

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/280798977>

Hydrodynamic Cavitation Reactors: A State of the Art Review

Article in *Reviews in Chemical Engineering* · January 2001

DOI: 10.1515/REVCE.2001.17.1.1

CITATIONS

282

READS

2,856

2 authors:



Parag R Gogate

Institute of Chemical Technology

495 PUBLICATIONS 30,527 CITATIONS

SEE PROFILE



Aniruddha Bhalchandra Pandit

Institute of Chemical Technology

573 PUBLICATIONS 32,471 CITATIONS

SEE PROFILE

AIMS AND SCOPE

The main aim of **Reviews in Chemical Engineering** is to develop new insights and to promote interest and research activity in chemical engineering and applied chemistry, as well as the application of new developments in these areas. The journal publishes authoritative articles of limited scope by leading chemical engineers, applied scientists and mathematicians. Long articles which review an entire field are also occasionally solicited. Because of the broad interest now shown in chemical problems which previously had a more limited appeal, **Reviews in Chemical Engineering** is sure to play a significant role in the growth of the field as a whole.

COPYRIGHT 2001

FREUND PUBLISHING HOUSE LTD.

Suite 500, Chesham House

150 Regent Street

London W1R 5FA

ENGLAND

HYDRODYNAMIC CAVITATION REACTORS: A STATE OF THE ART REVIEW

Parag R. Gogate and Aniruddha B. Pandit*

*Division of Chemical Engineering
University Department of Chemical Technology
University of Mumbai, Matunga
Mumbai-400019, India*

TABLE OF CONTENTS

ABSTRACT

1.0 INTRODUCTION

1.1 Types of Cavitation

1.2 Occurrence of Hydrodynamic Cavitation

1.3 Advantages and Disadvantages of Hydrodynamic Cavitation Reactors

2.0 CHEMICAL AND PHYSICAL EFFECTS OF HYDRODYNAMIC CAVITATION

3.0 BUBBLE DYNAMICS IN HYDRODYNAMIC CAVITATION

3.1 Approach of Yan *et al.* (1988)

3.2 Approach of Moholkar and Pandit (1997)

3.3 Approach of Lush (1998)

3.4 Approach of Senthilkumar and Pandit (1999)

3.5 Approach of Gogate and Pandit (2000)

3.6 Approach of Moholkar and Pandit (2000)

4.0 HYDRODYNAMIC CAVITATION REACTORS

4.1 Liquid Whistle Reactors

4.2 High Pressure Homogenizers

4.3 High Speed Homogenizers

4.4 Microfluidisers

*author to whom correspondence should be addressed

e-mail: abp@udct.ernet.in

Fax: 91-22-4145614

- 4.5 Orifice Plates Setup
- 5.0 DESIGN OF HYDRODYNAMIC CAVITATION REACTORS
- 5.1 Effect of Inlet Pressure
- 5.2 Effect of Physico-Chemical Properties of Liquid Medium
 - 5.2.1 *Effect of liquid vapour pressure*
 - 5.2.2 *Effect of liquid viscosity*
 - 5.2.3 *Effect of liquid bulk temperature*
 - 5.2.4 *Effect of liquid surface tension*
 - 5.2.5 *Effect of presence of dissolved gases*
 - 5.2.5.1 *Polytropic constant and thermal conductivity*
 - 5.2.5.2 *Gas solubility*
 - 5.2.6 *Effect of liquid medium constituents*
 - 5.2.6.1 *Effect of surfactant and electrolytes*
 - 5.2.6.2 *Effect of miscellaneous constituents of liquid*
- 5.3 Effect of Diameter of the Constriction
- 5.4 Effect of the Free Area for the Flow
- 5.5 Effect of Initial Radius of the Nuclei
- 5.6 Effect of Rotor Speed (Specific to HSH)
- 5.7 Recommendations for Efficient Design
- 5.8 Correlations for Collapse Pressure and Cavitation Yields
- 6.0 ANALOGY AND COMPARISON WITH ACOUSTIC CAVITATION
- 6.1 Analogy with Acoustic Cavitation
- 6.2 Comparison with Acoustic Cavitation Reactors
- 7.0 APPLICATIONS OF HYDRODYNAMIC CAVITATION
- 7.1 Hydrolysis Reactions
 - 7.1.1 *Hydrolysis of fatty oils*
 - 7.1.2 *Cellulose hydrolysis*
- 7.2 Cell Disruption Using Hydrodynamic Cavitation
- 7.3 Waste Water Treatment
- 7.4 Depolymerisation Reactions
- 7.5 Manufacture of Paper/Pulp
- 7.6 Miscellaneous Applications
 - 7.6.1 *Flotation cells*
 - 7.6.2 *Dental water irrigator employing hydrodynamic cavitation*
 - 7.6.3 *Synthesis of nanocrystalline materials*
 - 7.6.4 *Preparation of high quality quartz sands*
 - 7.6.5 *Preparation of free disperse system using liquid hydrocarbons*
- 8.0 CONCLUSIONS AND RECOMMENDATIONS

9.0 SUGGESTIONS FOR FUTURE WORK**10.0 NOMENCLATURE****11.0 REFERENCES****12.0 LIST OF TABLES****13.0 FIGURE CAPTIONS****ABSTRACT**

Hydrodynamic cavitation is produced by pressure variation in a flowing liquid caused by the velocity variation in the system. The present review aims at understanding the various stages in hydrodynamic cavitation starting with discussion about the methods of generation and advantages of the hydrodynamic cavitation over acoustic cavitation in general, followed by the most important part of bubble dynamics as a function of operating and geometric parameters of the hydrodynamically cavitating system and the scope of optimizing the same. Various hydrodynamic cavitation reactors have been described and comparison with the acoustic counterparts indicate higher energy efficiency for the hydrodynamic cavitation reactors, for certain applications.

The effects of various operating and geometric parameters viz. inlet pressure/operating speed, physico-chemical properties of liquid, geometry of the constriction, initial radius of the cavitation bubble nuclei on the overall cavitation efficiency have been discussed and recommendations regarding the selection of these parameters for efficient design of the reactors have been made.

Further, the effects of hydrodynamic cavitation are compared with its counterpart i.e. acoustic cavitation where the generation of cavities is due to the ultrasonic irradiation of the cavitating medium. Similarities between the two types of cavitation have also been documented for better understanding and various advantages of hydrodynamic cavitation reactors have been stressed with some experimental confirmations.

Various applications of hydrodynamic cavitation, though on a pilot plant/laboratory scale, have been highlighted. Some recommendations for future work have been made which can transfer the various laboratory scale applications into commercial scale operations.

Based on the detailed analysis done in the present work, it has been conclusively proven that conditions similar to acoustic cavitation can be

generated in hydrodynamic cavitation reactors in a much more energy efficient way and the reactors based on the hydrodynamic cavitation phenomena can be scaled up to industrial scale, bypassing the problems associated with acoustic cavitation reactors.

1.0 INTRODUCTION

Cavitation can in general be defined as the phenomena of the formation, growth and subsequent collapse of microbubbles or cavities occurring in an extremely small interval of time (milliseconds) releasing large magnitudes of energy. The local effects of the cavitation phenomena can be given as generation of very high temperatures (of the order of 1000 to 5000 K) and pressures (100 to 5000 bar). The magnitudes of the pressures and temperatures are a strong function of the operating hydrodynamic and geometric constructional features of the reactor. Thus the resultant effects are really spectacular and such events simultaneously occur at millions of places in the reactor. This is one of the methods of introducing discrete energy input, where the energy dissipated per unit volume (pockets) for the same amounts of average energy input are a few orders of magnitude higher than the conventional processes. Thus, there is concentration of energy in extremely small zones, but at millions of such locations.

Cavitation based processes promise a more energy efficient alternative to the conventional reactors for example a simple mechanically agitated contactor. To improve the performance of a conventional stirred reactor, you either can increase the size of active zone (by increasing the diameter of the impeller) or raise the exchange rates between the active and passive zones existing in the reactor (by increasing the speed of rotation). Unfortunately, both techniques lead to a substantial boost in overall energy consumption (Power consumption in stirred reactors is directly proportional to $N^3 d^5$, where N is the speed of rotation and d is the diameter of the impeller). On the other hand, by generating very high local temperatures and pressure, cavitation can achieve the twin objectives of increasing the rate of the transport processes and enhancing the intrinsic rate of the chemical reaction at much lower overall energy inputs.

1.1 Types of Cavitation

Generally cavitation is classified into four types based on the mode of its generation:

1. **Acoustic cavitation:** Here the pressure variations in the liquid are effected using sound waves, usually ultrasound (16 KHz- 100 MHz). The chemical changes taking place due to the cavitation induced by the passage of sound waves are commonly known as sono-chemistry.
2. **Hydrodynamic cavitation:** Cavitation is produced by pressure variations which is obtained using geometry of the system creating velocity variation. For example based on the geometry of the system the interchange of pressure and kinetic energy can be achieved as in flow through orifice, venturi etc.
3. **Optic cavitation:** It is produced by photons of high intensity (laser) light rupturing the liquid continuum.
4. **Particle cavitation:** It is produced by any other type of the beam of the elementary particles, e.g. a proton, rupturing a liquid, as in a bubble chamber.

Among the various modes of generating cavitation given above, acoustic and hydrodynamic cavitation have been of academic and industrial interest due to the ease of operation and the generation of the required intensities of cavitation conditions. The acoustic cavitation or sonochemical processes have been the widely studied phenomenon over the past few decades. Excellent reviews on the scope and the application of ultrasound and processes based on the same are available in the literature (Mason, 1986, Henglein, 1995, Lindley and Mason, 1987, Luche *et al.*, 1989, Moholkar and Pandit, 1996, Mason, 1999, Suslick *et al.*, 1999, Von Sonntag *et al.*, 1999, Keil and Swamy, 1999 and Shah *et al.*, 1999). Modelling of sonochemical reactors and the bubble dynamics under a variety of conditions have been also extensively studied in the past (Yan *et al.*, 1988, Yan and Thorpe, 1990, Kamath *et al.*, 1993, Naidu *et al.*, 1994, Moholkar and Pandit, 1997, Sochard *et al.*, 1998, Moss *et al.*, 1999, Storey and Szeri, 1999, Gogate and Pandit, 2000^a, Storey and Szeri, 2000). However it should be noted that, in spite of extensive research, there is hardly any chemical processing carried out on an industrial scale owing to lack of expertise required in such diverse fields as material science, acoustics, chemical engineering etc. for scaling up successful lab scale processes. Some attempts

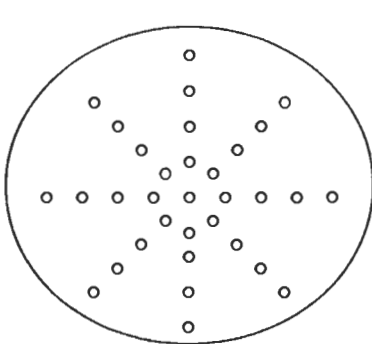
have been made to effectively scale up these reactors (Berlan and Mason, 1992 and Martin and Ward, 1993).

Similar cavitation phenomena can also be generated relatively easily in hydraulic systems. Engineers have generally been looking with caution at cavitation in hydraulic devices due to the problems of mechanical erosion and all the initial efforts to understand it were with the objective of suppressing it, to avoid the erosion of exposed surfaces. In the last decade, concentrated efforts were made by a few groups around the world to harness the spectacular effects of hydrodynamic cavitation for chemical/physical transformation (Chivate and Pandit, 1993, Pandit and Joshi, 1993, Save *et al.*, 1997, Suslick *et al.*, 1997, Vichare *et al.*, 1999, Senthilkumar *et al.*, 2000).

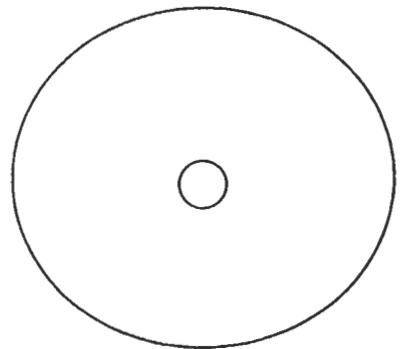
The present work aims at a detailed analysis of the hydrodynamic cavitation reactors, as these have been found to be more energy efficient and superior as compared to sonochemical reactors (Senthilkumar *et al.*, 2000, Gogate and Pandit, 2000^c). Of course this fact has been discussed in detail at a later stage also. An initial step towards understanding the possible use of hydrodynamic cavitation reactors for chemical engineering benefits would be to understand its occurrence and the behavior of bubbles/cavities under different hydrodynamic conditions and compare the behavior of the same under acoustic irradiation.

1.2 Occurrence of Hydrodynamic cavitation:

Hydrodynamic cavitation can simply be generated by the passage of the liquid through a constriction such as an orifice plate (Figure 1). When the liquid passes through the orifice, the kinetic energy/velocity of the liquid is



Multiple holes (Senthilkumar *et al.*, 2000)



Single hole (Yan *et al.*, 1988)

Fig. 1: Arrangement of holes on the orifice plate to generate cavitation

increased at the expense of the pressure. The typical axial pressure profile downstream of the orifice fitted in a pipe is shown in Figure 2. If the throttling is sufficient to cause the pressure around the point of vena contracta (C) to fall below the threshold pressure for cavitation (usually vapor pressure of the medium at the operating temperature), millions of cavities are generated. Subsequently as the liquid jet expands, the pressure recovers and this results in the collapse of the cavities. During the passage of the liquid through the constriction, boundary layer separation occurs and a substantial amount of

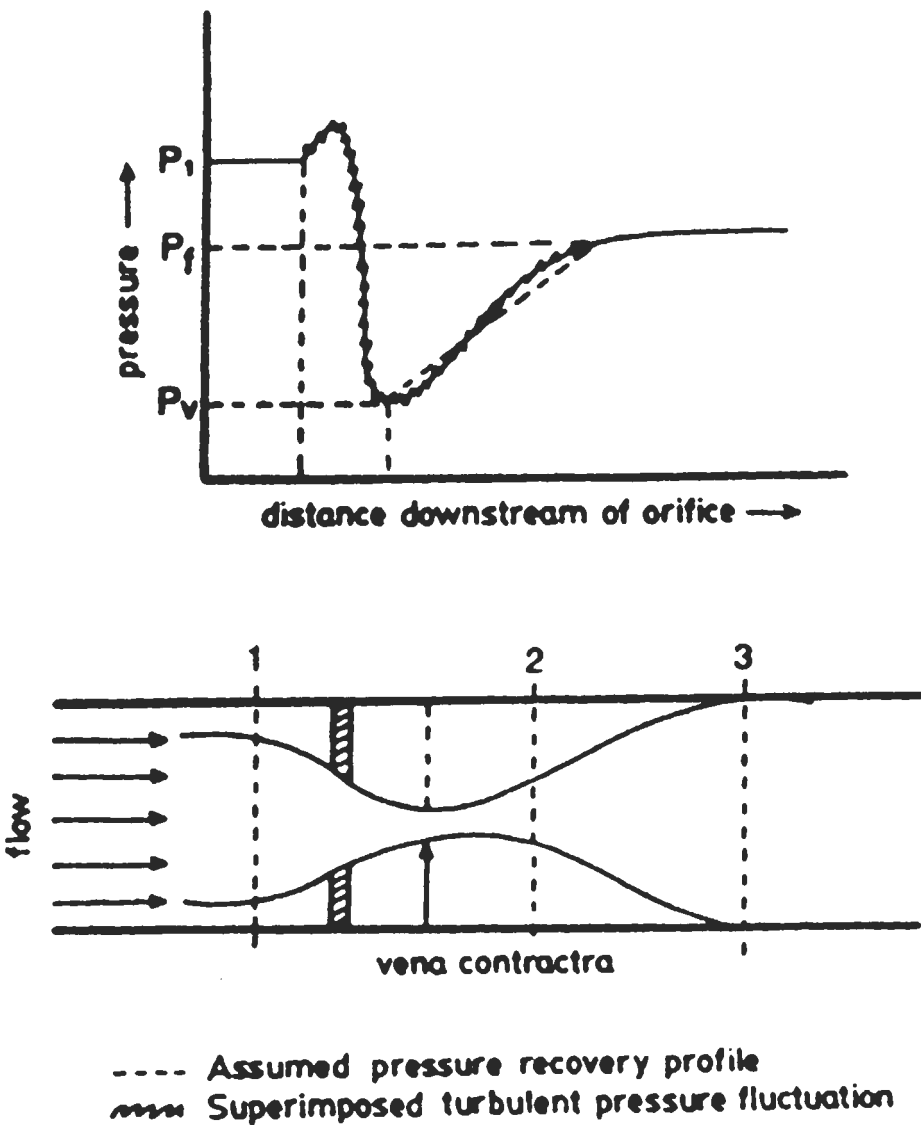


Fig. 2: Typical axial profile downstream of the orifice in hydrodynamic cavitation reactor

energy is lost in the form of permanent pressure drop. Very high intensity fluid turbulence is also present at the downstream side of the constriction; its intensity depends on the magnitude of the pressure drop, which, in turn, depends on the geometry of the constriction and the flow conditions of the liquid i.e. the scale of turbulence. The intensity of turbulence has a profound effect on the cavitation intensity as shown by Moholkar and Pandit (1997). Thus by controlling the geometric and operating conditions of the reactor, one can produce the required intensity of the cavitation so as to bring about the desired physical or chemical change with maximum energy efficiency.

A dimensionless number known as cavitation number (C_v) has generally been used to relate the flow conditions with the cavitation intensity.

$$C_v = \frac{P_2 - P_v}{\frac{1}{2} \rho v_{th}^2} \quad (1)$$

where P_2 is the fully recovered downstream pressure, P_v is the vapor pressure of the liquid and v_{th} is the velocity of the liquid at the throat of the constriction. The cavitation number at which the inception of cavitation occurs is known as cavitation inception number C_{vi} . Ideally, the cavitation inception occurs at $C_{vi}=1$ and there are significant cavitation effects at C_v value of less than 1. In the earlier work (Gogate and Pandit, 2000^b) it has been clearly shown (for $C_v > 1.0$) that the cavities oscillate under the influence of fluctuating pressure field and the magnitudes of pressure pulses generated are very low, insignificant to bring about a desired chemical change. However, cavitation has been found to occur at a higher cavitation number also possibly due to the presence of dissolved gases or some impurities in the liquid medium (Harrison and Pandit, 1992). Yan and Thorpe (1990) have also shown that C_{vi} is a function of the flow geometry and usually increases with an increase in the size of the constriction. Moreover comparison of experimental data of Yan and Thorpe (1990) for pipe diameter of 3.78 cm with data of Tullis and Govindrajana (1973) for pipe diameters of 7.80 and 15.4 cm indicates that the cavitation inception number is a strong function of the pipe diameter also and it increases with an increase in the pipe diameter. It is difficult at this stage to give a physical explanation for these observed variations with the orifice and pipe diameter. Still for maximum benefits from the reactor, the flow conditions and the geometry should be adjusted in such a way that the cavitation number lies below 1 but not very low leading to supercavitation resulting into vapor locking and no cavitation collapse (Yan and Thorpe, 1990).

1.3 Advantages and Disadvantages of Hydrodynamic Cavitation Reactors:

The major advantages of hydrodynamic cavitation are,

1. Reactions that require moderately rigorous conditions can be carried out easily under ambient conditions, as will be discussed in the subsequent stages.
2. It is one of the cheapest and most energy efficient methods of generating cavitation.
3. The equipment used for generating cavitation is simple.
4. Maintenance of such reactors is very low
5. The scale-up of the above process is relatively easy.

It should be noted at this stage that the hydrodynamic cavitation phenomenon provides substantially lower intensity of collapse of the individual cavities in terms of temperature and pressure than the acoustic cavitation (Senthilkumar, 1997 and Moholkar *et al.*, 1999) though the degree of cavitation intensity and the number of cavitation events can also be controlled by manipulating the operating and geometric conditions existing in the reactor (Gogate and Pandit, 2000^b). Another shortcoming of the hydrodynamic cavitation reactors is the poor pressure recovery downstream of the constriction (Typically for an orifice to pipe diameter ratio of 0.5, the total permanent pressure head loss is about 73% of the orifice pressure differential). Therefore to produce higher intensities of cavitation, discharge pressure of the pump should be higher. However it should be again noted that the conditions can be greatly improved by adjusting the geometry and operating conditions of the reactor altering the fluid turbulent structure as discussed in detail later. Also similar to the acoustic cavitation reactors, the performance of hydrodynamic cavitation reactors is low in the case of viscous mediums. In such a case cavitation is difficult to produce and the cost of pumping such viscous materials is very high, affecting the overall economy of the process.

2.0. CHEMICAL AND PHYSICAL EFFECTS OF HYDRODYNAMIC CAVITATION

Though the mechanism of chemical effects of hydrodynamic cavitation is similar to sonochemical process, one distinct difference is that the intensity of

collapse of the individual cavities in terms of temperature and pressure is substantially lower than the cavitation intensity caused by the passage of ultrasound (Senthilkumar, 1997). However the number of such cavitation events and also the intensity to some extent can be effectively controlled by adjusting the geometrical and operating parameters, as discussed later.

The mechanical and chemical effects of the collapsing cavity can be assumed to be felt in three distinct but hypothetical zones as shown in Figure 3.

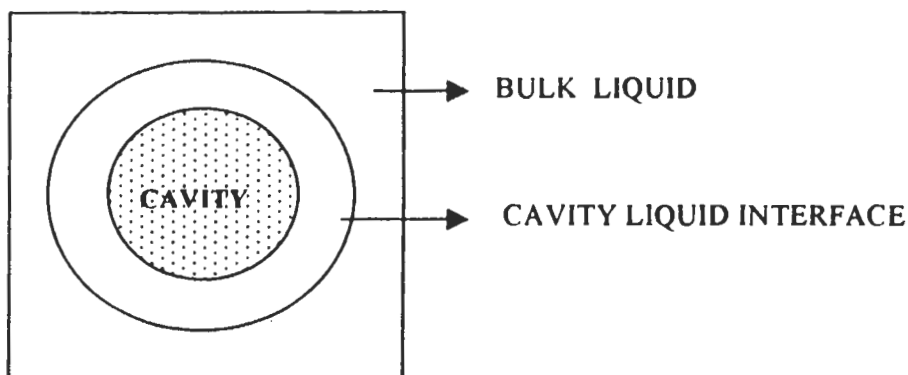


Fig. 3: Schematic representation of collapsing cavity zones

1. The interior of the cavity can be considered as high temperature microreactor. Extreme conditions of temperature and pressure exist inside the cavity essentially due to the adiabatic nature of the cavitation collapse. The contents of the cavity (usually solvents and solutes/reactants if it is volatile) thus suffer breakage of bonds to generate free radicals (pyrolysis). Again the number of free radicals generated depends on the intensity and number of the cavitation events. Naidu *et al.* (1994) and Sochard *et al.* (1998) have described in detail the method for the estimation of the number of free radicals generated under the given cavitating conditions.
2. In the cavity- liquid interfacial region, the temperature is high enough to induce reactions via free radical mechanism. The relative efficiency of the solute to undergo reaction depends on their ability to accumulate at the interface and on activation energies for bond breakage (Krishna *et al.*, 1989).
3. The free radicals generated in the cavity and interface region travel to the bulk liquid and undergo reaction with it if they have sufficiently long half life. The rate of transfer of the cavities also depend on the flow conditions and turbulence generated by flow as well as the collapsing cavities.

The important physical effect of cavitation is to increase the rate of mass and heat transfer, particularly in heterogeneous systems. The following are the known major effects of cavitation.

1. Generation of shock waves.
2. Liquid microjet formation.
3. Interfacial turbulence.

In heterogeneous systems, the collapsing cavity results in the formation of microjet at the interface due to the asymmetric rush of the liquid. The mechanism of the asymmetric collapse of cavities is schematically depicted in Figure 4. In the solid-liquid systems, this microjet of high velocity disturbs the boundary layer at the solid surface, leading to the breakdown of the liquid film responsible for the resistance to the mass transfer. If the energy of the microjet is sufficiently high, it leads to the fragmentation of the solid particles. The oscillating cavity, whose size is typically of the same order of magnitude as the film thickness (based on film theory), results in the generation of interfacial turbulence, when it approaches the interface. In the liquid-liquid systems, the action of cavitation is by way of liquid microjets leading to the breakdown of droplets and by generation of interfacial turbulence. The role of cavitation in the enhancement of the heat transfer can also be explained on the above lines. Kimoto and Sumita (1986) have found that heat transfer rate almost doubles in the presence of cavitation in a conduit. Kataoka (1985) also reported similar observations.

