Ultrasound as a Process Intensification Tool

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Abstract

Ultrasound is a novel technology, which is attaining widespread use in various scientific and medical fields. In the medical domain, high frequency ultrasound is being used to replace x-rays in diagnosis. In the process industry, high intensity, low frequency ultrasound is being used to enhance various chemical and physical processes such as reaction initiation and mixing.

Despite the growing use of ultrasound, there is still a large debate over the calibration methods employed to characterise the ultrasonic intensity dissipated in a solution. Current methods rely on computer simulations, which are then linked to experimental observations, on calorimetric methods which gauge the overall energy absorbed by a system and not necessarily the portion of energy which contributes to a particular stage in the reaction process, or on chemical dosimeters which rely only on the chemical effects of ultrasound to give a measure of its dissipation.

A new method of incorporating ultrasound into continuous micro-devices is given, and a novel method of measuring ultrasonic energy dissipation across this continuous system is proposed. This method makes use of a pressure drop generated due to ultrasonic exposure. Such measurements are linked directly to energy dissipation in solutions and mean that the experimenter can gauge more accurately the ultrasonic energy dissipation without relying on experimental fitting parameters.

Symbols

S.Y.	Sonochemical Yield
K,c	Constants in Eq. 1
$P_{collapse}$	Collapse pressure of bubble (atm)
ΔP	Pressure drop (atm)
L, D	Effective length and diameter of device (m)
f	Friction factor
ρ	Density (kg/m^3)
$\overline{V}$	Effective velocity (m/s)
V	Volume (m^3)
Φ_{total}, Φ_{US}	Global energy dissipation rate (total, ultrasonic) (W/kg)
Q	Flow rate (m^3/s)
EPDI, I	Electric power draw intensity (W), Intensity (W)
ν	Viscosity
ε	Local energy dissipation rate (W/kg)
FR	Flow rate
r_u	Bubble radius
P_A	Applied acoustic pressure (atm)
R_e, R_t	Initial bubble radius, bubble radius at time ‘t’ (m)
ω_r ω_a	Natural bubble frequency and applied ultrasonic frequency (rad)
T	Time (s)
C	Wave speed (m/s)
P_t, P_v, P_g	Pressure in bubble at time ‘t’, pressure of vapour and of gas in bubble (atm)

1. Introduction

When carrying out ultrasonically enhanced reactions, it is vital to know the power dissipated in the solution due to the passage of the ultrasonic wave. In order to estimate chemical activity, only the energy involved in enhancing chemical processes must be considered. If this quantity was known accurately, more precise correlations could be drawn, relating the enhancement effects to the amount of ultrasonic energy dissipated in a solution.

In order to quantify the effects of ultrasound on mixing, it is essential to know the relationship between ultrasonic intensity and cavitationally effective power per unit reactor volume or reacting mass. An exact relationship between the yield and the power dissipated still eludes researchers; still some headway has been made in this direction (Atchley & Crum, 1979; Kanthale et al., 2003; Margulis & Margulis, 2003; Shah, Pandit, & Moholkar, 1999). In addition to the power intensity per unit area (W/cm^2), the literature viewed reports power density (W/kg) (Koda et al., 2003; Neppiras, 1980; Todd, 1970) as another indication of the efficiency of the sonic reactor and measure of the chemical activity. These indications, presented below (section 2), were merely experiments correlations between the observed enhancements and a chosen variable ultrasonic parameter.

In terms of turbulent mixing, the power density would be the more appropriate indication. The power density is equivalent to the energy dissipation rate, though to have a direct impact on turbulent mixing. The problems associated with the current calibration methods are highlighted below, and a new technique for quantifying ultrasonic energy dissipation in a solution is presented.

2. Existing Methods

The simplest indication of ultrasonic energy dissipated in a reacting vessel is the transducer indication as many ultrasonic transducers come with panels (or dial knobs) indicative of the power drawn from the electric power source. However, several factors may contribute to this power not being dissipated in the vessel contents.

Firstly, a large portion of the energy goes to exciting the piezoelectric crystals in the ultrasonic transducer. Secondly, of the energy transmitted, only a portion is dissipated in the vessel. This is due to several reasons, as follows.First, the geometry of the equipment used affects power dissipation. This includes the size and shape of the vessel. These will affect the path of the wave, and whether or not standing waves will be formed. Moreover, the geometry and the ultrasonic intensity could result in the formation of a 'cushion' of bubbles which will hinder the passage of subsequent waves through the solution. The shape of the wave, and its progress and attenuation across the sonicated volume will affect the cavitation and consequently affect the energy dissipation. Second, the vessel contents themselves affect cavitation and hence power dissipation. For example, the contents' viscosity will influence the power required to generate the same amount of cavitation intensity. Other factors influencing the energy dissipated include dissolved gases and experimental temperature and pressure.

