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ABSTRACT

This paper investigates the production of a yeast-free pizza by gas foaming and the use of rheology to guide the process design. The novel process relies on the use of a gaseous blowing agent and a pressure program to form and stabilize bubbles during baking, avoiding the use of yeast and the associated lengthy leavening stage. The evolution of the dough structure during baking has been studied by a rheological characterization at leavening and baking conditions. These experimental pieces of information have been used to evaluate the time available for blowing agent sorption under pressure during early baking stage, and to guide the pressure release during the final baking, to achieve an optimally foamed pizza.

I. INTRODUCTION

Bread and pizza are very common aerated baked products mainly composed of water, flour, yeast, and salt. They are widespread among consumers around the globe.[1] Taste, texture, and aroma, not to mention aesthetics, are the reasons why air is incorporated in such products.[2] They are leavened by the use of yeast, a bio-chemical blowing agent releasing carbon dioxide as a product of a fermentation reaction, during the so-called proofing step. Leavening is a rather slow process that may take up to several hours depending on yeast concentration and, among others, external conditions of temperature and relative humidity, bounding production logistic, and productivity.

The principles of breadmaking, meaning dough preparation, proofing, and baking, have been established for a thousand years. Before commercially prepared yeast became widely available, breadmaking was conducted by mixing wheat flour and water and then allowing wild airborne yeasts settle and ferment the dough. This process required several hours. To increase productivity, the proofing as well as the other breadmaking phases have been extensively studied[3–8] and new processes have been proposed in the past decades.

In 1958, Collins discovered that the amount of mechanical work applied to the dough during mixing had an important effect on bread quality.[9] Based on such idea, he designed the Chorleywood bread process (CBP). In this process, air bubbles (cells) were formed by trapping air in the dough during an intense high-speed mixing. The cell morphology resulted from an inclusion/fragmentation process coming from the mechanical mixing action. The CBP needed more yeast to give the same dough volume increase with respect to the traditional method. More water was also needed due to the better flour hydration that occurs during intensive mixing.[9]

Activated dough development (ADD), a method that uses a combination of chemical and mechanical processes, requiring a very short bulk fermentation time, was also developed in the USA during the early 1960s.[10] Similarly, the Dutch Green Dough Process was developed in the same period, not involving any fermentation.[11]

Nowadays, yeast-free products are receiving an increasing interest. Indeed, as reported by Altman and Chiaramonte, yeast intolerance is a growing health problem.[12] A recent study conducted by Vitavigor, a leader company of yeast-free products, shows that 9/10 consumers prefer to buy yeast-free goods even without intolerances or allergies. Customers consider yeast-free products of higher quality (33.7%), light (27.6%), healthy (24%), and digestible (7.3%) compared to the yeasted products. The remaining (7.3%) prefer to buy yeast-free goods just for curiosity.[13]

To cope with these needs, yeast-free bread making technologies based on physical foaming were proposed. Douglish introduced a bread making method in which water is CO_2-saturated under high pressure and then (still at high pressure) mixed with flour. At the end of the mixing time, the dough is forced out of a nozzle by the internal pressure, with a resulting expansion.[14] Hicsasmaz *et al.* developed a yeast-free technology by extruding a dough with supercritical (SC) carbon dioxide.[15] This process allowed the continuous production of ready-to-bake leavened dough where yeast is substituted by SC-CO_2 as the leavening agent, attaining dough densities comparable to the ones with yeast. Della Valle *et al.* suggested that two phases of the bread-making process are fundamental for the cellular structure of the final product: proofing (i.e., chemical foaming) and baking.[16] Volume and porosity of the dough increase mainly in the proofing step, where the cellular structure is created. In this phase, bubbles grow freely due to CO_2 produced by the yeast. After a critical time, bubbles begin to connect each other and may coalesce.[17] It has also been noted that the final CO_2 concentration in the dough does not depend on yeast concentration and nuclei number after the mixing phase, but only on the solubility of the gas.[18] During the baking phase, the cellular structure is only slightly modified, but it is set through two concurrent phenomena, the dough/crumb transition (dough stiffening between 60 °C and 70 °C, increasing the elastic modulus by more than one decade) and the formation of the crust.[19,20] Available technologies, both traditional and yeast-free, always rely on two separate steps (and two different pieces of equipment) for proofing (or, technologically, foaming) and baking.

Recently, one of us developed a new process for combining the gas-foaming process with the chemical blowing agent of thermosetting polyurethane (PU).[21] Despite this juxtaposition may seem bold and incongruous, both bread and polyurethane are achieved after two concurring processes, curing and foaming. The former induces a solidification of the initially fluid formulation, and the latter determines the formation of a gaseous phase responsible for foam formation. A good solid foam (optimized for thermal insulation, in the case of PU, tasty and sensorially agreeable, in the case of pizza) is attained if the two reactions are concurrent, with typical characteristic time O(10^2 s). The novel PU foaming process consists in using an autoclave and a pressurizing and releasing system allowing sorption of a physical blowing agent under pressure, followed by a rapid pressure drop at an intermediate pressure to form a myriad of bubbles and, eventually, by a slow pressure decrease to ambient pressure to chase the ultimate stages of the curing reaction. A fine tuning of density and foam morphology was attained by adapting the pressure history to the specific polyurethane/blowing agent curing kinetics, as measured by infrared spectroscopy.

