Acoustic fields of acid suspensions containing cassava bagasse: estimating attenuation and the dependence on physical properties

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Abstract: High-intensity sonication can enhance the biomass conversion into bioethanol. So, it is interesting to evaluate how the acoustic energy behaves when treating residues with high aggregated value such as cassava bagasse (CB). For this, calorimetric method was used to estimate acoustic energy and the efficiency of electrical conversion in acid suspensions containing different CB concentration (2-10%) under input power from 160 to 400 W at 1.5–5.5 cm from the sonotrode. Acoustic intensity varied from 12.90 to 68.57 $W \cdot cm^{-2}$, increasing in suspensions with lower CB content under higher input power. It corresponded to 65.55–36.81% of conversion yield close to the sonotrode. Attenuation was also observed during sound wave propagation with a constant value of 0.021 cm^{-1}. Acoustic parameters were well-fitted to polynomial models and acoustic intensity showed

high correlation ($|r|$>0.87 and p_{value}≤0.05) with experimental thermophysical properties of the suspensions.

Keywords: acoustic fields, calorimetric method, ultrasound, attenuation, modelling.

1. Introduction

The second-generation (2G) ethanol appears as an interesting and alternative biofuel for reducing the exploitation of non-renewable resources and for giving an eco-friendly destination to the agro-industrial residues. Its production consists of biomass pretreatment and hydrolysis, fermentation of the resulting sugars and ethanol distillation. However, pretreatment and hydrolysis of biomass are the most challenging steps that should be addressed to reduce the processing costs and make possible the bioethanol production with good efficacy [1].

In order to reduce the feedstock costs, different residues from agroindustry can be employed. Among them, cassava bagasse can be considered an interesting raw material due to its rich composition of residual starch (>30% dry basis) and high availability in countries as Brazil (~2,000,000 tons of wet bagasse/year) (Polachini 2019a). Meanwhile, the performance of each biomass under a given process needs to be evaluated separately since their composition and structural arrangement can vary from one to another [2]. Similarly, the method used for treating these residues is of great importance for improving the technological issues linked to the biofuel production. In addition to conventional techniques, alternative and non-conventional ones such as microwave, CO_2 supercritical, ozone and ultrasound application has been highlighted [3, 4].

Although high-intensity ultrasound (US) is a versatile technology, a special focus has been given to its potential use for enhancing biomass conversion into bioethanol [5-7]. The sonication of biomass provides mechanical energy in the form of sound waves, which produces a series of bubble collapses close to the solid-liquid interface. It is able to break down the carbohydrate-lignin bonds, to depolymerize hemicellulose, cellulose and/or starch into sugars of low molecular chain and, consequently, to increase the surface area for further enzymatic treatment [8]. Those effects are enhanced if some catalyst, e. g. alkali and acids, are used together with sonication.

The success of such processes assisted by US is dependent on its yield of conversion but also on its reproducibility. Well-designed treatments can be adequately reproduced from small to large scale. For this, calorimetric method is considered the most adequate tool for measuring the real acoustic power transmitted to the medium from a given value of nominal electrical power. It assumes that all acoustic energy is converted into heat as a consequence of the collisions between the cavitation bubbles [9]. Such collisions generates pressure gradients which can be measured by hydrophone and, then, correlated with calorimetrically measured power [10]. But, the sensitivity of hydrophones to acids and higher input power could raise difficulties on working with suspensions with constant movement of particles. In this sense, calorimetric method can considered to be feasible for reproduction in distinct systems with estimated standard deviation less than 10% [11]. This real acoustic power is the energy responsible by the actual sonochemical effects on biomass, while the difference from the input electrical power is dispersed in form of wave reflection back to the transducer, noise, heating and weariness of the ultrasonic processor, etc [12, 13]. As seen as the sound waves suffer attenuation, the distance between the sonotrode tip and the sample should be also taken into account for the knowledge about the distribution of acoustic energy in the reactor [14]. It influences the correct positioning of the samples and the homogeneous treatment of heterogeneous medium as suspensions [15]. Gogate [16] highlighted the need of such data to understand the energy distribution from an irradiating at a given input power.

The properties of the medium play an important role on how the ultrasound propagates through the medium. Thermal properties relate the capacity of the medium for absorbing energy and transferring it. On the other hand, density and viscous properties reflect the resistance to the cavitation occurrence. Such properties, in turn, can vary according to conditions of temperature, biomass loading and catalyst concentration in the suspension. Thus, this work aimed at determining the acoustic parameters (acoustic power, intensity, density and yield of power conversion) for suspensions composed by different acid solutions (pH 3–7) and cassava bagasse concentration (2–10% $w\cdot w^{-1}$), at different distance from the sonotrode (1.5 – 5.5 cm) subjected to a range of nominal input power (160–400 W). The results were used to estimate the attenuation coefficient as well as the dependence of the acoustic parameters on the experimental physical properties of such suspensions.

2. Materials and Methods

2.1. Samples preparation

Dried and coarsely milled cassava (*Manihot esculenta*) bagasse was provided by TechnoAmido (São Pedro do Turvo, São Paulo, Brazil) from the cassava starch extraction process. The bagasse was then finely milled to obtain particle size lower than 0.147 mm by a Tyler sieve mesh 100. This material was chemically and physically characterized in the study of Polachini et al. (2019a).

