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DETERMINATION OF ACOUSTIC FIELDS IN ACIDIC SUSPENSIONS OF PEANUT SHELL DURING PRETREATMENT WITH HIGH-INTENSITY ULTRASOUND

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Abstract – The benefits of high-intensity ultrasound in diverse processes have stimulated many studies based on biomass pretreatment. In order to improve processes involving ultrasound, a calorimetric method has been widely used to measure the real power absorbed by the material as well as the cavitation effects. Peanut shells, a byproduct of peanut processing, were immersed in acidified aqueous solutions and submitted to an ultrasonic field. Acoustic power absorbed, acoustic intensity and power yield were obtained through specific heat determination and experimental data were modeled in different conditions. Specific heat values ranged from 3537.0 to 4190.6 $J \cdot kg^{-1} \cdot K^{-1}$, with lower values encountered for more concentrated biomass suspensions. The acoustic power transmitted and acoustic intensity varied linearly with the applied power and quadratically with solids concentration, reaching maximum values at higher applied nominal power and for less concentrated suspensions. A power yield of 82.7% was reached for dilute suspensions at 320 W, while 6.4% efficiency was observed for a concentrated suspension at low input energy (80 W).

Keywords: acoustic intensity, biomass pretreatment, ultrasonic hydrolysis, specific heat, power yield.

INTRODUCTION

The increase of CO_2 emissions combined with the search for nonpetroleum-based sources of energy has strengthened many studies involving lignocellulosic wastes conversion into biofuel (Alvira et al., 2010). Lignocellulosic biomass is a less expensive product and its availability in larger quantities as compared to sucrose, for example, represents a great source for the bioethanol industry (Zheng et al., 2009).

Peanut shell is a byproduct obtained from peanut processing and has a great potential to be used as lignocellulosic raw material for the second-generation ethanol industry. It has been widely used as a rotary culture for sugarcane, representing about 90 thousand tons of biomass per year, considering the grain/shell ratio (Godoy et al., 1982; IBGE, 2014).The average of 38% cellulose shows its capability of releasing sugars for posterior fermentation and distillation (Castro and Pereira-Jr, 2010).

Although peanut waste offers advantages, a viable cellulose treatment has been a bottleneck for bioethanol production. New technologies have been developed to enhance the process of biomass accessibility. Among them, there are processes involving supercritical fluids (Okajima and Sako, 2014), acid or alkaline treatments (Cabrera et al., 2014; Moe et al., 2012), steam explosion (Liu et al., 2013)

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and high-intensity ultrasound (Villa-Vélez et al., 2015b).

High-intensity ultrasound, or power ultrasound, is a technology able to reduce cellulose crystallinity and release polymers and monomers of carbohydrates from lignocellulosic material. Its success is directly related to the applied power, as well as the degree of cavitation (Kanthale et al., 2003). Determination of the real power applied by ultrasound is an important step to quantify the cavitation effects occasioned by the collapse of microbubbles (Kuijpers et al., 2002). This cavitation phenomenon can be influenced by many factors such as local high temperatures, electric fields and mechanical action on interfaces (Contamine et al., 1995).

The active energy is the main parameter responsible for the sonochemical reactions in sonication processes, and can be measured by absorbed acoustical energy. On the other hand, unabsorbed energy is the energy lost during the process and should not be taken into account during cavitation measurement. Studies of the efficiency of input energy conversion into absorbed power in the liquid volume have been developed to evaluate the energy output in different food processes, e. g., bioactive compounds extraction and meat brining (Cárcel et al., 2007a; McDonnell et al., 2014; Pingret et al., 2012). However, studies involving biomass treatment with ultrasound are still missing in the literature.

Different methods have been considered to determine the real power absorbed by the material of interest. Some of them intended to correlate physical effects by the dosage of radicals during sonication (Iida et al., 2005; Trabelsi et al., 1996), by calorimetry of thermal response (Margulis and Margulis, 2003) and by acoustic pressure using a hydrophone probe (Jenderka and Koch, 2006; Lewin, 1981; Zeqiri et al., 2006).

The calorimetric method is a highlighted practice due to its reproducibility and accuracy (Berlan and Mason, 1996; Raso et al., 1999). It assumes that all absorbed acoustical energy is transformed into heat, although acoustic streaming may happen as a dissipation form at high power levels (Margulis and Margulis, 2003). This method is based on continuous recording of the temperature change according to the sonication time (Raso et al., 1999).

Many independent variables influence the energy absorption during ultrasonic application, making it unique for each process. Among these variables, there are physical properties (specific heat, viscosity, surface pressure and vapor pressure), liquid volume and/or height, input power, sonotrode type and position, etc. (Toma et al., 2011).

These facts reinforce the need for evaluating the real power absorbed by different acidic suspensions of biomass used during ultrasonic pretreatment. Thus, this work aimed to determine the acoustic fields (acoustic power, acoustic intensity and power yield) in acidified suspensions of peanut shells. Determination and modeling of specific heat were necessary to apply the calorimetric method. Specific heat and acoustical properties could be written and evaluated as functions of the nominal input power, biomass concentration and pH.

MATERIALS AND METHODS

Raw material and sample preparation

Cleaned and dried peanut (*Arachishypogaea* L.) shells were acquired from the Agro-industrial Cooperative – COPLANA (Jaboticabal, São Paulo, Brazil). Using a knife mill MA380 (Marconi, Piracicaba, Brazil), the shells were milled and separated by Tyler sieves of 12 and 150 mesh to obtain powdered peanut shells with particle size between 104–1397 μm.This wide range of particle size was used to simulate a real situation that might be used in the second-generation ethanol industry.

