Engineering Design Method for Cavitational Reactors: I. Sonochemical Reactors

Parag R. Gogate and Aniruddha B. Pandit
Chemical Engineering Section, Dept. of Chemical Technology, Univ. of Mumbai, Matunga, Mumbai-400 019, India

High pressures and temperatures generated during the cavitation process are now considered responsible for the observed physical and chemical transformations using ultrasound irradiation. Effects of various operating parameters reported here include the frequency, the intensity of ultrasound, and the initial nuclei sizes on the bubble dynamics, and hence the magnitude of pressure generated. Rigorous solutions of the Rayleigh-Plesset equation require considerable numerical skills and the results obtained depend on various assumptions. The Rayleigh-Plesset equation was solved numerically, and the results have been empirically correlated using easily measurable global parameters in a sonochemical reactor. Liquid-phase compressibility effects were also considered. These considerations resulted in a criterion for critical ultrasound intensity, which if not considered properly can lead to overdesign or underdesign. A sound heuristic correlation, developed for the prediction of the pressure pulse generated as a function of initial nuclei sizes, frequency, and intensity of ultrasound, is valid not only over the entire range of operating parameters commonly used but also in the design procedure of sonochemical reactors with great confidence.

Introduction

Acoustic cavitation is the result of pressure variation in a liquid when high-frequency sound waves (ultrasound) pass through it. During the compression cycle the average distance between the molecules decreases, while during the rarefaction cycle it increases. If a sufficiently large negative pressure is applied to the liquid so that the average distance between the molecules exceeds the critical molecular distance required to hold the liquid intact, cavities or voids can be created. Cavities first grow in size until the maximum of the negative pressure is reached, and in the succeeding compression cycle they contract and collapse, producing shock waves that have a magnitude of several thousand atmospheres. A substantial amount of pressure and temperature are generated when the generated cavities collapse adiabatically in the medium. The magnitude of the pressure pulse or shock waves depends on various factors, such as the frequency and intensity of ultrasound, the initial radius of the nuclei, and the compressibility of the cavitating medium. Differential equations based on the momentum and mass balance describing the motion of a single cavity, which give the variation in cavity radius with time, have been solved (Moholkar and Pandit, 1997; Naidu et al., 1994; Vichare, 1999). The simulations done by these authors, under different assumptions, predicts the behavior of the cavity under the effect of ultrasound of a specific frequency and the intensity and the collapse of the cavities for acoustic as well as the hydrodynamic cavitation. The work of Moholkar and Pandit (1997) is based on the assumption of the complete adiabatic collapse of the cavity. Vichare (1999) and Naidu et al. (1994) used Flynn's assumption, which states that collapse of the cavity becomes adiabatic when partial pressure of the gas inside the cavity equals the liquid-medium vapor pressure. The present work aims at developing an empirical correlation for predicting the pressure generated when the cavity collapses as a function of intensity, the frequency of ultrasound, and the initial nuceli size. Such a correlation will be helpful in the design of sonochemical reactors and will predict the magnitude of pressure that will be generated following the collapse of the cavity, irrespective of the type of reaction for which the reactor is being used. The sonochemical yield for the reaction will, however, be different according to the type of reaction considered. A detailed discussion about the pressure

Correspondence concerning this article should be addressed to A. B. Pandit.

pulse and its impact on the sonochemical yield follows later. The variation of the cavity size and the pressure generated also depends on whether the compressibility of the medium is considered while solving the differential equations in a certain range of the parameters mentioned earlier.

The work describes an engineering approach, that is, rather than rigorously solving the Rayleigh-Plesset equation to estimate the pressure-pulse magnitude for a variety of conditions, which require considerable numerical skills, the results obtained from such rigorous solutions have been empirically correlated using easily measured global parameters.

Design engineers designing sonochemical reactors rather than attempting rigorous numerical solutions of the Rayleigh-Plesset equation can use these correlations.

Theory of Cavity Dynamics

This section deals with the development of the basic differential equation to describe the behavior of the bubble under the influence of an ultrasound pressure field, with and without the assumption of liquid-phase incompressibility.

For a spherical bubble in an infinite liquid, all the physical parameters can be described as a strong function of radial distance r from the center of the bubble. Applying the law of conservation of mass (equation of continuity) and the law of conservation of momentum, the values of velocity and pressure can be found at any point, when the bubble oscillates under the effect of a time-varying surrounding pressure field.

Considering the equation of motion and the equation of continuity for the moving bubble, the basic equation for bubble dynamics can be obtained.