Phosphoric acid (85% solution; Dinâmica, Diadema, São Paulo) was added to distilled water to obtain acid solutions in the pH of 3.0; 4.0; 5.0; 6.0 and 7.0. Powdered cassava bagasse was suspended in the acid solutions to obtain suspensions in the concentrations of 2, 4, 6, 8 and 10% (g of cassava bagasse per 100 g of suspensions) at the different pH, totaling 25 samples.

2.2. Acoustic field characterization

Acoustic parameters was determined by the calorimetric method, based on the temperature increase of the suspensions in the first 90 s of ultrasound application in which an adiabatic system is considered [17]. Temperature records were taken in the experimental set-up shown in Figure 1. In this apparatus, it was used an ultrasonic processor UP400S (Hielscher Ultrasonics GmbH, Germany) coupled with a titanium sonotrode with diameter of 22 mm (model H40, Hielscher Ultrasonics GmbH, Germany), operating at 24 kHz of frequency and maximum nominal input power of 400 W.

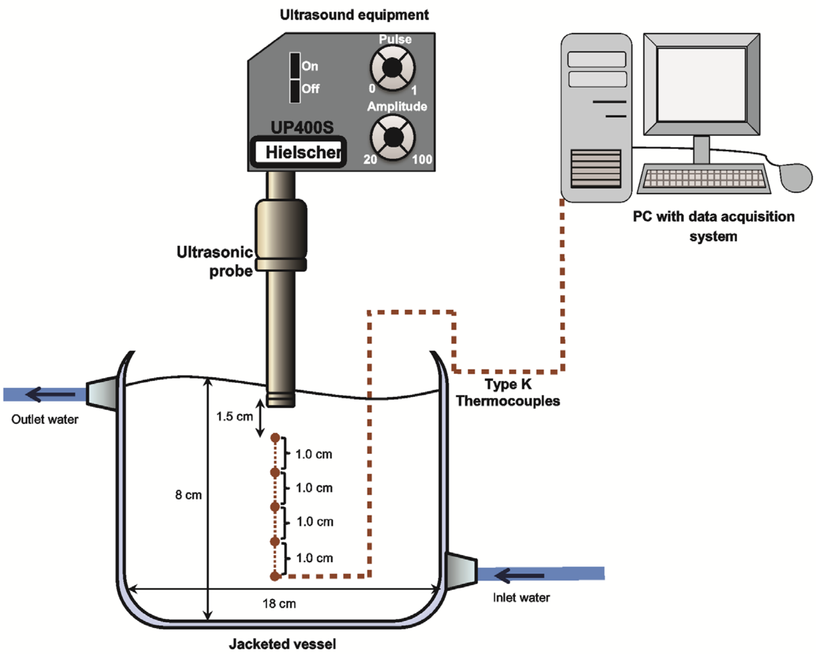

Figure 1. Apparatus used for the measurements of the acoustic fields produced on acid suspensions of cassava bagasse.

Approximately 2 L of each one of the 25 suspensions were inserted in a jacketed stainless steel chamber, and the samples were renewed for each analysis. The initial temperature of the suspensions was maintained constant at 20 °C through a thermostatic bath (model

MA-184, Marconi, Piracicaba, Brazil). Five type J thermocouples were placed at different position below the sonotrode: 1.5 cm, 2.5 cm, 3.5 cm, 4.5 cm and 5.5 cm, to be connected to a data acquisition system (LabView 2010, National Instruments, USA). Measurements were taken every 5 s over the ultrasound application. The experiments were varied according to the percentage of the maximum nominal power P_N: 40% (160 W), 60% (240 W), 80% (320 W), 90% (360 W) and 100% (400 W).

Thus, the acoustic power could be calculated by the Eq. (1):

$$P = V\rho c_p \frac{dT}{dt} \quad (1)$$

where P is the acoustic power (W), V is the volume of suspensions used in each experiment (m³), ρ is the suspension density (kg·m^{-3}), c_p is the specific heat of the acid suspensions (J·kg^{-1}·ºC^{-1}) and dT/dt heating rate (ºC·s^{-1}). Density and specific heat of the suspensions were acquired from the study of Polachini et al. (2019a) and the heating heat was obtained by the linear regression between the temperature increase over the sonication time.

Acoustic intensity (I, W·cm^{-2}), acoustic density (D; W·mL^{-1}) and acoustic power per mass of particles (D_p, W kg^{-1} of cassava bagasse) were given by the Eq. (2), Eq. (3) and Eq. (4), respectively:

$$I = \frac{P}{A} \quad (2)$$

$$D = \frac{P}{V} \quad (3)$$

$$D_p = \frac{P}{V\rho w_S} \quad (4)$$

where A is the area of the transversal section of the sonotrode (cm²) and w_S is the biomass fraction in the suspension (X_S/100).

2.3. Attenuation factor

Acoustic field affects differently a product according to its distance from the sonotrode. As seen it, acoustic intensity were correlated to the distance from the sonotrode by the exponential relation (Eq. (5)) as presented by Mamvura et al. [18]:

$$I = I_0 \exp(-2\alpha d) \quad (5)$$

where I_0 (W·cm^{-2}) is the pre-exponential factor, α is the attenuation factor (cm^{-1}) and d is the vertical distance (cm) from the sonotrode tip.

