Journal of Food Science and Technology (Iran)

Homepage: www.fsct.modares.ir

Scientific Research

Effects of ultrasonic intensity and duration on the apparent viscosity, consistency coefficient, and flow behavior index of guar gum solution

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ARTICLE INFO

Article History:

Received:2023/11/1
Accepted: 2023/12/18

Keywords:

Apparent viscosity;
Guar gum;
Power law;
Rheological models;
Ultrasound.

DOI: 10.22034/FSCT.20.140.193

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ABSTRACT

Guar gum is a biopolymer that is used in the food industry as a thickener, stabilizer, and edible coating. The aqueous solution of this gum has high viscosity and pseudoplastic behavior. This research aimed to analyze the impacts of sonication at different intensities (0, 75, and 150 W) and time intervals (0, 5, 10, 15, and 20 min) on the viscosity and rheological behavior of guar gum solution. The results showed that the apparent viscosity of guar gum solution (untreated sample) reduced from 0.070 to 0.030 Pa.s with increasing shear-rate from 12.2 s^{-1} to 134.5 s^{-1}. Also, the apparent viscosity of guar gum solution reduced from 0.046 to 0.021 Pa.s with increasing the sonication time from 0 to 20 min (shear-rate=49 s^{-1} and power= 150 W). Various rheological equations (Power law, Bingham, Herschel-Bulkley, Casson, and Vocadlo) were employed to fit the empirical values, and the findings of the current study confirmed that the Power law model was the best fit to explain the flow behavior of guar gum solutions. The consistency coefficient of guar gum solution significantly reduced from 0.202 $Pa.s^n$ to 0.063 $Pa.s^n$ ($p<0.05$) with increasing sonication time from 0 to 20 min. Furthermore, the consistency coefficient of guar gum solution decreased considerably ($p<0.05$) while the ultrasonic power enhanced. The flow behavior index of guar gum solution increased significantly ($p<0.05$) while the intensity and duration of ultrasound treatment increased.

1. Introduction

It is becoming increasingly common to utilize thickeners in food products to improve their rheological and textural characteristics as well as to increase their quality attributes [1]. Guar gum is a galactomannan consisting of a mannose spine with galactose side groups. This gum is a composite biopolymer, non- ionic, eco-friendly, and widely available, which has spurred the food industry to utilize guar gum as an edible coating or a thickening, stabilizing, suspending, emulsifying, and gelling agent. The aqueous solution of this gum produces high viscosity and pseudoplastic behavior [2-5].

The ability to modify food and increase the shelf-life by enhanced stability using nonthermal process is of interest to many food companies [6]. Today sonication process is used as a new green tool with unique impacts on food preservation and processing. The influence of ultrasonic waves is due to cavitation, heating, and shear-stress of the samples [7-9]. One of the more recent uses of sonication is to modify the composition and structural properties of polymers such as hydrocolloids (gums). Changes in the structure of gums lead to changes in their functional characteristics and rheological behavior [10-16]. The results of a study by Farizadeh and Abbasi [10] have shown that it is possible to alter and modify the qualitative properties of gums with the help of ultrasound and according to desired factors. In addition, process conditions should be considered different depending on the intended use of gums. Raoufi, *et al.* [11] reported that the application of high power sonication enhanced the solubility of Persian and Tragacanth gums by 90%. Li, *et al.* [12] results suggest that sonication is an effective means of polysaccharide (konjac glucomannan) degradation without considerable structural destruction.

Modifying food compounds to overcome problems encountered during use them has been one of the current topics in food research. Among the modification methods, physical methods are widely preferred in terms of green and environmentally friendly technology [17]. One of the recent applications of sonication is to modify the composition and structural properties of hydrocolloids [18, 19]. The aim of this work was to study the influence of ultrasonic treatments at different intensities (at 3 levels of 0, 75, and 150 W) and durations (at 5 levels of 0, 5, 10, 15, and 20 min) on the rheological properties, viscosity, consistency coefficient, and flow behavior index of guar gum solution.