If R is the radius of the bubble wall at time t, then dR/dt is the bubble-wall velocity. At a distance r from the center of bubble the simultaneous radial velocity in the liquid is dr/dt. For an incompressible liquid,

$$\frac{dr}{dt} = \frac{R^2}{r^2}\left(\frac{dR}{dt}\right). \tag{1}$$

The velocity potential for irrotational radial motion is

$$\phi = -\int_r^\infty \left(\frac{dr}{dt}\right) dr = -\frac{R^2}{r}\left(\frac{dR}{dt}\right). \tag{2}$$

If p is the pressure in the liquid at a distance r from the bubble/cavity center and p_∞ is the pressure in the liquid at infinity, then by Bernouli's theorem the equation of motion is given as

$$\frac{p - p_\infty}{\rho_l} = -\frac{\partial \phi}{\partial t} - \frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \frac{2R}{r}\left(\frac{dR}{dt}\right)^2 + \frac{R^2}{r}\left(\frac{d^2R}{dt^2}\right) - \frac{1}{2}\frac{R^4}{r^4}\left(\frac{dR}{dt}\right)^2. \tag{3}$$

To understand the motion of the bubble wall, $r = R$ is substituted in Eq. 3 and the following equation is obtained:

$$R\left(\frac{d^2R}{dt^2}\right) + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{p_{(R)} - p_\infty}{\rho_l}. \tag{4}$$

Equation 4 is the fundamental equation of the bubble dynamics and is known as the Rayleigh equation. The terms in Eq. 4 are as follows:

$p_{(R)}$ = pressure in the liquid at the bubble wall

R = radius of the bubble at time t

p_∞ = pressure in the surrounding liquid. For ultrasound irradiation, the time-varying pressure is expressed as $p_\infty = p_o - p_a \sin(2\pi \text{ft})$, where p_o is the ambient pressure and p_a = amplitude of driving pressure $= \sqrt{2I\rho_l C}$, where C is the velocity of sound in the liquid (in water $\cong$ 1500 m/s), I is the intensity of ultrasound (w/m^2), and ρ_l is the density of the liquid (kg/m^3).

For a spherical bubble the viscosity affects only the boundary conditions, so pressure in the liquid at the bubble wall is

$$p_{(R)} = p_i - \frac{2\sigma}{R} - \frac{4\mu}{R}\left(\frac{dR}{dt}\right). \tag{5}$$

If surface tension and viscosity effects are included in Eq. 4, then the equation of bubble dynamics becomes

$$R\left(\frac{d^2R}{dt^2}\right) + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho_l}\left[p_i - \frac{4\mu}{R}\left(\frac{dR}{dt}\right) - \frac{2\sigma}{R} - p_\infty\right]. \tag{6}$$

Equation 6 is known as the Rayleigh-Plesset equation, and p_i = pressure inside the bubble at time t.

The assumptions made for obtaining the solution of the Eq. 6 are as follows:

1. Spherical geometry of the bubble during its entire lifetime.
2. Uniform bubble interior, that is, no pressure and temperature gradients in the bubble.
3. The liquid is incompressible.
4. Body forces such as gravity have been neglected.

Moholkar (1996) studied the bubble behavior in acoustic cavitation, paying particular attention to the complete adiabatic collapse of the cavity. For the numerical simulations, growth of the cavity was considered isothermal and Flynn's assumption (Flynn, 1964), which states that the collapse of the cavity becomes adiabatic when partial pressure of the gas inside the cavity equals the liquid-medium vapor pressure, was also considered. Thus transition from isothermal collapse to adiabatic collapse takes place when Flynn's criterion is satisfied.

During the isothermal growth and isothermal collapse phase pressure inside the cavity is given by

$$p_i = p_{io}\left(\frac{R_o}{R}\right)^{3k}, \tag{7}$$

where p_{io} is the initial pressure inside the cavity and p_i varies as the bubble radius (R) changes. For the isothermal phase operation, the polytropic index $k = 1$.

Considering initial equilibrium, that is, the bubble and the surroundings are in equilibrium,

$$p_{io} = p_{go} + p_v = p_o + \frac{2\sigma}{R_o}. \tag{8}$$

During the collapse, when partial pressure of the gas equals the vapor pressure ($p_g = p_v$), adiabatic collapse starts. This is called as the critical point. The radius of the cavity corresponding to this point is critical radius, R_{crit}. So at the critical point, $p_i = 2p_v$, and R_{crit} is given as

$$R_{crit} = R_o \left(\frac{p_{io}}{2p_v} \right)^{1/3}. \tag{9}$$

Pressure inside the cavity during adiabatic collapse is thus given by

$$p_i = 2p_v \left(\frac{R_{crit}}{R} \right)^{3\gamma}. \tag{10}$$

The Rayleigh-Plesset equation is a second-order nonlinear differential equation, which can be solved by the fourth-order Runge-Kutta method. The Rayleigh-Plesset equation is valid up to the point when bubble-wall velocity (dR/dt) is less than the velocity of sound in the cavitating media due to the assumption of the incompressible nature of the liquid (for the present study water is considered as the cavitating media and velocity of sound is 1500 m/s).

