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Intensification of chemical processing applications using ultrasonic and microwave irradiations

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The present work offers insights into the use of ultrasonic and microwave irradiations for the intensification of chemical processing applications. A critical opinion on the governing mechanisms, reactor designs and effects of the operating parameters on the degree of intensification has been presented. Discussion on the possible combined application of ultrasound and microwave to yield synergistic effects have also been presented. Overall, it appears that significant process intensification benefits in terms of reduced reaction times, higher yields, use of ambient conditions and reduced chemical requirement can be harnessed based on the use of irradiations, possibly leading to considerable economic savings.

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Introduction

Process intensification can be achieved by use of irradiations especially ultrasound and microwave due to the significant effects induced in the processed liquids in terms of intense heating (even hot spots), intense turbulence and chemical effects [1]. One of the main motives for application of process intensification techniques is obtaining intensified rates of transfer processes (mass as well as heat transfer) which can be effectively achieved based on the use of ultrasound and microwave irradiations. The present work offers opinion on the important issues related to the application of ultrasound and microwave for intensification starting with the fundamental mechanisms, suitable reactors and operating conditions as well as the possibilities of combining the two modes of irradiation.

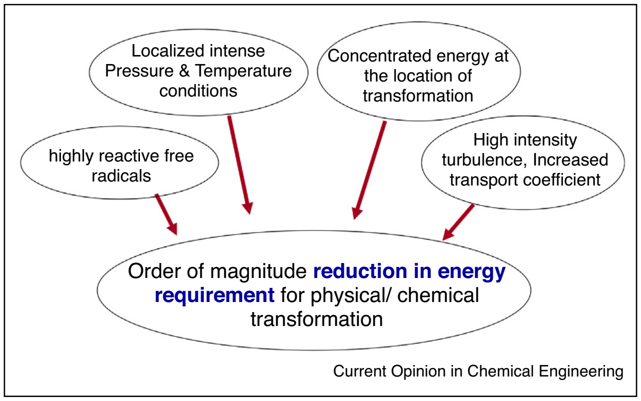
Sonochemical reactors based on the use of ultrasound offer immense potential for process intensification based on the significant cavitational effects induced in the liquid medium [2••]. The generation of cavitational events and the subsequent release of energy at microscopic level also mean that the energy is made available at the specific point of transformation or at the controlling active sites which can definitely increase the energy efficiencies and also yield enhanced processing rates. The variety of chemical processing applications where sonochemical reactors can be effectively applied for process intensification [3•,4,5–7] include chemical synthesis, wastewater treatment, nano-material synthesis, crystallization, emulsification, atomization, petroleum refining and also enzymatic reactions or the recovery of enzyme from cells.

Microwaves are the non-ionizing irradiations over the range of 300 MHz–300 GHz, which can aid in transmitting the energy to the reacting materials at a molecular level, also leading to much faster and uniform heating of the ingredients. The main intensification benefit due to the use of microwave irradiation is in terms of enhancing the reaction/transport rates significantly such that the required processing times can be reduced from several hours to few minutes [8••]. Use of microwave can immensely benefit the chemical processing industries [9•,10] with proven applications in the area of synthesis including organic homogeneous reactions and heterogeneous catalytic reactions; environmental engineering for remediation of hazardous pollutants and separations including distillation, membrane separation and adsorption.

Controlling mechanisms for intensification

The exact mechanism of intensification due to the use of ultrasound is mainly dependent on the fact whether the system is homogeneous or heterogeneous. In the case of homogenous systems, especially for the chemical reactions [3•], dominant chemical effects of cavitation as local hot spots (conditions of very high temperature and pressure locally which can give pyrolytic dissociation reactions) and generation of radicals drive the required intensification mechanisms. On the other hand, for the heterogeneous systems [11•] including reactions and separations, physical effects of cavitation such as intense turbulence and liquid circulation currents generated at micro-scale play a major role in deciding the intensification degree. For the chemical synthesis applications involving solids (either as reactants or gases) and gases,

Figure 1



Schematic representation of the cavitational effects driving the process intensification in ultrasound reactors.

both physical and chemical effects would play a major role and in such cases, a critical analysis of the controlling mechanisms is required to properly select the set of operating parameters. Presence of gas and solids to some extent in the system plays an important role in deciding the physical and chemical aspects of the nonlinearly oscillating bubbles including the maximum size reached, the energy released and the quantum of the free radicals produced [12]. In general both the chemical and physical effects of cavitation (Figure 1) would have some contribution to the overall effects but more importantly properly optimized conditions to give desired effects based on the controlling mechanism can lead to significant intensification and energy savings.

Microwaves interact with the liquids by two mechanisms of dipole rotation and ion migration giving confined and instantaneous heating at rates much faster than the conventional approaches [13]. The dipoles have a tendency of rotating in the direction of the applied electric field, which changes swiftly in the case of microwave driving the orientations of the dipole. Very high temperatures are generated locally due to the frictional forces between the intensely spinning polar particles and the surrounding medium [8••,14]. In ion migration, oscillations of the charged particles induced by microwave leads to dissipation of the kinematic energy resulting in high temperature and pressure gradients giving enhanced transport rates and also overcoming the necessary activation energies for the reactions. Microwave induced heating also offers distinct advantages as compared to the conventional heating especially in cases where there are lots of barriers restricting the transfer by convection, conduction and radiation.

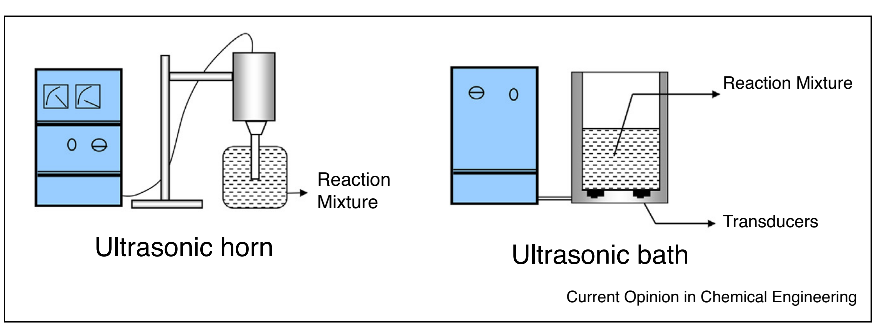
Reactor configurations

Ultrasound reactors

The main governing factor for developing efficient ultrasound reactors especially at larger scales of operation is the arrangement of transducers as the cavitationally active zone is usually concentrated in the close vicinity of the transducers [15]. In essence, using multiple transducers is a must for large scale designs and this also offers the flexibility of using multiple frequencies of irradiation which can aid in generating intense cavitation and also giving lower power dissipation per transducer which can avoid the decoupling effects and also prevent erosion of the transducers. Piezoelectric and magnetostrictive transducers are the most commonly used types and most of the recent innovations have been directed in terms of developing new materials for minimizing the erosions and giving higher energy transfer efficiencies as well as new designs which can give higher active volumes in the reactor and allow bonding of the transducers to the cylindrical surfaces.

Ultrasonic horn is the widely used design where the processed liquid is in direct contact with the transducer (Figure 2). The typical operating capacities are restricted especially for the batch operation and these designs are recommended for all the exploratory or characterization studies. Ultrasonic bath, which are typically cleaning tank type with transducers attached to the bottom of the vessel

Figure 2



Standard designs of the ultrasound reactors.