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The application of the ultrasonic method for evaluating the porosity of bread

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Abstract

For evaluation by using acoustic methods bread is complex structure due to its geometric shape, density and porosity. This article reviews the use of direct and indirect acoustic measurement methods for evaluating the porosity of bread. The basic principle along with advantages and shortcomings of such methods is explained. Physical-mechanical properties of bread are described, along with mathematical equations, which are necessary for their theoretical calculation. The ability to determine physical-mechanical properties of bread (like porosity) is necessary, because they are directly linked to the quality of the product from the consumer's point of view. Basic ingredients of bread are also briefly described. Ultrasonic waves are very suitable for the evaluation of porous food products due to their physical properties and wide range of operating frequencies. Correct preparation of the measurement sample is required for accurate results therefore guidelines are presented. This article can be of benefit to researchers, specializing in the evaluation of porous structures like bread.

Keywords: bread, bread composition, porosity, ultrasound, echolocation, absorption, direct evaluation, indirect evaluation

Introduction

In general, from a physical-mechanical point of view, bread is a composite multiphase structure with high porosity [1-20].

It can be classified as a cellular solid [1]. The crumb cell walls of bread mainly consist of starch, protein and water. These wheat constituents contribute to the structural architecture and a mechanical strength of bread.

Objective evaluation of structural parameters of porous cereal products – bread and crackers is important in the characterization of sensory properties [12, 17-20].

Therefore, porosity is one of the most important quality properties of grain products [1, 3-15].

The final crumb structure of bread is critical to consumer acceptance of baked products [2, 12]. Therefore, knowledge of the structural organization of bread is of critical importance for our understanding of the visual appearance of bread crumb and the concomitant consumer's perception of bread quality.

In general, mechanical, optical, electrical, photographic, radio isotopic, X-ray, infrared and spectrometric methods can be used to determine the porosity of bread [17-49].

We will review only spectrometric measurement methods [21-29, 30-36], which are part of a separate and interesting group of measurement methods. These methods were developed using electromagnetic and acoustic waves as carriers of information. From the spectrum of electromagnetic waves, infrared waves are used most frequently. Measurement methods from this group have a fairly high accuracy. The measurements of parameters of wave processes are widely applied in practice. Duration, frequency, amplitude and phase are easily measurable parameters of wave processes. Most frequently measured parameters in technical measurements are a time interval between signals [22-29], monochromatic and spectral measurements of signal's amplitude [30-55]. Out of previously mentioned methods, the spectrometric method is most complicated. It is difficult to apply this method for manufacturing processes in an environment with many disturbances. Therefore, the most suitable way for measuring porosity in such environment is to use a method based on measuring the time interval between signals or, in other words, method based on measuring ultrasound velocity in materials. In addition, method based on measuring signal's amplitude or, in other words, the method based on measuring ultrasound attenuation through materials, can successfully be applied. These methods provide the best results when a frequency from a wide range is chosen. The velocity of acoustic waves in various materials is not very high by comparison. For example, velocity in gas is around 300 m/s, in liquids – around 1500 m/s and in solid materials – around 5000 m/s. Velocity of acoustic waves is within range of 1000-2000 m/s for most of the food products. Such low velocity can easily be measured with a high accuracy.

Today there is a lively interest in acoustic measurement methods [21-48]. These methods can be direct [38-51] or indirect [52-58]. The most widely used direct method is when the parameter changes of the ultrasonic signal are measured after the signal has penetrated the porous product. Due to the complex propagation of ultrasonic signals, direct methods are rarely used in practice.

In addition, the direct method mentioned earlier can be combined with an acoustic echolocation method [53-58]. In this case, the ratio of reflected signal's parameters and penetrated signal's parameters is measured. Due to the properties of ultrasonic wave propagation, their application for evaluating porous materials is promising. When the optimal frequency of ultrasonic waves is chosen, structures composed of various particle sizes can be analyzed. To analyze liquid products, it is best to use ultrasonic waves of higher frequencies. For porous structures, the best results are obtained when using lower frequency ultrasonic waves [30, 38, 45, 48, 49, 51].