If the condition of the incompressibility of the medium is relaxed and the external pressure is considered to be the time-dependent pressure $p(t)$, the equation to describe the cavity dynamics is the one given by Tomita and Shima (1986). The equation is given as follows:

$$R\ddot{R}\left(1-\frac{2\dot{R}}{C}+\frac{23\dot{R}^2}{10C^2}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{4\dot{R}}{3C}+\frac{7\dot{R}^2}{5C^2}\right)+\frac{1}{\rho_l} \times\left[\begin{array}{l} p_{\infty(t)}-p_{2(r=R)}+\frac{R}{C}\left(p_{\infty(t)}-p_{1(r=R)}\right)+\frac{1}{C^2} \\ \times\left\langle\begin{array}{l} -2R\dot{R}\left(\dot{p}_{\infty(t)}-\dot{p}_{1(r=R)}\right)+\frac{1}{2}\left(p_{\infty(t)}-p_{1(r=R)}\right) \\ \times\left(\dot{R}^2-\frac{3}{\rho_l}\left(p_{\infty(t)}-p_{1(r=R)}\right)\right)\end{array}\right\rangle\end{array}\right]=0, \tag{11}$$

where the p_1 and p_2 as a function of R are given as follows:

$$p_{1(r=R)} = p_v + p_{go}\left(\frac{R_o}{R}\right)^{3\gamma} - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R} \tag{12}$$

$$p_{2(r=R)} = p_{1(r=R)} - \frac{4\mu}{3\rho C^2}\left(\dot{p}_{\infty(t)} - \dot{p}_{1(r=R)}\right). \tag{13}$$

Shima and Tomita (1979) have given the derivation of this equation in detail, and so is not repeated here. The dynamics of the bubble/cavity predicted by the numerical solutions of both these equations (Eqs. 6 and 11) are compared to check whether or not the consideration of the compressibility of the medium is significant in the prediction of cavity behavior. When the assumption of the incompressibility of the medium is relaxed, the earlier validity condition of the Rayleigh-Plesset equation with respect to the sonic velocity is not valid, and hence the pressure pulse generated will be slightly larger than was predicted earlier. The Results and Discussion section of the present work refers to the simulations based on the equation given by Tomita and Shima (1986), considering the compressibility of the medium. A detailed discussion of the solutions of the Rayleigh-Plesset equation for the various operating conditions can be obtained from Moholkar and Pandit (1997).

Results and Discussion

Numerical solutions of Eq. 11 for the acoustic cavitation considering compressibility of the medium are performed, and the effects of various parameters, such as intensity and frequency of ultrasound and the initial nuclei size, on the bubble/cavity behavior in acoustic cavitation are discussed.

Effect of the intensity of irradiation

The intensity of the ultrasonic equipment can be varied over a certain range at a constant frequency, depending on the type of equipment used. Increasing the intensity of the ultrasound, the sound pressure amplitude (p_a) increases. The range of intensity used for these simulations is 10–300 W/cm^2, which is typically found in ultrasonic equipment. The nature of the variation of bubble radius with time follows a trend where the radius initially increases with time, passes through a maxima, and then decreases up to less than 0.01 times the initial cavity size, which is considered as a collapse of the cavity (Figure 1). This trend is very similar to the variation observed in the numerical simulations of the Rayleigh-Plesset equation (Moholkar and Pandit, 1997), so these solutions are not discussed here in detail. The magnitude of the maximum size attained by the cavity is different in both cases, so the pressure pulse generated will be different. The ratio (R_{max}/R_o), which indicates the maximum size attained by the cavity during its growth phase, increases with an increase in intensity. A typical trend observed for an initial cavity size of 0.08-mm radius and ultrasound frequency of 60 kHz is given in Figure 2. The increase in the maximum size is large (about 30%) for an initial increase in the intensity, and after a certain intensity the increase is not substantial ($<10\%$). Hence the equipment intensity should not be increased beyond a