Secondly, detection of the power dissipated may also depend on the vessel size. Even if the overall power dissipated was the same, in two different vessels, it might not be as easy to measure power dissipation in the larger system, as the change in physical properties might not be significant enough. For example, sonicating 2L of water will result in a smaller temperature rise for the same amount of power, than sonicating 200ml. Moreover, the dissipation of ultrasonic energy may be localised, and thus limited to the close vicinity of the probe. In the case of big vessels, this volume may be insignificant compared to the overall volume of the vessel, and thus undetectable or ineffective in achieving desired affects.

Several methods have been suggested in the literature to quantify the ultrasonic energy absorbed by a system. These generally fall under four categories,

- Relating a simulated collapse pressure of a bubble (or cluster of bubbles) to experimental conditions using curve fitting parameters (Kanthale et al., 2003),
- Measuring the heat absorbed by a solution (Margulis & Margulis, 2003),
- Using chemical dosimetry to measure sonochemical efficiency (Kimura et al., 1996; Koda et al., 2003),
- Using the electric power draw to correlate experimental results

2.1. Simulation method

This method was proposed by Gogate and Pandit (2000). Initially, the behaviour of a single bubble was considered and studied using the Rayleigh-Plesset equation. A more recent paper considers the existence of the bubble in clusters and not in single entities. This assumption was supported by laboratory experiments (Kanthale et al., 2003). Computer simulations studying the effects the initial cluster size, ultrasonic frequency, ultrasonic intensity and energy emission on the collapse pressure were conducted individually. Subsequently, a correlation was drawn relating the collapse pressure to all these variables simultaneously. The authors then propose to relate the experimental sonochemical yield to this collapse pressure using (Gogate and Pandit 2000),

$$S.Y. = K(P_{collapse})^{c} \qquad \textbf{Eq 1.}$$

Where the constant K and c depend on the reactor geometry, operating parameters and the type of reaction. They indicate how much of the propagated ultrasonic energy is actually absorbed by the solution, and eventually how much of it contributes to the observed phenomena.

Despite the promise of a reliable prediction of the collapse pressure, the relationship to experiments was entirely dependant on experimental conditions. Thus, the equation would be tailored to a specific vessel and operating conditions, and would represent a way of quantifying ultrasonic yield rather than a way of determining ultrasonic power.The highlight of this method is that it re-iterates that the bubbles are responsible for the relay of the acoustic energy into the solution medium and can still be used to give an estimate of bubble size changes. However, even a simple change in the overall volume of the reactor or reacting fluid would warrant a change in the constants, and this would add further complications and difficulties towards considering the above a generalized formula for predicting sonochemical yield.

2.2. Calorimetric and dosimeter methods

Margulis & Margulis, (2003) recommend a calorimetric method to measure the acoustic power absorbed in a volume of liquid. This method measures the temperature rise of a volume of liquid due to irradiation with ultrasound. The assumption made is that all the energy absorbed is dissipated as heat, which eventually manifests as a temperature rise.

They maintain that not all the irradiated energy is sonochemically active, as not all of it is absorbed by the solution.

However, it is this absorbed energy which is responsible for the perceived enhancements (Margulis & Margulis, 2003). By measuring the temperature rise of the solution, automatically, an account of the vessel geometry and operating parameters, on which the constants K and c in Eq.1 are dependant, is made. However, there remains the effect of the type of reaction. It has been hypothesized that the extreme temperatures generated may affect the kinetics of reactions.

Based on this, chemical dosimeters were introduced as a means of calibrating the ultrasonic intensity (Kanthale et al., 2003). Three different chemical dosimeters were investigated, namely, the Fricke dosimeter, the KI dosimeter and the TPPS dosimeter. All were shown to give different results for different ultrasonic frequencies and intensities over a certain time period. The overall calibration time would require well over a minute, and it seems to have been devised for batch reactors, where it was also recommended that the calorimetrically determined power be provided as well. Unfortunately, this method describes what was termed 'sonochemical efficiency' and not the true acoustic power. It would still suffer from the problems associated with the heat calibration method. Furthermore, from a physical point of view, chemical dosimetry would not provide any direct indication of turbulence enhancement (if any). Notably, at the lower frequencies (under 100kHz, including 20kHz, and above 1MHz), the chemical effects per unit power were much smaller as compared to mid range frequencies (100-500 kHz) (Kanthale et al., 2003).

If mixing were enhanced by ultrasound, this would be attributed to the collapse of bubble and/or oscillations of bigger bubbles both of which contribute to the turbulent kinetic energy dissipation rate, ε via the release of shock waves (which are much stronger for collapsing bubbles as opposed to oscillating ones). Thus in term of mixing, the chemical effects may be ignored initially (the effect on the reaction rate may be accounted for later). In effect, the mixing rates were always seen to be the controlling step in the progress of fast reactions. The focus will be on enhancing the mixing step.

Calorimetric methods may provide a more accurate quantification of the total amount of energy absorbed by the system however, they still fail to capture the actual amount effective for mixing. Moreover, using the chemical dosimeter method means that both the effects on reaction kinetics manipulation induced by ultrasound will be measured. The singling out of the effects on mixing (via increased turbulence) was not found in the literature.