Rheology has been proved fundamental to study dough and its evolution during processing, to characterize texture and to control process and quality.[22–24] Dough is known to be highly non-Newtonian, time-dependent, strain-dependent, and viscoelastic.[25] The investigation of dough rheology goes back a long way. The series of articles by Schofield *et al.*[26,27] established the solid-like behavior of dough, with an elastic modulus G' always higher than the viscous modulus G'' in the whole spectrum of frequency. Since then, there have been many rheological investigations[28] and various modeling attempts with mechanical analogue models.[29,30] Dough is a soft-solid, which may be regarded as a filled elastomeric network made by hard starch particles.[30] Yeasted dough behaves rheologically in a similar manner to unyeasted dough.[25,30] Rheological measurements can provide information regarding the dough behavior during the different steps of leavening,[18] proofing,[31,32] and baking.[33–35] For a fundamental rheological analysis on dough systems, the linear viscoelastic region is usually interrogated since a dynamic oscillatory test is nondestructive if performed at low stress/strain.[36–39] With the use of rheology it is also possible to figure out the effect of single and specific ingredients (e.g., flour, salt water, and yeast) on the mechanical properties of the final product.[3,23,40] Keentok *et al.*[41] studied the influence of four different commercial flours on the rheological performances of bread dough, finding that stronger flours, i.e., with higher content of gluten, produce weaker dough. Such a behavior is in agreement with other works on similar systems.[42] Wehrle *et al.*[43] highlighted the importance of salt in the dough formulation, reporting that elasticity increases at increasing levels of salt. Angioloni and Dalla Rosa[33] showed that adding salt can significantly change the viscoelastic properties of the final product. By increasing the mixing speed of dough with salt, G' increases due to a better solubilization of the salt in the dough. Masi *et al.*[44] considered a dough as a concentrated polymer solution. They showed that water plays a key role on dough formulation acting both as inert filler, causing the decrease in viscoelastic moduli proportionally to the moisture content, and as a lubricant, enhancing the relaxation phenomenon and, hence, decreasing the longest relaxation time.[44] As mentioned above, yeast is one of the main ingredients in the dough formulation. Salvador *et al.*[34] investigated the influence of yeast content on dynamic moduli both in isothermal condition and during a heating process. They found that the viscoelastic properties decrease upon increasing the yeast concentration.[34]

In this context, we foresee the possibility to introduce the current methodology developed for PUs in the baking field, by avoiding yeast and by removing the lengthy leavening process, combining more processing steps (leavening and baking) in a single one. The keypoint of the novel process is the imposed pressure history which has to be designed according to the solubilization process as well as to the curing (baking in the case of bread or pizza) kinetics. In this way, it is possible to synchronize the moduli build-up with the pressure release. In particular, we adopted said procedure to a special baking process: pizza. We showed that it is possible to obtain a yeast-free Neapolitan pizza similar to the traditional one, where both density and cell morphology can be tuned by the foaming process variables.

II. MATERIALS AND METHODS

A. Materials

Wheat flour (Nuvola, Mulino Caputo, San Giovanni a Teduccio, Napoli, Italy), iodized sea salt (Sale marino iodato fino, Gemma di Mare, Porto Viro, Rovigo, Italy), tap water, and brewer's yeast (Lievito fresco per pizza pane e dolci, Lievital, San Quirico di Sissa Trecasali, Parma, Italy) were used without further purification to prepare the pizza dough.

B. Preparation of pizza dough

Traditional (yeast-foamed) pizza dough was prepared according to European commission regulation (EU) No 97/2010.[45] A kneading machine (Kneading Machine 5L, Hauswirt Electric, Shunde City, China) with a dough hook was used, according to the following procedure. 60 mL of tap water was poured into the kneading machine vessel, with water temperature, $T_{water} = 66\,°C - T_{room} - T_{ing}$, where T_{ing} is the temperature of the ingredients, according to Masi *et al.*[46] 2.5 g of sea salt was added and manually stirred. Then, 10 g of flour and 0.15 g of brewer's yeast were added and the dough kneader was started at 60 rpm. During mixing, additional 90 g of flour was gradually added within 8 min. Finally, the dough was worked by the kneader machine for additional 15 min, monitoring the temperature by a J-thermocouple. During the kneading step, dough temperature was measured in the range 24±2 °C. The obtained dough was stored at a temperature of 25±2 °C and at a relative humidity of 75% for the proofing stage. The humidity control was achieved by the use of a saturated solution of sodium chloride. For the yeast-free dough, the same procedure was used. The dough with yeast and without yeast are named, in the following, YD and NYD, respectively.

