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Experimental quantification of chemical effects of hydrodynamic cavitation

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Abstract

The classical ultrasonically induced reaction of the decomposition of aqueous KI Solution has been studied on a 501 hydrodynamic cavitation set-up. This reaction, which has been previously studied using acoustic cavitation, has been shown to be influenced by hydrodynamic cavitation as well. Methodology has been suggested to enhance the reaction rates, when using hydrodynamic cavitation set-up. Manipulation of the throttling device (orifice plates) and the operating conditions have increased the iodine liberation rates, three times more than acoustic cavitation at equivalent power dissipation rates. The scale-up possibilities of hydrodynamic cavitation as a means of an alternative to acoustic cavitation have been discussed.

Keywords: Acoustic cavitation; Hydrodynamic cavitation; KI decomposition; Energy dissipation rates; Optimisation and scale-up

1. Introduction

The efficacy of acoustic cavitation generated by the passage of ultrasound in inducing or accelerating many chemical reactions is a well-established concept. On the other hand, the use of hydrodynamic cavitation, generated by throttling the liquid flow through a constriction, for physical and chemical processing is relatively a new idea. Preliminary studies by Pandit and Joshi (1993) have shown that this method of driving chemical reactions is indeed promising. The physical processing of liquids can include homogenisation, emulsification, disruption of cells for the recovery of enzymes, etc. Pandit and Joshi (1993) studied hydrolysis of fatty oils. Moser, Marahik-Guerts, Barbara and Sunstrom Joseph (1996) successfully developed nanostructured catalysts possessing a number of unique properties. More recently, Suslick, Millan and Reis (1997) conducted Weissler's reaction in microfluidiser and the results show that the effect of various parameters such as the reaction temperature, and the nature of dissolved gas on reactions induced by the hydrodynamic cavitation are similar to that in sonochemical processes. Pandit and Joshi (1993) and Save, Pandit and Joshi (1997) have found that hydrodynamic mode of cavitation is more energy efficient than acoustic one atleast for the process studied by them. The scale of operation of these studies are vastly different. Suslick et al. (1997) have used it on a scale of few cm^3, whereas Save et al. (1997) have used it on 200 l scale of operation.

Yu, Ceccio Steven and Tryggvason Greater (1995) and Moholkar and Pandit (1997) have shown that a large shear can increase the rate of bubble collapse. This can be exploited in the cavitational activity behind an orifice plate. The present study deals with the quantification of chemical effect of hydrodynamic cavitation by using multiple hole orifice plates. The model reaction used in the present study is the decomposition/oxidation of aqueous KI solution, a widely studied reaction in sonochemistry. Collapse of cavities result in the generation of high temperatures and pressures locally, which induces the cleavage of water molecules to yield $OH^{\bullet}$ radicals. These $OH^{\bullet}$ radicals are responsible for the oxidation of KI solution, resulting in the liberation of iodine. This reaction has been discussed in detail by Prasad Naidu, Rajan, Gandhi, Arakeri and Chandrasekaran (1993).

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Nomenclature

C_v	cavitation number
H	liquid head developed by the pump, m
p_1	inlet pressure, psi
p_2	fully recovered discharge pressure, psi
p_v	vapour pressure of the liquid, N/m^2
P	power input to the pump, h_p
P_1	pressure gauge in inlet side
P_2	pressure gauge in discharge side
Q	liquid flow rate, m^3/s
V_{th}	orifice hole velocity, m/s
V_1	valve in suction line
V_2	valve in bye-pass line
V_3	valve in main line

Greek letters

α_s	parameter
β_0	ratio of total area of opening to pipe cross-sectional area
ρ	density of the liquid, kg/m^3

2. Experimental setup

The experimental pilot scale setup is essentially a closed-loop reactor comprising a holding tank of 100 l volume, a centrifugal pump (2900 rpm, 5.5 KW, Calama industries, India), flow control valves and necessary flanges to accommodate different orifice plates as shown in Fig. 1. The tank is provided with a jacket for cooling its contents. The suction side of the centrifugal pump is connected to the bottom of the holding tank and the discharge line of the pump branches into two lines. The main-line consists of a flange that houses the orifice plate and a sight glass adjacent to it, in order to visually observe the generation of cavitation. A bye-pass line is provided to control the flow rate of the liquid through the main line. Both the bye-pass line and the main line terminate well inside the tank, below the liquid level, to prevent the induction of air into the liquid due to the plunging liquid jet. The inside diameter of both the main and the bye-pass lines are 38 mm. Control valves are provided at appropriate places to manipulate or maintain the flow rate in the main line. The material used in the construction of the entire system is stainless steel (SS316). Pressure gauges are provided to measure the inlet pressure (p_1) and the fully recovered downstream pressure (p_2) as shown in Fig. 1.

