Acoustic cavitation events and solvation power of ionic liquid in a novel hybrid technique: A concept proposal toward a green pathway for cellulose decomposition

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A B S T R A C T

The present paper reports a numerical investigation of the feasibility of a hybrid concept associating the 1-Butyl-3-methylimidazolium Acetate ([C₄mim][CH₃COO]) to sonication, in terms of cavitation formation and generated extreme conditions allowing cellulose decomposition in the second reactivity site. The results of the proposed model revealed an acoustic power threshold of 1.8 atm, in order to expect a transient cavitation in the ionic liquid, leading to harsh conditions of 1559.8 K and 49 bar within the bulk volume of the acoustic cavitation bubble. The spatial and temporal variation of the temperature was simulated within the bulk volume of the bubble as well as in the thermal boundary layer jointly with the chemical kinetics. The first stage of the polymerization reduction was clearly attained and demonstrated through the decomposition rate of cellulose and the molar rate of emergence of anhydrocellulose, reaching the respective orders of magnitude of $1.71 \times 10^4$ mol/m$^3$s and $7.91 \times 10^4$ mol/m$^3$s.

1. Introduction

Cellulose is the most abundant natural polysaccharide, it constitutes the major proportion of biomass material and forms the framework of its cell walls [1]. Structurally speaking, cellulose is formed from repetitive β-D-glucose units, which are linked through β(1 → 4)-glycosidic bonds [2]. It has crystalline and amorphous zones according to whether the microfibrils are periodically or randomly distributed along the orientation of cellulose fibrils [3,4].

Owing to its exceptional structural and physical properties, but also its biocompatibility, biodegradability, thermal and chemical stability, cellulose and its derivatives have nowadays a large scope of applications in polymer, paper and paints industries [5]. Solvents are usually needed for the dissolution of cellulose in order to enable homogeneous phase reactions without prior derivatization. However, the multiple extensive intra and inter molecular hydrogen bonding interactions within the cellulose structure result in a semicrystalline polymer containing highly structured crystalline regions, which induces its high tensile strength [6]. Thus, cellulose is insoluble in water and most common organic solvents [7]. The few solvents which are classically used, such as carbon disulfide and phosphoric acid, pose serious environmental issues with fatal drawbacks. For instance, the Kraft process, which produces viscose rayon from cellulose xanthate and carbon disulfide, requires high temperature, pH control, and results in the release of organic sulfur in water and presents a risk of the lignin and hemicellulose destruction during the separation and purification of the biomass [8]. Hence, more benign strategies are needed, by excluding the utilization of toxic and non-recyclable chemicals and substituting them by environmental-friendly and more efficient solvents.

Swatloski et al. [9] first discovered the ability of some ionic liquids to dissolve cellulose. They demonstrated that ionic liquid, as a non-derivatizing solvent, strongly dissolve cellulose by disrupting and breaking the intramolecular hydrogen-bonding network. Ionic liquids have emerged afterwards as effective and green solvents [5,10,11], mainly due to their high thermal and chemical stability, nonflammable nature and miscibility with many other solvent systems [12].

The dissolution of cellulose in ionic liquid was described by several authors who presented various mechanistic explanations. Most of them agreed that cellulose was dissolved when anions formed hydrogen bonds with the cellulose [13], while some others demonstrated that dissolution of cellulose in the ionic liquids occurs when the anion and cation form hydrogen bonds with the cellulose’s hydrogen and oxygen atoms, mainly taking place between C6 and C3 hydroxyl groups of...
Neighborhood cellulose chain [14]. These mechanisms are coherent with the findings of Swatloski et al. [9] who demonstrated that the presence of water in the ionic liquid, even in a small proportion of 1% wt., significantly decreases the solubility of cellulose, presumably through competitive hydrogen-bonding to the cellulose microfibrils, as the 1-Butyl-3-methylimidazolium Acetate, are supposed to form neighborhood cellulose chain [14]. These mechanisms are coherent with the findings of Swatloski et al. [9] who demonstrated that the presence of water in the ionic liquid, even in a small proportion of 1% wt., significantly decreases the solubility of cellulose, presumably through competitive hydrogen-bonding to the cellulose microfibrils, which inhibits solubilization.

