during leavening and baking in dough such as Ostwald ripening (disproportionation) and coalescence of gas cells is relevant [Bloksma, 1990; Van Vliet et al., 1992].

The mechanism behind disproportionation is the diffusion of gas through the dough from small to large cells caused by differences in gas pressure between cells of different size [Kokelaar and Prins, 1995].

The result is the growth of large gas cells at the expense of small ones. Coalescence instead is defined as *“the process by which the thin lamella between two adjacent bubbles collapses to form one bigger bubble”* [Lallemand Baking Update]. This phenomenon of gas cells is initiated by fracture of the dough film between them [Van Vliet et al., 1992]. This results in a coarse bread crumb, while the fracture of dough films between gas cells and the surrounding air results in a loss of gas and a small loaf volume [Sliwinskia E.L. et al.2004]. Coalescence is the most important process by which bubbles disappear in porous bakery products such as bread and cakes, where gas retention is maximized by stabilizing the lamella between the bubbles.

Bakery products such as breads are characterized by a typical porous structure and a high specific volume. To obtain such a porous structure, air bubbles have to be incorporated during a mixing or blending step, as stated above. Then the gas produced during fermentation, baking or incorporated in mixing must be retained by the gas cells to have a good expansion for the baked product and their volume expansion directly related to the extent to which gas cells can expand. Then the rheological properties of the dough and the stability of the film around the gas cells control the expansion capacity. It therefore must have sufficient extensibility to respond to the gas pressure but also sufficient strength to resist collapse [Jang W. et al. 2005].

For this reason the contact area between bubbles and continuous phase is one of the key parameters controlling mass transfer in the baking industrial process.

In fact the rheological properties of gas cell walls in bread doughs, for instance, are considered to be important in relation to their stability and gas retention during kneading and baking, in particular their extensional strain hardening properties. Large deformation rheological properties of gas cell walls were measured by [B.J. Dobraszczyk \(2004\)](#) using biaxial extension for a number of doughs of varying breadmaking quality at constant strain rate and at elevated temperatures in the range between 25–60 °C. The stability of gas cell walls during baking is strongly related to their strain hardening properties, and that extensional rheological measurements can be used as predictors of baking quality [[B.J. Dobraszczyk, 2004](#)].

Gluten is the major protein in wheat flour doughs, responsible for their unique viscoelastic behaviour and their ability to retain gas during kneading and baking.

The gluten matrix forms membranes or sheets that surround the gas bubble. The elastic properties of the gluten matrix allow the gas cells to expand, thereby allowing the gas to be retained with the bubbles.

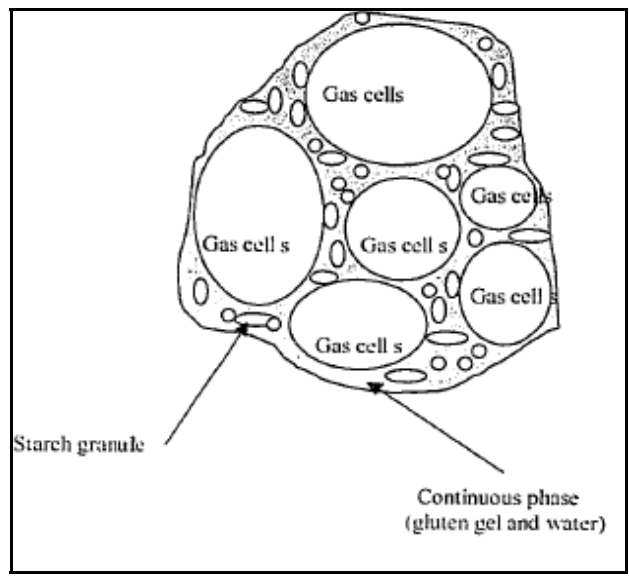


Figure 3. 1 – Dough Structure.

From the literature a positive correlation is confirmed between loaf volume and the bubble expansion. From another point of view, it is wrong to consider that dough has a foam structure in which individual gas cell are completely separated by a continuous starch-gluten matrix, but there is the rupture of gas cell membrane during fermentation and baking [[Gan Z. et al.,1990](#)]. This transforms the foam structure of dough with separate gas cells into a sponge with a continuous gas phase. The rupture of the membrane has been ascribed to the rapid increase in dough viscosity as starch gelatinizes at temperature above 60°C during baking. And [Gan Z. et al. \(1990\)](#) found that the

rupture of the film leads to the interconnection of gas cells and, eventually, to an open sponge structure as found in baked bread.

During fermentation and baking the gas cell can be subject to various types of physical instability: creaming, aggregation, Ostwald ripening or disproportionation and coalescence. The first two types of instability can be neglected due to the high viscosity of the dough, but the other two must be considered. The Ostwald ripening, as stated above, is the growth of large cells at the expense of small ones. This is caused by a gas pressure difference between gas cells of different size. Probably this phenomenon is not essential for gas retention, but affects the appearance of the bread crumb. It has been found that *disproportionation* can occur directly after mixing. This is the *coalescence* of gas cells initiated by rupture of the film between them. Rupture of films and surrounding air results in a loss of gas and a small loaf volume [Van Vliet et al., 1992, Kokelaar J.J. et al., 1995].

