Porous media characterization of breads baked using novel heating modes

Ashim K. Datta a,*, Serpil Sahin b, Gülüm Sumnu b, S. Ozge Keskin b

a Department of Biological and Environmental Engineering, Cornell University, Riley-Robb Hall, Ithaca, NY 14853-5701, USA
b Department of Food Engineering, Middle East Technical University, 06531 Ankara, Turkey

Received 24 September 2005; accepted 16 January 2006
Available online 10 March 2006

Abstract

The nature of pore spaces in breads baked using various heating modes (microwave–infrared (MIR), microwave–jet impingement (MJET) and jet impingement (JET)) were characterized in terms of total porosity, fraction of closed, blind and flow-through pores, and pore size distributions using several novel and old techniques (liquid extrusion porosimetry, scanned image analysis, pycnometry, volume displacement method and scanning electron microscopy or SEM). For the breads studies here, a very significant pore size distribution exists covering diameters of a few microns to several thousand microns. It appears that the pore size distribution is bimodal and only a combination of techniques can provide comprehensive information, i.e., any one technique cannot cover the large range of pore size, total porosity and flow-through vs. closed pores. A significant fraction of the pores was found to be closed. Breads baked in JET had the highest total porosity followed by MJET and MIR. Other measurements on breads baked in JET also lay on one end of the spectrum (either smallest or largest), which is consistent with SEM pictures where JET baked breads looked quite different from the ones baked in other ovens.

Keywords: Pore size distribution; Image analysis; Microwave; Infrared; Combination; SEM

1. Introduction

Transport and other properties of foods that depend significantly on the porous structure of the food often critically determine the final quality of a processed food (Datta, in press). Knowing the relationship between the formation of porous structure and the processing steps can allow development of customized quality (Aguilera, 2005; Rassis, Nussinovitch, & Saguy, 1997). The obvious first step in obtaining the relationships between the transport properties and the porous structure is to quantify the nature of the pores. However, quantitative characterization of food as a porous media has been rare (Karlsson, 1985; Kassama & Ngadi, 2005; Rassis et al., 1997).

Although there are many possible choices in foods to study porous media, an economically relevant as well as scientifically challenging food system to study is the baking of bread, where the structure of the food material changes profoundly during processing.

Previous scanning electron microscopy (SEM) studies have shown qualitative relationships between a bread’s mechanical properties and the size and distribution of gas cells in the crumb (Hayman, Hoseney, & Faubion, 1998; Zayas, 1993). Microstructure changes during baking of bread as affected by composition has been studied (Ahmad, Morgan, & Okos, 2001; Brennan, Blake, Ellis, & Schofield, 1996; Hayman et al., 1998; Pomeranz, Shogren, Finney, & Behtel, 1977; Rojas, Rosell, de Barber, Perez-Munuera, & Lluch, 2000) but the novel heating modes in this study (discussed later) have not been previously covered.

Pore size distribution in bread has been studied in the past using mercury porosimetry (Hicsasmaz & Clayton,
However, major improvements have been made in porous media measurements (Jena & Gupta, 2003). For example, Hicsasmaz and Clayton (1992), dried the bread in the oven before making measurements. Drying would not only shrink the material and change pore sizes, it can also change the nature of a pore, changing from closed to open. In what we propose here, the setup does not require the bread to be dried and the structure, therefore, stays closer to the original. Also, mercury porosimetry would require pressures that are order of magnitude higher than used here due to the higher surface tension of mercury and its high contact angle. It is desirable to avoid such high pressures for a soft material such as bread.

Other methods of structure determination, such as image analysis, have been developed that are complementary when combined with the type of porosimetry used by Hicsasmaz and Clayton (1992), as will be shown in this study. As multiple techniques are used, the suitability of the techniques themselves for a particular material can be compared and at the same time the food material can be studied more comprehensively. Computer image analysis has recently been successfully used to characterize structure properties for meat, fish, pizza, cheese and bread (Brosnan & Sun, 2004). Characterization of bread structure using image analysis has been done on bread crumb (Bertrand, Le Guerneve, Marion, Devaux, & Robert, 1992; Zghal, Scanlon, & Sapirstein, 2002), but these do not include comprehensive information on the porous media nature of bread.

