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Description of leavening of bread dough with mathematical modelling

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Abstract

Dough fermentation is a process very similar to the expansion of a pseudoplastic foam, in which initial germs (yeast) are quasi-homogeneously distributed. The present model considers the expansion as a chemical reaction, which producing gas leads to the growth and the coalescence of bubbles, which form in the pseudoplastic paste, thus conferring to the loaf its final volume. The fermentation kinetic was investigated by monitoring the variation of the dough volume vs time by means of image analysis. The leavening process can be divided into three stages: the lag stage, a positive acceleration stage and a negative acceleration stage. Aim of the model developed in this study was described the variation of dough volume y as a function of time t, i.e. $y = f(t)$. A modified Gompertz model was chosen as the best descriptive model of the leavening process. Quite good agreement was observed between experimental data and model parameters.

Keywords: Fermentation kinetics; Yeast growth curve; Image analysis; Non linear regression models; Bread dough

1. Introduction

Dough is a multiphase and multicomponent system mainly composed of proteins, lipids, carbohydrates, water and air. The dough ingredients, as well as the processing conditions, determine the macroscopic structure of baked products which, in turn, is responsible for their appearance, texture, taste and stability. To build up this structure, the ingredients are mixed and kneaded, the dough leavened and baked. Great structural changes take place during the bread making operations (Autio & Laurikainen, 1997). During mixing, the ingredients are transformated into a viscoelastic material as a consequence of the formation of a three-dimensional protein network, in which are uniformly dispersed starch granules. During kneading, air bubbles are included in the dough and they are assumed to be the initial nuclei of the gas bubble, which will develop during the subsequent stages. During leavening, the metabolism of yeasts chemically transforms assimilable carbohydrates into carbon dioxide and ethyl alcohol as the principal end products. As a relevant amount of alcohol forms, which is water-miscible, it influences the colloidal nature of the wheat proteins and alters the interfacial tension within the dough. In addition, carbon dioxide, which partly dissolves in the aqueous phase of the dough, migrates toward the initial nuclei of the air bubbles formed during kneading causing their growth. The growth of gas cells depends on the cell size and the dough composition. Certain ingredients are known to exert a stabilizing influence and retard coalescence (Gan, Ellis, & Schofield, 1995). It is important to distinguish between gas production and gas retention in fermented doughs (Cauvain, 2001). The first factor is controlled by the yeast performance and the last one depends on the bubble characteristics. The desiderable loaf volume of yeast-fermented products is achieved only if the dough provides a favorable environment for yeast growth and gas generation and, at the same time, possesses a gluten matrix capable of maximum gas retention (Sahlström, Park, & Shelton,

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Nomenclature

e	constant (2.718281828)	b	the slope of the curve
R^2	correlation coefficient	c	the point of inflection of the curve
V	volume (cm^3)	t	time (h)
A	lamina surface (cm)	t_{lag}	lag time (h)
r_g	the distance of the center of mass of the lamina from the axis (cm)	t_{∞}	exhaustion stage (h)
$w(t)$	the growth function	*Greek symbols*	
a	the value the growth function assumes as t approaches infinity	α	asymptotic phase
		μ	maximum specific growth rate (h^{-1})

