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Evaluation of porous food products by using ultrasonic methods

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Abstract

In this article, application of various methods for evaluating and measuring porous food structures are reviewed. It is noted, that ultrasonic vibrations and waves, due to their physical properties and wide frequency interval, can successfully be applied when analyzing porous food structures. These methods have a lot of advantages when comparing them with other non-acoustic measurement methods. We examine the application of the proposed acoustic echolocation method when evaluating porous food structures directly and indirectly. The possibilities to apply Lamb waves for evaluation of porous structures are also examined. The application of ultrasonic echolocation measurement method to evaluate porous structures is presented. This article can be beneficial to researchers, who specialize in evaluation of porous structures.
Keywords: ultrasonic measurement methods, physical-mechanical properties of porous food products, evaluation of porous products, acoustic echolocation method, direct and indirect acoustic measurement methods, asymmetrical Lamb wave.

Introduction

Porous food products make up a significant part of all of the food products being manufactured today. In general, from a physical-mechanical point of view, food is a composite material [1-10]. Due to the rising competition in food market share, and higher quality requirements, various methods of product quality control are being actively developed [11-26]. The largest portion of porous food consists mostly of grain products. Therefore, porosity is one of the most important quality properties of grain products [27-34].

Mechanical, optical, electrical, photographic, radio isotopic, X-ray, infrared and spectrometric methods can be used to determine the porosity [10-26]. We will briefly look into some of these methods.

Mechanical method has a drawback because it is non-technological and can not be applied in a non-interruptive production process. Today, porosity is determined by using a standardized mechanical method. This method is based on measuring the quantity of liquid, which is absorbed by pores of product. To determine the porosity, the sample of a product is submersed in liquid of 60 degrees Celsius and then is taken out after a given time. Before and after submersion the sample is weighed. By analyzing the weight difference and minding the volume of the sample, porosity is determined. This method requires accurateness and responsibility from an operator. When the sample is taken out of water, some liquid is being lost or the sample can simply break up. This method is destructive and produces little information. It does not determine in real time the quantity of water penetrating the sample. Also, it does not supply us information about the structure and defects of the sample's surface. This is very important when developing technology for high quality products.

Optical method enables us to evaluate only the surface of the product, but does not provide information about the inner structure. Sensitive radio isotopic method is not desirable, because there is a hazard to personal health and it has a negative influence on the products, which are analyzed using this method. Electrical method has influence on the product's chemical composition. Our tests showed that when electric current is passing through the product, conductive channels are being created. Because of these channels, large inaccuracies are present.

Spectrometric measurement methods [35-39] create 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 time interval between signals [40-42], monochromatic and spectral measurements of signal's amplitude [43-56]. Out of previously mentioned methods, 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 time interval between signals or, in other words, method based on measuring ultrasound velocity through materials. Also, method based on measuring signal's amplitude or, in other words, 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 a low velocity can easily be measured with high accuracy.

Today there is a lively interest in acoustic measurement methods [15-56]. These methods can be direct [40-56] or indirect [57-62]. The most widely used direct method is when parameter changes of 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.

Also, the direct method mentioned earlier can be combined with an acoustic echolocation method [63-67]. 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 [28,53,67].

By applying echolocation, we succeeded to develop a complex mechanical method for evaluating porous products [57-62]. We measured the quantity of absorbed liquid without taking the sample out of the measurement vessel. Also we determined the quantity of liquid penetrating the sample in 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.

To determine the density of porous materials, which are placed in thin-walled containers, Lamb waves can be used among other acoustic measurement methods [68-76].

Physical-mechanical parameters of porous materials

By the origin of their pores, porous materials can be separated into four main categories [11]:

a) when pores are separated from each other by layers of material;
b) when pores are interconnected;
c) when separating material is composed of fibers;
d) when separating material is composed of stripes.