For experimental measurements, acidic suspensions of powdered peanut shells (ASPPS) were prepared in weight/weight units using an analytical balance with an accuracy of 1×10^{-5} g (model AUX220, Shimadzu, Japan), obtaining biomass concentrations of 4, 6, 8, 10 and 12%. The acidification of the solutions was previously realized using 500 mL of distilled water, adding 0.05% H_2SO_4 and stabilizing for 3 days to obtain pH values of 3, 4, 5, 6 and 7. Only for the specific heat measurements, the suspensions were prepared with particle size of 104 μm to avoid particle sedimentation and microsyringe obstruction. This step ensured particle scattering and sample homogeneity to carry out the thermal analysis in the differential scanning calorimeter.

Specific heat measurements

Through a differential scanning calorimeter DSC 8000 (Perkin Elmer, Shelton, USA), specific heat (c_p) were determined by the standard ASTM method for thermally stable liquids and solids (ASTM-E1269, 2005). The analysis consists of applying a heat flow under a controlled atmosphere (nitrogen 99.5% of purity) to evaluate the heat flow and energy alterations in the material. Equipment was calibrated with indium (melting point 429.75 K, Δh_f = 28.45 J/g) under a heat flow of 10 K·min^{-1}. The same thermal program was used for the baseline, reference material of a sapphire disk of 3 mm (Archer, 1993), and ASPPS samples of approximately 5 μL. They were maintained isothermal at 273.13 K for 4 min, heat flow of 10 K·min^{-1} until reaching 333.13 K and isothermal for 4 more min. For all experimental runs, samples were placed in aluminum pans (ref 0219-0062, Perkin Elmer, EUA). The Software PYRIS 10.1 (Perkin Elmer, Shelton, USA) was used to obtain the thermal curves and to determine the specific heat from the following Equation (1):

$$c_P = \frac{D_S}{W_S \theta} \quad (1)$$

where D_S is the vertical displacement between the sample and reference material curves at a given temperature (mW), W_S is the sample weight (mg), and θ the heat flow ($K \cdot s^{-1}$).

Determination of the acoustic fields

Experimental procedures were realized in the ASPPS at biomass concentrations from 4 to12% using an ultrasound UP400S (Hielscher Ultrasonics GmbH, Germany). This equipment has a titanium sonotrode with diameter of 22 mm (model H40, Hielscher Ultrasonics GmbH, Germany), and operates at 24 kHz of frequency and maximum nominal input power of 400 W. The applied input power by the transducer could be modified from 0 to 100%.

Acoustic field determinations were carried out in a stainless steel chamber (with approximately 2.5 kg of liquid), starting at a temperature of 26 ± 0.1 °C. The calorimetric method was used in this research due to the sensitivity of the thermocouple to record the temperature in biomass solutions with minimal interference in the measurements (Moholkar et al., 2000; Raso et al., 1999). A type J thermocouple was connected to a data acquisition system (LabView 2010, National Instruments, USA) and placed at 2 cm from the sonotrode, where the maximum intensity was verified by a model TC4014 hydrophone (Teledyne Reson A/S, Slangerup, Denmark). The system, exemplified in Figure 1, recorded the temperature changes over the 225 s of ultrasound application.

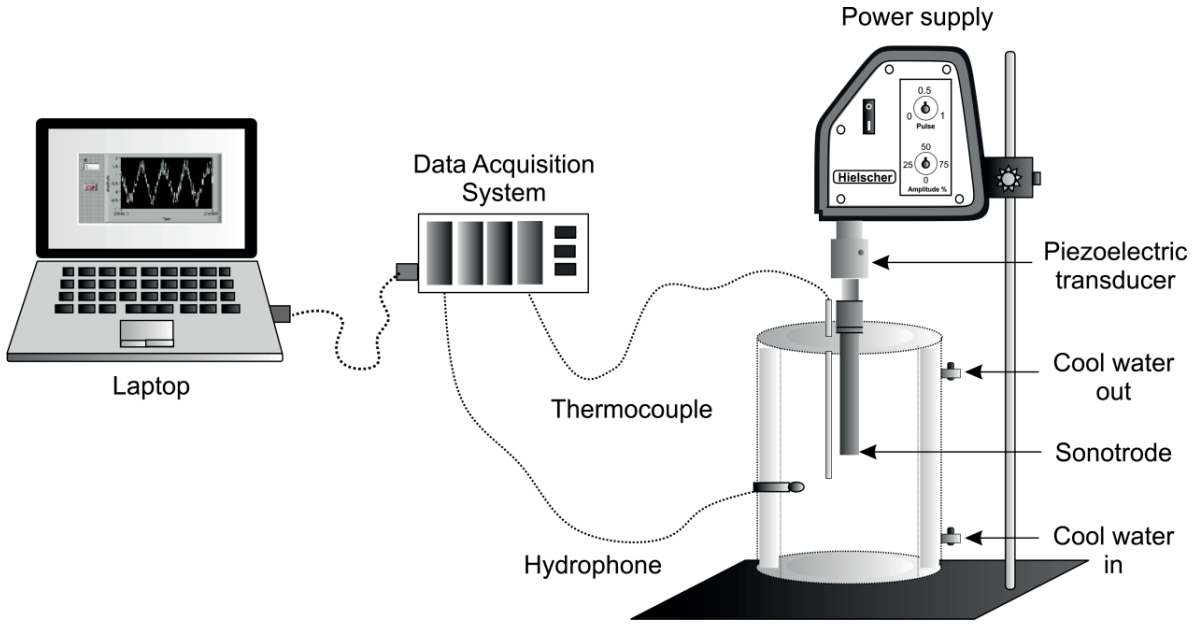

Figure 1 - System used in the ultrasonic experiments for acoustic fields measurements.

Once the temperature gradient data were obtained, the real power absorbed by ASPPS and the acoustic intensity transferred by the sonotrode were calculated using Equations (2) and (3), respectively.

$$P = mc_p \frac{dT}{dt} \quad (2)$$

$$I = \frac{P}{A} \quad (3)$$

In Equations (2) and (3), P is the real power absorbed at a determined position of the sonotrode (W), c_p is the specific heat of ASPPS ($J \cdot kg^{-1} \cdot K^{-1}$), m is the mass of liquid measured for each experiment (kg), dT/dt is the temperature gradient along time registered by the data acquisition system ($K \cdot s^{-1}$), I is the acoustic intensity ($W \cdot cm^{-2}$) and A is the sonotrode tip area (cm^2) (Raso et al., 1999).