C. Time-lapse experiment

A home-made time-lapse photography setup has been used to monitor the leavening stage. A special macro lens, specifically designed for macro-photography (MP-E 65 mm f/2.8 1–5 Macro Photo Lens), has been mounted on a full frame camera (Canon EOS 6D), offering exceptionally high-quality image. The camera focuses on a spherical dough sample of ca. 10 mm in diameter, positioned in an incubator equipped with a transparent window, kept at 25 °C, and with controlled humidity in the range 70%–80%. Snapshots of the dough spherical sample have been taken at fixed time intervals (20 min) by a specific home-made recording software.[47] The images were processed by ImageJ[48] software with edge detection plug-in, utilized to measure the volume change of the dough samples. The initial frontal area A_0 was evaluated by the edge detection tool available in ImageJ applied to the initial snapshot, while the time-varying section, A, was estimated likewise during the successive snapshots.

D. Traditional baking temperature history

A traditional, wood-fired pizza oven (Pizzeria Parco Sportivo Sant'Anna, Massa Lubrense, Napoli, Italy) was used to measure the actual temperature history experienced by the pizza dough during traditional cooking. To this aim, a J-thermocouple was embedded in the pizza dough during the whole baking process.

E. Rheological measurements

Rheological measurements were performed on a rotational stress-controlled rheometer (Discovery Hybrid Rheometer 2, TA Instruments, USA) equipped with a Peltier unit for temperature control and with sandblasted parallel plates with a diameter of 40 mm to prevent slip. A solvent trap was used to prevent sample drying. A coefficient of 0.957 μm °C was used to account for thermal expansion of the measuring system during the cooling/heating ramps.

Dynamic measurements were performed in linear viscoelastic regime (LV) by imposing a deformation of 0.01%. Such a strain guarantees to carry out frequency sweep test in LV in the whole range of frequency explored, 100–0.1 rad/s.[49] G', the elastic modulus stored during the deformation cycle, and G'', the viscous modulus dissipated by the material, are measured as a function of frequency at various leavening times.

Dynamic temperature ramp test were performed at 10 rad/s in a temperature range between 25 °C and 104 °C. During thermal ramps, it is convenient to present the norm of the complex modulus, $|G^*|$, as a function of time.[49] The heating rate was designed in a way to follow the real thermal history of pizza-dough during baking in the wood-fired oven. To this aim, the heating rates were: at 35 °C/min between 25 °C and 90 °C, 11 °C/min between 90 °C, and 102 °C and 2° C/min between 102 °C and 104 °C.

Reproducibility was verified by multiple measurements performed on fresh samples, with a relative error smaller than 5% (error bars not shown).

F. Foaming equipment

The *mini-batch* foaming autoclave described in Ref. 50 was utilized to prepare gas-foamed pizza. You can see a sketch of the home-made setup in the supplementary material (Fig. S1). In brief, it consists of a thermoregulated pressure vessel based on a 1/2″ NPT cross-fitting (model 15–24 NFD, from High Pressure Equipment Company, Erie, PA, USA). The pressure discharge system is composed of a discharge valve (model 15–71 NFB, HiP), an electromechanical actuator (model 15–72 NFB TSR8, HiP), and an electrovalve. The pressure history was registered by a data acquisition system (DAQ PCI6036E, National Instruments) and a pressure transducer (model P943, Schaevitz-Measurement Specialties, Hampton, VA, USA). A pressure-tight, 1/2″ NPT sapphire window for visual observation of the sample was also adopted (Precision Sapphire Technologies, Ltd., Vilnius, Lithuania). The autoclave was equipped with an electronic control to impose a precise pressure history, making use of two electrovalves connected to the gas dosing line and evacuation line, respectively. Valves opening and closing were controlled by an electronic board (Arduino MEGA 2560 Rev 3, Arduino S.r.l., Strombino, Turin, Italy), and the error with respect to the pressure programs was kept within 0.2 bar. Technical grade of CO_2 and He was purchased by Società Ossigeno Liquido (Monza, Italy) and used as blowing agents.

III. RESULTS AND DISCUSSION

A. Leavening

The effect of the leavening process on the dough final structure has been studied with the time-lapse photographic setup on YD and NYD. Figure 1(a) reports the time evolution of the frontal area of the sample normalized with respect to the initial area, A/A_0. YD shows a pronounced increase in A/A_0, with this process attaining a constant value after 24 h, with an area increase in roughly 20%. NYD, on the other hand, shows negligible volume changes over time. In particular, a small decrease in A/A_0 is observed for NYD, depending on the action exerted on the sample by the gravity force. The nonmonotonic trend of the ratio A/A_0 of YD could depend on the competing effects of the leavening and gravity forces.