2004). The latter attribute is most conveniently determined by measuring the volume increase of fermenting dough, whereas gas production can be estimated by any of the several available procedures such as the oven rise recorder (Marek & Bushuk, 1967), alveograph method (Approved Method 54-40, AACC, 2000) and pressure meter methods (Bailey, 1939; Malloch, 1939). Yeast-fermented doughs are difficult to study, because they are very complex, and the dimensions and physical properties of the dough change with time (Bloksma, 1990; Szczesniak, 1988). Furthermore invasive, continuous measurements on dough are generally not adequate as they may provoke dough collapse. The choice of the most appropriate analytical procedure is thus crucial for the full comprehension of the underlying mechanisms of leavening. From a structural point of view bread dough is an elastic foam and leavening is a process very similar to the expansion of a pseudoplastic foam, in which initial germs (yeast) are quasi-homogeneously distributed into the dough volume. Little is known about the physical processes governing foam formation. Some of the main issues are the lack of robust test methods to quantify their behavior, concerns about the reliability of the data, variability in the material properties and the need to relate structure to behavior (Lim & Barigou, 2004). There is a real need for robust quantitative methods for characterizing the structure of these materials, so that intrinsic relationships between structure and properties can be developed. Image analysis is potentially a non-intrusive, objective method for measurement and comparison of the structure of food foams that will allow quality control and process optimization (Cilliers & Sadr-kazemi, 1999). The most apparent physical change related to the development of fermentation in the dough is the increase in its volume (Pyler, 1988a). Although, an extensive the literature exists dealing with the control of the leavening process (De Cindio & Correra, 1995; Dixon & Kell, 1989; Pinter, 1988) and mathematical models and equations for expression of microbial growth in food (Fan, Yingying, Qian, & Gu, 2004; Fujikawa, Kai, & Morozumi, 2004; Vadasz, Vadasz, Abashar, & Gupthar, 2001), the description of such a process will always be a rough simplification of reality, since detailed picture of the various biological and physical phenomena responsible for bubbles growth during the leavening process are still difficult to model. Fermentation involves biochemical, rheological and thermodynamic phenomena, which are nonlinear distributed-parameter processes. Growth curves are generally of sigmoid shape with a first stage in which the specific growth rate starting from zero slowly increases for a period of time known as lag time. After this period, a fast increasing growth rate phase follows in which a maximum rate value is achieved at the inflection point. Finally, a plateau is reached in a final phase in which the rate decreases and eventually became zero. These kind of sigmoid curves can be fitted by different mathematical functions, such as monomolecular, von Bertalanffy, Gompertz and logistic (McCallum & Dixon, 1990). A major development in the analysis of growth curves has been the generalization of these sigmoid growths to a single function, i.e. the Gompertz function (Zwietering, Jongenburger, Rombouts, & van't Riet, 1990). Since that, the Gompertz $y = lnX(t)$ model has become the standard growth model in predictive microbiology for modelling growth of pathogens and spoilage bacteria in food (Whiting & Buchanan, 1994). To our knowledge, there was no report on modelling fermentation process of bread dough using Gompertz equation.

The purpose of this investigation was to present an analytical approach based on image analysis to describe by means of available mathematical model the structural development of dough during leavening.

2. Materials and methods

2.1. Sample preparation and Image analyses

All doughs were prepared in a Brabender farinograph (O.H. Duisburg, Germany) using commercial soft wheat flour (43.75 g, Barilla®: 7.5% proteins, 0.1% fat, 13.5% moisture content), deionised water (25 ml), salt (1.25 g), sugar (0.5 g) and yeast (Mastro Fornaio, Paneangeli®) at different quantity: 0.6–1.1 –1.7 –2.3 –3.4% of flour weight (w/w). Mixing time and temperature were kept constant and equal to 3 min and 25 °C, respectively.

After mixing, 45 g of dough were taken and inserted into a rubber mold (interior diameter: 45 mm, height: 30 mm). Sample was incubated inside a laboratory leavening chamber at 36 ± 1 °C, 75% U.R. for the time required to maxi-

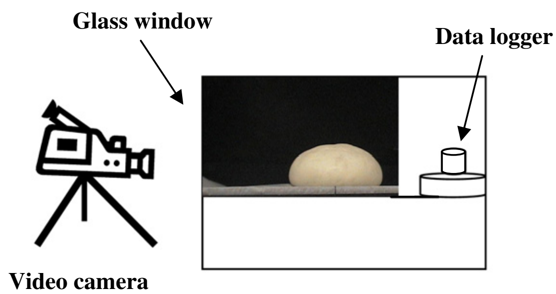

Fig. 1. Experimental image analysis set up.

mum development of dough (previously investigated). The experimental set up is shown in Fig. 1. The following parameters were continuously and automatically recorded:

- internal humidity and temperature by means of data logger (Logger Escort mod. 10D8, Gamma Instrument s.r.l., Naples, Italy)
- volume expansion by means of a MV450 camera (Canon INC, Japan) mounted on a photographic bench.

By assuming axial symmetry, the loaf can be considered as of a solid of revolution generated by the revolution of a lamina around the symmetry axis, accordingly its volume V was calculated as

$$V = 2\pi A r_g \tag{1}$$

where A is the lamina surface and r_g the distance of the center of mass of the lamina from the axis.