2.5. Statistical evaluation and mathematical modeling

The significant effects (p_{value} <0.05) among the linear and quadratic effect of the pH of the solution, solids concentration in the suspensions (X_S, % w·w^{-1}), nominal input power (P_N, W) and distance of the sonotrode (d, cm) on the dT/dt, acoustic power P, acoustic intensity I, acoustic density D, acoustic power per mass of particles D_{p} and yield of power conversion acoustic power P (W) was evaluated using the software STATISTICA 10.0 (StatSoft Enterprise, Tulsa, USA). Polynomial equations, based on the Equation (6), could be obtained for as a function of the significant parameters.

$$\phi = \beta_0 + \beta_1 pH + \beta_2 pH^2 + \beta_3 X_S + \beta_4 X_S^2 + \beta_5 P_N + \beta_6 P_N^2 + \beta_7 d + \beta_8 d^2 \quad (6)$$

Where ϕ is the studied variable (P, I, D, D_{p} and Yield) and β_0, β_1, β_2, β_3, β_4, β_5, β_6, β_7, and β_8 are empirical parameters of the polynomial model.

Graphical plot and non-linear regressions were carried out through the software OriginPro 8.0 (OriginLab Corporation, Northampton, USA). The accuracy of the obtained models was expressed by the determination coefficient R^2 and by the root mean square error (*RMSE*).

2.5. Correlation between acoustic and physical properties

As it is known that acoustic properties are dependent on the physical properties of the medium, it was evaluate the correlation between acoustic intensity and physical properties of the acid suspensions containing cassava bagasse. Among the physical properties, there are apparent viscosity (Polachini et al., 2019b), density, thermal conductivity and thermal diffusivity (Polachini et al., 2019a). A good agreement between acoustic intensity and a given physical property was evidence by a Pearson correlation coefficient *r* close to 1 and $p_{\text{value}} \leq 0.05$, considered significant at 95% of confidence.

3. Results and discussions

3.1. Acoustic properties

The ultrasound application over the 90 s of treatment resulted in a linear increase of temperature ($R^2 > 0.968$) for all acid suspensions at the different positions of the thermocouple. The slope d*T*/d*t*, corresponding to the linear variation of temperature during ultrasound application, differs from 0.0063 to 0.0326 ºC·s^{-1} according to the pH, solids concentration, nominal input power and distance from the sonotrode in the range of studied conditions. Making use of the experimental heating rates together with the density and specific heat of the acid suspensions (Polachini et al., 2019), acoustic power could be calculated for all conditions using Equation (1). These values were in the range between 49.05 and 260.64 W.

Other acoustic parameters could be calculated from the acoustic power values. Depending on the application system, one can be more practical than other. Therefore, acoustic intensity was determined, resulting values between 12.90 and 68.57 W·cm^{-2}. These values are in the range (<100 W·cm^{-2}) reccomended by Gogate and Pandit [14], where the level of power applied does not influence negatively the acoustic intensity as a consequence of the cavitation bubble overgrowth and the subsequent decrease on the bubble wall pressure.

Although acoustic density varied from 24.53 and 130.32 $kW{\cdot}m^{-3}$, another way to correlate the acoustic properties with the sonochemical effects generated on the particles in the suspension is to express acoustic power per mass of biomass. This acoustic density reached 6.66 $kW{\cdot}kg$ of cassava bagasse^{-1} while the lowest value was 0.24 $kW{\cdot}kg$ of cassava bagasse^{-1}.

Understanding how each factor affects the acoustic property can provide important information for the correct design of different processes assisted by ultrasound. The influence of each variable (pH, solids concentration, nominal input power and distance from the sonotrode tip) on the acoustic parameters was studied separately in the following sections:

3.1.1. Influence of pH on the acoustic properties

The analysis of the estimated effects promoted by each variable on the heating heat was firstly carried out. Variations in the pH of the solutions did not present significant relationship (p_{value}>0.05) with the heating rate. It indicated that altering the pH in the interval between 3.0 and 7.0 was not significantly enough to promote different levels of cavitation, in a similar way as observed for acid suspensions containing powdered peanut shells [19]. Figure 2 reinforces that no clear trend could be seen for the heating rate at different pH, i. e., suspensions containing biomass can be slightly acidified in order to obtain optimal conditions for a possible enzyme actuation without significant alterations on the cavitational activity, which could led to enzyme inactivation.

It was observed for all suspensions under the different nominal input power at any position from the sonotrode. From this point, pH was not taken into account for determining and modelling the following acoustic properties and their dependence by the solids concentration, nominal input power and distance from the sonotrode tip at a fixed pH of 7.0.