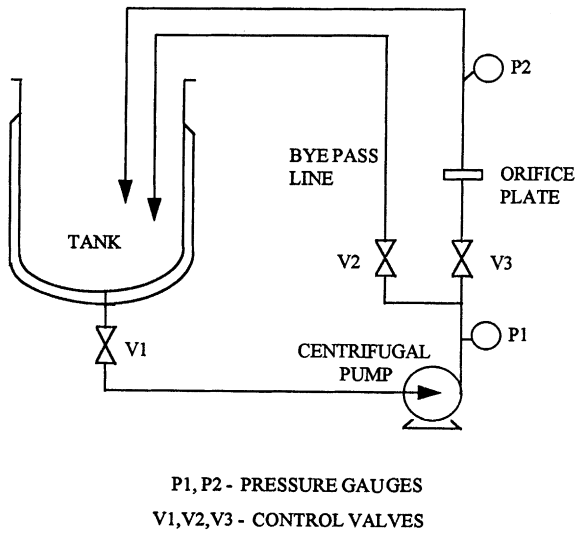

Fig. 1. Experimental pilot scale setup.

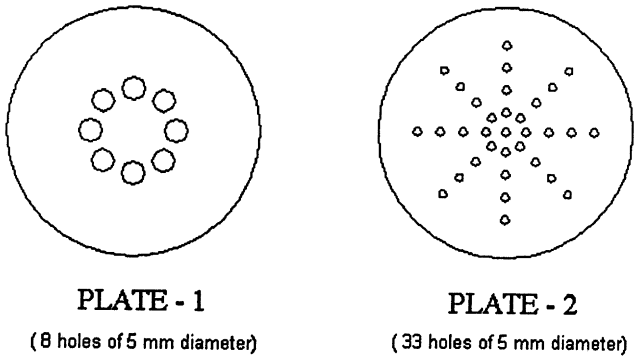

Fig. 2. Arrangement of holes in orifice plate.

Two types of multiple hole orifice plates were used in the present study and the detailed arrangements of the holes are as shown in Fig. 2. The Plate 1 consists of 8 holes of 5 mm diameter. The ratio of the total area of opening to cross-sectional area of pipe (β_0) is 0.138. Plate 2 consists of 33 holes of 2 mm diameter and hence the value of β_0 is 0.091.

3. Experimental procedure

The hydraulic characteristics of the orifice plates were studied using water. The given plate was inserted between flanges in the main line. The tank was filled to 80% of it's capacity with water and the pump was started with the valves V_1, V_2 and V_3 in completely open position. The valve in the bye-pass line (V_2) was partially closed to adjust the inlet pressure p_1 (which is also the pump discharge pressure) on the upstream side of the orifice plate. The corresponding fully recovered pressure, p_2 on the downstream side was measured. The flow rate was

calculated from the velocity in the main-line, measured using a standard pitot tube of 3 mm outside diameter. The pitot tube was traversed in the radial direction to locate the point of maximum difference between the static and stagnation pressure (Δh). For the range of flow rates studied, the variation of Δh with the radial distance from the pipe axis was found to be less than 5%, indicating a flat axial velocity profile, typical of the turbulent regime. Hence, the velocity calculated from the above value of Δh is taken as the mean flow velocity in the pipe. In order to determine the discharge coefficient of the orifice plates, the discharge from the main line was collected in a separate vessel after ensuring continuous feeding of water to the holding tank to avoid complete draining of the liquid. The above process was carried out for both the plates at two operating pressures of 10 and 50 psi. The value of the discharge coefficient is 0.65 with error less than $\pm 3\%$.