Kokelaar J.J. et al.(1995) measured the surface dilatational modulus, E , also called the surface elasticity modulus, and the surface tension, γ , to study the disproportion and the coalescence, because, from the literature data, if the decrease in surface tension of a shrinking bubble is great enough compared with the decrease in bubble radius, the driving force for disproportionation is absent and the process will be prevented. Moreover, against coalescence, it is good to have a low surface tension during expansion of the film and to have a surface tension gradient during expansion [Kokelaar J.J. et al., 1994]. To study coalescence, the dynamic surface rheological properties of wheat flour components have recently been published. It was stated that films with higher surface elasticity are supposed to have higher stability towards rupture. Higher surface elasticity in shear was found for a dough of a good making quality. To study the surface behaviour of dough components in relation to gas bubble stability in dough, it is more relevant to deform the surface in dilation, since this is the type of deformation around a growing (or shrinking) gas bubble. It was found by J.J. Kokelaar et al. (1995) that the coalescence of gas bubbles in bread dough may occur during oven rise, since dough films between expanding gas bubbles thin out. When the temperature in dough increases to ca. 60°C, starch gelatinises. Film stabilisation owing to surface properties is only relevant until this transformation from a foam into a sponge structure occurs. An estimate of film thickness, h , where surface and bulk properties contribute equally to film resistance against extension, can be made with the following equation:

$$2(\gamma + E) = h\sigma_B \quad (3.1)$$

The left hand side of the equation gives the resistance of a film during expansion due to the presence of surface tension, γ , and the extra resistance owing to increase of the surface tension by

this expansion, E . The film has two surfaces, which explains factor 2. The right hand side gives the contribution of the bulk properties, where σ_B is the biaxial stress of the dough. However, surface properties are important in determining the rate of disproportionation of the gas bubbles directly after mixing, and they may be important in determining the film stability against rupture for very thin films.

When baking proceeds, the dough around the growing gas cell is tangentially extended in two directions and compressed radially. This deformation is called biaxial extension. For this reason many authors have tested the doughs carrying out biaxial extensional experiments. [Van Vliet et al. \(1992\)](#), analyzing doughs from different wheat cultivars, found that the stress increases with increasing strain at constant biaxial strain rate and also with increasing biaxial strain rate at constant strain. They found that the film is unstable if the extension of the thinner part is accelerated (and this can cause bubble rupture), the contrary happens if the thinner part extension is slower. In every case the potential gas retention of wheat flour dough is largely due to bulk rheological property [[Van Vliet et al., 1992](#); [Janssen et al., 1996](#); [Kokelaar et al., 1996](#)]. An earlier analysis of the bread making process revealed the requirements for a satisfactory performance of wheat flour doughs that can be expressed in rheological terms [[Bloksma, 1990](#)]:

- the viscosity has to be high enough to prevent the ascent of the gas cells. This condition is met by virtually all doughs;
- the dough must be extensible in order to prevent coalescence and thus premature fracture of membranes between gas cells. The extensibility must be maintained long enough under baking conditions to permit sufficient oven rise;
- [Van Vliet et al. \(1992\)](#) proposed an addition dough property to favour gas retention: strain hardening of the dough in biaxial extension has to exceed a specific power limit.

In this chapter a new bubble growth model is proposed. The previous proposed criterion for bubble expansion in an infinite visco-elastic medium does not consider any interaction of a bubble with surrounding ones. This hypothesis is acceptable for the mass transfer model, but an interaction mechanism should be considered from a mechanical point of view. In fact, when the bubble radius increases the bubbles start interacting and eventually coalescing. As a consequence of the model reported in the previous chapter, bubble growth stops both if the reactants are completely consumed, according to irreversible kinetics, and temperature remains constant and the water reaches the equilibrium conditions. Moreover, it is well-known that bubble stabilisation happens

earlier than that stated above and, therefore, another mechanical stabilisation mechanism should be taken into account.

From a physical point of view, when a bubble expands, the mass around it becomes thinner and thinner, and at a certain time it cannot be any longer assumed as an infinite medium as proposed above. Some authors [Gan et al., 1995] state that coalescence occurs when the uniform starch/protein layer surrounding the bubble becomes thin enough to break, therefore a critical dough thickness value should be evaluated. This theory has been successfully applied to bread dough mainly composed of flour and water, but the same authors report that stabilisation is affected by the dough recipe, especially when plasticizer ingredients are involved, such as fat and sugar in biscuit recipes. In addition, the evaluation of a critical thickness implies that the layer should be uniform, i.e. a spatial uniform interaction between bubbles should be assumed. On the contrary physical evidence indicates that the material surrounding bubbles do not form a layer of constant thickness and the region of layer reduction can be individuated, depending on the spatial distribution of the bubbles. Other authors [Van Vliet et al, 1992] proposed the hypothesis of different bubble spatial distributions, but difficulties in experimental validation make this solution unreliable for modelling purposes.

To overcome this problem, a new modelling approach is proposed: the bubble rupture/coalescence phenomenon is linked to the elastic deformation energy accumulated in the dough layer as result of bubble expansion. From a mass balance, if the bubble size distribution is known and the mass of paste associated with any bubble is constant during the process, if the water content does not change, the initial layer around the bubble may be computed. The material contained in this layer is subjected to a variable force that tends to squeeze it out from the gap when two contiguous bubbles interact with each other. As a consequence, the material distribution around the bubble is not a uniform layer nor time dependent. This effect starts to be relevant only when the radius becomes sufficiently large so that the infinite paste hypothesis does not apply any longer. During this phenomenon a certain amount of elastic energy is accumulated in the material, according to the time dependent rheological properties of the dough. When a maximum energy load is reached the dough layer may break and the bubble eventually coalesces.