Figure 1 also reports the elastic (b) and (d) and viscous (c) and (e) moduli, at T = 25 °C, of the two samples (YD, NYD) during the leavening process. In both cases and for any test time, $G' > G''$, meaning that the dough has a dominantly solid-like behavior.[36] The viscoelastic moduli decrease with increasing leavening time, although the NYD sample shows a stronger softening. For both samples, the gluten degrading enzyme, protease,[51] springs into action during time. For the YD sample, together with the protease action, the volume fraction of gas bubbles increases due to the yeast chemical reaction. As previously proven theoretically,[52,53] the presence of voids in a real material causes a reduction of the static shear modulus. This would suggest that the leavening and the protease processes are synergical, and they could play a similar role in affecting the dough elasticity. Nevertheless, this hypothesis is not supported by the experimental data shown in Fig. 1, where the YD sample shows a higher elasticity in comparison with the

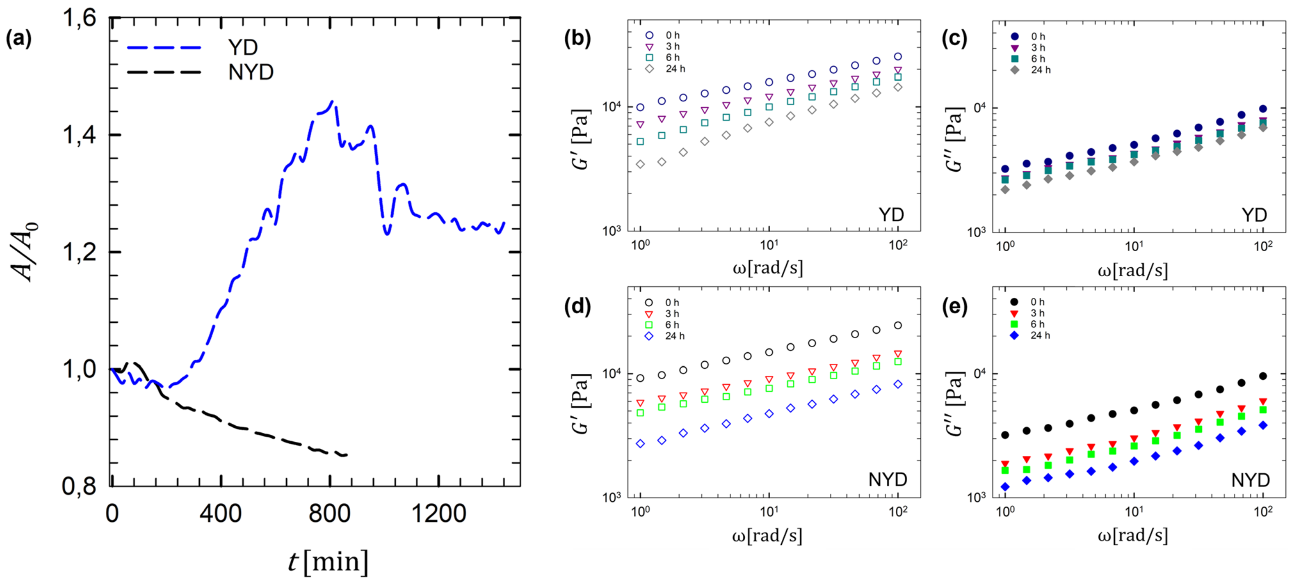

FIG. 1. (a) Results of the leavening time lapse experiment: Area ratio (measured as the transient area of the dough sample divided by the initial one) as a function of time. (b)–(c): G' and G'' for the YD samples, at different leavening times. (d)–(e): G' and G'' for the NYD samples at different leavening times.

NYD sample, as the leavening time increases. Although a definitive explanation is not achieved in the current paper, we can assert that the mechanism is surely not trivial. We could speculate that the protease process is influenced by the yeast presence and/or that the ongoing gelation depends on how the dough morphology develops in time (i.e., the presence of voids changes the gelation kinetics).[25]

B. Baking

The thermal profile of pizza-dough during baking in the wood-fired oven is reported in Fig. 2(a). It is worth of note that, despite the temperature of 350 °C ca. of the oven, a much lower temperature is observed in the dough, due to the heat transfer resistance and the endothermicity of the water evaporation reaction, among others.[46,54] The thermal history experienced by the gas measured by the J-thermocouple embedded in the dough can be divided into three temperature ranges i.e., 25–90 °C, 90–102 °C, and 102–104 °C. By performing linear regressions on each temperature range, it is possible to detect the heating rate of pizza-dough during baking. Fits are shown with gray lines, heating rates being 35, 11, and 2 °C/min, respectively. Figure 2(a) also reports the temperature history attained in the rheometer after having imposed the observed heating rates. The agreement allows us using the rheological data to design the processing stages.

