How to Avoid Total Dissolved Gas Supersaturation in Water from Hydropower Plants by Employing Ultrasound

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Maren Elise Rognerud*, **Bjørn W. Solemslie**
Waterpower Laboratory, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

E-mail: marenrog@stud.ntnu.no

Md H. Islam, Bruno G. Pollet
Hydrogen Energy and Sonochemistry Research Group, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Abstract. In Norway, more than 10 hydropower plants are known to have caused biologically relevant levels of total dissolved gas supersaturation in the rivers downstream power plants. This phenomenon is causing fish kills due to gas bubble disease and have large impacts on the biodiversity. The gas supersaturation is often caused by undersized or blocked brook intakes creating turbulent flows and resulting in large amounts of air dragged into the tunnel. One possible solution to this problem is employing power ultrasound (20 kHz - 1 MHz) for degassing water prior to releasing it back into the river system. Acoustic cavitation is known to have a positive effect on the degassing mechanism, and this paper is investigating whether ultrasound can be applied to create acoustic cavitation and avoid biologically relevant levels of total dissolved gas supersaturation from hydropower plants. The objective is to develop background knowledge for constructing an experimental setup in the Waterpower Laboratory at NTNU to investigate whether gas supersaturation can be decreased from power plants by application of ultrasound. Preliminary experiments, carried out at the NTNU Hydrogen Energy and Sonochemistry Laboratory, exploring the behaviour of the degassing process at different ultrasonic frequencies and amplitudes conclude that the most effective degassing occur at high acoustic amplitude and a frequency of 24 kHz.

1. Introduction

Hydropower is the most important resource for energy production in Norway as 94 % of the electricity production is based on hydroelectric power generation. Technological development has enabled power demanding industry and power system technology to evolve throughout the past 100 years [1]. During this century knowledge about hydropower systems has grown, and researcher's attention has been directed towards new challenges like preservation of environmental values and biodiversity. One of these more resent challenges is the issue of gas supersaturation in rivers and lakes downstream hydropower plants. This phenomenon was first observed downstream river power plants in the Colombia and Snake rivers in the 1960s [2]. In Norway suspicion that supersaturated water from power plants could cause fish kills were raised in 1972 when dead fish were observed downstream Matre power plant in Masfjorden [3].

Gas supersaturation occur if the amount of dissolved air in water is higher than the solubility threshold at a given ambient pressure and temperature. Supersaturated water can occur in hydropower plants when pressurized water with high concentration of dissolved gas is exposed to atmospheric pressure in the downstream river or lake. Air is usually entering the water system through the brook intakes [4]. The intakes are designed to avoid air from entering the system, although, undersized intakes and flood situations with high water levels cause turbulent flows around the intakes and results in air transportation into the tunnel system. When this phenomenon appear, fish and other aquatic species die from gas bubble disease if the supersaturation levels are high over a longer period of time [3, 5]. The supersaturated water is degassing slowly, especially in deep and calm rivers or lakes. This results in supersaturated water being transported for tens of kilometres downstream the power plant and affecting biodiversity in vast areas of the water system [3].

One possible solution to the challenge of minimizing emission of supersaturated water from hydropower plants, is by using ultrasound to enhance the degassing process. Utilizing ultrasound for degassing has been used widely in the food industry to improve quality and durability of food products, and in material technology to ensure better quality of metal, glass and other products. When ultrasound is applied to supersaturated water, the rarefaction induces cavitation bubbles that can contribute to accelerate the degassing mechanism [6]. Performing a literature review on acoustic cavitation creates a foundation of knowledge to perform experiments with degassing water with ultrasound, further, the hypothesis is tested by applying ultrasound to small amounts of oxygen saturated water and measuring the decay of dissolved oxygen over time.

2. Theory

The solubility of air in water increase with increasing pressure and decreasing temperature[7]. When the water is undersaturated air is slowly dissolving in the water, and conversely, when the water is supersaturated air is transported from the water[3]. This degassing mechanism can be enhanced by applying ultrasound to supersaturated water, and the background theory explaining this phenomenon is given in the following section.

