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Review

A review of applications of cavitation in biochemical engineering/biotechnology

Parag R. Gogate*, Abhijeet M. Kabadi

Chemical Engineering Department, Institute of Chemical Technology, Matunga, Mumbai 40019, India

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ABSTRACT

Cavitation results in the generation of hot spots, highly reactive free radicals, and turbulence associated with liquid circulation currents, which can result in the intensification of various physical/chemical operations. The present work provides an overview of the applications of the cavitation phenomenon in the specific area of biochemical engineering/biotechnology, discussing the areas of application, the role of cavitation, the observed enhancement and its causes by highlighting some typical examples. The different methods of inducing cavitation and the dominance of one over the other, mostly with respect to energy requirements, in different areas of biotechnological application are discussed. The major applications discussed in the work include microbial cell disruption for the release or extraction of enzymes, microbial disinfection, wastewater treatment, crystallization, synthesis of biodiesel, emulsification, extraction of bio-components, freezing and gene transfer into cells or tissues. Some recommendations for optimal operating/geometric parameters have also been made. Overall, it appears that the combined efforts of physicists, chemists, biologists and chemical engineers are required to effectively use cavitational reactors for industrial applications.

Contents

* Corresponding author. Tel.: +91 22 24145616; fax: +91 22 24145614.
E-mail address: parag@udct.org (P.R. Gogate).

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1. Introduction

The process industry demands that operations be performed in the most efficient way with respect to either product quality, energy or time, or in terms of economics. Alternative novel technologies are constantly being sought to reduce the total processing cost while maintaining or enhancing product quality in an environmentally benign manner. Cavitation offers immense potential for intensification of physical or chemical processing in an energy-efficient manner. Cavitation is generally defined as the generation, subsequent growth and collapse of cavities, resulting in very high local energy densities [1]. Cavitation, when it occurs in a reactor, generates conditions of very high temperatures and pressures (100–5000 atmospheres of pressure and 500–15000 K of temperature) locally, but with the overall environment remaining equivalent to ambient atmospheric conditions [1]. This enables the effective execution under ambient conditions of the various physical processes or chemical reactions that require stringent conditions [2–3]. Moreover, free radicals are generated in the process due to the dissociation of vapors trapped in the cavitating bubbles, which results in either intensification of the chemical reactions or in alteration of reaction mechanism. Cavitation also results in the generation of local turbulence and liquid micro-circulation (acoustic streaming) in the reactor, enhancing the rates of transport processes; in addition, they also eliminate mass transfer resistances in heterogeneous systems [2]. Based on the degree of intensity, which may be described in terms of the magnitude of pressure or temperature, cavitation can also be classified as either transient or stable. The energy requirements for the generation of these two types are significantly different, and hence proper care must be taken when selecting the operating parameters for the specific type of application [4]. Transient cavitation is a process where the generated bubble/cavity will eventually collapse to a minute fraction of its original size, at which point the gas present within the bubble dissipates into the surrounding liquid via a rather violent mechanism, releasing a significant amount of energy in the form of an acoustic shock-wave and as visible light. At the point of total collapse, the temperature of the vapor within the bubble may be several thousand Kelvin, and the pressure may be several hundred atmospheres. In the case of stable or non-inertial cavitation, small bubbles in a liquid are forced to oscillate in size or shape due to some form of energy input, such as an acoustic field, when the intensity of the energy input is insufficient to cause total bubble collapse. This form of cavitation causes significantly milder cavitational effects than the transient cavitation.

Cavitation is also classified into four types based on the mode of generation: acoustic, hydrodynamic, optic and particle. Only acoustic and hydrodynamic cavitation have been found to be efficient in producing the desired chemical/physical changes in processing applications [2,5], whereas optic and particle cavitation are typically used for single bubble cavitation, which fails to induce any physical or chemical change in the bulk solution. The spectacular effects of cavitation phenomena generated using ultrasound (acoustic cavitation) have been more commonly harnessed in food and bioprocessing industries [6]. Similar cavitation phenomena can also be generated relatively easily in hydraulic systems. Engineers have generally been cautious regarding cavitation in hydraulic devices due to the problems of mechanical erosion, and thus all initial efforts to understand it were mainly with the objective of suppressing it in order to avoid the erosion of exposed surfaces. However, a careful design of the system allows for generation of cavity collapse conditions similar to acoustic cavitation. This enables different applications requiring varying cavitational intensities that have been successfully carried out using acoustic cavitation phenomena but with much lower energy input as compared to sonochemical reactors. In the last decade, concentrated efforts were made by few researchers around the world to harness the spectacular effects of hydrodynamic cavitation for chemical/physical transformation [7]. The present work provides an overview of different applications of cavitational reactors with an emphasis on different operations in biochemical engineering/biotechnology.

2. Reactor designs

Reactors in which cavitation is generated by ultrasound are usually described as sonochemical reactors, whereas reactors in which cavities are generated by virtue of fluid energy are described as hydrodynamic cavitation reactors.

2.1. Sonochemical reactors

Ultrasonic horns are the most commonly used reactor designs among the sonochemical reactors, although the cavitational effects are only observed close to the vibrating surface. The cavitational intensity decreases exponentially on moving away from the horn and vanishes at a distance of as low as 2–5 cm, depending on the supplied energy to the equipment and on the operating frequency [8]. Thus, the efficacy of the horn type system with larger scales of operation is poor compared to systems based on multiple transducers due to the fact that ultrasonic horns cannot effectively transmit the acoustic energy throughout a large process fluid volume. Additionally, ultrasonic horn type reactors, suffer from erosion and particle shedding at the delivery tip surface due to high surface energy intensity; cavitational blocking (acoustic decoupling), and large transducer displacement (amplitude) increases stress on the material of construction, resulting in the possibility of stress-induced fatigue failure. Typically, these reactors are recommended for laboratory scale characterization studies or for larger scale operations where lower residence times are sufficient to bring about the desired change.

Reactors based on the use of multiple transducers irradiating identical or different frequencies seems to be a logical approach. The use of multiple transducers also results in lower operating intensities at similar levels of power dissipation, and hence, problems of cavitational blocking, erosion and particle shedding at the delivery surface are reduced. The position of the transducers can also be easily modified in order for the wave patterns generated by the individual transducers to overlap, resulting in an acoustic pattern that is spatially uniform and non-coherent above the cavitational threshold throughout the reactor working volume. Arrangements such as triangular pitch in the case of ultrasonic baths, tubular reactors with either two ends irradiated with transducers or one end with a transducer and other with a reflector, parallel plate reactors with each plate irradiated with identical or different frequencies, and hexagonal flow cells are possible as represented schematically in Fig. 1 [8–10]. The vessels can be operated in a batch mode or, for larger-scale work, in a continuous mode where multiple units can be combined in a sequential manner, which also increases residence time. In summary, a plurality of low electrical and acoustic power (1–3 W/cm^2) transducers produce 25–150 W/L, with an ideal range of 40–80 W/L [10]. The power can be applied continuously or in a pulsed mode.

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 parameters of the sonochemical reactors. Intensity and frequency of irradiation along with the geometrical arrangement of the transducers and the liquid phase physicochemical properties affect the initial size of the nuclei and the nucleation process. Proper selection of the operating, geometric parameters and physicochemical properties of the