2. Materials and methods

2.1. Preparation of gum solutions

Guar gum powder (food grade) was prepared from Abdullabhai abdul kader Co. (India). The guar gum solutions (0.30%, w/v) were provided by solving the powder of gum in distilled water using a stirrer. Provided guar gum solution was stored for 1 h at 25°C to complete hydration process of the gum.

2.2. Sonication process

To apply the sonication treatments on the guar gum solution, the tank of the ultrasonic bath (40 kHz, vCLEAN1-L6, Backer, Iran) was filled with 2 L of guar gum solution (0.30%, w/v) at 25°C. Ultrasonic waves were applied to the solution inside the device at three power levels (0, 75, and 150 watts) and five various intervals (0, 5, 10, 15, and 20 min).

2.3. Apparent viscosity

The apparent viscosity of unsonicated and sonicated guar gum solutions was calculated by utilization of a rotational viscometer (Brookfield, DV2T, RV, USA) after each treatment. The viscosity and shear-stress of guar gum solutions at different shear-rates (12-134.5 s^{-1}) were studied using UL Adapter Kit at 25°C [20].

2.4. Rheological properties

Various viscous flow models, including Power law, Bingham, Herschel-Bulkley, Casson, and Vocadlo were used to match the empirical shear-stress and shear-rate data of the sonicated and unsonicated guar gum solutions [18, 19]. Data modeling was carried out with multilinear and nonlinear regression analysis parameters and functions associated with various equations calculated from empirical values using Matlab software (version R2012a).

2.5. Statistical analysis

Means were compared via Duncan's multiple range test using an alpha level of 0.05 for significant effects, using SPSS Version 21.

3. Results and discussion

3.1. Apparent viscosity

Ultrasonic induces viscosity change resulting in distinct functions and better processing properties [21]. The influence of sonication intensities on the apparent viscosity of guar gum solutions as a function of shear-rate are demonstrated in Figure 1. The application of ultrasound to the guar gum solution reduces its viscosity. This behavior was observed at all conditions and 150 W power leading to a greater reduction in gum viscosity. The results demonstrated that the average apparent viscosity of guar gum solution reduced from 0.041 to 0.022 Pa.s with increment in ultrasonic power from 0 to 150 W (20 min). The decrease in the viscosity of gums when exposed to ultrasonic waves can be attributed to the breakdown of their large molecular structures into smaller shapes due to the cavitation effect [13, 22].

