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ORIGINAL RESEARCH PAPER

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OPTIMIZATION OF WASTE WATER TREATMENT TECHNIQUES USING ADVANCED PROCESS INTENSIFICATION STRATEGIES

KEY WORDS: cavitation, holistic,Process Intensification (PI), sustainable,ultrasonic-crystallization.

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ABSTRACT

Process Intensification (PI) can revolutionize the waste water treatment process and plant design by critical examination and holistic consideration of the process. PI offers safer, cleaner, smaller, efficient and cost effective techniques. PI provides effective and viable solutions to scale up efficiencies of various chemical treatment process. PI not only transforms inefficient plants, but also intensifies the performance of existing equipment to reduce energy consumption to acceptable and sustainable levels. PI can make existing systems more cost efficient through significant enhancements in the performance of a process. This paper presents detailed discussion on fundamentals, mechanism, advantages and limitations of certain PI methods like cavitation assisted water treatment and ultrasonic crystallization with few examples.

INTRODUCTION

Waste water treatment plants

The function of a wastewater treatment plant is to speed up this natural cleansing process. The practice of wastewater collection and treatment has been developed and perfected, using some of the most technically sound biological, physical, chemical and mechanical techniques available. As a result, public health and water quality are protected better today than ever before. Typically 200 to 500 liters of wastewater are generated for every person connected to the system each day. The amount of flow handled by a treatment plant varies with the time of day and with the season of the year.

Treatment facilities incorporate numerous processes which in combination achieve the desired water quality objectives. These processes involve the separation, removal and disposal of pollutants present in the wastewater. The treatment of wastewater is accomplished by four basic methods or techniques; physical, mechanical, biological and chemical. Physical methods of treatment include the use of tanks and other structures designed to contain and control the flow of wastewater to promote the removal of contaminants. Mechanical treatment techniques involve the use of machines, both simple and complex in design and operation. The action of bacteria and other micro-organisms are biological methods of treatment, which play a vital role in the removal of pollutants which cannot be effectively achieved by other means. Chemical treatment methods enhance the efficiency of other process operations and provide specialized treatment as a result of their addition at various treatment stages.

PI- Process Intensification

'Process Intensification' refers to the development of radical technologies for the miniaturization of process plants while achieving the same production objective as in bulky conventional processes. The goal is to bring down the plant size by 10-1000 times [1] by replacing large, expensive and energy-intensive equipment or processes with ones that are smaller, less costly and more efficient [2].Hybridization of multiple unit operations and processes into a single compact device is the rule of thumb for process intensification. Smaller is safer! Hence, process intensification dramatically increases the intrinsic safety of chemical processes.

Fundamental Principles of PI

The PI aim of "drastic improvement of equipment and process efficiency" has been previously translated to "achieve a process that is only limited by its inherent kinetics and not anymore by transfer of mass, heat or momentum (hydrodynamics)".[3]However, this view severely suffers from the drawbacks of using old paradigms such as transport phenomena and unit operations for new challenges.

The principles describes the aspect of process intensification which until now have received the least attention within the PI community, yet which may become the most important ones in the future. According to the simplest collision theory, the factors responsible for the effectiveness of a reaction event include: number/frequency of collisions, geometry of approach, mutual orientation of molecules in the moment of collisions, and their energy. Processes, in which all molecules undergo the same history, deliver ideally uniform products with minimum waste. Here not only macroscopic residence time distribution, dead zones, or bypassing but also meso- and micromixing as well as temperature gradients play an important role. It is not only about aiming at processes limited only by their inherent kinetics; it is primarily about changing that kinetics.

The above principles, in one form or another, are obviously not entirely new to chemical engineering. In process intensification, however, they are seen as explicit goals that an intensified process aims to reach. Besides, the PI interpretation of these principles often goes beyond the boundaries of the classical chemical engineering approach.

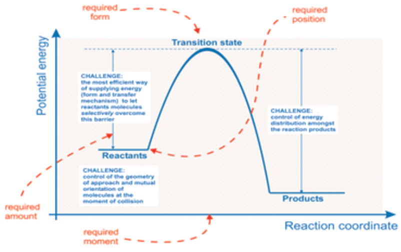

Figure 1. Engineering challenges related to the first principle of process intensification.

