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The application of ultrasound for the regulation of the starch gel viscosity

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Abstract

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The use of the ultrasonic exposure has an enormous potential for a wide range of processes in the food industry. Ultrasound allows modifying and improving the process characteristics of many food ingredients, widely used in food production. Among these food ingredients is potato starch. The purpose of this research is studying the influence of the low-frequency ultrasound on the viscosity of starch gel and the kinetics of changes in the properties of the starch gel depending on the time, the power of the ultrasonic exposure and the initial concentration of starch. The objects of the research are water solutions of potato starch exposed to ultrasonic treatment at the frequency of 22±1.65 kHz. To control the viscosity, we used SV 10 vibratory viscometer with the range of viscosities from 0.3 to 10000 mPa·s and the vibration frequency of 30 Hz. The viscosity measurement error is ±3%. It is established that the ultrasonic exposure can effectively increase or decrease the viscosity of starch solutions. Changing the time and the power of the ultrasonic exposure can help to reach a desired viscosity of the starch gel. The viscosity of the starch solution with the concentration of 5% can be twice increased in relation to the control sample while using ultrasonic treatment in the following conditions: power 120 W, exposure time 10 min (up to 20 mPa·s). It can be also reduced by 28-30% by increasing the ultrasonic exposure up to 20 min. The effects of reducing the amount of amylose in the starch gel are observed with an increasing power and duration of the ultrasonic exposure. Thus, ultrasound can be used to adjust the viscosity of starch solutions used in the food industries.

Keywords: potato starch; starch gel; physicochemical properties; viscosity of the starch gel

Introduction

In the food industry, starch is widely used as a thickener, gellant, emulsifier and stabilizer. The active use of starch is preconditioned by its naturalness, non-toxicity, as well as inexhaustibility and a constant renewal of its production sources. The starch production resources are such crops as potatoes, corn, rye, wheat, peas, rice, etc. A significant advantage of potato starch over other types is a higher gelling ability, the transparency of its pastes and their increased viscosity. Unlike cereals, potato starch contains a reduced amount of protein, does not contain lipids, has a lower caloric content and a larger mineral content.

At the same time, native potato starch does not always have the physical and chemical properties required in technological processes, it has a low water solubility and an undesirable retro gradation after gelatinization (Fu et al., 2012), which dictates the need for searching and adapting its effective modification methods.

Currently, several directions of starch modifications are known: chemical (acidic, oxidative hydrolysis); biochemical (enzymatic hydrolysis) and physical exposure (mechanical, temperature, ultrasonic and wave).

Ultrasonic exposure, as a physical starch modification method, shows significant advantages in terms of a higher selectivity, reduced use of chemicals and the treatment time, ease of the integration into the process stream, and, finally, serves as an environmentally friendly treatment (Ashokkumar et al., 2008; Naumenko et al., 2016; Shestakov et al., 2013; Zuo et al., 2009; Bai et al., 2016; Bykov et al., 2011). The use of the ultrasonic technologies in various areas of the food industry has been studied and described by such authors as Chandrapala et al. (2012), Knorr et al. (2004).

Several papers have been published, which deal with the application of ultrasonic treatment for various types of granular native starch or starch pastes. It follows from an extensive analysis of the available literature that ultrasonic treatment influences such physicochemical properties of starch as solubility, swelling degree, gelatinization temperature, depolymerization, viscosity and morphology (Chen et al., 2015; Czechowska-Biskup et al., 2005; Huang et al., 2007; Jambrak et al., 2010; Huang et al., 2007; Lima & Andrade, 2010; Montalbo-Lomboy et al., 2010; Wu et al., 2011; Zhu et al., 2012; Zuo et al., 2009, 2012).