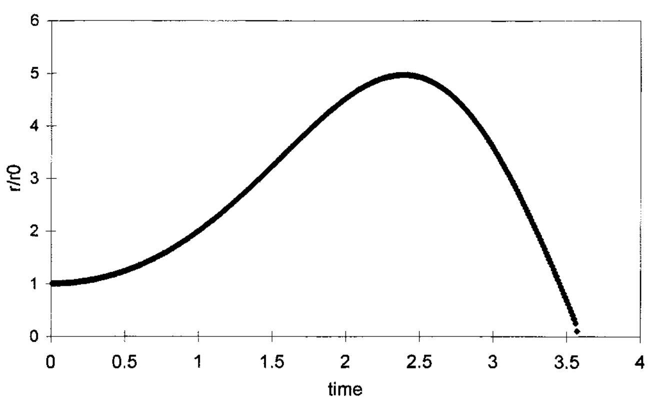

Figure 1. Variation of R/R_0 with time at initial radius of 0.1 mm.

Frequency = 50 kHz and intensity of 120 W/cm^2.

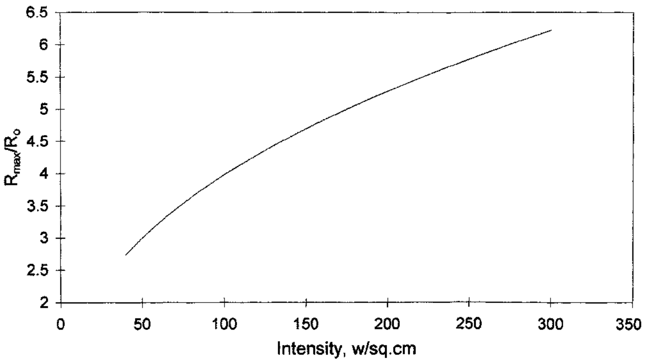

Figure 2. Variation of R_{max}/R_0 with the intensity at constant $R_0 = 0.1$ mm and frequency = 60 kHz.

certain limit. This will have a negative effect on the amount of pressure pulse generated, which is clearly observed in Figure 3. Keeping the initial size of the cavity (R_o) and frequency (f) constant, with an increase in the intensity of the ultrasound, the bubble wall pressure at the collapse point of the cavity decreases. This is a result of the increase in the size of the bubble and also an increase in the lifetime of the cavity during which the energy associated with the bubble can be taken up by the compressible liquid medium. From Figures 2 and 3 it can also be said that the optimum range of intensity of ultrasound is < 100 W/cm^2.

Shirgaonkar (1997) has shown that there is a reduction in the rate of the liberation of iodine when the actual power input (measured calorimetrically) is increased for the ultrasonic horn with a constant area operating at a fixed frequency of 20 kHz. Studies on emulsification of the oil–water system using ultrasonic horn and bath showed better emulsion characteristics for the bath, though the power input to the horn and the bath is nearly the same (Mujumdar et al., 1997). This results in a lower intensity for the bath. Shirgaonkar and Pandit (1997) have found that the degradation rates of NaCN in the presence of ultrasound decreased marginally with an increase in the ultrasound intensity. Entezari and Kruus (1994, 1996) have also shown that the rate of iodine liberation at constant power input for equipment with different irradiation areas decreases with an increase in the intensity of irradiation, that is, decreasing the area of irradiation for constant power input. Shah et al. (1999) have explained the decrease in the reaction rates for high intensities of the ultrasonic horns. The effect is attributed to the bubble shrouding of the sonic horn and the overgrowth of the bubbles. Penetration of sound into the body of the liquid is hindered if cavitation is so intense that the radiating surface becomes shrouded in a layer of bubbles. Conversely, it may simply be that the bubble growth becomes so rapid that the boundary for transient cavitation is exceeded before the next compression cycle. There are also reports in the literature stating that the rate of reaction reaches a maximum with respect to the intensity of ultrasound. Hua et al. (1995) (cf Shah et al., 1999) reported a maximum in the rate of sonochemical degradation of p-nitrophenol in a near-field acoustic processor (NAP) at an intensity of 1.2 W/cm^2, after which the rate of reaction decreased with a further increase in the intensity. Similar trends are observed for the acid-catalyzed hydrolysis reaction of methyl ethanoate at 303 K (Henglein, 1993).

Thus, the variation of the pressure pulse generated, and hence the sonochemical yield, with the intensity of irradiation as obtained by the numerical simulations is confirmed by various reports obtained from the literature, as discussed earlier.