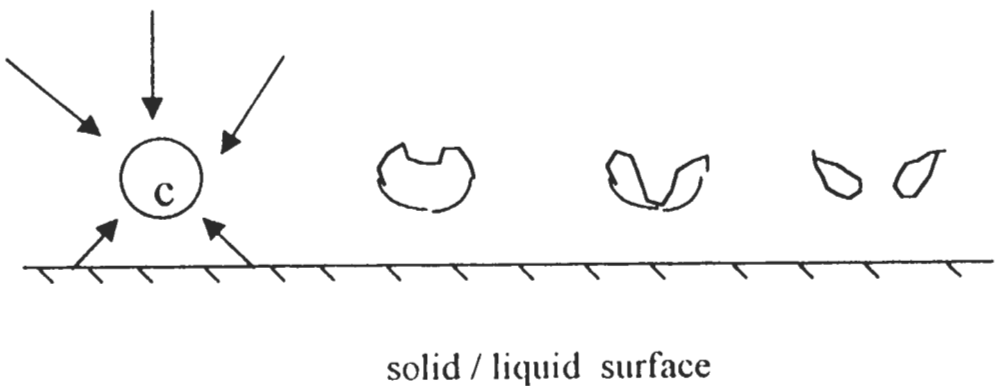


Fig. 4: Assymmetric collapse of the cavity near heterogenous surface

3.0 BUBBLE DYNAMICS IN HYDRODYNAMIC CAVITATION

Modeling of hydrodynamic cavitation with extensive study of bubble dynamics in the hydraulic systems can aid in a better understanding of the overall cavitation process and also in optimizing the operating parameters as well as the geometry of the cavitation set-up. Two important factors viz., 1) the effect due to the action of individual cavity and 2) total number of cavities generated, contribute to the overall effect of cavitation. Bubble dynamics i.e. variation in the radius of bubble/cavity with time and the total number of cavities that will be formed will be affected significantly by the operating and geometric conditions in the reactor as a result of time dependent pressure variation in the surrounding medium. Moreover, the number of cavitation events is usually decided by the existing cavitation number and also the cavitation inception number which is a strong function of the operating and geometric parameters. The predicted time dependent radius profiles of a single cavity will also depend on the methodology used for the solution of bubble dynamics equations along with the various considerations such as single cavity, cluster of cavity, effect of turbulence, compressibility of medium, viscosity, surface tension etc. used in the numerical scheme.

The basic bubble dynamics equation governing the variation of the bubble/cavity under the cavitating conditions which also includes the surface tension and viscosity effects, known as the Rayleigh Plesset equation (Plesset, 1949) is given as follows;

$$R \frac{d^2R}{dt^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 = \frac{1}{\rho} \times \left(P_i - \frac{2\sigma}{R} - \frac{4\mu}{R} - \frac{dR}{dt} - P_\infty \right) \quad (2)$$

where d^2R/dt^2 represents the acceleration of the bubble/cavity, dR/dt is the bubble wall velocity, σ is the surface tension of liquid and μ is the viscosity of the medium. P_i and P_∞ is the pressure inside the bubble and the actual pressure downstream of the constriction respectively.

Solution of this bubble dynamics equation using the knowledge of the pressure fields existing at the downstream of the constriction gives the cavity radius history and the collapse pressures for a cavity of certain size, travelling with the fluid. In the following sections, different approaches used in the numerical simulations to predict cavity dynamics have been discussed.

3.1 Approach of Yan *et al.* (1988)

Yan *et al.* (1988) have used an approach where a single bubble was assumed to be existing independent of the other bubbles and a linear pressure recovery profile downstream of the orifice was considered neglecting the turbulent pressure fluctuations. Such an approach may be adequate when the intensity of turbulence is quite low, i.e. venturi type or any other smooth variation in the cross-sectional flow area, and thus the pressure recovery from the point at which cavitation starts to any downstream pipe position can be approximated by a linear expression with respect to the distance downstream of the constriction. In such a case, the local pressure at any downstream position can be estimated as:

$$P = P_v + \frac{(P_2 - P_v)}{\tau} t \quad (3)$$

where τ is the pressure recovery time and P is the axial pressure downstream of the orifice to be substituted for P_∞ in the Rayleigh-Plesset equation to obtain a time dependent discrete (at any time 't') solution. P_v is the vapour pressure of the medium which is assumed to be present at vena-contracta under cavitating conditions.

The approach of Yan *et al.* (1988) certainly loses validity when the intensity of turbulence increases and pressure recovery is no longer linear, especially with changing geometry of the orifice i.e. sharp edge orifice. In this case significant alteration is likely to occur in the local pressures encountered by the vapor/bubble cavity in the passage along with the fluid flow downstream of the constriction.

Figure 5 gives a typical radius history, i.e. the variation of radius of the cavity/bubble during different stages of cavitation for the numerical solution scheme assuming no turbulence. It can be clearly seen from the figure that the bubble just oscillates (does not collapse violently) and produces pressure pulses of very small magnitudes. Such a condition is very similar to the case with cavitation number greater than 2. In the earlier work (Gogate and Pandit, 2000^b), analysis has been done for the condition of $C_v = 2.5$ and it was clearly observed that the bubble just keeps on oscillating without generating significant magnitudes of collapse pressure pulses. Such low magnitude pressure pulses are unlikely to bring about the observed chemical effects (discussed later) and hence this approach is not suitable and these predictions cannot be relied upon. Thus consideration of turbulence and understanding the role of the same is crucial for efficient scale-up and design of the hydrodynamic cavitation reactors.

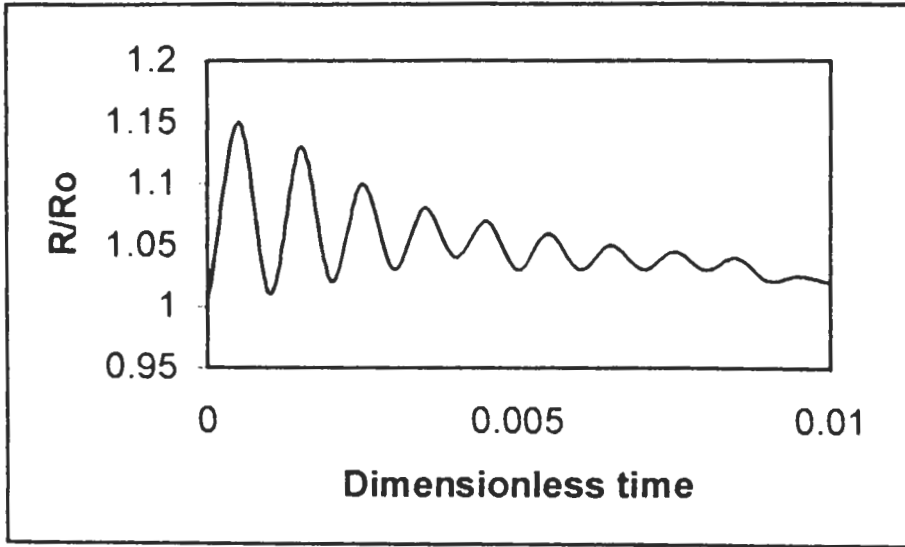


Fig. 5: Typical radius profile under conditions of no turbulence in the reactor (Approach of Yan *et al.* 1988)

3.2 Approach of Moholkar and Pandit (1997)

Moholkar and Pandit (1997) have studied the effect of turbulence on the bubble dynamics in the case of hydrodynamic cavitation. The important assumptions used in the numerical scheme were, single cavity is present in isolation, the cavitation medium is inviscid and incompressible, relative motion between the gas and liquid phase (i.e. the slip velocity) and hence the gas-liquid interfacial friction loss is negligible and heat and mass transfer effects are negligible due to the fact that the cavitation process is significantly fast and hence adiabatic. For a pipe flow, the turbulent pressure fluctuations are due to velocity perturbations as a result of the formation of the eddies. In their approach, Power input per unit mass (P_m) of the system was estimated by considering the permanent pressure head loss which is a function of the ratio of the orifice to pipe diameter. From the value of P_m , and the length scale of eddy calculated as, $l = 0.08 d_c$, where d_c is the diameter of the conduit through which the fluid and associated cavity flows, the fluctuating component of velocity can be calculated. Moholkar and Pandit (1997) have used d_c same as the diameter of orifice which may not give a ideal picture as the cavity generated and associated liquid is experiencing two levels of turbulence, once passing through the pipe and the other when it encounters a sudden

constriction at the hole in the orifice plate. Gogate and Pandit (2000^b) have used a modified approach for the eddy length scale as discussed later.

The instantaneous turbulent velocity was calculated by assuming a sinusoidal velocity variation in the instantaneous local velocity with the frequency of the velocity perturbations and is given by the following equation:

$$V_{in} = V_t + V' \sin(2\pi f_T t) \quad (4)$$

where V_t is the local mean velocity, f_T is the frequency of turbulence and V_{in} is a function of time with t being the numerical integration step for time. Use of this instantaneous velocity was made to estimate the instantaneous local static pressure using Bernoulli's equation of the following form;

$$P_t = P_v + 1/2 \rho (V_o^2 - V_{in}^2) - \Delta P \quad (5)$$

where ΔP is the permanent pressure loss across the constriction. P_t was then used in the place of P_∞ in the solution of Rayleigh-Plesset equation.

Figure 6 shows the typical radius history profile simulated considering the turbulence effects. It can be clearly seen from the figure that there is large growth in the size of the bubble/cavity (around 200 times growth is observed as compared to maximum of 1.2 times in the non turbulent conditions) which also results in significant magnitudes of pressure pulse at the time of the collapse

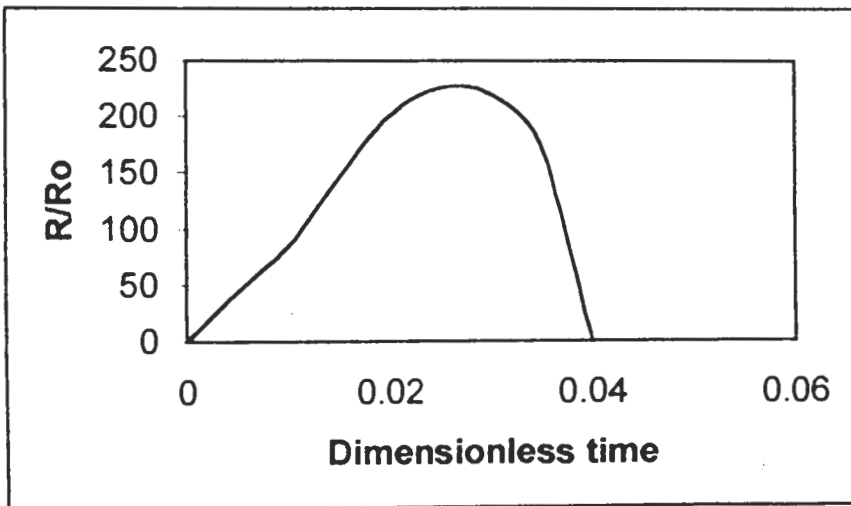


Fig. 6: Typical radius profile for simulations considering turbulence in the reactor (Approach of Moholkar and Pandit, 1997)

(cavity does not oscillate as in the earlier case but collapses). It should be noted at this stage that the radius history profile given in **Figures 5 or 6** is just a schematic representation and is a strong function of the operating and geometric conditions.

This important result has shown that the bubble behavior under turbulent conditions is transient and resembles the behavior of a cavity under acoustic cavitation. It should be noted at this stage that the behavior under the non-turbulent conditions was oscillatory without leading to any pressure pulses of significant magnitudes. Thus, the work of Moholkar and Pandit (1997) could be taken as a step ahead in the field of bubble dynamics in hydrodynamic cavitation though certain assumptions such as the single cavity and incompressible nature of the liquid medium can be relaxed as discussed later. Moreover the change from stable to transient cavitation by the consideration of turbulence have conclusively proved that the hydraulic devices can be used to generate conditions similar to acoustic cavitation in a relatively simple manner if only, one can manipulate the level of fluid turbulence. This conclusion has been given credence if one compares the identical metal erosion rates obtained under acoustic and hydrodynamic conditions (Hansson *et al.*, 1977). To obtain, identical metal erosion rates, the pressure pulses produced by the collapsing cavities need to be of similar magnitude which can be only obtained with transient cavitation (with turbulence) and not by stable or oscillatory cavitation (without turbulence).

3.3 Approach of Lush (1988)

Lush (1988) presented a model for the dynamics of the cavities in a rectangular duct flow. One dimensional mass and momentum equation for the duct flow and Rayleigh-Plesset equation governing the cavity wall motion were developed and solved numerically. It was found that the collapse time obtained by the above scheme is greater as compared to the prediction made by the Rayleigh classical theory, if the duct parameter based on maximum cavity size, duct cross sectional area, flow length scale is greater than one. The predictions agree very well with the measurements derived from the cine films, when the flow length scale is taken to be equal to mean length of the attached cavity. This also, in a way, states that the consideration of the turbulence gives a more realistic picture of the conditions and more rigorous models should be developed for efficient design of hydrodynamic cavitation reactors.

3.4 Approach of Senthilkumar and Pandit (1999)

Senthilkumar and Pandit (1999) have modeled the hydrodynamic cavitation phenomena in a venturi tube and high speed homogenizer and observed that the modeling of the cavitation phenomena in hydraulic systems based on single cavity dynamics equation is not a realistic picture as the visual observations indicated the presence of cavity clusters rather than individual cavities. The dynamics of the individual cavities are also affected by the neighboring cavities due to the generation of shock waves as a result of the neighboring cavity collapse. The important assumptions in the approach of Senthilkumar and Pandit (1999) are a spherical cavity cluster in isolation, inviscid and incompressible liquid, no slip condition i.e. no relative motion between liquid and the cavity cluster and the last, nucleation phase is neglected and a predetermined initial size of the cluster has been used. It should be noted that the last assumption will not have any significant effects on the magnitudes of the collapse pressures generated and hence the design, as the collapse phase i.e. trajectory followed from the maximum size reached to the collapse conditions is very important. This approach is again a further step in presenting more realistic picture as it considers a cluster of cavity and turbulence effects instead of a single cavity in isolation as considered in the earlier approach. The length scale of eddy is again calculated based on the Prandtl eddy given as;

$$l = 0.08 d_c \quad (6)$$

As the simulations were carried out for the case of a venturi, d_c was estimated based on the knowledge of the throat and exit velocity, which yields the distance traveled by the cluster in a given time (Newton's law) as follows:

$$d_c = 2\alpha + d_v \quad (7)$$

where d_v is the diameter of the venturi throat and α is defined as:

$$\alpha = (d_p - d_v) / 2L \quad (8)$$

L is the length of the expansion section of the venturi and d_p is the pipe diameter.

The estimation of the instantaneous local velocity and the turbulent pressures is similar to the approach of Moholkar and Pandit(1997) as described earlier.

Also Rayleigh Plesset equation governing the dynamics of bubble/cavity under the influence of varying pressure fields with certain modifications to account for the use of cavity cluster instead of the single cavity was used in the simulations.

Three models have been proposed in the literature to explain the cavity cluster collapse. One model assumes that the shock waves from individual cavity collapses are superposed to form a single high-intensity damaging shock wave and the second model proposed by Hansson and Morch (1980) assumes that a collective or simultaneous collapse of individual cavities results in a single large magnitude shock wave. Experimental studies on metal erosion indicate the presence of a diffused erosion zone around a specific point and size of both the zones i.e. the one due to the presence of single large shock wave and the other diffusively eroded zone, is macroscopic in nature and far higher than the size of individual cavities. Hansson and Morch (1980) proposed a third model based on the idea of energy transfer from the cavities which collapse first, to the cavities that have not yet collapsed. The collapse of outer cavities creates a field of increased pressure, greater than the surrounding bulk pressure of the flowing liquid, around the remaining part of the cluster. Thus the damage potential or the collapse intensity of the individual cavities increases towards the center of the cluster. Senthilkumar and Pandit (1999) have used the above model to explain the collapse of the cavity cluster.

The modified Rayleigh Plesset equation which was used in the simulations of Senthilkumar and Pandit (1999) to account for the cavity cluster is given as:

$$R \frac{d^2 R}{dt^2} + \left[\frac{3}{2} - \frac{1}{2} \times (1 - \gamma) \times (1 - \beta) \right] \left(\frac{dR}{dt} \right)^2 = - \frac{p_x - p_v}{\rho \beta} \quad (9)$$

where p_x will be substituted by the appropriate equations depending on the type of the reactor considered viz., venturi, high speed homogenizer or an orifice set-up, β is the cavity void fraction and γ is the energy conservation factor. For the special case of $\beta = 1$, the above equation boils down to the conventional Rayleigh Plesset equation as used by Moholkar and Pandit (1997). The values of β and γ as used in the present approach are 0.01 and 0.25 respectively. The values of β was taken based on the results of Naidu *et al.* (1994) who have predicted the number of cavities generated per unit volume for acoustic cavitation. The cluster collapse pressure was predicted by the following equation:

$$P_c = S^2 \rho \beta (1-\beta) \quad (10)$$

where S is the bubble wall velocity at the collapse conditions of the cavity based on the numerical solutions of bubble dynamics equation (Equation 9) using the fourth order Runge Kutta method. In the above approach used by Senthilkumar and Pandit(1999), homogenous distribution of cavities in the cluster is assumed and the simulations are terminated at the point at which the cluster radius reaches the mean cavity spacing Δl . The void spacing is given by the following equation:

$$\Delta l = a_0 (4\pi/3\beta)^{\alpha} \quad (11)$$

where a_0 is the size of the individual cavity in the cluster.

Figure 7 gives the variation of the cluster size with time. It can be observed that there is not much growth in the size of the cavity cluster, unlike the case of simulations using a single cavity (Moholkar and Pandit, 1997), but the overall process of cluster collapse is completed within much less time resulting in higher magnitudes of collapse pressures.

The approach of cavity clusters was found to explain the experimentally observed results on the decomposition studies of aqueous KI as a model reaction. Also the trends predicted by the model in terms of the effects of the

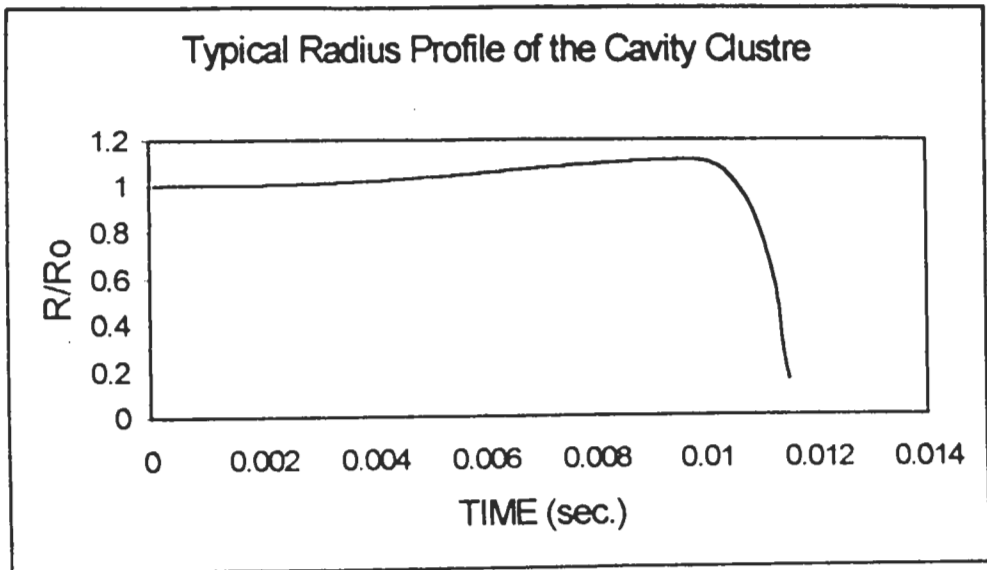


Fig. 7: Typical radius profile for simulations considering cavity clustre in the reactor (Approach of Senthilkumar and Pandit, 1999)

various operating parameters and the geometrical conditions were found to satisfactorily explain the experimental results. Figure 8 gives the variation of the collapse pressures generated and the iodine liberation rates as observed experimentally with the speed of rotation in the high speed homogenizer reactor. The two curves exactly match with significant collapse pressures and iodine liberation observed after a critical cavitation number of 1.36 which is possibly the cavitation inception number.

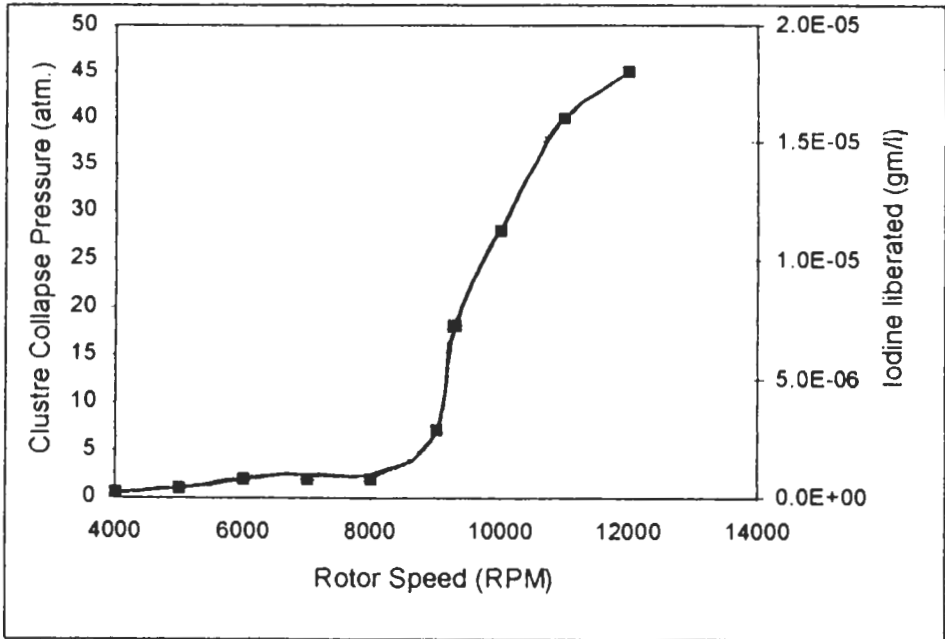


Fig. 8: Variation of collapse pressure and experimental iodine liberation rate with speed of rotation in High speed homogenizer (Senthilkumar and Pandit, 1999)

Thus it can be said that the modeling of hydrodynamic cavitation using the concept of cavity cluster depicts a better picture of cavitation as compared to the consideration of a single cavity in isolation in the flow field. The work of Senthilkumar and Pandit (1999) could be taken as a standard for the bubble dynamics studies in the venturi type of reactors and the high speed homogenizers. There is still a doubt regarding the number of clusters in the hydrodynamic cavitation reactor. No results have been reported for estimation of the number of cavity clusters though some illustrations are available for the estimation of number of individual cavities (Kamath *et al.*, 1993, Naidu *et al.*, 1994 and Sochard *et al.*, 1998). It should be noted that the experimental yield

can be correlated either with the single cavity or clusters and the number of the same is an adjustable parameter (Gogate *et al.*, 2000^c).

3.5 Approach of Gogate and Pandit (2000^b)

In all the above models, the liquid medium was assumed to be incompressible which results in underprediction of the values of the collapse pressures generated during the cavitation phenomena which will result in tremendous overdesign in the reactors, increasing the overall cost of the process. Gogate and Pandit (2000^a) have explained this effect of liquid phase compressibility in details for the case of acoustic cavitation and found that the underprediction or overprediction in the magnitudes of collapse pressures was a strong function of the initial cavity/bubble size existing in the reactors.

Gogate and Pandit (2000^b) have used the bubble dynamics equation given by Tomita and Shima (1986) which considers the compressibility of medium in the following form:

$$\begin{aligned} R \ddot{R} \left(1 - \frac{2 \dot{R}}{C} + \frac{23 \dot{R}^2}{10 C^2}\right) + \frac{3}{2} \dot{R}^2 \left(1 - \frac{4 \dot{R}}{3 C} + \frac{7 \dot{R}^2}{5 C^2}\right) + \frac{1}{\rho} [P_{\infty(t)} - P_{2(r=R)}] \\ + \frac{R}{C} (\dot{P}_{\infty(t)} - \dot{P}_{1(r=R)}) + \frac{1}{C^2} (-2\dot{R}R (\dot{P}_{\infty(t)} - \dot{P}_{1(r=R)})) + \\ 1/2(P_{\infty(t)} - P_{1(r=R)}) \left(\dot{R}^2 + \frac{3}{\rho} (P_{\infty(t)} - P_{1(r=R)})\right)] = 0 \end{aligned}$$

where P_1 and P_2 as a function of R are given as follows:

$$\begin{aligned} P_{1(r=R)} &= P_v + P_{g0} \left(\frac{R_0}{R}\right)^{3\gamma} - \frac{2\sigma}{R} - \frac{4\mu}{R} \dot{R} \\ P_{2(r=R)} &= P_{1(r=R)} - \frac{4\mu}{3\rho C^2} (\dot{P}_{\infty(t)} - \dot{P}_{1(r=R)}) \end{aligned}$$

The turbulence model used is similar to that used by Moholkar and Pandit (1997) except for the modification in the calculation of the Prandtl eddy length scale given by the following equation:

$$l = (d_o + d_p)/2 \quad (15)$$

The justification for use of average pipe and orifice diameter instead of the diameter of the constriction have already been explained earlier.