Process Intensification using Equipment Modification

Recently, the spinning disc reactor (SDR) was recommended as an unconventional to traditional stirred tank based processing technology. As a part of a modification of the equipment intended at process intensification, use of a continuously operating spinning disc reactor (SDR) was investigated. SDR developed by Ramshaw's group at Newcastle University (Newcastle, U.K.) mainly is targeted at fast and very fast liquid/liquid reactions with large heat effect, such as nitration, sulfonation, and polymerization (e.g., styrene polymerization.)[4-7]. A classic example for the mass transfer limited reaction is the polymerization of unsaturated esters where the reaction is carried by the removal of glycol from the reaction system. Commercial polymerization processes have conventionally been carried out in large stirred tanks and unagitated batch or continuous pipe-line/ tubular reactors. There are some limitations of stirred tank reactor with respect to conversions. The common problem encountered in polymerization process is the inefficient heat transfer surfaces for the removal of the heat liberated during the polymerization reaction, due to poor mixing in high viscosity/high polymer mixtures .These problems are more severe in bulk processes where the viscosity of the mixture increases by about seven orders of magnitude during the course of the polymerization, which generates `hot spots' and `temperature peaking' resulting in poor polymer product quality. This is a challenging problem for a chemical engineer to efficiently operate polymer reactors.

The way out of this problem can be through the SDR. Schematic representation of the spinning disc reactor is shown in Fig. 2. In the SDR, the reactive reagents and substrates are well mixed in the center well of the spinning disc through two feed inlets. A positive displacement pump is used to pump reactants and solvents. The spinning disc is horizontally oriented and can be heated or cooled by a heat transfer medium. An actual operating temperature range of -20-170 °C was achieved. An air-driven motor at rotational speeds up to 5000 rpm, rotates the spinning disc. The temperature of walls of the vessel can also be maintained using jackets, and there is provision for two drain pipes for the process materials to leave the reactor. A feasible residence time on the disc is of 1-5 second; thus, the SDR can be used for the reactions with half-lives in the range of 0.1-1 second.[8] As reaction fluids are passed over the spinning disc, based on the viscosity of the fluid, a film thickness in the range 50-600 μm is formed. The SDR offers elevated heat and mass transfer rates, concerning the film/disc and the liquid streams due to very high shear stress produced, respectively. In addition, photographs of the SDR in action show that ripples are formed in the fluid film on the disc due to the surface instabilities generated, leading to further enhanced mass transfer. This makes SDR a strong option to carry out fast exothermic reactions and reactions which are limited by mass transfer rates. Multiple disc can be mounted on the same shaft to increase the throughputs.

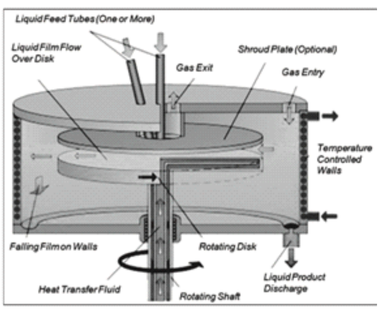

Fig.2. Schematic representations of the spinning disc reactor

Rotating packed bed (RPB) The rotating packed bed is an innovative and compact functional unit that utilizes centrifugal acceleration to increase mass transfer rate. Operation such as gas purification, distillation and Nano-material synthesis applications can be employed with rotating packed beds with a low investment cost.[9] Comparison between the sizes of RPB and conventional packed bed reactor are shown in Fig. 4 for an industrial desulfurization process.[10] Most refineries which are having a packed bed for desulfurization, but, high investment costs and large absorbing solution require huge volume of conventional PBs. The RPB can overcome these flaws of the PB. A conventional PB reactor can be modified to a RPB to enhance mass transfer by replacing gravity with centrifugal force, which can be used in absorption, distillation, stripping, extraction, and other separation processes.[11]

Conventional vs PI Approach

Conventional approaches to perform chemical operations typically have drawbacks in terms of requirement of longer reaction times, unsatisfactory yields, requirement of large amounts of toxic or expensive reagents and high temperatures giving an unsafe and sometimes uneconomical approach. The heterogeneous systems offer drawbacks in terms of the mass transfer resistances depending on the presence of different phases such as a solid, liquid or gas. In addition, the problems such as agglomeration of particles resulting into lower surface area and deposition of impurities on the solid surface offer problems during the processing which can lead to significantly slower progress of reactions.

All these problems associated with the conventional approaches point towards the requirement of an efficient process intensification approach that can help in eliminating some or most of the problems and give enhanced productivity. Use of ultrasonic reactors offer a lucrative approach for process intensification of different chemical and physical processing applications based on the cavitational effects introduced in the liquid. [12,13] Application of ultrasound can improve reactions that are intrinsically slow, resulting into lower product yields and require expensive reagents for progress.[14,15] .

The significant benefits that can be obtained by the use of ultrasound assisted chemical operations bearing similarity with the concepts of green chemistry include: increased selectivity, use of less hazardous solvents, lower energy consumption for desired transformations, use of renewable and sustainable feed stocks, reduction in the reaction time, better utilization of the raw materials and the catalyst.