The nature of processing affects the formation of the structure. For example, microwave heating and conventional hot air heating are expected to give different structures and properties (e.g., Ahmad et al., 2001). Recently there is increased interest in combination heating where microwave heating is combined with other modes of heating such as halogen lamp (infrared) or air jet impingement, creating novel heating modes. Since the many processing parameters and their interactions in combination heating are expected to influence the pore formation in a complex way, it would be particularly useful and novel to develop appropriate experimental data.

Our objective is to combine four different methods of measurement (liquid extrusion porosimetry (LEP), image analysis, volume displacement method and SEM) to obtain comprehensive and quantitative information on the porous structure during baking of bread in novel combination microwave heating ovens. We first introduce some porous media concepts and describe the measurement procedures. Pore size distributions are calculated using LEP and image analysis and observed qualitatively using SEM for each of the heating modes. From these measurements and the volume displacement method, the fraction of closed, flow-through and blind pores is determined in order to characterize the porous structure. Differences between the crust and crumb areas are observed and the suitability of the methods in covering the entire range of pore sizes in bread is also established.

2. Methodology

To define certain parameters in the measurement process, some basic concepts of porous media are first reviewed for clarity. As illustrated in Fig. 1, pores in a porous medium can be divided into three groups—closed pores that are closed from all sides, blind pores that have one end closed and flow-through pores where the flow of fluid typically takes place.

2.1. Principle of obtaining pore size distribution by LEP

Fig. 2 shows a schematic of the liquid extrusion porosimetry (LEP) that is used in this study. The gas pressure applied and the amount of liquid flowing out of a membrane are measured. The pressure required to displace the liquid from a pore is found by equating the work done by the gas to the increase in surface energy, given by

$$p = \frac{4\gamma \cos \theta}{D}$$  \hspace{1cm} (1)

where $p$ is the pressure difference across the length of the pore, $\gamma$ is the surface tension of the wetting liquid, $\theta$ is the contact angle of the liquid with the sample and $D$ is the pore diameter. Galwick™, a liquid with a surface tension close to zero (chemical name Propene, 1,1,2,3,3,3-hexafluoro, oxidized, polymerized), was used. As shown by Eq. (1), the lowest pressure will push out the liquid from the largest of the pores and the higher pressures will empty progressively smaller pores. The membrane is chosen such that its pores are smaller than the smallest pores in the sample. Thus, gas pressures required to empty the pores of the sample cannot remove liquid from the pores of the membrane, while the liquid pushed out of the sample is able to pass through the membrane.

From the measured pressure (that corresponds to a diameter, as given by Eq. (1)) and the corresponding volume of liquid collected, distribution of pore volume as a function of diameter is calculated. The median pore
2.2. Volume of flow-through pores

The total volume of flow-through pores, $V_{fp}$, is also obtained from LEP. Since LEP reports the volume measurements on a per unit (solid) mass or specific volume basis, the calculations in Table 2 are reported in terms of specific volume.

2.3. Volume of bulk solid

The bulk volume of the bread, $V_{bs}$, is also measured using the rapeseed displacement method (discussed later).

2.4. Volume of true solid plus closed pores

Helium gas pycnometry uses the ideal gas law to determine the true volume of a solid. However, the closed pores are not reached by the gas (flow-through and blind pores are reached) and the volume of the closed pores becomes included with the true volume of solid. In this procedure, the change in pressure in a sample chamber is noted as a porous solid is introduced into the chamber. Symbolically, if $V$ is the volume of the sample chamber and $P$ is the initial pressure, when the sample of true solid volume $V_{ts}$ is introduced, pressure increases to $P_{1}$. Using the ideal gas law

$$P_{1} \left( \frac{V}{C_{0}} \right) = \frac{PV}{(2)}$$

From which the volume of true solid (and closed pores), $V_{ts} + V_{cp}$, can be found as

$$V_{ts} + V_{cp} = \left( \frac{1 - \frac{P}{P_{1}}} {C_{0}} \right) V$$

(3)

2.5. Volume of true solids

True solid volume, $V_{ts}$, is determined by the rapeseed displacement method after mechanically compacting the bread to exclude all the pores.

2.6. Volume of closed pores

The difference between the volume ($V_{ts} + V_{cp}$) determined by gas pycnometer and true solid volume ($V_{ts}$) gives the volume of closed pores, $V_{cp}$.