2.1. Ultrasound

Ultrasound is acoustic waves with frequencies above the human hearing range i.e. above 10 kHz [8]. One way to classify ultrasound is according to frequency and power. Ultrasound with frequencies above 1 MHz is defined as low power ultrasound and is transmitting low levels of power with high frequencies. This type of ultrasound usually has an acoustic power of less than 10 W and is not affecting the medium of propagation. Therefore, it can be used for medical imaging and diagnostics [9]. Ultrasound with low frequencies, between 20 kHz and 1 MHz, is power ultrasound. These acoustic waves are transferred through a medium with power larger than 10 W, and the acoustic waves are altering the medium of propagation. This range of ultrasonic frequencies is used in sonochemistry where sound waves are introduced to produce chemical reactions in the medium of propagation, for instance to produce hydrogen from water [10].

An acoustic wave can be described mathematically with Equation 1.

$$P = P_a sin(2\pi ft)[Pa] \tag{1}$$

P_a is the maximum pressure amplitude, f is the frequency and t is time [11]. The maximum pressure amplitude is directly proportional to the input power from the transducer. One important measure used for ultrasound is the ultrasonic intensity, I, defined as follows.

$$I = \frac{{P_a}^2}{2\rho a}[W/m^2] \tag{2}$$

ρ is the density and a is the speed of sound in the medium. The intensity is defined as the average rate of flow of energy through a unit area normal to the direction of propagation [8].

2.2. Acoustic Cavitation

Ultrasonic waves are pressure pulsations moving through a medium like illustrated in Figure 1. If the rarefaction pressure is below the vapour pressure for water, small bubbles of water vapor starts to form in the liquid. The rarefaction is followed by a compression phase where the pressure no longer can sustain the water vapour, resulting in a violent collapse of the bubble. This collapse launch shock waves into the water that can increase temperatures to about 5000 °C and pressure to 2000 atm at this point [10]. The bubble implosion can induce light emission (sonoluminescence) and chemical reactions where highly reactive radicals are produced (sonochemistry) [12]. If the bubble collapse happens close to a solid wall, the bubble implodes in a nonlinear manner and creates a jet with speeds up to 200 m/s directed towards the solid surface [10]. The forces induced by the collapse have erosive effects on the wall [8]. The process of bubble formation, growth and collapse due to changes in acoustic pressure is called acoustic cavitation. Acoustic cavitation is comparable to boiling, with two major differences. First, boiling is a result of increased temperature in a liquid, not a pressure decrease. Secondly, in boiling the bubble collapse is not present [8].

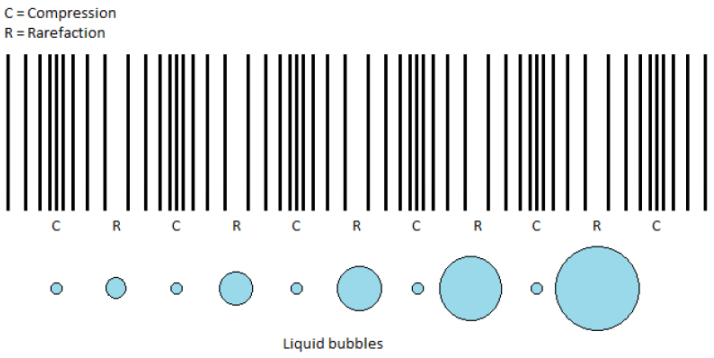

Figure 1. Ultrasonic pressure wave propagation and growth of a cavitation bubble during some cycles of ultrasound [13].

2.3. Other Phenomena Introduced by Ultrasound

In an ideal system with a fluid exposed to an ultrasonic wave, one parcel of fluid is moving back and forth to the same place with the ultrasonic pressure pulsation. However, in a real fluid the parcel will not move in this manner, and the position will change over time. This phenomenon is called acoustic streaming and results in a direct current flow in the wave propagation direction. This motion can be explained by the fact that the pushing of a viscous fluid along the direction of the acoustic wave is stronger than the pulling of it due to the moment of inertia of the fluid. This creates motion in the liquid. Acoustic micro-streaming is a phenomenon that occurs when the length scale of streaming caused by viscous stress near an object or wall is smaller than the acoustic wavelength [8].