The area and centre of mass were determined by a computer assisted image analyser (Jandel Sigma Scan® Pro Version 2.0, Jandel Corporation, 1995). Each average value represents the mean of 3–7 independent measurements.

2.2. Fitting of the data

CurveExpert 1.3 (Hyams, 1995) was used to fit the data from each leavening experiment to a modified Gompertz model. The model parameters were determined using a nonlinear regression procedure and were obtained by minimizing the sum of squares of the prediction errors (SSE).

3. Results and discussion

3.1. Leavening curves

The dough once partitioned and shaped in loaves were placed into the leavening chamber where they could expand in every directions without constrains. As described by Tronsmo, Faergestad, Schofield, and Magnus (2003), the optimal proving time would be the time giving the highest possible volume with an acceptable form ratio. Fig. 2 shows the evolution of dough volume during leavening in terms of volume expansion ratio $\left(\frac{V_{(t)}-V_0}{V_0}\right)$. The dough expansion is due to the generation of carbon dioxide (CO_2) in the dough and its migration toward the initial nuclei of air bubbles formed during kneading which result in a foam-like structure (Autio & Laurikainen, 1997). The CO_2 production rate is strictly related to the metabolism of yeast (enzyme), with the consumption of simple sugars according to the irreversible reaction:

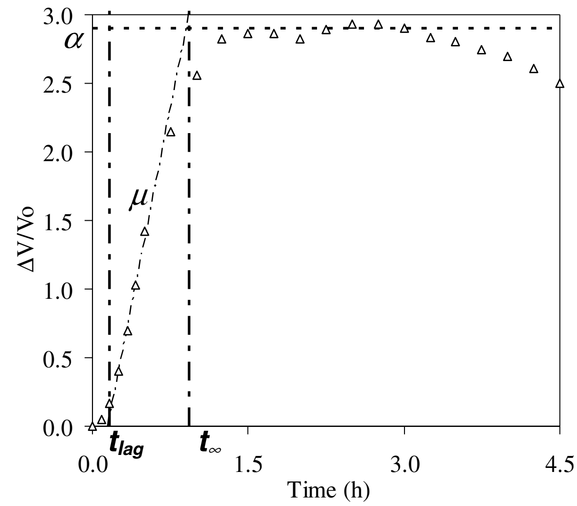

Fig. 2. Volume expansion on time of doughs during leavening with model parameters.

$$C_6H_{12}O_6 + \text{yeast} \Rightarrow 2CH_3CH_2OH + 2CO_2 + \text{yeast} \tag{2}$$

It is therefore not surprising that the shape of the curve which describes the dough volume expansion is quite similar to the typical self-limited growth curve of yeasts, that is characterized by three distinct phases (Buchanan, Whiting, & Damert, 1997; Poschet, Vereecken, Geeraerd, Nicolai, & Van Impe, 2005; Weiss, Delproposto, & Giroux, 2004): (1) lag; (2) growth; (3) stationary. During lag phase the volume variation relative to the onset of yeast activity results from both the time taken for the yeast to start fermenting the sugars and the time taken for the CO_2 to diffuse through the dough matrix to the air nuclei (Cooper & Reed, 1968). In the subsequent phase, the dough expands exponentially reaching its maximum volume value, next a balance between the gas produced by reaction 2 and the gas leaving the dough establishes and the volume expansion ratio remains constant (the subsequent phase during, which the volume declines is not considered in this study). Such a behavior is accurately described by a sigmoid shaped curve, which increases with a growth rate monotonically reaching an inflection point and then decreases to zero while the curve approaches asymptotically a constant value.

3.2. Reparameterization of Gompertz growth curves

Sigmoidal models differentiate for the number of parameters used in the equation. The most common ones are the three-parameter growth functions (logistic, Gompertz and Von Bertalanffy) and the four-parameters (Richards, Weibull and Morgan–Mercer–Flodin) (Maruyama, Vinyard, Akbar, Shafer, & Turk, 2001). The Gompertz function is a nonlinear sigmoid growth function and, historically, it was developed by Gompertz (1825) for the calculation of mortality rates of microorganisms. It assumes the form:

$$w(t) = a\exp(-\exp(b - ct)) \tag{3}$$

where $w(t)$ is the growth function, a the value it assumes as t approaches infinity and b and c are parameters, which account for the slope, and the point of inflection of the curve, respectively.