From a modelling point of view, the problem may be split into two parts: the calculation of the dough layer thickness profile and, secondly, the calculation of the elastic energy associated with the deformation process owing to the smallness of the interaction zone. The local layer thickness

evolution was modelled referring to a planar equivalent squeezing flow whilst the elastic energy is calculated using the mechanical theory of shell and membranes subjected to an external load.

3.2 Squeeze flow modelling

When the distance between two bubbles is reduced as an effect of expansion, owing to the pressure inside the gas cells, a local squeeze flow of paste takes place and the dough is forced to flow out of the gap (Figure 3.2). Since interest is focused on the local reduction of the distance between the two bubbles, the flow of the paste was locally approximated as a planar between two equivalent parallel plates, under a constant force F related to the gas pressure P_G . A “quasi-steady” flow was supposed, whilst the boundary condition of the force is assumed to be time dependent (Bird et al., 1977).

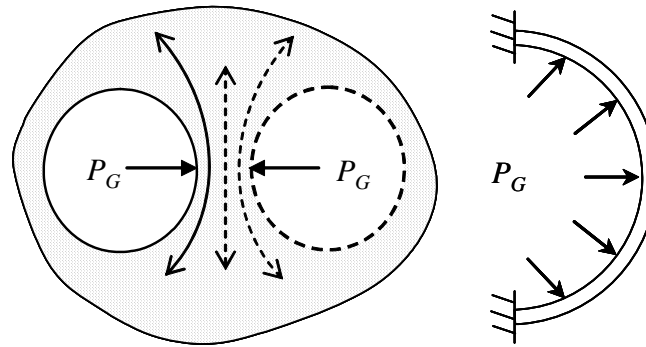


Figure 3. 2 – Membrane equivalent geometry

In accordance with that, referring to fig.4 and neglecting inertial terms, continuity equation and r -component and z -component of motion equations in cylindrical coordinates become:

$$\frac{1}{r} \frac{\partial (rv_r)}{\partial r} + \frac{dv_z}{dz} = 0 \quad (3.2)$$

$$-\frac{dp}{dr} - \left(\frac{1}{r} \frac{\partial (r\tau_{rr})}{\partial r} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z} \right) = 0 \quad (3.3)$$

$$-\left(\frac{1}{r} \frac{\partial (r\tau_{rz})}{\partial r} + \frac{\partial \tau_{zz}}{\partial z} \right) = 0 \quad (3.4)$$

where for geometrical reasons it is assumed $v_r = v_r(r, z)$, $v_z = v_z(z)$ and $p = p(r)$.

According to the fact that a cereal paste subjected to a stationary shear flow often may be fitted by a power-law equation, the following constitutive equation was used:

$$\tau_{ij} = -m \left(\frac{\dot{\gamma}_{rr}^2 + \dot{\gamma}_{\theta\theta}^2 + \dot{\gamma}_{zz}^2 + 2\dot{\gamma}_{rz}^2}{2} \right)^{(n-1)/2} \cdot \dot{\gamma}_{ij} \quad (3.5)$$

If the quasi-stationary solution is adopted, the previous r -component of motion equation becomes:

$$-\frac{dp}{dr} - \frac{\partial \tau_{rz}}{\partial z} = 0 \quad (3.6)$$

while all the terms in eq.3.3 vanish. If it is also assumed that the decrease in viscosity results predominantly from velocity gradients associated with shear and not with elongation, the previous constitutive equation becomes

$$\tau_{ij} = -m (\dot{\gamma}_{rz})^{n-1} \cdot \dot{\gamma}_{ij} \quad (3.7)$$

where obviously the only τ_{rz} term is needed. In such a way it is possible to apply the lubrication theory and the following results are obtained:

$$v_r = \frac{h^{1+(1/n)}}{1+(1/n)} \left(-\frac{1}{mr^n} \frac{dp}{dr} \right)^{1/n} \left[1 - \left(\frac{z}{h} \right)^{1+(1/n)} \right] \cdot r \quad (3.8)$$

$$p - p_a = \frac{-\dot{h}^n}{h^{2n+1}} \left(\frac{2n+1}{2n} \right)^n \cdot \frac{m R^{n+1}}{n+1} \left[1 - \left(\frac{r}{R} \right)^{n+1} \right] \quad (3.9)$$

$$F = \frac{-\dot{h}^n}{h^{2n+1}} \left(\frac{2n+1}{2n} \right)^n \cdot \frac{\pi m R^{n+3}}{n+3} \quad (3.10)$$

Where R_d is the radius of the equivalent plate having the same surface as the bubble, therefore R_d may be calculate at any time as follow:

$$R_d = 2 \cdot R \quad (3.11)$$

Eq.3.10 is known as Scott's equation. Since h is half of the gap between two plates, in the dough this value was measured as the distance between the considered bubble and a stress-free surface.