Effect of frequency of irradiation

The frequency of ultrasonic equipment is usually fixed and cannot be varied over a wide range, as the maximum transfer efficiency is obtained only when the transducer is driven at its resonating frequency. The range of frequency used for simulation is 20–200 kHz, again typically used in the application of ultrasound power. With an increase in frequency, the maximum size attained by a cavity decreases substantially (Figure 4). With constant intensity (I) and initial cavity size (R_o), an increase in the frequency decreases the lifetime of the cavity. The collapse of the cavity is rapid and more violent at higher frequencies, resulting in an increase in the magnitude of pressure generated at the time of breakup (Figure 5). The earlier explanation for the variation of pressure pulse with the radius and lifetime of the bubble also holds good here.

Petrier et al. (1992) have shown that the oxidation of aqueous KI to iodine is 6 times faster and the generation of H_2O_2 in water 12 times faster when the frequency of ultrasound is increased from 20 to 514 kHz. Seymore and Gupta (1996, 1997) have shown that oxidation of KI is significantly en-

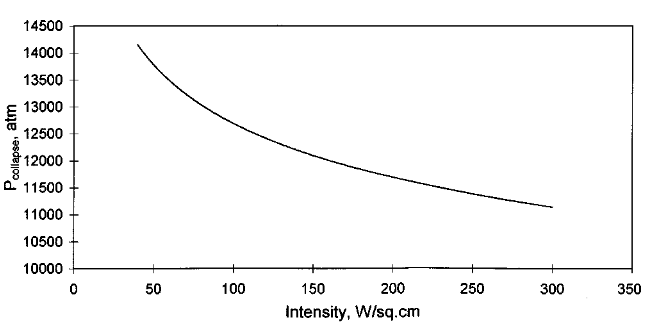

Figure 3. Variation of collapse pressure with intensity at constant $R_0 = 0.1$ mm and frequency = 60 kHz.

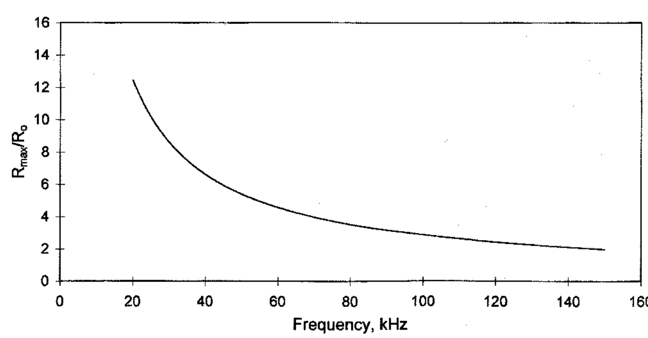

Figure 4. Variation of R_{max}/R_0 with the frequency at constant $R_0 = 0.1$ mm and intensity of 120 W/cm^2.

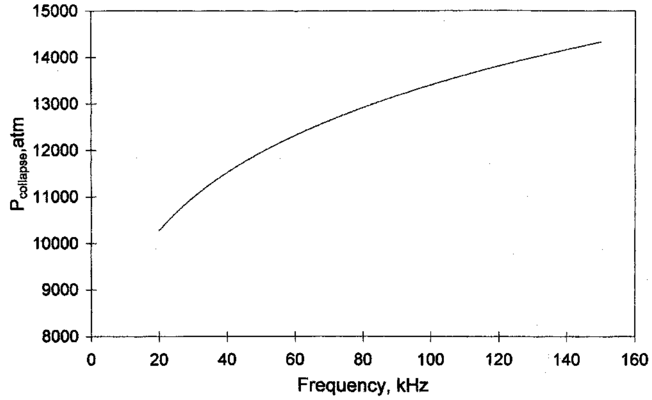

Figure 5. Variation of collapse pressure with the frequency at constant $R_0 = 0.1$ mm and intensity $= 120$ W/cm^2.

hanced with an increase in the frequency of the ultrasound. Also, Mokrey and Starchevsky (1987) have shown that the efficiency of the OH^- radical production process increases with an increase in the irradiation frequency. Petrier and Luche (1987) have shown that in presence of Ar and O_2 oxidation processes in water occur in enhanced yields when a high frequency of 514 kHz is used instead of the more commonly used 20-kHz frequency. Petrier et al. (1992) have also shown that for the same acoustic powers (30 W), the destruction of phenol in dilute aqueous solutions is more efficient at higher frequencies. Thus, there are several reports in the literature that clearly support the observed variation of the pressure pulse that will be generated at the collapse of the cavity with the frequency of ultrasound.