3. New proposed method

The methods of quantifying ultrasound used so far can all be described at best as experimental correlations. They relate a readily observable quantity (e.g. heat absorbed or simulated pressure) to a measured result, and obtain an experimentally fitted curve applicable only in the specific conditions of their experiments. Thus while these methods may be useful in limited design exercises, they fail to explain or justify the use of specific ultrasonic conditions. It was hypothesized that ultrasound may induce a turbulence-like effect through the generation and collapse of cavitation bubbles. Since turbulence may be seen to increase an effective viscosity, it is conceived that ultrasonic irradiation in a continuous flow device will induce turbulence and result in a change in the pressure drop across it. The pressure drop due to liquid flow across a device may be given by (Baldyga & Bourne, 1999),

$$\frac{\Delta P}{L} = \left(\frac{2 f \rho \overline{V}^2}{D} \right) \qquad \textbf{Eq. 2}$$

In laminar flow, the friction factor is inversely proportional to the Reynolds number, resulting in a linear dependence of the pressure drop on the Reynolds number (and flow rate), while in turbulent flow, the relationship deviates from linearity. This is due to the change in effective viscosity caused by turbulence. Across a 1.6mm diameter, 0.03cm length pipe, the pressure drop profile will fall under two types, laminar and turbulent. Since mixing devices may have different diameters at different points, it will be easier to subsequently plot the pressure drop changes vs. flow rates, as these will not vary with position (like the Reynolds number). The change of pressure drop with flow rate (when the variation of 'Re' is due only to a change in the effective viscosity) and flow rate is shown in Figure 1. Subsequently, the energy dissipated in the device may be given by (Baldyga & Bourne, 1999),

$$\Phi_{flow} = \left(\frac{Q \Delta P_{flow}}{\rho V} \right) \qquad \textbf{Eq. 3}$$

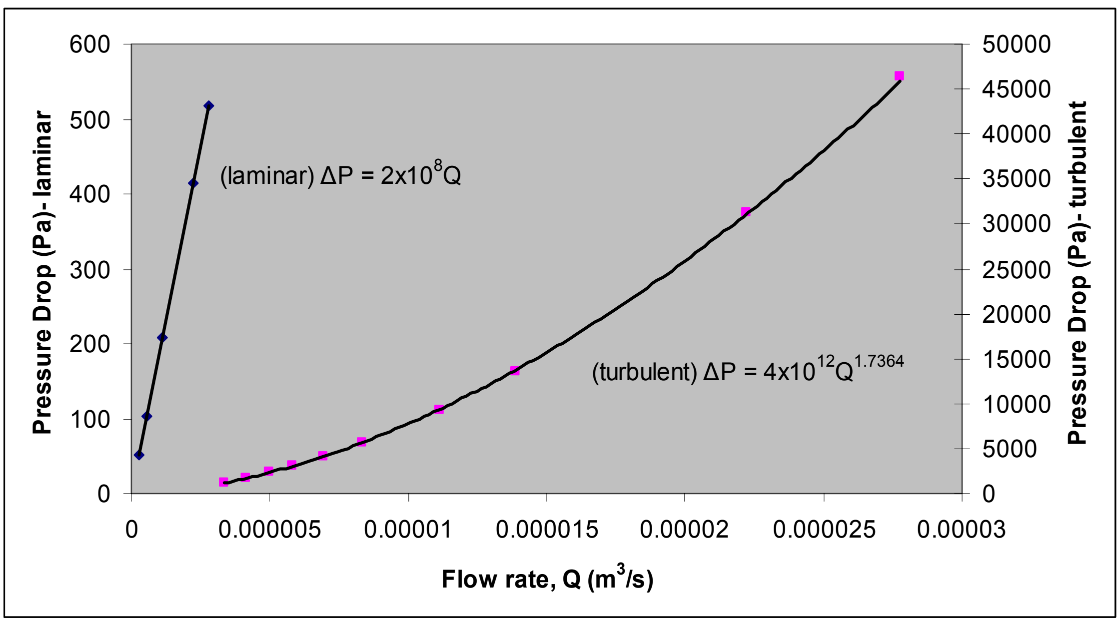

Figure 1. Graph of pressure drop vs. Flow rate for 1.6mm, 0.03m length t-piece.

Thus it is established that for laminar flow, the pressure drop is linearly dependant on the Reynolds number and flow rate, whereas for turbulent flow, it is not. Moreover, the energy dissipation rate is proportional to the square of the flow rate, in laminar flow, whereas it is not, in turbulent flow. This is due to the difference in dependence of the friction factor on Re. When the total inlet diameters are equal to the outlet diameters, the above equation and graph may be applied to a continuous mixing device with constant flow, in order to determine the flow pattern within it. Following on from the flow pattern determination, additional energy input, using an ultrasonic tip can be quantified using the change in the pressure drop. Eq. 3 can be re-written as

$$\Delta P = \left(\frac{\Phi_{total} \rho V}{Q} \right) \qquad \textbf{Eq. 4}$$

This allows a conversion of a measured pressure drop to an energy dissipation rate, which is thought to influence the mixing times (micro and meso). Φ_{total} refers to the total global energy dissipation rate across the device, and is due to two energy sources, the pump and ultrasonic horn. The conversion of ultrasound to turbulence can then be given by the difference of sonicated and non-sonicated values of Φ, at any given flow rate. Thus the energy input converted to turbulence due to ultrasound can be given by

$$\Phi_{US} = \Phi_{total} - \Phi_{flow} \qquad \textbf{Eq. 5}$$

Pressure can be used to quantify the parameter most relevant to mixing, the turbulent energy dissipation rate, assuming that the ultrasonic exposure did not affect the flow rate. Doulah (1979) measured this effect by finding the change in the diffusion coefficient. The pressure drop measurements are much simpler to carry out, requiring less demanding setups and may be applied readily in any laboratory.