To make this result representative of the situation under consideration, the force F must take into account the effect of distribution radius, pressure and amount of adjacent bubbles.

$$F = F * \cdot \Psi^{2/3} \quad (3.12)$$

A random spatial distribution of bubbles was assumed, and an interaction parameter Ψ , depending on void fraction, was introduced to take into account the interaction increasing when the bubble expands. This interaction parameter may be reasonably assumed as the ratio between the current bubble volume

and its initial value, taking into account the physical evidence that the effect of squeeze flow becomes relevant only when bubbles expand and their volume increases:

$$\Psi = \frac{R^3(t)}{R^3(t=0)} \quad (3.13)$$

The 2/3 exponent was inserted to adjust the solution for the planar flow hypothesis by means of a surface-volume ratio. The effective force F^* has to take into account the amount of interacting bubbles, according to the evidence that the more they are, the lower will be the force. Therefore F^* was defined as:

$$F^* = 4\pi R^2 \cdot P_G \cdot \frac{I}{N_{int}} \quad (3.14)$$

where N_{int} is the number of interacting bubbles. By introducing Eq.s3.12-3.14 into Eq.3.10, owing to known experimental values of m and n , the value of $h(t)$ is obtained at any time step by integration using a Runge-Kutta method.

3.3 Elastic energy and “coalescence ability”

The mass squeezed out of the gap by the bubble internal pressure is not distributed symmetrically thus the mechanical resistance of different areas are different too. This means that rupture may occur in the spatial region where the thickness has the smallest value. To model this phenomenon, it is suggested that the aside accumulated mass would act as fixed supports (Figure 3.2), thus the kinematics corresponds to a shell loaded with a constant P_G . The thickness at the pole of the shell corresponds to the value of $h(t)$ computed by the squeezing flow and, according to its low thickness, the mechanical analysis of membranes applies [Williams, 1973]. Since the deformation of the material separating the bubbles may be locally approximated as a biaxial extension of a shell, the thickness $h(t)$ was used as a measure of deformation with respect to the initial thickness:

$$\lambda = \frac{h(t)}{h_0} \quad (3.15)$$

The thickness $h(t)$ is easily calculated at any time from the mass balance if the amount of paste surrounding the bubble is known as initial condition.

Even though the shell thickness does not remain uniform during the deformation, because the main interest is to determine when the bubble breaks, the evaluation of the elastic energy may be limited to the apex of the membrane where a pure biaxial extension is realised and where breakage occurs.

In this geometrical configuration [Williams, 1973], the elastic energy is obtained by multiplying the stress tensor by the deformation tensor. since as stated above the analysis is limited only to the apex of the shell, the first deformation gradient tensor may be expressed in terms of principal components:

$$\underline{\underline{F}} = \begin{pmatrix} \lambda_I & 0 & 0 \\ 0 & \lambda_{II} & 0 \\ 0 & 0 & \lambda_{III} \end{pmatrix} \quad (3.16)$$

and also the stress tensor is expressed in term of principal components:

$$\underline{\underline{\sigma}} = \begin{pmatrix} \sigma_I & 0 & 0 \\ 0 & \sigma_{II} & 0 \\ 0 & 0 & \sigma_{III} \end{pmatrix} \quad (3.17)$$

With reference to principal components a simple expression for the strain energy is obtained by integrating the expression [Williams, 1973]:

$$dW = \sigma_I \lambda_{II} \lambda_{III} d\lambda_I + \sigma_{II} \lambda_I \lambda_{III} d\lambda_{II} + \sigma_{III} \lambda_I \lambda_{II} d\lambda_{III} \quad (3.18)$$

By assuming incompressibility, it holds:

$$\lambda_I \lambda_{II} \lambda_{III} = 1 \quad (3.19)$$

and because the assumed kinematics valid in the shell apex is a pure biaxial extension the following expression applies:

$$\begin{cases} \lambda_I = \lambda \\ \lambda_{II} = \lambda_{III} = \frac{1}{\sqrt{\lambda}} \end{cases} \quad (3.20)$$

Thus the first deformation gradient tensor assumes the following form:

$$\underline{\underline{F}} = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & 1/\sqrt{\lambda} & 0 \\ 0 & 0 & 1/\sqrt{\lambda} \end{pmatrix} \quad (3.21)$$

and the incremental work becomes:

$$dW = \sigma_I \frac{1}{\lambda} d\lambda + \sigma_{II} \frac{\lambda}{\sqrt{\lambda}} d \frac{1}{\sqrt{\lambda}} + \sigma_{III} \frac{\lambda}{\sqrt{\lambda}} d \frac{1}{\sqrt{\lambda}} \quad (3.22)$$

According to biaxial extension $\sigma_{II} = \sigma_{III}$, the following expression is finally found:

$$dW = (\sigma_I - \sigma_{II}) \frac{d\lambda}{\lambda} \quad (3.23)$$

To integrate the equation above it is necessary to know the transient values of the deformation through the value of $h(t)$ obtained by the squeezing flow:

$$W = \int_0^W dW = \int_0^{\ln \lambda} (\sigma_I - \sigma_{II}) d \ln \lambda \quad (3.24)$$

It is worth noticing that the integral at the right side is implicitly dependent on time, because $\lambda = \lambda(t)$. To complete the computation a constitutive equation is needed for the stress tensor the linking stress component to the deformation. This must be done relating the stress tensor to a proper deformation tensor, as Cauchy tensor, defined in terms of principal components as:

$$\underline{\underline{C}} = \underline{\underline{F}}^T \cdot \underline{\underline{F}} = \begin{pmatrix} \lambda_I^2 & 0 & 0 \\ 0 & \lambda_{II}^2 & 0 \\ 0 & 0 & \lambda_{III}^2 \end{pmatrix} \quad (3.25)$$