[14] studied the effect of ultrasonic frequency and power on the bubble size of cavitation bubbles. Looking at bubble size for frequencies from 20 kHz to 1136 kHz it was shown that the bubble size decreased considerably with increasing frequency and increased with increasing power. Also, the study concluded that the difference in bubble size was larger for lower frequencies and higher power. To understand this phenomenon one can look at the mechanism of bubble collapse in an ultrasonic field. When a cavitation bubble is created it is vibrating with a natural frequency much higher than the ultrasonic frequency. The bubble starts growing and when the surface area becomes larger, the natural vibration frequency decreases. This process will continue until the oscillation frequency of the bubble equals the frequency of the ultrasonic field. When this happens, the bubble collapses [15]. At high frequencies, the maximum bubble size is therefore limited to a smaller size compared to lower frequencies.

[11] investigated the effect of ultrasonic power on the propagation medium. It was found that low frequencies produce high temperatures due to energy dissipation from high power ultrasound, cavitation and micro-streaming. For higher frequencies cavitation becomes less violent, and for frequencies in the MHz - range, only acoustic streaming is observed. The article concludes that the mode of action of ultrasonic waves changes as a function of input power. At low input powers no chemical or physical changes are detected, while at high power the medium changes chemically or physically. Additionally, [15] points out that bubble collapse is an almost adiabatic process where all energy is converted into heat. For low frequencies, the bubbles are larger and the energy discharge from the bubble collapse is stronger compared to smaller bubbles.

When a bubble collapses it produces highly reactive radicals due to the high temperature and pressure and fewer cavitation bubbles are introduced at low frequencies compared to higher frequencies. All together this means that the radical production which is attractive to achieve when doing sonochemistry will have a maximum when both bubble size and bubble numbers are large. For creating share stress and movement in the solution on the other hand, frequencies lower than this are effective [15].

The theoretical cavitation threshold in water, the limit pressure where cavitation is initiated, is calculated by the pressure that is needed to overcome the tensile strength of pure water. Theoretically this limit is at about 1000 atm. Although, experiments show that the actual cavitation threshold is much lower than this limit. The reason for this phenomenon is that the cavity is more easily able to form around micro particles or bubbles that are already present in the water, so-called cavitation nuclei. In water small bubbles will always be present and the amount of bubbles will increase with the amount of dissolved air in the water [15]. [8] presents experimental results showing a decrease in cavitation threshold with increased dissolved air. This is evidence that the cavitation bubbles also contain air, not only water vapor. Therefore, cavitation bubbles can theoretically enhance the degassing process.

2.4. Degassing with Ultrasound

Ultrasound can have many effects on the medium of propagation. During the rarefaction phase acoustic cavitation occur if the rarefaction pressure is below the cavitation threshold pressure. When cavitation bubbles starts to form, they are pulsating and dissolved air is transported into the bubbles with diffusion [16]. When the pressure is high the bubble decrease in size and the gas diffuses from the bubble into the liquid. Conversely, when the pressure decreases, the bubbles expand, and gas diffuses from the liquid into the bubble. During the rarefaction the surface area is larger, and more gas can diffuse in through the bubble surface compared to the amount that escapes during the compression phase. This phenomenon is called the area effect on gas diffusion. Additionally, there is a resistance for molecules to move from a low density environment inside the bubble to a high density environment in the water phase. This effect is called the shell effect. Both the area effect and the shell effect is preventing air from leaving the bubble [15]. Hence, the bubble acts like a pump; for each expansion the bubble gain more

gas than it loses during the compression and is gradually filled with air. Therefore, the bubble manages to grow and after some time it floats to the surface driven by buoyancy forces. This process is called rectified diffusion. Additionally, microscopic acoustic streams are generated in the viscous boundary layers around the bubble surface and contribute to mass transfer that supplies the bubble with new liquid at the bubble surface. When the bubbles starts moving it creates convective flows in the liquid that contribute to increase the degassing efficiency because the bubbles are distributed around in the liquid [6]. The growth of a cavitation bubble during some cycles of ultrasound is described in Figure 1.