2.7. Volume of the blind pores

Volume of blind pores is obtained by subtracting the volume of true solids, volume of closed pores and the volume of flow-through pores from the volume of bulk solids, i.e.,

$$V_{bp} = V_{bs} - V_{ts} - V_{cp} - V_{fp}$$

(4)

2.8. Porosity

The total volumetric porosity of the sample can be determined by taking the difference between the volume of bulk solids, $V_{bs}$ and true solid volume, $V_{ts}$
2.9. Dough preparation

Bread flour containing 30% wet gluten, 10% moisture and 0.57% ash was used in this study. The composition of the prepared dough was on flour weight basis (this composition corresponds roughly to the accepted recipe for hamburger bread); 100% flour, 8% sugar, 6% milk powder, 2% salt, 3% dry yeast, 8% margarine, 60% water. Dough containing 500 g flour was prepared by using straight dough method. First the dry ingredients were mixed. Milk powder and dry yeast were dissolved in water at 24 ± 1 °C separately. Margarine was melted and added to the dry ingredients in liquid phase together with dissolved yeast and milk powder. All the ingredients were mixed by a mixer (Kitchen Aid, KSM90WH, Greenville, OH, USA) for 3 min. After complete mixing of the dough, it was placed into the incubator at 30 °C. The total duration of the fermentation was 105 min. After the first 70 min, the dough was taken out of the incubator, punched (to obtain small and spatially uniform gas distribution) and placed into the incubator again. A second punch took place at the end of the 105 min. The dough was divided into 50 g pieces after fermentation. Each piece was shaped and placed into the incubator for proofing for 20 min under the same incubation conditions.

2.10. Heating modes in baking

Three different heating modes of jet impingement baking, microwave-impingement combination baking and microwave–infrared combination baking were used, with the processing conditions listed in Table 1.

2.11. Jet impingement baking (JET)

JET baking was performed in Thermador Double Jet Direct™ Convection Oven CJ302UB (Enersyst Development Center, Huntington Beach, CA, USA) by using high-speed convection heat (see Table 1). The velocity of air was 10 m/s. The oven was preheated to the set temperature before placing the dough samples into it. Four breads were baked at a time.

2.12. Microwave–jet impingement combination baking (MJET)

MJET baking combines the convection mode of the JET described above and microwave mode (see Table 1). The velocity of air was 10 m/s. Microwaves are introduced from the top and air jets are introduced from both the top and the bottom. The oven was preheated to the set temperature before placing the dough samples into it. Four breads were baked at a time.

2.13. Microwave–infrared combination baking (MIR)

MIR baking, which combines microwave and infrared heating, was performed in an Advantium™ oven (General Electric Company, Louisville, KY, USA). The rotary table in the oven was used to improve the heating uniformity of samples. Halogen lamps at the top and bottom were operated at the same power. Four breads were baked at the conditions shown in Table 1.

2.14. Temperature measurement

Fiber optic temperature probes (FISO Technologies, Inc., Quebec, Canada) were placed at the center of the bread and temperatures were obtained using a computer-based real time data acquisition system from the same company.

2.15. Volume measurement using rapeseed displacement

Rapeseed displacement (AACC, 1988) is a common method for measuring volumes of irregular solids and has been used for bread (Keskin, Sumnu, & Sahin, 2004). Rapeseeds have a diameter of approximately 1.7 mm. In the rapeseed method, first the tapped bulk density of rapeseeds is determined by filling a glass container of known volume uniformly with rapeseeds through tapping and smoothing the surface with a ruler. Then, the sample and rapeseeds are placed together into the container. The container is again tapped and the surface is smoothed with a ruler. Tapping and smoothing is continued until constant weight is reached between consecutive measurements. The volume of the sample is calculated as follows for volume of bulk solids, $V_{bs}$:

$$m_{\text{seeds}} = m_{\text{total}} - m_{\text{sample}} - m_{\text{container}}$$

(6)

$$V_{\text{seeds}} = \frac{m_{\text{seeds}}}{\rho_{\text{seeds}}}$$

(7)

$$V_{bs} = V_{\text{container}} - V_{\text{seeds}}$$

(8)

where $m$ is mass and $\rho$ is the density.