Therefore, in the case of a biaxial deformation, the Cauchy strain tensor for an incompressible material with reference to principal axis becomes:

$$\underline{\underline{C}}(t) = \begin{pmatrix} \lambda^2 & 0 & 0 \\ 0 & 1/\lambda & 0 \\ 0 & 0 & 1/\lambda \end{pmatrix} \quad (3.26)$$

The constitutive link for a cereal paste considered as viscoelastic solid like reads:

$$\underline{\underline{\sigma}}(t') = -p\underline{\underline{I}} + \int_0^{t'} \mu(t' - t'') \cdot \underline{\underline{C}}(t'') dt'' \quad (3.27)$$

where $\mu(t' - t'')$ is the memory function of the considered material. The time dependency was concentrated into the memory function, which in turn may be put in terms of derivative of an elastic time dependent modulus [Ferry, 1976] as:

$$\mu(t) = -\frac{dG(t)}{dt} \quad (3.28)$$

Thus by applying Eq.s 3.22-3.23, it is possible to evaluate the stress component difference of interest at any instant t' as a sum of the contribution weighted by a time-dependent modulus:

$$\sigma_I - \sigma_{II} = -\int_0^{t'} \frac{dG(t' - t'')}{dt''} \left(\lambda^2 - \frac{1}{\lambda} \right) dt'' \quad (3.29)$$

By inserting this result into eq. 3.22, the transient elastic strain energy at any time t is found by integration as a function of deformation. It is worth noting that the relaxation was taken into account

with the time dependence of the elastic modulus $G(t)$ at any time, for which the weak gel constitutive equation was assumed to hold [Gabriele et al., 2001].

As coalescence criterion a maximum deformation energy may be identified for the material under biaxial extension flow conditions (see paragraph below) and when the calculated one exceeds that value the bubble may potentially coalesce. By using this approach, a bubble “coalescence-ability” criterion was identified with bubble breakage instead of a critical shell thickness. In fact, this choice looks more physically acceptable and therefore it was assumed that breakage occurs at the maximum value of elastic strain energy W , corresponding to the deformation work at rupture. This proved to be realistic enough, because rupture happens either owing to low thickness or when high stresses are exhibited, in addition rupture work is a quantity that may be measured by means of an inflation technique, obtaining reliable experimental data.

3.4 Rupture work calculation and coalescence sensitivity

The elastic energy at rupture point was measured using a patented prototype performing bi-axial extension tests [de Cindio et al, 2003]. Flat dough samples were inflated at constant air flow rate up to the rupture point (fig. 3.3) and data of bubble height with time were collected using a laser measurer (Baumer, Germany). Starting from the already developed model for polymeric materials [Schmidt and Carley, 1975], the kinematic analysis of the flat membrane can be developed if a circular sample locked at the borders is inflated and a spheroid geometry may be assumed. According to Hart-Smith and Crisp (1967) the geometry of the expansion may be simplified by assuming that the shape of the deformed sample is always a perfect sphere. In this case, referring to fig.8, principal deformation included in Finger’s tensor are:

$$\lambda_{II} = \lambda_{III} = \frac{\cos^2\left(\frac{\mathcal{G}}{2}\right)}{\cos^2\left(\frac{\mathcal{G}_{\max}}{2}\right)} \quad (3.30)$$

$$\lambda_I = \frac{1}{\lambda_{II} \cdot \lambda_{III}}$$

The maximum local stress is always realised at the pole of the sphere where the deformation becomes:

$$\lambda_{II} = \lambda_{III} = \frac{1}{\cos^2\left(\frac{\mathcal{G}_{\max}}{2}\right)} \quad (3.31)$$