3. Experiment Setup

A small scale experimental setup was used to look at the degassing effect of different frequencies of ultrasound on 1.2 litres of oxygen saturated, distilled water. The water was pumped between two glass vessels at a flow rate of approximately 0.5 L/min. The first vessel had a cooling system and the ultrasonic transducers attached to it, and in the second vessel the measurements were taken. The measurements were separated from the ultrasonic transducer to avoid disturbances from the ultrasound. The two vessels are connected with silicon tubing to circulate the water between them. The silicon tubes should not be put in vicinity of the ultrasound. Therefore, glass pipes were used in the vessel with the ultrasonic transducer to circulate the solution and add oxygen to the water.

The probes used to measure pH, dissolved oxygen (DO) and electrical conductivity (EC) are Hanna Instruments Edge measurement probes. Three ultrasonic transducers were used to conduct experiments on ultrasonic degassing of oxygen from water. To produce the frequencies 580 kHz, 860 kHz and 1140 kHz, the Meinhardt Ultrasonics Multi-frequency System was used. A Meinhardt Ultrasonics Transducer was used for 40 kHz and the Hielscher UP400St was used for 24 kHz. The Multi-frequency system and the 40 kHz system use plate transducers while the Hielscher system uses a sonotrode.

The experimental procedure begun by filling the vessels with 1200 mL distilled water and the circulation pump was started. When the pH, EC and DO readings stabilized, oxygen was bubbled into the circulating solution at atmospheric pressure until it reached an oxygen saturation of about 19 mg/L. The oxygen bubbling was stopped, and the solution circulated until the saturation level stabilized and started to decrease. When the saturation level reached 18 mg/L the ultrasound was turned on, as well as the cooling system. The cooling system kept the solution at approximately 25°C. The transducer was on until the dissolved oxygen level decreased to its original level, about 7.8 mg/L. During this process the DO, pH and EC were logged once every minute, as well as the temperature. Each experiment was repeated three times to reduce the random experimental error and the presented results are the averaged values from the experiments.

4. Results and Discussion

The decay of dissolved oxygen for different frequencies is presented in Figure 2. The most effective degassing frequency was 24 kHz, therefore, different acoustic pressure amplitudes were tested for this frequency to look at the effect of acoustic intensity on the degassing effect. The results are shown in Figure 3. The change in pH and EC during the experiments is presented in Tables 1 and 2. Additionally the transferred energy from the transducer to the water was determined for the experiments on 24 kHz with calorimetry and the results are shown in Figure 4 [17, 18].

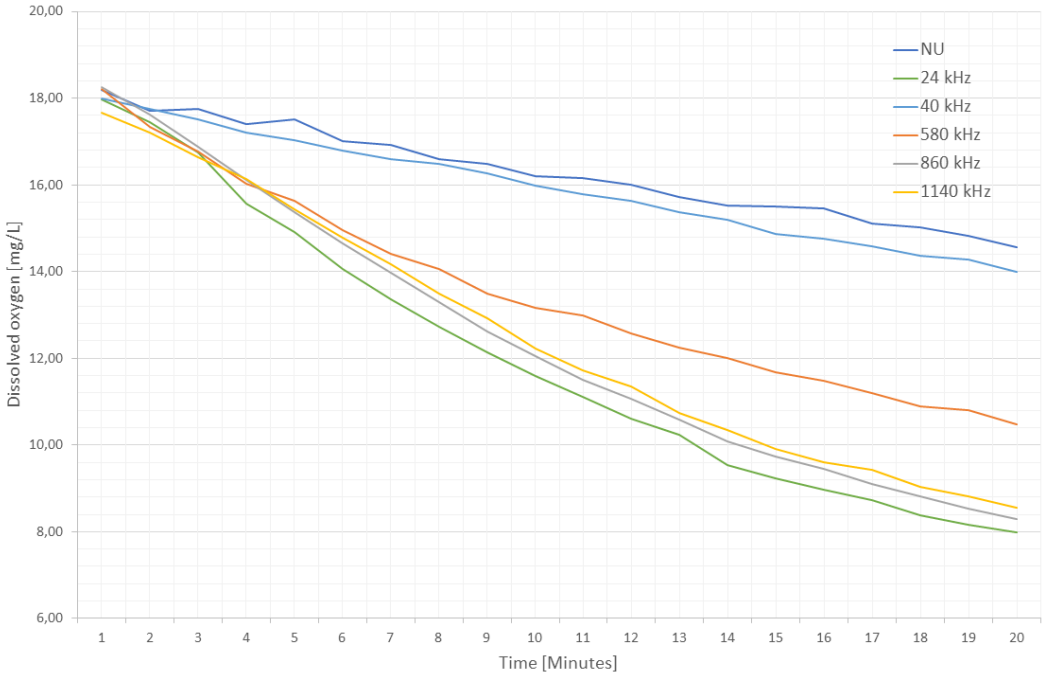

Figure 2. The decay of dissolved oxygen with time for ultrasonic frequencies 24 kHz, 40 kHz, 580 kHz, 860 kHz, 1140 kHz and no ultrasound (NU).