Effect of initial cavity size

At constant intensity (I) and frequency (f) with an increase in the initial cavity size (R_o), the lifetime of the cavity increases. The range of initial cavity radius used for simulation studies is 0.01 to 0.1 mm, which is again typical of the reported nuclei sizes in acoustic cavitation (Moholkar, 1996; Naidu et al., 1994). The maximum radius ratio (R_{max}/R_o) attained by a cavity decreases with an increase in the initial cavity size. The higher the initial size of the cavity, the less it grows, that is, R_{max}/R_o decreases with an increase in R_o (Figure 6). Small cavities collapse more violently due to their larger growth. The magnitude of the pressure pulse generated at the end of the cavity collapse increases with a decrease in the initial cavity size (Figure 7).

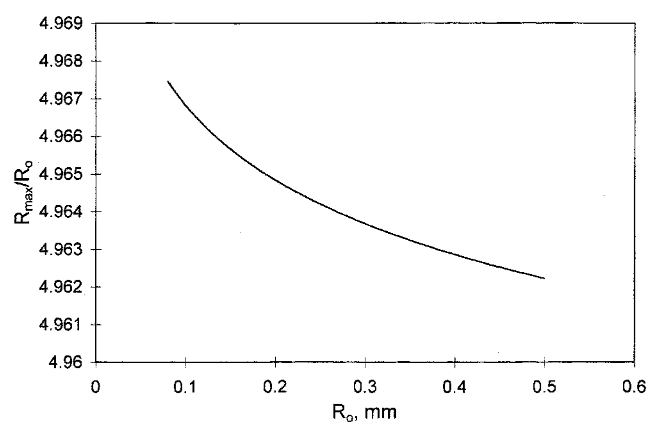

Figure 6. Variation of R_{max}/R_0 with the initial cavity radius at $f = 50$ kHz and $I = 120$ W/cm^2.

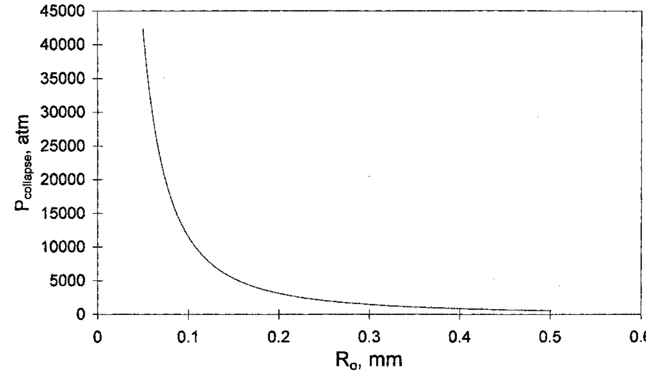

Figure 7. Variation of collapse pressure with the initial cavity radius at $f = 50$ kHz and $I = 120$ W/cm^2.

It is difficult to give the exact nuclei size that will be generated in the reactor on the cavitation, but some trends can be obtained, depending on medium vapor pressure and the presence of the dissolved gases in the medium. As the vapor pressure of the medium increases, the size of the bubble or cavity formed will increase at the same power and ultrasound frequency, resulting in a decrease in the magnitude of the pressure pulse generated. Mujumdar and Pandit (1998) have indicated a decrease in the yield of fumaric acid with an increase in the medium vapor pressure obtained by using ethanol–water mixtures. The degradation of polymers follows a similar trend with variation of the medium vapor pressure, as with an increase in P_v, the cavitation becomes less violent (Shah et al., 1991). The presence of the dissolved gases also affects the initial cavity size generated, but the effect on the sonochemical yield cannot be generalized due to the difference in the physicochemical properties of the gases. Hart and Henglein (1985) have also shown that different rates of iodine formation are obtained when different gases, such as nitrogen, oxygen, or argon, are used as the dissolved gases in the KI solution. There is a large number of other illustrations (Petrier and Luche, 1987; Petrier et al., 1982, 1984) in the literature, which also indicate that the rates of the reaction are different depending on both the type of gas present in the medium and the amount of gas dissolved in the medium.

Effect of compressibility of the medium

Figure 8 shows the variation in the maximum radius obtained during the growth of the cavity with the intensity of ultrasound for the two cases: (1) simulation of the Rayleigh-Plesset equation (Eq. 6), and (2) simulations considering the compressibility of the medium (Eq. 11). There is a substantial difference in the value of the maximum bubble size obtained in two cases, and as explained earlier, this will also affect the pressure pulse generated at the collapse of the cavity. The crossover of the two plots is defined as the critical intensity.