Among the ionic liquids known nowadays, the Acetate-based ILs, such as the 1-Butyl-3-methylimidazolium Acetate, are supposed to form N-heterocyclic carbine ligands, which makes possible the ring opening reaction leading to the formation of covalent bonds between cellulose and imidazolium core [1]. The 1-Butyl-3-methylimidazolium Acetate [C₄mim][CH₃COO] is indeed one of the most powerful solvents of cellulose according to several studies [6,14,15] and particularly offers high dissolution rates at near room temperature, it displayed for instance 23 g/mol solubility at 40 °C [10].

Most of experiments of cellulose dissolution in ILs aim to disrupt its highly crystalline structure, reduce its degree of polymerization, and enlarge the surface of the substrate which is accessible for further reaction such as lysis, making it more susceptible to transform into less bulky soluble species in the single acoustic cavitation bubble (mol/m³)

\(c_i\) Initial concentration (mol/m³)

\(E_i\) Activation energy (J/mol)

\(f\) Frequency (Hz)

\(n\) Total molar yield (mol)

\(n_i\) Molar yield of the \(k^{th}\) species within the single acoustic cavitation bubble (mol)

\(n_0\) Initial molar yield (mol)

\(P_A\) Acoustic amplitude (Pa)

\(P_i\) Partial pressure (Pa)

\(P_g\) Pressure of gas (Pa)

\(P^0\) Initial pressure of gases (Pa)

\(P_s\) Saturating pressure (Pa)

\(P_w\) Ambient pressure (Pa)

\(R\) Bubble radius (m)

\(R_w\) Bubble wall velocity (m/s)

\(R_a\) Bubble wall acceleration (m/s²)

\(R_g\) Ideal gas constant (J/mol K)

\(R_0\) Initial bubble radius (m)

\(T\) Temperature within the bubble (K)

\(T_w\) Median temperature in the thermal boundary layer (K)

\(V\) Volume of the bubble (m³)

\(V_i\) Volume of the thermal boundary layer (m³)

\(\alpha\) Refers to the \(k^{th}\) species

\(\beta\) Refers to the \(i^{th}\) reaction

\(\delta\) Refers to the \(i^{th}\) reaction

2. Theoretical approach

In the present model, the 1-Butyl-3-methylimidazolium Acetate [C₄mim][CH₃COO] was selected among the ionic liquids for its high cellulose solvation power [6,10]. The ionic liquid [C₄mim][CH₃COO] is supposed saturated with argon, and though very few studies dealt with the solubility of argon in ionic liquids [26–29], the reported solubility rates are considered acceptable to create gaseous inclusions and induce acoustic cavitation when sufficient tensile strength is applied [30]. The
The physical properties of 1-Butyl-3-methylimidazolium Acetate at 353 K. indicated in Ref. [33].

The operating temperature is set to 353 K in order to attain an acceptable value of dynamic viscosity of the ionic liquid. The physical properties of the 1-Butyl-3-methylimidazolium Acetate are given in Table 1.

Table 1

| Properties | ρ (aN/m) | μ (kg/m²s) | η (mPa s) | c (m/s) |
|------------|----------|------------|-----------|---------|
| Values     | 36       | 1019.28    | 24.4      | 1521.92 |

The vapor pressure of the 1-Butyl-3-methylimidazolium Acetate is negligible [32], thus, the bubble content is only due to the presence of argon. The initial pressure of gas inside the bubble is given by Eq. 2, in accordance with the mechanical equilibrium.

\[ P_{\text{in}} = P_{\text{atm}} + \frac{2\sigma}{R} \]  

(2)

The energy balance applied to the single acoustic cavitation bubble during its oscillation is expressed in Eq. 3.