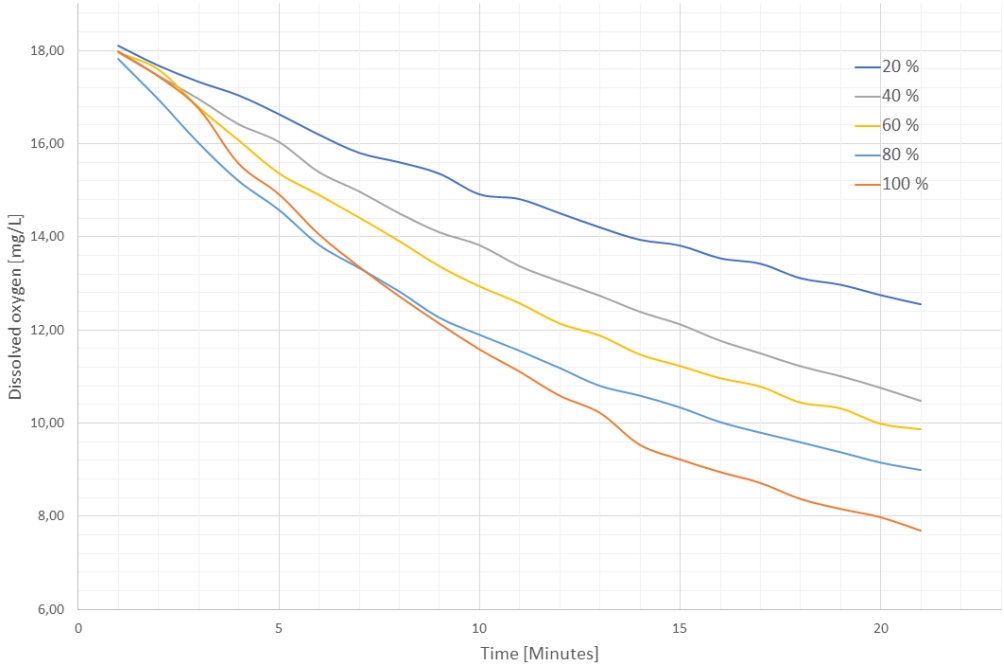

Figure 3. The decay of dissolved oxygen with time for ultrasonic frequency of 24 kHz and amplitudes 100 %, 80 %, 60 %, 40% and 20 %.

The explanation of this degassing behaviour is based on the provided theory. The effects that are increasing degassing efficiency are share stresses created in the flow and thicker boundary layers around the bubbles. This increases the mass transfer of oxygen into the bubbles as micro-streaming is supplying the bubbles with high saturation levels of oxygen. A large bubble size allows each bubble to contain more oxygen that is transported out of the water when it floats to the surface. All these effects are dominating for low frequencies of ultrasound and can explain how 24 kHz can be the most effective degassing frequency.

For higher frequencies favourable effects that may increase the efficiency of degassing are the facts that a higher number of bubbles are created at higher frequencies and acoustic streaming is stronger and creates secondary flows inside the glass vessel. This leads to a larger amount of air inside bubbles in total, that is transported to the surface by the streaming effect. Although, if the frequency becomes too high the bubbles will collapse before they are transported to the surface and the degassing effect will be limited by this phenomenon. Therefore, the increase of acoustic frequency above 860 kHz is not increasing the degassing efficiency further.

In between the high frequencies and lower frequencies, the degassing effect is lower. When going from low to higher frequencies the bubble size decreases as well as acoustic micro-streaming decreases, lowering the degassing efficiency. While further increasing the frequency the number of bubbles increases as well as the acoustic streaming. Therefore, the degassing efficiency increases to a new maximum point until the more frequent early bubble collapse limits the amount of bubbles that can float to the surface. This can explain why frequencies of 40 kHz and 580 kHz are clearly less effective for degassing purposes.