Statistical analysis

Mathematical modeling was carried out using linear and non-linear models as a function of the significant variables through the software OriginPro 8.0 (OriginLab Corporation, Northampton, USA). Statistical analyses involving analysis of variance were done using the software STATISTICA 10.0 (StatSoft Enterprise, Tulsa, USA). The influence of each variable on the response, as well as the interactions between them, was evaluated with a 95% confidence interval. Estimated effects were useful to predict an equation involving the significant terms that

influenced the acoustical properties. Also, the adjusted determination coefficient (R^2_{adj}) and the mean relative error (*MRE*) were used to evaluate the goodness of fit and accuracy of the estimation, respectively.

RESULTS AND DISCUSSION

Specific heat and mathematical modeling

The specific heat of the suspensions was determined as a function of solids concentration (0 – 12%), temperature (274.13 – 333.13 K) and pH (3 – 7), showing values in the range of 3537.0 to 4190.6 $J \cdot kg^{-1} \cdot K^{-1}$.These results were similar to those reported for acidified aqueous solutions with added flower stalk biomass (Villa-Vélez et al., 2015a), where a direct relationship of c_p with biomass concentration and temperature was observed.

The c_p of ASPPS showed a linear dependence on pH and temperature, while a quadratic dependence on solids concentration ($p_{value} < 0.05$) was observed. A linear effect of pH was verified for c_p, because it showed approximately constant values at the same temperature and solids content. To reinforce this idea, a Tukey test was applied among samples at different pH and practically none showed significant differences at the 95% level of confidence, as observed in Table 1.

Table 1. Specific heat values at different solids concentrations, temperature and pH.

Biomass concentration (%)	T (K)	c_p ($J \cdot kg^{-1} \cdot K^{-1}$)				
		pH=3	pH=4	pH=5	pH=6	pH=7
0	274.13	4164.5 ± 2.4 [a]	4174.7 ± 2.4 [a]	4176.1 ± 2.7 [a]	4175.2 ± 12.0 [a]	4176.4 ± 2.1 [a]
	283.13	4164.4 ± 4.7 [a]	4174.4 ± 1.3 [a]	4174.7 ± 2.9 [a]	4174.8 ± 12.0 [a]	4174.8 ± 8.5 [a]
	293.13	4165.3 ± 1.0 [a]	4175.0 ± 2.7 [a]	4175.9 ± 1.6 [a]	4175.5 ± 12.0 [a]	4176.8 ± 2.1 [a]
	303.13	4166.7 ± 2.7 [a]	4177.5 ± 1.4 [b]	4179.1 ± 3.4 [b]	4177.8 ± 6.7 [b]	4178.5 ± 0.6 [b]
	313.13	4170.7 ± 2.9 [a]	4180.4 ± 1.4 [a]	4181.3 ± 2.1 [a]	4181.4 ± 0.6 [a]	4181.5 ± 2.1 [a]
	323.13	4174.2 ± 1.0 [b]	4183.5 ± 5.7 [a,b]	4184.5 ± 1.8 [a]	4184.3 ± 12.0 [a]	4184.6 ± 9.1 [a]
	333.13	4179.9 ± 3.4 [b]	4188.6 ± 10.7 [a,b]	4190.0 ± 2.0 [a]	4190.6 ± 4.4 [a]	4189.7 ± 9.1 [a,b]
4	274.13	3901.4 ± 6.6 [a]	3938.4 ± 12.7 [a]	3916.9 ± 6.0 [a]	3883.2 ± 15.1 [a]	3858.4 ± 17.5 [a]
	283.13	3914.2 ± 13.1 [a]	3940.1 ± 3.1 [a]	3879.7 ± 11.1 [a]	3882.9 ± 10.6 [a]	3879.8 ± 11.0 [a]
	293.13	3929.1 ± 3.1 [a]	3924.5 ± 8.7 [a]	3923.8 ± 5.3 [a]	3880.5 ± 11.1 [a]	3858.8 ± 23.4 [a]
	303.13	3898.6 ±7.3 [a]	3877.6 ± 12.7 [a]	3926.0 ± 5.1 [a]	3925.6 ± 5.2 [a]	3887.4 ± 12.5 [a]
	313.13	3931.8 ± 3.4 [a]	3915.6 ± 8.1 [a]	3915.1 ± 7.3 [a]	3890.1 ±14.2 [a]	3881.4 ± 20.7 [a]
	323.13	3951.8 ± 8.5 [a]	3914.7 ± 7.3 [a]	3920.6 ± 7.1 [a]	3888.7 ± 11.3 [a]	3915.7 ± 8.0 [a]
	333.13	3937.9 ± 7.4 [a]	3919.5 ± 7.8 [a]	3957.4 ± 6.4 [a]	3925.2 ±7.1 [a]	3920.5 ± 8.2 [a]
6	274.13	3885.5 ± 11.0 [a]	3834.4 ± 6.6 [a]	3885.5 ± 1.2 [a]	3835.4 ± 5.8 [a]	3849.8 ± 6.4 [a]
	283.13	3871.2 ± 1.2 [a]	3885.4 ± 11.9 [a]	3888.4 ± 2.0 [a]	3789.7 ± 20.8 [a]	3859.8 ± 2.7 [a]
	293.13	3788.0 ± 12.1 [a]	3881.8 ± 4.1 [a]	3882.8 ± 9.0 [a]	3790.4 ± 13.4 [a]	3860.5 ± 7.4 [a]
	303.13	3881.3 ± 2.2 [a,b]	3799.2 ± 12.1 [b]	3857.5 ± 3.3 [a,b]	3899.8 ± 12.2 [a,b]	3872.0 ± 6.9 [a,b]
	313.13	3890.4 ± 3.8 [a]	3900.1 ± 4.1 [a]	3887.2 ± 5.0 [a]	3887.7 ± 21.3 [a]	3887.3 ± 9.0 [a]
	323.13	3887.9 ± 2.2 [a]	3805.5 ± 11.8 [a]	3891.3 ± 11.0 [a]	3812.0 ± 11.2 [a]	3843.8 ± 6.0 [a]
	333.13	3899.0 ± 4.6 [a]	3894.7 ± 4.1 [a]	3872.5 ± 12.2 [a]	3816.7 ± 11.3 [a]	3855.4 ± 5.4 [a]
8	274.13	3802.6 ± 6.7 [a]	3812.4 ± 7.9 [a]	3671.4 ± 28.0 [a]	3813.5 ± 4.4 [a]	3800.0 ± 8.6 [a]
	283.13	3706.5 ± 19.0 [a]	3809.3 ± 3.2 [a]	3808.9 ± 8.7 [a]	3804.7 ± 8.3 [a]	3809.0 ± 2.7 [a]
	293.13	3795.7 ± 7.8 [a]	3741.3 ± 12.5 [a]	3813.8 ± 8.2 [a]	3737.5 ± 8.4 [a]	3803.3 ± 0.7 [a]
	303.13	3804.7 ± 5.8 [a]	3807.1 ± 1.4 [a]	3808.1 ± 10.6 [a]	3807.1 ± 2.6 [a]	3739.2 ± 8.3 [a]
	313.13	3793.9 ± 17.9 [a]	3809.8 ± 7.6 [a]	3804.3 ± 1.7 [a]	3812.0 ± 1.3 [a]	3804.6 ± 0.3 [a]
	323.13	3808.4 ± 4.7 [a]	3822.2 ± 6.5 [a]	3808.2 ± 5.1 [a]	3817.7 ± 6.5 [a]	3815.7 ± 1.4 [a]
	333.13	3815.9 ± 3.0 [a]	3811.9 ± 10.9 [a]	3812.8 ± 4.0 [a]	3826.5 ± 12.4 [a]	3818.1 ± 2.2 [a]
10	274.13	3657.0 ± 6.1 [a]	3692.2 ± 11.9 [a]	3672.2 ± 5.6 [a]	3640.6 ± 14.2 [a]	3617.4 ± 16.4 [a]
	283.13	3669.0 ± 12.2 [a]	3693.8 ± 2.9 [a]	3637.3 ± 10.4 [a]	3640.3 ± 10.0 [a]	3637.4 ± 10.3 [a]
	293.13	3682.9 ± 2.9 [a]	3679.3 ± 8.1 [a]	3678.7 ± 5.0 [a]	3638.1 ± 10.4 [a]	3617.7 ± 21.9 [a]
	303.13	3654.4 ± 6.8 [a]	3635.3 ± 11.9 [a]	3680.7 ± 4.8 [a]	3680.4 ± 4.9 [a]	3644.6 ± 11.8 [a]
	313.13	3685.5 ± 3.2 [a]	3670.9 ± 7.6 [a]	3670.5 ± 6.9 [a]	3647.1 ± 13.4 [a]	3638.9 ± 19.4 [a]
	323.13	3704.3 ± 8.0 [a]	3670.0 ± 6.9 [a]	3675.7 ± 6.6 [a]	3645.7 ± 10.6 [a]	3671.1 ± 7.5 [a]
	333.13	3691.3 ± 7.0 [a]	3674.5 ± 7.3 [a]	3710.1 ± 6.0 [a]	3680.0 ± 6.7 [a]	3675.6 ± 7.7 [a]