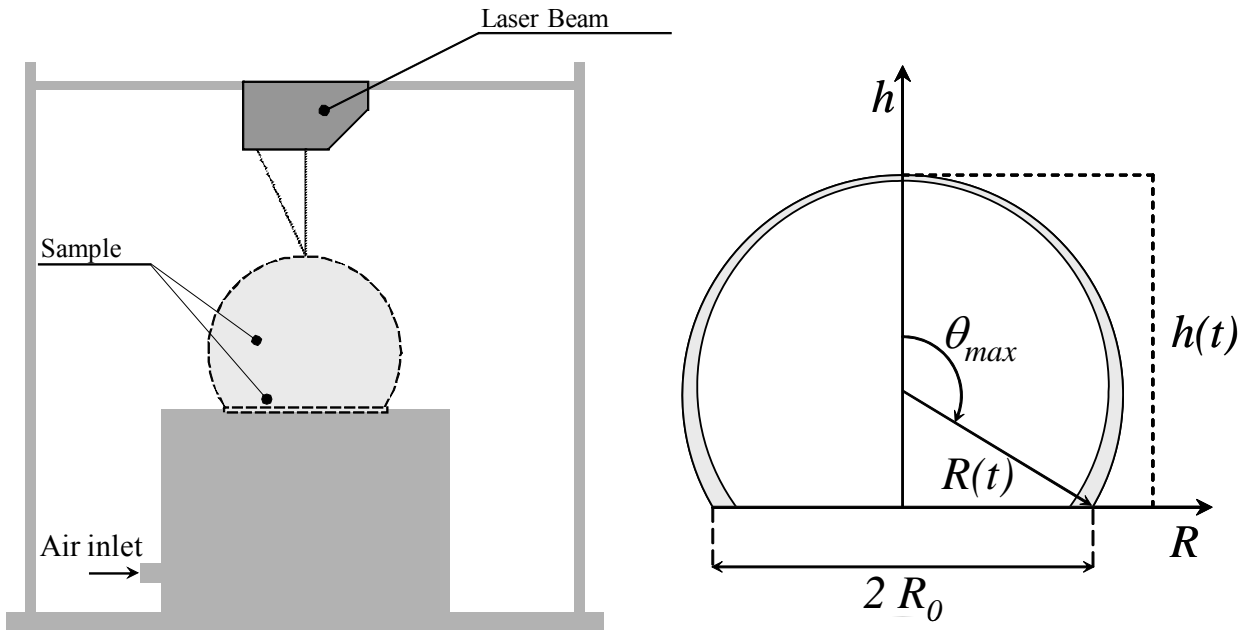


Figure 3.3 – Biaxial expansion schematization

In addition, because of the small curvature in the pole region, the extension may be locally approximated to a planar biaxial extension and stress computation may be done consequently as reported in the previous paragraph. If the bubble height evolution during experiment is measured up to the bubble bursting, according to the geometric relationship of fig. 3.3, the angle θ_{max} may be obtained and therefore deformation can be calculated during experiment time.

Following the hypothesis formulated, the application of eq.s 3.17-3.23 allows the calculation up to the rupture point of the elastic deformation energy during time W_{rup} .

The coalescence criterion was assumed comparing deformation work W during expansion calculated in the layer of dough surrounding the bubble and the maximum energy at rupture derived from experimental test. When deformation work exceeds the measured rupture value the bubble may coalesce with the closest ones and the time at which it holds is called coalescence time t_c .

Deformation depends on the thermal history, in fact, different baking profiles cause different coalescence times. To show model sensitivity to the temperature profile, three different baking profiles Short, Normal and Long, are reported in the figs. 3.4 and 3.5, respectively with temperature rising quickly, slowly and very slowly and with bubble growth evolution up to coalescence.

The model is sensitive also to the different initial conditions, like the quantity of raising agents (figs. 3.6-3.7). This behaviour is in agreement with the physical evidence, because changing the rising agent (R.A.) quantity changes the pressure inside the bubbles, then the load on the bubble membrane causes

the thinning of the material distribution around the bubble. Specifically, lowering the R.A. increases the coalescence time because the pressure inside the bubble decreases, owing to the lesser quantity of reaction products (fig. 3.6).

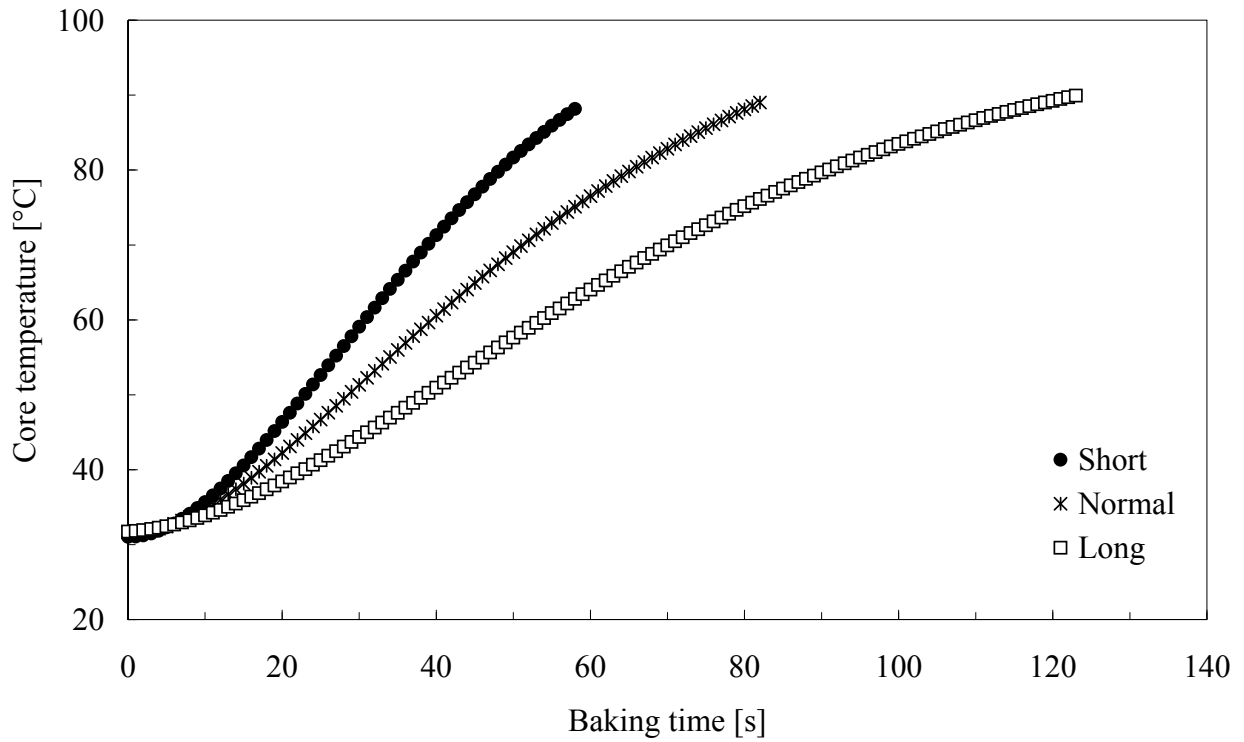


Figure 3. 4 – Temperature profile at Biscuit Core in three different cases.