By applying echolocation, we succeeded to develop a complex mechanical method for evaluating porous products [52-58]. We measured the quantity of absorbed liquid without taking the sample out of the measurement vessel. In addition, we determined the quantity of liquid penetrating the sample in the real time. To achieve this, we measured the change of liquid's level in the measurement vessel. For this purpose, a highly accurate level meter for liquids was used.

After the sample is submersed, the level of liquid begins to change in the measurement vessel. The velocity of this change depends on the material's porosity. Among other methods, the ultrasonic echolocation method can be used to measure the change of liquid's level. The obtained results, when using this method to measure porosity of various materials, were described by us in [52-58].

To investigate the quality of waffle sheets, we proposed a non-contact ultrasonic method [55, 56]. For quality evaluation of food products (bread, cakes, crackers, pretzels) we used an acoustic contact measurement method. The latter is based on determining the swell of bread products in various liquids. Further investigations to increase the accuracy of measurement results in the swelling process of products in various liquids were performed using a special measurement vessel [52, 55]. This vessel has an improved design of the sample-keeping lattice. It enables us to avoid the negative influence of gas bubbles, which are raising from sample, on the measurement results. Additionally, we make it possible to transfer the information from the measurement equipment to a PC for automatic measurements and processing.

Basic ingredients of bread

Water and flour are the most significant ingredients in a bread recipe, as they affect texture and crumb the most. Flour (14.5% moisture, 13% protein, 0.55% ash, pH 5.7–6.1) [3], is always present, and the rest of the ingredients are a percent of that amount by weight. Approximately 50% water results in a finely textured, light bread. Most bread formulas contain anywhere from 60% to 75% water. In yeast breads, the higher water percentages result in more CO_2 bubbles, and a coarser breadcrumb. In addition to flour, the rest of the ingredients will be approximately: leavening agent yeast 2%, sugar 4%, salt 2% and shortening agent (ghee or margarine) 3%. Bread is a different food compared to some other common food items, as it is a leavened product obtained from fermentation of wheat flour sugars, released from starch by the action of natural flour enzymes. Fermentation is caused by baker's yeast, which is the trade name of the organism Saccharomyces cerevisiae. As water vapor and CO_2 expand due to a high temperature, they act as an insulating agent preventing high rate of temperature rise of bread crumb and the possibility of excessive moisture evaporation. Sugar is added to initiate fermentation. Salt is added to strengthen the gluten and to convert the action of yeast for controlled expansion of the dough. Shortening (ghee or margarine) is added to increase the machine ability or specifically slice ability. Nowadays, mechanization, large scale production and increased consumer demand for high quality, convenience and a longer shelf life have created the need for functional food additives such as emulsifiers and anti-staling agents in bread to achieve those desired qualities [12]. Addition of emulsifiers is particularly important for a large scale industrial bread baking as these impart greater dough strength to withstand machine handling, improve rate of hydration, improve crumb structure, improve slicing characteristic, improve gas holding capacity and extend shelf life.

Physical-mechanical parameters of bread

In an article [3], an apparent density of bread crust and crumb as a function of porosity was determined. Results of the experiment showed that the apparent density ρ (kg/m^3) of the crumb and the crust follows a linear trend as a function of porosity ε (percentage):

$$\rho_{crumb} = 979 - 9.90\varepsilon \,. \tag{1}$$

$$\rho_{crust} = 895 - 9.0\varepsilon \,. \tag{2}$$

However, this result is questionable as crust is generally found to be heavier than crumb due to reduction of pores and moisture.