Table 1. Cont.

Biomass concentration (%)	T (K)	c_p (J·kg^{-1}·K^{-1})				
		pH=3	pH=4	pH=5	pH=6	pH=7
12	274.13	3642.9 ± 5.3 [a]	3610.2 ± 11.6 [a]	3590.6 ± 11.6 [a]	3559.7 ± 9.8 [a]	3537.0 ± 16.0 [a]
	283.13	3593.2 ± 12.1 [a]	3611.8 ± 2.9 [a]	3556.5 ± 13.7 [a]	3559.4 ± 10.3 [a]	3556.6 ± 10.1 [a]
	293.13	3625.3 ± 1.8 [a]	3597.5 ± 8.0 [a]	3597.0 ± 6.2 [a]	3557.3 ± 10.0 [a]	3537.3 ± 20.8 [a]
	303.13	3619.3 ± 2.5 [a]	3554.5 ± 11.6 [a]	3599.0 ± 10.8 [a]	3598.6 ± 12.0 [a]	3563.6 ± 9.5 [a]
	313.13	3647.5 ± 3.6 [a]	3589.3 ± 7.4 [a]	3589.0 ± 12.3 [a]	3566.1 ± 9.9 [a]	3558.1 ± 14.2 [a]
	323.13	3639.1 ± 6.5 [a]	3588.5 ± 6.7 [a]	3594.0 ± 6.5 [a]	3564.7 ± 10.2 [a]	3589.5 ± 7.5 [a]
	333.13	3659.7 ± 3.8 [a]	3573.9 ± 9.9 [b]	3627.7 ± 5.9 [a,b]	3598.2 ± 6.5 [a,b]	3593.9 ± 8.0 [a,b]

[a,b] Same letters in the same line represent no significant difference at the 95% level of confidence by a Tukey test.

Table 2 presented the fitting values of three selected models and their statistical parameters. In this modeling, c_p was correlated with temperature and biomass concentration and the pH term was excluded due to the absence of statistical significance. Higher values of c_p were encountered for less concentrated suspensions since dry biomass has a lower specific heat than water (Collazo et al., 2012). Specific heat as a function of multiple variables may be incorporated into the energy balance equation in order to predict the temperature profiles with great accuracy (Koufopanos et al., 1991). Similar equations were obtained for lignocellulosic waste materials, such as banana flower-stalk (Villa-Vélez et al., 2015a) and woods (Koufopanos et al., 1991).