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

The main physical-mechanical parameters of porous materials 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. Pattern describes the volume ratio of pores and separating layers. The density of a porous material [11]:

$$\rho_P = (m_g + m_l)/V_P = (\rho_g V_g + \rho_l V_l)/V_P \ , \qquad (1)$$

where m_g and m_l – mass of gas and of separating layer respectively; ρ_g and ρ_l – density of gas and of separating layer respectively; V_P, V_g, V_l – volume of porous material, of gas and of separating layer respectively.

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

$$\rho_P \approx \rho_l V_l / V_P = \rho_l / n \ , \qquad (2)$$

where n is a pattern of porous material and

$$n = V_P \ / V_g \ . \qquad (3)$$

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

In this case the density of porous materials:

$$\rho_P = (\rho_l V_l)/V_P = m_l / V_P \ . \qquad (4)$$

The pattern n of porous materials can be determined using an indirect electrical measurement method [11,15]:

$$n = X_l / (X_P B) \ , \qquad (5)$$

where X_l and X_p – specific electrical conductivity of separating layer and porous material respectively; B=1.5...3 – coeficient of a porous material.

The pattern of a porous material can also be determined using an indirect radio isotopic method [11]:

$$n = \rho_l / \rho_P = [\ln(N_0 / N_l)]/[\ln(N_0 / N_P)] \ , \qquad (6)$$

where N_0, N_P, N_l – pulse count through gas, porous material and separating layer respectively.

Porous materials are also characterized by the size of their pores. One of the direct methods for evaluating their size is photography [11]. By using this method it is possible to obtain information about the diameter and shape of pores, and about the width of the separating layer. The pores are photographed in direct or reflected light by magnifying them from 10 to 100 times.

It needs to be noted that various corrective multipliers need to be added to most of the expressions used for calculating physical-mechanical properties of porous materials. The corrective multipliers depend on the chosen measurement method. These expressions are most suitable when research is being done in laboratory conditions, but can not be used when designing automated systems used for manufacturing porous products.

Best suitable methods for designing automated control systems are: method based on measuring ultrasound velocity through materials [40-42] and method based on measuring ultrasound attenuation [42-47] through materials. Both of these methods require very little time to determine the final result. Also 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.

Usage of direct acoustic methods for evaluating parameters of porous materials

To determine the porosity of materials, ultrasonic methods can be used both directly [16-26] and indirectly [58-62]. A direct measurement method is when parameter changes of ultrasonic signal are measured before entering and after the signal has penetrated the porous product [22,23]. 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 from expression [49]:

$$A_{out} = K_0 A_{in} e^{-\alpha \rho_P l_P} , \qquad (7)$$

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

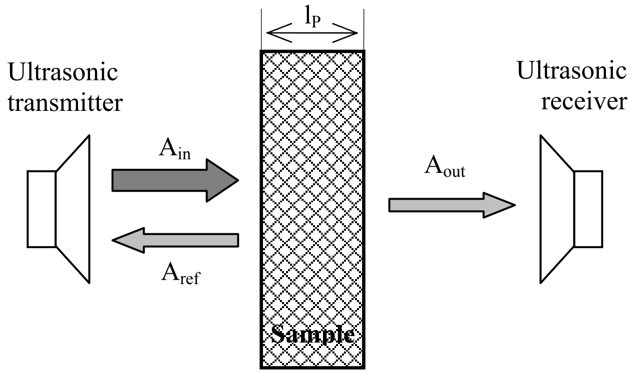

Fig.1. **Diagram of porous material evaluation by using a direct ultrasonic method**

This method can be improved by additionally measuring the amplitudes of signal, which has 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 from expression [62]:

$$\rho_P = \ln\left(A_{ref} / \left(3.422 \cdot A_{out}\right)\right) / 15.379 , \qquad (8)$$

where A_{ref} is amplitude of reflected signal.

To determine the porosity of food products, Lamb waves are an interesting option. Excitation and propagation of Lamb waves in elastic plates, placed in gas and liquid environments, is thoroughly researched in scientific papers [68-76]. We think that propagation of Lamb waves in plates was not yet researched, in case when a porous material is loaded on only one surface of a plate.

