International Academic Institute for Science and Technology

International Academic Journal of Innovative Research
Vol. 10, No. 2, 2023, pp. 71-75.

ISSN 2454-390X

International Academic Journal of Innovative Research

www.iaiest.com

Principles And Applications of Intensification of Chemical Reactions Using Ultrasonic Tubular Reactors

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Abstract

Ultrasonic microreactors are becoming more popular for tasks like particle synthesis, crystallization, and organic synthesis involving solids, mainly because ultrasound helps prevent clogging. However, the scaling problems of ultrasonic flow reactors limit the wider application of this technology. The demand for efficient wastewater treatment is become more pressing as industrial activity increases. The volume of liquid waste is increasing while water purification standards are becoming more stringent. Numerous physical and chemical techniques, such as electrocoagulation, sorption, biological approaches, ultraviolet exposure, oxidation, coagulation, and flocculation, have been developed to treat wastewater in response to market demands. The advantages and disadvantages of each of these approaches dictate the situations in which they can be used successfully. Studies have indicated that the physical and chemical processes involved in these methods can be improved by ultrasonic treatment. For example, ultrasonic stimulation can shorten reaction times or increase purification levels by ultrasonic oscillations, while also drastically reducing the number of reagents required, such as coagulants and flocculants. However, the challenge lies in the need to treat large volumes of water that contain only small amounts of impurities, which complicates the use of powerful ultrasound for enhancing wastewater treatment on an industrial scale.

Keywords: Ultrasonic Tubular Reactor, Flow Reactor.

DOI: 10.71086/IAJIR/V10I2/IAJIR1016
Received: 29 March 2023/Revised: 17 April 2023/Accepted: 27 May 2023/Published: 30 June 2023

Introduction

In recent years, scientists have been on a mission to find new energy sources that can keep up with the growing demands of our global population and booming economies. An astounding 81% of the world's energy currently comes from non-renewable sources like fossil fuels, while just roughly 13% comes from renewable sources, mostly biomass, waste, and hydroelectric power. The use of nuclear and renewable fuels is still quite low compared to these other options. Thankfully, we've made some progress in tackling the energy crisis through the successful reprocessing of nuclear waste and rare earth materials (Utikar & Ranade, 2017). Various metal extraction facilities and nuclear industries generate a significant amount of waste during their processes. Additionally, power plants and metal industries produce a lot of slag that ends up sitting in nearby areas for extended periods. Even common household items, like fluorescent lights and electronic devices, can contain non-useful byproducts such as phosphoric acid, which could be extracted for future use. All these different types of waste hold a treasure trove of rare earth materials that can be repurposed. To address the future fuel shortages, it's crucial to extract nuclear and rare earth materials, along with e-waste that contains high-energy components, for further applications. The effectiveness and safety of any nuclear power system largely hinge on the success of the reactor's energy and fuel materials. The reprocessing of materials from nuclear reactors, along with rare earth elements and other less immediately useful materials found in used fuel, poses quite a challenge for academics and researchers. There are several methods available for separating and reprocessing these energy materials. Techniques such as the PUREX process, pyrochemical reprocessing, liquid-liquid extraction, and ultrasonic-assisted extraction have become focal points in the effort to manage these wastes and recover rare earth elements (Gogate & Patil, 2017). Among these methods, ultrasonic extraction stands out due to its numerous advantages, including being a non-destructive technique, cost-effectiveness, and its ability to interact with atomic and subatomic spaces, making significant contributions to extraction processes. The ultrasonic-assisted solvent extraction method is particularly efficient and economical for separating these types of materials. Overall, recovering and reprocessing nuclear waste enables the recycling of valuable fissile materials like uranium and plutonium, as well as some minor actinides such as americium, neptunium, and curium. Uranium and plutonium are crucial in the nuclear industry, but they are also highly toxic in the environment. Uranium is found throughout the Earth's crust and is naturally radioactive. It primarily exists in rocks, soils, and even in various rivers and seawater. Interestingly, uranium is more common than tin and is about 500 times more abundant than gold globally. However, recent predictions indicate that global uranium resources are quite limited, raising concerns about their availability for the coming decades. Ultrasonic assisted solvent extraction has proven to be an effective method for extracting solid/liquid mixtures in high-concentration suspensions. The beauty of ultrasonic waves is that they can penetrate various parts of biphasic or multiphase systems, which can be tricky to reach with other extraction techniques. Plus, when you compare it to continuous ultrasound, using a pulsed mode not only reduces heating effects but also seems to enhance efficiency and save energy. That’s why pulsed mode is often the go-to choose when scaling up water or sewage treatment processes. One thing to keep in mind for any flow system is that you’ll need pumping (or gravity feed) to keep the circulation going through the flow cell. This isn’t usually an issue for water processing, but it can be a factor to consider when dealing with sewage and sludge treatment. In the lab, a high-power, low-volume system can be achieved with a probe system that has a flow cell attachment (Banakar et al., 2022). However, tip erosion may become an issue when using high powers. A far bigger Sono chemical treatment zone might be created by inserting many probes through a vessel's walls in an alternate configuration. Even though this system would encounter the same difficulties as a single flow cell, it would continue to function even in the event that one or two probe units failed.