Table 2. Fitting parameters of different models for the specific heat (J·kg·K^{-1}).

Equation	Model	Parameters	R^2_{adj}	*MRE* (%)
(6)	$c_P = \alpha_1 + a_2X$	α_1 = 4149.3 J·kg^{-1}·K^{-1} α_2 = -47.42 J·kg^{-1}·K^{-1}	0.959	0.85
(7)	$c_P = \alpha_1 + a_2X + a_3T$	α_1 = 4125.1 J·kg^{-1}·K^{-1} α_2 = -47.42 J·kg^{-1}·K^{-1} α_3 = 0.07 J·kg^{-1}·K^{-1}	0.959	0.85
(8)	$c_P = \alpha_1 + a_2X^M + a_3T$	α_1 = 4149.8 J·kg^{-1}·K^{-1} α_2 = -75.73 J·kg^{-1}·K^{-1} α_3 = 0.07 J·kg^{-1}·K^{-2} M = 0.82	0.967	0.74

α_1,α_2,α_3 and M are parameters of the models, T is the absolute temperature (K), X is the biomass concentration (%) and c_p is the specific heat (J·kg^{-1}·K^{-1}).

In general terms, the three models showed good and simple descriptions of the experimental data as functions of all parameters studied (R^2_{adj} > 0.967). Although all the parameters of the tested models were statistically significant, it is recommended the simplest equation that is in accordance with the analysis of variance. In this way, Equation 8 was selected among the three models to proceed with the acoustic field calculation. The agreement between the experimental and calculated values for the c_p can be seen in Figure 2.

Acoustic fields

The temperature gradient versus time was registered and followed a linear tendency, where *dT/dt* was extracted from the slope of the straight line. In Figure 3, it was observed that the slope of the registered points decreased as the solid concentrations increased. At a fixed biomass concentration, the temperature variation (*dT/dt*) increased when higher input powers were applied. An effect related to different pH was not observed, and could not be distinguished as observed for specific heat. Toma et al. (2011) and Cárcel et al. (2007b) also recorded a linear increase of temperature for different solvents (both at 500 and 20 kHz of frequency) and for sucrose solutions, respectively.

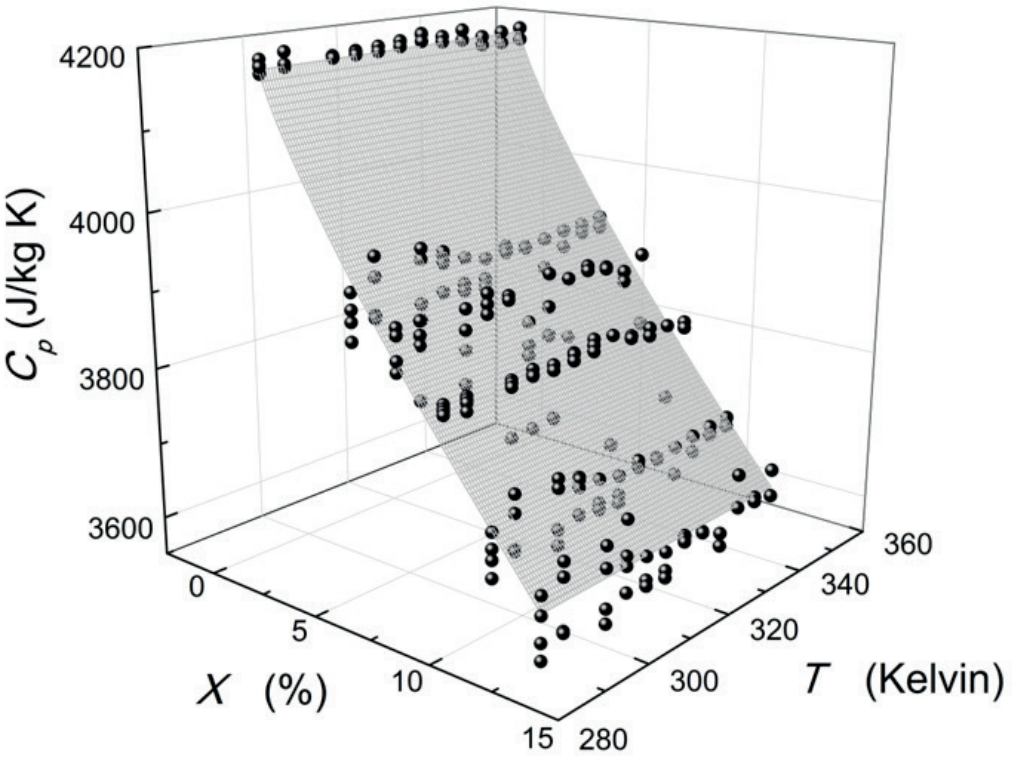

Figure 2 - Representation of the specific heat values fitted to Equation (8).