When the experiments on frequency dependence were conducted, one acoustic frequency was chosen to experiment with amplitudes. 24 kHz was the most effective frequency for degassing but was very close to the 860 kHz degassing efficiency. [13] preformed calorimetry experiments using the Multi-frequency transducer and the Heilcher sonotrode and found that the power transmitted to 250 mL water at 860 kHz was 34.5 % of the power transmitted at 24 kHz. These numbers are not directly comparable to the setup used in this experiment but shows that the energy usage is considerably larger for 24 kHz. Although, it was observed that the increase in pH was lower at 24 kHz, and the degassing efficiency was slightly better. Hence, 24 kHz was chosen.

The amplitude effect on degassing in Figure 3 shows that the higher acoustic pressure amplitude used, a more effective degassing was observed. When increasing the amplitude with 20 % steps the degassing efficiency increases almost linearly. This means that increasing the pressure amplitude, i.e. the acoustic intensity, improves the degassing efficiency at this frequency. With this in mind, another possible explanation of the poor degassing efficiency of 40 kHz is that the acoustic power transferred to the water using the 40 kHz plate transducer transmitted a significantly lower amount of acoustic power compared to the 24 kHz sonotrode, although this has not been proven in experiments. The degassing efficiency is highly dependent on the power and the ultrasonic intensity supplied to the water.

The water was saturated to 18 mg/L, corresponding to a 230 % saturation level at 25°C. The results in Figures 2 and 3 clearly show that the degassing efficiency is depending on the saturation level in water. The degassing slope is steeper for high saturation levels and flattens out when the saturation level is closer to the solubility limit. The explanation to this phenomenon is that the air content of the water supplied to the bubbles is lower at lower saturation levels. Therefore, the bubble growth is slower, and hence, the degassing is slower. This represents a challenge for using ultrasound for degassing in hydropower plants. The water in a hydropower plant is moving through an ultrasonic field and will only be exposed to the ultrasound for a short amount of time. If saturation levels are high, it might be possible to reduce the saturation level to some extent, but the exposure time will always be an issue. The question whether the degassing can be effective in these conditions is yet to be investigated.

Frequency	$\frac{dpH}{dt}$	$\frac{\frac{dpH}{dt}}{\frac{dpH}{dt}_{NU}}$	$\frac{dEC}{dt}$	$\frac{\frac{dEC}{dt}}{\frac{dEC}{dt}_{NU}}$
No ultrasound	-0.0051	1	0.0216	1
24 kHz	-0.0137	2.7	0.0626	2.9
40 kHz	-0.0151	2.9	0.0348	1.6
580 kHz	-0.0290	5.7	0.1185	5.5
860 kHz	-0.0210	4.1	0.0576	2.7
1140 kHz	-0.0311	6.1	0.0706	3.3

Table 1. The slopes of decrease of pH and increase of EC over time for the different frequencies. Additionally, the relative slopes compared to no ultrasound (NU) are listed.

Amplitude	$\frac{dpH}{dt}$	$\frac{\frac{dpH}{dt}}{\frac{dpH}{dt}_{NU}}$	$\frac{dEC}{dt}$	$\frac{\frac{dEC}{dt}}{\frac{dEC}{dt}_{NU}}$
20 %	-0.0197	3.9	0.0148	0.7
40 %	-0.0119	2.3	0.0254	1.2
60 %	-0.0097	1.9	0.0332	1.5
80 %	-0.0148	2.9	0.0500	2.3
100 %	-0.0137	2.7	0.0626	2.9

Table 2. The slopes of decrease of pH and increase of EC over time for the different amplitudes at frequency 24 kHz. Additionally, the relative slopes compared to no ultrasound (NU) are listed.