3.1. Aim

The aim of this experiment was to carry out various tests in order to calibrate the ultrasonic device. The experiments were carried out using a t-piece in order to quantify the amount of ultrasonic energy that contributed to turbulence by calculating the energy dissipation rates. The changes in pressure drops across the device were measured at different flow rates for different ultrasonic intensities.

3.2. Materials and Equipment

The experiment was conducted using water as the fluid medium for the ultrasound to induce cavitation. Water was chosen as it has a low viscosity, and future experimentation with reactive tracers would be conducted in water.

The ultrasonic generator was the XL-2020 provided by Misonix Labs. The horn used had titanium, ¼”-diameter tip. The electrical power going into the converter will end up as acoustic energy into the sample and all of the losses associated with the crystal stack and metallic vibratory elements. These are both electrical (joule heating) losses and mechanical losses (internal friction, heating) (Misonix, 2003). Thus the intensity of sonication will depend on how much electric power is converted to acoustic energy, and how much of this energy is transmitted into the liquid medium.

3.3. Experimental Set-up

The equipment was set-up in a way to allow a smooth fluid flow through the mixers, while allowing the ultrasonic waves in from one end, and out through the other end. The pressure drop across the device relied on the change in height of a water column. A pressure of 1 atm (1 x 10^5 Pa) is equivalent to 1000 cm of water. Thus the difference in height of the two water pipes was converted to a pressure drop. The mixer used was a t-piece mixer, with 2 inlets and one outlet (I.D=1.6mm) and length 3cm.

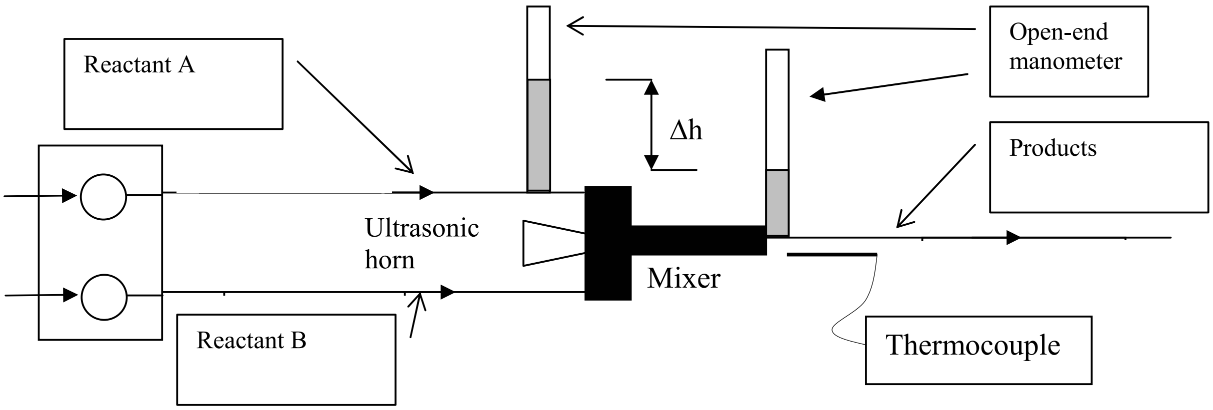

Figure 2. Schematic of Experimental set-up

3.4. Results and Discussion

The effects of ultrasonic irradiation for different flow rates were also studied. Increasing the ultrasonic intensity resulted in an increase in the pressure drop across the device, and hence an increase in the overall energy dissipation in the contained fluid. Plots of Φ_{US} vs. EPDI and Φ_{total} vs. EPDI can be seen in Figure 3 and Figure 4 for different flow rates.

It can be seen from Figure 3 that there is a jump in the amount of energy absorbed due to ultrasound between an electric power draw of 80 and 100 W. This may be indicative of the transition between stable and transient cavitation. Furthermore, in a small pipe it seems the majority of the energy dissipation rate will stem from the flow and not the ultrasonic irradiation. To illustrate this, a plot of the ratio of the ultrasonic energy absorbed to the total energy dissipation rate at different flow rates, was plotted versus the ultrasonic intensity. This is shown in Figure 4.