2.16. LEP measurement of bread porous structure

A schematic of the sample chamber in liquid extrusion porosimetry is shown in Fig. 2. The sample chamber, its insert, and container for the wetting liquid supported on the weighing balance were cleaned and reassembled. The wetting liquid Galwick™ was used for the test. The sample chamber was filled with the wetting liquid up to the level of the membrane. The thin membrane was put in place.
A clean and greased o-ring was placed on the membrane. The insert was placed on the o-ring. A cylindrical piece of sample (with the approximate dimensions of 36.5 mm diameter and 19 mm height) was punched from the bread avoiding areas that show very large pores visually. This bread sample was loaded in the sample chamber and the cap of the sample chamber (connected to the pressurized gas supply) was attached. The program was instructed to start the test. The test program recorded the initial differential gas pressure and the initial reading of the weighing balance, and increased the gas pressure in small steps, recording the differential gas pressures and readings of the balance. At the end of the test the report program automatically computed and displayed all the required results. The accuracy of the pressure measurement is about 0.15% of the actual value, while the accuracy of the flow measurement is approximately 1% of the full scale.

2.17. Image analysis based measurement of bread porous structure

Breads baked with different heating modes were cut into two halves vertically. The cut side of one of the halves was placed over the glass of a scanner (HP Scanjet 5470C, USA) having a resolution of 300 dpi. The scanned image was analyzed using the software Image J (http://rsb.info.nih.gov/ij/; Abramoff, Magelhaes, & Ram, 2004; Braadbaart & Van Bergen, 2005) that uses the contrast between the two phases (pores and solid part) in the image. The scanned color image is first converted to gray scale. Using bars of known lengths, pixel values are converted into distance units. The largest possible rectangular cross-section of the bread halves was cropped, as shown in Fig. 6 later. After adjusting the threshold, area-based pore size distribution, median pore diameter and pore area as fraction of total area were determined using the software.

2.18. SEM analysis of bread structure

Small portions of bread and dough samples were cut with a razor blade and prepared for SEM analysis. Both bread and dough samples were frozen in liquid nitrogen slush. The frozen samples were fractured with a razor blade while under liquid nitrogen into sizes of about 0.5 × 0.5 × 0.5 cm. They were then placed in a freeze-dryer and dried at −42 °C for 3–5 days. The freeze-dried bread and dough samples were mounted on specimen stubs with double stick tape and sputter-coated with 180 A of gold-palladium in a Baltec SCD 050 sputter coater (Balzers Union, Liechtenstein). The samples were viewed with a Hitachi S4500 scanning electron microscope operating at an accelerating voltage of 3 kV. Digital images at 50x were acquired on a Sun workstation using Imix software (Princeton Gamma Tech, Princeton, NJ).

3. Results and discussion

3.1. Pore size distribution using LEP and image analysis

Fig. 3 shows a typical curve obtained from liquid extrusion porosimetry (LEP) showing pore volume associated with a range of pore diameter. It is important to note that these measurements are restricted to the range of detection for LEP (5–1000μ), to pores that are flow-through and also
to the two cylindrical samples (approximately 36.5 mm diameter and 19 mm height) of the bread that has diameter up to 77 mm and height up to 55 mm. The samples were also taken from regions that did not have visibly large pores and were away from the edge (crust). In this particular curve for MIR at the power levels mentioned earlier, over 65% of the flow-through pores have diameter between 100 and 200 μm.

Fig. 4 shows pore size distributions of the flow-through pores (considering the same restrictions mentioned in the previous paragraph) for a number of different heating modes. For each heating mode, two samples were used, as shown in Fig. 4. A general trend shown in the data is a significant pore size distribution in bread. Although the shapes of the pore size distributions in the range of LEP (5–1000 μm) appear to be unimodal (see discussions in the following paragraphs), this is not the complete picture as explained later in this section.

Fig. 5 shows the scanned images of breads baked in different ovens. From these scanned images, pore areas (and statistics) are extracted by the software, an example of which is shown in Fig. 6 for the MIR heating. The area-based pore size distributions obtained this way for breads heated in three different modes are shown in Fig. 7. The long bar at the lower diameter end of the distribution is unlikely to have any significant meaning and it should be ignored. This is so because at the resolution of 300 dpi of the scanner, a pixel is about 85 μm wide and noise at this low end (discriminating one pixel is difficult) would make the data unreliable until areas that include several pixels are considered. Thus the median and mode of the data in Fig. 7 are in the large values of diameters (see Table 2). Although this procedure cannot give true volume fractions, it has been tried in other fields to obtain an estimate of pore size distribution and can be advantageous in our case since the whole surface of the bread (that has significant spatial...
variations) could be analyzed as opposed to porosimetry where only a small sample had to be taken. From the cumulative data (not shown here) corresponding to Fig. 7, about 70% of the pores in breads baked in JET had diameter above 1000 μm while 60% of the pores had diameter above 1000 μm in MIR. However, in breads baked in MJET oven the amount of smaller pores were higher, only 40% of the pores had diameter above 1000 μm.