Among the available newer energy sources, use of sound energy or energy associated with the liquid flow, can be used to generate cavitation phenomena which can result in significant degree of PI. Thus, the concept as described in section 2.4. i.e. deliver/ removal energy in the required form at the actual location of the targeted transformation can be employed using the concept of acoustic (ultrasound based) or hydrodynamic (liquid flow) cavitation.

The different ways in which cavitation based on the use of sound and flow energy can be effectively used for PI are summarized in Table 1.

Table.1 Comparison of various parameters that effective in PI.

Energy source	Form of application	Intensified element	Reported magnitude of possible improvement as compared to conventional technology
Acoustic field	Ultrasound irradiation	Reaction time	25 times
		Product yield	In some cases, 100% yield of the product which could not be synthesized at all via conventional methods
		Gas liquid mass transfer	5 times
	Low frequency acoustics	Liquid solid mass transfer	20 times
		Gas solid mass transfer	3 times
		Gas liquid mass transfer	2 times
Flow	Hydrodynamic cavitation	Reaction time and product yield	Similar to that of an Ultrasound, however 10 times higher cavitational yield for same energy input

	Supersonic flow	Gas liquid mass transfer coefficient	10 times
		Fluid bed reactor capacity	2.25 times

Ultrasonic Crystallization

The use of ultrasound provides a non-invasive way of improving crystal properties and process controllability, chiefly by controlling the size distribution and the habit and morphology of the crystals. The following benefits can be achieved using cavitation:

1.Improved product and process consistency; 2. Improved crystal purity; 3. Improved secondary physical properties (flow ability, packing density, etc.) of the product;4. Shorter crystallization cycle times; 5. Shorter and more reliable downstream processes through manipulated crystal size distribution (CSD).

Additionally, ultrasound can be used to replace seeding as a nucleator in difficult-to-nucleate systems. By varying the power and duration of insonation, the crystal size distribution can be tailored to optimize the ease in downstream processing. Nucleation by insonation shows a marked increase in the mean crystal size, but with continuous insonation a dramatic reduction in the mean crystallize has been observed.

The size and habit of the product crystals can be manipulated to achieve the following benefits:

1. More rapid filtration: crystals of a more uniform size and compact habit can be filtered much more rapidly.

2. Similarly, better access to the inter crystal voids greatly improves the speed of washing and drying, as well as the achievable decontamination level, reducing encapsulation.

3. The milling of crystals is a messy process that risks mutual contamination of the product and environment. By sonically tailoring crystal size distribution, the milling step may be eliminated altogether.

4. Powder filling operations can be rendered much more reliable and unproblematic because sonically nucleated crystals usually flow much better (due to rounding) than those produced conventionally.

Cavitation assisted wastewater treatment

The efficiency of the biological oxidation techniques is often hampered by the presence of bio-refractory materials, though these are the most conventionally used and economically important treatment strategies. Cavitation can be used as a supplementary technique to conventional biological oxidation to reduce the toxicity of the effluent or, in other words, to increase the biodegradability.[16] In biological wastewater treatment, large quantities of bio solids (sewage sludge) are produced. The sludge is highly susceptible to decay.

Therefore, the sludge has to be stabilized by an aerobic digestion in order to enable its environmentally safe utilization and disposal. Anaerobic digestion process is achieved through several stages: hydrolysis, acidogenesis and methanogenesis. Due to the rate-limiting step of biological sludge hydrolysis, anaerobic degradation is a slow process and large fermenters (digesters) are necessary. Typical digestion periods are more than 30–40 days. Ultrasonic reactors can be effectively used to improve sludge hydrolysis resulting in significant reduction of the digestion time.

The treatment of wastewater produces large amounts of sludge, estimated at between 5 and 25% of the total volume of treated water. The sludge generated from municipal waste treatment plants can be converted into useful fertilizers, but the sludge generated from industrial waste treatment plants is difficult to dispose as it contains large amounts of noxious chemical substances. Thus, any improvements in reducing the quantity of sludge by virtue of efficient dewatering are always beneficial to the overall wastewater treatment process. Ultrasonic energy was reported to be quite effective in dewatering of these suspensions such as slurries and sludges. Changes of structure and properties of sludge influence the efficiency of the dewatering process.

CONCLUSION

Process intensification characterized and defined in a variety of ways presents a quick and optimized solution to chemical engineers. Emerging equipment, processing techniques and operational methods promise spectacular improvements in performance of process plants, markedly shrinking their size and dramatically boosting their efficiency. These developments may result in the extinction of some traditional equipment, if not whole set of unit operations. PI appears to be very effective for intensification of chemical processing operations like the waste water treatment plants in the present study and harnessing the spectacular effects of cavitation, chemical as well as mechanical, for physical and chemical processing applications would lead to a considerable economic savings. The case study illustrations depicted in the work have clearly illustrated the efficacy of this novel technology. 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.

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