Literature Review

Ultrasound has been recognized for years as an effective way to eliminate micro-organisms. Recent research also indicates that it can help break down chemical contaminants. However, these oxidative processes tend to demand a lot of power, especially for the high flow rates seen in today’s water treatment systems, which can handle several cubic meters per second. Because of this, it seems that high-intensity ultrasound might not be practical in this field. On the other hand, in specialized treatment scenarios that deal with smaller volumes, high-intensity ultrasound could be a cost-effective option. For larger operations that require this kind of ultrasound, using a sonic horn or any other high-power ultrasound source is most effective when integrated into a flow system. This configuration could be a simple one-pass treatment inside a processing plant or a loop outside the main reactor. Compared to a straightforward batch arrangement, it has a number of important advantages and enables the processing of enormous volumes: By varying the input power to the transducer or the flow rate through the cell, high-intensity sonication can be applied to a continuously flowing liquid response with controllable exposure and power levels. Sound, after all, is a natural phenomenon that carries energy from one place to another, but it can only do so through matter, not through a vacuum (Haase et al., 2022). Sound waves are essentially the vibrations that travel through different materials. Without a

medium to carry those vibrations, sound simply can't exist. One of the key characteristics of sound is its frequency, which refers to how fast the sound source and the material are vibrating. It's interesting to note that the human ear isn't capable of detecting every single sound frequency out there. The typical range of sounds that we can hear is between 20 Hz and 20,000 Hz (20 kHz). On the other hand, ultrasonics refers to sound technology and the science of acoustics that deals with frequencies above 20 kHz, extending into several MHz, which we can't hear. Low amplitude waves are particularly noticeable in the frequency range of 2 to 10 MHz. Sounds with frequencies below what we can hear are known as infrasonic. For gases, the upper frequency limit is around 5 MHz, while for liquids, it can go up to 500 MHz.

Methodology

One of three waveguide systems connected to a magneto strictive transducer that runs at a frequency of 20 kHz and a power of 1 kW was used to treat the reagent using ultrasonic waves prior to use. The duration of each treatment was one minute. We matched the resonance frequency of the magneto strictive transducer with the geometrical dimensions of all three waveguide systems. A cylinder waveguide, a rod waveguide with rectangular protrusions, and a tubular waveguide were among the systems we employed. The cylindrical waveguide is the most straightforward and economical to design and manufacture of these (Gogate et al., 2003). It does, however, have certain technological restrictions, especially with relation to amplitude. There are regions of maximum displacement (antinodes) and regions of zero displacement (nodes) in the acoustic field generated by a cylindrical waveguide. Using a greater surface area is one method to deal with this problem. Extended surface designs abound, some of which are already well-known and in widespread use. For example, the rectangularly protruded rod waveguide that we used in our studies is also known as a "cascade sonotrode" and has been used in a variety of industries. We used a dynamic pressure sensor, the PS 01-03, which has a single-crystal element that functions across a broad dynamic range, to investigate the acoustic fields produced by the various waveguide systems. At signal frequencies higher than 20 kHz, its nonlinearity is less than 2% and its sensitivity is 400 nC/bar. We believe that the ideal dimensions for possible industrial reactors are a quarter and three-quarters of a wavelength from the waveguide system's surface, which is where our observations were made (Dong et al., 2020).