A significant part of the studies is aimed at studying the physicochemical properties of the starch suspension treated with ultrasound (US). Singh et al. (2008) has found that ultrasonic treatment of an aqueous suspension of rice starch can reduce the average molecular weight. Kang et al observed a noticeable decrease in the viscosity (η) and the hydrodynamic radius (RH) of the corn starch gel (5 or 10% by weight) after ultrasonic treatment (frequency of 20 kHz). Yasuo et al. (2008) studied the decrease in viscosity of various starch gels (corn, tapioca, potato starch) after ultrasonic treatment (power 120 W, treatment time up to 30 min). The results showed that the viscosity was reduced at a low ultrasonic frequency and that the cavitation at a lower temperature was more effective than the mechanical effects at a higher temperature. According to Sujka et al. (2013), which exposed suspensions of potato, wheat, corn and rice starches in water and ethanol to untrasonic treatment (frequency 20 kHz, power 170 W, 30 min), ultrasonic treatment resulted in a decrease in the viscosity of the starch gel.

Thus, it is believed that the ultrasonic technology is an effective method of modifying the potato starch gel. In this study, the efficiency of the ultrasonic process of the potato starch gel modification was evaluated by measuring the viscosity changes under various conditions of ultrasonic treatment and the initial concentration of starch. This study is aimed at obtaining a mathematical model describing the process of adjusting the starch gel viscosity by changing its ultrasonic treatment conditions.

Materials and Methods

For the study, we used commercially available native potato starch (humidity 12.6%, amylose 21.4%), manufactured by Combined Complex of Food Concentrates LLC, Kopeisk, Chelyabinsk region, Russia. Distilled water was used.

Preparation of samples

To obtain *starch suspensions*, we used distilled water and dry starch. The suspensions were prepared with the starch content of 5 and 7% (on the dry matter). As a control, we considered a heat-treated starch paste prepared by brewing starch in the distilled water (5 and 7%) at the temperature of 60°C for 30 min with a continuous stirring at 160 rpm for a complete gelatinization of the starch granules.

Modified samples were prepared using ultrasonic treatment on the distilled water and dry native starch mix. Distilled water and starch were combined in the appropriate proportions, and the mixture was treated by ultrasonic waves immediately after introduction of starch.

Since ultrasound causes matter to heat up, our ultrasonic treatment was performed while mixture container located within a cooling sleeve. That allowed for temperature control, so the liquid was never heated above 60°C. All the samples were treated in the following conditions: frequency 22 ± 1.65 kHz, intensity 10 W/cm^2. The exposure power and time were changed according to Table 1.

The liquid volume comprised 100 ml.

Table 1. Experiment plant

Levels	Input parameters	
	Ultrasonic treatment time, min	Ultrasonic treatment power, W
Basic 0	3	80
Upper+	15	160
Lower–	27	240
Factor combination		
1	–	–
2	+	–
3	0	–
4	–	+
5	+	+
6	0	+
7	–	0
8	+	0
9	0	0

Volna-M UZTA-0.4/22-OM ultrasonic technological submerged device with an operating tool of a mushroom type was used as an ultrasound generator to treat the studied objects (Khmelev & Popov, 1997).

The ultrasonic oscillatory system is built on piezoelectric ring elements and made of VT5 titanium alloy. The operating principle is based on using the properties of high-intensity ultrasonic oscillations in liquid and liquid-dispersed media. The engineering solutions used are protected by the RF patent No. 2141386.

Ultrasonic treatment was performed in the conditions of a cooling jacket, the temperature was controlled, the rise was limited to no more than 60°C.

To measure the viscosity, we used SV-10 sinusoidal vibration viscometer (A&D Company Limited, Japan). The operating principle of the device is based on the fact that the viscosity is measured using the tuning-fork vibration method. The measurements are based on the electric current value necessary to maintain constant vibration amplitude of the viscometer sensor plates in a liquid medium. This method allows to makereal-time measurements with tracking the changes in the viscosity and the temperature of the sample.

The viscosity of the starch gel samples was continuously studied for 5 min. We evaluated the viscosity of both the starch gel samples just exposed to ultrasonic treatment and the samples after their accelerated cooling to the temperature of 20°C.

Statistical analysis

Response surface methodology (RSM) is a statistical technique to efficiently evaluate the significance of interactions among various parameters and determine the optimal combination based on an empirical model (Giovanni, 1983). RSM was widely used in food science field (Tahmouzi, 2014; Yu et. al., 2015).