Rheological properties of dough are also important for both product quality and process efficiency [12]. Rheological properties of dough can be related to bakery products specific volume and textural attributes. In an article [4], some rheological properties like results of storage relaxation and loss module over wide range of strain, frequency and time were presented. Water content was used as an independent variable for analysis of storage modules, but other modules were not as the function of water content. All data of the experiment were used to construct relaxation spectra and to test various linear viscoelastic relations. Finally, an excellent agreement was found between the relaxation spectra and between the derived data and original data, which confirmed the consistent testing procedure and high quality data. The relaxation time is one of the important rheological properties, which is related with disappearance of free liquid water at certain temperature. The following relation of the relaxation time τ as a function of temperature T is obtained [5]:

$$\tau = 9\left(\frac{2}{\pi}\arctan\left(\frac{T-65}{2}\right)+1\right)+2 \,. \tag{3}$$

However, effect of moisture content on the relaxation time is lacking.

Farinograph is the most frequently used equipment for empirical rheological measurements [6]. An artificial neural network (ANN) technology was used to predict the correlation between farinographic properties of wheat flour dough like water absorption, dough development time, dough stability time, degree of dough softening with its chemical composition like protein content, wet gluten, sedimentation value and falling number etc. Since the approach of ANN analysis is a black box simulation, this type of study fails to reveal the physical understanding behind established correlations, even though these might be excellent.

The texture and density of baked products such as bread and cakes are controlled by the way their rheology and vapor content change during the baking process. Article [7] reviewed the rheological properties of gluten polymers of wheat flour, which in turn affects the rheological properties of bread. This is a review where viscosity is shown to be a function of the time without extending the concept to viscoelastic parametric determinations under static and dynamic conditions.

Staling of bread is another complex phenomenon, which is not yet fully understood. During storage time, a large physical-chemical alteration occurs, which leads to crumb firming, flavor changes and crust cracking loss. Crumb firming is one of the important parameters, which is generally used to evaluate staling development. It is believed that bread staling is closely associated with starch retro-gradation. Amylose retro-gradation occurs during the first hour after baking and this amylopectin retro-gradation is the major phenomena involved in bread firming [7]. However, there is no experimental evidence presented to quantify these findings.

Objective evaluation of physical-mechanical parameters is important when characterizing taste properties of bread products.

The main physical-mechanical parameters of bread are dispersion, pattern of pores (repeatability) and density. Porous materials are described by the size of their pores and uniformity. The separating layers between pores can be thinner or thicker. These layers can also be elastic or solid. The pattern of a porous material is inversely proportional to density. The pattern describes the volume ratio of pores and separating layers. The density of a porous material is given by [11]:

$$\rho_P = \left(m_g + m_l\right)/V_P = \left(\rho_g V_g + \rho_l V_l\right)/V_P \ , \qquad (4)$$

where m_g and m_l – masses of gas and of separating layer respectively; ρ_g and ρ_l – densities of gas and of separating layer respectively; V_P, V_g, V_l – volumes of porous material, of gas and of separating layer respectively.

Because the density of the separating layer is more than a 1000 times higher than the density of gas (n>1000), then

$$\rho_P \approx \rho_l V_l / V_P = \rho_l / n \ , \qquad (5)$$

where n is the pattern of porous material and

$$n = V_P / V_g \ . \qquad (6)$$

The simplest way to determine the density of porous materials is to use a direct measurement of volume and mass.

In this case the density of porous material is:

$$\rho_P = \left(\rho_l V_l\right)/V_P = m_l / V_P \ . \qquad (7)$$

The best suitable method for designing automated control systems are the method based on measuring ultrasound velocity through materials [24-29] and method based on measuring ultrasound attenuation [44-48] through materials. Both of these methods require very short time to determine the result. In addition, they do not require special sample preparation or any kind of sample destruction. They can be used for on-line process control, which makes them even more attractive.

Direct acoustic methods for evaluating parameters of bread

To determine the porosity of materials, ultrasonic methods can be used both directly [38-51] and indirectly [52-58]. A direct measurement method (Fig. 1) is when the parameter changes of the ultrasonic signal are measured before entering and after the signal has penetrated the porous product [29]. The porosity (density) is then determined by analyzing the ratio of these signals. If the porosity of the material is high and the pores are quite large, then the parameter changes of ultrasonic signals are smaller and difficult to measure. When comparing samples of material, their thickness should be as equal as possible. In this case, the amplitude of the signal, which has penetrated through the porous product, is calculated using expression [56]:

$$A_{out} = K_0 A_{in} e^{-\alpha \rho_P l_P} \ , \qquad (8)$$

where A_{in} and A_{out} are the amplitudes of transmited and received signals respectively; K_0 is the corrective multiplier dependent on measurement environment; α is the attenuation of ultrasound in porous material; l_P is the thickness of the sample.