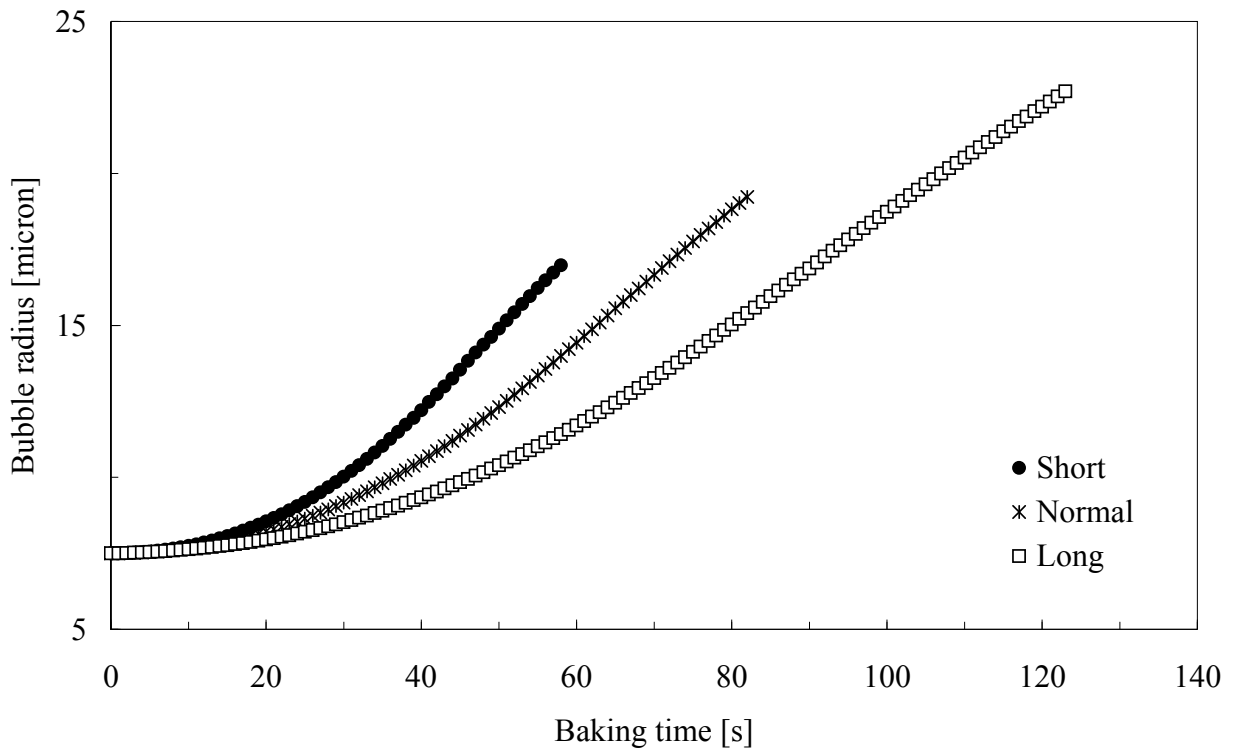


Figure 3. 5 – Bubble radius profile for three different temperature profiles.