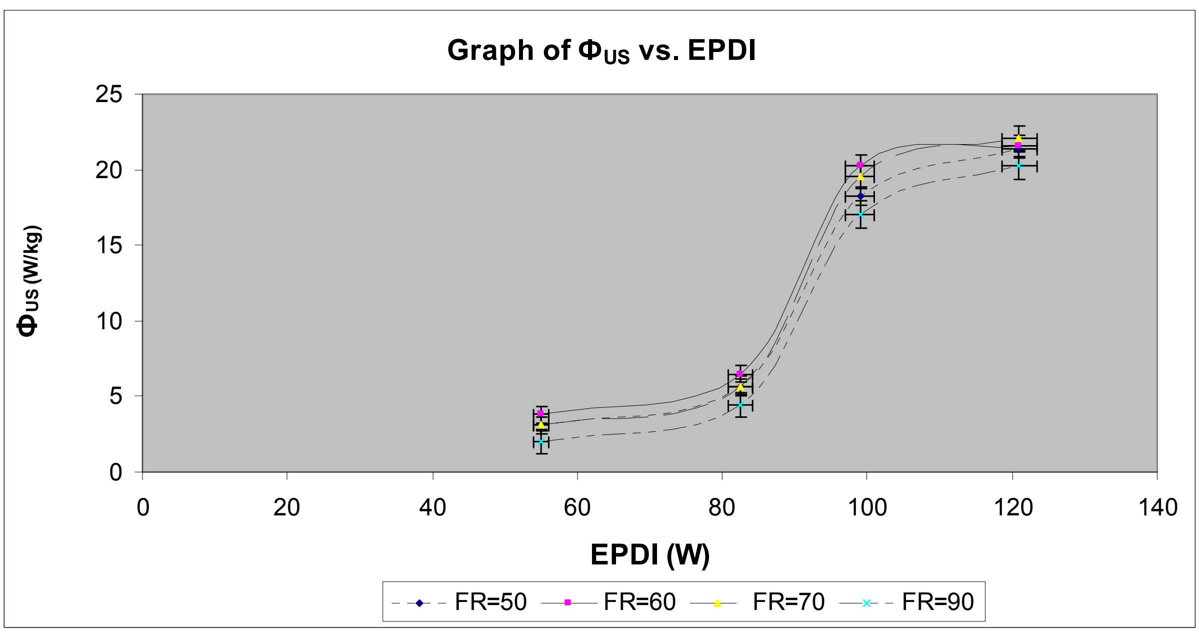

Figure 3. Graph of Φ_{US}, as inferred from change in pressure drop versus EPDI for different flow rates.

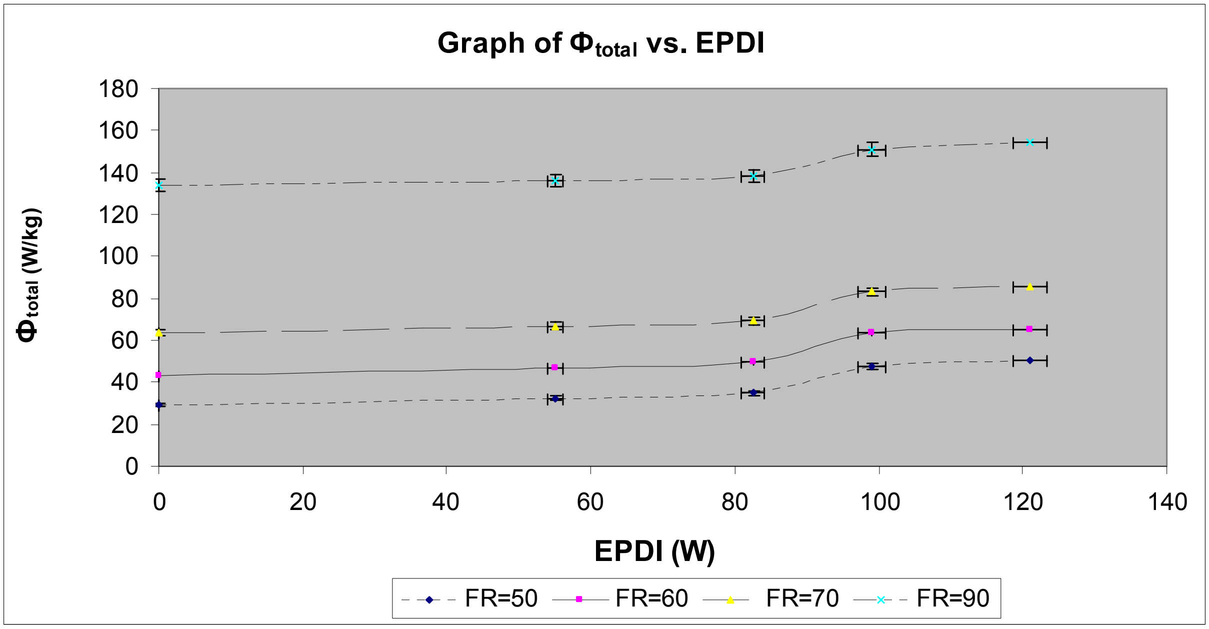

Figure 4. Graph of Φ_{total}, as inferred from change in pressure drop versus EPDI for different flow rates.