The model proposed in this work derives from the model originally used for describing the bacterial growth in pH-controlled batch cultures (Schepers, Thibault, & Lacroix, 2000). Its choice derive from a preliminary comparison with other sigmoid models (Romano, 2004) which demonstrated that the Gompertz model was the best compromise between quality of fit and model complexity.

In addition, the modified Gompertz equation offers the possibility to be parameterized in terms of quantities easily related to the leavening process. Eq. (1) can, in fact, be written as

$$y(t) = \alpha\exp\left(-\exp\left(\frac{\mu e}{\alpha}(t_{lag} - t) + 1\right)\right) \tag{4}$$

where α represents the maximum relative volume expansion ratio of the loaf; μ the maximum specific volume growth rate, t_{lag} the time lag of the leavening process and e the Neper number. According to the model each fermentation curve exhibits three steps: the induction, the growth and the stationary growth. However this model do not consider the death phase.

Fig. 3 shows the capability of the model to predict experimental data in experiments, where different yeast contents was used. The same figure shows the residuals. The model appears to be simple, robust and accurate (correlation coefficient greater than 0.99). Table 1 summarizes α, μ, t_{lag} and the exhaustion stage t_∞, as obtained from the fitting of the data sets. They provide an idea about speed and intensity of the growth process. All model parameters, with except the parameter α, which accounts for the maximum volume expansion, depend on the yeast concentration. It is interesting to note that the observed behaviour is congruent with the influence that yeast content exerts on physical and biological processes taking place during dough leavening (Pyler, 1988b). As far as the volume expansion concerns, it depends on the amount of gas produced by the biological activity of yeast and the gas trapped into dough structure capable to enhance the bubble growth without collapsing. Fig. 4 shows the dependence of α from dough yeast content. The final volume expansion range between 2 (0.6% yeast) and 3 times the initial dough volume. By applying analysis of variance (ANOVA) within 95% confidence interval, to the experimental data one find that the concentration of the yeast does not influence significantly the value of α for doughs with yeast content higher than 1.1% (w/w). This confirm the practical baker's experience that exists a limiting value of yeast content equal to 0.8–1% of the flour weight at 37 °C for a standard 1-pound loaf (Vieira, 1999) above which final volume expansion is independent of yeast content. From the mathematical point of view this result allows one, for practical application, to set the parameter α as a constant equal to 2.9, considering as parameters of Eq. (4) only μ and t_{lag}.

With increasing the yeast content the gas production rate will increase and the model parameters, which are related to gas formation process (μ, t_{lag}) vary accordingly showing a monotonically dependence on yeast concentration. As one would expect, because of the kinetic nature of the process (Whitworth & Alava, 1999), the volume growth rate changes with time and there is a strong relationship between the yeast concentration and the parame-

Table 1
Values of estimated parameters for doughs with different yeast content

Yeast (%)	α	μ (h^{-1})	t_{lag} (h)	t_∞ (h)
0.6	2.44	1.14	0.70	2.84
1.1	2.97	2.36	0.62	1.87
1.7	2.81	2.65	0.27	1.33
2.3	2.78	4.29	0.28	0.92
3.4	2.93	4.27	0.14	0.82