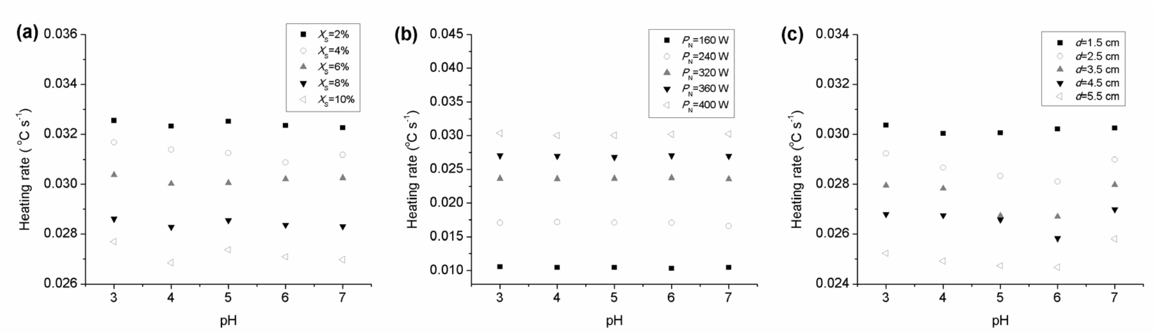

Figure 2. Heating rate as affected by pH at different (a) solids concentration (P_N=400W and *d*=1.5 cm), (b) nominal input power (X_S=6% and *d*=1.5 cm) and (c) distances from the sonotrode (X_S=6% and P_N=400 W).

3.1.2. Influence of P_N on *I*

Positive variations in the nominal electrical power caused linear increase in the heating rate, and consequently in the acoustic intensity ($p_{value}<0.05$). This linear dependence was previously reported for different systems in literature for different solvents [20, 21], distilled water [18], municipal wastewater with suspended particles [22] and peanut shell suspensions [19]. Increasing the nominal applied energy enhanced the heating rate in the suspensions, which tended to increase the acoustic intensity in all the suspensions at the different points of measurement (Figure 3). The increase in the electrical input power could have increased the acoustic intensity by the generation of a more violent collapse between cavitation bubbles [23]. Moreover, the differences of the slope and intercept of the curves may be attributed to the efficiency of energy conversion at different electrical power in the varied conditions [21].

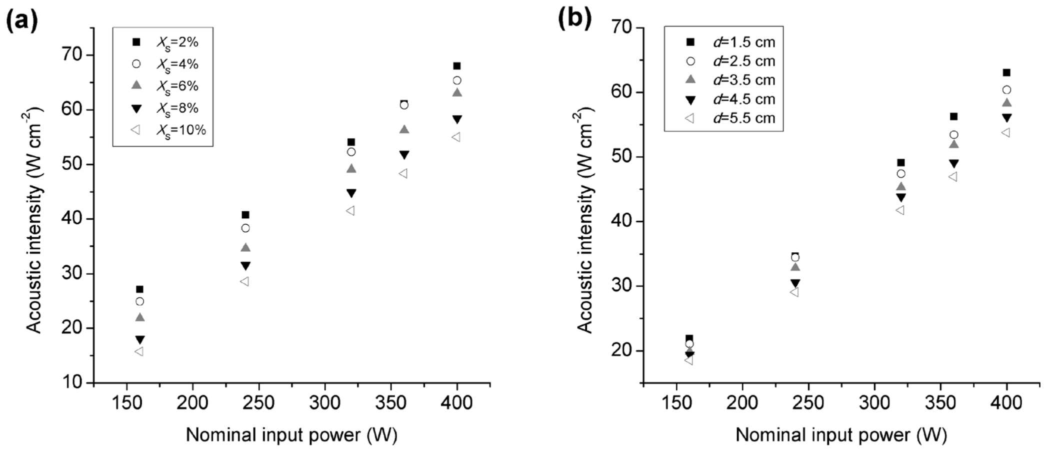

Figure 3. Acoustic intensity I (W·cm^{-2}) as affected by the nominal input power at (a) different solids concentration (d=1.5 cm) and (b) different distances from the sonotrode (X_S=6%).

3.1.3. Influence of X_S on I

A significant linear and quadratic effect (p_{value} <0.05) was observed by the solids concentration on the heating rate. The increase in the solids content resulted lower heating rates, probably due to the higher viscosity of concentrated suspensions in comparison to dilute ones (Polachini et al, 2019b). Consequently, higher acoustic intensity was observed for the more diluted suspensions at the higher amplitude of nominal input power in the closer position to the tip (Figure 4). The presence of suspended particles promotes the energy attenuation, as higher energy levels are required to overcome the molecular interaction in the decompression zones during sound wave propagation. Same behavior was evidenced in a previous studied, where powdered peanut shells was suspended in water [19]. In addition, the reduced acoustic intensity in suspensions with higher concentrations of cassava bagasse may be attributed to the difference between the liquid and particle impedance. As the ultrasound propagates through the medium and come across a particle, it is expected the reflectance and scattering of acoustic fields [24, 25].