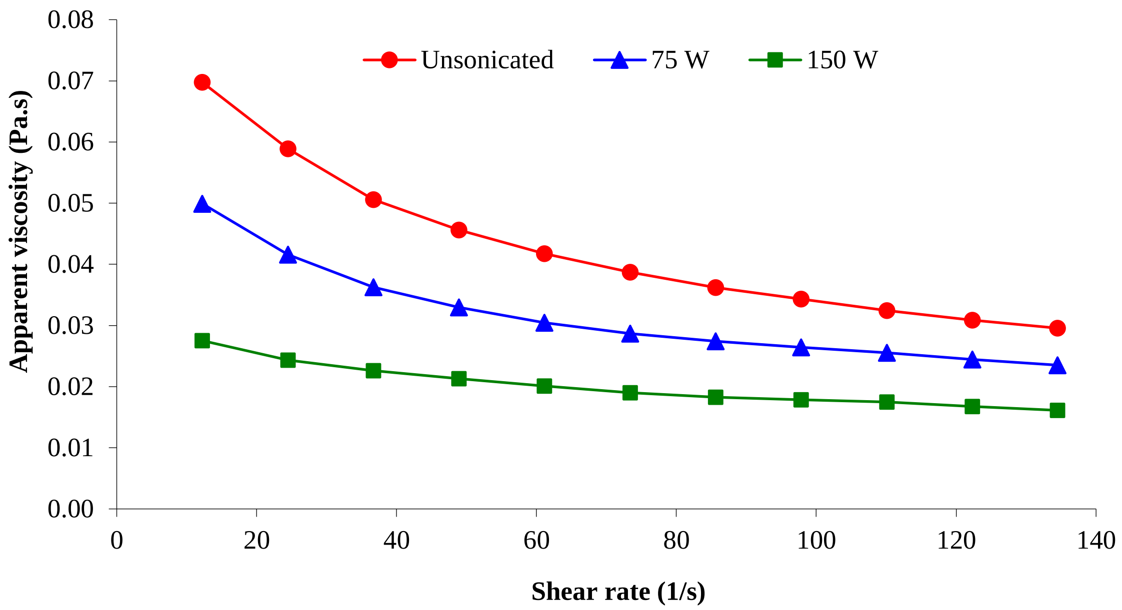
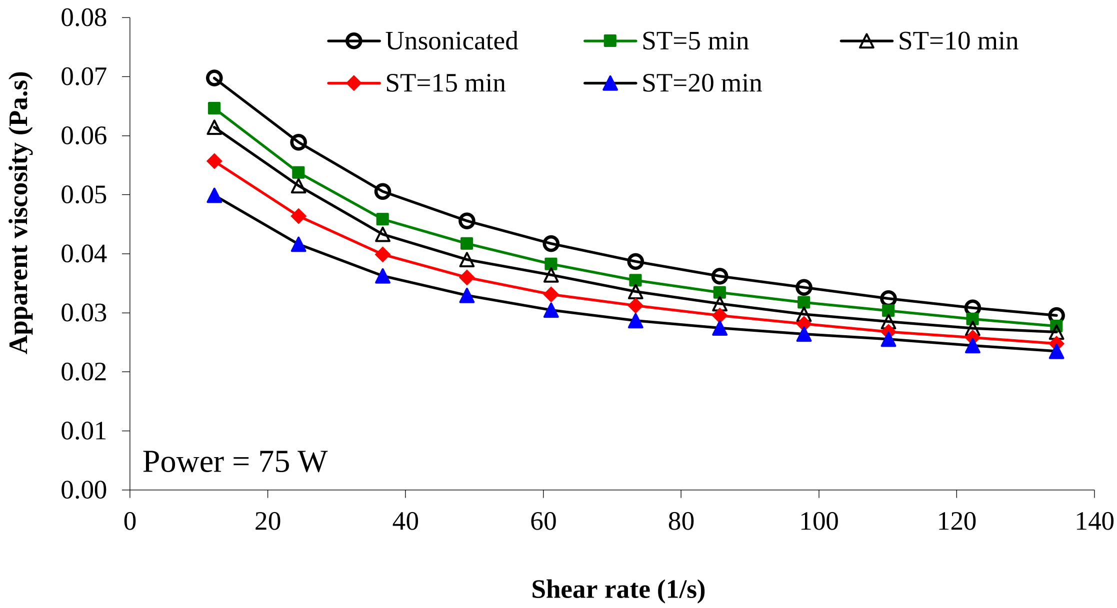


Fig. 1. Impact of sonication power on the apparent viscosity of guar gum solution (sonication time=20 min).

In the case of pseudoplastic fluids, high-shear microcurrents lead to reduced viscosity. As reported by Cui [23], the viscosity of the gum dispersion reduced with enhancing the shear-rate as the number of entangled chains decreased at high shear-rates. The shear-rate dependence of the apparent viscosity of guar gum solutions under different conditions is shown in Figure 1. It is seen that the apparent viscosity of guar gum solution decreases as the shear-rate increases. The apparent viscosity decreased markedly from 0.050 Pa.s to 0.024 Pa.s with the shear-rate increased from 12.2 to 134.5 s^{-1} (sonication power=75W and time=20 min). Consistent with the results of this research, Sarraf, *et al.* [24] confirmed that the viscosity of xanthan gum solution reduced with enhancing shear-rate, indicating pseudoplastic behavior. Farizadeh and Abbasi [10] studied the flow behavior of sonicated and unsonicated locust bean gum solutions and their results demonstrated that the apparent viscosity of all samples reduced as the shear-rate enhanced, showing their pseudoplastic behavior.

