Hydrodynamic and Acoustically Generated Cavitation: Opportunities and Limitations

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Abstract

Cavitational reactors are a novel and promising form of multiphase reactors, based on the principle of release of large magnitude of energy due to the violent collapse of the cavities. The present work gives an overview of the different areas of application such as chemical synthesis including nanomaterials, water and effluent treatment and biotechnology. Some experimental case studies using industrially important reactions have been presented, highlighting the degree of intensification achieved as compared to the conventional approaches. Comparison of the energy efficiencies and cavitational yields for the sonochemical and hydrodynamic cavitational reactors will also be presented based on the recent work carried out at Institute of Chemical Technology, Mumbai. Also possible limitations hampering the successful installations of cavitational reactors at commercial scale operations will also be discussed.

Keywords: Sonochemical Reactors; Hydrodynamic Cavitation, Process Intensification, Scale up

1. Introduction

Cavitation phenomena generated by using pressure field variations, which can be brought about by the use of ultrasound or alternations in the fluid flow, results in conditions which are extremely suitable for intensification of different chemical and physical processing applications. The mechanical effects of cavitation, in terms of generation of local turbulence and liquid micro-circulation (acoustic streaming) in the reactor enhancing the rates of the transport processes, are mainly responsible for the intensification of physical processing applications and also chemical processing limited by mass transfer. The chemical effects such as generation of hot spots and reactive free radicals are responsible for intensification of chemical processing applications. The present lecture will highlight the opportunities offered by the cavitational reactors for intensification of chemical and physical processing applications in different fields starting with the recommendations for design and operating parameters for maximizing the cavitational effects.

2. Recommendations for Design and operating parameters:
The magnitudes of collapse pressures and temperatures as well as the number of free radicals generated at the end of cavitation events are strongly dependent on the operating and geometric parameters of the reactor. In the case of sonochemical reactors the important operating parameters are intensity and frequency of ultrasonic irradiation along with the geometrical arrangement of the transducers and the liquid phase physicochemical properties, which affects the initial size of the nuclei and the nucleation process. In the case of hydrodynamic cavitation reactors, the inlet pressure/operating velocity depending on the equipment, geometry of the constriction critically affects the cavitational intensity. Various bubble dynamics models can be used to predict the cavitational intensity as a function of these parameters and the important considerations for the sonochemical as well as hydrodynamic cavitation reactors regarding the selection of operating parameters will be presented for maximizing the targeted effects at minimum energy consumption.

3. Overview of Applications
Among the different modes of cavitation phenomena, only 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 cavitational conditions suitable for different physical and chemical transformations. We now present overview the different applications, where cavitation can be used efficiently with a focus on the chemical engineering.

3.1 Chemical Synthesis:
The ways in which cavitation has been reported to improve chemical synthesis include, Reaction time reduction and also reduction in the induction period where applicable; Increase in the reaction yield and selectivity; Use of less forcing conditions (temperature and pressure) as compared to the conventional routes; Possible switching of the reaction pathways resulting in increased selectivity; Increasing the effectiveness of the catalyst used in the reaction and Initiation of the chemical reaction due to generation of highly reactive free radicals. In general, cavitation reactors have been reported to affect different types of chemical reactions which include oxidation, hydrolysis, nucleophilic reactions, radical initiated reactions, polymerization/depolymerization reactions, organometallic synthesis, thermolytic decomposition, substitution/addition/condensation reactions and phase transfer catalyst based reactions. Sonochemical reactors also can intensify processes or create conditions for effective synthesis of nanoparticles/nanospheres, porous and non porous particles.

3.2 Wastewater and Water Treatment:
Cavitation can be used effectively for the destruction or complete mineralization of the contaminants in water because of the localized high concentrations of the oxidizing species such as hydroxyl radicals and hydrogen peroxide, higher magnitudes of localized temperatures and pressures and the formation of the transient supercritical water. The type of the pollutants in the effluent stream affects the extent of intensification in rates of the degradation obtained due to the presence of cavitating conditions. The hydrophobic compounds react with OH and H at the hydrophobic gas/liquid interface, while the hydrophilic species react to a greater extent with the OH radicals in the bulk aqueous phase. Depending on the extent of loading and the nature of the effluents in the stream, the efficacy of acoustic and hydrodynamic cavitation reactors for wastewater treatment will be decided. Optimization of aqueous phase organic compound degradation rates can be achieved by adjusting the energy density, the energy intensity and the nature and properties of the saturating gas in solution. The rates of mineralization using acoustic cavitation can be optimized by controlling the power dissipation, operating frequency whereas in the case of hydrodynamic cavitation reactors the inlet pressure and geometry of the cavitation chamber decides the net effects.