We propose an improved measuring method (Fig. 2) for porous materials. To improve the acoustic contact between the sample and the plate, a weight should be placed on top of a sample. The weight should be as high as possible, but should not change the physical-mechanical properties of the sample.

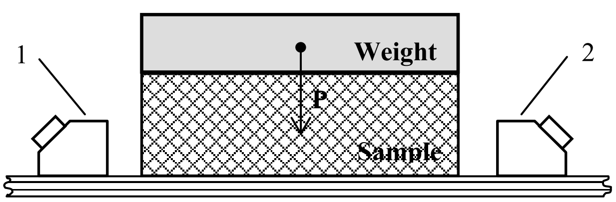

Fig.2. **Measuring diagram for porous materials by using Lamb waves; 1 – Lamb wave transmitter, 2 – Lamb wave receiver**

Regarding papers [62, 73-75] we propose to use an asymmetrical A_0 mode Lamb wave. The attenuation for this wave is directly proportional to the density of porous material and inversely proportional to the thickness of the plate. In practice, the thickness of the plate is known. Therefore the attenuation depends only on the density of a porous material. In practice it is advisable to use thin plates.

Usage of indirect acoustic methods for evaluating parameters of porous materials

The indirect measurement methods [57-62] are based on the property of a porous material to absorb liquid. Some time needs to pass until the pores are completely filled with liquid. 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 [78,79].

Measurement vessel is mounted on a hard and solid support. 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 is held constant.

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

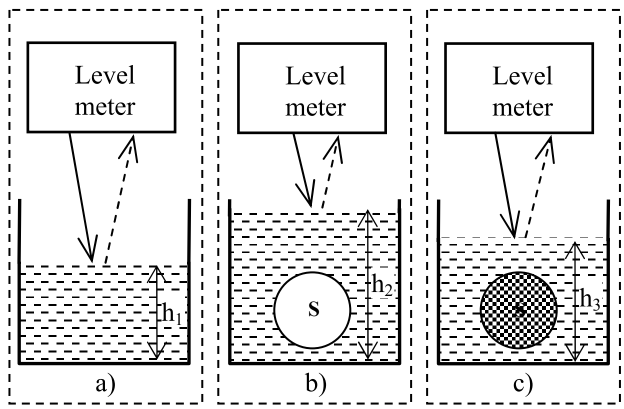

Fig.3. **Stages of the porosity evaluation process using acoustic echolocation**

Then a sample of a porous material is submersed in the water. The rise of the 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:

$$V_P = \left(h_2 - h_1\right) \cdot S , \qquad (9)$$

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

From the moment of the sample's submersion, the falling water level is being constantly recorded until it reaches 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 is the process. The penetration rate of the water is directly proportional to the porosity of the sample.

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

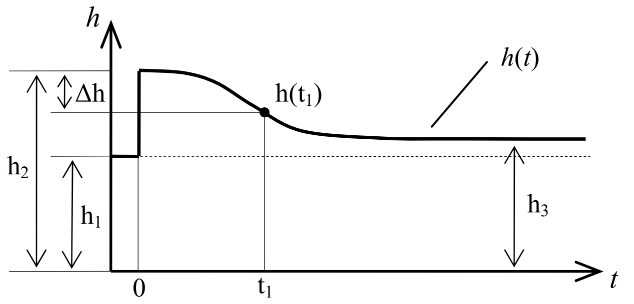

Fig.4. **Changes of the water level in the measurement vessel**

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

$$\Delta h = h_2 - h(t_1) \ , \quad (10)$$

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

In general, $\Delta h = h(t)$ is a function of water level change in time. 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:

$$V_g = (h_2 - h_3) \cdot S \ , \quad (11)$$

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 (3), (9) and (11), is calculated from expression:

$$n = V_p / V_g = (h_2 - h_1)/(h_2 - h_3) \ , \quad (12)$$

If the porous food product has a surface layer with little or no defects, than the water penetrates it slowly, and the change of 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.

The diagram of other indirect measurement method is shown in Fig. 5.