[DOI: 10.22034/FSCT.20.140.193]

Ultrasound is capable of breaking down complex hydrocolloids into their smaller molecular components thereby reducing the viscosity of the solution prepared from these hydrocolloids [12]. The impact of sonication time on the apparent viscosity of guar gum solution as a function of shear-rate and sonication power (75 and 150 W) is shown in Figure 2. As seen in these charts, the viscosity of the guar gum solutions decreased with increasing ultrasonic treatment time. At all shear-rates, the viscosity of the unsonicated guar gum solution was higher than that of the proceed samples. Compared with the sonicated samples, the shear-rate has a greater influence on the unsonicated sample. The maximum apparent viscosity involved the control sample and the minimum apparent viscosity related to the samples sonicated for 20 min. The influence of ultrasonic waves on the rheological properties of locust gum solution was investigated by Farizadeh and Abbasi [10]. Their results demonstrated that with enhancing ultrasonic treatment time, the viscosity of the locust bean gum solution decreased. Salehi and Inanloodoghouz [19] studied on the rheological properties and color indexes of ultrasonic treated aqueous solutions of basil, Lallemantia, and wild sage gums. Their results showed that the apparent viscosity of aqueous solutions of these gums decreased with increasing shear-rate. In addition, the apparent viscosity of aqueous solutions of these gums reduced with increasing the sonication time from 0 to 20 min.



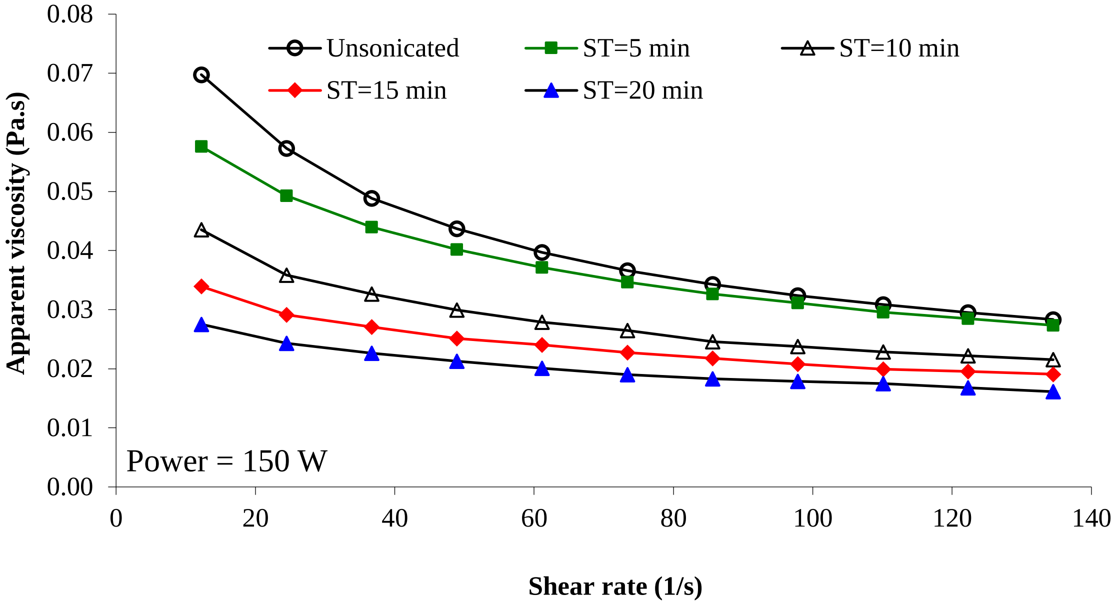


Fig. 2. Impact of sonication time (ST) on the apparent viscosity of guar gum solutions.

3.2. Rheological model parameters

Rheological properties play an important role in process design. In numerous recent researches, sonication has been used for controlled degradation of natural gums resulting in changes in viscosity and rheological properties [10, 12, 13]. Table 1 demonstrates the statistical parameters obtained to verify the fit of each rheological model to the observed shear-rate/shear-stress data of guar gum solution. The statistical parameters reported in this table confirm that the Power law model is appropriate to explain the rheological behavior of untreated and treated guar gum solution. The Power law model showed a good fit with the highest r-value and the lowest SSE (sum of squared error) and RMSE (root mean squared error) values for all solutions compared to that of the other equations. Furthermore, Figure 3 demonstrates the fit of different rheological models to the experimental data. This figure confirms that the Power law equation can model well the rheological behavior of untreated and sonicated guar gum solution. The Power law was considered to be the suitable model for characterizing the rheological behavior of many gum solutions such as xanthan gum solution at different temperatures (20–100°C) and concentrations (0·3–1·3%) [25], and concentrated xanthan gum solution [26].