\[ \dot{T} = \frac{1}{nC_v(T)} \left( -P_{\text{atm}}R^2 \dot{R} - \varphi(t) \right) \]  

(3)

\( \varphi(t) \) represents the heat flow across the thermal boundary layer of width \( \xi \), its expression relies on the continuity of the thermal flow across the bubble interface at instant \( t \).

\[ \varphi(t) = \frac{4\pi eR(R - \xi)}{\xi} \int_0^T \dot{\varphi}(T) dT \]  

(4)

In Eqs. 3 and 4, \( C_v(T) \) and \( \dot{\varphi}(T) \) represent, respectively, the isochoric molar heat capacity and the thermal conductivity of argon, varying in function of the temperature. Both are given as polynomial functions as indicated in Ref. [33].

The pressure of gases inside the bubble volume is simply deduced using the Van der Waals state equation as indicated below.

\[ P_s = \frac{n^2a}{V^2} (V-nb) = nR_sT \]  

(5)

The width of the thermal boundary layer \( \xi \) is situated in the gaseous side owing to the order of magnitude of the thermal conductivity of the ionic liquid [34,35], almost 10 times higher than that of argon. The resistance to thermal diffusion is then deemed concentrated in the gaseous side and consequently, the boundary layer of thermal diffusion is considered there. The width \( \xi \) is given by Eq. 6 [36].

\[ \xi = \min \left( \sqrt{\frac{R\kappa}{R}}, \frac{r}{\pi} \right) \]  

(6)

In this equation, \( \kappa \) represents the thermal diffusivity, which depends of the density, heat capacity and thermal conductivity of argon and is consequently temperature dependent.

The resolution of Eq. 3 allows the determination of the temperature in the bulk volume of the single acoustic cavitation bubble. The temperature is assumed to be spatially uniform within this volume except for the thin boundary layer of the width \( \xi \) [37]. The radial distribution of the temperature across the thermal boundary layer is determined by resolving for each value of \( r \) comprised between 0 and \( \xi \), the Eq. 7, resulting of the integration of Eq. 4 with the polynomial form of \( \dot{\varphi}(T) \) and giving the value of \( T(R-r) \).

\[ 1.79435 \times 10^3 T(R-r)^2 + 6.81277 \times 10^{-3} T(R-r) - 4.6408 = \frac{\varphi(t)}{4\pi R(R-r)} \]  

(7)

According to the two-site model [38], the thermal boundary layer constitutes the seat of chemical reactions due to the thermal effect induced by the hot spots at the bubble interface. When the bulk temperature is high enough, the surrounding temperature is sufficient to initiate pyrolysis reactions, the cellulose is expected to thermally decompose according to the mechanism proposed by Diebold [39] and presented in Table 2.

Owing to the chemical inertia of the bubble content, the sono-chemical kinetics is attributed to the thermal effect generated inside the thermal boundary layer, i.e., the second reactivity site. The chemical kinetics taking place there is modeled according to Table 2 as a chain mechanism of first order reactions, where the molar yield of each species \( k \) is governed by Eq. 8.

\[ \frac{dn_i}{dt} = V_r \sum_{i=1}^{2} (\delta_{ii} - \delta_{ii}) A_i \exp \left( \frac{q_i}{RT} \right) \prod_{j=1}^{k} c_j^{\delta_{ij}} \]  

(8)

In this equation, \( T \) represents the effective temperature affecting the chemical kinetics of cellulose decomposition, and since it is spatially evolving in function of \( r \), as shown in Eq. 7, the median value is considered to approximate the conditions of the thermal decomposition of cellulose. The molar concentrations \( c_j \) of each species \( k \) are reported to the boundary layer volume \( V_r \) given in Eq. 9.

\[ V_r = \frac{4}{3} \pi \left( R^3 - \left( R - \min \left( \frac{\kappa R}{R}, \frac{r}{\pi} \right) \right)^3 \right) \]  

(9)

The system of non-linear and dependent differential equations composed of Eqs. 1, 3 and 8 is simultaneously resolved with the non-
linear equations 4, 5, 7 and 9 using appropriate numerical algorithms, and accounting for the initial conditions reported in Table 3.