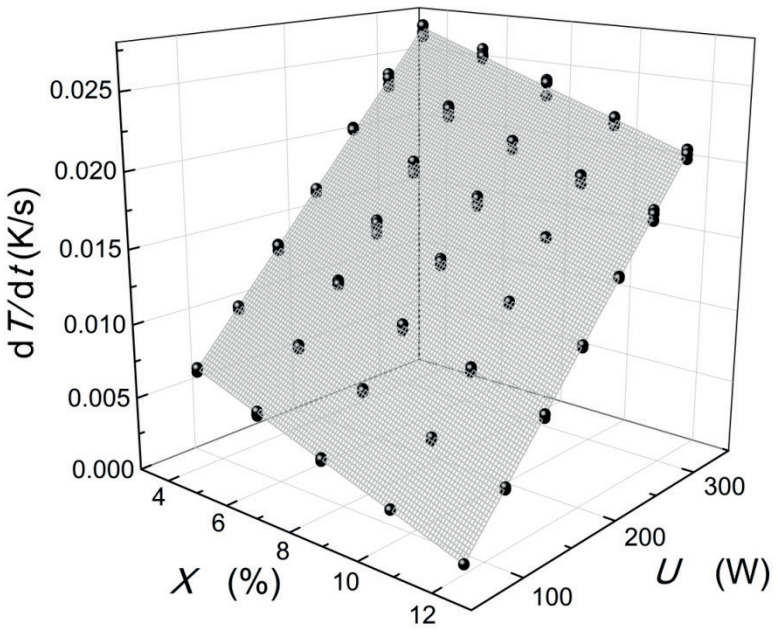

Figure 3 - Temperature gradient with time as a function of the biomass concentration (X, %) and nominal power output of ultrasound (U, W) for all pH values

Using *dT/dt* values calculated by linear regressions, the real power transmitted (*P*) and the acoustic intensity (*I*) as a function of the nominal power applied (*U*) from 80 to 320 W, biomass concentration (*X*) from 4 to 12% and pH from 3 to 7 were determined by Equations (2) and (3). The results are shown in Figure 4.

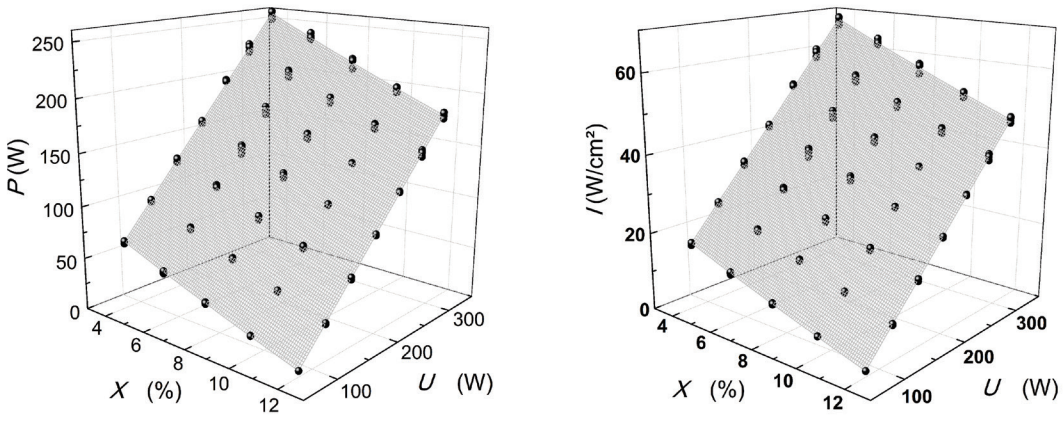

Figure 4 - Power transmitted (P) and acoustic intensity (I) as a function of nominal power applied (U) and biomass concentration (X). Properties were determined at a distance of 2 cm from the sonotrode.

In Figure 4 (left), the measured power transmitted increased when an increase in nominal power was applied. The increases of biomass concentration showed a decrease in the power absorbed, similar to the specific heat behavior. The values of acoustic power ranged from 5.12 to 260.2 W, while acoustic intensity followed the same tendency, with values in the interval of 1.35 and 68.45 W·cm^{-2}, presented in Figure 4 (right). A non-linear equation was fitted based on the significant parameters, and acoustic power (*P*) and acoustic intensity (*I*) could be expressed using the coefficients contained in Table 3.

Table 3. Fitting results and statistical validation of acoustic power (*P*) and acoustic intensity (*I*) by ASPPS.

	P (W)				*I* (W·cm^{-2})			
Parameters	Coefficient	p_{value}	R^2_{adj}	MRE (%)	Coefficient	p_{value}	R^2_{adj}	MRE (%)
Intercept	32.96	-			8.67	-		
U	0.84	$< 1\times10^{-28}$			0.22	$< 1\times10^{-28}$		
X	-8.25	$< 1\times10^{-28}$	0.999	2.090	-2.17	$< 1\times10^{-28}$	0.999	2.090
X^2	0.09	1.23×10^{-4}			0.02	1.23×10^{-4}		
$U\times X$	-0.01	3.69×10^{-28}			-0.002	3.69×10^{-28}		

U is the nominal power applied (W), *X* is the biomass concentration (%) and p_{value} is the probability of the factor *F* (IC = 95%).

Results from the analysis of variance showed that the acoustic power transmitted has a quadratic dependence on solids concentration ($p_{value} < 1\times10^{-28}$) and linear dependence on nominal power applied ($p_{value} < 1\times10^{-28}$), with a linear interaction between them. In a previous study, the acoustic powers were linearly correlated with input power. Such correlations are specific for frequencies at 24 kHz and they can be useful to make sure that all ultrasonic devices are working well (Contamine et al., 1995). The effect of pH showed a linear dependence ($p_{value} = 0.05$), indicating a weak effect when compared to the other variables. Acoustic power at different pHs had a mean deviation of 4% between values, demonstrating that the linear effect was almost a constant line. This fact allowed us to exclude the pH effect and consider only biomass concentration and input power in the modeling.

Efficiency of the ultrasound power transmitted

As known, not all nominal power applied is transferred to the system. Determination of the power yield (100* *P/U*) makes it necessary to evaluate how much energy is missing along each kind of process. These losses generally occur during electrical conversion into mechanical energy, where noise and thermal energy could be dissipated to the environment.

The maximum yield (82.7%) was observed for less concentrated suspensions, which is in accord with the values obtained by Toma et al. (2011) for water. This

high yield could be justified by the high yields obtained for ultrasound application using an apparatus with the sonotrode immersed instead of an ultrasonic bath (Kimura et al., 1996; Wu et al., 2001). In addition, the thermocouple was positioned where the maximum cavitation occurs (2 cm from the sonotrode).