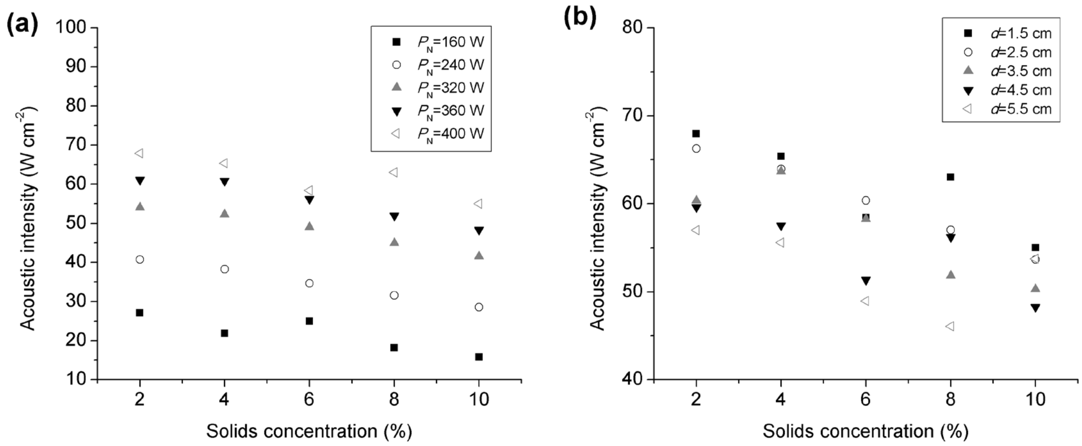

Figure 4. Acoustic intensity I (W·cm^{-2}) as affected by solids concentration (a) under different nominal input power (d=1.5 cm) and (b) at different distances from the sonotrode (P_N=400 W).

3.1.4. Influence of *d* on *I*

It could be observed the acoustic intensity decreased if measurements are taken away from the probe, evidencing that energy attenuation occurs through the material during sonication (Figure 5). Possible reasons for this attenuation are related to the reflection, refraction, diffraction or scattering of the wave or even as a result of the viscous interactions that degrade the acoustic energy into heat [18, 26].

Although acoustic intensity showed to be linearly dependent on the distance from the tip increased ($p<0.05$), I is commonly correlated with d by an exponential relation. It allows the estimation of the attenuation factor (α) and the pre-exponential term (I_0) contained in the Equation (5).

In this sense, acoustic intensity values for all suspensions under different input power levels were plotted against the distance from the tip of the sonotrode and fitted to Equation

(5) (Figure 5). The fitting procedure resulted good accuracy (R^2>0.8416 and $RMSE$<1.79), presenting close agreement of the predicted values with the observed ones (Table 1). From the analysis of variance, the pre-exponential term (I_0) demonstrated to be dependent on the cassava bagasse concentration and on the input power (p<0.05). It tended to increase with decreasing solids concentration and increasing input power. On the other hand, attenuation factor (α) did not present a significant relationship with these variables. All values of acoustic intensity are supposed to be in the region of linear decrease of the exponential equation (Figure 5), leading to the absence of correlation of α with X_S and P_N with a constant mean attenuation value of 0.021 cm^{-1} for the conditions applied to the suspensions. The constant α/(frequency)^2, considered unique for each solution [27], can be so determined as a constant value 3.64×10^{-11} $cm^{-1}\cdot s^2$ for the studied suspensions. Even more, the distance of half-acoustic intensity in which acoustic intensity decreases by 50% (-log(I/I_0)) would be assumed equal to approximately 11.8 cm. This value is lower than the ones observed by Son et al. [27] for tap water at higher frequency than 35 kHz, indicating that suspended particle of cassava bagasse could have actuated as attenuating material in contrast to pure water. Analogously, the constant α/(frequency)^2 was higher in this study when comparing with the previous authors, leading to the same observation. When measuring acoustic pressure by indirect methods, Chivate and Pandit [28] found that the zone of exponential decrease of pressure was found below 1 cm from the sonotrode, almost touching it. In other words, it is probable that acoustic intensity decreased in a constant way from 1.5 cm up to 5.5 cm away from the sonotrode because the maximum acoustic intensity decreased exponentially when too little distances close to the tip are taken. Mamvura et al. [18] and Son et al [27] also reported similar linear trend when applying electrical power above 100 W in distilled water over higher distances. Therefore, concerning the design reactors for heterogeneous systems,

calculations about the acoustic intensity could be done considering that acoustic intensity would not suffer abrupt decreases, characteristic of exponential behavior, in the region between 1.5 and 5.5 cm.

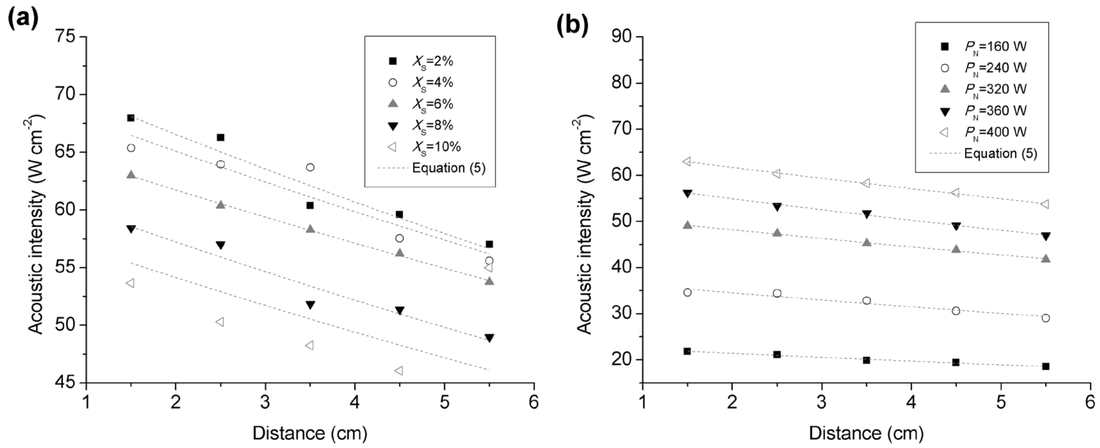

Figure 5. Acoustic intensity I (W·cm^{-2}) as affected by the distance from the sonotrode at different (a) solids concentration (P_N=400W) and (b) nominal input power (X_S=6%); data are fitted to the Equation (5).