Table 1- The statistical parameters obtained to verify the fit of each rheological model

Model name	Model constants	r	SSE	RMSE
Power law	$k=0.1163$ Pa.s^n $n=0.6754$	0.9998	0.00217	0.01559
Bingham	$\tau_{0B}=0.539$ Pa $\eta_B=0.0205$ Pa.s	0.9947	0.07339	0.09030
Herschel-Bulkley	$\tau_{0H}=2.31E-8$ Pa $k_H=0.1163$ Pa.s^n $n_H=0.6754$	0.9998	0.00219	0.01653
Casson	$\tau_{0C}=0.1867$ Pa $\eta_C=0.1179$ Pa·s	0.9984	0.02201	0.04945
Vocadlo	$\tau_{0V}=2.65E-7$ Pa $n_V=0.6716$ $k_V=0.0417$ Pa$^{1/n}$.s^n	0.9997	0.18850	0.15350

[DOI: 10.22034/FSCT.20.140.193]

* Where, r is correlation coefficient; SSE is sum of squared error; RMSE is root mean squared error.

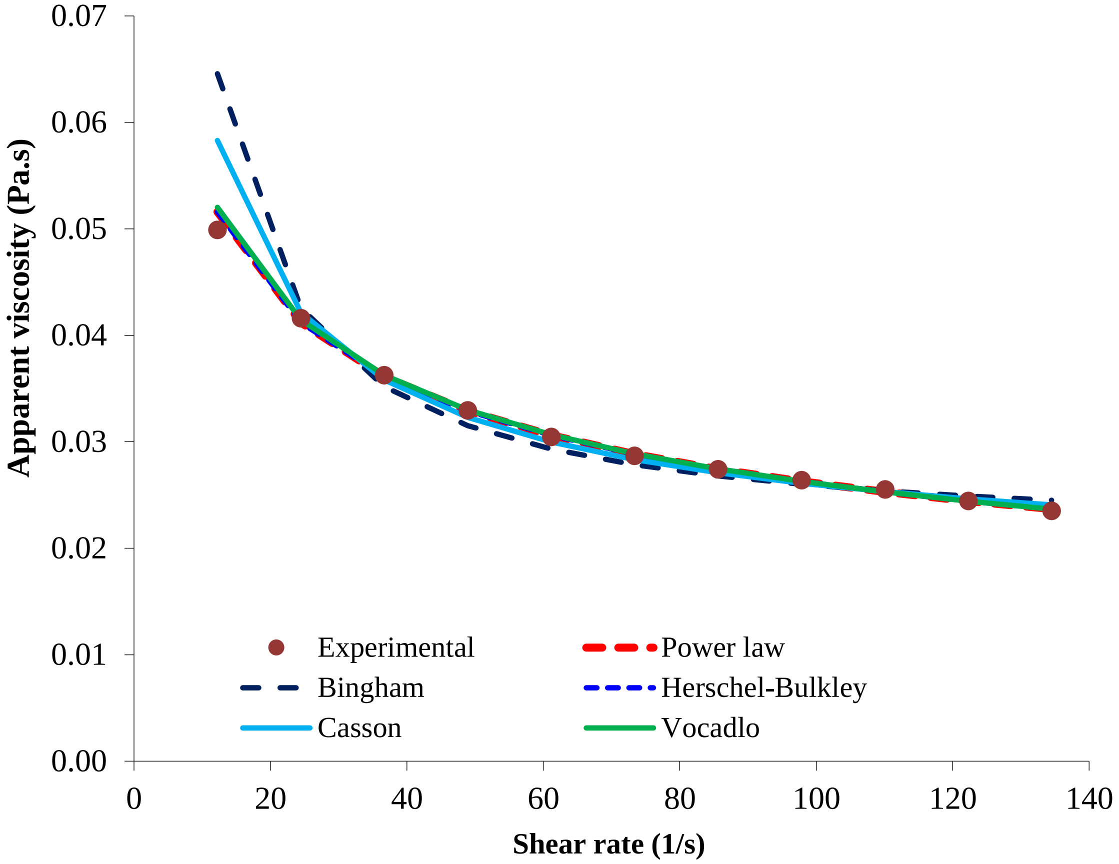


Fig. 3. Fitting ability of different rheological models to experimental data (75W and 20 min).

