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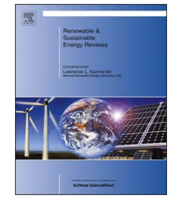

Sonochemical reactors: Review on features, advantages and limitations

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ABSTRACT

Sonochemical reactors operate based on the release of high amount of energy from ultrasonic irradiations. More application in chemical processes are being developed using these reactors. But the potential of their applications are still limited largely due to the lack of understanding about their design, operational and performance characteristics. A detail review is therefore conducted on available literature in this paper. From the review, the design features of sonochemical reactors are defined by different types, number and position of ultrasonic transducers, whereas their operational parameters are determined by ultrasonic frequency and intensity. As in the case of stirred vessel, sonochemical reactors can be also characterized for their performance based on mass transfer, mixing time and flow pattern. The review claims that sonochemical reactors have potential to be more energy efficient compared to stirred vessel if designed and operated appropriately.

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1. Introduction

Sonochemical reactors, based on the use of ultrasound as a source of energy, are being used for various applications due to

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their special features [1,2]. The phenomenon of acoustic cavitation, as the most important feature of sonochemical reactors, can be defined as the generation, growth and violent collapse of micro-bubbles under ultrasonic irradiations which can release high amount of energy in a small location [3–6]. This released energy causes a dramatic increase in temperature and pressure (few thousand Kelvin temperature and few hundred atmospheric pressure) near the ultrasonic transducer which can lead to great amount of process intensification [7,8]. In addition to this phenomenon, propagation of ultrasonic waves in the liquid medium generates local turbulence and micro-circulation in liquid which is known as acoustic streaming [5]. Acoustic streaming can mainly cause physical effects and also influence chemical processing limited by mass transfer [5].

These two phenomena also lead to some other significant properties such as high shear stress near the bubble wall, free radical production, high rate of heating and cooling, formation of liquid jet, generation of shock waves and streaming of the liquid near the bubble [3,9–16]. Due to these properties, sonochemical reactors can be effectively applied for various chemical and physical processes such as chemical synthesis, biotechnology, wastewater treatment, polymers degradation, extraction, textile processing, crystallization, leaching, emulsification and petrochemical industries, etc. [5,17–21]. Despite wide range applications of ultrasound and sonochemistry, this type of reactors mostly apply in laboratory scale and practical usage of sonochemical reactors for industrial scale will face with some difficulties.

The aim of this paper is to provide an overview of features, applications and limitations of sonochemical reactors. In addition, the hydrodynamic behavior of different sonochemical reactor configurations and the relationships of mass transfer, mixing time and flow pattern with operating parameters, based on some experimental and computational case studies have been investigated. Ultrasonic systems are extremely sensitive and vulnerable to operational parameters, which cannot be controlled without a good knowledge and understanding of physical and chemical phenomena. Therefore, the present work also aims at discussing the main parameters which should be considered for the intensification of cavitational activity. Furthermore, reviewing the application of sonochemical reactors in different areas and comparing these reactors with stirred vessels in terms of energy efficiency and mixing pattern are other objectives of this article.

2. Features of sonochemical reactors

Having sufficient knowledge about features and characteristics of sonochemical reactors leads to appropriate design and obtainment of optimum operating parameters which plays a crucial role in process efficiency based on specific applications. Choosing the suitable type of transducer with proper frequency range and power intensity, number of transducers and their positions in the reactor can be extremely effective in optimizing the cavitational activity, acoustic streaming and enhancement of sonochemical reactor efficiency.

2.1. Type of sonochemical reactors

There are a few types of sonochemical reactors with different ultrasonic transducers which are usually applied in laboratory scale applications. Ultrasonic horn is the most common type of sonochemical reactor which is applied in many experimental studies such as micromixing, transesterification of biodiesel, saccharification, microfiltration, etc. [20,22–28]. A schematic picture of ultrasonic horn reactor is illustrated in Fig. 1. The ultrasonic horn involves a cylindrical probe which submerges in the liquid and transmits the wave into the medium directly. According to the literature, the diameter of this probe is usually between 5 mm and 1.5 cm and it is usually made of transition metals such as titanium [29,30]. Ultrasonic horn can generate a high magnitude of intensity close to the probe and they can be beneficial for vigorous stirring in small scale operations [31].

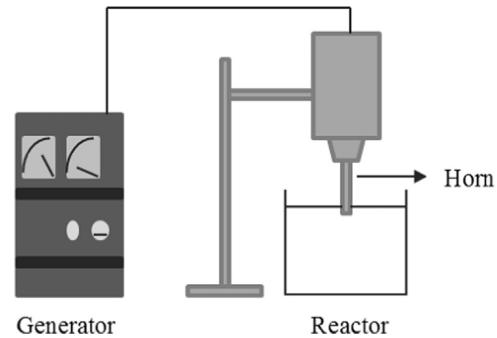

Fig. 1. Ultrasonic horn reactor, adapted from [2].

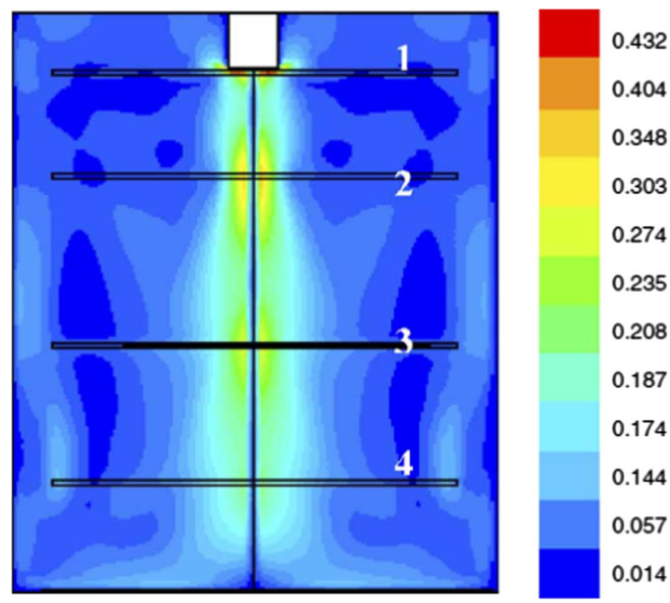

Fig. 2. Locations of boundary conditions (BC). 1 at $z=0.05$ H, 2 at $z=0.32$ H, 3 at $z=0.71$ H, 4 at $z=0.94$ H. The contours represent the mean velocity magnitude in ms^{-1} [32].

The immersion depth of probe into the medium and also the ratio of probe diameter to vessel diameter are the parameters that should be considered in designing horn ultrasonic reactors [32]. Kumar et al. [32] analyzed the effect of this ratio on mixing time by modifying the size of vessels and they claimed that an optimum diameter for vessel could be found in order to gain a uniform mixing. They also studied the fluid velocity in axial, radial and tangential direction and obtained high axial and radial velocity close to the horn and lower at the vessel wall. In another study, Faïd et al. [30] analyzed the effect of three types of sonochemical reactor and mentioned that the number of cavitation bubble near the transducer was much higher than other positions in ultrasonic horn reactor. Fig. 2 shows distribution of the mean velocity and locations of boundary conditions for CFD simulation in the vessel [32]. It can be seen from Fig. 2 that ultrasonic horn can provide significant cavitation in the medium by focusing its energy on a specific zone of sample.

Ultrasonic horn can also be used longitudinally in the vessel for different applications. Bhirud et al. [33] applied a longitudinal