Table 1. Fitted values for I_0 and α at different input power and cassava bagasse concentrations.

P (W)	Parameters	Solids concentration, X_S (%)				
		2	4	6	8	10
160	I_0 (W·cm^{-2})	29.16	26.67	23.23	19.28	16.94
	α (W·cm^{-1})	0.0208	0.0228	0.0205	0.0171	0.0221
	R^2	0.9435	0.9894	0.9921	0.9557	0.9152
	RMSE	0.46	0.19	0.13	0.22	0.35
240	I_0 (W·cm^{-2})	43.66	40.98	37.85	33.99	30.55
	α (W·cm^{-1})	0.0202	0.0205	0.0229	0.0198	0.0204
	R^2	0.9858	0.9599	0.9577	0.9723	0.9686
	RMSE	0.32	0.52	0.55	0.34	0.34
320	I_0 (W·cm^{-2})	57.79	57.41	52.20	48.26	44.15
	α (W·cm^{-1})	0.0200	0.0229	0.0199	0.0207	0.0194
	R^2	0.9544	0.8426	0.9977	0.9561	0.9660
	RMSE	0.77	1.78	0.15	0.65	0.49
360	I_0 (W·cm^{-2})	65.71	65.43	60.02	55.83	52.12
	α (W·cm^{-1})	0.0230	0.0230	0.0221	0.0235	0.0227
	R^2	0.9536	0.9536	0.9962	0.9679	0.9794

	RMSE	0.99	0.99	0.24	0.71	0.51
400	I_0 (W·cm^{-2})	72.99	70.79	66.73	62.76	59.35
	α (W·cm^{-1})	0.0230	0.0210	0.0194	0.0230	0.0229
	R^2	0.9634	0.9184	0.9988	0.9601	0.9906
	RMSE	0.98	1.36	0.13	0.88	0.39

3.1.5. Conversion yield

Yield of power conversion is useful not only from an economical point of view but also for designing appropriate ultrasonic processors to produce a given acoustic effect from specific electrical input power. In the treatments of cassava bagasse by US, an improvement of the conversion of electrical into acoustic energy was obtained as the solids content decreased and the input power increased, attaining a maximum of 65.55% in the studied conditions at the closer position to the tip. Löning et al. [13] and Polachini et al. [19] reported close conversion yield values in similar conditions for water and peanut shell suspensions, respectively. In the same point, yield could decrease to 36.81% if the solids concentration is increased to 10% and nominal power was established at the minimum value of 160 W. McDonnell et al. [29] also found better conversion rates when operating ultrasound at higher nominal power, indicating that sonochemical effects are supposed to be more intense at highest nominal power. Although it is not always evidenced, Gibson et al. [22] and Polachini et al. [19] found that the efficiency of power conversion increased non-linearly with nominal power when studying biomass suspensions, which approached to a plateau level at higher P_N. Cárcel et al. [30] also found a non-linear trend for sucrose solution, emphasizing that electrical input power does not provide enough information about the actual acoustic intensity transmitted to the medium. Similarly, a non-linear increase was observed in this study as the cassava bagasse concentration increased, reaching a plateau above approximately 8% (Figure 6). Such deviations from linearity are more noticeable both at higher nominal powers and solids concentration. It highlights that controlling of the operations conditions and reactor design can provide the required energy with the maximum efficiency of energy conversion [21, 26].

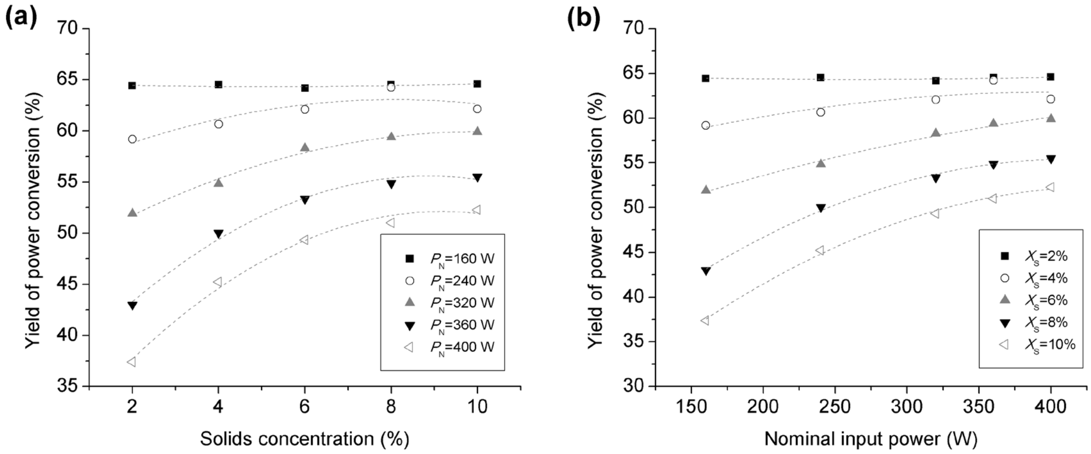

Figure 6. Yield of power conversion measured at the point of maximum cavitation (*d*=1.5 cm) as a function of (a) nominal input power and (b) solids concentration.