3. Results and discussion

The simulation of the dynamics of bubble oscillation in the 1-Butyl-3-methylimidazolium Acetate was preceded by several preliminary trials under an acoustic frequency of 200 kHz. These preliminary simulations were conducted by incrementing the acoustic amplitude from an initial value of 1.2 atm, with a step of 0.1 atm, until reaching the lowest acoustic amplitude allowing the achievement of a nonlinear bubble oscillation with a subsequent violent collapse and abrupt increase in temperature and pressure of the gaseous phase inside the bubble volume. The initial acoustic amplitude, i.e. 1.2 atm, was selected as a minimum value that slightly exceeds the pressure to which the ionic liquid is submitted, i.e. 1 atm, and hence is susceptible to break the liquid molecules cohesion in the presence of liquid germs, and lead to the apparition of non-linear oscillation of the bubble as indicated by the Blake Threshold [40]. The step 0.1 atm was set in order to obtain a reasonable balance of accuracy and number of iteration, until reaching the minimum acoustic pressure allowing the occurrence of transient cavitation [41].

The harsh and abrupt increase of pressure and temperature inside the bubble was only achieved when reaching an acoustic amplitude of 1.8 atm, in fact, the high viscosity of the ionic liquid, almost 60 times higher than that of water, prevented any noticeable bubble dynamics when applying lower acoustic powers. This was highlighted by Hernoux-Villière et al. [42] who employed a low power ultrasonic bath to irradiate ionic liquid containing dissolved cellulose, they noticed the absence of even physical effects and explained their observation by the highly viscous system requiring intense acoustic power and direct sonication mode. Fig. 1 reports the oscillation dynamics results as well as the width of the thermal boundary layer evolving with the bubble oscillation.

Fig. 1 (a) demonstrates that the bubble expansion leads to a maximum radius of 12.8 µm, i.e., 2.56-fold the initial radius, the abrupt collapse occurs afterwards at a velocity reaching 36.5 m/s toward the bubble center. The bubble contraction stops when the bubble radius attains 2.39 µm, a rebound is then observed at a velocity that suddenly reaches 20.04 m/s, as shown in Fig. 1(b). The compression ratio is estimated in this case at 5.36, this value is by far lower than the usual orders of magnitude reported for acoustic cavitation bubble oscillating in water [43]. However, since the studied system is completely different in terms of bubble content (no vapor, and only inert gas), the examination of the energy balance result is required to estimate the thermal outcome of the transient bubble oscillation, this is carried out in Fig. 2.

In the other hand, the width of the thermal boundary layer, which is directly dependent of the bubble oscillation dynamics, reveals a slight variation around the strong collapse between the values 0.76 and 1.45 µm. This range is particularly important as it defines the volume of the second reacting site in the two-site model of sonochemical reactivity adopted in the present paper.

Fig. 2(a) reports both temperature and pressure evolution inside the bulk volume of the bubble, as announced previously, while Fig. 2(b) presents the thermal flow passing through the boundary layer and the resulting temperature value at the mid-width across this layer. Fig. 2(a) indicates that the maximum temperature attained within the bulk volume is 1559.8 K, while the maximum pressure does not exceed 49 bar.

Table 3

| Parameter | \( R_0 \) (µm) | \( R_0 \) (m/s) | \( n_0 \) (Argon) | \( c_0 \) (Cellulose) | \( P_0 \) (Pa) | \( T_0 \) (K) |
|-----------|----------------|----------------|-------------------|----------------------|----------------|----------------|
| Value     | 5              | 0              | 2.064 x 10^{-14} mol | 1 mM                | 115700         | 353            |

Fig. 1. Evolution of the radius and the thermal boundary layer width (a) and the bubble wall velocity (b) of a single acoustic cavitation bubble oscillating in \([C_4\text{mim}][\text{CH}_3\text{COO}]\) versus time under 1.8 atm and 200 kHz, during one acoustic cycle.