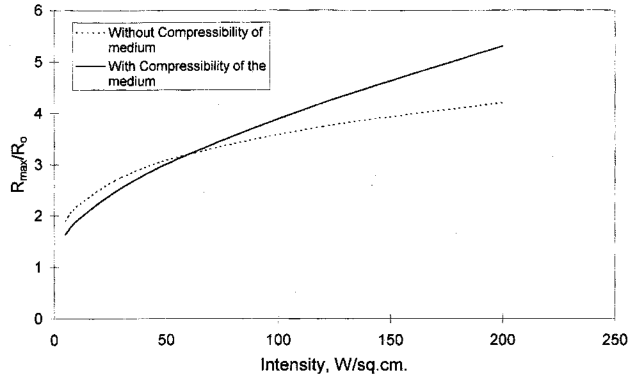

Figure 8. Variation of R_{max}/R_0 with the intensity at a sample $R_0 = 0.09$ mm and frequency = 60 kHz.

Below the critical intensity, it is important to consider the compressibility of the cavitating medium, otherwise the simulations will predict a lower magnitude of the pressure pulse, prompting the designer to use higher ultrasound intensities (up to the maximum value discussed earlier). This critical intensity is found to be a strong function of initial nuclei size, as can be seen from Figure 9, and is practically independent of the ultrasound frequency. Above the value of critical intensity, the simulations using the Rayleigh-Plesset equation predict small cavity growth, which results in higher values of the pressure pulse. Hence if the compressibility of the medium is not considered over this range of intensity, the design will be such that it will predict a large value of pressure pulse, prompting the designer to use lower intensities, or the cavitational effects may not be observed. It is therefore quite important to consider the compressibility of the medium while getting the numerical solutions of the Rayleigh-Plesset equations, which then can be used for the design of sonochemical reactors.

Development of Correlation

Figure 10 shows the results of the simulations of Eq. 11 considering the compressibility of the medium plotted against the pressure generated at the time of collapse of the cavity.

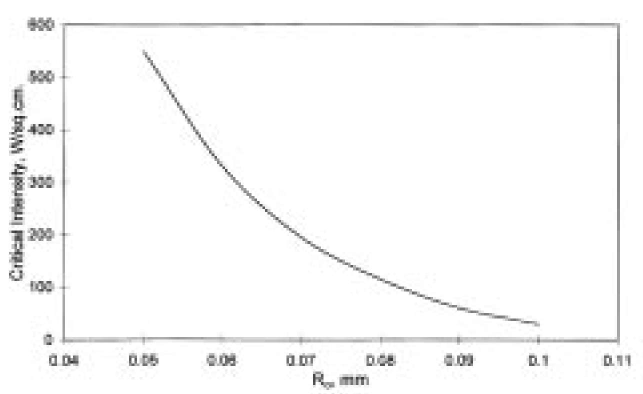

Figure 9. Variation of critical intensity with the initial cavity radius.

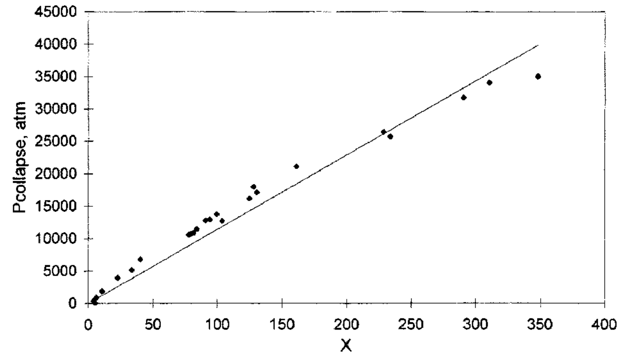

Figure 10. Equation fitting for the collapse pressure as a function of different parameters.

The quantity that is plotted on the X-axis is given as

$$X = (R_o)^{-1.88}(I)^{-0.17}(f)^{0.11}. \qquad (14)$$

The exponents over the initial cavity size, intensity, and frequency of ultrasound are obtained from Figures 3, 5, and 7.

The correlation obtained for the prediction of pressure pulse generated can be given as follows:

$$P_{\text{collapse}} = 114(R_o)^{-1.88}(I)^{-0.17}(f)^{0.11}. \qquad (15)$$

The preceding correlation uses the initial cavity size in mm, frequency in kHz, and intensity of ultrasound in W/cm^2, while the collapse pressure is given in atmospheres and is developed for the following range of parameters:

Initial cavity size = 0.05–0.5 mm

Frequency of ultrasound = 10–120 kHz

Intensity of ultrasound = 10–300 W/cm^2.

Thus the developed correlation is simple to use and valid over the range of parameters that are commonly used in the sonochemical applications. Moreover, as the development of correlation is based on numerical results obtained from the solution of the theoretical equation and considers the effect of compressibility of the medium, it can be said that the correlation can be used in the design procedure for all kinds of sonochemical applications where rigorous numerical solutions may not be feasible.