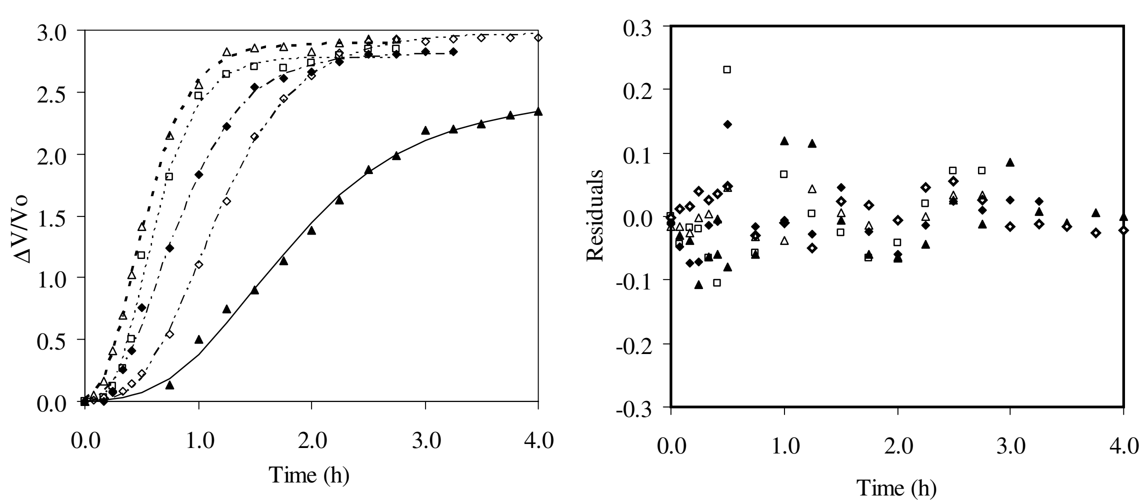

Fig. 3. Resulting plots for model of leavening process of doughs with ▲0.6%; ◇1.1%; ◆1.7%; □ 2.3%; Δ3.4% yeast content.

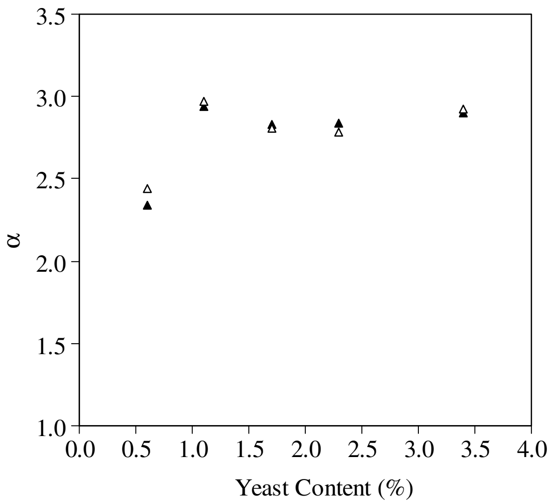

Fig. 4. Experimental (▲) and numerical (Δ) results of α value with yeast.

ter μ (Fig. 5). By contrast the time lag, t_{lag}, decreases with the yeast content (Fig. 6). Once α, μ and t_{lag} are known, it is possible to estimate the time t_∞, at which the leavening process is basically completed and dough is ready to be baked. The influence of yeast content on t_∞ is shown in Fig. 7. A strong quadratic correlation is observed between yeast content and t_∞, with increasing the yeast content, t_∞ decreases becoming almost constant at above yeast content higher than 2%. In conclusion, according to our experience this model can be chosen to depict the leavening of bread dough, since it contains just three parameters, fits very well to the observations and also seems appropriate to derive parameters that have technological meaning instead of simply fitting growth curves empirically.

In order to check the predictive features of the curves in Figs. 6 and 7, doughs were prepared with 2.9% yeast concentration. Fig. 8 shows the growth curve with μ and t_{lag} obtained through the regression curves in Figs. 6 and 7 (predicted growth curve). The results showed that the predicted values are in good agreement with the experimental ones (correlation coefficient greater than 0.99).

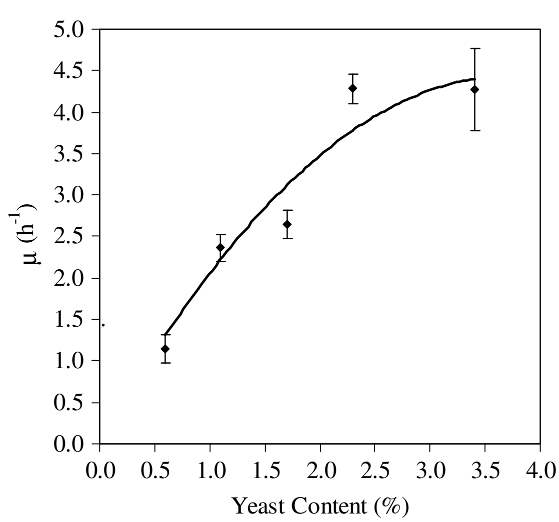

Fig. 5. Regression between yeast content and μ.