The rheological behavior of untreated and treated guar gum solutions was fitted with the Power law model. The determined constant coefficients of the Power law equation consisting of k and n are presented in Table 2 together with the corresponding statistical error values (r and RMSE) for all solutions. Mean values of SSE, RMSE, and r for all guar gum solutions ranged from 0.0018-0.0207, 0.0141-0.0479, and 0.9986-0.9999, respectively. Based on the Power law model, all guar gum solutions demonstrated marked pseudoplastic behavior, described by the flow behavior index values lower than 0.75 under all conditions. The results confirmed that the values of the consistency coefficient ranged from 0.055 Pa.s^n to 0.215 Pa.s^n and the flow behavior index ranged from 0.59 to 0.75 (indicating the pseudoplastic nature of guar gum solution).

Table 2. Impact of sonication power and treatment time on the Power law model parameters

Sample	Sonication power (W)	Sonication time (min)	k (Pa.s^n)	n	SSE	r	RMSE
1	75	0	0.2027	0.6047	0.0148	0.9992	0.0397
2	75	5	0.1837	0.6134	0.0078	0.9995	0.0292
3	75	10	0.1746	0.6182	0.0074	0.9996	0.0284
4	75	15	0.1569	0.6392	0.0109	0.9994	0.0333
5	75	20	0.1186	0.6775	0.0056	0.9996	0.0241

[DOI: 10.22034/FSCT.20.140.193]

6	150	0	0.2024	0.5993	0.0104	0.9994	0.0339
7	150	5	0.1518	0.6465	0.0095	0.9995	0.0304
8	150	10	0.0936	0.6944	0.0043	0.9996	0.0217
9	150	15	0.0725	0.7258	0.0031	0.9997	0.0183
10	150	20	0.0634	0.7417	0.0061	0.9993	0.0246

* Where, SSE is sum of squared error; r is correlation coefficient; RMSE is root mean squared error.

The rheological or flow properties (in the Power law model) are solved by parameters such as the flow behavior index and consistency coefficient [18]. The impact of sonication power on the consistency coefficient of guar gum solutions is shown in Figure 4. From the results, sonication considerably decreased the consistency coefficient of guar gum solutions. The consistency coefficient of the guar gum solutions was found to be lower than 0.215 $Pa.s^n$ and was significantly affected by sonication treatment. This behavior was observed at all conditions and 150 W power leading to a greater reduction in the consistency coefficient. The results demonstrated that the consistency coefficient value of guar gum solution reduced from 0.202 to 0.063 $Pa.s^n$ with enhancing ultrasonic power from 0 to 150 W (sonication period=20 min).

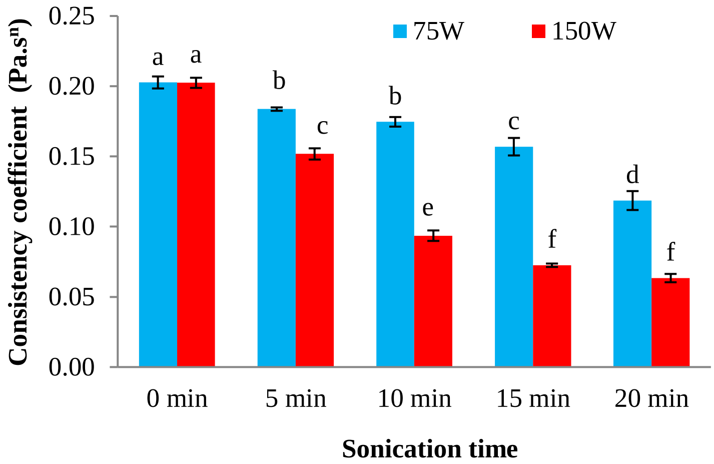


Fig. 4. Impact of sonication power and duration on the consistency coefficient of guar gum solutions.