It should be noted, however, that the preceding correlation is just an indication of the magnitude of the pressure pulse generated in the sonochemical reactor. The effects of the cavitation may be different, depending on the variety of conditions existing in the reactor. In general, the sonochemical yield of the process can be expressed as follows:

$$\text{Sonochemical yield} = K(P)^c_{\text{collapse}},$$

where the constant K and the exponent c depend on the reactor geometry, the operating parameters, and the type of reaction that is being carried out. It may happen that even if the pressure pulse generated at the collapse of cavity is large, the effective sonochemical yield could decrease due to the negative value of exponent c, depending on the type of the reaction considered.

The quantitative information required to use the magnitude of the pressure pulses in predicting the microscopic rates of the specific reactions is lacking in the literature. The information about the formation of intermediate species and their role in the formation of the desired product has not been elucidated at all in the literature. The only publications in this area are by Naidu et al. (1994) and Monnier et al. (1999) plus that for a model reaction of KI decomposition, which has no industrial relevance. We have used macroscopic reaction rates to clearly establish an equivalence in the trend of predicted pressure-pulse intensities and its variation with parameters such as intensity, frequency, and initial cavity size.

Thus, the present work is only a first step in a direction that is useful for engineers, rather than scientists, working in the area of sonochemistry, and a lot more work is required with specific reactions of industrial relevance by following the method proposed by Naidu et al. (1994) and Monnier et al. (1999).

Conclusion

In the case of acoustic cavitation bubble behavior depends upon the operating conditions. The effect of operating parameters such as ultrasound intensity, driving frequency, and initial cavity size on bubble behavior considering the compressibility of the medium is similar to that predicted by the Rayleigh-Plesset equation as studied by Moholkar and Pandit (1997).

The selection of suitable operating parameters, such as intensity and frequency of ultrasound and the vapor pressure of the cavitating media, is essential for carrying out any chemical reaction using ultrasound. Bubble behavior in acoustic cavitation can be significantly altered by varying the parameters like ultrasound intensity, the driving frequency of ultrasound, and initial cavity size (medium vapor pressure of the amount of dissolved gases), and the required conditions for the specific reaction can be achieved. The effect of the compressibility of the medium on the bubble dynamics has been studied and a critical intensity, which strongly depends on the initial cavity size, is defined in the present work. It is important to consider the compressibility of the medium while designing the sonochemical reactors, as a significant amount of overdesign or underdesign, depending on the critical intensity, may result if only the predictions of the Rayleigh-Plesset equations are considered.

Correlation has been developed for the prediction of the magnitude of the pressure pulse generated at the collapse of cavity as a function of initial cavity size, frequency, and intensity of the ultrasound. The correlation considers the effect of the compressibility of the medium and is valid over the entire range of parameters that are commonly used in the sonochemical applications. The developed correlation, which is the first of its kind in the area of sonochemical reactors, can be considered as a major step in the direction of engineering design of the sonochemical equipment.

Notation

c = constant in expression for sonochemical yield
C = velocity of sound in the liquid (m/s)
f = frequency of ultrasound (Hz)
I = intensity of ultrasound (W/m^2)
k = polytropic constant
K = constant in expression for sonochemical yield
p = pressure in the liquid at distance r (N/m^2)
p_{collapse} = pressure generated at the collapse of the cavity (N/m^2)
p_∞ = pressure in the liquid at infinity (N/m^2)
$p_{(R)}$ = pressure in the liquid at the bubble wall (N/m^2)
$p_{(t)}$ = time varying pressure field (N/m^2)
$p_{\infty(t)}$ = time varying pressure field in the bulk (N/m^2)
p_a = pressure amplitude of the sound wave (N/m^2)
p_{go} = initial gas pressure (N/m^2)
p_g = partial pressure of gas (N/m^2)
p_i = pressure inside the bubble (N/m^2)
p_{io} = initial pressure inside the bubble (N/m^2)
p_o = ambient pressure (N/m^2)
p_v = vapor pressure (N/m^2)
r = radial distance from the center (m)
R = radius of cavity/bubble (m)
$R = dR/dt$ bubble wall velocity (m/s)
$R = d^2R/dt^2$ bubble wall acceleration (m/s^2)
R_{crit} = critical radius—radius of the bubble at $p_g = p_v$ (m)
$R_{\max}$ = maximum radius of the bubble/cavity (m)
t = time (s)
γ = specific heat ratio
μ = viscosity of liquid (Ns/m^2)
ρ_l = density of liquid (kg/m^3)
σ = surface tension of liquid (N/m)
ϕ = velocity potential

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