The variety of chemicals that have been degraded using cavitation reactors though in different equipments and on a wide range of operating scales are p-Nitrophenol, rhodamine B, trichloroethene, parathion, pentachlorophenate, phenol, CFC 11 and CFC 113, o-dichlorobenzene and dichloromethane, potassium iodide, sodium cyanide, carbon tetrachloride among many others. Excellent reviews are available in the literature covering different aspects related to wastewater treatment applications. The lecture will also discuss some case studies for mineralization of different synthetically prepared effluent streams using acoustic and hydrodynamic cavitation reactors.

3.3 Biotechnology:
A key factor in the economical production of industrially important microbial components is an efficient large-scale cell disruption process. The need for an efficient microbial cell disruption operation has always hindered the large-scale production of commercial biotechnological products of intracellular derivation. For the large scale disruption of microorganisms, mechanical disintegrators such as high-speed agitator bead mills and high pressure homogenizers are commonly employed, but the typical energy efficiencies of the above methods are in the range of 5-10%. The rest of the energy is dissipated in the form of heat, which needs to be efficiently removed to retain the integrity of these delicate bioproducts. With the aim of improving the efficacy of the cell disruption process, keen interest has developed in the last decade in newer techniques, including acoustic and hydrodynamic cavitation. It has been observed that the use of hydrodynamic cavitation for cell disruption has been conclusively proven for large scale applications with much higher energy efficiencies as compared to acoustic cavitation reactors. Additionally, all cavitation reactors explored are more energy efficient compared to the conventional techniques based on the use of mechanical energy. Based on the location of the enzyme, suitable modulation of the cavitation intensity can be achieved, by selection of proper optimum parameters or even the type of the cavitation reactor, with an objective of maximizing the release per unit energy consumption. The energy efficiencies can be further increased due to the use of the pre-treatment strategies such as heat, pH and chemical treatment, which helps in preferential translocation of the target enzyme to facilitate the easy release of the same during the disruption process.
4. Experimental Case Studies:

The utility of the cavitational reactors have been established for many industrially important chemical reactions. Among these, the most significant synthesis reactions investigated by our research group are the synthesis of biodiesel from different sustainable raw materials, oxidation reactions and synthesis of nanosuspensions/nanomaterials. It has been conclusively established that cavitational reactors result in about 50 to 400% intensification in the rates of reaction as compared to the conventional reactions. Comparison of the energy efficiencies (amount of net energy available for generation of cavitation events as a fraction of the supplied electrical energy) and cavitational yields (net quantification of the desired effect per unit supplied energy) obtained for different cavitational reactors for these applications indicated that the hydrodynamic cavitation reactors are much better as compared to the acoustic cavitation based reactors. For example for the case of synthesis of rubber nanosuspensions\(^7\), it has been observed that, for acoustic cavitation reactor, the energy dissipation per kg of the solids varies from \(2.52 \times 10^7\) J/kg to \(1.38 \times 10^8\) J/kg depending on the operating parameters, whereas for the hydrodynamic cavitation reactors these values vary from \(2.026 \times 10^4\) J/kg to \(6.316 \times 10^5\) J/kg, showing at least three orders of magnitude reduction in the energy consumption.

5. Limitations in Commercial Scale applications:

Even though there is a good theoretical understanding of the parameters, responsible for controlling the dynamics of the cavity, the uncertainty associated with the cavitation phenomena and non-uniform distribution of the cavitational activity has hampered the successful application of cavitational reactors at industrial scale operation. The main challenges in the case of sonochemical reactors include achieving spatial uniformity of cavitational activity in the entire volume of the reactor and development of new materials for the vibrating surfaces and focusing the sound energy away from the surface. Also the scale up of sonochemical reactors is generally carried out on the basis of gross parameters such as power per unit volume, same operating frequency etc. but these are inadequate and do not result into the same level of intensification observed on bench scale, especially for organic synthesis applications. On the other hand, hydrodynamic cavitation is generally observed to produce less intense cavitation especially as compared to the sonochemical reactors and hence the applicability of these reactors is limited for applications requiring milder conditions. Also, well defined experimental design strategies and efficient operation for a broad variety of applications are still lacking, perhaps due to the fact that the research into useful applications of this technology has only started recently as compared to the sonochemical reactors (initial research in hydrodynamic cavitation phenomena was with an objective of avoiding the occurrence).

6. Concluding Remarks:

Overall it appears that considerable economic savings is possible by means of harnessing the spectacular effects of cavitation in chemical and physical processing. The future of sonochemical reactors lies in the design of multiple frequency multiple transducer based reactors whereas for hydrodynamic cavitation reactors, orifice plate or venturi type configuration of different geometries appears to be most suitable. Overall, it can be said that, cavitation is a well established technology at laboratory/pilot scale and combined efforts of chemists, chemical engineers and physicists are required to effectively harness this technology on an industrial scale of operation.

References