Response surface methodology (RSM) Experimental design for optimization was performed using Mat Cad 13.0 for windows. The experimental data was fitted to a second order polynomial model as. The final equation with model terms and optimality conditions were calculated by the software. Confirmation experiments were still necessary to verify the validity of predicted values and the fitted RSM model.

Results and Discussion

It is known that the rheological characteristics of starch depend on the content of two polymers – amylose and amylopectin. Their ratio determines the ability of starch to dissolve during heating with the formation of viscous colloidal systems called pastes. These polymers are formed in the polymerization of glucose molecules, while amylose has a linear structure and starch with a high amylose content shows the gelling properties, amylopectin is very highly branched and greatly contributes to the increase in viscosity.

Whereas the starch granules almost do not dissolve in cold water, and when heated they swell strongly, during a prolonged boiling, about 15–25% of starch pass into the solution as a colloid. When the starch suspension is exposed to heat treatment, the structure of the starch grains changes (Figure 1).

With an increase in the temperature of aqueous starch suspensions of over 40°C, the hydrogen bonds of the molecules in the starch grain partially break, which leads to a change in its microstructure. At the same time, the hydration of amylose and amylopectin sharply increases and, accordingly, the grains increase in size – the so-called "swelling" occurs. When the temperature is raised to 60°C, amylose partially passes into the solution, and amylopectin basically remains in the undissolved state. When the grains are destroyed, the crystalline part of the grains is destructed, polysaccharides pass into the solution, and the gelatinization process begins. The processes of swelling and gelatinization are accompanied by a change in the viscosity of the suspension and flow differently for different types of starches (Khalikov et al., 2015; Rosalina & Bhattacharya, 2002; Ruskina et al., 2017).