As the flow rate is increased, the percentage of energy dissipation rate contributed by ultrasound gets progressively smaller. Moreover, at the lower flow rates, this percentage is higher, for a given ultrasonic intensity, than at the higher flow rates. Thus it seems that to best study the effects of ultrasonic energy input, low flow rates and high electric power draws will be required.

Provided no back flow or excessive pressure build up occurs, high average turbulent energy dissipation rates may be obtained with high flow rates. Should the induction of turbulent energy dissipation be possible with ultrasound, it seems most logical that a device may be supplemented with ultrasound and not depend entirely on it – provided the ultrasonic energy is directed towards the regions of lowest turbulent energy dissipation within the device.

3.4.1. Possible mechanism

In turbulent flow, Φ is made up from the energy required/lost to drive the fluid and the boundary layer (and hence lost due to friction) and the energy dissipated as eddies. In laminar flow, this last term is zero.

The rise in the pressure drop could have risen from an increase in overall flow rate, an increase in flow velocity or an increase in the eddy generation, leading to turbulent energy dissipation, contributing to an overall dissipation across the device.

As expected for a peristaltic pump, preliminary tests show that the overall flow rate was unchanged in the presence and absence of ultrasound. Hence the change in the overall flow rate could not be responsible for the rise in the pressure drop across the device, and the bubbles do not cause back flow.

The presence of bubbles may lead to a decrease in the overall cross-sectional area of the outflow. Since the flow rate is maintained, the velocity of the flow is increased. This then is a measure of the total volume of the bubbles formed and is indicative of the cavitation intensity. Tap water was used in the above experiment, and typically it contains

50,000 nuclei per cm^3. If it is assumed that the average value will be the size of the collapsing bubble (10 μm), and even if all the bubbles are assumed to cavitate and grow according to the Rayleigh-Plesset Equation (relating bubble radius to applied pressure), the total volume of the bubbles (6.3×10^{-12} m^3) will be much smaller than the volume of the device and the bubbles are assumed to have negligible impact on the cross sectional area and therefore the flow velocity.

The generation of eddies due to the collapse of the bubbles seems the most viable explanation to the observed increase in turbulent energy dissipation within the flowing liquid by changing the friction factor, in the same way as turbulent eddies. Collapse of the bubbles is hypothesized to result in the generation of turbulent eddies which may also cause a break-up and further dissipation of the larger eddies already present in the liquid (in the case of turbulent flows) and it remains to be found which of the two effects contributes more. The interaction between the eddies generated by flow and those generated by ultrasound is possible because the length scales of the flow generated eddies and their time scales are comparable to those generated by ultrasound.

The length scales of the eddies generated by flow, for the different flow rates, range in size from the diameter of the inlets down to the Kolmogorov length scale (if not smaller). The smallest eddy size, λ_s and the time taken for them to dissipate, t_λ, may be given by (Baldyga & Bourne, 1999),

$$\lambda_s = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$ **Eq. 6**

$$t_s = \left(\frac{\nu}{\varepsilon}\right)^{1/2}$$ **Eq. 7**

If the turbulent energy dissipation rate, ε, is taken to be 50% of the global energy dissipation rate (it may range from 30-90%, (Baldyga & Bourne, 1999)), then the smallest eddy length scales and the time taken for them to dissipate are calculated using Eq. 6 and Eq. 7 respectively, and the values for the different FR-values, are shown in Table 1.

Table 1. Kolmogorov length and time to dissipate of smallest eddies generated by different FR-values.

FR	Kolmogorov scale (m)	Time (s)
50	1.62×10^{-5}	0.000261
60	1.47×10^{-5}	0.000215
70	1.33×10^{-5}	0.000177
90	1.11×10^{-5}	0.000122

The length scales fall within the range of the expected eddies generated by ultrasound (size of the typical nuclei in water), and the eddies' lifetime are long enough for the ultrasonically generated eddies (lifetime estimated at one-fifth of the cycle time, 0.00001s) to have the possibility of interacting with them.

Furthermore, if the size of the eddy is taken to be equal to the mean size of the available nuclei (1×10^{-5}), and the typical collapse times of the bubbles are taken to be one fifth of the cycle period (1 x 10^{-5}s), then the velocity of the eddy, U_λ, found by dividing the length by the collapse time, will be 1m/s. Since the length of the eddies generated by bubble collapse was of the same order as the bubble sizes, the following equation may be used to estimate the energy dissipation due to the eddies (Doulah 1979),

$$\varepsilon \approx \frac{U_\lambda^3}{\lambda} \qquad \textbf{Eq. 8}$$

If the typical values of the water nuclei are used (10^{-5}m), this gives a value for ε = 10^5W/kg. However, this energy dissipation occurs in a minute volume, compared to the overall size. Multiplying this amount by the number of sites (i.e. cavitationally active bubbles), we can obtain a total value. Since the bubbles are assumed to be spread out over the volume of the reactor, this value is assumed to dissipate over the entire volume of the sonicated region. To take this into account, it is then multiplied by the ratio of the volume occupied by the bubbles to the volume of the sonicated region. Thus, ε_{total} = 20.9W/kg, and assuming that $\varepsilon_{total} = \Phi$, then using Eq. 4, this was converted to a pressure drop (in units of cm-water), at the different flow rates. The results are plotted in Figure 5. as a dotted line. Experimentally, this value of Φ was obtained at the highest ultrasonic intensity used. The results are plotted in the same figure as a straight line and show a close agreement with theory, indicating that the explanation is feasible as the dotted line represents the mean value of the bubble nuclei size in water (10^{-5}m), and the estimate used here was also 10^{-5}m.