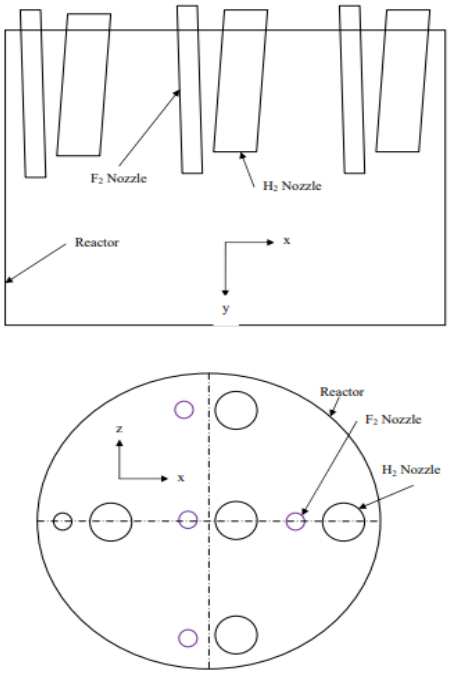


Fig. 1: Sketch of Scale-Up Reactor

The waves generated by the waveguide system and those bouncing off the reactor walls won't cancel one other out when the reactor diameters are around these values. According to our studies of the purification of the model emulsions, ASFC reaches its maximum efficiency during 96 hours of exposure at 25 °C, after which its efficacy begins to decline.

We treated ASFC reagent solutions ultrasonically in two vessels of varying diameters in order to more accurately replicate actual industrial circumstances, which might fluctuate greatly between facilities. This was an attempt to comprehend the situations in which different volumes of water require treatment. The larger vessel was 500 mm in diameter, while the smaller one was 250 mm. The length of both vessels was 700 mm. Throughout the trials, flow rates were kept at about 10 l/min while the treatment was conducted at 25 °C and 0.2 MPa of pressure. We employed the KN-3 equipment, which is intended to assess the concentration of petroleum compounds in contaminated water samples, to analyze the cleaning effectiveness of the model emulsions (Sancheti & Gogate, 2017). For our measurements, we made model emulsions using oil both before and after they were processed in carbon tetrachloride. Optical microscopy, which can measure as small as 1 μm at a 1000× magnification, was used to evaluate the particle sizes of ASFC.

Results and Discussion

Temperature control can be achieved by managing the overall temperature of the large volume of circulating reaction mixture, whether that's in a flow loop, through a heat exchanger located downstream from the ultrasonic source, or by using a pulsed option for intermittent sonication. Right now, ultrasonic techniques are widely utilized across a range of applications, from household uses to natural safety measures and even heavy industrial production.