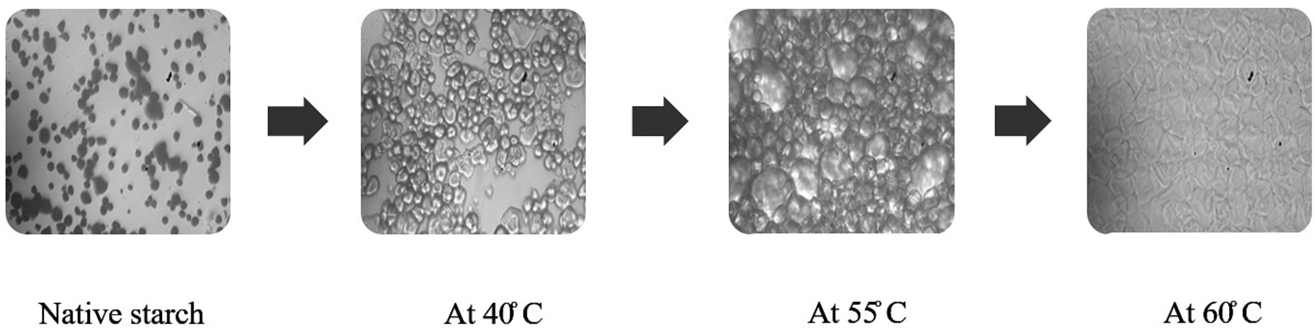
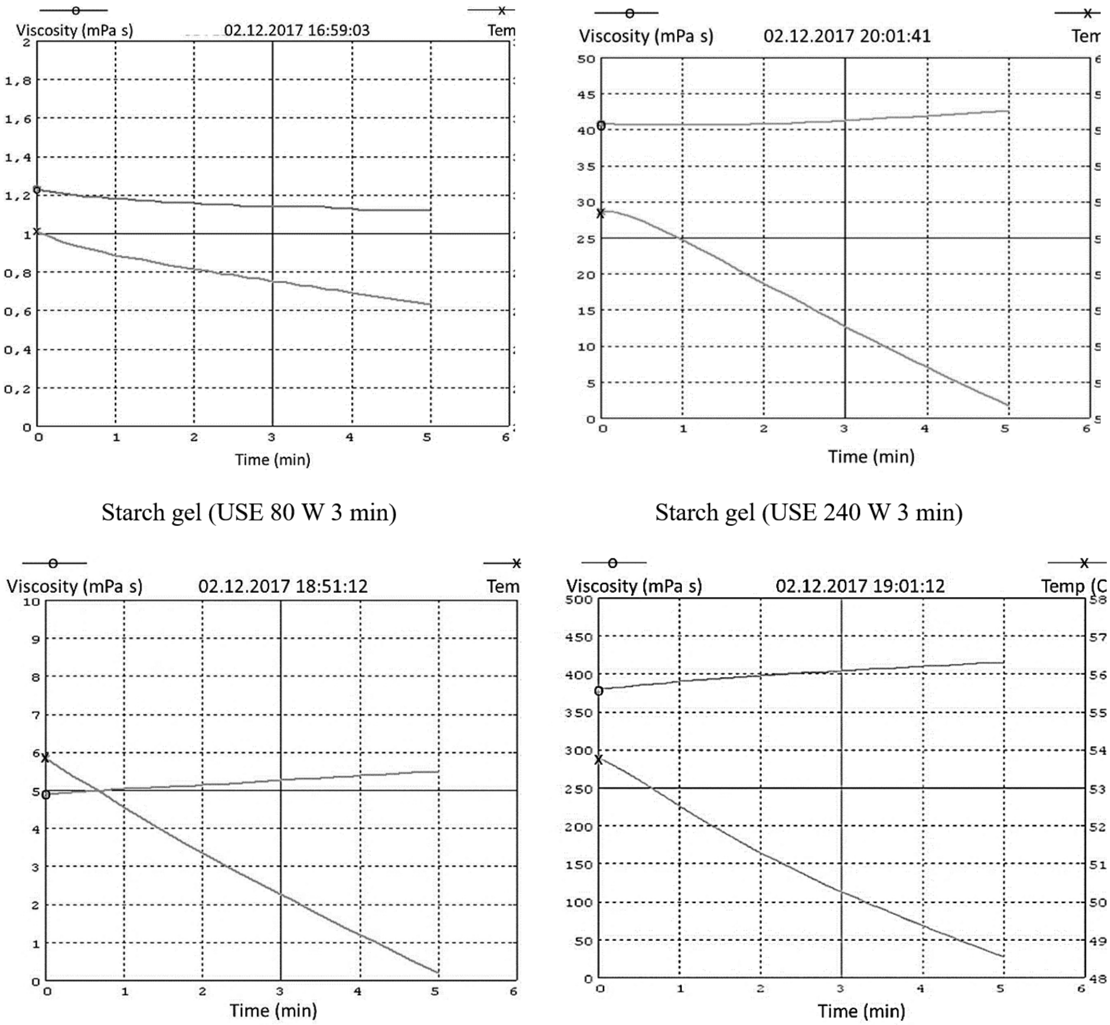


Fig. 1. Scheme of the process changes of the starch grains with heating (Ruskina, 2015)



Starch gel (USE 80 W 3 min)

Starch gel (USE 240 W 3 min)

Starch gel (USE 180 W 5 min)