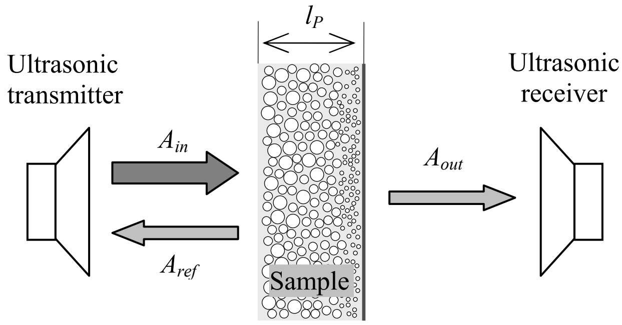

Fig.1. **Diagram of bread evaluation by using a direct ultrasonic measurement method, where A_{in} , A_{out} and A_{ref} – amplitudes of transmitted, received and reflected signals respectively, l_P – thickness of the sample**

This method can be improved by additionally measuring the amplitude of a signal, which has been reflected of the porous material. The frequency of this signal must be 17.20 kHz. In this case, the density ρ_P (g/cm^3) of the porous material can be calculated using expression [54]:

$$\rho_P = \ln\left(A_{ref} / \left(3.422 \cdot A_{out}\right)\right)/15.379 \ , \qquad (9)$$

where A_{ref}, A_{out} are amplitudes of reflected and received signals respectively.

When evaluating bread products using a direct acoustic method in the low frequency range, it is recommended to use a measurement scheme, presented in Fig. 2. This scheme enables to avoid the emerging "standing" waves in the acoustic measurement system between the ultrasonic transmitter and the measurement sample [47]. These "standing" (multiply reflected) waves negatively influence the measurement results, because the amplitude of the reflected wave adds to the amplitude of the transmitted wave. This measurement scheme (Fig. 2) is also well suitable to use at higher measurement frequencies [59-66].

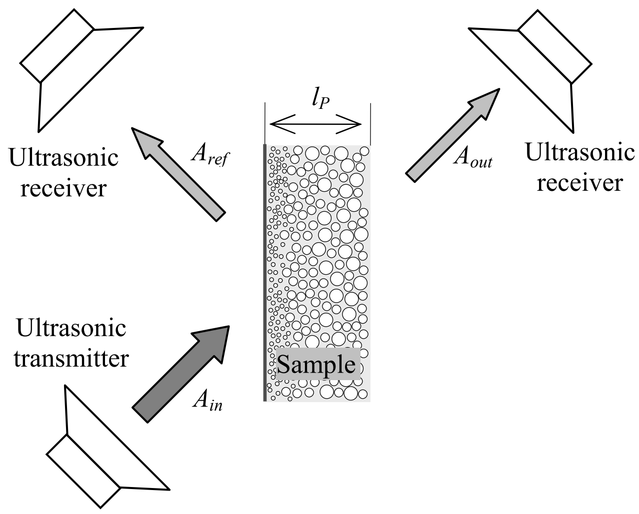

Fig.2. **Diagram of porous material evaluation by using a direct ultrasonic measurement method, where A_{in} , A_{out} and A_{ref} – amplitudes of transmitted, received and reflected signals respectively, l_P – thickness of the sample**

Indirect acoustic methods for evaluating parameters of bread

The indirect measurement methods [52-58] are based on the property of a porous material to absorb liquid. Some time needs to pass until air in the pores is completely displaced by liquid. After sample submersion, the level of liquid begins to change in the measurement vessel. The rate of this change depends on the material's porosity. Among other methods, the ultrasonic echolocation method can be used to measure the change in the level of the liquid. The obtained results, when using this method to measure porosity of various materials, were described by us in [52, 55].