In the measurement unit the piston creates pressure P, which forces the volume of air through the porous material of a specified thickness (sample):

$$V_g = h_{p0} \cdot S \ , \quad (13)$$

where h_p is the height of the gas chamber; S is the surface area of the piston.

The time, during which the piston reaches the bottom of the chamber, along with the speed of piston's descent, are measured (Fig. 6).

Time t is inversely proportional to the porosity of the sample. By comparing the piston's descent times for various products, the differences of their porosity are

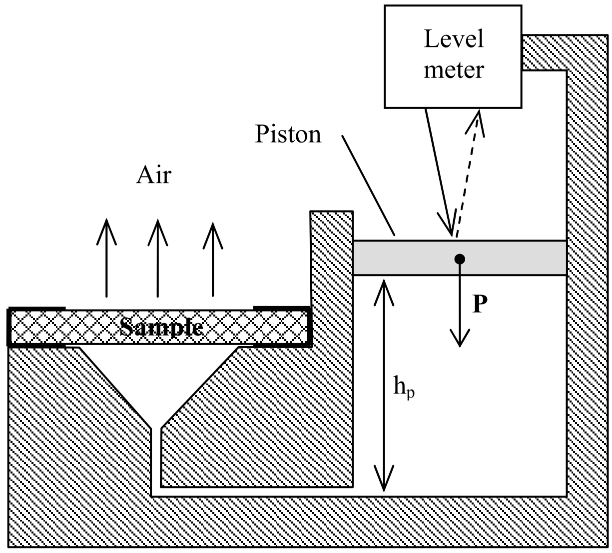

Fig.5. **Diagram of an indirect measurement method for determining the porosity of food products by using compressed air and acoustic level meter**

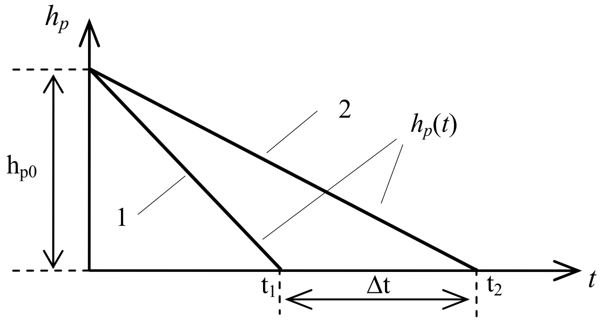

Fig.6. **Diagram of the piston's descent; 1 – the descent when the sample is more porous; 2 – the descent when the sample is less porous**

determined. The speed of the piston's descent (dh_p/dt) is used to determine the size of the product's pores, pore pattern and the thickness of separating layers between pores. This measurement method can also be applied when evaluating loose products (grains).

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 porous materials.

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.

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). Because of that, liquid's level in a measurement vessel changes very slowly. To detect such low changes in the liquid's level (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.

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 combining acoustic level meters for small distances with special technological measurement equipment, they can be used to determine porosity of materials. Therefore, such equipment can be used in research projects for the food industry.

Acoustic level meters for small distances can be used when designing measurement equipment to analyze and evaluate food products.

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A. Petrauskas

Poringų maisto produktų įvertinimas naudojant ultragarsinius matavimus

Reziumė

Apžvelgiamos galimybės taikyti įvairius metodus poringoms maistinėms struktūroms tirti ir matuoti. Pabrėžiama, kad utragarsiniai virpesiai ir bangos dėl savo fizinių savybių ir plataus darbinių dažnių intervalo pakankamai geri poringoms maistinėms struktūroms tirti ir turi nemažai pranašumų, palyginti su kitais metodais. Pasiūlyta akustinį aidolokacinį metodą taikyti tiesioginiam ir netiesioginiam poringų maistinių struktūrų tyrimui. Apžvelgiamos galimybės Lembo bangas naudoti poringoms struktūroms įvertinti, ultragarsinį aidolokacinį matavimo metodą taikyti poringoms struktūros tyrinėti. Straipsnis gali būti naudingas poringų struktūrų įvertinimais užsiimantiems tyrėjams.

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