Figures 2(b) and 2(c) report the complex modulus as a function of time for YD and NYD, respectively, during the baking process, at ambient pressure and imposing the temperature history described in Fig. 2(a). As in Sec. III A, samples at different leavening times have been considered. In both YD and NYD samples, a lag time for structure development of the order of 100 s can be observed. As expected, $|G^*|$ slightly decreases as the temperature increases from 20 °C to about 65 °C, probably due to water freed from damaged starch in the early stage of baking.[34] After the lag time, a steep increase in $|G^*|$ can be observed, which marks the onset of the dough/crumb transition.[19] A steep increase in the complex modulus can be ascribed to the gelation of the starch contained in the flour.[55] Indeed, the gluten network is strengthened through formation of additional cross-links, such as disulfide bonds, which leads to thermosetting of the structure.[46,54] A plateau value is eventually attained at roughly 200 s for both samples. YD and NYD samples display a similar behavior, evidencing a minor effect of the yeast on the final structure, as also supported by Singh *et al.*[35] The phenomena of gelation of starch granules drives the modulus development of the dough during the baking phase. As a consequence, only ingredients that affect the starch gelation will affect the modulus development.[35]

The observed results proved encouraging to adopt the novel process of baking and foaming on the NYD sample. The lag time represents an important opportunity for gas loading into the dough structure by pressurization. During this time, the physical blowing agent is able to diffuse and solubilize into the dough, primarily into the liquid phase, as in the traditional YD sample.[54,56] A gradual pressure release could induce bubble formation and expansion, while high temperatures set the foam structure due to starch gelatinization reaction and gluten protein aggregation. A careful and ingenious use of pressure and temperature could bring to the right texture required for an optimal pizza.

C. Baking and foaming

By considering the temperature profiles reported in Fig. 2(a) and the actual design of the autoclave, we decided to work in isothermal mode. After a procedure similar to the one described in Sec. II D, the control temperature of the autoclave was set at 145 °C. The pressure history required to induce blowing agent solubilization and successive dough expansion is reported in Fig. 3 (Multimedia views), superimposed to the $|G^*(t)|$ described in Sec. III B. Namely, after the dough