An important observation can be made by combining the pore size distributions from LEP in Fig. 4 and image analysis of breads used in image analysis. The line underneath bread represents 2.54 cm. See Table 1 for the details of the heating modes used.

Fig. 6. Illustration of how the software ImageJ uses contrast in the scanned image to find the edges of pores and defines the regions representing voids before measuring their areas. Shown is the picture for MIR heating.

Fig. 7. Pore size distributions obtained using image analysis of breads baked using different heating modes.

Fig. 5. Scanned images of breads used in image analysis. The line underneath bread represents 2.54 cm. See Table 1 for the details of the heating modes used.
analysis in Fig. 7. Note that their ranges of operation are almost non-overlapping. Thus, the combined pore size distribution over the entire range of diameters would be bimodal. Since the pores accounted for by LEP are in the smaller diameter range and are only a fraction of the total pores (e.g., 0.182 for MIR in Table 2 as compared to a total porosity of 0.918) while image analysis also picks up a considerable fraction of pores (0.383 for MIR) in the larger diameter range, this further confirms the significant bimodality of the pore size distribution.

The median pore diameter values based on image analysis of breads baked at different heating modes are shown in Table 2. The largest pores were observed in breads baked in JET oven, with an area-based median pore size of 2500 \( \mu \)m. Addition of microwaves to JET reduced the median diameter to a much smaller value, 900 \( \mu \)m. The median diameter for MIR was 1400 \( \mu \)m. As can be seen in Fig. 5, these findings are somewhat consistent with visual observations of the breads. Pore sizes should relate to a balance between rate of heating and the time needed for the outer region of the dough to develop some rigidity so that sustained expansion can take place as opposed to the gas leaving the dough. It appears that as microwave heating (which heats more volumetrically and faster, as shown in Fig. 8) is included, there is not enough time for the outer region to become rigid and the expansion is much less. This should lead to a small median pore size. The MIR heating, that leads to a much faster heating than JET (see Fig. 8), also leads to reduced expansion which explains its lower median diameter.

The LEP findings, while different, are not inconsistent with the results obtained from image analysis. As mentioned, LEP measures pore sizes typically between 5 and 1000 \( \mu \)m, uses a sample size that is small compared to the entire bread loaf and measures only flow-through pores (not the closed or blind pores). In contrast, image analysis considers pores larger than 1000 \( \mu \)m (which happens to be quite significant for the breads baked using the novel