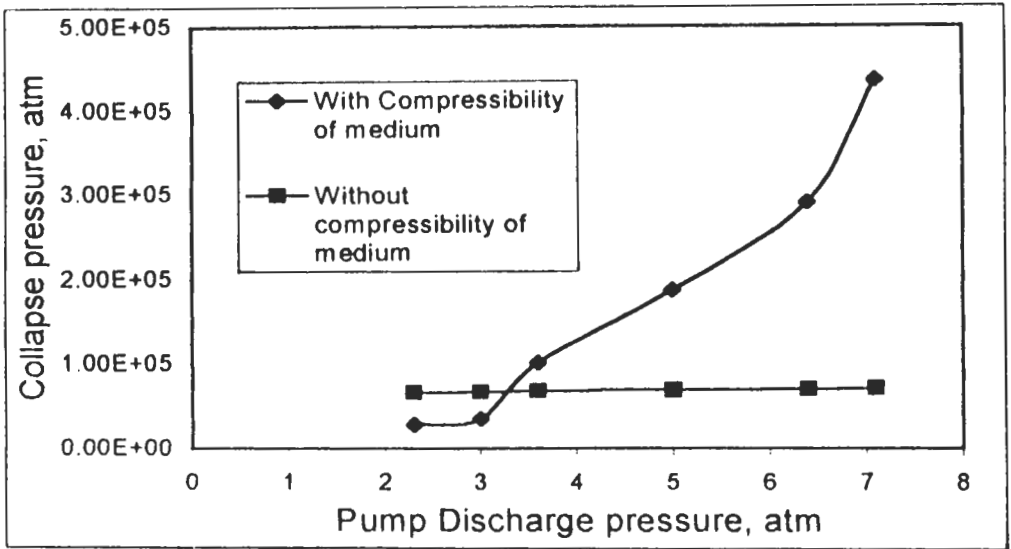


Fig. 9: Effect of compressibility of medium on the collapse pressure generated (Approach of Gogate and Pandit, 2000^b)

Figure 9 gives the comparison of the numerical predictions for the conditions with and without considering the compressibility of the medium. It can be seen from the figure that beyond an inlet pressure 3.6 atm, the Rayleigh-Plesset equation underestimates the values of the collapse pressures. The transfer from a condition of overprediction to underprediction for the Rayleigh-Plesset equation is similar to that observed in the case of acoustic cavitation (Gogate and Pandit, 2000^a).

Thus it is important to decide upon the collapse conditions while doing the numerical simulations. If the Rayleigh Plesset equation given by equation (2) is used with an assumption of incompressible liquid (Yan *et al.* (1988), Moholkar and Pandit (1997)), the simulations should be terminated at a bubble wall velocity equal to the velocity of sound in the liquid medium (for the medium as water, value of velocity is 1500 m/s). In the case of cavity cluster collapse, the simulations can be terminated at the point where the void fraction, β equals the mean cavity spacing. However if the liquid is taken as compressible, bubble wall velocities can be allowed to increase beyond that of the velocity of sound and the criteria deciding the collapse needs to be modified. Gogate and Pandit (2000^b) have taken the collapse conditions when the ratio of radius of bubble at any instant to the initial radius reaches a value of 0.1 (near complete collapse) which is a fair assumption at the current level of accuracy.

It should be noted that the work of Gogate and Pandit (2000^b) is by far the

most realistic one though it considers a single cavity. This is due to the fact that the number of cavities formed during the process can easily be estimated (Kamath *et al.*, 1993, Naidu *et al.*, 1994 and Sochard *et al.*, 1998). The overall magnitude of the pressure pulse can then be calculated as the product of the pressure pulse generated due to the collapse of the single cavity and the number of cavities generated. This then becomes a basic quantifiable cavitation yield equation. As said earlier, the experimental yield can be correlated either with a single cavity or clusters where the number of the same is an adjustable parameter and best fitting is a system dependent property.

3.6 Approach of Moholkar and Pandit (2000)

Moholkar and Pandit (2000) have considered bubble/bubble and bubble/flow interaction using the nonlinear continuum bubbly mixture model while simulating the bubble dynamics. This is again a step ahead in explaining the complex process of bubble dynamics although the liquid medium is assumed to be incompressible. The modified Rayleigh Plesset equation considering the interaction of the bubbles with the flow is given as follows:

$$R \frac{D^2 R}{Dt^2} + \frac{3}{2} \left(\frac{DR}{Dt} \right)^2 = \frac{1}{\rho} \times \left(P_i - \frac{2\sigma}{R} - \frac{4\mu}{R} \times \frac{DR}{Dt} - P_\infty \right) \quad (16)$$

where $D/Dt = \delta/\delta t + u \delta/\delta x$ is the lagrangian derivative.

Equations of continuity and motion for the two phase flow coupled with the above non-linear bubble dynamics equation were solved based on the assumption of steady state cavitating flow for a constant mass flow rate (Wang and Brennen, 1998). Runge Kutta fourth order method with adaptive step size control (Press *et al.*, 1992) have been used for the numerical simulations and bubble collapse is assumed to be complete at R/R_0 ratio (ratio of the instantaneous radius to the initial radius) becomes less than 0.05. This ratio of 0.05 gives a step ahead in achieving complete collapse conditions using numerical simulations but as there is no quantitative comparison with the earlier predictions, recommendations cannot be made at this stage regarding the use of ratio value of 0.05 as against 0.1 as considered by Gogate and Pandit (2000^b).

The various design parameters such as the throat to pipe diameter ratio, operating inlet pressures etc. were found to affect mainly two aspects of the cavitating flow;

1. Distance that the cavity clusters or individual cavities travel from the point of inception which is the throat of the venturi. This decides the active volume of the cavitation events downstream of venturi and aim of the designers should be at maximizing this active volume.

2. The pressure pulse generated at the collapse of the clusters.

A detailed discussion about the effect of various geometric and operating parameters in the case of various reactors viz. venturi, orifice plate setup, high speed homogenizer, high pressure homogenizer, has been given later based on both the numerical simulations and the experimental work.

Though the approach used by Moholkar and Pandit (2000) is a modified one as compared to some of the earlier approaches, no quantitative comparison has been reported with the earlier predictions. Hence, at this stage, it is impossible to assess the importance of using the lagrangian derivatives in the numerical simulations for the hydrodynamic cavitation reactors. It should be noted that the model developed by Senthilkumar and Pandit (1999) uses Morch's model and is based on the eulerian derivatives which is valid for a fixed frame of reference. The same can also be extended for the discrete time intervals treating independent solution at each time interval having a fixed frame of reference which has been indeed done in the cluster model put forward in the work of Senthilkumar and Pandit (1999). Thus the requirement of using a lagrangian derivative for the flowing conditions may not be required and a simple eulerian derivative approach can be used to explain the bubble dynamics of the moving cavity cluster.

From the bubble dynamics analysis presented above, the work of Gogate and Pandit (2000^b) is recommended for predicting the overall pressure pulses generated during the cavitation phenomena along with the work of Naidu *et al.*(1994) for the calculation of the number of cavities that will be generated.

Future work in presenting a realistic picture of the bubble dynamics and flow conditions in the hydrodynamic cavitation reactors can be aimed at using the tools of Computational Fluid Dynamics (CFD) for the prediction of the conditions downstream of the constriction. CFD modelling can be used for the prediction of local mean and fluctuating pressures and velocities as a function of radial and axial distance downstream of the constriction, rates of kinetic energy dissipation and the eddy size distribution. Work in this direction is also in progress in this department.

4.0 HYDRODYNAMIC CAVITATION REACTORS

Hydrodynamic cavitation reactors are much simpler to design and also for the scale-up as compared to their acoustic counterparts. The various lab scale/pilot plant scale reactors which have been used for the studies for different applications of cavitation process have been discussed with relative merits and demerits. Few advantages of hydrodynamic cavitation reactors can be given as: a) Cavitation is uniform throughout the reactor due to efficient mixing and hence there is no problem of directional sensitivity, b) Cavitation is at the shear layer of the bulk liquid and hence metal erosion problems are less severe, c) Quantification and control over the design parameters is relatively easy, leading to optimization of the required cavitating conditions.

4.1 Liquid Whistle Reactors:

The first reactor operation on the principles of hydrodynamic cavitation was the liquid whistle reactor which has been depicted in Figure 10. One of the primitive use of these type of reactors is mixing and homogenization. Here vibrations are generated in a steel plate as liquid passes over it at high velocity. The liquid couples itself with the vibrations to produce cavitation in the flow which results in highly efficient mixing.

The major feature of the operation of liquid whistle reactors is that the transfer of power is reverse i.e. power is transferred from medium to the device.

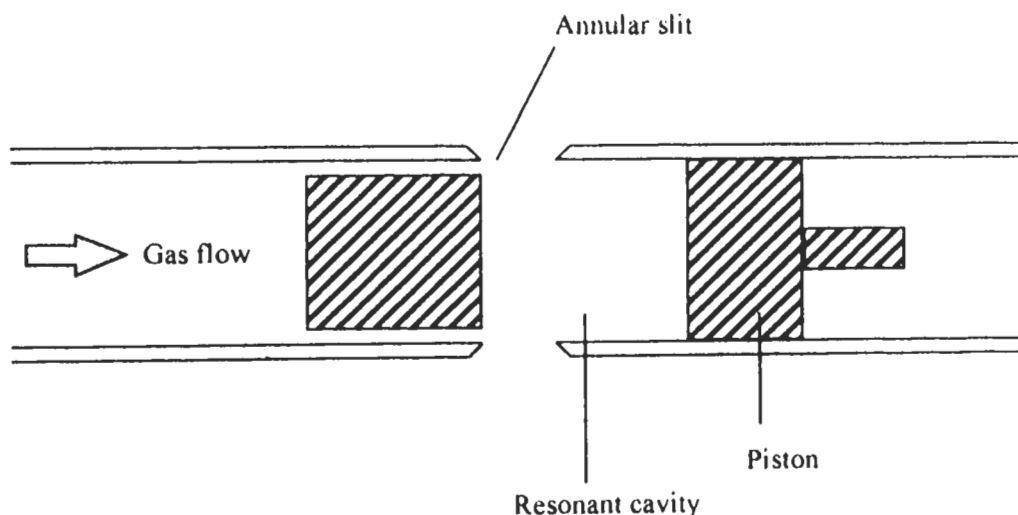


Fig. 10: Schematic representation of liquid whistle reactor

The merits of these type of reactors are;

1) It used flow systems for its operation and hence is very flexible. It can be used as an on-line homogenization/mixing device.

2) There are no moving parts and hence maintenance problems are very low.

Apart from these merits, these suffer from shortcomings such as very low vibrational power, unavailability of an optimum irradiation frequency in the case of viscous materials and high pumping costs as well as erosion of blade in the presence of particulate matters. Moreover there are no reports where these reactors have been used for the chemical processing as the intensity of cavitation produced in these type of reactors is very low.

4.2 High pressure homogenizer (HPH)

The high pressure homogenizer is basically a high pressure positive displacement pump with a throttling device (Figure 11) which operates according to the principle of high-pressure relief technique. Typically a High

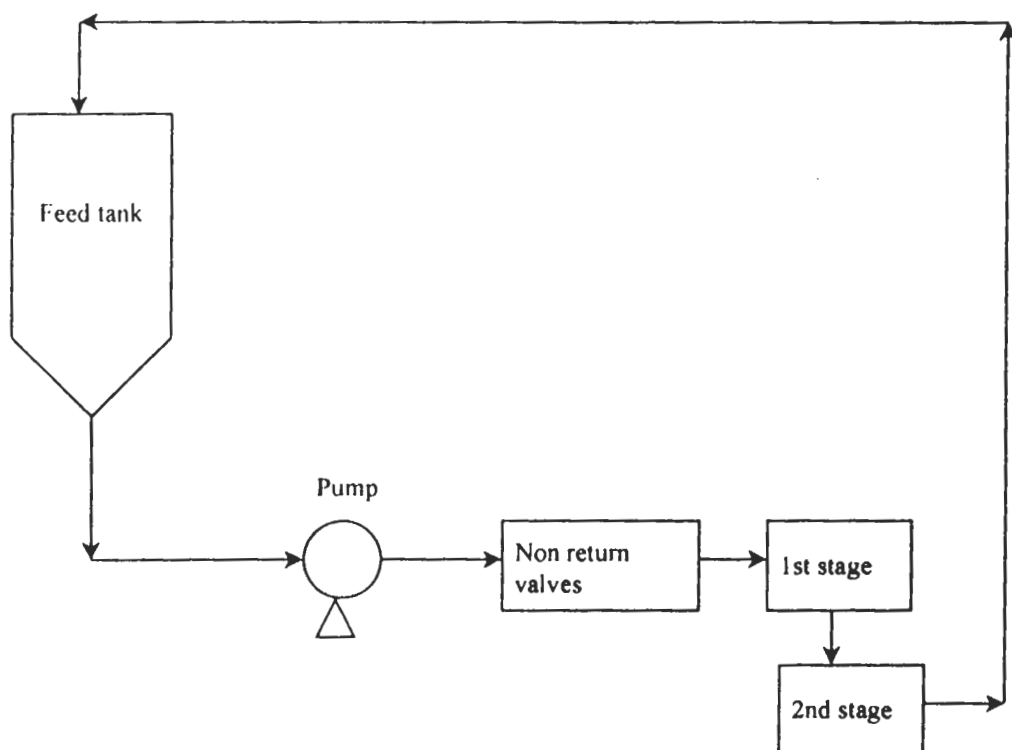


Fig. 11: Schematic representation of flow loop in high pressure homogeniser

Pressure Homogenizer reactor consists of a feed tank and two throttling valves designated as first stage and second stage. The liquid from the feed tank is driven by a pump to the first stage valve. Pressure upto 1000 psi can be attained by throttling this valve. Further increase in the pressure is achieved by using the second stage valve. Upstream pressure up to 10000 psi can be obtained in the second stage. From the second stage valve the liquid is recirculated back to the feed tank. With an increase in the throttling pressure, there is a rise in the temperature of the liquid. To maintain the temperature at ambient conditions, a coil immersed in the feed tank can be used through which cooling water is circulated. There is a critical discharge pressure at which cavitation inception occurs and significant cavitation yields are obtained beyond this pressure. It should be also noted that the value of critical discharge pressure leading to the desired cavitation effect is also dependent on the type of application and the geometry of the throttling valve.

HPH are especially suitable for the emulsification processes in industries like Food, Chemical, Pharmaceutical and Biochemical industries. The cavitation intensities are not that high and there is not enough control over the cavitational active volume and the magnitude of the pressure pulses which will be generated at the end of the cavitation events. Again there are no reports where these reactors have been used for carrying out chemical reactions except some model reaction studies as reported by Shirgaonkar (1997).

4.3 High speed homogenizer (HSH)

Cavitation can also be generated in rotating equipments. When the tip speed of the rotating device (impeller) reaches a critical speed, the local pressure near the periphery of the impeller falls and gets closer to the vapor pressure of the liquid. This results in the generation of the vaporous cavities. The original research in hydrodynamic cavitation can be attributed to this effect namely cavitation occurring on the propellers of the ship and erosion of the propeller blades caused by them. Subsequently, as the liquid moves away from the impeller to the boundary of the tank, the liquid pressure recovers at the expense of the velocity head. This causes the cavities which have travelled with the liquid bulk to collapse. High Speed Homogenizers utilize the above principle. A typical cross-sectional view of the HSH is shown in the Figure 12.

A high speed homogenizer which has been used by our group for the experimentation has been described to give an overall idea of the assembly. It consists of an impeller and a stator both of which are made of stainless steel.

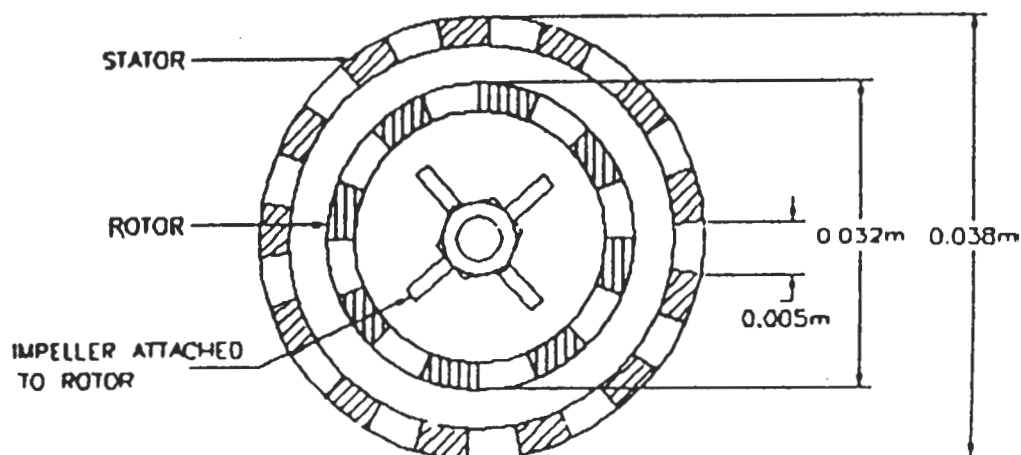


Fig. 12: Schematic representation of stator and rotor assembly in high speed homogeniser

The impeller is driven by a variable voltage motor (the limit permitted for the homogenizer is 30 V or 3.5 A). The impeller blades are 6 mm apart whereas stator blades are 6 mm. The distance between the outer diameter of the impeller blade and the inner diameter of stator blades is 2 mm. This distance can be varied by using different impeller and stators. The impeller has 9 blades while the stator has 13 blades. A plate with holes attached to the stator has been provided which can be used for inserting baffles so as to avoid vortex formation and surface aeration in the bulk liquid. The speed of rotation of the homogenizer can be varied by changing the applied voltage on the power supplier.

Senthilkumar and Pandit (1999) have found that the critical speed for the inception of cavitation to occur in HSH is 8500 rpm for the size and geometry of the stator-rotor used by them and it depends upon the dissolved gas content. Thus the operation of the high speed homogenizers should be at speeds higher than the critical speeds and at such high speeds the energy consumption is prohibitive. Senthilkumar and Pandit (1999) have successfully carried out degradation of potassium iodide to liberate iodine and also Shirgaonkar *et al.* (1998) have used these reactors for cell disruption purposes.

It should be noted that the energy consumption in these types of reactors is much higher and also flexibility over the design parameters is not much as compared to multiple plate orifice plates setup which is discussed later.

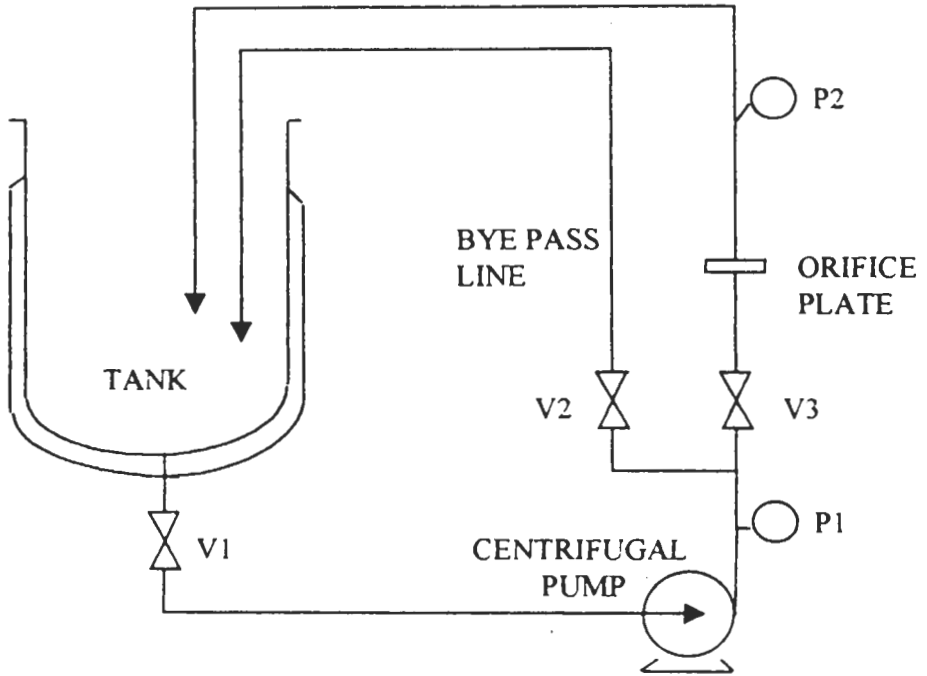
4.4 Microfluidizers

The recent advent of high pressure jet fluidizers capable of pressure drops as high as 2 kbar and jet velocities approaching 200 m/s has led to numerous applications in physical processing of liquids such as emulsification, cell disruption etc. Suslick *et al.* (1997) have used micro jet fluidizers (air driven model M-110Y from Microfluidics International Corp., 30, Ossipee Rd., Newton, MA 02164) for the decomposition of aqueous KI solutions liberating iodine with conditions of 1.24 kbar liquid inlet pressure and velocities of 190 m/s. The reaction solution is first sparged with high purity argon or Ar/He mixtures and light proofed to prevent CCl_4 photodecomposition and then injected into the pressurized reservoir through a self sealing septum. A portion of the reaction solution is pressurized by a large pneumatically driven pump into an interaction chamber, where two pulsed flows are redirected at each other through jewel orifices with velocities of 190 m/s controlled by a back pressure regulator. Cavitation occurs when there is sufficient turbulence upon the liquid jet impact or a sufficient pressure drop is created as the streams pass through the orifices. High velocity pumping results into heating of the liquid medium and hence the reactor alongwith the accessories is immersed in a thermally equilibrated bath. The cavitation inception was obtained at inlet pressure of 150 bar.

No quantitative data is available till now on the energy efficiency of the microfluidizers as compared to the sonochemical reactors and Suslick *et al.* (1997) have shown that the rates of Weissler reaction are much less in these types of reactors as against the acoustic cavitation. Also the data regarding the flexibility of geometric conditions in terms of the orifices to generate cavitation of different intensities is missing in the available open literature.

4.5 Orifice Plates Setup

In these types of reactors, the flow through the main line passes through a constriction where the local velocities suddenly rise due to the reduction in the flow area resulting into lower pressures which may even go below the vapor pressure of liquid medium generating the cavities. The constriction can be a venturi (Senthilkumar and Pandit, 1999), a single hole orifice (Yan *et al.*, 1988) or multiple holes (Senthilkumar *et al.*, 2000). One such set-up which has been designed and built with the help of local fabricators has been described to give an idea about the constructional features of the system.



P1, P2 - PRESSURE GAGES
V1, V2, V3 - CONTROL VALVES

Fig. 13: Orifice plate (pilot plant scale) hydrodynamic cavitation set-up

Figure 13 gives the schematic representation of the set-up. The set-up consists of a closed loop circuit comprising a holding tank of 50 L volume, a centrifugal pump (2900 rpm, 5.5 kW, Calama Industries Ltd, India), control valve and flanges to accommodate the orifice plates. The suction side of the pump is connected to the bottom of the tank. The discharge from the pump branches into two lines which helps in control of the inlet pressure and the inlet flow rate into the main line with the help of valves V_2 and V_3 . Care should be taken that the liquid lines must terminate well inside the tank, below the liquid level in order to avoid any induction of air into the liquid due to plunging liquid jets. The main line consists of a flange to accommodate the orifice plates, along with a hard glass tube next to these plates to make a visual observation easier. The holding tank is provided with cooling jacket to control the temperature of the circulating liquid. The inlet pressure and the fully recovered downstream pressure can be measured with the pressure gauges P_1 and P_2 , respectively.