Starch gel_Control

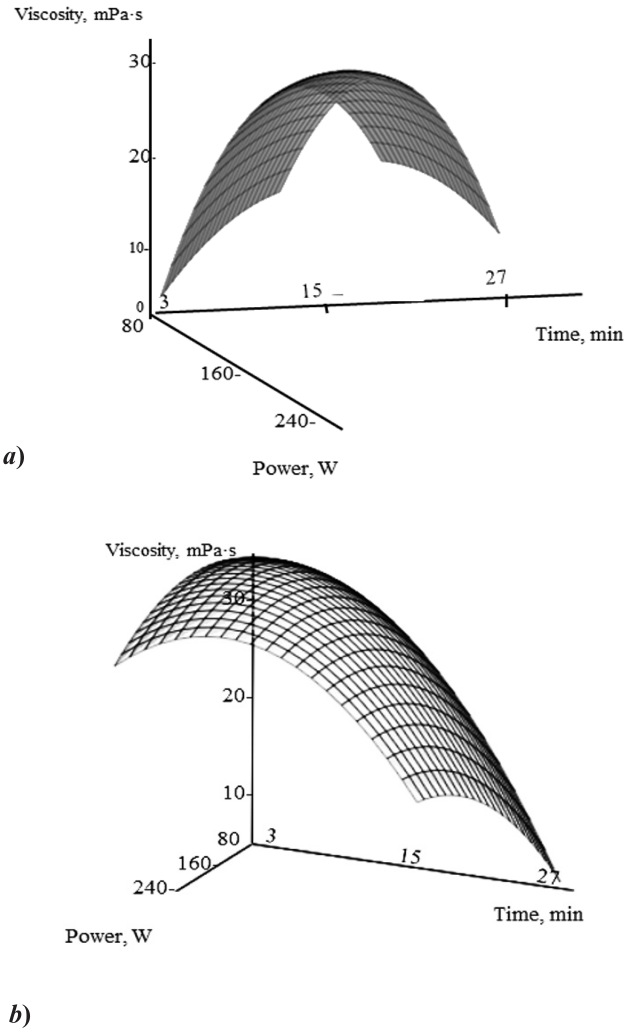
Fig. 2. Curves of measuring the viscosity of potato starch gel samples

The gel formed during heating of starch is a colloidal system (starch dispersion), in which the dispersed phase is the swollen starch grains, and the dispersion medium is formed by starch dissolved in water (mainly amylose). The viscosity of the starch dispersion is closely connected with the volume fraction and deformability of the dispersed swollen starch grains. In this regard, the viscosity of the continuous phase and the interaction between the phases determine the rheological properties of the entire system.

All the obtained curves of the apparent viscosity of the starch gel samples under study were of a similar nature (Figure 2), but differed in the viscosity value and the rate of its change in time.

In real production conditions, when starch gels are used, there is a need for a strict control of their viscosity in order to ensure the equilibrium state of individual components in the system and the formation of good organoleptic properties of the product. To study the rheological characteristics of starch gels, their apparent viscosity was evaluated. The results of determining the apparent viscosity in different ultrasonic treatment conditions for the starch gels with different initial concentrations of starch, which were freshly treated and cooled to 20°C were used to build the two-factor models shown in Figure 3.

The presented results show that starch suspensions are very sensitive to ultrasonic cavitation. It has been estab-



$$Y = -2.451\cdot10^{-4}X_1^{2} - 0.093\,X_2^{2} - 4.643\cdot10^{-3}\,X_1 X_2 + 0.175X_1 + 3.672X_2 - 16.795$$

$$Y = -2.995\cdot10^{-4}X_1^{2} - 0.017\,X_2^{2} - 1.302\cdot10^{-4}X_1 X_2 + 0.105X_1 + 0.323X_2 + 19.21$$

Fig. 3. Dependence of the viscosity of starch gels on the power and duration of ultrasonic treatment (*a* – starch gel with the initial concentration of 5%, immediately after the treatment, *b* – starch gel with the initial concentration of 5% cooled to 20°C)

lished that ultrasonic treatment can effectively change, both increase and decrease the viscosity of starch solutions. A change in the time and the power of ultrasonic exposure can provide the desired viscosity of the starch gel. The viscosity of the starch gel with the initial starch concentration of 5% can be increased by about two orders of magnitude as compared to the control sample when using ultrasonic treatment in the following conditions: power 120 W, exposure time 10 min (up to 20 mPa·s). It can be also reduced by 28-30% by increasing the ultrasonic exposure to 20 min.

Conclusions

The obtained results give evidence of a pronounced influence of the ultrasonic treatment process on the rheological characteristics of the potato starch gel.

The presented results show that the aqueous suspension of native potato starch is very sensitive to ultrasonic cavitation. We obtained the working models that allow to predict the final viscosity of the starch gel depending on the initial concentration of potato starch, various conditions of ultrasonic treatment, and in different temperature conditions for its use.

Thus, ultrasound can be effectively used to adjust the viscosity of starch solutions used in the food industry.

The study could provide some information for optimizing the industrial production process of related functional starch products.

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