3.1. Decomposition/oxidation of aqueous KI solution

50 l of 1% KI solution was prepared using distilled water and transferred to the holding tank. A sample of the solution was collected and the pump was started. The upstream pressure (p_1) is adjusted quickly by partially closing the valve V_2 in the bye-pass line. All the other valves namely V_1 and V_3 were kept in fully open condition. The entire pressure range over which the study was made was attained by adjusting the valve in the bye-pass line only, without disturbing the other valves. Samples were collected after 5 min of operation for various values of the inlet pressure p_1. The temperature of the circulating liquid was maintained at 36 ± 2^0C by adjusting the flow rate of the cooling water through the jacket of the holding tank. Samples were analysed for absorbance on UV/VIS spectrophotometer at 355 nm for the estimation of iodine concentration. The above experimental procedure was repeated for plate 2 using fresh KI solution. For comparing the relative efficiency of hydrodynamic and acoustic cavitation in driving the model chemical reaction, 50 ml of the same solution prior to its processing in the hydrodynamic setup at 30 psi was collected in a beaker and irradiated with ultrasound with an ultrasonic horn (20 kHz, 600 W, 10% amplitude, Ace Horn, New York, USA) for 5 min. The iodine concentration of the solution at the end of sonication was measured spectrophotometrically and compared with the value obtained from the hydrodynamic cavitation setup over equivalent time intervals. The energy efficiency of the ultrasonic horn was determined by calorimetric method using water by measuring the temperature rise of water kept in an insulated reactor for the given period of irradiation of the liquid.

To obtain information about the cavitational activity due to the throttling of the liquid through valve V_2 and possibly in valves V_1, V_3 and pump, blank runs with KI solution in the absence of the orifice plates were conducted. It should be noted that valves V_1, V_2 were kept fully open and the level of liquid in the tank was well above the pump axis. The runs were conducted for various positions of the valve V_2, the positions at which upstream pressures of 5, 30 and 50 psi can be attained in the presence of both the orifice plates.

4. Results and discussion

4.1. Hydraulic characteristics of orifice plates

As explained before, p_1 is adjusted by partially closing the valve V_2. This also results in an increased flow through the main-line. Fig. 3 shows the effect of inlet pressure (p_1) on the flow rate through the main line. Flow conditions in the main-line is also characterised in terms of the cavitation number, which takes into account the downstream side conditions. Cavitation number (C_v) is the dimensionless number, defined as,

$$C_v = \frac{p_2 - p_v}{1/2\rho V_{\text{th}}^2},$$

where p_2 is the fully recovered downstream pressure, p_v is the vapour pressure of the liquid at the bulk liquid temperature, and V_{th} is the velocity of the liquid through the orifice holes, which was estimated with the knowledge of the total flow rate and the geometry of the plate (number of holes, total flow area).

Fig. 4 shows the relationship between the effect of inlet pressure p_1 and cavitation number C_v. It can be observed that the cavitational activity over a wide range of cavitation number can be studied with plate 1, providing

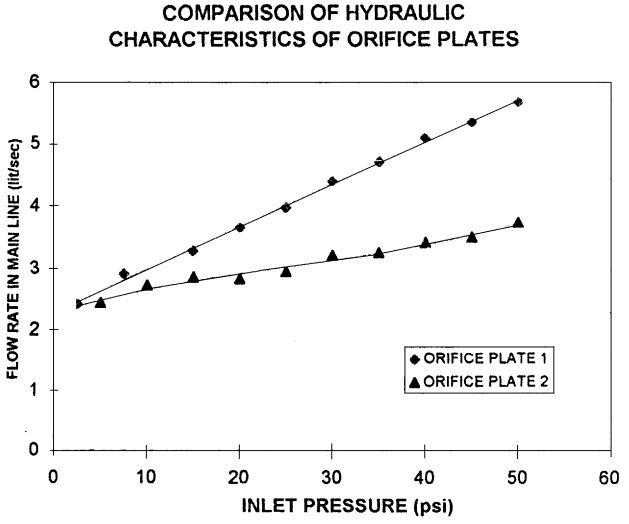

Fig. 3. Hydraulic characteristics of the orifice plates: effect of inlet pressure on flow rate through mainline.