3.2. Mathematical modelling

Acoustic properties can be predicted by both empirical and theoretical models. The obtained values for acoustic power, intensity, density and acoustic power per mass of particles could be fitted with good accuracy to polynomial equations in order to provide ready-to-use information for reproducing a given condition. Table 2 shows the fitting parameters of each corresponding acoustic variable.

Table 2. Fitting parameters of the Equation (6) for heating rate (d*T*/d*t*) acoustic power (*P*), acoustic intensity (*I*), acoustic density (*D*), acoustic power per mass of particles (D_p) and yield of power conversion.

Parameter	d*T*/d*t* (ºC·s^{-1})	*P* (W)	*I* (W·cm^{-2})	*D* (kW·m^{-3})	D_p (kW·kg^{-1})	Yield (%)
β_0	4.03×10^{-3}	34.85	9.17	17.42	5.18	54.32
B_1	-	-	-	-	-	-

B_2	-	-	-	-	-	-
B_3	-4.81×10^{-4}	-4.04	-1.06	-2.02	-1.45	-1.57
B_4	-1.21×10^{-5}	-0.13	-0.03	-0.06	0.08	-0.04
B_5	7.49×10^{-5}	0.59	0.15	0.29	6.91×10^{-3}	0.09
B_6	-	-	-	-	-	1.19×10^{-3}
B_7	-8.54×10^{-4}	-6.75	-1.77	-3.37	-0.08	-2.24
B_8	-	-	-	-	-	-
R^2	0.9923	0.9921	0.9921	0.9921	0.9198	0.9199
RMSE	6.32×10^{-4}	4.87	1.28	2.43	0.45	2.11
EMR (%)	2.90	2.99	4.45	3.50	32.78	4.30

3.3. Correlation between acoustic and physical properties

Physical properties of the medium are supposed to affect the cavitation degree. In this sense, acoustic intensity were correlated with experimental values of density (ρ), specific heat (c_p), thermal diffusivity (α), thermal conductivity (λ) and apparent viscosity at fixed shear rate of 10 s^{-1} ($\eta_{app,10s^{-1}}$) in the temperature of 25 ºC.

All of the physical properties showed to be highly correlated with the acoustic intensity, with p_{value} ≤0.05 and high Pearson's correlation coefficient (Table 3). As expected, acoustic intensity was strongly influenced by c_p and ρ since these properties are embedded in the calculation of acoustic power from heating rate data. As the specific heat capacity of the medium is increased and the density is decreased, the acoustic intensity is supposed to increase (Figure7a and 7b). The thermal properties (thermal diffusivity and thermal conductivity) of the medium influenced positively the resulting values for acoustic intensity, indicating that higher cavitation occurs more intensely in fluids with higher α and λ (Figure 7c and 7d). On the other hand, suspensions with increased viscosity presented lower acoustic intensity as characterized by the negative correlation coefficient (Figure 7e). Toma et al. [21] observed that solvents with elevated viscosity seemed to present lower acoustic power, similarly as noticed for cassava bagasse. According to Raso et al. [17], the molecular motion is reduced in liquids with higher viscosity, i. e. more energy is required by the molecules to overcome the critical molecular distance necessary to induce the formation of cavitation bubbles.