Multiple hole orifice plates having different combinations of number and diameter of holes, varying free area offered for the flow are represented in Figure 14. Such an arrangement helps in achieving different intensities of cavitation and also number of cavitation events generated differ. Thus the set-up described above offers tremendous flexibility in terms of the operating (control of the inlet pressure, inlet flow rate, temperature) and geometric conditions (different arrangements of holes on the orifice plates). A detailed

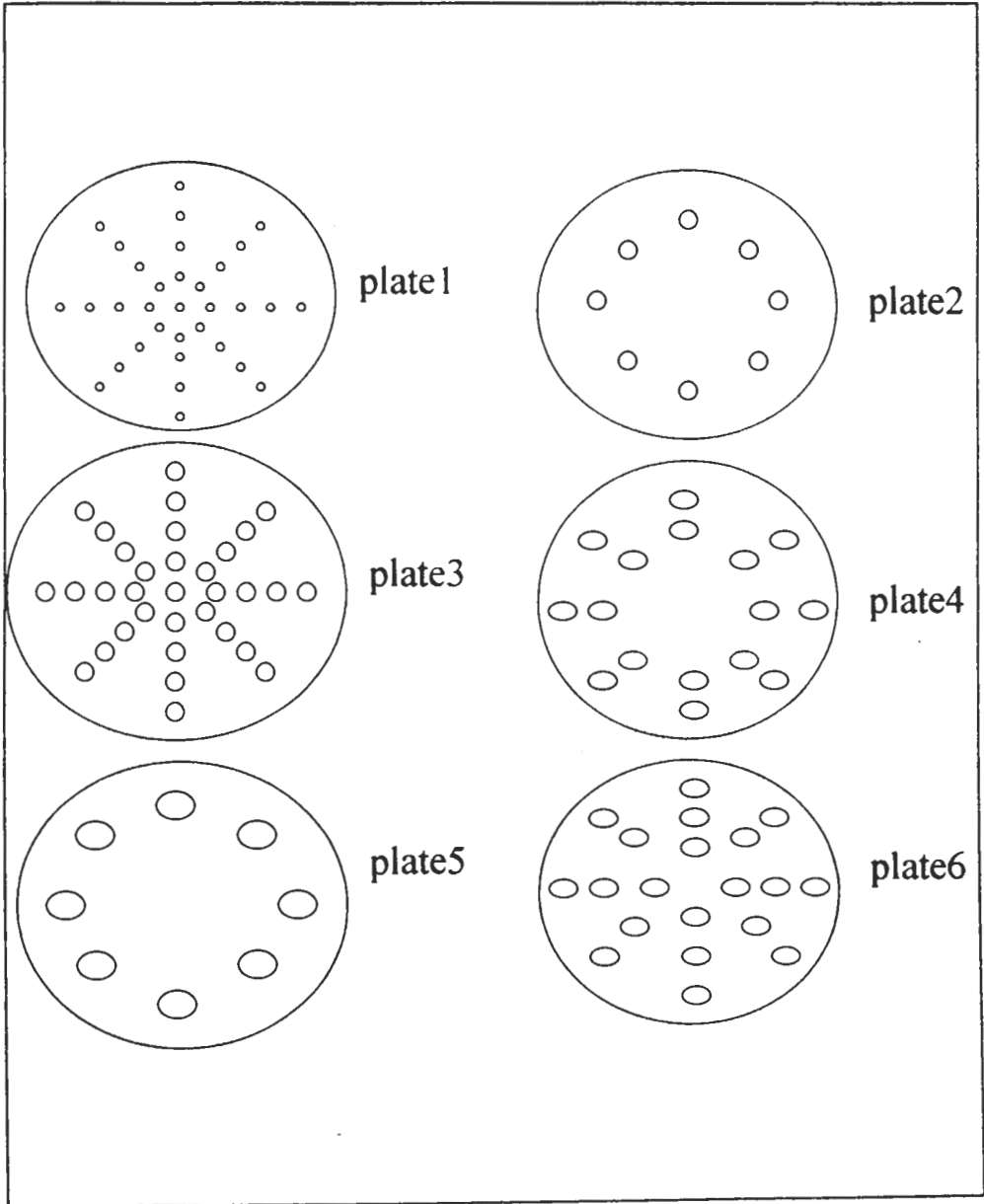


Fig. 14: Multiple hole orifice plates having different combinations of number and diameter of holes

discussion about the effect of all the parameters will be presented later. Thus depending on the type of application and requirements, geometry and operating conditions can be selected in the reactor. For example, cell disruption requires milder cavitation intensity whereas decomposition of chemicals such as Rhodamine B require very high cavitation intensities.

From the discussion about various reactors given above, it can easily be concluded that the orifice plate set-up offers maximum flexibility and can be used for a large range of applications ranging from cell disruption to decomposition of various chemicals and also can be operated at relatively larger scales of operation. It should also be noted that the scale-up of such reactors is relatively easier as the efficiency of the pump increases with an increase in size (flow rate and discharge rate) which will necessarily result into higher energy efficiencies. In the earlier work (Gogate *et al.*, 2000^c), it has been clearly pointed out that the energy efficiency for the pilot plant scale orifice plant set-up is 10 and 30 % higher as compared to high pressure and high speed homogenizer respectively.

5.0 DESIGN OF HYDRODYNAMIC CAVITATION REACTORS:

The important parameters which decide the efficiency and overall cavitation yield in the case of hydrodynamic cavitation reactors are given as follows;

- 1) Inlet liquid pressure into the system (which also affects the recovered pressure at the downstream of the constriction),
- 2) Physico-chemical properties of liquid,
- 3) Geometry of the constriction used i.e. Diameter of the constriction used and Percentage free area offered for the flow,
- 4) Initial radius of the nuclei,
- 5) Effect of rotor speed (*specific to High Speed Homogenizer*)

The effect of the various design parameters mentioned above has been studied extensively in terms of the collapse pressures generated at the end of a cavitation event based on the numerical simulations using bubble dynamics equations (Moholkar and Pandit, 1997, Tataka *et al.*, 1999, Senthilkumar and Pandit, 1999, Gogate and Pandit, 2000^b and Moholkar and Pandit, 2000) and also on the basis of experiments done in different reactors (Suslick *et al.*, 1997, Shirgaonkar *et al.*, 1998, Vichare *et al.*, 2000 and Senthilkumar *et al.*, 2000).

5.1 Effect of Inlet Pressure:

The collapse phase of cavitation phenomena depends on the rate of pressure recovery downstream of the constriction in terms of the final value of the recovered pressure and also the time in which the pressure is recovered. An increase in the inlet pressure of the system increases both these factors; the energy dissipation rate also increases due to an increase in the permanent pressure drop across the orifice. So the collapse of the cavity becomes more violent which results in an increase in the pressure pulse generated at the collapse of the cavity. In the earlier work (Gogate and Pandit, 2000^b), it has been shown that the collapse pressure is proportional to (inlet pressure)^{2.46} based on the numerical simulations. Thus higher cavitation yields will be derived at the higher operating pressures; however, its effect on the number of cavities should be considered before deriving any firm conclusions which is discussed below. Senthilkumar and Pandit (1999) have also clearly illustrated with the bubble dynamics simulations that the cluster collapse pressure increases with an increase in the inlet pressure. This is because, at high inlet pressure and large pressure drops across the venturi, the energy dissipation rate and the turbulent intensities are very high, consequently making the cavity cluster collapse more violent.

It should also be noted that the increase in the inlet pressure (if operated at constant flow rate) increases the cavitation number. This gives an interesting relationship between cavitation number and the collapse pressure generated. Generation of cavities generally occur near the saturation vapour pressure of the liquid at the operating temperature. Increase in the inlet pressure, increases the throat pressure and decreases the cavity generation. Hence the cavitation number increases with an increase in the inlet pressure and the number of cavities generated decreases (Oba *et al.*, 1986). The quantum of the total collapse pressure (collapse pressure due to a single cavity x number of cavities) may decrease beyond a certain inlet pressure as the effect of the number of cavities will be more pronounced. Thus there is an optimum of the inlet pressure that should be used for getting the maximum benefits from the system (where there is a condition that the flow rate must be kept constant). Experimental studies on cell disruption using an orifice plate indicate that the percentage cell breakage increases with an increase in the operating pressure up to a point and then decreases (Gareth and Danver, 1996). Similar results were obtained for high-pressure homogenizer (Harrison and Pandit, 1992). Gopalkrishnan (1997) have also shown that the extent of cell disruption in a

high-pressure homogenizer increases with an increase in the orifice upstream pressure up to a certain discharge pressure. Similar observations were made by other investigators while carrying out cell disruption (Shirgaonkar *et al.*, 1998, Save *et al.*, 1997). An optimum pressure at which the effect due to the collapse intensity (and hence the pressure pulse generated due to the cavity collapse) and the number of cavities are maximum could probably exist. Experimental studies using aqueous KI decomposition as a model reaction also indicated that such an optimum pressure does exist at which the iodine liberation is maximum (Figure 15, Vichare *et al.*, 2000).

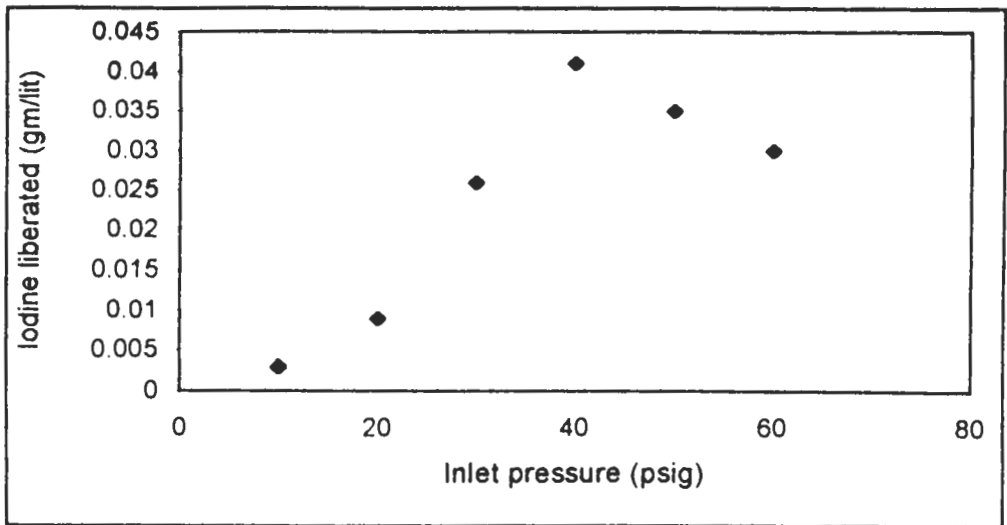


Fig. 15: Effect of inlet pressure on the iodine liberation rate in orifice setup (Vichare *et al.*, 2000)

Lowering of cavitation yields and existence of an optimum pressure can also be explained on the basis of a phenomena described as, "Supercavitation". Supercavitation or choked cavitation can be defined as a formation of vapour cloud resulting into a cavity collapse in a compressible vapour cloud resulting into substantially reduced collapse pressures. The critical cavitation number depends on the geometry of the system in particular on the value of β' , i.e. the ratio of diameter of holes in the orifice to the diameter of the pipe (Yan and Thorpe, 1990). Yan and Thorpe (1990) have reported critical cavitation number for the onset of choked cavitation in the range of 0.005 to 0.08 depending on the value of β' in the range 0.026 to 0.13 for a single hole orifice plate. Vichare *et al.* (2000) have shown that for a multiple plate orifice plate, critical cavitation number is 0.11 for the β' value of 0.02. The higher value of critical cavitation

number for choked cavitation can be attributed to the fact that larger number of locations are available for inception of cavitation as larger area is covered by the shear layer due to the multiple liquid jets. Thus it should be noted that the phenomena of supercavitation should be avoided by adjusting the operating conditions to obtain a desired cavitation number, and the work of Yan and Thorpe (1990) and Vichare *et al.* (2000) is recommended to get an idea of the critical cavitation number based on the geometry used in the reactors.

Senthilkumar *et al.* (2000) have used a setup where the pump discharge line branches into two lines, mainline consisting of a flange which houses the orifice plate and a bypass line which controls the liquid flow through the mainline. In such a case the pump discharge pressure can be adjusted by partially shutting the control valve provided in the bypass line, which will also result in an increased flow rate through the main line though the total flow rate from the pump discharge reduces (centrifugal pump characteristics). The extent of increase in the flow rate through the mainline of the system is much larger than the increase in the pressure (Vichare, 1999) and hence the cavitation number of the system also decreases. Thus the number of cavities that will be generated also increases thereby increasing the quantum of pressure energy released due to number of pressure pulses from the collapsing cavities in such a system. The experimental work done on the degradation of KI in a hydrodynamic cavitation setup with orifice plates clearly confirms this fact (Vichare 1999). Suslick *et al.* (1997) with experiments on the microfluidisers have also shown that the rate of iodine liberation was found to increase linearly with an increase in the inlet pressure in the range, 150 to 1500 bar.

Thus it is clear from the above discussion that higher operating pressures in the system are preferred up to a optimum value which is a strong function of the geometry of the system. A detailed analysis of the chemical system for the critical cavitation number is a must, based on the available literature and also some experiments on laboratory scale.

5.2 Effect of physico-chemical properties of the liquid medium:

Liquid properties are by far one of the most important parameters that affect the cavitation processes, though the magnitude of the effect due to the difference in different liquid properties may not be the same. Most of the liquid properties affect cavitation in more than one way. For example, while increase in the surface tension of the liquid, increases the threshold pressure required for the inception of the cavitation making generation of cavities more difficult,

the collapse of the cavities is more violent. These opposing effects of liquid properties give ample scope for optimization of all the liquid properties. This can generally be effected by selecting proper solvent or more easily, the reaction temperature can be manipulated. The important liquid phase physico-chemical properties which affect the cavitation phenomena can be listed as follows;

- 1) Liquid vapour pressure
- 2) Liquid viscosity
- 3) Liquid bulk temperature
- 4) Liquid surface tension
- 5) Presence of dissolved gases and
- 6) Liquid medium constituents e.g. surfactant, immiscible phase (resulting in interfacial cavitation).

5.2.1 Effect of Liquid Vapour Pressure:

Liquid phase vapor pressure has an important role in all the phases of cavity dynamics. It is more difficult to induce cavitation in a pure solvent of low vapour pressure; so for the ease of formation of cavities, volatile solvents are suitable. Thus the number of cavities generated increases with an increase in the vapor pressure of the medium. Chivate and Pandit (1993) have confirmed this effect with some polymerization/depolymerization experiments. However increase in the vapour pressure, increases the vapour content of reactants, in many cases inside the cavity, as a result of which the intensity of cavity collapse decreases due to the cushioning effect of the vapour due to continuous vapour phase condensation with increasing pressure. Senthilkumar (1997) has shown for the case of acoustic cavitation that the collapse pressure generated due to the collapse of single cavity decreases with an increase in the vapor pressure and also the lifetime of the transient cavity increases. The same logic can be extended to the case of hydrodynamic cavitation.

The two phenomena explained above, i.e. increase in the number of cavities generated and decrease in the cavitation intensity, are taking place simultaneously and hence it results into a maxima for the cavitation effects at a certain threshold vapour pressure. Bebchuk (cf Flynn, 1964) have reported that the metal erosion (which can be taken as a indirect measure of the overall cavitation effect) was maximum when the vapour pressure of the liquids are in the range between 35 to 80 mm of Hg for numerous liquids such as water, ethyl alcohol, carbon tetrachloride. Mujumdar and Pandit(1998) have indicated a decrease in the yield of fumaric acid with an increase in the medium vapour pressure obtained by using ethanol-water mixtures. Suslick *et al.* (1997) have

also shown that the rate of iodine liberation during the Weissler reaction decreases with an increase in temperature which results in an increase in the vapour pressure of the liquid over the range studied in the experimentation.

Thus in the case of hydrodynamic cavitation, selection of liquid medium depends on the type of application. Certain applications which require less intensity of cavitation events such as cell disruption can be performed with liquids with higher vapour pressures where the number of cavities will increase resulting into higher overall yields of cavitation effects whereas for the case of applications requiring higher intensity of cavitation, lower vapour pressure of liquid will be preferred.

5.2.2 Effect of Liquid Viscosity:

For cavitation to occur in a liquid, it has to overcome its natural cohesive forces maintaining the liquid continuum. Any increase in these forces will tend to increase the threshold pressure required to generate the cavitation event and hence the energy required. If cavitation occurs after overcoming these cohesive forces, the changes in the pressure effects resulting from bubble collapse are not substantial. Table (1) provides the values of threshold pressure for various liquids (Mason, 1988).

Table 1
Effect of viscosity on threshold pressure (Mason, 1988)

Liquid	Viscosity (poise)	Threshold pressure (atm)
Castor Oil	6.3	3.90
Olive Oil	0.84	3.61
Corn Oil	0.63	3.05
Linseed Oil	0.38	2.36
CCl ₄	0.01	1.75

From the table it can be clearly seen that in spite of manifold increase in viscosity between different liquids, the variation in threshold pressure is minimal. Senthilkumar (1997) performed numerical simulations for various viscosity liquids assuming the liquid to be showing Newtonian behavior and found that, with an increase in viscosity, the variation in cavity collapse conditions are not significant. Though viscous fluids generate marginally higher collapse pressure, because of the increased threshold pressure, the

number of cavitation events are reduced and hence the overall macroscopic effect of cavitation is lower for liquids having higher viscosities. For highly viscous non-Newtonian fluids the phenomenon is altogether different and also not promising. Hence the cavitation effect is maximum in low viscosity fluids.

Though the numerical simulations of Senthilkumar (1997) are performed for the case of acoustic cavitation, a similar analogy can be applied to hydrodynamic cavitation due to an analogous behavior of the two types of cavitation.

5.2.3 Effect of Liquid Bulk Temperature:

In general, for chemical reactions conducted by conventional means, it is observed that the reaction rate increases with an increase in the temperature. For reactions which are enhanced by the cavitation process, the above general rule may not hold good. Temperature affects the dynamics of the cavity through the properties of the liquid such as vapour pressure, viscosity, surface tension, gas solubility. Increase in the temperature, increases vapour pressure and reduces the viscosity and surface tension. A rise in temperature reduces the gas solubility which is the chief source of cavity nuclei and reduces the rate of occurrence of cavitation events. Thus the overall number of the cavities formed decreases thereby reducing the efficiency of cavitation phenomena. Variation of vapour pressure with temperature is greater than the variation due to other properties and hence the overall effect is sometimes unpredictable.

Senthilkumar (1997) with numerical simulations for the case of acoustic cavitation has reported that the collapse pressure of a single cavity decreases with an increase in the temperature over the range 10 to 80 °C which is most commonly observed in the cavitation processes. Sivakumar *et al.* (2000) with experiments in dual frequency ultrasonic flowcell for degradation of 2,4 p-nitro phenol have shown that the kinetic rate constants obtained for the reaction decreases with an increase in the temperature from 25 to 45°C. Lorimer *et al.* (1991) and Shirgaonkar and Pandit (1997) have also reported similar experimental observations, again for the case of acoustic cavitation. Again, as said earlier, though the effects have been well established for the sonochemical reactors, as the effect is on the process of cavitation itself and not on the mode of generation, the same analogy would be applicable to the present case of hydrodynamic cavitation. Suslick *et al.* (1997) have also shown that the rates of reaction decreases with an increase in the liquid temperature in the case of microfluidisers which is based on the hydrodynamic means of cavity generation.

5.2.4 Effect of Liquid Phase Surface Tension:

Liquids with the highest values of surface tension such as water experience the maximum cavitation intensity. So aqueous liquids and organic liquids such as glycerol show higher cavitating effect than acetone, ethanol, formamide (Plesset, 1970). Surface tension affects the nucleation stage by controlling the size of the stable gas or vapor nuclei that can be present in the liquid. These nuclei are the weak spots in the liquid which in turn affects the cavitation threshold. For a cavity at stable equilibrium with the surrounding liquid, the pressure inside the cavity is equal to sum of external liquid pressure and surface tension forces. The critical size of a stable nuclei in liquid saturated with a gas is given by:

$$R_c = \sqrt{\frac{3GT}{2\sigma}}$$

where $G = 3 R_g M/4\pi$

The higher the surface tension, the faster will be the dissolution of the gas nuclei into the liquid due to surface tension forces ($2\sigma/R$) and the smaller will be the number of gas nuclei present in the liquid at any instant before being subjected to cavitation. Since these gas nuclei form weak spots in the liquid, it reduces the threshold pressure for cavitation. This can be an important reason for the induction period observed in many aqueous reaction systems. At the start of the process, the nuclei may not be present in sufficient numbers to get any significant impact on cavitation. But during collapse, the cavities become fragmented at high implosive velocities and these fragments can subsequently become nuclei for the next cycle. Thus over a period of time the nuclei become sufficient in number when the maximum cavitation effect is observed. Thus surface tension has an important role in the nucleation process. An increase in surface tension also increases the time gap between subsequent cavitation events due to higher cavitation threshold. The presence of a small amount of surfactant reduces the surface tension and greatly reduces the cavitation threshold.

It should also be noted that the surface tension affects the final collapse pressure though not significantly. During the collapse process, as cavity size reduces, the surface tension forces ($2\sigma/R$) come into the picture as the cavity radius becomes smaller. Hence the collapse becomes more violent and the final collapse temperature and pressures are marginally higher for the liquids having higher surface tension values. Senthilkumar (1997) has clearly illustrated this

fact with numerical simulations of the bubble dynamics. For the liquids commonly used as mediums in cavitation phenomena (surface tension value of $< 0.2\text{N/m}$), there is a marginal increase in the collapse pressure (Figure 16).

Thus for getting maximum benefits from the cavitation phenomena, higher surface tension values should be preferred.

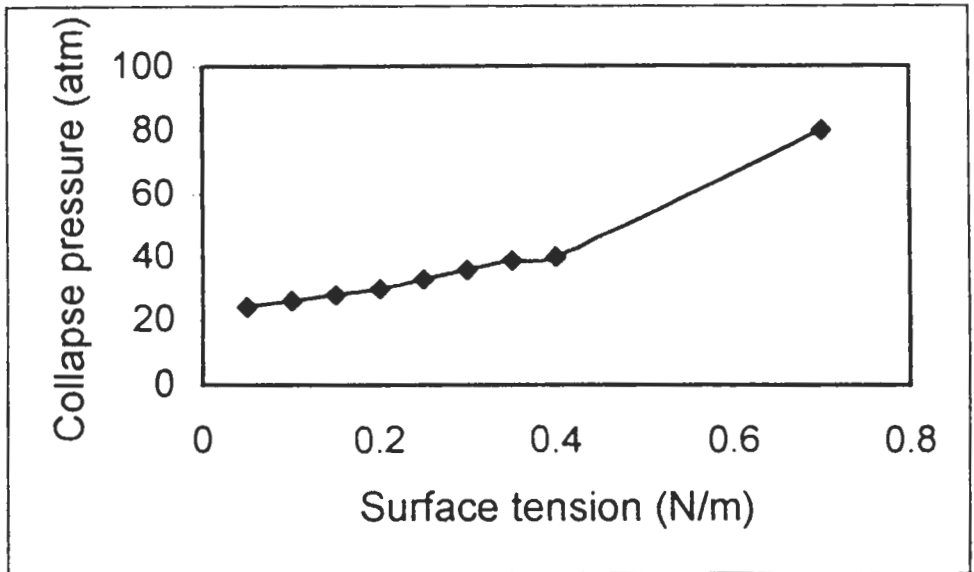


Fig. 16: Effect of surface tension on collapse pressure generated (Senthilkumar, 1997)

5.2.5 Effect of Presence of Dissolved Gases:

The presence of dissolved gases significantly enhances the cavitation effect by supplying the nuclei for the process; in addition, the quantity of the gas inside the cavity significantly affects the final collapse temperature and pressure. Most of the sonochemical reactions are carried out in the presence of gas atmosphere to enhance the sonochemical yield and also the effect of presence of various gases has been well understood (Petrier and Luche, 1987, Petrier *et al.*, 1982, 1984, Hart and Henglein, 1985, Shah *et al.*, 1999). Different properties of the dissolved gases significantly affect the cavitation process.

5.2.5.1 Polytropic constant and thermal conductivity

The nature of the gas and its mole fraction at the beginning of the adiabatic process play an important role in final cavitation effect in terms of temperature and pressure. This can be attributed to polytropic index (n) of the

contents of the cavity, which varies between 1 and γ depending upon the mole fraction and the type of the gas and vapour inside the cavity. The polytropic index is a measure of the heat released during the adiabatic compression of the gas and is responsible for raising the temperature. The larger the amount of gases present inside the bubble than vapour, the higher will be the value of 'n', because gases have a relatively higher value of γ than liquid vapour, and the smaller is the amount of heat released during the adiabatic compression of the collapsing cavity. The dramatic nature of the polytropic effect may be illustrated by considering cavitation in the presence of monotonic gas and a typical polytropic gas such as Freon. The polytropic indices of the two are 1.66 and 1.1 respectively and the maximum temperature for the monotonic gas is about seven times that for Freon (Doraiswamy, 2000). Again among the gases, monoatomic gases such as helium and argon have higher values of γ (1.66) than diatomic gases such as N_2 , O_2 and air (1.2-1.4).

Senthilkumar (1997) has performed simulations for understanding the effects of different gases with varying polytropic constants and Figure 17 shows the results of the simulation for various gases. From the figure, it can be found that the pressure developed during the collapse of the cavity increases with an increase in the polytropic constant. Studies on spectral distribution of the sonoluminescence of water saturated with different gases

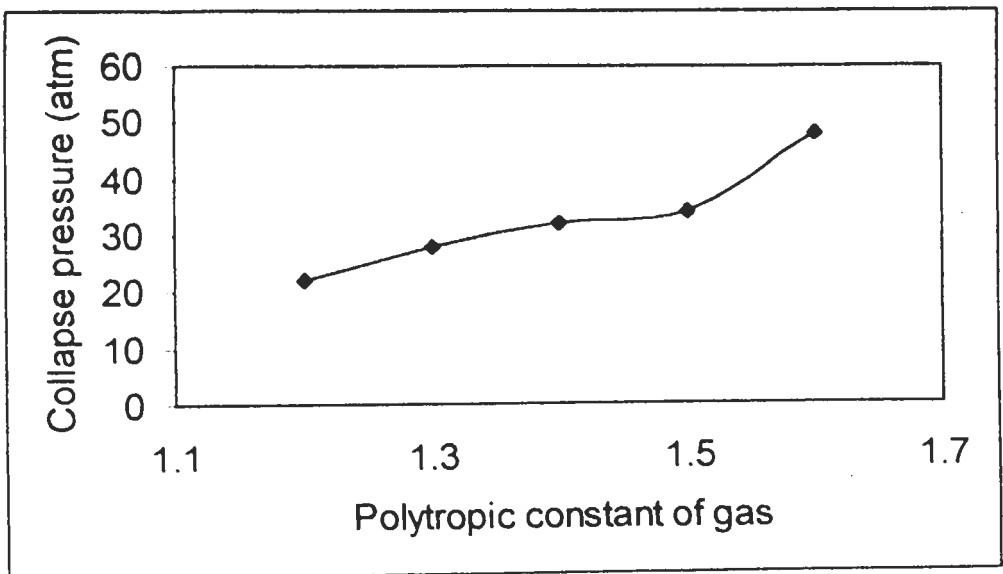


Fig. 17: Effect of polytropic constant of gas on collapse pressure generated (Senthilkumar, 1997)

show that the spectrum was continuous and the spectral distribution closely resembled that of a blackbody radiation of 10,000 K for water saturated with monoatomic gases and 8,800 K for water saturated with diatomic gases (Suslick *et al.*, 1983). Triatomic gases like CO₂ suppress both sonoluminescence and sonochemical reactions. It should be remembered that this dependence on polytropic index is a simplistic view since the extent of the effect will also depend upon the thermal conductivity of the gas. Higher the thermal conductivity of the gas, more is the heat dissipated to the surrounding liquid during the collapse phase and effectively decreasing the final maximum temperature. Hence, the best cavitation effect can be achieved for monoatomic gases such as argon, helium etc. The passage of the monoatomic gas helps to counteract the degassing of the system by the action of cavitation.