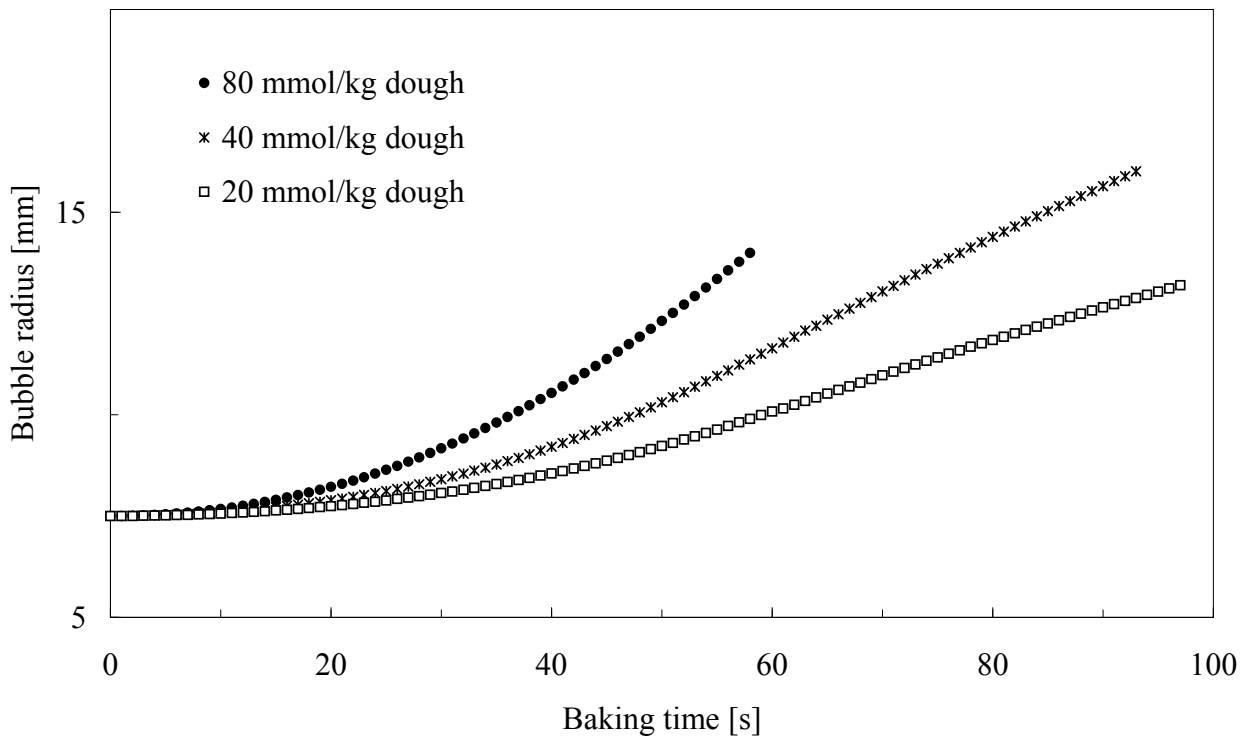


Figure 3. 6 - Bubble radius profile for three different raising agent quantities.

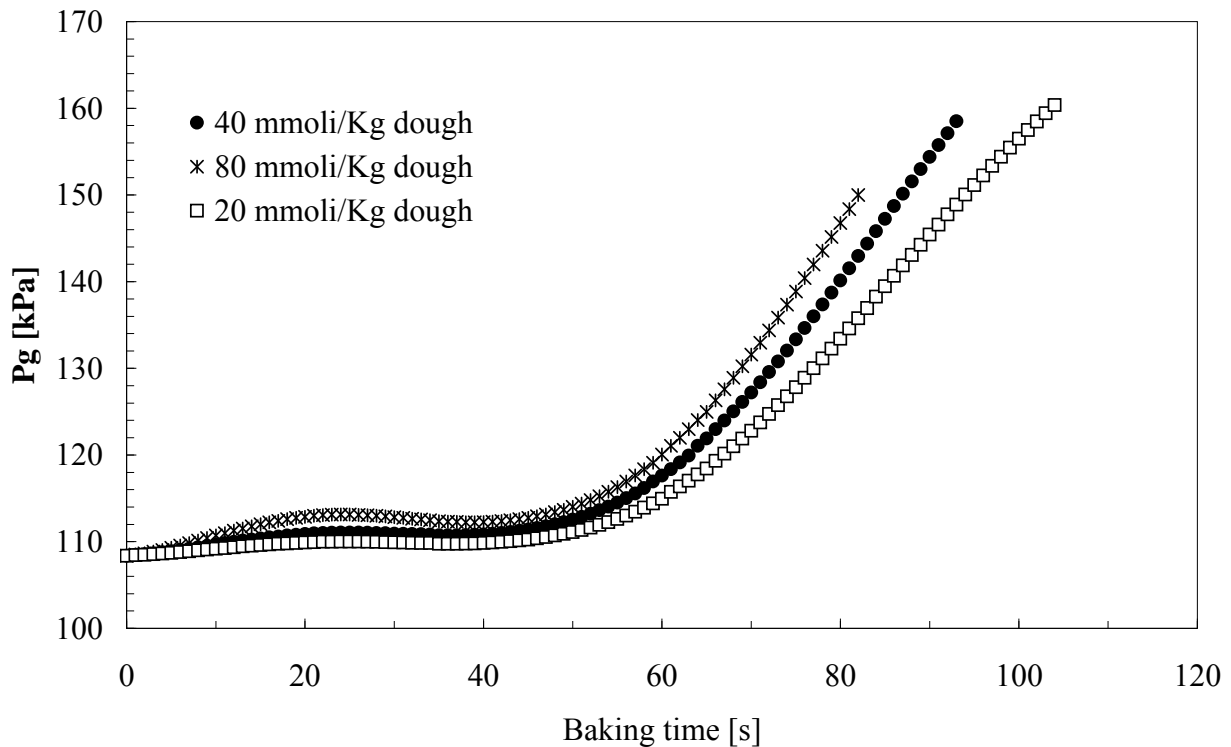


Figure 3. 7 - Pressure profile inside the bubble for three different raising agent quantities.

3.5 Conclusions

In this chapter a realistic approach was proposed, being based on the mechanical theory of shell and membranes subjected to an external load, taking into account the dimension, the shape and distribution of the bubbles. It was assumed that when two contiguous bubbles interact with each other, the material contained between them, is subjected to a variable force that tends to squeeze it out of the gap. As a consequence, the material distribution around the bubble is not a uniform layer of constant thickness.

The thickness change of the paste surrounding the bubble during its expansion, was studied as an equivalent squeezing flow. This effect starts to be relevant only when the radius becomes sufficiently large so that the infinite paste hypothesis does not apply any longer. During expansion the squeezed material accumulates alongside the bubble and in a restricted zone, characterized by low thickness and high local stresses are generated. In this zone rupture may occur. Thus as coalescence criterion the condition was assumed that the deformation work exceeds a measured rupture work W_{rup} . In the case of a visco-elastic solid-like behaviour, the deformation work corresponds reasonably to the strain elastic

energy. The time at which holds $W=W_{rup}$ is called coalescence time t_c and is considered a kind of switch from closed to open cell.

An important conclusion from the presented results is also that the bubble growth model is very sensitive to the initial and baking condition that then controls bubble expansion and coalescence.

It was shown too that the radius increase is determined by the mass of gas in the bubble that thus determines the mechanical force, then the pressure inside the bubble, acting on the bubble membrane and controlling the final texture of the biscuit, causes the open structure of some bakery products.

3.6 References

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