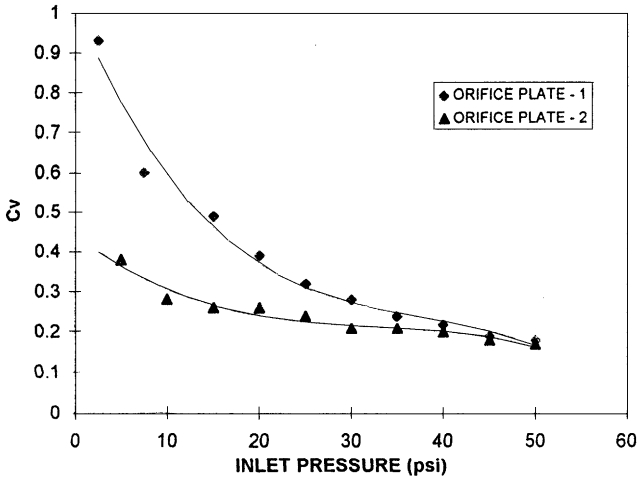

Fig. 4. Hydraulic characteristics of the orifice plates: effect of cavitation number on flow rate through mainline.

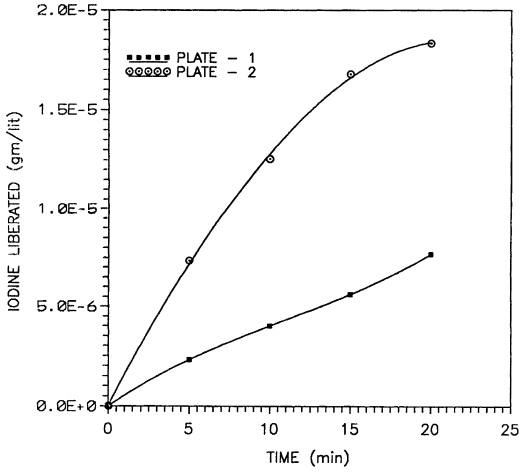

Fig. 5. Iodine liberation with respect to time ($p_1 = 50$ psi).

a means of generating the desired degree of cavitational intensity or optimising the cavitational intensity in the system. This is chiefly due to the higher value of β_0 for plate 1. Also, the variation of C_v with p_1 follows the same trend in the results as that of the studies made with a single hole orifice plates of varying β_0 (Yan & Thorpe, 1990) and venturi (Cadence, 1993).

4.2. Iodine liberation with respect to time

Fig. 5 shows the iodine liberation with respect to time for both the plates at a discharge pressure of 50 psi. It can be observed that similar to sonochemical oxidation of aqueous KI solution, the iodine concentration is varying almost linearly with time at least up to 15 min of operation. The iodine liberation for plate 2 is higher than that for plate 1 at least 3 times. This is due to enhanced collapse of cavities due to high shear as shown by the numerical study of Yu et al. (1995) and Senthil Kumar (1997). Also due to the larger number of smaller holes in the case of plate 2, the high shear zones are more evenly distributed across the cross section of the pipe. This will also result in a larger probability for the cavity to experience this shear zone and collapse violently. As this work demonstrates, the hole size and increase in the total perimeter of the holes, seem to have an advantageous effect on the cavitational activity.

4.3. Effect of inlet pressure

The data from the above study gives the information on iodine liberation/concentration for 5 min of operation at various inlet pressure (p_1). The number of times a given volume of solution experiences the hydrodynamic cavitation varies for two plates under identical values of p_1 for 5 min of operation due to the variation in the liquid flow rates for the same liquid content of the holding tank. Thus, it would be more appropriate to compare the iodine liberation for a fixed number of passes through the orifice plate. From Fig. 5, it is evident that the concentration of iodine is varying almost linearly with respect to time till it reaches a maximum. Shirgaonkar (1997) and Shirgaonkar et al. (1998) studied the same reaction using hydrodynamic cavitation generated in high-pressure homogeniser and the time and yield relationship was also found to be linear. From these results and from the knowledge of inlet/upstream pressure (p_1) V_s main line flow rate, iodine liberation for 15 passes through the cavitation zone can be calculated. Fig. 6 shows the iodine liberation for 15 passes of the solution at various values of inlet pressures. Neglecting the first point (see explanation given later), for both plates, we observe that the iodine liberation increases with inlet pressure (p_1), reaches a maximum and then decreases. Over the major portion of the operating range of inlet pressure, the iodine liberation for plate 2 is higher than plate 1. This reaction rate enhancement is due to the increase in the volume of liquid jets exposed to the zone of intense shear or/and turbulence.