5.2.5.2 Gas solubility

Even with gases having the same γ value, the overall cavitation effect may vary due to its dependence on gas solubility. Solubility of gas would alter the number and the size of the nuclei. It is a well established fact that as the gas content decreases the violence of cavitation events increases (Flynn, 1964). The decrease in the intensity at high gas content inside the bubble has also been attributed to the compressibility of gas-vapour mixtures (Plesset, 1970). The greater the solubility of the gas the greater will be the amount which penetrates into the cavitation bubble during the growth phase. Subsequently during the compression phase, redissolution of the gas back into the liquid occurs which essentially reduces the mass contents of the cavity as the collapse progresses and results in the reduced cavitation intensity.

Sometimes, the effect of solubility of gas outweighs that of the polytropic ratio as in carbon disulfide decomposition. The reaction rate in the presence of helium is higher than in the presence of argon, even though $n_{Ar} > n_{He}$ because of the greater solubility of helium than that of argon (Entezari *et al.*, 1997). When hydroxyl radicals are generated and are responsible for the observed reaction, oxygen accelerates the reaction more than a polytropic gas such as argon (Hart and Henglein, 1985, Berlan *et al.*, 1994).

For maximum cavitation effect, the presence of dissolved gas is preferable to the extent of supplying the necessary nuclei for cavitation. But care should be taken while selecting the gas because at these high temperatures, the gases may break into radicals which may alter the

mechanism of the reaction, especially for polyatomic gases. The reactivity of the gas and its solubility should therefore be taken into account.

Senthilkumar *et al.* (2000) have reported a higher cavitation yield for the Weissler reaction in the initial stages of experiment when the liquid medium is saturated with dissolved gases and later, when the deaeration is complete, the reaction rates were found to be much lower.

5.2.6 Effect of Liquid medium constituents

5.2.6.1 Effect of Surfactant and Electrolytes

Even though these compounds are not frequently encountered in reaction systems, their presence in small quantities will significantly affect the cavitation phenomenon. The presence of surfactant lowers the surface tension of the liquid and stabilizes the gas nuclei present in the liquid which otherwise would have redissolved in the liquid under the effect of surface tension forces. Also it 'lubricates' the difficult process of pulling the molecules apart during the cavity generation phase in the cavitation process, thereby facilitating cavitation (Mason, 1991). The presence of surfactant also enhances the coupling property of the liquid, thereby making transfer of the sound energy to the liquid much more efficient, though this factor may not be of much significance in the hydrodynamic cavitation phenomena.

The effect of the presence of the electrolyte is through its decreasing effect on vapour pressure of the solution. Apart from this aspect it does not have a very significant impact. Maximum cavitation intensity for pure distilled water was observed at 40°C. The presence of 3% NaCl in the distilled water enhances this temperature to 60°C (Plesset, 1970). Also it lowers the dissolved gas content which increases the cavitation threshold and might also lower the number of cavitation events due to the lowering of the number of nuclei.

5.2.6.2 Effect of Miscellaneous Constituents of the Liquid

Apart from the above properties of the liquid, certain other constituents present in the liquid affect the cavitation process. They are mentioned below.

1. **Suspended solids:** Suspended solids present in the liquid act as the chief source of nuclei. These solid particles will have entrapped gas in the crevices depending upon the nature of its surface. Thus it reduces the cavitation threshold. But the suspended solids in large quantity can also affect the pump characteristics and overall operation will be critical with some

possible problems of choking or solid particle erosion of the components of the pump.

2. Immiscible liquid phase: The presence of a second immiscible liquid has a significant effect on the cavitation process though studies in literature are restricted to acoustic cavitation. Two significant effects have been observed for the sonochemical reactions (Kumar, 1997). The dispersed phase tends to reduce the number of bubbles per unit volume of the continuous phase because of the sound scattering effect due to the presence of dispersed phase. On the other hand the total number of bubbles tends to increase because of an increasing number of cavities getting generated at the interface (interfacial cavitation). Thus there is an overall increase in the number of cavitation events. This is an important reason for increased iodine liberation when KI solution is sonicated in the presence CCl_4 . A similar observation has also been made by Shirgaonkar and Pandit (1997) with studies on the reaction of degradation of potassium iodide in high pressure homogenizer.

In the above sections, the effect of various physico-chemical properties of liquid has been discussed with possible recommendations for the maximum utilization of cavitation processes and Table 2 summarizes all the discussion about the said effects.

5.3 Effect of the geometry of the constriction

The geometry of the constriction has a crucial effect on both the number of the cavitation events and also the pressure pulse generated due to the collapse of a single cavity. Moreover the geometry affects the pressure distribution and pressure recovery profile downstream of the constriction and hence the active cavitation volume, which is very important considering the global effect of the hydrodynamic cavitation reactor. When orifice plates are used for the generation of the cavitation events, the geometry, in terms of the free area offered for the flow and also the distribution of the same free area in different combinations of number and diameter of the holes, has a significant effect on the intensity of cavitation and the overall pressure pulse generated which is also discussed in detail later.

5.3.1 Effect of the diameter of the constriction

The diameter of the constriction used affects the inception of cavitation. Yan and Thorpe (1990) have shown that the cavitation inception number (defined as the cavitation number for the onset of cavitation process)

Table 2

Effect of liquid phase properties on performance of hydrodynamic cavitation reactors: A summary

S.No.	LIQUID PROPERTY	AFFECTS	FAVORABLE CONDITIONS
1.	Dissolved gas A. Solubility B. Polytropic constant and thermal conductivity	Gas content, nucleation, collapse phase Intensity of cavitation events.	Low solubility Gases with higher polytropic constant and lower thermal conductivity(monatomic gases)
2.	Liquid Vapour pressure	Cavitation threshold, Intensity of cavitation, rate of chemical reaction.	Liquids with low vapour pressures
3.	Viscosity	Transient threshold	Low viscosity
4.	Surface tension	Size of the nuclei (Cavitation threshold)	Low surface tension
5.	Bulk liquid temperature.	Intensity of collapse, rate of the reaction, threshold/nucleation, almost all physical properties.	Optimum value exists, generally lower temperatures are preferable
6.	Surfactants & Electrolytes	Cavitation threshold, reaction kinetics	Case study of each system is necessary to ascertain the exact nature of the effect.
7.	Solid constituents Immiscible liquid phase.	Cavitation threshold/nucleation, Attenuation of sound intensity. Interfacial cavitation, number of bubbles per unit volume, reaction kinetics.	Low concentrations Depends on the nature of the system.

increases with an increase in the diameter of the hole. Thus for larger diameter holes, the cavitation starts at a higher cavitation number; thereby the extent of the cavitation also increases for the same cavitation number in the system (as long as it is below the cavitation inception number) resulting in a higher number of cavitation events occurring during the process. Gogate and Pandit (2000^b) using bubble dynamics simulations have clearly shown that, as the diameter of the hole increases, the collapse pressure generated for a single cavity also goes on increasing (Figure 18). The cavity collapse pressure was found to be proportional to $(d_o)^{2.37}$. It should be noted that the effect of diameter of hole is studied for a constant percentage free flow area occupied by the orifice holes and constant inlet pressure thereby maintaining a constant cavitation number in the system. Thus for the same free area, as you increase the diameter of the hole, the number of holes decreases, thereby decreasing

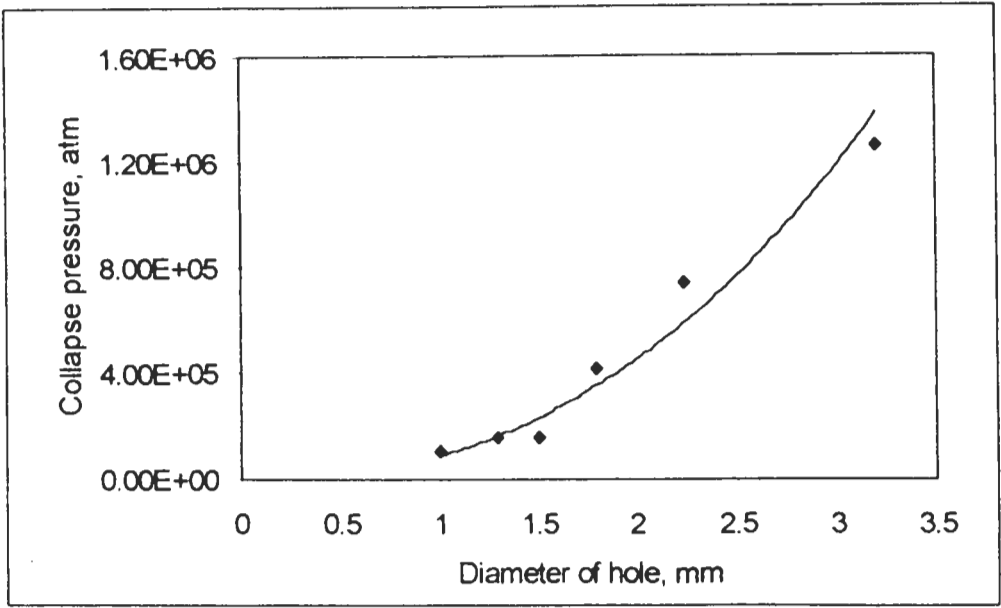


Fig. 18: Effect of hole diameter on orifice plate on the collapse pressure generated using theoretical simulations (Gogate and Pandit, 2000^b)

the number of cavities generated. Thus again an optimization is needed on the basis of desired applications. Vichare *et al.* (2000) have shown that for the same free area, if you increase the diameter of the hole, the rate of iodine liberation in the Weissler reaction decreases (Figure 19). On the other hand,

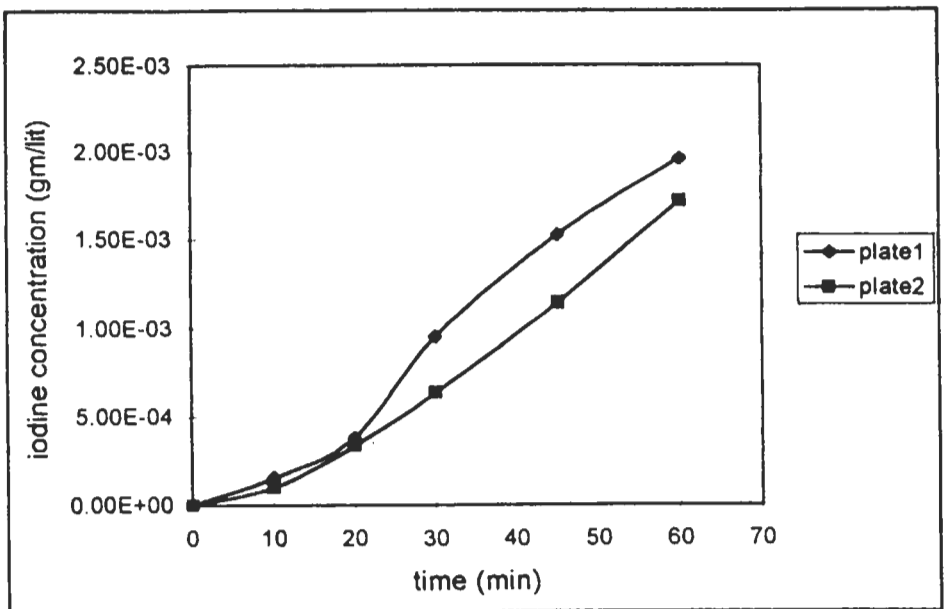


Fig. 19: Effect of diameter of hole for same free area on the iodine liberation (Vichare *et al.*, 2000)

Sivakumar and Pandit (2000) have observed that the rate of destruction of rhodamine B effluent increases with an increase in the diameter of the hole which leads to more intense cavitation (Figure 20). This contradiction in the observed results may be attributed to the fact that degradation of iodine requires comparatively lesser cavitation intensities, and hence, as the number of cavitation events increases with an increase in the number of holes, cavitation yields also increase though the collapse pressure generated due to single cavity collapse decreases. On the other hand, degradation of rhodamine B complex requires higher cavitation collapse intensities, and hence, as the diameter of the hole decreases, the collapse intensities also decrease thereby decreasing the overall cavitation yields.

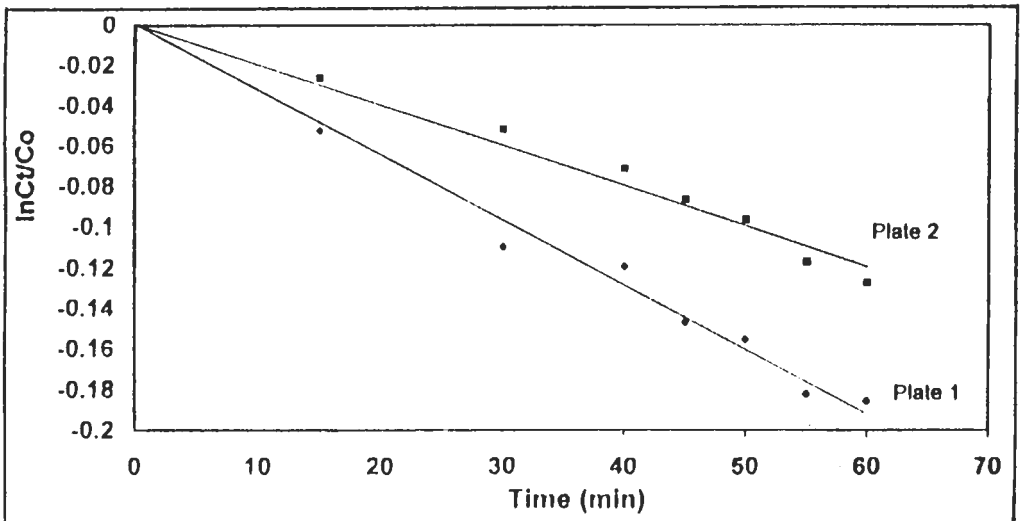


Fig. 20: Effect of hole diameter on the degradation of Rhodamine B for same free area (Sivakumar and Pandit, 2000)

The variation in the collapse pressure with the diameter of holes can also be confirmed from an illustration from the acoustic cavitation. For low frequencies of operation (< 8 kHz), the collapse pressure generated at the time of the collapse increases with the decrease in the frequency (Gogate and Pandit, 2000^b). In the case of hydrodynamic cavitation the typical operating frequencies of turbulence are less than 8 kHz and also for the same free area in the system, the frequency of the turbulence decreases with an increase in the diameter of the hole (Appendix 1). Thus, as illustrated from the acoustic cavitation case, the collapse pressure should increase with decrease in frequency and hence with increase in the diameter of hole. However, it should also be noted that such low frequencies are never used in the acoustic

cavitation. Hence the variation of frequency was studied only in the range of 20 to 200 kHz in the earlier work (Gogate and Pandit, 2000^a) where the collapse pressure was found to increase with an increase in the frequency. This is also a well established fact with a number of experimental illustrations which state that the sono-chemical yield increases with the increase in the frequency of operation (Petrier *et al.*, 1992^a, Petrier *et al.*, 1994), if operating in the ultrasonic range (>20 kHz), whereas the opposite trend has been observed in the case of hydrodynamic cavitation. The numerical scheme does indicate this variation correctly.

5.3.2 Effect of the Free Area for the Flow

The increase in the free area of the orifice results in lower orifice velocity when the mainline flow rate is kept constant resulting in a slower recovery of the pressure downstream of the orifice and also increase in the cavitation number. This results in lower magnitude of the collapse pressure generated during the cavity collapse. Also the cavitation number goes on increasing with the decrease in the orifice velocity resulting into a reduced number of cavities that will be generated in such a system. Thus the quantum of the pressure energy released will decrease with an increase in the free area available for the flow. The effect of free area on the cavitation intensity and hence the yield has been well studied both on the basis of theoretical analysis of the bubble dynamics behavior and also experimentally.

Gogate and Pandit (2000^b) have indicated that the collapse pressure generated by the collapse of cavities decreases with an increase in the percentage free area offered by the holes in the orifice plates (Collapse pressure $\propto A^{-2.55}$, where A is the percentage free area offered for the flow [Figure 21]). Senthilkumar *et al.* (2000) have studied the effect of the free area by using different combinations of holes on the orifice plates. The system used was the decomposition of aqueous potassium iodide resulting in iodine liberation. The extent of iodine liberation was found to be more with the plates where the free area available for the flow is less. To give a quantitative idea, the cavitation yield (defined as the amount of iodine liberated per unit electrical energy supplied to the system) was 4.96×10^{-9} gm/Joule for the flow area of 25.92 mm² whereas it was 3.79×10^{-9} gm/Joule for the flow area of 103.67 mm². Vichare *et al.* (2000) have also obtained similar results for the variation of the cavitation yield with the free area for the flow on the Hydrodynamic cavitation setup of 50 liter capacity (Figure 22).

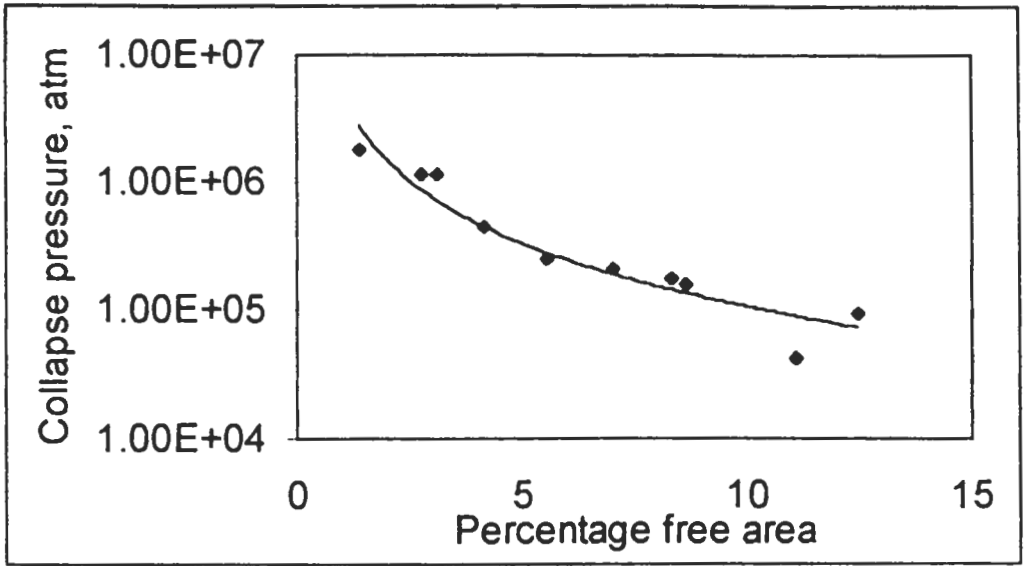


Fig. 21: Effect of percentage free area on the collapse pressure generated (Gogate and Pandit, 2000^b)

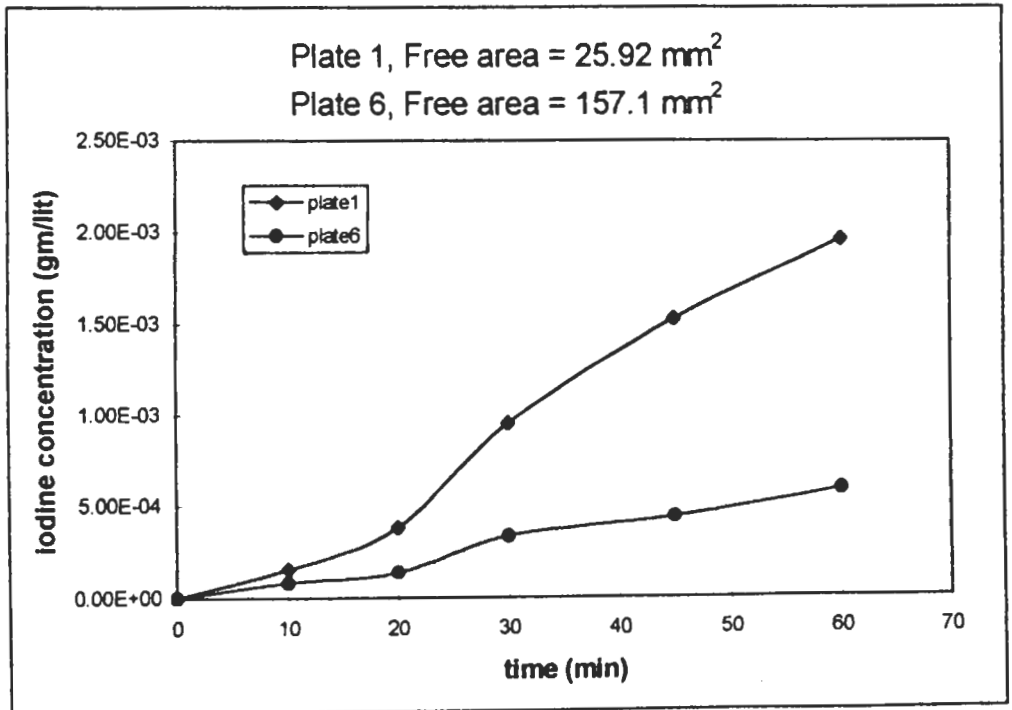


Fig. 22: Effect of percentage free area on the iodine liberation (Vichare *et al.*, 2000)

Thus lower free areas offered for the flow are preferred while designing the hydrodynamic cavitation reactors.

5.4 Effect of Initial Radius of the Nuclei

Although it is difficult to obtain the exact size of the initial nuclei, the vapor pressure of the cavitating medium and the presence of the dissolved gases give an indication of the size of the cavity which will be generated in the system. Gogate and Pandit (2000^b) have indicated that the pressure pulse generated at the time of the collapse increases with the decrease in the initial radius of the nuclei. This effect of the initial radius on the extent of the collapse pressure generated is similar to that obtained for the case of acoustic cavitation (Gogate and Pandit, 2000^a). Moholkar and Pandit (1997) have also indicated that the smaller bubbles contribute significantly to the overall effect of cavitation phenomena.

It should also be noted that the presence of the dissolved gases affects the final value of collapse pressure generated. Due to the dissolved gases in the system, though the initial size of the nuclei is higher (which indicates that the collapse pressure will be lower), the number of the cavities generated will be higher. Thus the total quantum of pressure energy released (number of cavities \times pressure pulse generated by the collapse of a single cavity) may be higher thereby increasing the yield of any reaction. Senthilkumar *et al.* (2000) have indicated this fact with the experiments on decomposition of KI in a 50 liter hydrodynamic cavitation setup with different orifice plates. The decomposition rates were found to be much larger at the beginning of the experiment where the dissolved gases were present in the system. After a stabilization period of 15-20 minutes, complete de-aeration of the system occurs and true kinetics of the aqueous KI decomposition can be obtained showing linear relationship between the time and the iodine yield. Thus, the true effect of the variation of the initial size of the nuclei on the collapse pressure generated will be seen only after the initial stabilization of the system and it should also be noted that the time required for the stabilization varies from system to system.

The effect of initial radius is in reality an indirect effect as there is no direct method by which one can measure and manipulate the initial radius of the nuclei existing in the reactor. While designing, care should be taken to adjust the physical properties of the liquid on the basis of discussion made above for the effect of liquid properties to get the desired range of initial cavity sizes and hence the desired effects in cavitation process.

5.5 Effect of Rotor Speed (Specific to HSH)

The discussion about the effect of rotor speed is specific to the high speed homogenizer type of hydrodynamic cavitation reactors but the effect will be similar to the effect of inlet pressure in the other types of reactors. The cavitation activity is solely affected by the extent of turbulence created by the rotating stator which in turn depends on the energy dissipated by the rotor. An increase in the rotor speed results in a corresponding increase in the energy dissipation though at very high speeds there is a decrease in the energy dissipation due to induction of air. Senthilkumar and Pandit (1999) have shown that the cavity cluster collapse pressure increases with an increase in the rotor speed though the rate of increase at higher speed is less (Figure 8). As the number of cavities also increases with an increase in the rotor speed (Tullis, 1971), the overall effect of cavitation also increases. Senthilkumar and Pandit (1999) have also shown, based on the experimentation with the Weissler reaction, that the rate of iodine liberation increases with an increase in the rotor speed (Figure 8).