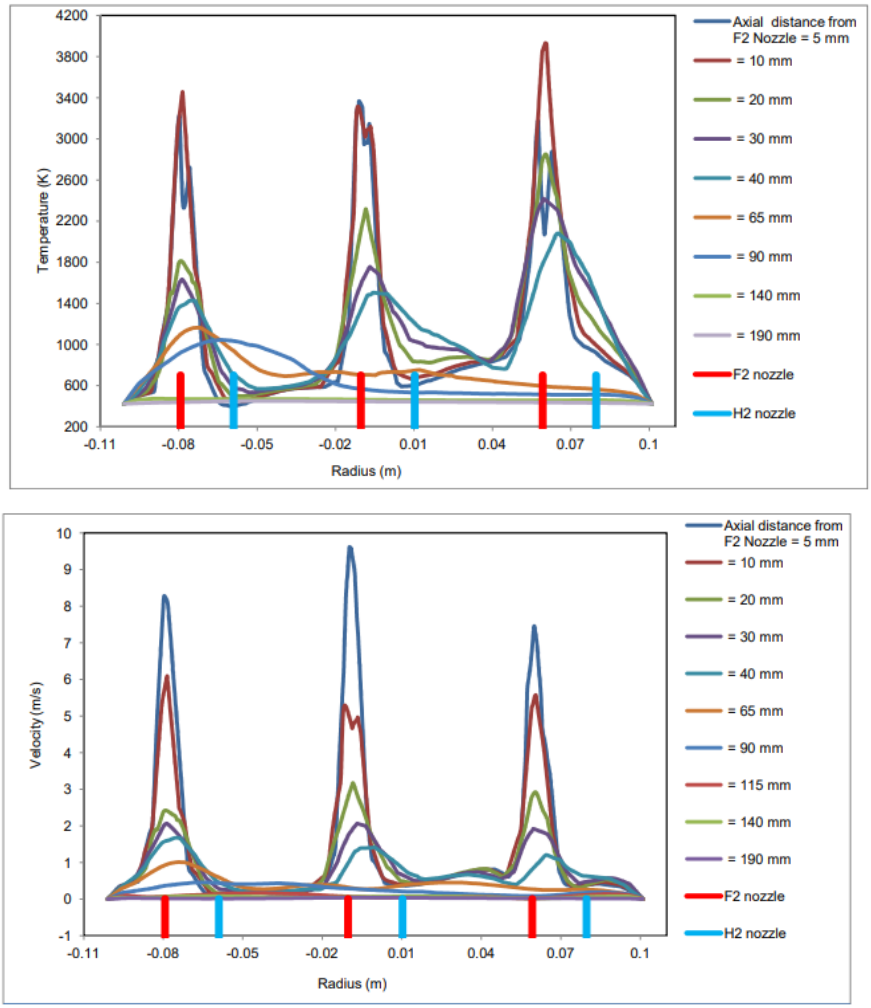


Fig. 2: (a) Temperature and (b) Velocity Plots for the Multiple Nozzle Scale-Up Reactor

The ultrasonic technique is widely used as a power source, transmitting energy through a liquid medium by creating micro bubbles due to cavitation. This process has applications across various fields, including manufacturing, biotechnology, organic synthesis, and materials chemistry. When it comes to the challenges mentioned earlier, ultrasonic methods are incredibly effective for selecting the right solvent for extraction by examining the different

physical and chemical properties of the liquid molecules involved (Gogate, 2008). By applying ultrasonic waves in a liquid, we can generate various acoustic forces. Micro bubbles occur as a result of the medium's temperature rising as these waves spread and produce acoustic energy. This phenomenon can help modify certain undesirable properties of the solvent that hinder the extraction process. Temperature control can be managed through the overall temperature of a large circulating reaction mixture, using a flow loop, a heat exchanger positioned downstream from the ultrasonic source, or by employing a pulsed option for intermittent sonication. Nowadays, ultrasonic techniques are extensively utilized for a wide range of applications, from household uses to ensuring natural safety and even in heavy industrial production. The ultrasonic technique is often used as a power source, transmitting energy through a liquid medium by creating tiny bubbles due to cavitation. This approach can be applied across various fields, including manufacturing, biotechnology, organic synthesis, and materials chemistry. When it comes to the issue at hand, ultrasonic methods are incredibly useful for determining the right solvent for extraction by examining the different physical and chemical properties of the liquid molecules involved. By applying ultrasonic waves in a liquid, we can generate various acoustic forces. Microbubbles emerge as a result of the medium's temperature rising as these waves spread and produce acoustic energy. This procedure can assist in changing some of the solvent's unwanted characteristics that usually impede the extraction process.

Conclusion

We investigated in detail how the distribution of acoustic fields from various waveguide systems impacts the effectiveness of ultrasonic activation for different water purification coagulants. Our research showed that several coagulants can be reactivated after their shelf life has passed, regardless of the industrial equipment being used. However, the pressure amplitude close to the reactor walls must be high enough to disintegrate the particles for activation to be successful in a big reactor. We found that the reactor's design and the technology selected have a major impact on the treatment's efficacy at the same ultrasonic power and frequency. We can reduce the amount of solid waste produced after purification, minimize the use of chemicals, and lower the residual concentration of petroleum products by carefully choosing the appropriate equipment and optimizing every process parameter. The process scaling up example we looked at emphasizes how important it is to select the appropriate waveguide and reactor size for success. Understanding this relationship is particularly valuable when evaluating processes, as using the wrong waveguide or reactor could render a potentially effective method inefficient.

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