On the other hand, a higher percentage of energy (93.6%) is lost for suspensions with higher content of biomass under low nominal applied power (80 W). The low yield could be attributed to the paste characteristics of biomass that offer a mechanical resistance to the sonotrode in transforming small amounts of electrical energy into acoustic power.

Power yield data were plotted as a function of nominal applied power and solids concentration, as shown in Figure 5, and fitted to a non-linear equation. The coefficients and statistical values of each significant variable are presented in Table 4. Similarly, a non-linear relationship was found by Cárcel et al. (2007b) when comparing the electrical energy supplied with the ultrasonic intensity. The necessity of correlating these variables is emphasized by Sivakumar and Pandit (2001), which confirms that the electrical input of an ultrasonic generator does not supply enough information about the ultrasonic power that promotes chemical transformations.

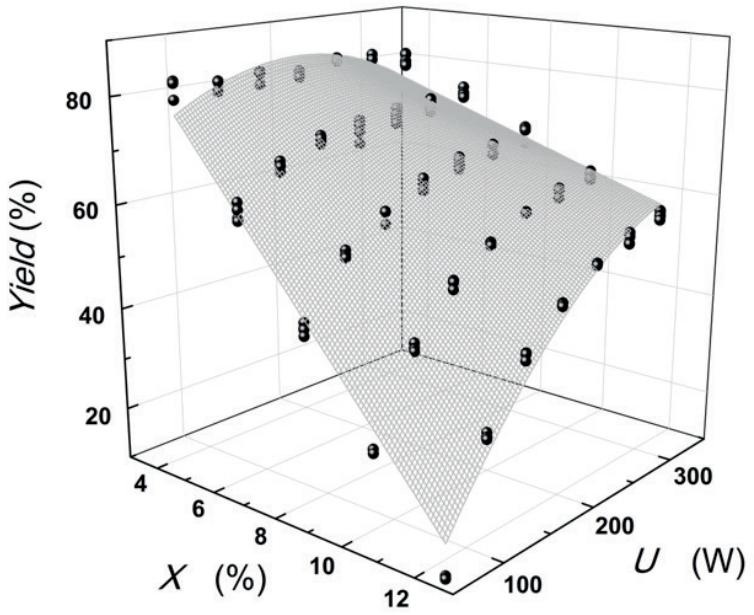

Figure 5 - Power yield as a function of biomass concentration (%) and nominal applied power (W).

Table 4. Statistical and fitting parameters to represent the power yield (%).

		Power yield (%)		
Parameters	Coefficient	p_{value}	R^2_{adj}	MRE (%)
Intercept	102.15	-		
U	0.12	$< 1\times10^{-28}$		
U^2	-5.40×10^{-4}	$< 1\times10^{-28}$	0.977	6.410
X	-9.86	$< 1\times10^{-28}$		
$U\times X$	0.024	$< 1\times10^{-28}$		

U is the nominal applied power (W), X is the biomass concentration (%) and p_{value} is the probability of the factor F (IC = 95%).

Although these results provide significant information regarding the acoustic fields at a local position, the procedures involved in this research can be adapted and applied to identify P and I for different positions from the sonotrode, mapping the acoustic power at all chamber points. Studies regarding the geometry of the acoustic system and the capacity of ultrasound processing of biomass suspensions on a large scale are suggested for future studies.

CONCLUSIONS

This study reported data of the acoustic fields produced by ultrasound application to acidified aqueous solutions of peanut waste. In order to evaluate the acoustic properties, the specific heat was determined. This thermophysical property could be modeled as a function of solids concentration and absolute temperature, where the pH did not present significant effects. Lower values were encountered for more concentrated suspensions due to the lower capacity of storing energy of lignocellulosic material relative to pure water. Acoustic power and intensity data were calculated and fitted according to the significant parameters of influence. As these properties are a function of specific heat, they follow the same behavior, being higher for less concentrated suspensions under higher input powers. Ultrasound application was demonstrated to be more efficient at low concentration and higher input power, showing a maximum power yield value of 82.7%. These conditions could maximize the hydrolysis and biomass pretreatment during sonication.

Finally, the determination of the maximum acoustic field is an important step for designing and building acoustic processor systems. Data about acoustic fields in biomass suspensions make possible the development of sonication processes involving the bioconversion of renewable sources into second-generation ethanol.

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REFERENCES

Alvira, P., Tomás-Pejó, E., Ballesteros, M. and Negro, M. J., Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: A review. Bioresource Technology, 101 (13), 4851-4861 (2010).

Archer, D. G., Thermodynamic Properties of Synthetic Sapphire (α-Al2O3), Standard Reference Material 720 and the Effect of Temperature-Scale Differences on Thermodynamic Properties. Journal of Physical and Chemical Reference Data, 22 (6), 1441-1453 (1993).

ASTM-E1269, Standart test method for determining specific heat capacity by differentail scanning calorimetry. ASTM Internacional, West Conshohocken (2005).

Cabrera, E., Muñoz, M. J., Martín, R., Caro, I., Curbelo, C. and Díaz, A. B., Alkaline and alkaline peroxide pretreatments at mild temperature to enhance enzymatic hydrolysis of rice hulls and straw. Bioresource Technology, 167 (0), 1-7 (2014).

Cárcel, J. A., Benedito, J., Bon, J. and Mulet, A., High intensity ultrasound effects on meat brining. Meat Science, 76 (4), 611-619 (2007a).

Cárcel, J. A., Benedito, J., Rosselló, C. and Mulet, A., Influence of ultrasound intensity on mass transfer in apple immersed in a sucrose solution. Journal of Food Engineering, 78 (2), 472-479 (2007b).

Castro, A. M. and Pereira-Jr, N., Production, properties and application of cellulases in the hydrolysis of agroindustrial residues. Química Nova, 33 (1), 181-188 (2010).

Collazo, J., Pazó, J. A., Granada, E., Saavedra, Á. and Eguía, P., Determination of the specific heat of biomass materials and the combustion energy of coke by DSC analysis. Energy, 45 746-752 (2012).