It should also be noted at this stage that, similar to an inception point with respect to inlet pressure in high pressure homogenizers or orifice plate hydrodynamic cavitation set-up, there is a critical rotor speed at which inception of the cavitation occurs resulting in significant cavitation effects. Senthilkumar and Pandit (1999) have clearly shown that the iodine liberation rates are significant beyond a critical speed of 8000 rpm. Shirgaonkar *et al.* (1998) have also shown that, though no critical speed exists for the cell disruption application (protein release increases gradually with speed), the rates of protein release are significantly higher at a speed of 10000 rpm as compared to 5000 rpm (about 100-125% more depending on time of operation, Figure 23).

Thus the operation should be within a predetermined range of speed, well above the critical speed for the onset of cavitation but below a certain maximum speed beyond which there is no appreciable increase in the cavitation effects.

5.6 Recommendations for Efficient Design

From the above discussion, regarding the various operating and geometric parameters that critically affect the efficiency of hydrodynamic cavitation reactors, the following useful guidelines/recommendations can be made as

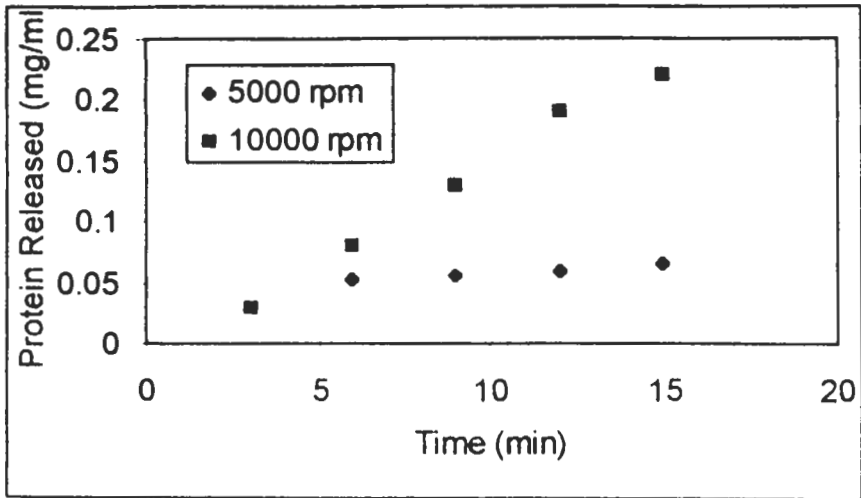


Fig. 23: Comparison of protein release rate at 5000 rpm and 10000 rpm confirming mechanism of disruption (Shirgaonkar *et al.* 1998)

regards their selection:

- 1) Select higher inlet pressures of the system but just below the onset of supercavitation
- 2) Select optimum combination of liquid physical properties based on the recommendations made in Table 2
- 3) Optimize the number and diameter of the holes for the same free area based on the type of applications; smaller number of large diameter for applications which require higher cavitation intensity, e.g., destruction of complex chemicals, and higher number of smaller diameter for applications requiring relatively lower intensities, e.g. cell disruption.
- 4) Design the hydrodynamic cavitation reactor with lower free area for the flow
- 5) Choose speed of rotation in the case of high speed homogenizers much above the critical speed for inception and below the speed where air induction takes place
- 6) Last but not least, adjust the initial size of the nuclei generated by manipulating the liquid properties and the liquid medium constituents.

5.7 Correlations for collapse pressure and cavitation yields

Gogate and Pandit (2000^b) have given a quantitative correlation for the

prediction of the collapse pressures generated as a function of the inlet pressure, initial radius of the nuclei, the diameter of the hole which affects the frequency of turbulence for the same free area and the percentage free area available for the flow which decides the liquid flow rate through the orifice.

$$P_{\text{collapse}} = 7527 (A)^{-2.55} * \{ (P_{\text{in}})^{2.46} (R_o)^{-0.80} (d_o)^{2.37} \} \quad (18)$$

The above correlation uses initial cavity size in mm, inlet pressure in atmospheres and the diameter of the hole in the orifice plate in mm, while the collapse pressure is given in atmospheres and is developed for the following range of parameters,

Initial cavity size = 0.01 to 0.1 mm

Inlet pressure = 1 to 8 atmosphere

Diameter of the orifice = 1 to 10 mm

Percentage free area of the holes = 1-20 %

The collapse has been assumed to be complete when the radius of the cavity becomes equal to or less than 0.1 times the initial radius. The collapse conditions used in the present work are specific to the equation considering the compressibility of medium and simulation techniques used. It should also be noted that the actual values of the pressure pulse will be dependent on the collapse conditions used (bubble wall velocity equal to velocity of sound in the medium or R/R_o ratio equal to 0.4 or 0.05 etc.) as the constant in equation (18) will be affected though the dependencies of the various other parameters (i.e. P_{in} , R_o and d_o) will not be affected by the collapse conditions used in the simulation techniques.

If one compares the exponent over the initial pressure with that over the acoustic intensity (2.46 and -0.17 respectively, Gogate and Pandit, 2000^a), we can see the advantage of the hydrodynamic cavitation. As the driving pressure in the case of the acoustic cavitation is proportional to $I^{1/2}$, the driving pressure dependence on the collapse pressure is very small as against the exponent of 2.46 in the present case. This indicates that the hydrodynamic cavitation converts the fluid pressure energy (driving pressure field) into cavitation collapse pressures much more efficiently than acoustic cavitation. This fact emerges very clearly from the earlier experimental results as well (Save *et al.*, 1997 and Gopalkrishnan, 1997), where the cavitation yield per unit electrical energy consumed is significantly higher in the hydrodynamic cavitation case (almost 3 to 5 times, Senthilkumar *et al.*, 2000).

The exponent over the initial cavity radius also indicates a similar behavior. Lower negative exponent (-0.8 as against -1.88 for acoustic cavitation [Gogate and Pandit, 2000^a]) also indicates a higher contribution to the pressure pulse by the collapsing cavity in the case of hydrodynamic cavitation, indicating higher cavitation efficiency (energy released by the collapsing cavity per unit work done on the cavity for its growth). Independent energy efficiency analysis of a single cavity (Vichare *et al.*, 2000) also supports this conclusion.

Gogate *et al.* (2000^c) have given correlation for cavitation yield with experiments on decomposition of KI in a 50 liter capacity orifice plant set-up, which is given below:

$$\text{Cavitation yield} = 8.834 \times 10^{-11} (P_{\text{collapse}})^{1.1633} \quad (19)$$

It should be noted that the correlation given above is specific to the type of the reaction and the reactor used in the study and should not be taken as a generalized correlation. Based on the studies on laboratory/pilot plant scale equipments, such correlations should be developed for the specific cavitation transformation. Still the work of Gogate *et al.* (2000^c) is pioneering, for the fact that it is the first to depict the pathway for the design of hydrodynamic cavitation reactors by correlating the cavitation yields directly with the collapse pressures generated as a function of various operating and geometric parameters.

There are no other reports where such correlations are given for the prediction of the pressure pulse or the cavitation yields. Thus, correlations given by Gogate and Pandit (2000^b) for the collapse pressure can be used for the design of a hydrodynamic cavitation setup for all kinds of applications using the orifice as the system for generation of hydrodynamic cavitation where rigorous numerical solutions may not be feasible. Credence for this hypothesis is given through the recent work of Tataka (2000) and Tataka and Pandit (2000) for the case of acoustic cavitation, where a clear correspondence is indicated between the reactor yields and the measured pressures in the system.

6 ANALOGY AND COMPARISON WITH ACOUSTIC CAVITATION

6.1 Analogy with Acoustic Cavitation

Acoustic cavitation is the result of passage of ultrasound waves through the medium while hydrodynamic cavitation is the result of the velocity variation in the flow due to the changing geometry of the path of flow such as an orifice or a throttling valve. In spite of this difference in the mechanisms of generation of these two types of cavitation, the bubble behavior shows similar trends with the variation of parameters in both types of cavitation. The two main aspects of bubble behavior in cavitation are:

1) The amplitude of oscillation of cavity/bubble radius, which are reflected in the magnitude of the resultant pressure pulses of the cavity collapse; and

2) The lifetime of the bubble, which is reflected in the distance traveled and hence the extension of the zone of cavitation influence from point of its inception.

Moholkar *et al.* (1999) have studied the effect of operating parameters viz. recovery pressure, time of the recovery and intensity, frequency of irradiation on the cavity behavior in the case of hydrodynamic and acoustic cavitation respectively. From their study, it can be seen that the increase in the frequency of irradiation and reduction in the time of the pressure recovery results in an increment in the lifetime of the cavity whereas amplitudes of cavity oscillations increase with an increase in the intensity of irradiation and the recovery pressure and the rate of recovery. Thus it can be said that the intensity of ultrasound in the case of acoustic cavitation and the recovery pressure in the case of hydrodynamic cavitation are analogous to each other. Similarly, the frequency of the ultrasound and time or rate of pressure recovery are analogous to each other.

Thus it is clear that the hydrodynamic cavitation can also be used for carrying out so called sonochemical transformations and the desired cavitation intensities can be obtained using proper geometric and operating conditions as discussed above.

6.2 Comparison with Acoustic Cavitation Reactors:

Since cavitating conditions identical to acoustic cavitation can be

generated in the hydrodynamic cavitation reactors and hence these can serve as a replacement for sonochemical reactors, it is necessary to compare the hydrodynamic and acoustic cavitation reactors to come to firm conclusions.

Suslick *et al.* (1997) have reported that the acoustic cavitation provides significantly higher rates (compared to the hydrodynamic cavitation) for the Weissler reaction for the specific setup (microfluidiser) used in the experimentation but no quantitative comparisons in terms of energy efficiencies were made. Moholkar *et al.* (1999) have also indicated that cavitation generated using ultrasound is much more intense as compared to that generated by hydrodynamic means. In our earlier work (Gogate *et al.*, 2000^c), the Weissler reaction has been used for the comparison of different cavitation reactors. The important results are reproduced in Table 3 to give readers a quantitative idea. It can be clearly seen from the table that the hydrodynamic cavitation equipments are relatively far more energy efficient and the efficiency increases from HPH (typically a laboratory scale equipment and energy efficiency of 54%) to orifice set up of 50 L capacity (typically a pilot plant scale with observed energy efficiency of 60%). Also the operating scales in the case of hydrodynamic cavitation (capacity of equipment of the order of few liters) are much larger than those in the acoustic cavitation (of the order of a few ml) which indicates that the scale up of hydrodynamic equipment will be much easier as compared to the acoustic equipment where the scale up ratio required will be of the order of a few hundred to a few thousand (for ultrasonic horn). The values of cavitation yields (defined as iodine liberated per unit power density) are found to be higher for the hydrodynamic cavitation reactors as compared to their acoustic counterparts, at least for the model reaction considered in the work. Some earlier studies (Pandit and Joshi, 1993 and Chivate and Pandit, 1993, Save *et al.*, 1994, 1997) also reveal that hydrodynamic cavitation is far more energy efficient than acoustic cavitation.

Thus it can be said from these results that the hydrodynamic cavitation equipment gives better performance than acoustic equipment at industrial scales of operation. It should however be noted that the comparison made here is valid only for a model reaction (decomposition of potassium iodide) and the efficiencies of the various equipments may be different for the variety of cavitation based transformations and also other applications as indicated earlier for the case of the degradation of Rhodamine B in complex dye.

In hydrodynamic cavitation reactors, the cavitation is produced at the shear layer. The liquid vaporized at vena contracta downstream of the orifice

Table 3
Summary of characterization of various equipments used
(Gogate and Pandit, 2000⁶)

Equipment	Electrical consumption (W)	Volume used (ml)	Time of treatment (min)	Actual energy dissipated (W)	Energy efficiency (%)	Iodine concentration at the end of reaction (gm)	Cavitational yield per unit power density gm/(J/ml)
Dakshin horn	240	50	10	7.31	3.04	1.02 E-5	3.53 E-9
Dakshin bath	120	500	10	46.63	38.86	8.4E-5	5.83 E-7
Ace horn	40	50	10	7.77	15.43	1.00E-6	1.39 E-9
	80	50	10	13.42	16.77	7.55E-6	5.25 E-9
	120	50	5	19.08	15.9	5.90E-6	5.48 E-9
Flow Cell	120	1500	15	51.66	43.05	4.47E-5	6.21 E-7
	120	1500	15	32.37	26.97	4.22E-5	5.85 E-7
	240	1500	15	71.14	33	1.31E-4	9.12 E-7
High pressure homogenizer (5000 psi)	2090	2000	30	1136.97	54.4	6.637E-5	7.38 E-5
High speed homogenizer	105	1500	30	45.23	43.07	1.83E-4	6.645 E-7
Pilot plant scale (Orifice plates)	5500	50,000	60	3277	59.58	9.82E-2	2.48 E-4
% free area =2.28%							
% free area =9.14%	5500	50,000	60	3344	60.8	7.50 E-2	1.90 E-4

is proportional to the area of this shear layer. This fact enables a designer to control the bubble population in the flow. By changing the shape of the orifice (making it triangular or hexagonal etc.), the area of shear layer can be varied (obviously it is lowest for a circular orifice) and hence the rate of vaporization and the bubble/cavity population can be controlled. Bubble behavior similar to acoustic cavitation can be obtained in the hydrodynamic cavitation reactor by simple modifications in the orifice design. If a rotating valve is installed instead of a permanent orifice, bubbles formed in the shear layer will experience a sinusoidally varying pressure field rather than a constant or linearly increased one. Also if two or three orifices are installed one after the other at the downstream of the pump then the bubbles that are generated experience a highly fluctuating pressure field and collapse is more and more violent giving rise to high temperatures and pressure pulses of the magnitudes comparable to that under acoustic cavitation. It is also possible that the cavities generated at the upstream orifice or their fragments can act as nuclei for other orifices downstream. Moreover air or steam bubbles of required sizes can be introduced in the flow and the resultant pressure pulse magnitude can be manipulated.

Thus it can be concluded that the hydrodynamic reactors are much more versatile, energy efficient and also amenable to an efficient scale up to meet the industrial scale demands. Since hydrodynamic cavitation reactors use principles of fluid mechanics, a large amount of literature and data is available for the designer to scale up the reactor.

7.0 APPLICATIONS OF HYDRODYNAMIC CAVITATION

7.1 Hydrolysis Reactions

7.1.1 Hydrolysis of fatty oils

Conventional methods of hydrolysis of fatty oils using steam or water require operating temperature between 250 to 350°C and pressures of 3 - 15 atmospheres. Pandit and Joshi (1993) studied the hydrolysis of castor oil and kerdi oil using both acoustic (ultrasonic generator) and hydrodynamic cavitation (in a flow loop at cavitation number less than that required for inception). The experimental setup is a loop reactor with a gate valve, used as a throttling device to cause cavitation. Oil-water mixtures without any

catalyst of different proportions totalling 200 L were subjected to cavitating conditions by circulating the liquid a number of times through the throttling valve with the temperature in the reactor being maintained constant with the help of cooling coils. The extent of hydrolysis was monitored by determining the acid value of the oil-water emulsion in the tank (AOCS: method 39-63). The trends i.e. increase in acid value with time observed for the hydrodynamic cavitation are similar to acoustic cavitation. Thus, the work was first to depict that the flow loops with some constrictions for generation of cavitating conditions produce similar results to that of the acoustic cavitation. It was also found that the energy dissipation required for same degree of hydrolysis using hydrodynamic cavitation (1080 J/ml of emulsion) was 30% lower than acoustic cavitation (1384 J/ml of emulsion). The work also clearly illustrated that the rate of hydrolysis increased when the severity of cavitation was increased (decreasing the cavitation number). The scales of operation in the two cases are also vastly different; 200L for the case of hydrodynamic cavitation whereas 220 ml for ultrasonic irradiation. Thus, simple configuration of the experimental setup and the higher efficiency of the hydraulic devices at larger capacities favors hydrodynamic cavitation for large scale processes.

7.1.2 Cellulose Hydrolysis

A patented process (Zeitsch, 1987) is available for the improved hydrolysis of cellulose or hemicellulose. In the above process, aqueous suspensions are heated to approximately 100°C and fed to a reactor based on hydrodynamic cavitation (details not known). Thus the liquid is subjected to explosive formation of cavitation bubbles (due to higher temperature) which then undergo shocklike condensation, producing intense hydrolysis.

7.2 Cell Disruption Using Hydrodynamic Cavitation

A key factor in economical production of industrially important microbial components is an efficient large scale cell disruption process. For the large scale disruption of microorganisms, mechanical disintegrators such as high-speed agitator bead mills (Limon-Lason *et al.* [cf Save *et al.*, 1994]), industrial scale high pressure homogenizers (Hetherington *et al.*, 1971) are commonly employed. The typical energy efficiencies of the above methods are in the range of 5%-10% and the rest of the energy is dissipated in the form of heat. Much of the research work has been reported in the literature

using the above methods; however, there is no integrated approach for cell disruption. Pioneering studies have been carried out by Harrison and Pandit (1992) in the application of cavitating devices to rupture the microbial cells. These devices require just 5% - 10% of the total energy consumed by conventional methods. Save *et al.* (1994, 1997) studied large scale disruption of microbial cells using hydrodynamic cavitation and compared the performance with conventional methods of cell disruption using mixer-blender and ultrasonication. They concluded that cell disruption is indeed taking place in the large scale hydrodynamic cavitation setups and the energy requirement of hydrodynamic cavitation setup is lower than the other two methods by more than two orders of magnitude for equivalent protein release.

Though cell disruption is one of the most important applications of hydrodynamic cavitation that has been widely studied, certain doubts have been raised. They are,

(1). It has been theoretically predicted that adiabatic collapse of the cavities results in very high temperature and pressure. Large scale chemical effects in hydrodynamic cavitation have been attributed to this phenomenon. If that is the case, will it not deactivate/denature the proteins or enzymes released from the cell?

As pointed out earlier, the intensity of the cavitation phenomenon can be easily controlled by adjusting the operating and geometric parameters in the system. Moreover the mechanism of the cell disruption process is also different depending on the equipment used (Balasundaram, 2000). It can be due to breakage of the individual cells releasing the intracellular enzymes in certain devices or can be shear driven where only cell wall breaks as a result of which the enzymes present at the wall or periplasm will be released (leached slowly). This has been conclusively proven with the location factor studies (Balasundaram and Pandit, 2000) done in a variety of cell disruption equipments. Save *et al.* (1997) studied the activity of the released proteins after disrupting the yeast cells and found that the loss of activity is insignificant (Table 4). One possible explanation can be based on the phenomenon of asymmetric collapse of the cavity near the solid surface (Figure 4) which has been discussed in the earlier sections. Moreover, as the timescales over which these high temperatures and pressures are generated are very small (of the order of nanoseconds), physical effects due to these hot spots are not felt by the enzymes.

Table 4

Effect of hydrodynamic cavitation on fresh actively growing yeast glucosidase activity (Save *et al.*, 1997)

Treatment		Absorbance of supernatant at 400 nm
Pressure (psig)	Time (min)	
0	0	0.047*
45	0.5	0.05
	2.5	0.05
	4.5	0.05
	12.5	0.05
50	1	0.05
	5	0.049

* Activity of the untreated sample

(2). During passage of cell broth through a constriction as in the case of an orifice, a number of forces such as impact, shear, etc., also contribute to the disruption of cells apart from cavitation. So, what is the role of hydrodynamic cavitation in the cell disruption process?

Gopalkrishnan (1997) and Shirgaonkar *et al.* (1998) have conclusively shown that the main mechanism for cell disruption is cavitation. Shirgaonkar *et al.* (1998) have reported that the rates of protein release at 10000 rpm are much higher than at 5000 rpm in a high speed homogenizer. This can be explained on the basis of cavitation inception speed of 8000 rpm reported by Senthilkumar and Pandit (1999) for a high speed homogenizer unit. Thus at 10000 rpm the major contribution to cell disruption is by cavitation and mechanical forces, whereas at 5000 rpm only mechanical forces (shear) are contributing to the overall cell disruption (Figure 23).

Thus use of hydrodynamic cavitation has been conclusively proven for large scale cell disruption applications, that too with much higher energy efficiencies and also a particular reactor can be chosen based on the location of the enzymes in the cells. The work of Balasundaram (2000) and Balasundaram and Pandit (2000) is recommended for the details of the concept of location factor and for the optimization studies for selective intracellular protein release using varying intensity hydrodynamic cavitation.

7.3 Waste water treatment

In an earlier work (Pandit *et al.*, 1999), the advantages of the oxidation technologies over the conventional waste water treatment techniques such as biological, chemical methods etc. have been highlighted. Cavitation can also be used as effective oxidation technology due to the formation of free radicals (especially OH^\bullet) during the process. The application of sonication to waste water treatment is not new to researchers (Cheung *et al.*, 1991, Kotronarou *et al.*, 1991, 1992, Petrier *et al.*, 1992^b, Cheung and Kurup, 1994, Serpone *et al.*, 1994, Hua and Hoffmann, 1997, Hung and Hoffmann, 1998, Weavers and Hoffmann, 1998, Weavers *et al.*, 1998, Pandit *et al.*, 2000, Sivakumar and Pandit, 2000, Gogate *et al.*, 2000^d, Gogate *et al.*, 2000^e). There have been reports which indicate that the sonication alone leads to the formation of lower molecular weight compounds (Kotronarou *et al.*, 1992) and is not an energy efficient treatment method; hence hybrid methods such as SONIWO (Ingale and Mahajani, 1995), sonophotochemical treatment schemes (Shirgaonkar and Pandit, 1998, Gogate *et al.* 2000^e) and sono-electrochemical methods (Trabelsi *et al.*, 1996 and Compton *et al.*, 1997) have been developed.

It has been discussed in the earlier sections that conditions similar to acoustic cavitation can be easily generated using hydrodynamic cavitation reactors. Violent collapse of the cavities in hydrodynamic cavitation systems results in the formation of reactive hydrogen atoms and hydroxyl radicals which recombine to form hydrogen peroxide. Numerous illustrations (Suslick *et al.*, 1997, Senthilkumar, 1997, Shirgaonkar, 1997, Senthilkumar and Pandit, 1999, Vichare *et al.*, 2000, Senthilkumar *et al.*, 2000) can be obtained from the literature where significant liberation of iodine, indicating the formation of OH^\bullet radicals, has been reported with studies on the oxidation of aqueous KI solution using hydrodynamic cavitation at different scales of operation and in different equipments.

However there are not many reports indicating the applications of hydrodynamic cavitation reactors for waste water treatment scheme. Kalumuck and Chahine (1998) have studied destruction of p-nitrophenol in recirculating flow loops using a variety of cavitating jet configurations and operating conditions and shown that, indeed, hydrodynamic cavitation degraded p-nitrophenol. Submerged cavitating liquid jets were found to generate a two order of magnitude increase in energy efficiency compared to the ultrasonic means. Sivakumar and Pandit (2000) have reported that an

orifice plate hydrodynamic cavitation set-up can be used for the destruction of rhodamine B complex in an efficient way as compared to acoustic cavitation. Gogate *et al.* (2000^f) have also highlighted the fact that hydrodynamic cavitation reactors can be effectively used for the waste water treatment. Jyoti and Pandit (2000) have studied disinfection of water using different techniques and reported that hydrodynamic cavitation is an economically attractive alternative compared to techniques such as ozonation and heat sterilization for reducing bacterial counts.

It should also be noted that processes based on the hydrodynamic cavitation can be supplemented by other processes that could supply the necessary amount of oxidizing agents to take care of the pollutant load in the effluent. These processes can be ozonation, oxidation with hydrogen peroxide, and/or UV irradiation. Thus a combination of oxidative processes generally increases the destructive efficiency, while at the same time maintaining the cost effectiveness. Botha (1993) and Botha and Buckley (1994) studied a combination of hydrodynamic cavitation and UV irradiation and reported higher cavitation yields.

There exists one such commercial process, known as the CAV-OX[®] process, developed by Magnum Water Technology Inc., California. This is a hybrid system involving hydrodynamic cavitation, UV irradiation and oxidation with hydrogen peroxide. Several contaminants of concern such as pentachlorophenol (PCP), benzene, toluene, ethyl benzene, xylenes, cyanide, phenol, atrazine have been successfully degraded to a significant extent. Case studies at pilot plant scale showed that the process is effective for a wide variety of effluents obtained from various chemical industries.