The measurement vessel is mounted on a hard and solid support [67]. Electro-acoustic unit of an ultrasonic echolocation level meter is also mounted on the same support above the measurement vessel. This way the distance between the electro acoustic unit and the bottom of the measurement vessel remains constant.

At first, the measurement vessel is filled with water and the water level h_1 is measured (Fig. 3. a)).

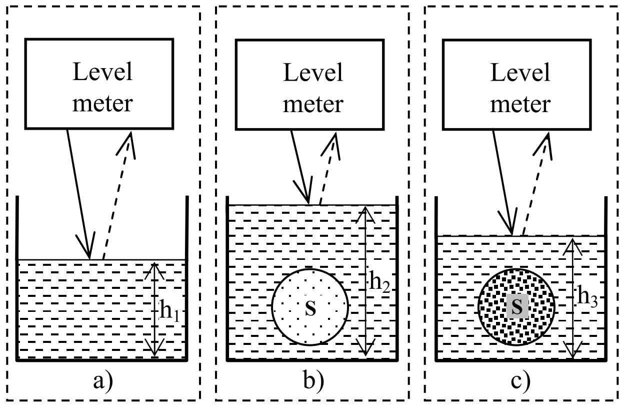

Fig.3. **Stages of the porosity evaluation process using acoustic echolocation**

Then a sample of a porous material is submersed in the water. The increase in water level in the measurement vessel is proportional to the volume of the sample. The suddenly risen water level h_2 is measured with the level meter (Fig. 3. b)). Given that the walls of the measurement vessel are vertical, the volume of the porous material is:

$$V_P = (h_2 - h_1) \cdot S \ , \tag{10}$$

where S is the area of the water's surface.

From the moment of submersing the sample, the falling water level is being constantly recorded until it reaches the lowest level h_3 (Fig. 3. c)). When the level reaches h_3, the process ends and the water level remains constant.

The water level is falling, because it is penetrating into the pores of the sample, replacing air in the process. The penetration rate of the water is directly proportional to the porosity of the sample.

The changes of the water level are presented in Fig. 4.

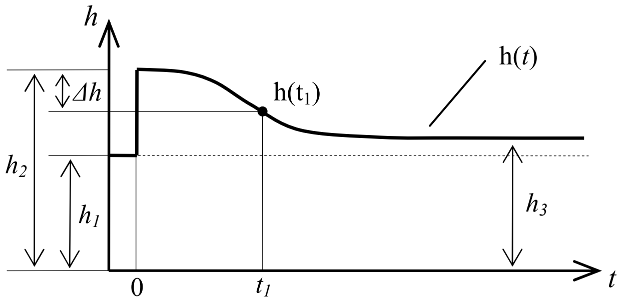

Fig.4. **Changes of the water level in the measurement vessel**

After a chosen time t_1, the water level recedes by:

$$\Delta h = h_2 - h(t_1) \ , \tag{11}$$

where $h(t_1)$ is the water level at the moment t_1.

In general, $\Delta h = h(t)$ is a function of water level change in time. The derivative dh/dt is the penetration rate of water. This rate, at a chosen moment, is proportional to the porosity of the sample.

The volume of water which has penetrated the sample, is:

$$V_g = (h_2 - h_3) \cdot S \ , \tag{12}$$

where h_3 is final level of water after the gas in pores of the sample was completely displaced by water.

The value V_g shows the amount of gas, which was present in the pores of the sample before submersion. Keeping that in mind, the pattern of the sample's pores, according to expressions (6), (10) and (12), is calculated from expression:

$$n = V_p / V_g = (h_2 - h_1)/(h_2 - h_3) \ . \tag{13}$$

If the porous food product has a surface layer with little or no defects, then the water penetrates it slowly, and the decrease in water level h is also slow. When the surface layer disintegrates, the penetration rate increases, and the derivative dh/dt only depends on the porosity of the product and the properties of the separating layer between pores.

It needs to be noted that if the product is made from grain products, the separating layers between pores can melt or swell. Therefore, the recipe of the product also influences the dynamic of water penetration (dh/dt). This information can be used to correct the production process of food products.