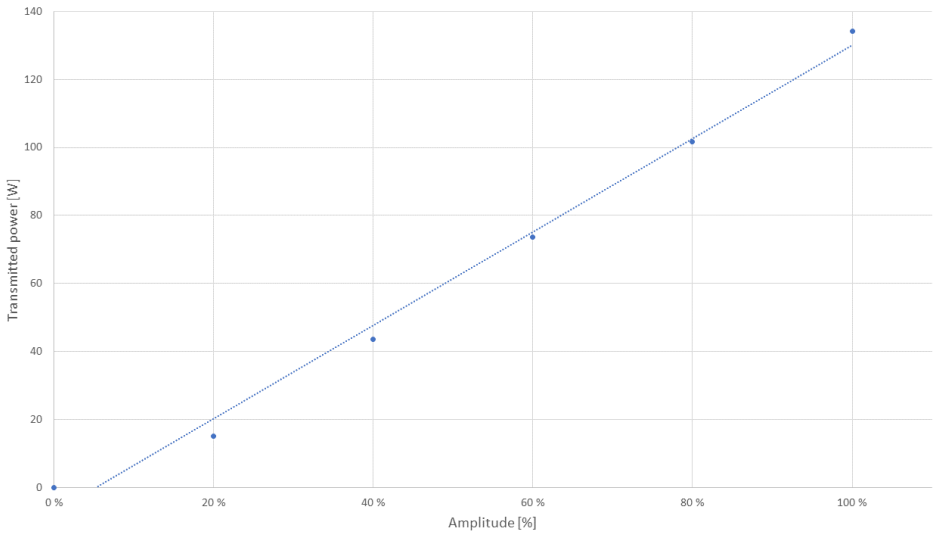

Figure 4. Relationship between acoustic pressure amplitude and acoustic power transferred to the system for 24 kHz ultrasound applied to a system containing 1200 mL water. The dotted line is a linear curve fitting to the data points.

The pH development shows a negative trend throughout all the experiments. In general, the negative slope is steeper when ultrasound is used compared to experiments without ultrasound. One explanation for the negative trend when ultrasound is not used is that deionized water was used to conduct the experiments. This water is neutral until it comes into contact with air. When

that happens, CO_2 gas starts dissolving in the water, making it slightly acidic. This process is continuing throughout the experiment because the glass vessels are open to the atmosphere, explaining the decay in pH. Further, the experiments with ultrasound induce an additional effect making the slope even more negative. The EC measurement is an indication of the amount of ions in the solution because electrically charged ions increase the electric conductivity. The EC is increasing gradually during the experiment for no ultrasound and the increase is steeper when ultrasound is used. One can understand the change of pH and EC over time as measures of sonochemical activity. In general, the sonochemical activity is high for high temperatures and pressures generated from the cavitation bubble collapse. This occurs at lower frequencies where large bubbles create high pressure and temperature, and at a large number of bubbles i.e. at higher frequencies. Therefore, there should be a best point at medium frequencies where radical production is high. At 580 kHz both the pH and EC- slopes are relatively steep, and this might indicate closeness to a point of high sonochemical activity. It is not favourable to have a decrease in pH in the water downstream a hydropower plant. It is best to avoid using frequencies that produce the steepest gradients of pH although the increase of pH when exposing water to ultrasound for a short amount of time is expected to be very small.

5. Conclusions

From the experiments it is found that the degassing effect is dependent on both acoustic power and frequency. Various phenomenon introduced by acoustic cavitation results in a high degassing effect for low frequencies around 24 kHz and higher frequencies around 860 kHz with a less effective region in between them. The sonochemical activity is high for medium frequencies around 580 kHz and should be avoided in degassing purposes for environmental reasons. The increase in power results in a higher degassing efficiency, and the power must be increased to maintain the degassing efficiency when the sonicated water volume is increased. The fastest completed degassing of 1200 mL water from 230 % saturation with a frequency of 24 kHz and a transmitted acoustic power of 134 W was measured to take about 20 minutes.

The presented results show that the application of ultrasound on oxygen-supersaturated water is making the degassing process more effective. Although, some challenges for future work are revealed. The sonochemical activity that is initiated when ultrasound is applied to water creates highly reactive radicals contributing to lowering the pH and increase the electrical conductivity. The extent of these phenomenon needs to be further investigated to ensure good water quality in the water systems. Additionally, the exposure time of ultrasound in these experiments have been in the order of twenty minutes. In a hydropower system this time may be in the order of one second, and proving that the concept works in cases of smaller exposure times will become an important task in further research.

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