The higher initial rate of decomposition of KI (first point in all the cases) could be due to the following reasons:

(1) Degassing effect of cavitation is a well known phenomenon. The presence of dissolved air in the solution, decreases the threshold pressure at the inception of cavitation. This results in substantial rise in the number of cavities generated, leading to higher reaction rates, initially. As observed, when time progresses, the dissolved air is liberated by degassification and its role in generating cavitation becomes insignificant in subsequent runs.

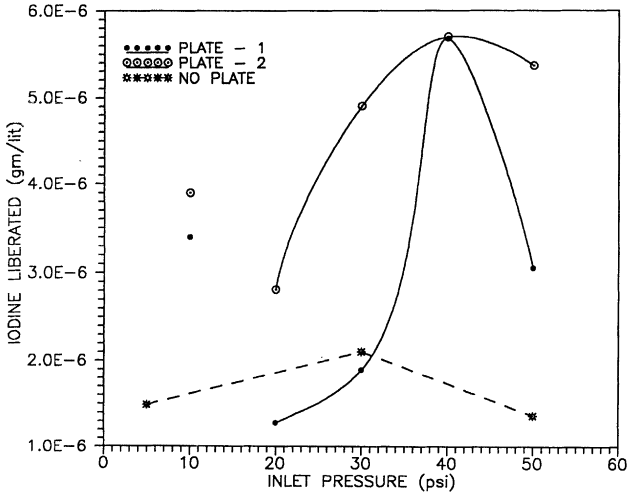

Fig. 6. Effect of inlet pressure on KI decomposition.

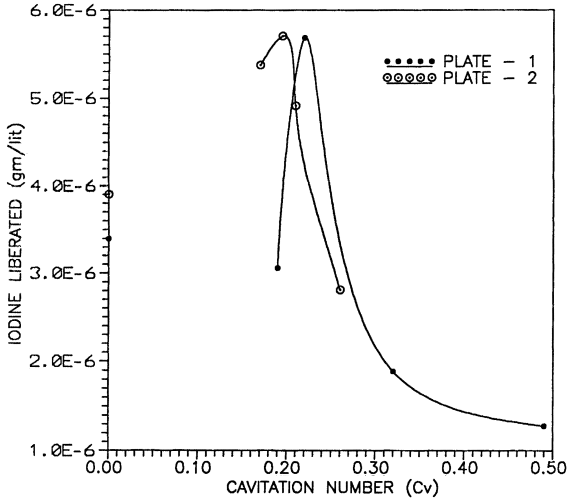

Fig. 7. Effect of cavitation number on KI decomposition.

(2) The initial temperature of the solution for the first run was 31°C which rose to 36°C at the end of the run. As the cooling water was available at the same temperature of the solution, the temperature could not be maintained below 36°C. In subsequent runs, temperature was maintained at 36 ± 2°C by using cooling water in higher flow rates. A reduction in reaction temperature also leads to higher reaction rate, as shown by Suslick et al. (1997).

The dotted line in Fig. 6 shows the Iodine liberation for 15 passes in the absence of the orifice plates. As stated before, valves V_1 and V_3 are kept fully open and the flow is manipulated by the valve V_2. The position of the valve V_2 corresponding to 5 psi, is completely open. The reading for this position of iodine concentration shows that the cavitation caused by the valves when they are fully open, and the pump are very small, in spite of this being the initial run. Consequently, unlike the orifice plates case, complete degassification of KI solution does not take place for this run. So, the effect of dissolved gas is also felt for the second run as the same KI solution is used. For position 2 (corresponding to 30 psi), when the valve V_2 is partially closed, cavitation intensity is comparatively more severe, showing degassification from valve V_2. Subsequent to this degassification, for position 3, corresponding to 50 psi, the cavitation intensity is once again insignificant due to the overthrottling and marginal change in the cavitation number (Fig. 6). This shows that contribution from the valves and the pump in the degassification is insignificant.