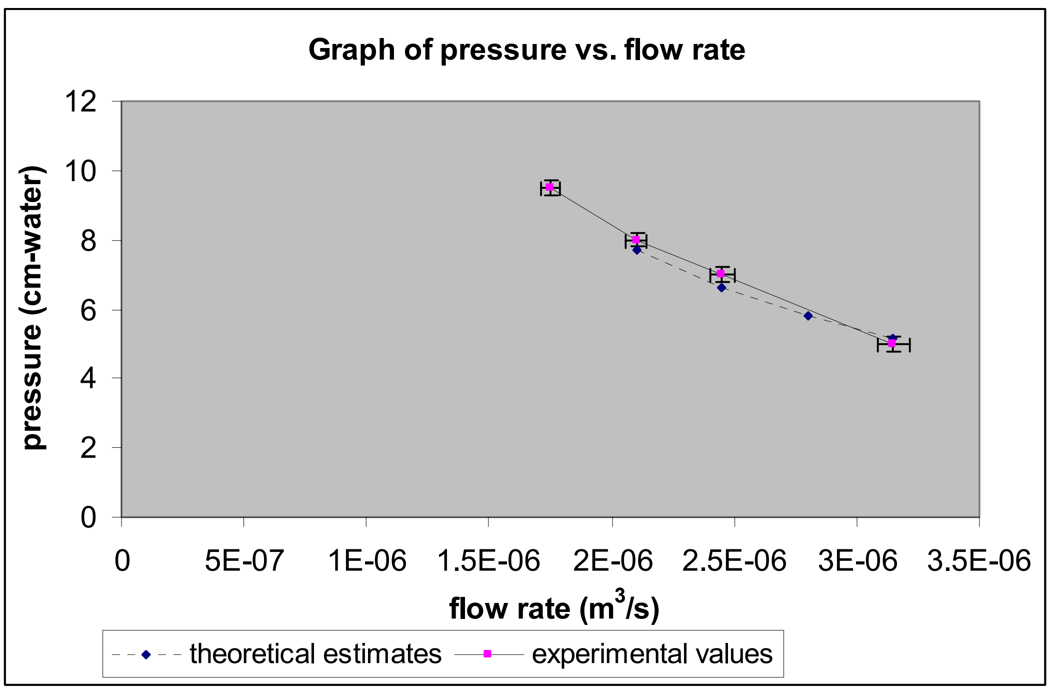

Figure 5. Graph of change in pressure drop versus flow rate for the highest ultrasonic intensity.

3.4.2. Relating Experimental Parameters

Different initial assumption for the bubble sizes would have lead to different theoretical estimates. It is suggested that the three existing methods should be used in conjunction to obtain a closer estimate for these sizes.

The sizes of bubbles that undergo collapse may be obtained using the solutions to the Rayleigh-Plesset Equations, and assuming that the collapsing bubbles generate eddies of comparable sizes. One solution is (Gogate and Pandit, 2000) (valid for bubbles large enough to neglect viscous and surface tension effects),

$$r_u = \frac{P_A}{\rho R_e (w_r^2 - w_a^2)}\left[\sin w_a t - \frac{w_a}{w_r}\sin w_r t\right] \qquad \textbf{Eq. 9}$$

Instead of using random values for P_A, it may be found by calculating the overall energy dissipated via calorimetry. Then, the ultrasonic intensity per unit area can be found, by dividing this intensity by the area of the tip, to obtain 'I' (Gogate and Pandit, 2000),

$$P_A = \sqrt{2I\rho\, c} \qquad \textbf{Eq. 10}$$

This then may be inserted in Eq. 9, and the initial values for the radii of the bubbles set at the typical values found in water, to give an indication of the range of collapsing sizes and thus generated eddies. One such solution, for a 20kHz applied acoustic wave with P_A = 4atm, for three different initial bubble sizes is shown in Figure 6.

The large bubbles are not greatly affected by the applied field, bubbles with sizes resulting in their natural frequency being close to the applied frequency, will exhibit the largest radius change and collapse, while smaller bubbles will oscillate in size around their mean value, and not collapse.