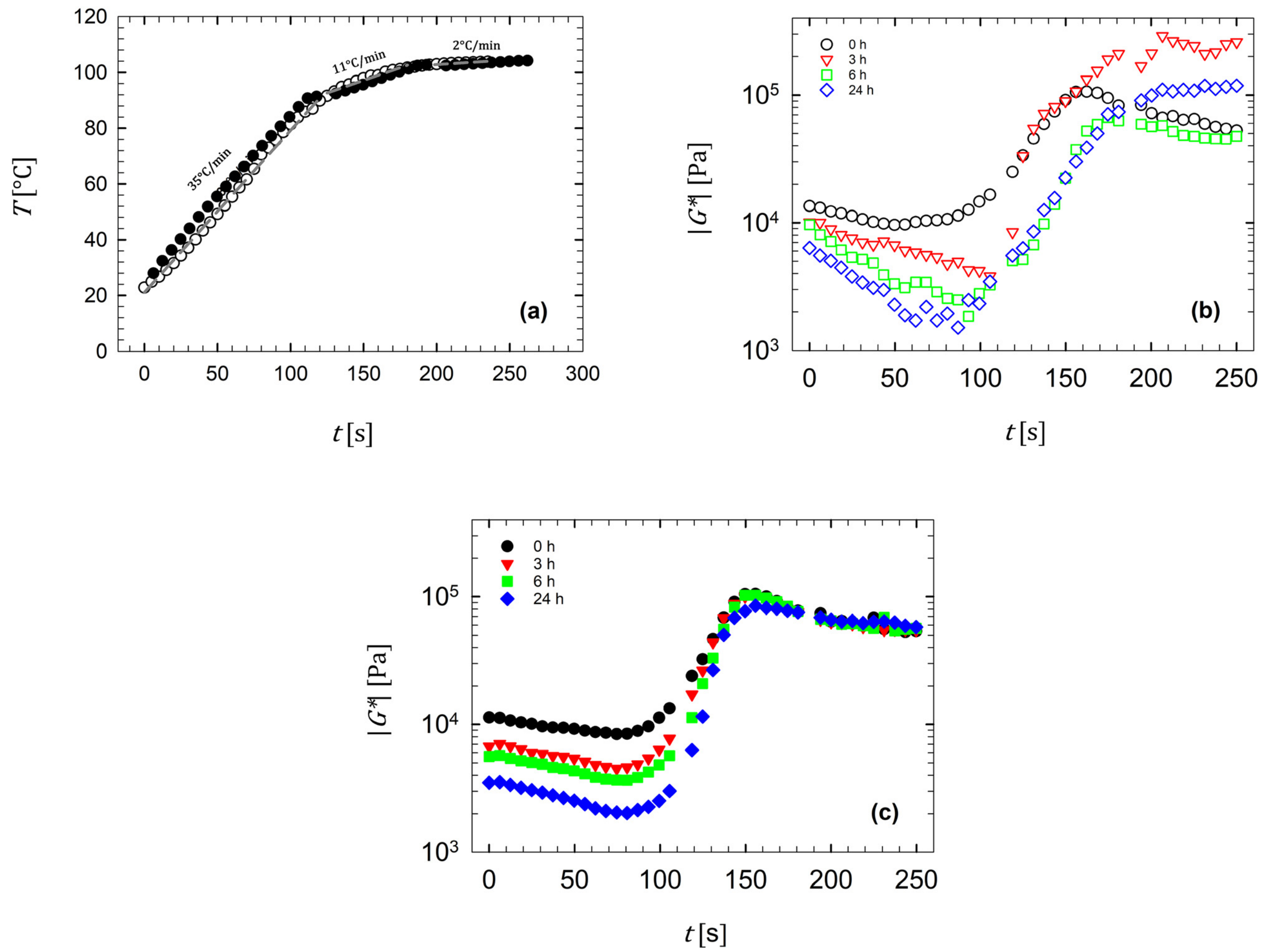

FIG. 2. (a) Comparison of temperature histories: dough temperature history resulting from cooking in the pizza oven (sensor embedded in the dough—open symbols) and rheometer temperature history by the adopted temperature program (closed symbols). (b) and (c): Rheological results of the dough cooking tests after different leavening times (0–3–6–24 h) at ambient pressure: complex modulus as a function of time, (b) YD and (c) NYD samples.

sample is put into the autoclave, the pressure is linearly increased from ambient to 6 bar in 30 s. Then, it is kept constant for 70 s, followed by a linear depressurization to ambient pressure in 100 s. Sorption of the blowing agent initiates immediately with the linear pressure increase and continues for the 70 s of the isobaric stage. The mild, 30 s pressurization stage is used not to induce stresses and not to destroy any possible presence of voids produced by mechanical aeration during the mixing step.[57,58] Sorption is inducing both solubilization of the blowing agent into the dough and pressurization of the voids formed with mechanical aeration. It is conducted on a low-moduli dough, as observed in the first 100 s of the dynamic temperature ramp test. It is worth of note, here, that achieving a uniform foam requires a uniform concentration profile of the blowing agent into the sample. To this aim, sorption time should be comparable to—or larger than—the characteristic diffusion time.[59]

Diffusivity data of the adopted blowing agents in the dough at baking conditions are scarce, due to the difficulty in conducting reliable experiments on a rapidly evolving matter. Among others, Park and Dealy[60] proposed an interesting indirect method to measure CO_2 diffusivity in molten high-density polyethylene by using a high-pressure sliding plate rheometer, taking into account the coupled effect of pressure, polymer swelling, and temperature. An estimate of the diffusivity of low molecular weight penetrants in dough can be given, based on the literature available for dough and starch, pointing to a range 10^{-9}–10^{-7} $m^2 \times s^{-1}$.[61,62] In our case, the latter value is consistent with the experimental evidence of the absence of morphological gradients in the foamed NYD.

According to Aissa *et al.*,[63] the solubility of CO_2 (in terms of weight fraction, ω_{CO_2}) in the liquid phase of dough (LPD—it is assumed that CO_2 solubilizes only in the liquid phase) can be estimated via a semi-empirical model,

$$\omega_{CO_2} = p \cdot e^{\frac{2052.3}{T} - 18.541}, \tag{1}$$

where p is the CO_2 pressure in kPa, and T is in Kelvin. In our case, LPD fraction is 0.38, and, at 105 °C and 6 bar, $\omega_{CO_2} = 3 \times 10^{-4}$.

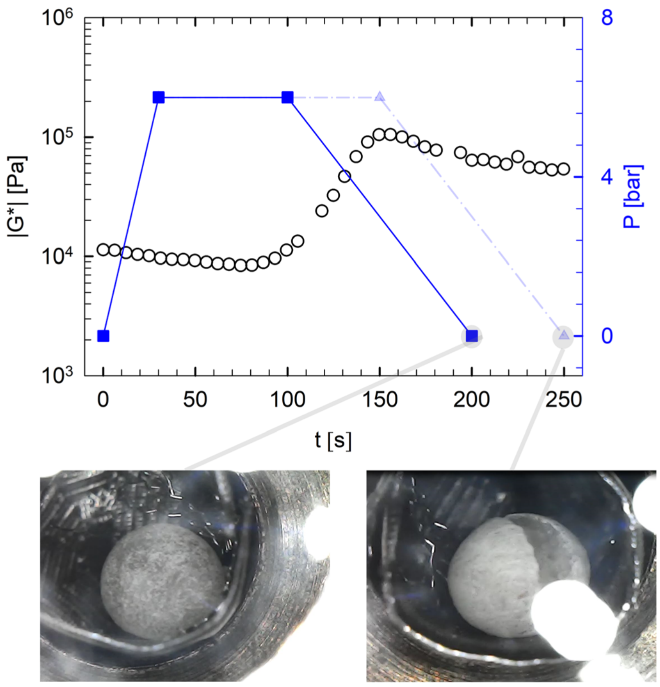

FIG. 3. Foaming processing program (pressure vs time—closed symbols) and the rheological cooking curves [data from Fig. 2(c)—open symbols]. As a comparison, a pressure profile (dash-dot line) in which pressure is kept constant for a longer time (before the autoclave depressurization) is also included. The pressure drop is 3.6 bar/min. The image at the bottom left shows the sample obtained with the pressure history represented by the continuous line. The image at the bottom right shows the sample obtained with the pressure history represented by the dash-dot line. Multimedia views: https://doi.org/10.1063/5.0081038.1; https://doi.org/10.1063/5.0081038.2