Fig. 2. Evolution of the temperature and pressure in the bulk volume of a single acoustic cavitation bubble (a) and the median temperature and thermal flow across its thermal boundary layer (b) versus time, when oscillating in \([C_4\text{mim}][\text{CH}_3\text{COO}]\) under 1.8 atm and 200 kHz, during one acoustic cycle.
Looking to the few works that dealt with the modeling of the acoustic cavitation evolving in ionic liquids, we surprisingly notice divaricated orders of magnitude of pressure and temperature values reported in the bulk volume of the bubble. In an attempt to critically observe the obtained values, we suggest to closely inspect the physical properties and conditions of the considered (ionic liquid–gas) matrix. Kanthale et al. [44] presented a very interesting work measuring via the methyl radical recombination method the temperature of acoustic cavitation generated in the 1-Ethyl-3-methylimidazolium-ethyl sulfate (EMIS) using a plate transducer operating at 213 kHz and 40 W of acoustic power (measured calorimetrically). The authors noted that though acoustic cavitation in ionic liquid, being a nonvolatile liquid, is expected to generate a significantly higher temperature compared to that generated in water (or volatile solvents), the temperatures measured in pure EMIS were in the range of 3000–5000 K, thus, in the same order as those observed in volatile solvents. The most plausible explanation to such an observation is the weaker oscillation dynamics of acoustic cavitation bubbles, as shown in Fig. 1. Elder and Calvisi [45] developed a finite element model to describe the oscillation of an acoustic cavitation bubble in the 1-butyl-3-methylimidazolium tetrafluoroborate having a dynamic viscosity of 99.2 mPa s at 293.15 K, which is the considered working temperature. They demonstrated that bubbles with bigger initial radius tend to reach higher temperatures and pressure when submitted to lower frequencies. Yet, the bubble equilibrium radius is hardly expected to attain values higher than in water, under similar acoustic conditions, owing to the high viscosity of the ionic liquid. When considering an acoustic frequency of 200 kHz and an equilibrium radius of 5 µm while adopting the conditions of Elder and Calvisi [45], the bulk and surface temperature and pressure are almost undetectable unless lowering the viscosity by increasing the operating temperature. If the dynamic viscosity is decreased below 10 mPa s, Elder and Calvisi [45] report a bulk temperature exceeding 1200 K and a bulk pressure exceeding 12 bar. Overall, though transient cavitation can be formed in ionic liquid, the extreme collapse conditions are not as spectacular as in water; the viscosity of the ILs is the principal reason for this observation.

The temperature in thermal boundary layer is the most important parameter in the present study, since it defines the conditions within the second reactivity site and hence, the opportunity for cellulose to thermally decompose around the acoustic cavitation bubble. Fig. 2(b) presents the thermal flow passing through the boundary layer in function of time during one acoustic cycle and clearly exhibits an abrupt increase to 3.15 mW at the instant of strong collapse. The harsh collapse manifests at its turn when the bubble contraction attains its extremum, which is simultaneously accompanied by a narrowing of the boundary layer width. Thus, the higher the heat flow, the narrower the width of the thermal layer and the higher the temperature attained inside the layer according to Fourier’s law. The noticed increase in the thermal flow is then systematically equivalent to higher temperature values attained inside the layer. Fig. 2(b) shows effectively a peak of the median temperature attaining 1000 K and lasting almost 30 ns per cycle. This order of magnitude of the temperature is reported in several studies of cellulose pyrolysis [3,4,18,46], however, the punctual increase of temperature in the form of pulses during infinitesimal timeslots requires deeper examination of its effect on the cellulose decomposition kinetics, this is discussed later in Fig. 4.