Contamine, R. F., Wilhelm, A. M., Berlan, J. and Delmas, H., Power measurement in sonochemistry. Ultrasonics Sonochemistry, 2 (1), S43-S47 (1995).

Iida, Y., Yasui, K., Tuziuti, T. and Sivakumar, M., Sonochemistry and its dosimetry. Microchemical Journal, 80 (2), 159-164 (2005).

Jenderka, K. V. and Koch, C., Investigation of spatial distribution of sound field parameters in ultrasound cleaning baths under the influence of cavitation. Ultrasonics, 44 (0), 401-406 (2006).

Kanthale, P. M., Gogate, P. R., Pandit, A. B. and Wilhelm, A. M., Mapping of an ultrasonic horn: link primary and secondary effects of ultrasound. Ultrasonics Sonochemistry, 10 (6), 331-335 (2003).

Kimura, T., Sakamoto, T., Leveque, J. M., Sohmiya, H., Fujita, M., Ikeda, S. and Ando, T., Standardization of ultrasonic power for sonochemical reaction. Ultrasonics Sonochemistry, 3 (3), S157-S161 (1996).

Koufopanos, C. A., Papayannakos, N., Maschio, G. and Lucchesi, A., Modelling of the pyrolysis of biomass particles. Studies on kinetics, thermal and heat transfer effects. The Canadian Journal of Chemical Engineering, 69 (4), 907-915 (1991).

Kuijpers, M. W. A., Kemmere, M. F. and Keurentjes, J. T. F., Calorimetric study of the energy efficiency for ultrasound-induced radical formation. Ultrasonics, 40 (1–8), 675-678 (2002).

Lewin, P. A., Miniature piezoelectric polymer ultrasonic hydrophone probes. Ultrasonics, 19 (5), 213-216 (1981).

Liu, Z. H., Qin, L., Pang, F., Jin, M. J., Li, B. Z., Kang, Y., Dale, B. E. and Yuan, Y. J., Effects of biomass particle size on steam explosion pretreatment performance for improving the enzyme digestibility of corn stover. Industrial Crops and Products, 44 (0), 176-184 (2013).

Margulis, M. A. and Margulis, I. M., Calorimetric method for measurement of acoustic power absorbed in a volume of a liquid. Ultrasonics Sonochemistry, 10 (6), 343-345 (2003).

McDonnell, C. K., Lyng, J. G., Arimi, J. M. and Allen, P., The acceleration of pork curing by power ultrasound: A pilot-scale production. Innovative Food Science & Emerging Technologies, 26 (0), 191-198 (2014).

Moe, S. T., Janga, K. K., Hertzberg, T., Hägg, M. B., Øyaas, K. and Dyrset, N., Saccharification of Lignocellulosic Biomass for Biofuel and Biorefinery Applications – A Renaissance for the Concentrated Acid Hydrolysis? Energy Procedia, 20 (0), 50-58 (2012).

Moholkar, V. S., Sable, S. P. and Pandit, A. B., Mapping the cavitation intensity in an ultrasonic bath using the acoustic emission. AIChE Journal, 46 (4), 684-694 (2000).

Okajima, I. and Sako, T., Energy conversion of biomass with supercritical and subcritical water using large-scale plants. Journal of Bioscience and Bioengineering, 117 (1), 1-9 (2014).

Pingret, D., Fabiano-Tixier, A. S., Bourvellec, C. L., Renard, C. M. G. C. and Chemat, F., Lab and pilot-scale ultrasound-assisted water extraction of polyphenols from apple pomace. Journal of Food Engineering, 111 (1), 73-81 (2012).

Raso, J., Manas, P., Pagan, R. and Sala, F. J., Influence of different factors on the output power transferred into medium by ultrasound. Ultrasonics Sonochemistry, 5 (4), 157-162 (1999).

Sivakumar, M. and Pandit, A. B., Ultrasound enhanced degradation of Rhodamine B: optimization with power density. Ultrasonics Sonochemistry, 8 (3), 233-240 (2001).

Toma, M., Fukutomi, S., Asakura, Y. and Koda, S., A calorimetric study of energy conversion efficiency of a sonochemical reactor at 500 kHz for organic solvents. Ultrasonics Sonochemistry, 18 (1), 197-208 (2011).

Trabelsi, F., Ait-lyazidi, H., Berlan, J., Fabre, P. L., Delmas, H. and Wilhelm, A. M., Electrochemical determination of the active zones in a high-frequency ultrasonic reactor. Ultrasonics Sonochemistry, 3 (2), S125-S130 (1996).

Villa-Vélez, H. A., Váquiro, H. A., Lopes-Filho, J. F., Telis, V. R. N. and Telis-Romero, J., Study of the specific heat capacity of biomass from banana waste for application in the second-generation ethanol industry. Environmental Progress and Sustainable Energy, 34 (4), 1221-1228 (2015a).

Villa-Vélez, H. A., Váquiro, H. A. and Telis-Romero, J., The effect of power-ultrasound on the pretreatment of acidified aqueous solutions of banana flower-stalk: Structural, chemical and statistical analysis. Industrial Crops and Products, 66 (0), 52-61 (2015b).

Wu, J., Lin, L. and Chau, F., Ultrasound-assisted extraction of ginseng saponins from ginseng roots and cultured ginseng cells. Ultrasonics Sonochemistry, 8 (4), 347-352 (2001).

Zeqiri, B., Hodnett, M. and Carroll, A. J., Studies of a novel sensor for assessing the spatial distribution of cavitation activity within ultrasonic cleaning vessels. Ultrasonics, 44 (1), 73-82 (2006).

Zheng, Y., Pan, Z. and Zhang, R., Overview of biomass pretreatment for cellulosic ethanol production. International Journal of Agricultural and Biological Engineering, 2 (3), 51-67 (2009).