Various letters above the columns indicate a significant differences ($p<0.05$).

The rheological characteristics of hydrocolloids are extremely important because of the structural, functional and textural properties of food products [27, 28]. As seen in Figure 4, the consistency coefficient value of the samples decreased significantly with increasing ultrasonic duration ($p<0.05$). The highest k value involved the unsonicated sample and the lowest k value related to the samples sonicated for 20 min. The effect of sonication on the rheological behavior of sugar beet pectin was examined by Yang, *et al.* [29]. Their results demonstrated that the values of viscosity and consistency coefficient of the samples reduced after sonication. In addition, the apparent viscosity decreases as the shear-rate increases over the test range and shows a pseudoplastic fluid characteristic.

Ultrasound modification is proposed as a superior strategy to achieve good hydrocolloids with valuable physicochemical characteristics and molecular structure [14]. It is clear from the Power law model that a non-Newtonian fluid ($n\neq1$) with pseudoplastic behavior has a value of n lower than 1 [21]. The impact of

[DOI: 10.22034/FSCT.20.140.193]

sonication power on the flow behavior index of guar gum solutions is shown in Figure 5. The application of ultrasound to the guar gum solution increases its n value (decreases in pseudoplastic behavior). This behavior was observed at all conditions and 150 W power leading to greater increases in the n values. The results demonstrated that the n value of guar gum solution enhanced from 0.599 to 0.742 with increasing ultrasonic power from 0 to 150 W (sonication period=20 min).

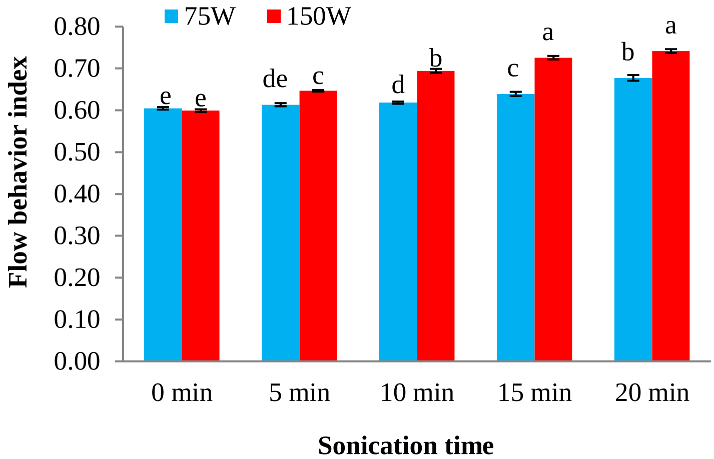


Fig. 5. Impact of sonication power and duration on the flow behavior index of guar gum solutions.

Various letters above the columns indicate a significant differences ($p<0.05$).

The rheological characteristics of food hydrocolloids are strongly influenced by temperature, pressure, concentration, and physical state of dispersion [6, 17]. The impact of sonication duration on the flow behavior index of guar gum solution is shown in Figure 5. As seen in this chart, the n values of the samples significantly increased (less shear thinning solution) with increasing ultrasonic treatment time ($p<0.05$). The lowest n value involved the unsonicated sample and the highest n value related to the samples sonicated for 20 min. In this study, the n value increased significantly from 0.605 to 0.677 with the sonication time increased from 0 to 20 min ($p<0.05$) (power=75W). The change in the k and n indexes of the guar gum solution may be due to the structural change of the guar gum during ultrasound treatment. Ultrasound energy is known to drive a number of physicochemical reactions that lead to altered functional characteristics of hydrocolloids in liquid food systems [22]. The influence of sonication on the rheological behavior and interactions of chitosan-sodium alginate solution was studied by Xu, *et al.* [30]. Their results demonstrated that the sonication considerably reduces the viscosity and consistency coefficient and enhances the flow behavior index of the mixture, leading to a modification in the flow behavior from pseudoplastic to near-Newtonian behavior.