Fig. 3 presents further details regarding the spatial and temporal evolution of temperature within the thermal boundary layer. In Fig. 3 (a), the radial variation of the temperature is shown at five selected instants preceding and following the harsh collapse, this latter occurs exactly at 3.62 µs. It is clearly observed how the rapid increase in temperature occurs between 3.6 µs, where it reaches at the mid-width a value of 645.6 K, and the instant of the strong collapse where a value of 1000 K is recorded, revealing an augmentation of almost 17.7 K/ns. The rapid cooling is also noticeable from the moment of the harsh collapse, until 3.8 µs, where the temperature returns to the equilibrium value, i.e., that of the ionic liquid, at an average cooling speed of 3.59 K/ns.

Fig. 3. Spatial evolution of the temperature across the thermal boundary layer at various instants (a) and evolution of the temperature at different positions within the thermal boundary layer versus time during one acoustic cycle (b) for a single acoustic cavitation bubble oscillating in [C₅mim][CH₃COO] under 1.8 atm and 200 kHz.

In the other hand, Fig. 3 (b) presents the evolution of temperature at five equidistant positions within the thermal boundary layer in function of time. At the instant of the strong collapse, the width of the thermal boundary layer is equal to 0.76 µm, Fig. 3(b) shows that at 0.152 µm from the gaseous side of the thermal layer, the temperature attains 1332.9 K, while it is estimated at the same distance from the liquid side at 623.3 K. The temporal variation indicates that no evolution is observed except during the timeframe surrounding the collapse. The sensitivity of the dissolved cellulose toward the temperature variation is studied by inspecting its decomposition kinetics, assuming an arbitrary initial concentration of 1 mM. The molar rates of cellulose decomposition and products emergence around a collapsing acoustic cavitation bubble oscillating in [C₅mim][CH₃COO], under 1.8 atm and 200 kHz.

Fig. 4 demonstrates that starting from the bubble contraction phase, the first stage of cellulose decomposition begins with an increasing rate
that attains $1.71 \times 10^4 \text{mol/m}^3\text{s}$ at the instant of the strong collapse (3.62 $\mu$s). This first stage corresponds to the reduction of the degree of polymerization by the formation of the so-called “anhydrocellulose” or “active cellulose” [4] at a rate that reaches $7.91 \times 10^5 \text{mol/m}^3\text{s}$. The decomposition rate decreases afterwards while the initiated chain mechanism gives rise to primary and secondary gases, mainly composed of CH$_4$, CO$_2$ and CO as detected by the TG-FTIR by Shen and Gu [4], as well as bio-oil (tars) composed of levoglucosan, pyruvaldehyde, hydroxyacetone and hydroxyacetaldehyde. The emergence of gases and tars remain limited during the simulation timeframe, Fig. 4 reveals a total emergence rate of gases that equals $5.68 \times 10^{-2} \text{mol/m}^3\text{s}$, and a production rate of bio-oil neighboring $2.59 \times 10^{-10} \text{mol/m}^3\text{s}$. This observation is explained by the predominance of the reaction: Cellulose $\rightarrow$ Active cellulose during short timeslots owing to its pre-exponential factor. However, it is believed that longer reacting time would lead to clearer insights into the yields of decomposition products and allow a quantitative appreciation of the US/Ils hybridization concept toward cellulose decomposition, especially when including the bubble population dimension in the modeling study. This track may define the perspective of this initial study.

4. Conclusion

The present paper suggests a numerical investigation of the feasibility of a US/Ils hybrid concept toward cellulose decomposition. The study of the acoustic cavitation bubble dynamics under 200 kHz demonstrated that a bubble of 5 $\mu$m requires an amplitude of 1.8 atm or higher to achieve a transient state, the relatively high power ultrasound oscillation did not manifest the extreme expansion and collapse ratios usually retrieved with bubble evolving in water, both were limited to 2.56 and 5.36, respectively.