Mathematical evaluation of the absorption of liquid

When investigating liquid absorption into a sample, as the first step, we assumed that there is a homogeneous cylindrical body. The rate of liquid absorption depends on the area of moistened surface [55]. We also assume that the penetration speed is greater in the parts where the porosity greater. If we take a cylinder of radius r_0 and the unit length of pivot, then the volume of the absorbed liquid depends on the radius of cylindrical moistened volume:

$$V_S(t,r_0)=\pi v_d t(2r_0-v_d t) \ . \tag{14}$$

where v_d is the penetration rate; the time is $t \leq r_0/v_d$.

If the cylindrical sample is not homogeneous and its porosity changes with depth into the cylinder, we can assume several dependencies of porosity distribution along the cylinder radius r.

When the porosity increases with depth, the penetration rate changes according to

$$v_d(r)=v_{d1}\frac{r_0-r}{r_0}+v_{dp} , \tag{15}$$

where v_{dp} is the penetration rate on the surface of cylinder, v_{dl} is the decrease of rate with a radius. The absorbed amount of liquid in this case is

$$\begin{aligned} V_{st} &= \pi(v_{dp}t+\frac{v_{dp}v_{d1}t^2}{r_0-v_{d1}t})\times \\ &\times[2r_0-(v_{dp}t+\frac{v_{dp}v_{d1}t^2}{r_0-v_{d1}t})] \end{aligned} \ . \tag{16}$$

In actual conditions, the porosity with depth may change nonlinearly. We assumed the square root law of dependence of the penetration speed with depth

$$v_{ds}(r)=v_{d2}\sqrt{\frac{r_0-r}{r_0}}+v_{dp} , \tag{17}$$

where v_{d2} is the increase of penetration rate. The volume of the absorbed liquid is

$$\begin{aligned} V_{ss} &= \pi t[\frac{v_{d2}}{2r_0}(v_{d2}t\pm\sqrt{(v_{d2}t)^2+4v_{dp}tr_0})+v_{dp}]\times \\ &[2r_0-t[\frac{v_{d2}}{2r_0}(v_{d2}t\pm\sqrt{(v_{d2}t)^2+4v_{dp}tr_0})+v_{dp}] \end{aligned} \ . \tag{18}$$

These penetration rate dependencies were modeled and the dependencies of absorbed liquid volumes versus time were obtained. Although the amount of the absorbed liquid monotonously increases in all three cases, but the behavior of derivatives differs noticeably. In the case of homogenous structure, the rate of changes of the absorbed liquid volume decreases with time. If penetration rate increases with depth, the change of volume is rather uniform. The speed of volume changes decreases with time nonlinearly when the penetration speed increases with depth according to the square root law.

When the porosity decreases with depth, the penetration rate also decreases as

$$v_d(r)=v_{dl}r+v_{d0} \ . \tag{19}$$

If we decide that speed increases with radius as a square root then the expression is

$$v_{ds}=\sqrt{v_{d2}(r)}+v_{d0} \ , \tag{20}$$

where v_{d0} is the penetration rate in the center of the cylinder.

The modeling process in this case is similar to the previous cases [55].

Sample preparation for the evaluation of bread using acoustic methods

When evaluating bread products using acoustic methods, stages of evaluation are presented in Fig. 5.