4. Conclusion

The sonication process has been commonly employed in the food industry due to its many physicochemical impacts. In the current work, the impact of ultrasonic intensities and durations on the rheological characteristics of guar gum solution was examined. This gum demonstrated the pseudoplastic flow behavior. The application of ultrasound to the guar gum solution reduces its viscosity. In addition, the viscosity of the guar gum solution is reduced with increasing ultrasonic treatment time. The Power law model proved to be the most appropriate equation to explain the rheological behavior of guar gum solutions over the entire empirical range. The consistency coefficient value of the samples was significantly reduced with an increment in ultrasonic process duration ($p<0.05$). The

[DOI: 10.22034/FSCT.20.140.193]

lowest n value involved the unsonicated sample and the highest n value related to the samples sonicated for 20 min. The results of this work suggest that sonication offers a good opportunity to alter the physicochemical characteristics of guar gum solution and can significantly improve the rheological properties of this gum by sonication.

5. Acknowledgements

The present study was financially supported by Bu-Ali Sina University, Hamedan, Iran.

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[DOI: 10.22034/FSCT.20.140.193]

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سایت مجله: www.fsct.modares.ac.ir

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اطلاعات مقاله

تاریخ های مقاله :

تاریخ دریافت: ۱۴۰۲/۸/۱۰

تاریخ پذیرش: ۱۴۰۲/۹/۲۷

کلمات کلیدی:

صمغ گوار،

فراصوت،

قانون توان،

مدل‌های رئولوژیکی،

ویسکوزیته ظاهری.

DOI: 10.22034/FSCT.20.140.193

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چکیده

صمغ گوار یک بیوپلیمر است که در صنایع غذایی از آن به‌عنوان عامل غلیظ کننده، تثبیت‌کننده و پوشش خوراکی استفاده می‌شود. محلول آبی این صمغ دارای ویسکوزیته بالا و رفتار شبه پلاستیک است. این پژوهش با هدف تجزیه و تحلیل اثرات فراصوت در شدت‌ها (۰، ۷۵ و ۱۵۰ وات) و بازه‌های زمانی (۰، ۵، ۱۰، ۱۵ و ۲۰ دقیقه) مختلف بر ویسکوزیته و رفتار رئولوژیکی محلول صمغ گوار انجام شد. نتایج نشان داد که ویسکوزیته ظاهری محلول صمغ گوار (نمونه تیمار نشده) با افزایش سرعت برشی از ۱۲/۲ به ۱۳۴/۵ برثانیه، از ۰/۰۷۰ به ۰/۰۳۰ پاسکال ثانیه کاهش یافت. همچنین، ویسکوزیته ظاهری محلول صمغ گوار با افزایش زمان فراصوت از ۰ تا ۲۰ دقیقه، از ۰/۰۴۶ به ۰/۰۲۱ پاسکال ثانیه کاهش یافت (سرعت برش = ۴۹ برثانیه و توان = ۱۵۰ وات). معادلات رئولوژیکی مختلف (قانون توان، بینگهام، هرشل بالکلی، کاسون و وکادلو) برای برازش مقادیر تجربی مورد استفاده قرار گرفتند و یافته‌های مطالعه حاضر تأیید کرد که مدل قانون توان بهترین برازش برای توضیح رفتار جریان محلول صمغ گوار را ارائه می‌دهد. ضریب قوام محلول صمغ گوار با افزایش زمان فراصوت از ۰ تا ۲۰ دقیقه به‌طور معنی‌داری از ۰/۲۰۲ $Pa.s^n$ به ۰/۰۶۳ $Pa.s^n$ کاهش یافت (p<۰/۰۵). علاوه بر این، ضریب قوام محلول صمغ گوار با افزایش توان فراصوت به‌طور قابل‌توجهی کاهش یافت (p<۰/۰۵). شاخص رفتار جریان محلول صمغ گوار نیز با افزایش شدت و زمان تیماردهی با فراصوت به‌طور معنی‌داری افزایش یافت (p<۰/۰۵).