7.4 Depolymerization Reactions

Chivate and Pandit (1993) have studied degradation/depolymerization reactions using cavitation, both acoustic and hydrodynamic. The experiments were performed using a throttling valve setup as a means of generating hydrodynamic cavitation and the rate of degradation was followed by measuring the viscosity of the solution by a rotoviscometer. The viscosity of 0.5 weight % CMC solution was found to reduce from an initial value of 30 mPa-s to a final value of 5 mPa-s over 2 hours of cavitating conditions (Fig 24). The rate of the decrease of viscosity i.e. rate of degradation reaction was observed to be a strong function of presence of air in the CMC solution. The presence of air in the solution has been reported to decrease the rate of

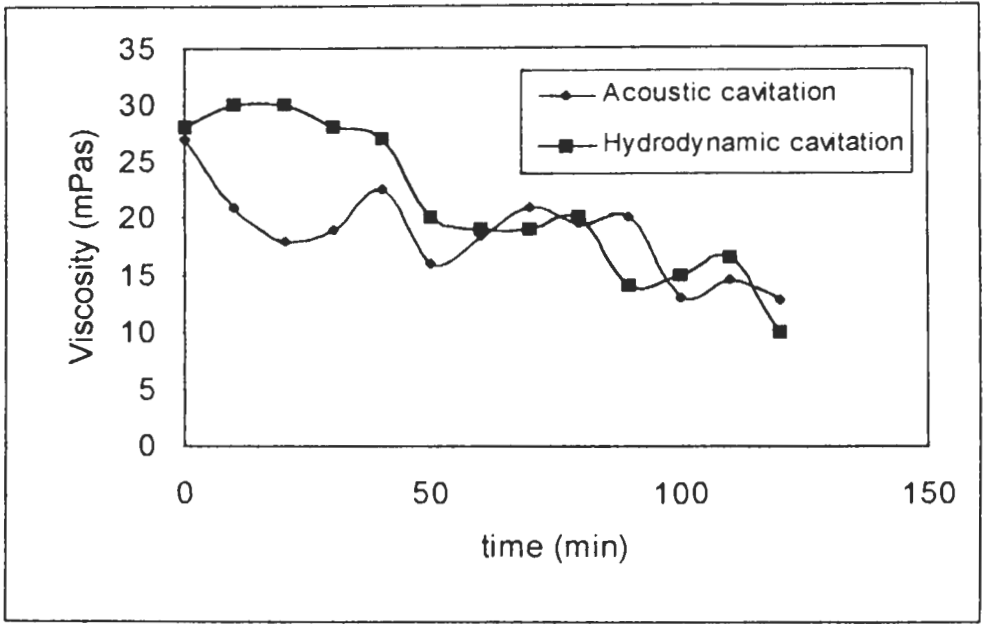


Fig. 24: Effect of acoustic and hydrodynamic cavitation on the degradation of polymers (Chivate and Pandit, 1993)

reaction (less than 5% decrease in viscosity has been observed). This has been attributed to the fact that the presence of air as a second phase and not as a dissolved gas decreases the cavitation intensity in the liquid medium, and also, due to an increase in the compressibility of liquid, some amount of energy released during the collapsing cavity is absorbed by the dispersion. Yan *et al.* (1988) have shown that the measured peak pressure of the collapsing cavity is reduced by at least an order of magnitude when air is introduced in the cavitating flow on the basis of experimental and theoretical studies.

Comparison with acoustic cavitation has also shown that hydrodynamically generated cavitation is far more energy efficient, i.e. 76.5 Joules/ml as against 14337 Joules/ml needed for sonically generated cavitation, for the same degradation process i.e. equivalent viscosity reduction.

7.5 Manufacture of Paper/Pulp

Solonitsyn *et al.*, (1991) have extensively reviewed the beneficial effect of hydrodynamic cavitation in the manufacture of paper from synthetic fibers, in intensification of pulp bleaching, preparation of highly-disperse sizes, and wastepaper de-inking.

One of the important applications of hydrodynamic cavitation that has been commercially exploited is the treatment of suspensions of the fibrous materials in the cavitation devices. Refining of wood pulp is an energy intensive process and in gross this accounts for one-third of the energy consumption in the pulp industry. The quality of the refined pulp has a strong bearing on the efficiency of the downstream processes such as bleaching. Danforth (1986) has introduced the concept of impact intensity in the refining theory, showing that the number of impacts received by the fibers during the refining process critically affects the pulp quality.

The formation of microjets due to the collapse of the cavities near the fibre surface results in conditions analogous to impact forces experienced in conventional refiners. The mechanism of deformation of the wood pulp can be described in terms of increased capillary and swellability of the amorphous regions. On dewatering, these fibers form a dense stock, having strong interfibrillar bonds, which result in enhanced bursting strength of sheets made from such fibres. It has been reported that hypochlorite bleaching rate of sulfite pulp at 20°-60° increased by 7- 9 fold after cavitation treatment and with increasing the bleaching temperature to 60°C and decreasing the final pH level to 7.0-8.0 (Solonitsyn *et al.*, 1987). The cavitation treated hypochlorite bleached pulp had increased tensile strength and brightness rating.

Defibration of waste paper under intense hydrodynamic cavitation in continuous setup gave pulp with higher fibre strength, lower amount of crill and a higher retention of water by fibers than common defibration of waste paper in defibrators equipped with knives (Solonitsyn *et al.*, 1987). IR spectra showed an 8-10% increase in the amount of OH^{*} groups, as well as amorphisation of cellulose in pulp obtained by cavitation defibration. The pulp could be easily dewatered and the resultant paper made was relatively strong.

7.6 Miscellaneous Applications

There are several applications already developed on a laboratory scale which have received little attention industrially. The following are a few such potential uses of hydrodynamically generated cavitation which can be commercially exploited.

7.6.1 Flotation cells

Zhou *et al.* (1997^a) and Rao *et al.* (1998) have highlighted the beneficial effects on the flotation kinetics using experiments on fine silica and zinc sulfide precipitates. One contributing factor to the high flotation kinetics can be the *in-situ* bubble formation by hydrodynamic cavitation on hydrophobic particles. Hu *et al.* (1998), using numerical procedures developed for solving the turbulent kinetic energy/dissipation rate model with boundary fitted coordinates, have shown that the cavitation occurs at a pressure drop below ~10 m water. The bubble formation results in particle aggregation through gas nucleus bridging with the consequently larger particles having a higher collection rate. Further, the presence of surfactants and dissolved gas was found to preserve the bubbles generated by cavitation, thus producing more small bubbles.

Zhou *et al.* (1997^b) have also studied the effect of a hydrodynamic cavitation reactor on the flotation performance of a conventional flotation cell in the Matte Sepn. Plant at Copper Cliff, Inco Ltd., Sudbury, on a larger scale of operation. Samples drawn from the feed to the rougher and first cleaner were tested in a portable continuous mini flotation cell. The use of the reactor improved flotation kinetics on both the samples. The effect on selectivity was mixed: it improved for the cleaner feed, but some decline was observed for the rougher feed. The present test work, although limited, illustrates that the reactor offers the potential benefit of increasing circuit capacity while maintaining selectivity. Additional test work is required to define fully the potential of the reactor.

7.6.2 Dental water irrigator employing hydrodynamic cavitation.

Cox (1999) has recently invented a dental water irrigator employing hydrodynamic cavitation whereby the individual manipulates the handpiece of the irrigator to wash his teeth with cavitated water. A handpiece has an inbuilt cavitation orifice. A pump supplies water from a reservoir through the cavitation orifice to produce cavitation in the water downstream from the orifice generating OH[•] radicals and ions in the water flow. The water flow is directed onto dental surfaces. The OH[•] radicals and ions have been proven effective against bacterium. The arrangement used in this application is quite similar to the closed loop orifice plate set-up used for carrying out complex chemical reactions (Vichare *et al.*, 2000, Senthilkumar *et al.*, 2000).

7.6.3 Synthesis of nanocrystalline materials

Though research on hydrodynamic cavitation has been carried out by a few groups worldwide, the recent interest on the topic arose after the publication of their findings by Moser *et al.* (1995^{a,b}). They applied hydrodynamic cavitation generated by a microfluidiser for the synthesis of a large variety of catalysts in the form of nanometer sized grains. The grains agglomerated into particles of 100 nm to a few microns. This process was found to provide high purity catalysts containing several metal ions not found in classical synthetic methods.

Sunstrom *et al.* (1996) have also used hydrodynamic cavitation generated with the use of a high-pressure fluid system, for the generation of the nanocrystalline oxides. The precipitant stream is subjected to a large pressure drop (21,000 psi ambient) across a patented geometry interaction chamber. Due to the large pressure drops, bubbles are formed and collapse, causing localized heating of the solvent. In addition, the precipitate undergoes a high degree of mechanical shear in the interaction chamber, leading to nanosize particles.

This technique of hydrodynamic cavitation offers a good route to the synthesis of homogeneous solid solutions of complex catalysts, where one attempts to understand the relation between ion modification of a host and catalytic performance. Moser *et al.* (1996) have reported the use of larger scale equipment with capacities of 400-2000 kg/h depending on the desired intensity of the cavitation effect.

7.6.4 Preparation of high quality quartz sands

The quality of the quartz sands used for crystal glass manufacture was improved using hydrodynamic cavitation (Zuchenko *et al.*, 1977). In this study, high quality of quartz sands containing 0.04%(avg.) Fe was examined. The residence time of the suspension in the reactor was 16.8 seconds. The reactor was fabricated using non-metallic materials such as ceramics, to avoid contamination of iron. The possibility of decreasing the content of iron oxides in quartz sands to 0.01 % was demonstrated at pilot plant scale.

7.6.5 Preparation of free disperse system using liquid hydrocarbons

Recent work by the group of Kozyuk (Kozyuk, 1996, 1998, 1999 and Kozyuk *et al.*, 1996) has illustrated the use of hydrodynamic cavitation for obtaining free disperse system in liquids, particularly in liquid hydrocarbons. It has been found that, by following the above method, there is substantial

improvement in the quality of the obtained free dispersion, even in the absence of any catalyst. Also the geometry of a flow-constricting baffle body (Kozyuk, 1996) effectively increases the degree of cavitation to improve substantially the quality of obtained free disperse system. This fact is also confirmed by the discussion made earlier regarding the effect of various design parameters on the performance of hydrodynamic cavitation reactors.

Kravets (1996) has also patented a process for the production of liquid emulsion systems or suspensions using a hydrodynamic cavitation field. The liquid stream is passed through a housing comprising two end chambers separated by a confusor, a middle section with a cavitator in the shape of an open hollow truncated cone positioned with its axis along the axis of the flow line, and a diffusor. The first chamber also contains a cone cavitator. Liquid from the second chamber can be recycled to the first chamber for repeated passage through the cavitation field. Again the system is similar to the orifice plate set-up where there is provision for recirculating the liquid through the cavitating zone number of times.

A few additional applications of hydrodynamic cavitation can be cited as:

- 1) Implementation of hydrodynamic cavitation equipment to decrease viscosity of fuel oils (Bulgakov *et al.*, 1998)
- 2) Improvement in the quality of clinker in raw processing (Sulimenko and Krivoborodov, 1997)

Thus, use of hydrodynamic cavitation to disrupt yeast cells, hydrolyze fatty oils, decompose KI, degrade polymeric solutions and treat waste water has been well proven on a pilot plant scale and some more potential uses have been highlighted in the above discussion. These results can serve as a basis for development of commercial scale reactors for treating large quantities of reactants or mixtures on a continuous basis. A few reactions that can be carried out using hydrodynamic cavitation (Shah *et al.*, 1999) have been given in Table 5 However, its commercialization and use for a number of other important reactions need to be explored.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Hydraulic devices with simple constrictions such as throttling valve, venturi, and orifice in the flow loop can be used to generate cavitating conditions similar to that generated by the effect of the passage of ultrasound in the liquid medium. The intensity of collapsing cavities can be controlled

Table 5

Chemical reactions which can carried out using hydrodynamic cavitation
(Shah *et al.*, 1999)

Description process	Temperature (°C)	Pressure (atm)
Hydrolysis of fatty oils such as Kerdi Oil etc.	250-300	3-15
Cyclohexane formation by hydrogenation of benzene	170-230	25
Tetralin preparation by hydrogenation of naphthalene	400	25-30
Hydrogenation of mesityl oxide followed by its reduction to MIBK and further reduction to 4 methyl pentane-2-ol	step (1) = 30, step (2) = 50, step (3) = 150-200	step (1) = 1, step (2) = 3, step (3) = 10
Sorbitol production by large scale hydrogenation of D-glucose	140	30-70
Nitrobenzene to aniline reduction by hydrogenation with catalyst	300-475	5-15

by using different geometries or types of the constrictions.

Cavity dynamics studies, i.e. the behavior of cavity with time and location under the influence of varying pressure fields, are very important for fundamental understanding of the hydrodynamic cavitation phenomena. Various considerations such as the effect of turbulence, the effect of compressibility of the medium, single cavity or cluster of cavity, different types of eddy such as Prandtl eddy etc., bubbly flow with bubble/bubble and bubble/liquid interactions, critically affect the bubble dynamics and hence must be considered for the estimation of the magnitude of the collapse pressures and temperatures. The work of Gogate and Pandit (2000) is recommended for the bubble dynamics analysis in orifice plate type of reactors along with the work of Naidu *et al.* (1994) and Sochard *et al.* (1998) for the calculation of number of cavities existing downstream of the orifice.

In the case of venturi or high speed homogenizer type of reactors, the work of Senthilkumar and Pandit (1999) which considers clusters of cavities, is recommended as a starting point for any further studies.

The orifice plate type of set-up offers tremendous flexibility in terms of operation and construction among the various reactors discussed in the present work. The type of orifice plate in terms of difference in number and diameter of holes on the plate and also the number of orifice plates itself in the flow loop can be changed in order to achieve desired degree of turbulence depending on the type of the applications. Hydrodynamic cavitation reactors also allow introduction of air at the constriction for enhancing the rates of oxidation reactions. Scale-up of such units is much easier as knowledge regarding the hydrodynamic conditions existing downstream of the orifice is easily available in the literature or through modern CFD codes and also due to the fact that pumps offer higher energy efficiency at larger scales.

The important parameters that affect the collapse pressures generated and hence the overall cavitation yield are found to be inlet pressure/speed of rotation (specific to HSH), physico-chemical properties of liquid medium, constituents of liquid, geometry of the holes (number and diameter of the holes) on the orifice plate and initial radius of the nuclei. These must be properly selected or manipulated while designing the reactors based on the guidelines given in the present work for achieving maximum benefits from the cavitation phenomena. The work of Gogate and Pandit (2000) is recommended for a quantitative estimation of pressure generated at the collapse of cavities and its effect on the overall cavitation yield from the reactor.

Hydrodynamic cavitation reactors are much more energy efficient as compared to their acoustic counterparts, at least for the applications discussed in the current work, and also can be operated at a larger scale. This fact has been conclusively illustrated in the article on the basis of various experimental studies described earlier such as hydrolysis of fatty oils (Pandit and Joshi, 1993), cell disruptions (Harrison and Pandit, 1992, Save *et al.*, 1994, 1997, Shirgaonkar *et al.*, 1998), decomposition of KI (Senthilkumar *et al.*, 2000, Gogate *et al.*, 2000^c, Suslick *et al.*, 1997) and destruction of rhodamine B complex (Sivakumar and Pandit, 2000). Scale up potential for these types of reactors is also very good.

The various applications of hydrodynamic cavitation reactors are presently at bench scale but further research can necessarily transfer these into commercial scales. Moreover, hydrodynamic cavitation offers

possibilities of using it in combination with other techniques such as ultrasonic irradiation (some preliminary work in this direction has already been started in our department), photocatalysis, use of the concepts of electrochemistry etc.

Although much work needs to be done in this area (a few suggestions have been made later), it is quite clear that hydrodynamic cavitation reactors will turn out to be an efficient option to replace sonic reactors in the long run and at least for some industrial applications. After observing the splendid performance of these reactors at lab scale and pilot plant scale, we feel confident that both the sonochemists and industrialists will have hydrodynamic cavitation reactors as a viable option for the conduction of high pressure and high temperature reactions or for demonstrating the sonochemical effects.

9.0 SUGGESTIONS FOR FUTURE WORK

The issues and aspects of hydrodynamic cavitation discussed earlier point out the following gray areas which require exhaustive further study. The work necessary to translate this lab technique into technology can be split-up into two broad areas viz. firstly theoretical analysis to develop the fundamentals and second, experimental studies to establish pathways for transferring the fundamental knowledge into practice.

Unlike the field of sono-chemistry, which started as a chemist's fantasy transformed to reality in the lab, the phenomenon of hydrodynamic cavitation has been in existence in the real systems for a much longer period although all the work was concentrated at avoiding cavitation in hydraulic devices till recent years. The earlier efforts of suppressing this phenomenon now need to focus on controlling it to harness its effects in a positive way.

On the theoretical front the issues which need to be studied are as follows;

1) Realistic modelling of the turbulence phenomena which then can be used to model the cavity/bubble dynamics either in isolation or in the form of cavity clusters in high velocity flow. The modern sophisticated CFD codes can be employed to get the flow field information i.e., mean and fluctuating velocity components, Reynolds stresses, turbulent pressure fluctuations etc. This, then can be used to understand the role of these flow field parameters in altering the cavity dynamics.

2) A major area of research should now concentrate on establishment of

the relationship or correspondence between the predicted cavity/bubble/cluster dynamics and the chemistry associated with such a cavity behavior. Such an exercise has been done in the case of acoustic cavitation (Kamath *et al.*, 1993, Naidu *et al.*, 1994, Sochard *et al.*, 1998, Storey and Szeri, 1999, 2000) but no such attempt is available in the literature in the case of hydrodynamic cavitation. Thus till such a relationship, based on thermodynamic principles, is developed, one has to resort to empirical relationships developed in the literature (Gogate and Pandit, 2000^b, Gogate *et al.*, 2000^c). This necessarily involves experimentation with these specific chemical systems along with the theoretical study of cavity/bubble dynamics, which is expensive and time consuming.

3) It is necessary to develop user friendly computer codes (similar to modern CFD codes) for the use of engineers, which will allow them to change the geometrical and operating parameters of the hydrodynamic cavitation set-up, define physico-chemical properties of the chemical system under consideration. These codes, with the help of bubble/cavity dynamics and the equilibrium chemistry at cavity collapse conditions, will then predict the expected chemical effects, avoiding a trial and error type of experimentation for the engineers.

Efforts required on the experimental front are as follows;

1) Design and fabrication of different types of hydrodynamic cavitation set-up differing in flow field, turbulence characteristics and geometry to study their effect on cavity/bubble/cluster dynamics. Sophisticated measuring techniques such as Laser Doppler anemometry, hydrophones, and cavity luminescence spectral measurement need to be adapted for fast flowing cavities/clusters to be able to measure the magnitudes of cavity/cluster oscillations/collapse pressure pulse and temperature generated and the identification of the intermediate chemical species along with their concentrations.

2) Experiments are needed on different scales of operation to understand and address the scale up issues, such as alteration in the flow field and turbulence characteristics due to the scale of operation.

3) Experiments are also required to study the various chemical systems and to study the physico-chemical transformations occurring due to the cavity/cluster behavior and the ease of manipulation of the same in terms of alteration of flow-field to achieve desired transformation with maximum energy efficiencies.

The studies discussed above should allow the engineers to compute the following quantities:

- i) The type of cavity/cluster dynamic behavior required to bring about the desired physico-chemical transformation.
- ii) The parameters and their magnitude manipulation required to bring about the desired cavity/cluster dynamic behavior.
- iii) The type of equipment including the geometrical configuration required to make the cavity/cluster behave in a required manner most energy efficiently and,
- iv) The energy efficiency of such a cavitation transformation process, which can then be compared with the conventional transformation processes.

The above four steps are the essential steps required in any process selection/optimization. The information and design procedures for the individual steps (with some gaps as outlined before) are available in the literature but an integrated design approach is necessary.

The development of such an integrated equipment design procedure should be the final aim of such an exercise.

APPENDIX 1: CALCULATION OF FREQUENCY OF TURBULENCE

- 1) Assume a typical cavitation number = 1
- 2) For a typical inlet pressure of 3 atm and standard solvent vapour pressure, orifice velocity can be obtained as = 24.08 m/s from the definition of cavitation number
- 3) Pipe velocity = 6.12 m/s obtained from orifice to pipe diameter ratio
- 4) Pressure recovery time = 0.0257 s as obtained from the typical pressure recovery profile downstream of the orifice (Moholkar and Pandit, 1997, Gogate and Pandit, 2000^a)
- 5) Length scale of the eddy = 3.048×10^{-3} m/s obtained from the equation

$$l = 0.08 (d_p + d_x) / 2$$

where d_p is the diameter of pipe and d_x is the diameter of the constriction i.e. orifice hole in the present case.

- 6) Power input for unit mass of the cavitating liquid = 15855 W/kg as obtained from the equation:

$$\text{Power/mass} = (\Delta P_{\text{permanent}}) (\text{volumetric liquid flow rate}) / (\text{Density}) \\ (\text{active cavitation volume})$$

7) Turbulent fluctuating velocity = 3.39 m/s obtained from the correlation

$$\text{Velocity} = (\text{Power/mass} \times \text{eddy length scale})^\alpha$$

8) Frequency of turbulent pressure variations = (velocity / eddy length scale) = 1.12 kHz

With increase in the diameter of the orifice for the same free flow area, the eddy length scale increases with all other parameters remaining the same and hence frequency of turbulence decreases (proportional to (eddy length scale)^{-2/3})

Thus it is clear that the frequency of turbulence is of the order of few kHz and moreover it decreases with an increase in the diameter of the hole.

10.0 NOMENCLATURE

a_0	Size of the individual cavity in the cluster (m)
A	Percentage free area offered for the flow
C	Velocity of sound in the medium (m/s)
C_v	Cavitation number
C_{vi}	Cavitation inception number
d	Diameter of the impeller (m)
d_c	Diameter of conduit (m)
d_v	Diameter of the venturi throat (m)
d_p	Pipe diameter (m)
d_o	Orifice diameter (m)
f	Frequency of turbulence (Hz)
I	Intensity of ultrasonic irradiation (w/m^2)
l	Eddy length scale (m)
Δl	Mean cavity spacing (m)
L	Length of the expansion section of the venturi (m)
M	Molecular weight of the dissolved gas (gm)
N	Speed of rotation (rps)
ΔP	Permanent pressure drop across the constriction (N/m^2)
P_2	Fully recovered downstream pressure (N/m^2)
$P_{collapse}$	Pressure pulse generated at the collapse of cavity (N/m^2)
P_i	Pressure inside the bubble (N/m^2)
P_{in}	Inlet pressure into the system (N/m^2)
P, P_t , P_x	Pressure in the liquid at any distance from constriction (N/m^2)

$P_{4(t)}$	Time varying pressure field a60 downstream of the orifice (N/m^2)
$\dot{P}_{4(t)}$	Rate of change of pressure downstream of the orifice (N/m^2)
$P_{1(t=R)}$	and $P_{1(t=R)}$ Instantaneous pressure values downstream of the pressure during two integration step of time t sec
P_{go}	Initial gas pressure (N/m^2)
P_m	Power per unit mass (w/Kg)
P_v	Vapor pressure of the medium (N/m^2)
R	Radius of bubble/cavity at any time (m)
R_c	Critical radius of the bubble (m)
\ddot{R}	Bubble wall acceleration (m/s^2)
R_g	Gas constant
R_o	Initial radius of the bubble/cavity (m)
S, \dot{R}	Bubble wall velocity (m/s)
t	Time (s)
T	Liquid bulk temperature ($^{\circ}C$)
v_{th}	Velocity at the throat of the constriction (m/s)
V_m	Instantaneous velocity downstream of the orifice (m/s)
V_o	Orifice velocity (m/s)
V_t	Local mean velocity (m/s)
V'	Instantaneous fluctuating component of velocity (m/s)

Greek Letters:

ρ	Density of liquid (Kg/m^3)
σ	Surface tension of medium (N/m)
μ	Viscosity of medium (Ns/m^2)
τ	Pressure recovery time (s)
γ	Energy conservation factor
β	Void fraction
β'	Ratio of pipe to orifice diameter

11.0 REFERENCES

1. Balasundaram, B., 2000, "Studies in cell disruption", *M.Sc.Tech. Thesis*, University of Mumbai, Mumbai, India.
2. Balasundaram, B. and Pandit, A.B., 2000, "Significance of location of enzymes on their release during microbial cell disruption", *Biotech. Bioengg.*, submitted for publication .
3. Berlan, M.J. and Mason, T.J., 1992, "Sonochemistry from research laboratories to industrial plants", *Ultrasonics*, **30**, 203-212.
4. Berlan, J., Trabelsi, F. and Delmas, H., 1994, "Oxidative degradation of phenol in liquid media using ultrasound", *Ultrason. Sonochem.*, **1(2)**, S97.
5. Botha, C.J., 1993, "A study on hydrodynamic cavitation as a method of water treatment" *MS Thesis*, Univ. of Natal, Durban, South Africa.
6. Botha, C. J. and Buckley, C. A. , 1994, "Disinfection of potable water: The role of hydrodynamic cavitation", *Water Supply*, **13(2)**, *IWSA International Specialized Conference on Disinfection of Potable Water, 1994*), 219.
7. Bulgakov, B. B., Bulgakov, A. B., Bulkin, Yu. P., Presnov, G. B., Bykov, S.A., Dobronogov, V. G., Kirnitskii, V. V. and Kuzina, N. N., 1998, "Implementation of hydrodynamic cavitation equipment to decrease viscosity of fuel oils", *Elektr. Stn.*, **5**, 37.
8. CAV-OX[®] Cavitation Oxidation Process, 1994, Application Analysis Report, Magnum Water Technology, Inc., Risk Reduction Engg. Laboratory, Office of Research and Development, U.S.E.P.A., Cincinnati, Ohio 45268..
9. Cheung, H.M. and Kurup, S., 1994, Sonochemical destruction of CFC 11 and CFC 113 in dilute aqueous solution, *Env. Sci. Tech.*, **28**, 1619.
10. Cheung, H.M., Bhatnagar, A. and Jansen, G., 1991, "Sonochemical destruction of chlorinated hydrocarbons in diluted aqueous solutions", *Env. Sci. Tech.*, **25**, 1510.
11. Chivate, M.M and Pandit, A.B., 1993, "Effect of hydrodynamic and sonic cavitation on aqueous polymeric solutions", *Ind. Chem. Engr.*, **35** (1,2), 52.
12. Compton, R. G., Eklund, J. C., Marken, F., Rebbitt, T. O., Akkermans, R. P., Waller, D.N., 1997, "Dual activation: coupling

- ultrasound to electrochemistry-an overview”, *Electrochim. Acta*, **42** (19), 2919.
13. Cox, D. W., 1999, “Dental irrigator employing hydrodynamic cavitation” U.S. Patent number US 5860942 A, 19 Jan 1999, 7 pp..
 14. Danforth, D.N., 1986, Effect of Refining Parameters on Paper Properties, *Proc. Intl. Conf. New Technologies in Refining*, **Vol.2**, PIRA, Birmingham, England, Dec 9-11.
 15. Doraiswamy, L.K., 2000, “Sonoorganic Synthesis Engineering”, Personal Communication.
 16. Entezari, M.H., Kruus, P. and Otson, R., 1997, “The effect of frequency on sonochemical reactions III: Dissociation of carbon disulfide”, *Ultrason. Sonochem.*, **4**, 49.
 17. Flynn, H.G., 1964, “Physics of acoustic cavitation in liquids” in *Physical Acoustics* (Ed. Mason, W.P.), Academic Press, New York, USA, 57.
 18. Gareth, L.C. and Danver, E.I., 1996, “The disruption of microbial cells by hydrodynamic and ultrasonic cavitation”, *Project Report*, University of Capetown, Capetown, South Africa.
 19. Gogate, P.R. and Pandit, A.B., 2000^a, “Engineering design methods for cavitation reactors I: Sonochemical reactors”, *AIChE Jrnl.*, **46**(2), 372.
 20. Gogate, P.R. and Pandit, A.B., 2000^b, “Engineering design methods for cavitation reactors II: Hydrodynamic cavitation reactors”, *AIChE Jrnl.*, **46**(8), 1641.
 21. Gogate, P.R., Shirgaonkar, I.Z., Sivakumar, M., Senthilkumar, P., Vichare, N.P and Pandit, A.B., 2000^c, “Cavitation reactors: Efficiency analysis using a model reaction”, *AIChE Jrnl.*, Submitted for publication.
 22. Gogate, P.R., Mujumdar, S. and Pandit, A.B., 2000^d, “Sonochemical reactors for waste water treatment”, *AIChE Annual Meeting*, Los Angeles, USA, Accepted for presentation.
 23. Gogate, P.R., Mujumdar, S., Shirgaonkar, I.Z. and Pandit, A.B., 2000^e, “Sonophotochemical Reactors for Waste Water Treatment”, *NASCRE I*, Houston, TX, USA, Accepted for Presentation.
 24. Gogate, P.R., Sivakumar, M. and Pandit, A.B., 2000^f, “Hydrodynamic Cavitation reactors: A techno-economically viable alternative”, *NASCRE I*, Houston, TX, USA, Accepted for Presentation.