Maximum temperature and pressure in the bulk volume of the bubble demonstrated moderated values of 1595.8 K and 49 bar, which was in perfect agreement with some previous experimental and modeling findings. At the instant of strong collapse, the bulk volume of the bubble was exclusively composed of an inert gas, argon, and hence, the reacting site was defined as the boundary layer surrounding the bubble, according to the two-site model of sononochemical reactions. The spatial and temporal evolution of the temperature within this layer exhibited a value of 1000 K at the mid-width and the instant of strong collapse (3.62 $\mu$s). The chemical kinetics of decomposition of dissolved cellulose at the thermal boundary layer revealed a maximum rate of cellulose decomposition of $1.71 \times 10^4 \text{mol/m}^3\text{s}$ at 3.62 $\mu$s, mainly explained by the first stage of polymerization reduction of cellulose into anhydrocellulose, this latter showed an emergence rate reaching $7.91 \times 10^5 \text{mol/m}^3\text{s}$. This mechanism was accompanied of the apparition of primary and secondary gases as well as bio-oil at infinitesimal rates; however, it is believed that longer simulation time would be more telling on the outcomes of the concept toward cellulose decomposition. This is set as a perspective for the present study, along with introducing the bubble population dimension in the expected model.

CRediT authorship contribution statement

Kauther Kerboua: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. Oualid Hamdaoui: Project administration, Visualization, Supervision, Writing - review & editing. Abdulaziz Alghyamah: Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
[24] W. Lan, C.F. Liu, F.X. Yue, R.C. Sun, J.F. Kennedy, Ultrasonic-assisted dissolution of cellulose in ionic liquid, Carbohydr. Polym. 86 (2011) 672–677, https://doi.org/10.1016/j.carbpol.2011.05.013.

[25] K.S. Suslick, Sonoluminescence and sonochemistry, Proc. IEEE Ultrason. Symp. 1 (1997) 523–532, https://doi.org/10.1109/59.6227410-5/00953-4.

[26] T. Song, M.J. Lubben, J.F. Brennecke, Solubility of argon, krypton and xenon in ionic liquids, Fluid Phase Equilib. 504 (2020), 112334, https://doi.org/10.1016/j.fluid.2019.112334.

[27] J. Jacquemin, M.F. Costa Gomes, P. Husson, V. Majer, Solubility of carbon dioxide, methane, oxygen, nitrogen, hydrogen, argon, and carbon monoxide in 1-butyl-3-methylimidazolium tetrafluoroborate between temperatures 283 K and 343 K and at pressures close to atmospheric, J. Chem. Thermodyn. 38 (2006) 490–502, https://doi.org/10.1016/j.jct.2005.07.002.

[28] B.-C. Lee, S.L. Outcalt, Solubilities of gases in the Ionic Liquid 1- n -Butyl-3- methylimidazolium Bis(trifluoromethylsulfonyl)imide, J. Chem. Eng. Data. 51 (2006) 892–897, https://doi.org/10.1021/jf050357y.

[29] J.L. Anthony, J.L. Anderson, E.J. Maginn, J.F. Brennecke, Anion effects on gas solubility in ionic liquids, J. Phys. Chem. B. 109 (2005) 6366–6374, https://doi.org/10.1021/jp046404v.

[30] R.E. Apfel, Acoustic cavitation, Methods Exp. Phys. 19 (1981) 355–411, https://doi.org/10.1016/S0076-695X(08)60338-5.

[31] J. Safarov, M.H. Rausch, K. Krzeminski, D. Assenbaum, P. Wasserscheid, A. Leipertz, Thermal conductivity of ionic liquids: Measurement and prediction, J. Phys. Chem. C. 111 (2007) 18461–18463, https://doi.org/10.1021/jp0610148.

[32] J.O. Valderoma, W.W. Sanga, Critical Properties and vapor pressure of twenty imidazolium based ionic liquids used in extraction bioprocesses, in: 2nd Int. Symp. Biothermodynamics Frbr. 2008, Frankfurt-Germany, 2008, pp. 1–9.