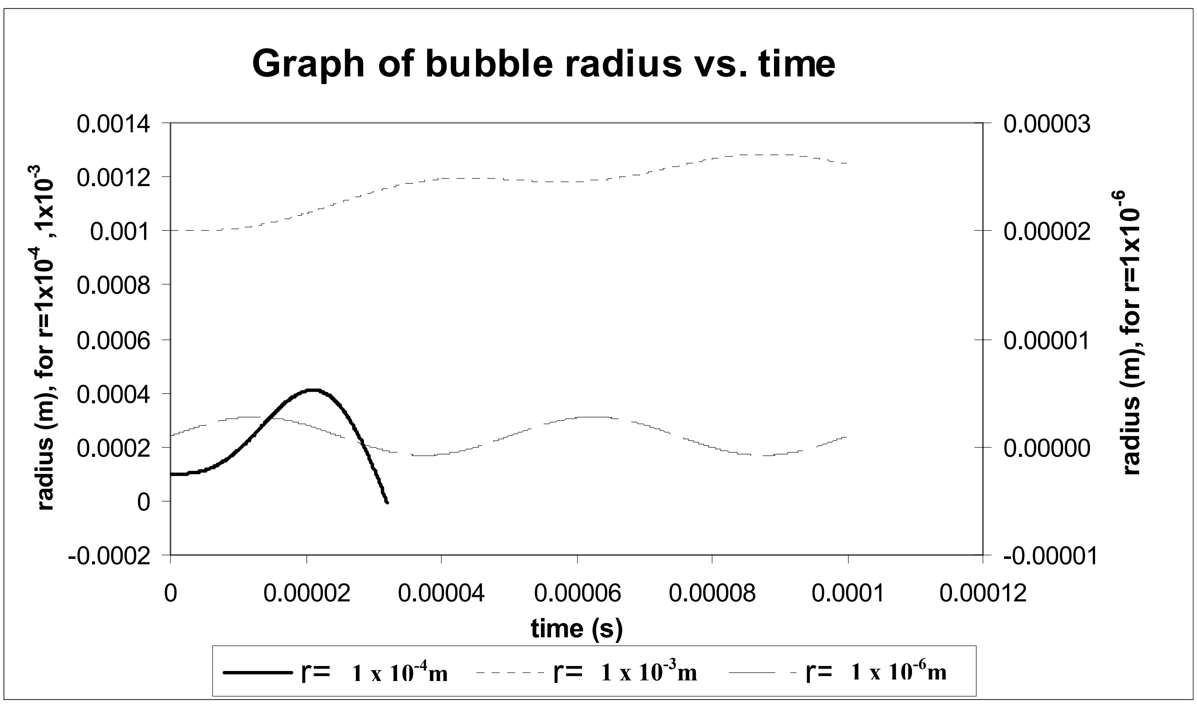

Figure 6. Behaviour of various bubbles in sinusoidal ultrasonic field.

Increasing the ultrasonic intensity will result in a larger size gain for the bubbles. This would lead to several effects, some of which may lead to an increase in ε, while others may lead to a decrease. If the larger bubbles increase in size, the danger lies in increasing their surface area, which would increase the overall attenuation of the wave. The medium size bubbles may attain a larger size and collapse more violently or reach a size whereby collapse is no longer possible as the timescale might become longer than a fifth of the acoustic cycle, according to

$$\tau = 0.91 R_t \sqrt{\frac{\rho}{P_t - P_v - P_g}} \qquad \textbf{Eq. 11}$$

Finally, smaller bubbles will also attain a larger size and hence be able to collapse. Thus the increase of applied acoustic pressure changes the range of collapsing bubble sizes, but runs the risk of increasing wave attenuation.

It should still be noted that the pressure drop method may not work for bigger devices as the energy dissipated is spread across a larger volume, significantly diminishing the average value of ε in the device, making the pressure drop undetectable over the whole device. However, the combination of the calorimetric method with the numeric simulations of the Rayleigh-Plesset Equation solutions, together with a better estimate of the range of nuclei sizes in water, should give a better indication of the behaviour of cavitation in solutions.

4. Conclusions and Recommendations

The pressure drop method of quantifying ultrasound was demonstrated to be a viable and useful method when attempting to study the generation of turbulence by ultrasound. The overall energy dissipation rate due to ultrasound was detectable in a small device though it was smaller than the contribution due to flow (at high flow rates).

It was seen that the turbulent energy dissipation rate (as a pressure drop) increased with an increase in the ultrasonic intensity. This value was found to be constant at a specified ultrasonic intensity, and therefore was a higher percentage of the overall energy dissipation rate at the lower flow rates. Thus it will be more noticeable at the low flow rates.

Ultrasound will not be enough as a stand-alone source of turbulence in order to promote mixing. Instead it is recommended that it be used in conjunction with a highly turbulent device in order to supplement the generation of turbulence, and thus it should be directed toward regions within the device suffering from low turbulence energy generation. The turbulent energy dissipation rates generated due to ultrasound were quite small compared to the rates generated by the flow, even in a simple device like the t-piece mixer. It is hoped that a better design and assembly of the system could rectify this, and increase the effective ultrasonic energy dissipation.

Regions of low turbulence may subsequently be identified using CFD, and rectified either by manipulating the design or by using ultrasound. A more accurate theoretical estimation of the ultrasonic intensity may be accomplished by closer inspection of the effects of the variable pressure field on the change in bubble radius, using the Rayleigh-Plesset Equation.

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