This value can be considered sufficient for achieving a properly foamed product with sufficient density reduction.

After sorption, a pressure drop induces de-sorption, both in terms of blowing agent escape from the dough/blowing agent solution and of expansion of the pressurized voids, inducing dough foaming. If an abrupt pressure drop to ambient pressure is used, the low-moduli foamed dough will collapse under the extensional stresses and a poorly expanded pizza will be achieved. Following the idea of Brondi *et al.*, a controlled pressure program can be used to chase the moduli buildup, attaining ambient pressure only when the system is fully cured (baked).[21] To this aim, a linear pressure-release program can be utilized, starting from 6 bar and reaching ambient pressure in 100 s, when the dynamic temperature ramp tests showed completion of the baking process. Figure 4 reports the results of the visual observation by the mini-batch of both the YD sample (leavened for 6 h) baking at ambient pressure and the NYD sample baking and foaming by using two different blowing agents (carbon dioxide and helium). Results are reported in terms of the relative volume change of the samples as a function of time. Figure 4 also reports images of the initial and final samples (before and after baking or baking and foaming) and of a cross section of the samples to show the obtained cellular structure, along with the cell size distribution.

Results prove the efficacy of the novel baking and foaming process, with the attainment of densities and morphologies for the NYD baked and foamed samples comparable with the YD baked samples. As a benchmark, a NYD sample was subjected to an ambient pressure baking process (same as the YD) showing, as expected, a negligible final volume change (<5%; data not reported). Furthermore, the results show that the sorption stage was properly designed to avail an amount of blowing agent suitable for expansion ratios comparable to the YD baking. It is worth of note here that sorption, as well as desorption, is strictly related to diffusion coefficients among the species at play and strongly depend on the water content,[61,63] not to mention the blowing agent nature and processing conditions of temperature and pressure. The above-mentioned process parameters can be suitably changed in order to obtain well-defined densities and morphologies as a common approach in foaming technology.[64,65]

In particular, density and morphology (and in turn, the final properties) of the dough structure strongly depend on the maximum pressure (in this work, equal to 6 bar), the isobar timing and the pressure decrease rate.[66] For instance, the increase in the maximum pressure induces an increase in the blowing agent availability and, in turn, the increase in final expansion ratio. Here, maximum pressure is upper bounded by the specific autoclave design. In our case, the limiting pressure is 10 bar, corresponding to the maximum working pressure of the electrovalves. The isobar timing defines the length of the sorption stage, the amount of blowing agent solubilization, and the curing degree of the dough before the pressure release. Selection of short isobar timings would mean earlier foaming, which could induce either premature foaming or attainment of lower foam densities. Conversely, selection of long isobar timings could determine poor foaming. In fact, pressure release on a dough at later stages of curing, i.e., virtually undeformable, will result in the buildup of triaxial tensile stresses by the expanding gas, possibly leading to fracture. Figure 3 reports such a case (dash-dot pressure profile) characterized by long isobar timing, with the right inset picture showing a fractured sample. Pressure decrease rate can be adjusted to the overall process timing to allow reaching ambient pressure as the dough attains a final curing degree, which in our case occurs after 200 s. However, in general, slower pressure decrease rates should help preventing coalescence phenomena by limiting expansion, with the consequence of giving foams with larger densities.

As pointed out in the underlying foaming literature, the nature of the blowing agent is also a common and effective processing variable to tune foam density and morphology.[64] Figure 4 reports the comparison between carbon dioxide and helium as the blowing agents. In particular, larger relative volume changes were observed when carbon dioxide was used as blowing agent with a final foam density of ca. 0.55 g/cm^3, while a final foam density of ca. 0.65 g/cm^3 was attained when using helium. The cell morphology was also affected by the nature of the blowing agent, with a larger and broader size distribution for the case of helium[67] (as shown in the bar graphs of Fig. 4).