25. Gopalkrishnan, J., 1997, "Cell disruption and enzyme recovery", *M.Sc. Tech. Thesis*, University of Mumbai, Mumbai, India.
26. Hansson, I., Morch, K.A. and Preece, C.M., 1977, "A comparison of ultrasonically generated cavitation erosion and natural flow cavitation erosion", *Proc. of Ultrasonics Intl. Conf.*, Brighton, U.K., 267 .
27. Hansson, I. and Morch, K.A., 1980, The dynamics of cavity clusters in ultrasonic (vibratory) cavitation erosion, *J. Appl. Phys.*, **51**(9), 4651.
28. Harrison, S.T.L. and Pandit, A.B., 1992, "The disruption of microbial cells by hydrodynamic cavitation", *Proceedings of 9th Int. Biotech. Symp.*, Washington, USA.
29. Hart, E.J. and Henglein, A., 1985, "Free radical and free atom reactions in the sonolysis of aqueous iodide and formate solution, *J. Phys. Chem.*, **89**, 4342.
30. Henglein, A., 1995, Chemical effects of continuous and pulsed ultrasound in aqueous solutions, *Ultrasonics Sonochemistry*, **2**(2), S 115-121.
31. Hetherington, P., Follows, M., Dunnill, P., and Lilly, M.D., 1971, Release of Protein from Baker's Yeast (*Saccharomyces cerevisiae*) by Disruption in an Industrial Homogeniser, *Trans. Inst. Chem. Engrs.*, **49**, 142.
32. Hu, H., Zhou, Z., Xu, Z. and Finch, J. A., 1998, "Numerical and experimental study of a hydrodynamic cavitation tube ", *Metall.Mater. Trans. B*, **29**(4), 911.
33. Hua, I. and Hoffmann, M.R., 1997, "Optimization of ultrasonic irradiation as an advanced oxidation technology", *Env. Sci. Tech.*, **31**, 2237.
34. Hung, H. and Hoffmann, M.R., 1998, "Kinetics and mechanism of the sonolytic degradation of chlorinated hydrocarbons: Frequency effects", *J. Phy. Chem. A*, **103**(15), 2734.
35. Ingale, M.N. and Mahajani, V.V., 1995, "A novel way to treat refractory waste: Sonication followed by Wet Oxidation (SONIWO), *J. Chem. Tech. Biotech.*, **64**, 80.
36. Jyoti, K.K. and Pandit, A.B., 2000, "Water disinfection by acoustic and hydrodynamic cavitation", *Biochem. Engg. Jrnl.*, Accepted for publication.

37. Kalumuck, K. M. and Chahine, G. L., 1998, "The use of cavitating jets to oxidize organic compounds in water", *FED (Am. Soc. Mech. Eng.)*, **245**, 3/45.
38. Kamath, V., Prosperetti, A. and Egolfopoulos, F.N., 1993, "A theoretical study of sonoluminescence", *J. Acous. Soc. Am.*, **94**, 248.
39. Kataoka, K., 1985, "Special flow techniques for heat transfer enhancement", *Kagaku Kogaku*, **49**(4), 269.
40. Keil, F.J. and Swamy, K.M., 1999, "Reactors for Sonochemical Engineering- Present Status", *Reviews in Chem. Engg.*, **15**(2), 85 .
41. Kimoto, H. and Sumita, Y., 1986, "Heat transfer characteristics of a circular cylinder in a conduit under cavitation", *Nippon Kikai Gakkai Ronbunshu*, **52**(477), 2312 .
42. Kotronarou, A., Mills, G. and Hoffmann, M.R., 1991, "Ultrasonic irradiation of p-Nitrophenol in aqueous solution", *J. Phys. Chem.*, **95**, 3630.
43. Kotronarou, A., Mills, G. and Hoffmann, M.R., 1992, "Decomposition of parathion in aqueous solution by ultrasonic irradiation", *Env. Sci. Tech.*, **26**, 1460.
44. Kozyuk, O.V., 1996, "Method and device for obtaining free disperse system in liquid", US patent application No. 602, 069, February 15.
45. Kozyuk, O.V., Litvinenko, A.A. and Kravets, B.K., 1996, "Method for effecting catalyst free chemical reactions in liquid hydrocarbons by subjecting them to hydrodynamic cavitation", US patent application No. 96/US2, 612, February, 20.
46. Kozyuk, O. V., 1998, "Method for changing qualitative and quantitative composition of mixture of liquid hydrocarbons based on effects of cavitation", *Int. patent Appl. WO 9811983 A1*, 26 Mar 1998, 28 pp..
47. Kozyuk, O. V., 1999, "Method and apparatus for producing ultra-thin emulsions and dispersions" *U.S. Patent, US 5931771 A*, 3 Aug 1999, 9 pp. (English)..
48. Kravets, B. K., 1996, "Production of liquid systems of emulsions or suspensions using a hydrodynamic cavitation field", Ger. Offen. DE 4433744 A1 28 Mar 1996, 11 pp. (Germany).
49. Krishna, M.C., Takashi, A. and Riesz, P., 1989, "Sonochemistry of alcohol-water mixtures: Spin trapping evidence for thermal decomposition and isotope exchange reactions", *J. Phys. Chem.*, **93**, 5166.

50. Kumar, R., 1997, "Analysis of a Batch Sonochemical Reactor Involving Two Liquid Phases", *Proceedings of Intl. Symp. in Honour of Prof. M. M. Sharma*, Mumbai, India, 11.
51. Lindley, J. and Mason, T.J., 1987, "Use of ultrasound in chemical synthesis", *Chem. Soc. Rev.*, **16**, 275.
52. Lorimer, J. P., Mason, T. J. and Fiddy, K., 1991, "Enhancement of chemical reactivity by power ultrasound: an alternative interpretation of the hot spot", *Ultrasonics*, **29**, 338.
53. Luche, J.L., Einhorn, C. and Einhorn, J., 1989, "Sonochemistry: The use of ultrasound waves in Synthetic Organic Chemistry", *Synthesis (J. Syn. Appl. Chem.)*, 787.
54. Lush, P.A., 1988, "Dynamics of cavities in duct flow", *Int. J. Heat Fluid Flow*, **9**(1), 8.
55. Martin, P.D. and Ward, L.D., 1993, "Reactor design for sonochemical engineering", *Chem. Engg. Res. Des.*, **70** (A3), 203-212.
56. Mason, T.J., 1986, "Use of ultrasound in chemical synthesis", *Ultrasonics*, **24**, 245.
57. Mason, T. J., 1991, *Practical Sonochemistry*, Ellis Horwood, p. 27.
58. Mason, T.J., 1999, "Sonochemistry: current uses and future prospects in the chemical and processing industries", *Phil. Trans. R. Soc. Lond. A*, **357**, 355.
59. Moholkar, V.S. and Pandit, A.B., 1996, "Harness cavitation to improve processing", *Chem. Engg. Prog.*, **96**, 57.
60. Moholkar, V.S. and Pandit, A.B., 1997, "Bubble behaviour in hydrodynamic cavitation: Effect of turbulence, *AIChE J.*, **43**(6), 1641.
61. Moholkar, V.S., Senthilkumar, P. and Pandit, A.B., 1999, "Hydrodynamic cavitation for sonochemical effects", *Ultrasonics Sonochemistry*, **6**, 53.
62. Moholkar, V.S. and Pandit, A.B., 2000, "Numerical investigations in the behaviour of one dimensional bubbly flow in hydrodynamic cavitation", *ISCRE 16*, Poland, Presented.
63. Moser, W.R., Marshik-Geurts, B.J., Kingsley, J., Lemberger, M., Willette, R., Chan, A., Sunstrom, J.E. and Boye, A.J., 1995^a, "The synthesis and characterization of solid state materials produced by high shear hydrodynamic cavitation", *J. Mater. Research*, **10**, 2322.

64. Moser, W. R., Marshik-Geurts, B. J., Sunstrom, J. E., 1995^b, "The synthesis of nanostructured, pure phase catalysts by hydrodynamic cavitation" *Prepr. - Am. Chem. Soc., Div. Pet. Chem.*, **40**(1), 100.
65. Moser, W. R., Sunstrom, J. E., Marshik-Guerts, B., 1996, "The synthesis of nanostructured pure-phase catalysts by hydrodynamic cavitation", *Proc. Adv. Catal. Nanostruct. Mater.*, Edited by: Moser, W. R., 285-306..
66. Moss, W.C., Young, D.A., Harte, J.A., Levatin, J.L., Rozsnyai, B.F., Zimmerman, G.B. and Zimmerman, I.H., 1999, "Computed optical emissions from sonoluminescing bubble", *Phys. Rev. E*, **59**, 2986.
67. Mujumdar, S. and Pandit, A.B., 1998, "Study of catalytic isomerisation of Maleic acid to Fumaric acid: Effect of Ultrasound", *Ind. Chem. Engr.*, **40** (B:2), 187.
68. Naidu, D.V., Rajan, R., Gandhi, K.S., Kumar, R., Chandrasekaran, S. and Arakeri, V.H., 1994, Modelling of Batch Sonochemical Reactor, *Chem. Eng. Sci.*, **49**(6), 877.
69. Oba, R., Ikohagi, T., Ito, Y., Miyakura, H. and Sato, K., 1986, "Stochastic behaviour (Randomness) of desinent cavitation", *Trans. ASME J. Fluid Engg.*, **108**, 438.
70. Pandit, A.B., and Joshi, J.B., 1993, "Hydrolysis of Fatty Oils: Effect of Cavitation", *Chem. Eng. Sci.*, **48**(19), 3440.
71. Pandit, A.B., Senthilkumar, P. and Sivakumar, M., 1999, "Improve reactions with hydrodynamic cavitation", *Chem. Engg. Prog.*, **95**(5), 43.
72. Pandit, A.B., Gogate, P.R. and Mujumdar, S., 2000, "Ultrasonic degradation of 2-4-6 trichlorophenol in presence of TiO₂ catalyst", *Proceedings of ESS7*, Toulouse, France.
73. Petrier, C., Gemal, A. L. and Luche, J.L., 1982, "Ultrasound in organic synthesis 3: A simple high yield modification of the Bouveault reaction", *Tetrahedron Letters*, **23**, 3361.
74. Petrier, C., Luche, J.L. and Dupuy, C., 1984, "Ultrasound in organic synthesis 6: An easy preparation of organozinc reagents and their conjugate addition to α -enones, *Tetrahedron Letters*, **25**, 3463 .
75. Petrier, C., and Luche, J.L., 1987, "Ultrasonically improved reductive properties of an aqueous Zn-NiCl₂ system 1: Selective reduction of α - β unsaturated carbonyl compounds, *Tetrahedron Letters*, **28**, 2347 .

76. Petrier, C., Jeanet, A., Luche, J.L. and Reverdy, G., 1992^a, "Unexpected frequency effects on rate of oxidative processes induced by ultrasound", *J. Am. Chem. Soc.*, **114**, 3148 .
77. Petrier, C., Micolle, M., Merlin, G., Luche, J-L. and Reverdy, G., 1992^b, Characteristics of pentachlorophenate degradation in aqueous solutions by means of ultrasound, *Env. Sci. Tech.*, **26**, 1639.
78. Petrier, C., Lamy, M-F., Francony, A., Benahcene, A., David, B., Renaudin, V. and Gondrexon, N., 1994, "Sonochemical degradation of phenol in dilute aqueous solutions: Comparison of the reaction rates at 20 and 487 kHz", *J. Phy. Chem.*, **98**, 10514.
79. Plesset, M.S., 1949, "The dynamics of cavitating bubbles", *J. Appl. Mech. Trans ASME*, **16**, 277.
80. Plesset, M. S., 1970, "Cavitation Erosion in Non-aqueous Liquids", *Trans. ASME J. Fluid Engng.*, **92**, 807.
81. Press, W.H., Teukolsky, S.A., Fannery, B.P. and Vesserling, W.T., 1992, *Numerical Recipes*, Cambridge University Press, NY, USA.
82. Rao, S. R., Finch, J. A., Zhou, Z. and Xu, Z., 1998, "Relative flotation response of zinc sulfide: mineral and precipitate", *Sep. Sci. Technol.*, **33**(6), 819.
83. Save, S. S., Pandit, A.B., and Joshi, J.B., 1994, "Microbial cell disruption: Role of cavitation", *Chem. Engg. J.*, **55**, B67.
84. Save, S.S., Pandit, A.B. and Joshi, J.B., 1997, "Use of hydrodynamic cavitation for large scale cell disruption", *Chem. Engg. Res. Des.*, **75**(C), 41.
85. Senthilkumar, P., 1997, "Studies in Cavitation: Modelling and Scaleup of cavitation reactors", *M.Chem.Engg. Thesis*, Univ. of Mumbai, Mumbai, India.
86. Senthilkumar, P. and Pandit, A.B., 1999, "Modelling Hydrodynamic Cavitation", *Chem. Engg. Tech.*, **22**(12), 1017.
87. Senthilkumar, P., Sivakumar, M. and Pandit, A.B., 2000, "Experimental quantification of chemical effects of hydrodynamic cavitation" *Chem.Engg. Sci.*, **55**(9),1633.
88. Serpone, N., Terzian, R., Hidaka, H. and Pelizzetti, E., 1994, "Ultrasonic induced dehalogenation and oxidation of 2-, 3- and 4-Chlorophenol in air-equilibrated aqueous media: Similarities with irradiated semiconductor particulates", *J. Phys. Chem.*, **98**, 2634.
89. Sivakumar, M. and Pandit, A.B., 2000, "Hydrodynamic cavitation assisted Rhodamine B degradation: A technologically viable waste

- water treatment technique”, *Int. Conf. on Science and Technology*, October 12-13, New Delhi, India, Presented.
90. Sivakumar, M., Tatke, P.A. and Pandit, A.B., 2000, “Kinetics of p-Nitorphenol degradation: Effect of reaction conditions and cavitation parameters for a multiple frequency system”, *Chem. Engg. Tech.*, Forwarded for Publication.
 91. Sivakumar, M. and Pandit, A.B., 2000, “Ultrasound enhanced degradation of Rhodamine B: Optimisation with power density”, *Proceedings of ESS7*, Toulouse, France.
 92. Shah, Y.T., Pandit, A.B. and Moholkar, V.S., 1999, *Cavitation Reaction Engineering*, Plenum Publishers, U.S.A..
 93. Shirgaonkar, I.Z., 1997, “Effect of ultrasonication on chemical reactions”, *Ph.D. Thesis*, University of Mumbai, Mumbai, India.
 94. Shirgaonkar, I.Z. and Pandit, A.B., 1997, “Degradation of aqueous solution of potassium iodide and sodium cyanide in presence of carbon tetrachloride”, *Ultrasonics Sonochemistry*, **4**(1), 245.
 95. Shirgaonkar, I.Z., Lothe, R.R. and Pandit, A.B., 1998, “Comments on the mechanism of microbial cell disruption in High Pressure and High speed devices”, *Biotech. Prog.*, **14**(4), 657.
 96. Shirgaonkar, I.Z. and Pandit, A.B., 1998, “Sonophotochemical destruction of aqueous solutions of 2,4,6 trichlorophenol” *Ultrasonics Sonochemistry*, **5**(1), 53.
 97. Sochard, S., Wilhelm, A.M. and Delmas, H., 1998, “Gas vapour bubble dynamics and homogenous sonochemistry”, *Chem. Eng. Sci.*, **53**, 239.
 98. Solinitsyn, R.A., Fumbarov, A.G., Tomashchuk, G.I. and Grinin, T.V., 1987, “Advantages of cavitation method for activation of waste paper”, *Bum. Prom-st.*, **1**, 25.
 99. Solonitsyn, R. A., Fumbarev, A. G. and Pilipenko, S.D., 1991, “Use of hydrodynamic flow cavitation in pulp and paper technology”, *Bum.Prom-st.*, **(8-9)**, 16.
 100. Storey, B.D. and Szeri, A.J., 1999, “Mixture segregation within sonoluminescence bubbles”, *J. Fluid Mech.*, **396**, 203.
 101. Storey, B.D. and Szeri, A.J. 2000, “Water Vapour, sonoluminescence and sonochemistry”, *Proc. R. Soc. Lond. A*, **456**, in press .

102. Sulimenko, L. M. and Krivoborodov, Y. R. , 1997, "Influence of physical-chemical hydrodynamics processing of raw mix on clinker quality", *Proc. Int. Congr. Chem. Cem., 10th*, **Volume 1**, pp li040.
103. Sunstrom, J. E., Moser, W. R., Marshik-Guerts, B., 1996, "General Route to Nanocrystalline Oxides by Hydrodynamic Cavitation" *Chem. Mater.*, **8(8)**, 2061.
104. Suslick, K. S., Gawlenowski, J.J., Schubert, P.F. and Wang, H.H., 1983, "Alkane Sonochemistry", *J. Phys. Chem.*, **87**, 2299.
105. Suslick, K. S., Mdleleni, M.M. and Reis, J.T., 1997, "Chemistry Induced by Hydrodynamic Cavitation", *J. Am. Chem. Soc.*, **119(39)**, 9303.
106. Suslick, K.S., Didenko, Y., Fang, M.F., Hyeon, T., Kolbeck, K.J., McNamara, W.B., Mdleleni, M.M. and Wong, M., 1999, "Acoustic cavitation and its chemical consequences", *Phil. Trans. R. Soc. Lond. A*, **357**, 335.
107. Tatake, P.A., Vichare, N.P. and Pandit, A.B., 1999, "Effect of turbulence in hydrodynamic cavitation", *CHEMCON-99*, Chandigarh, India.
108. Tatake, P.A., "Studies in cavitation", 2000, M.Chem. Engg. Thesis, University of Mumbai, Mumbai, India.
109. Tatake, P.A. and Pandit, A.B., 2000, "Cavitation intensity distribution in an ultrasonic bath: Analysis and effects on the local chemical yield", *Ultrasonics Sonochemistry*, Accepted for Publication.
110. Tomita, Y. and Shima, A., 1986, Mechanisms of impulsive pressure generation and damage pit formation by bubble collapse, *J. Fluid Mech.*, **169**, 535.
111. Trabelsi, F., Ait-Lyazidi, H., Ratsimba, B., Wilhelm, A.M., Delmas, H., Fabre, P-L. and Berlan, J., 1996, "Oxidation of phenol in wastewater by Sonochemistry", *Chem. Engg. Sci.*, **51(10)**, 1857.
112. Tullis, J.P., 1971, "Choking and supercavitating valves", *J. Hydraulics Div.*, **HY12**, 1931 .
113. Tullis, J.P. and Govindrajana, R., 1973, "Cavitation and size scale effect for orifices", *J. Hydraulics Div.*, **HY13**, 417.
114. Vichare, N.P., 1999, "Studies in Sonochemistry and cavitation phenomena", *M.Chem. Engg. Thesis*, University of Mumbai, Mumbai, India.

115. Vichare, N.P., Gogate, P.R. and Pandit, A.B., 2000, "Optimization of hydrodynamic cavitation using a model reaction", *Chem. Engg. Tech.*, **23**, 623.
116. Vichare, N.P., Senthilkumar, P., Moholkar, V.S., Gogate, P.R. and Pandit, A.B., 2000, "Energy analysis in acoustic cavitation", *Ind. Eng.Chem. Res.*, **39**, 1480.
117. Von Sonntag, C., Mark, G., Tauber, A. and Schuchmann, H.P., 1999, "OH radical formation and dosimetry in the sonolysis of aqueous solutions", *Adv. Sonochem.*, **5**, 109.
118. Wang, Y.C. and Brennen, C.E., 1998, "One dimensional bubbly cavitating flows through a converging-diverging nozzle", *Trans. ASME J. Fluid Engg.*, **120**, 166.
119. Weavers, L.K. and Hoffmann, M.R., 1998, "Sonolytic decomposition of ozone in aqueous solution: Mass transfer effects" *Env. Sci. Tech.*, **32**, 3941.
120. Weavers, L.K., Ling, F.H. and Hoffmann, M.R., 1998, "Aromatic compound degradation in water using a combination of sonolysis and ozonolysis", *Env. Sci. Tech.*, **32**, 2727.
121. Yan, Y., Thorpe, R.B. and Pandit, A.B., 1988, Cavitation noise and its suppression by air in orifice flow, *Proc. of the Int. Symp. on Flow Induced Vibration and Noise*, Chicago, USA, American Soc. of Mechanical Engineers, 25-40 .
122. Yan, Y. and Thorpe, R.B., 1990, "Flow regime transitions due to cavitation in flow through an orifice", *Int. Jl. of Multiphase flow*, **16**(6), 1023.
123. Zeitsch, K.J., 1987, "Apparatus for improved hydrolysis of cellulose and hemi-cellulose", *German Patent No. 3,545,746*, June 25.
124. Zhou, Z.A., Xu, Zhenghe, Finch, J.A., Hu, H. and Rao, S.R., 1997, "Role of hydrodynamic cavitation in fine particle flotation", *Int. J. Miner. Process.*, **51**(1-4), 139.
125. Zhou, Z. A., Langlois, R., Xu, Z., and Finch, J. A., 1997, "In-plant testing of a hydrodynamic cavitation reactor in flotation" *Proc. of 2nd Int. Symp. Fundam. Miner. Process.*, Edited by: Finch, J. A., Rao, S. R. and Holubec, I., 185.
126. Zuchenko, V.A., Milchailov, B.V. and Sobolev, G.I., 1977, "Use of hydrodynamic cavitation during beneficiation of quartz sands, *Sb. Tr. Vses. Nanchno-Issled Inst. Nerd. Stroct. Mater. Gidromelch.*, **42**, 74