<table>
<thead>
<tr>
<th>Characterization of pore space in breads baked in different heating modes</th>
<th>MIR</th>
<th>MJET</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median pore diameter (( \mu )) based on volume, for flow-through pores by LEP, in the range 5–1000( \mu )m</td>
<td>150.60</td>
<td>100.30</td>
<td>90.75</td>
</tr>
<tr>
<td>Standard deviation of pore diameter (( \mu )), from LEP, for two samples</td>
<td>49.8, 61.1</td>
<td>44.0, 32.7</td>
<td>35.1, 29.4</td>
</tr>
<tr>
<td>Median pore diameter (( \mu )) based on area by image analysis</td>
<td>1400</td>
<td>900</td>
<td>2500</td>
</tr>
<tr>
<td>[A] Specific volume of pores measured using LEP, flow thorough pores in the range 5–1000( \mu )m (cc/g)</td>
<td>0.411</td>
<td>0.498</td>
<td>0.729</td>
</tr>
<tr>
<td>[B] Specific volume measured using gas pycnometry, true solid + closed pores (cc/g)</td>
<td>0.644</td>
<td>0.638</td>
<td>0.534</td>
</tr>
<tr>
<td>[C] Specific volume measured after compaction (using rapeseed method), true solid (cc/g)</td>
<td>0.185</td>
<td>0.180</td>
<td>0.065</td>
</tr>
<tr>
<td>[D] Specific volume of the bulk bread, measured using rapeseed method, true solid + blind pores + flow-through pores in the 5–1000( \mu )m range + closed pores + pores outside the 5–1000( \mu )m range (cc/g)</td>
<td>2.25</td>
<td>2.40</td>
<td>2.50</td>
</tr>
<tr>
<td>[E] Specific volume of closed pores, [B] – [C] (cc/g)</td>
<td>0.460</td>
<td>0.458</td>
<td>0.471</td>
</tr>
<tr>
<td>[F] Specific volume of blind pores and pores outside the 5–1000( \mu )m range, [D] – [B] – [A] (cc/g)</td>
<td>1.196</td>
<td>1.264</td>
<td>1.236</td>
</tr>
<tr>
<td>Fraction of flow-through pores in the 5–1000( \mu )m range, ([A]/([A] + [E] + [F]))</td>
<td>0.199</td>
<td>0.224</td>
<td>0.299</td>
</tr>
<tr>
<td>Fraction of closed pores, ([E]/([A] + [E] + [F]))</td>
<td>0.222</td>
<td>0.206</td>
<td>0.193</td>
</tr>
<tr>
<td>Fraction of blind pores and pores outside the 5–1000( \mu )m range, ([F]/([A] + [E] + [F]))</td>
<td>0.579</td>
<td>0.569</td>
<td>0.507</td>
</tr>
<tr>
<td>Total porosity (fraction) calculated from the bulk and compacted bread data obtained using the rapeseed method, (([D] – [C])/[D])</td>
<td>0.918</td>
<td>0.925</td>
<td>0.974</td>
</tr>
<tr>
<td>Porosity obtained using pycnometry if closed pores are ignored, (([D] – [B])/[D])</td>
<td>0.714</td>
<td>0.734</td>
<td>0.786</td>
</tr>
<tr>
<td>Porosity based on area fraction obtained by image analysis</td>
<td>0.383</td>
<td>0.399</td>
<td>0.418</td>
</tr>
<tr>
<td>Porosity of flow-through pores (in 5–1000( \mu )m range) using LEP data and bulk bread data from rapeseed method, (([A]/[D]))</td>
<td>0.182</td>
<td>0.207</td>
<td>0.292</td>
</tr>
</tbody>
</table>

Rows 1, 3 and 4 are arithmetic average for two samples.
heating modes in this study), uses the entire bread loaf and can include all pore types. Thus, the distribution calculated from LEP is only representative of a portion of the pore volume present while image analysis provides a more comprehensive picture. In an infusion application, for example, it is conjectured by some (Hicsasmaz & Clayton, 1992) that even the higher end pores within the range are likely to have little resistance to flow of oils (due to low values of surface tension and contact angles of less than 90°), thus still larger pores may not contribute much in such an application.

3.2. Characterization of pore space in breads baked using different heating modes

Although porosity can be calculated using the LEP, gas pycnometry, rapeseed method (together with compaction), and the image analysis, they all have their limitations. Notice from Fig. 1 that to obtain the total porosity, the volume of solid has to be obtained, ignoring the closed, blind and flow-through pores. The rapeseed method, where mechanically compacted (that presumably destroys all pores) bread volume is measured, appears to be the closest in obtaining the total solid volume and therefore the true total porosity. This can be seen in the data in Table 2 where the highest porosity values are obtained for the rapeseed method. We feel the porosity values obtained using the compacted volume and the rapeseed method give the most accurate estimation of the total porosity. Porosity values calculated from pycnometry data is lower (see Table 2) since pycnometry adds the closed pore volumes to the volume of solid (we estimate a significant portion of pores to be closed for the breads used in this study). Porosity obtained from the image analysis, which really provides the areal porosity, is lower, most likely since a lot of the smaller pores are outside the range of this measurement and also perhaps the 2D measurement does not represent the 3D situation very accurately. As expected, the porosity values obtained by LEP are the most inaccurate in the case of this particular bread since LEP considers only the flow-through pores in the 5–1000 μ range.

The nature of pores (e.g., closed vs. flow-through) makes a difference in the transport processes. The volume of closed pores can be calculated from the difference between specific volume measured using gas pycnometry and specific volume measured by the rapeseed after compaction (Table 2). It appears that a large fraction (≈20%) of the pores are closed pores, which is in contrast with literature data (Hicsasmaz & Clayton, 1992) on commercial white sandwich bread where closed pores were only quantified as 1.0–1.5% of the total pores. However, Hicsasmaz and Clayton (1992) had completely dried their bread, which changes the structure drastically and would certainly increase the open pores due to shrinkage. For the particular breads used here, it turns out that the volume of blind pores could not be determined since LEP data combines blind pores as well as the significant amount of pores outside the 5–1000 μ range of these breads. Of the volume of flow-through pores, only those in the range 5–1000 μ were picked up in this study (by LEP) and were in the 20–30% range for the breads studied.