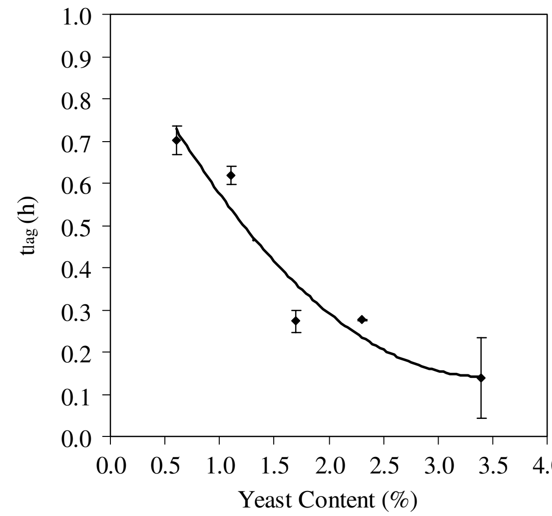

Fig. 6. Regression between yeast content and t_{lag}.

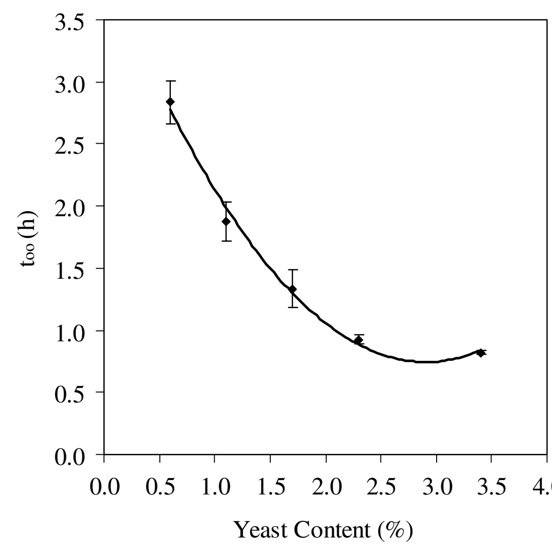

Fig. 7. Regression between yeast content and t_∞.

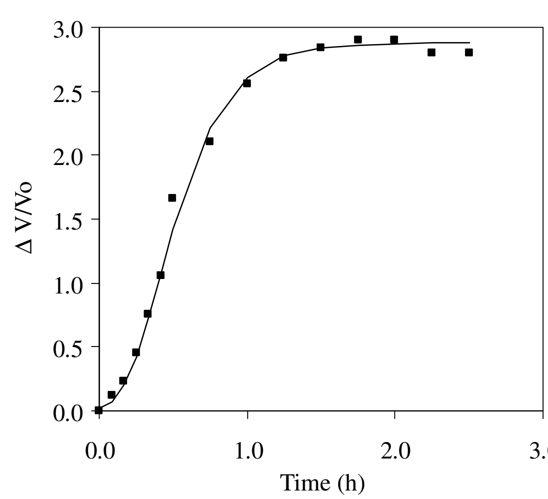

Fig. 8. Predicted growth curve plot for doughs with 2.9% yeast content.

4. Conclusions

Image analysis results to be an effective non-destructive technique for measuring dough volume expansion. Amount and quality of digital information enable an accurate quantitative analysis of the dough during leavening. As the loaf volume is often considered the key quality tests against, which other tests are evaluated, this is an important result.

The mathematical model selected and validated in this work appears very suitable as descriptive of the fermentation kinetic of wheat flour doughs. It is more appropriate than other models reported in the literature, because it is based on a more realistic phenomenological hypothesis. Meaningful parameters such as maximum specific growth rate (μ), lag time (t_{lag}), the maximum relative volume expansion ratio of loaf (α) were estimated from the fitting curves. Stronger relationships were found between the yeast content and model parameters. Moreover their behaviour with varying the yeast concentration is congruent with physicochemical and biological phenomena responsible for the development of the sponge structure of leavened dough. The main advantage of this model is that the whole process is described by means of only one experimental measure (volume). The present results underline that the choice of the most appropriate analytical procedure is vital in assessing the effect of composition on dough volume during leavening. The obtained quantitative information can be advantageously used to describe the relationships among physical structure and bread quality. In fact, this work represents also a starting point for studying the influence of formulation on bread dough structure by means of image analysis.

Work is in progress in order to explore the development of a more sophisticated version of the model that included appropriate terms for the variances, thus more accurately describing the transition between lag and exponential growth phases. The model will be of great interest to baking technologists, as it can be used to describe the different growth phases of leavening and to determine the boundaries of each phase, and thus enable a rational and intelligent exploitation of this complex process.

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