4.4. Effect of cavitation number (C_v)

Fig. 7 shows the effect of cavitation number on decomposition of KI solution for 15 passes through the mainline. It can be observed that iodine liberation increases with a decrease in cavitation number, reaches a maximum and then drops. Tullis (1971) observed that at very low cavitation number, a significantly large number of cavities are generated which may tend to coalesce to form larger bubbles. These bubbles are carried away with the liquid without collapsing, resulting in the reduced reaction rates. Both plates show optimal performance in different ranges of C_v. In ranges where they overlap, the performance of plate 2 is better than plate 1. For a given cavitation number, conditions for the generation of cavities are identified for both the plates. The higher reaction rate for plate 2 can be attributed to more violent collapse of cavities, due to larger number of cavities entering the shear layer as expected. The role of intense turbulence zone adjacent to the liquid jet on a violent cavity collapse should be acknowledged. As the diameter of the liquid jets issuing from plate 2 is smaller, the overall area of the jet exposed to this intense shear and turbulence zone is much higher.

The first two points of Fig. 6 for both the plates have been omitted in Fig. 7 because of the degassing effect as explained before.

5. Comparison of the energy efficiency of hydrodynamic and acoustic cavitation

5.1. Acoustic cavitation

Temperature rise during 5 min of irradiation = 6°C

Energy input into the liquid

$$= 4184(\text{J/kg°C}) \times 0.05(\text{kg}) \times 6(\text{°C})$$

$$= 1255.2\ \text{J}.$$

Total iodine liberated

$$= 8.884 \times 10^{-6}(\text{gm/l}) \times 0.05(\text{l})$$

$$= 4.442 \times 10^{-7}\ \text{gm}.$$

Iodine liberated per unit energy input (or)

cavitational yield

$$= \frac{4.442 \times 10^{-7}(\text{gm})}{1255.2(\text{J})}$$

$$= 3.539 \times 10^{-10}\ \text{gm/J}.$$

5.2. Hydrodynamic cavitation

Energy input to the liquid in 5 min of operation

$$= H\rho g Q \times t,$$

where Q is the flow rate of liquid through the main line at 30 psi discharge pressure,

$H = 30.5$ m of water head $= 0.0032\ \text{m}^3/\text{s}$. (Fig. 3) and t is time in seconds

$$= 30.5 \times 1000 \times 9.81 \times 0.0032 \times 300$$

$$= 287237\ \text{J}.$$

Iodine liberated in 15 passes at 30 psi discharge pressure (Fig. 6) $= 5.0 \times 10^{-6}$ gm/l.

Time required for 15 passes of 50 l. of solution at 30 psi (Fig. 3)

$$= \frac{\text{Total volume} \times \text{No. of passes}}{\text{Volumetric flow rate}} \quad \text{(at 30 psi)}$$

$$= \frac{50(\text{l}) \times 15}{3.2(\text{l/s})}$$

$$= 234.4\ \text{s}.$$

Thus, expected iodine liberation in 5 min (300 s) of operation at 30 psi discharge pressure, assuming linear variation with time