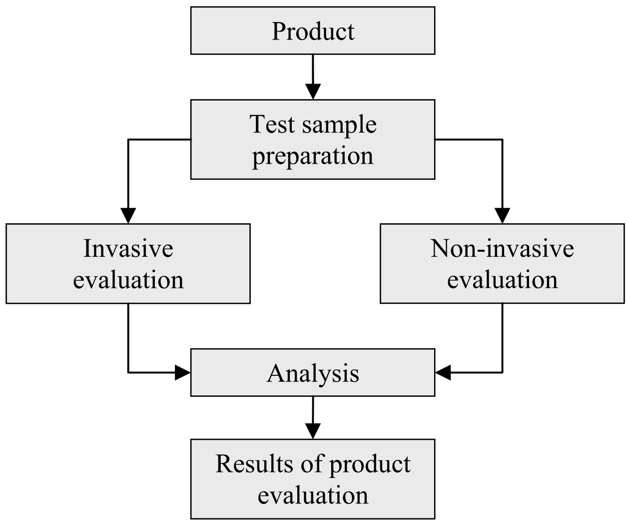

Fig.5. **Stages of bread evaluation**

Since bread is a product with a complex structure, samples for evaluation have to be correctly prepared. To evaluate the properties of bread crust, two cylindrical pieces have to be cut (Fig. 6).

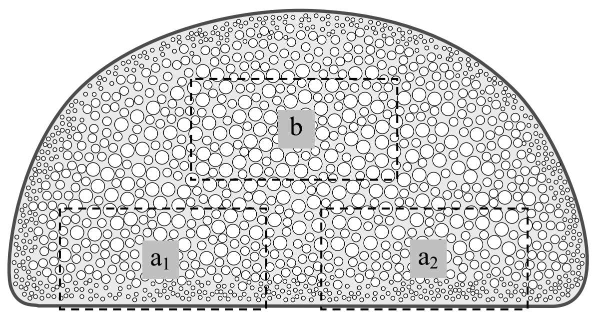

Fig.6. **Illustration of the porosity of bread (cross-section). Cylindrical sample pieces are taken from locations a_1, a_2 and b**

These pieces are then sandwiched together with their sides with higher porosity in contact. Then they are placed in a containment ring, as presented in Fig. 7.

This ring is placed in the measurement vessel [59] (Fig. 8). Upper measurement vessel is submersed into liquid, which is in the lower measurement vessel. The liquid penetrates through the crust of the sample, and the inner porosity has no effect on the level of the liquid during the initial phase of the measurement process.

When the porosity of inner layers of bread needs to be evaluated, the sample is cut from the inner layer of bread (Fig. 6b). In this case, the sample can be a one continuous piece and the ring is placed vertically in the measurement vessel. To avoid the negative influence of the transitional process on the change of the level of liquid, the surface of the sample should be covered in a thin, quickly soluble film. This way, the absorption of liquid will begin after the protective film dissolves and the results will be more accurate. It needs to be noted, that the rate of absorption will be least dependant on the influence of the pressure of the column of liquid, when the diameter of the containment ring will be smaller than the thickness of the sample.

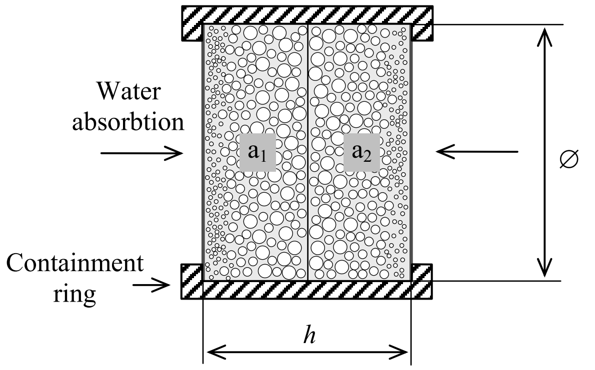

Fig.7. **Diagram of sample preparation for evaluating the porosity of crust for bread or cracker (cross-section), where *h* – height of the sample, a_1, a_2 – cylindrical pieces of the sample, cut from bread loaf, *D* – diameter of the sample**