Different heating modes affect the fraction of closed, blind and flow-through pores in different ways (Table 2). JET has the highest value of total porosity, followed by MJET and MIR. This trend is also seen in porosity based on area fraction using image analysis, in the flow-through porosity using the LEP and porosity estimated from pycnometry data (when closed pore volume is lumped with the solid volume, as it would be in a typical pycnometry).

3.3. Pore characteristic from SEM microstructure

Figs. 9–11 shows the microstructure at (50× magnification of breads baked using the three different heating modes. From the microstructure, we can make some qualitative observations about the pore characteristics.

Fig. 9. Microstructure of bread baked in MIR oven analyzed by using SEM at 50× for (a) crumb, (b) crust. Bars represent 300 μm.
In the crumb region (inner portion of the bread), pores were larger and more spherical as compared to those in the crust region (outer portion of the bread). The pores for the JET oven appear to be the biggest. This is consistent with the highest porosity for JET (Table 2) and visual observation (Fig. 5). Bread baked in JET oven looks different than the ones baked in other ovens with respect to appearance of pores. Structure of the bread is very fragile with open and larger pores since the bread baked in JET oven is highly expanded. In breads baked in JET oven, the walls were very narrow being just a thin strand separating the gas cells. The pores are no longer spherical. They are so close to each other that the gas cells coalesce to form channels. This is consistent with the fraction of open pores predicted using LEP. The gas cell walls were thicker in breads baked in MJET and MIR oven. The pores baked in an MIR oven were less developed (smaller) than in MJET.

In the crust region, pores were smaller and close to each other; they form channels and therefore effectively large pores. This may be due to the generally higher temperature at the crust region as compared to that in the crumb region. Crust portion of breads baked in JET oven is heterogeneous with respect to pores. The thin crust having a large separation with the interior in JET can happen due to the strong evaporation front near the surface. In MJET, heating is not as restricted near the surface, resulting in a not as clearly defined crust region as in JET. MIR also involves reduced surface heating and, therefore, a not as well defined crust formation.

4. Conclusions

Pore spaces in breads baked in JET, MIR and MJET ovens were characterized in terms of total porosity, fraction of closed pores and pore size distributions using several techniques. A very significant pore size distribution exists in bread, covering diameters of a few microns to several thousand microns. For the breads studied here, it appears that only a combination of techniques can provide comprehensive information, i.e., any one technique cannot
cover the large range of pore size and their characteristics (e.g., flow-through vs. closed). Although area-based porosity from scanned image may not be highly accurate, this technique can cover pore sizes outside the range of typical porosimetry apparatus, would include pores that are closed and may provide representative data on the pore size distribution for materials having large pores such as bread. Also, scanned image based information would typically include a larger portion that can be more representative of the original bread. Combined measurements using the LEP and the image analysis shows that the pore size distribution in the breads studied is bimodal.

In breads, pore sizes should relate to a balance between the rate of heating and the time needed for the outer region of the dough to develop some rigidity so that sustained expansion can take place as opposed to the gas leaving the dough. Breads baked in JET had the highest total porosity followed by MJET and MIR, a trend consistently seen in area based porosity from image analysis, porosity from pycnometry and the LEP. A large fraction of the pores was found to be closed. The closed pore fraction was the highest in breads baked in MIR oven which is followed by MJET and JET. According to SEM analysis, breads baked in JET oven looked quite different than the ones baked in other ovens. SEM analysis also showed that the crust region of bread had smaller pores which were close to each other as compared to the crumb region.

Acknowledgements

The authors greatly acknowledge the operation of the LEP instrument by T. Murray at Porous Materials, Inc., and the discussions with Drs. A. Jena and K. Gupta, also from the same company. They also very much appreciate the work of C. Daugherty of the Cornell Integrated Microscopy Center in obtaining the SEM micrographs. Discussion with Professor D. Aneshansley regarding the image processing was also helpful. This work was supported by the grant INT-0422806 from the National Science Foundation of the United States and the grant TÜBİTAK-NSF 2004-03 from The Scientific and Technological Research Council of Turkey (TÜBİTAK).

References