The different bubble size distributions (BSD) are a consequence of the different expansion mechanisms. In the case of YD sample, the expansion is mainly due to a balance between Laplace pressure and diffusion-controlled mechanisms of the gas produced by the yeast. The process is, therefore, moving in a quasi-equilibrium state with all bubbles growing similarly, with a consequent smaller and narrower BSD. In the case of the novel baking and foaming process, the

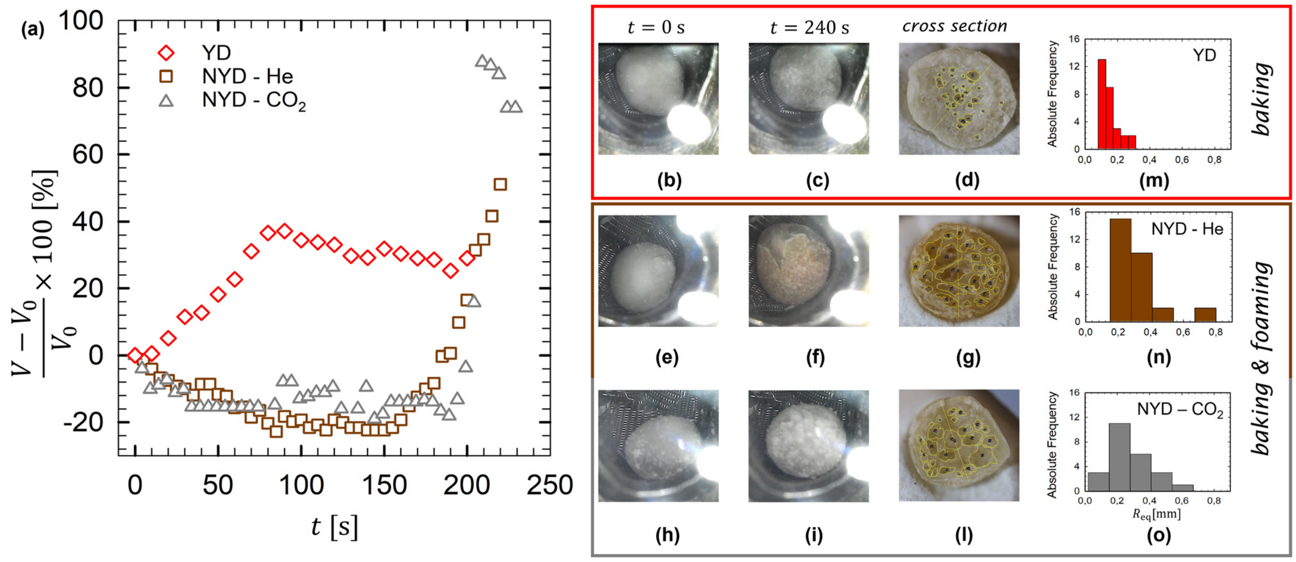

FIG. 4. Results of the visual observation of the baking and foaming of the pizza. Relative volume change as a function of time for the YD (leavening time of 6 h) and NYD samples foamed by using He or CO_2 as blowing agent (a). Optical images of the samples at initial conditions, 0 s and after 240 s. Figures (d), (g), and (l) report the cross sections of the baked and foamed samples retrieved from the equipment after treatment (pore perimeters are highlighted in yellow). The size distributions, as measured by the software ImageJ, are reported in (m)–(o) using bar graphs. YD: (b)–(d) and (m). NYD foamed with He: (e)–(g) and (n). NYD foamed with CO_2: (h)–(l) and (o).

expansion is attained by the nucleation and growth of the gaseous phase escaping the dough/blowing agent solution as a consequence of the thermodynamic instability induced by the pressure drop. At the present state, we can only speculate that in the adopted experimental range the latter brings to a smaller number density of nucleated bubbles which may grow larger due to the available blowing agent. Furthermore, long pressure-decrease stages justify the broad BSD, as bubbles are nucleated at different times during the pressure decrease and avail different amount of blowing agent and time for growth.

The nature of the blowing agent, along with the numerous processing parameters, namely, temperature, maximum pressure, isobar timing, pressurization, and de-pressurization times, represent a large set of process-tuning knobs, proving the versatility of the novel process to achieve both traditional and novel aerated baked products. Finally, the possibility to specifically design the dough to adapt and exploit the new process is an opportunity for development of new products.

IV. CONCLUSIONS

We designed a novel baking process for a yeast-free pizza dough, making use of the gas foaming by a physical blowing agent and a pressurized oven. A rheological testing campaign has been used to design the new process, which can be described in terms of baking and foaming. The evolution of the viscoelastic moduli of the dough at cooking temperature has allowed us to define the time window for blowing agent sorption under pressure and the depressurization stage to allow bubbles formation and growth. Mild pressures (as high as 6 bar) and a temperature of 145 °C were required to bake and foam in ca. 4 min, consistent with the time required for the moduli buildup. A well-foamed pizza was achieved with densities and morphologies similar to the ones of a traditional dough with yeast. Moreover, the novel baking and foaming process parameters, as well as the physical blowing agent nature, can be suitably tuned in order to obtain a desired density and morphology of the final foamed product.

SUPPLEMENTARY MATERIAL

See the supplementary material for some details of the minibatch foaming equipment.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

P.R.A. and P.I. contributed equally to this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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