$$= 5.0 \times 10^{-6} \times \frac{300}{234.4}$$

$$= 6.4 \times 10^{-6}\ \text{gm/l}.$$

Therefore, total iodine liberated

$$= 6.4 \times 10^{-6}\ \text{gm/l} \times 50\ \text{l}$$

$$= 3.2 \times 10^{-4}\ \text{gm}$$

So, iodine liberated per unit energy input (or) cavitational yield

$$= \frac{3.2 \times 10^{-4}\ \text{gm}}{287237\ \text{J}}$$

$$= 1.11 \times 10^{-9}\ \text{gm/J}$$

From the above analysis, it can be found that iodine liberated per unit energy input (cavitational yield) for hydrodynamic cavitation is 3 times higher than acoustic cavitation. Similar analysis was carried out for plate 1 at 30 psi discharge pressure and it was found that the cavitational yield was 32% lower than for plate 2 and about 2 times that of acoustic cavitation. The above analysis indicates that the chemical effects of hydrodynamic cavitation are better than or at least comparable to acoustic cavitation based on energy criteria for the model reaction considered in this study. The basic reason for low cavitational yield of ultrasonic equipment is due to poor energy conversion efficiency. Even the largest and efficient transducers available have overall efficiencies of less than 35%. Unlike acoustic cavitation, the efficiency of the pumps increases with the capacity and hence better cavitational yield can be achieved with larger scale of operation. It can also be stated here that plate 2 is not the most optimised constriction and there exists a definite possibility of further improvement and enhancement in the cavitational yields in the hydrodynamic cavitation setup.

6. Conclusions

The generation of chemical effects by hydrodynamic cavitation has been proved qualitatively and quantitatively using cavitation generated by a simple flow setup consisting of 50 l of model reacting system. This is the first study of this kind to show the chemical effect of cavitation on such a large scale subsequent to the study of Suslick et al. (1997). By manipulating the operating conditions, the intensity of cavitation and hence the chemical effect associated with it can be controlled like any conventional chemical process. The role of the intense turbulent shear zone behind the orifice plate in enhancing cavitational activity has been qualitatively established. The efficacy of hydrodynamic cavitation was found to be comparable or more than acoustic cavitation with possibility of further improvements. Experiments are currently being conducted to make an in-depth study of the effect of various operating parameters affecting hydrodynamic cavitation. Considering scaleup and better energy efficiency of hydraulic equipment, hydrodynamic cavitation holds a potential for large scale applications in cavitationally assisted chemical or physical transformations.

Acknowledgements

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References

Cadence James Botha (1993). *A study of hydrodynamic cavitation as a method of water treatment*. M.Sc. (Eng) Thesis, University of Capetown, South Africa.

Moholkar, V. S., & Pandit, A. B. (1997). Bubble behaviour in hydrodynamic cavitation: Effect of turbulence. *A.I.Ch.E. Journal*, *43*(6), 1641–1651.

Moser William, R., Marahik-Guerts, Barbara, J., & Sunstrom Joseph, E. (1996). The synthesis of nanostructured, pure phase catalysts by hydrodynamic cavitation. *Prep-American Chemical Society*, *40*(1), 100–112.

Pandit, A. B., & Joshi, J. B. (1993). Hydrolysis of fatty oils: Effect of cavitation. *Chemical Engineering Science*, *48*(19), 3440–3442.

Prasad Naidu, D. V., Rajan, R., Gandhi, K. S., Arakeri, V. H., & Chandrasekaran, S. (1993). Modelling of a batch sonochemical reactor. *Chemical Engineering Science*, *49*(6), 377.

Save, S. S., Pandit, A. B., & Joshi, J. B. (1997). Use of hydrodynamic cavitation for large scale cell disruption. *Chemical Engineering Research Design*, *75*(Part-C), 41–49.

Senthil Kumar, P. (1997). *Studies in cavitation*. M. Chem. Engg. Thesis. University of Mumbai, Mumbai, India.

Shirgaonkar, I. Z. (1997). *Effect of ultrasound irradiation on chemical reactions*. Ph.D. Thesis. University of Mumbai, Mumbai, India.

Shirgaonkar, I. Z., Lothe, R. R., & Pandit, A. B. (1998). Comments on mechanism of microbial cell disruption using high pressure homogeniser. *Biotechnology Progress*, *14*(4), 657.

Suslick, K. S., Millan, M. M., & Reis, J. T. (1997). Chemistry induced by hydrodynamic cavitation. *Journal of American Chemical Society*, *119*(39), 9303–9306.

Tullis, J. P. (1971). Choking and supercavitating valves. *Journal of Hydraulics Division, HY12*, 1931.

Yan, Y., & Thorpe, R. B. (1990). Flow regime transitions due to cavitation in flow through an orifice. *International Journal of Multiphase Flow*, *16*(6), 1023–1045.

Yu Po-wen, Ceccio Steven, L., & Tryggvason, Greater. (1995). The collapse of a cavitation bubble in the shear flows — a numerical study. *Physics of Fluids*, *7*(11), 2608–2616.