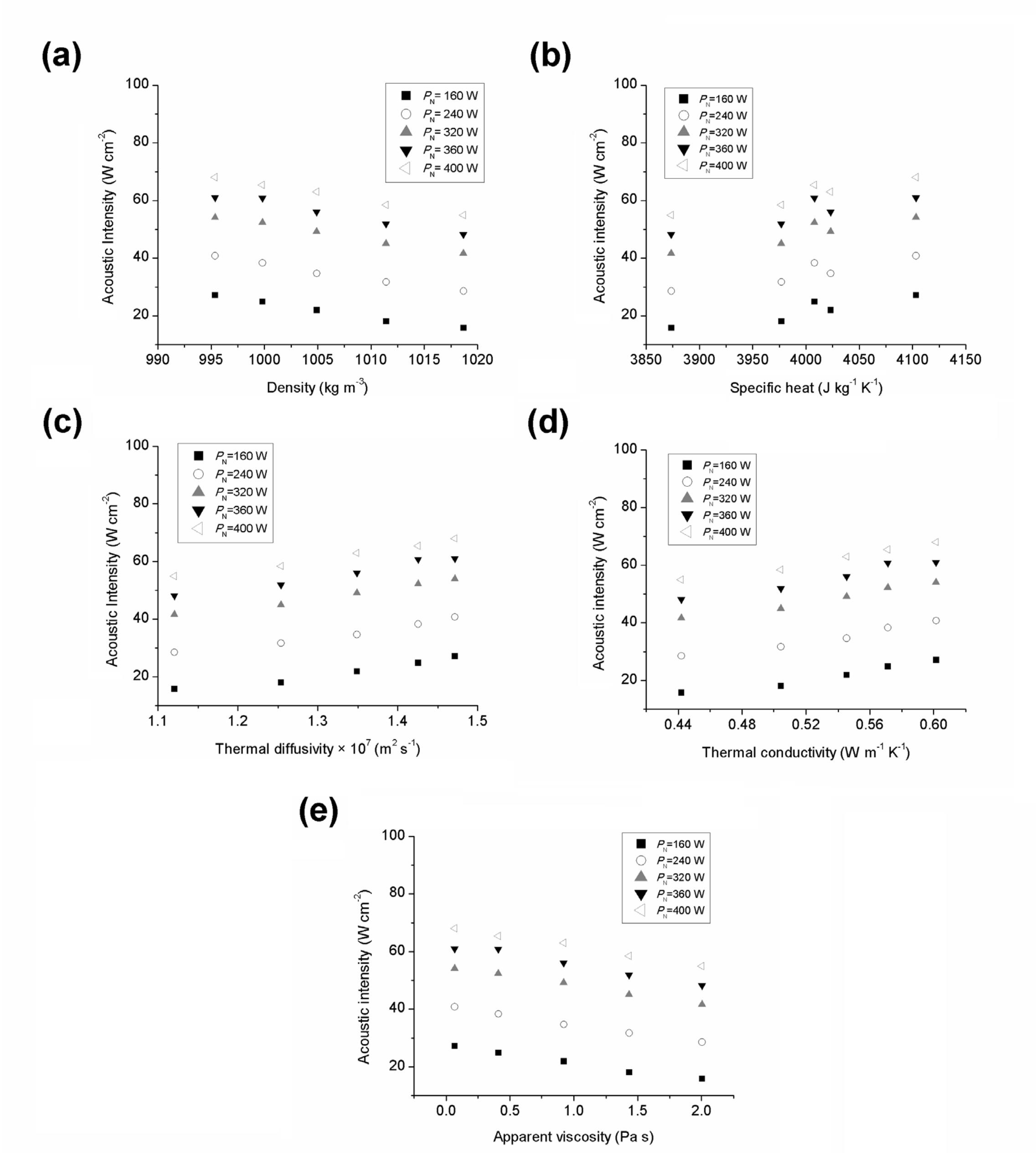

Figure 7. Acoustic intensity (I) as a function of (a) density, (b) specific heat, (c) thermal diffusivity, (d) thermal conductivity and (e) apparent viscosity of the suspensions under different nominal input power (P_N).

Table 3. Parameters of Pearson correlations between acoustic intensity and each physical property in the different nominal input power at the closest position to the sonotrode.

P_N (W)	Parameter	Physical Property				
		ρ	c_p	α	λ	$\eta_{app,10s^{-1}}$
160	r	-0.9940	0.9099	0.9837	0.9798	-0.9965
	p_{value}	5.5×10^{-4}	3.2×10^{-2}	2.5×10^{-3}	3.4×10^{-3}	2.52×10^{-4}
240	r	-0.9944	0.9150	0.9843	0.9811	-0.9977
	p_{value}	5.0×10^{-4}	$2.9\times10^{--2}$	2.3×10^{-3}	3.1×10^{-3}	1.3×10^{-4}
320	r	-0.9975	0.9168	0.9939	0.9893	-0.9979
	p_{value}	1.5×10^{-4}	2.8×10^{-2}	5.6×10^{-4}	1.3×10^{-3}	1.1×10^{-4}
360	r	-0.9868	0.8774	0.9877	0.9769	-0.9895
	p_{value}	1.8×10^{-3}	5.0×10^{-2}	1.6×10^{-3}	4.2×10^{-3}	1.3×10^{-3}
400	r	-0.9978	0.9353	0.9926	0.9916	-0.9963
	p_{value}	1.2×10^{-4}	2.0×10^{-2}	7.7×10^{-4}	9.3×10^{-4}	2.7×10^{-4}

4. Conclusions

The application of ultrasound in acid suspensions containing cassava bagasse resulted in different heating rates (from 0.0063 up to 0.0326 ºC·s^{-1}) in the first seconds of sonication, being significantly enhanced by decreasing the solids concentration in the suspensions and increasing nominal input power, without significant influence of the pH in the studied conditions. It also demonstrated to be less intense as the measurements are taken away from the sonotrode tip, evidencing that attenuation occurred. This type of observation also reinforces the need by agitating suspensions for a homogeneous treatment.

From the values of heating rates, acoustic intensity could be determined in the range of 12.90 and 68.57 W·cm^{-2}, following the same dependence on the studied variables as presented by the heating rate. Acoustic power, acoustic density and acoustic density per mass of particles could be also obtained. They were all well-fitted to polynomial models, presenting good accuracy (R^2>0.9198) in order to make available ready-to-use information. The evaluation and modelling of acoustic intensity at different positions from the sonotrode provided interesting data about the attenuation, which showed a constant attenuation factor of 0.021 ± 0.002 cm^{-1} for any suspensions in the range of studied conditions with distance of half-acoustic intensity approximately equal to 11.8 cm..

Additionally, acoustic intensity was well correlated ($|r|$>0.87 and $p_{\text{value}}\leq 0.05$) with some physical properties of the suspensions containing cassava bagasse. It tended to increase in suspensions with increased thermal properties (specific heat capacity, thermal diffusivity and thermal conductivity) and decreased density and viscosity. In this sense, cavitation and, consequently the sonochemical effects on the biomass, could be enhanced by modifying the physical properties of a given suspensions. Although better energy efficiency and more intense cavitation can be obtained when applying higher input power in diluted suspension, energy and water expenses should be assessed together with the sonochemical effects to obtain an overall optimization of the process.

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