[33] K. Yasui, T. Tuziuti, W. Kanematsu, Extreme conditions in a dissolving air nanobubble, Phys. Rev. E. 94 (2016) 1–13, https://doi.org/10.1103/PhysRevE.94.013106.

[34] A.P. Froba, M.H. Rausch, K. Krzeminski, D. Assenbaum, P. Wasserscheid, A. Leipertz, Thermal conductivity of ionic liquids: Measurement and prediction, Int. J. Thermophys. 31 (2010) 2059–2077, https://doi.org/10.1007/s10765-010-0889-3.

[35] A.Z. Hezave, R. Raissi, M. Lashkarbolooki, Estimation of thermal conductivity of ionic liquids using a perceptron neural network, Ind. Eng. Chem. Res. 51 (2012) 9886–9893, https://doi.org/10.1021/ie202681b.

[36] T. Sivasankar, V.S. Moholkar, Physical insights into the sonochemical degradation of recalcitrant organic pollutants with cavitation bubble dynamics, Ultrason. Sonochem. 16 (2009) 769–781, https://doi.org/10.1016/j.ultsonch.2009.02.009.

[37] K. Yasui, Alternative model of single-bubble sonoluminescence, Phys. Rev. E - Stat. Phys. Plasmas, Fluids, Relat. Interdiscip. Top. 56 (1997) 6750–6760, https://doi.org/10.1103/PhysRevE.56.6750.

[38] G. Chatel, D.R. Macfarlane, Ionic liquids and ultrasound in combination: Synergies and challenges, Chem. Soc. Rev. 43 (2014) 8132–8149, https://doi.org/10.1039/c4cs00193a.

[39] J.P. Diebold, A unified, global model for the pyrolysis of cellulose, Biomass and Bioenergy. 7 (1994) 75–85, https://doi.org/10.1016/0961-9534(94)90039-V.

[40] K. Kerboua, O. Hamdaoui, Ultrasonic waveform upshot on mass variation within a single cavitation bubble: Investigation of physical and chemical transformations, Ultrason. Sonochem. 16 (2009) 769–781, https://doi.org/10.1016/j.ultsonch.2009.02.009.

[41] K. Kerboua, O. Hamdaoui, Sonochemistry Involv. Inorg. Syst., National Institute of Advanced Industrial Science and Technology, Anagahora-Japan, 2011, pp. 1–29, doi:10.1007/978-90-481-3887-6.

[42] A. Hemous-Villiere, J.M. Lévéque, J. Kärkkäinen, N. Papaiononomou, M. Lajunen, U. Lassi, Task-specific ionic liquid for the depolymerisation of starch-based industrial waste into high reducing sugars, Catal. Today. 223 (2014) 11–17, https://doi.org/10.1016/j.cattod.2013.09.027.

[43] K. Kerboua, O. Hamdaoui, Ultrasonic waveform upshot on mass variation within single cavitation bubble: Investigation of physical and chemical transformations, Ultrason. Sonochem. 42 (2018) 508–516, https://doi.org/10.1016/j.ultsonch.2017.12.015.

[44] P.M. Kanthale, M. Ashokkumar, F. Grieser, Estimation of cavitation bubble temperatures in an ionic liquid, J. Phys. Chem. C. 111 (2007) 18461–18463, https://doi.org/10.1021/jp0610148.

[45] R.M. Elder, M.L. Calvisi, Thermal Effects in ultrasonic cavitation of ionic liquids, Phys. Rev. E - Stat. Phys. Plasmas, Fluids, Relat. Interdiscip. Top. 56 (1997) 1864–1877, https://doi.org/10.1103/PhysRevE.56.1877.

[46] P.K. Chatterjee, Chain reaction mechanism of cellulose pyrolysis, J. Appl. Polym. Sci. 12 (1968) 1859–1864, https://doi.org/10.1002/app.1968.070120807.