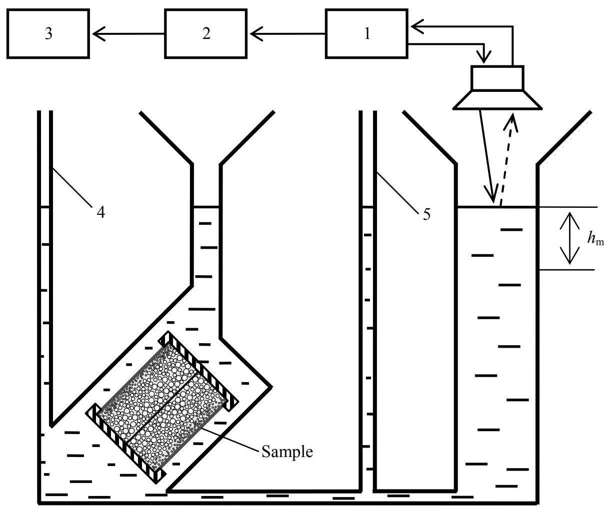

Fig.8. **Porosity evaluation model using acoustic echolocation method: 1 – acoustic level meter, 2 – interface, 3 – PC, 4 – upper measurement vessel with the measurement sample, 5 – lower measurement vessel with liquid**

From the moment of the sample's submersion, the receding water level is being constantly recorded until it reaches h_m (Fig. 8). The water level is falling, because it is penetrating into the pores of the sample, replacing air in the process. The penetration rate of the water is directly proportional to the porosity of the sample [7]. During the first moments of submersion, porous materials with a defect-free surface layer absorb liquid very slowly and the absorbed quantity of water is very low (up to 10 mm^3) [58]. Because of that, the level of liquid in a measurement vessel changes very slowly. To detect such low changes in the level of liquid (corresponding to the volume of 1 mm^3), a very precise ultrasonic acoustic level meter is required. The level meter must be able to measure distance interval of 1 to 40 mm. The absolute error of the unit should be no more than 5 microns, when the temperature is 60°C.

Conclusions

Direct acoustic methods for determining porosity of materials can successfully be applied when designing automated control systems, because these methods are fast and provide a lot of information about the material. Lower ultrasonic frequencies are more suitable when implementing these methods, because the attenuation of such frequencies is lower in bread.

Since the direct acoustic measurement method is non-destructive, it can be successfully used as an on-line process control tool to investigate the textural properties and quality of bread products. This method can be recommended for both laboratory and industrial applications.

Indirect acoustic methods for determining porosity can be used in laboratory conditions, because they are faster when comparing them with mechanical measurement methods. When measuring the changes of liquid's level by using an acoustic level meter, the sample remains submersed the whole time. This way, the dynamics of water absorption (penetration) process can be recorded.

When using an indirect acoustic method for measuring porosity, additional information about the defects of the product's surface is obtained, along with the time, during which the product completely disintegrates.

When using acoustic methods to evaluate the porosity of bread, correct sample preparation is critical.

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A. Petrauskas

Ultragarsinio metodo taikymas duonos poringumui įvertinti

Reziumė

Akustiniai matavimai parodė, kad duonos gaminiai yra sudėtingos geometrinės formos, poringumo ir tankio struktūros. Todėl daugiausia dėmesio, akustiniais metodais įvertinant duonos poringumą, turi būti skiriama bandiniams paruošti. Apžvelgiamos galimybės taikyti tiesioginius ir netiesioginius akustinius metodus duonos struktūrai tirti ir įvertinti. Pabrėžiama, kad ultragarsiniai virpesiai ir bangos dėl savo fizinių savybių ir plataus darbinių dažnių intervalo yra tinkami poringoms maistinėms struktūroms, iš jų ir duonos gaminiams, tirti ir turi nemažai pranašumų, palyginti su kitais metodais. Teigiama ir pagrindžiama, kad akustinis aidolokacinis metodas suteikia kompleksinę informaciją tiek apie duonos tekstūrą, tiek apie duonoje vykstančius procesus vandens įgėrimo metu ir gali būti siūlomas taikyti praktikoje - aukštesnės mitybinės vertės produktams gauti, juos suskirstyti į rūšis pagal kokybę ir pasisavinimą. Pasiūlyta akustinį aidolokacinį metodą taikyti poringoms maistinėms struktūroms tirti tiesiogiai ir netiesiogiai. Apžvelgiamos akustinių metodų, taikomų sudėtingoms poringoms struktūroms tyrinėti, matavimo schemos. Straipsnis gali būti naudingas poringų struktūrų, ypač duonos gaminių, tyrėjams.

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