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Review

A review of process intensification applied to solids handling

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ABSTRACT

Process intensification (PI) is a strategy aimed at transforming conventional chemical processes into more economical, productive and green processes. Its fundamental concept hinges upon the volume reduction of processing equipment resulting in enhanced mixing and heat/mass transfer as well as a multitude of other benefits. To date, the focus of PI has been on processes mainly involving gas/liquid systems. Solids handling applications have been more limited as fouling and blockages can occur due to large concentrations of solids in smaller equipment sizes. Appropriately designed equipment is therefore a key consideration for intensifying industrially-relevant solids handling processes.

In this review paper, we highlight a number of solid processing applications including precipitation, separation, granulation and milling, etc. where PI has been demonstrated. Much effort has been directed at reactive crystallization and precipitation in various intensified technologies, exploiting their enhanced mixing capabilities to produce uniformly distributed nano-particles. Generally, the objective in many of these processes has focused on transforming solids handling in batch processes into continuous ones with processing time reduction and improved energy efficiency. The review highlights the considerable opportunity for further development of multifunctional technologies in solids handling applications such as granulation and drying, the subject of a European Commission-funded HORIZON 2020 project.

1. Introduction

Process intensification (PI) is a concept that has evolved over the last three decades since it was first introduced to become diverse in its implementation and practice. For many, miniaturization remains the fundamental basis of PI, with microreactor being the most typical example. For others, PI is based on functional integration, with reactive distillation being a prominent example. Thus, the original definition of PI focusing on "*the physical miniaturization of process equipment while retaining throughput and performance*" [1] has been broadened to "*the development of innovative apparatus and techniques that offer drastic improvements in chemical manufacturing and processing, substantially decreasing equipment volume, energy consumption, or waste formation, and ultimately leading to cheaper, safer, sustainable technologies.*" [2]. The latter definition widens the PI concept to include processing techniques such as alternative energy input alongside novel equipment design for miniaturization.

Whilst the original idea of PI is based upon the significant reductions of equipment size (typically at least a ten-fold volume reduction) and the associated cost savings [3], several other potential benefits related to business, process and environmental aspects can also be envisaged, as highlighted in Fig. 1. Where some of these processing benefits may be attained without a dramatic reduction in equipment size, this can be still be considered as the more modern interpretation of process intensification [2].

In terms of process safety, the reduction of plant size results in a smaller volume of toxic and flammable inventories within processes, thereby reducing the possibility of explosions. In addition, the lower number of unit operations can further simplify the process. PI is also capable of mitigating the risk of thermal runaway in highly exothermic chemical reactions by carrying out the process in the reactors. It offers greatly enhanced surface area to volume ratios for rapid removal of liberated heat e.g. in microreactors and spinning disc reactors [3–6].

PI equipment for reactions is designed with efficiency in productivity, selectivity and conversion of reactants in mind with important beneficial implications for the environmental awareness of such processes. With less by-product formation, fewer and more simplified downstream purification steps can be envisaged together with dramatically reduced net energy consumption [3,7]. On the basis of enhanced mixing and heat and mass transport rates, which have the potential to

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Nomenclature

ACR	Coflore® agitated cell reactor
API	active pharmaceutical ingredient
ATR	Coflore® agitated tube reactor
CBR	compact bed reactor
CPR	catalytic plate reactor
CSD	crystal size distribution
CSTR	continuous stirred tank reactor
DIJ	dual impinging jet
EBR	TORBED Expanded Bed Reactor
EJAC	Elbow-Jet Air Classifier
FAME	fatty acid methyl ester
IS	impinging stream
MAFBR	membrane assisted fluidized bed reactor
MSB	magnetically-stabilized bed
MSFBR	magnetically-stabilized fluidized bed reactor
MVD	microwave-assisted vacuum drying
OBR	oscillatory baffled reactor
PDG	pneumatic dry granulation
PI	process intensification
RE	reactive extraction
RFB	rotating fluidized bed
RPB	rotating packed bed
RSSD	rotor-stator spinning disc
SCR	spinning cone reactor
SDR	spinning disc reactor
SSHE	scraped-surface heat exchanger
TCR	Taylor–Couette reactor
TSG	twin screw granulator
WSMM	wet-stirred media milling

reduce reaction times significantly, PI plants require less solvent and energy. This would result in further carbon emission mitigation. As an example, compact heat exchangers, such as welded or brazed plate units where approach temperature differences can be very small, can be very efficient.

Over the years since it was first conceptualized, the implementation of PI has evolved into two distinct classifications involving the development of equipment and methods. PI equipment includes reactive and non-reactive apparatus. The former includes spinning disc reactors (SDR), static mixer reactors, monolithic reactors, micro reactors, rotating packed beds (RPB) and jet impingement reactors. The latter includes intensive mixing devices and units for separation e.g. static mixers, rotor/stator mixers and rotating packed beds as well as heat transfer devices e.g. compact heat exchangers and microchannel heat exchangers. PI methods also include multifunctional reactors, hybrid separations and the usage of alternative energy sources such as microwaves, ultrasound, and other electric fields. Multifunctional reactors enhance chemical conversion and integrate reactions and downstream operations into a single unit. Examples include membrane reactors, reactive distillation, reactive crystallization, etc. [2]. Multi-functional systems need not be limited to those incorporating reactors.

Besides liquid/liquid and liquid/gas reactions, solids handling is also an important process in many industries such as pharmaceuticals, ceramics, and mineral processing. In the case of PI, solids can be considered as the literal "blockers" to the application of PI, as PI equipment based on the miniaturization concept (on spatial domain) sometimes has narrow channels (e.g. microreactors), which large solids would foul or cut-off channels completely [3]. It is therefore important to understand the challenges and limitations presented by solids handling within the fold of PI.

In this paper, a review of the development in PI technologies and techniques for solids handling is presented. To date, several of the PI technologies discussed in this paper have been successfully developed and commercialized e.g. rotating packed beds [8] and micro reactors [9]. Other PI technologies are still under development or at the prototyping stage. One way in which one may categorize the PI characteristics of processes, including many where the size reduction associated with what one might call 'ideal' PI examples is not present, is that of Van Gerven and Stankiewicz [10] where the PI approach is classified into spatial, thermodynamic, functional or temporal domains. In this paper, particularly in Table 1 which summarizes the PI equipment discussed, the applicable approaches are identified for each technology. The extent of intensification achieved for each of the technologies reviewed is also highlighted in Table 1 in qualitative and quantitative terms, depending on the availability of information.

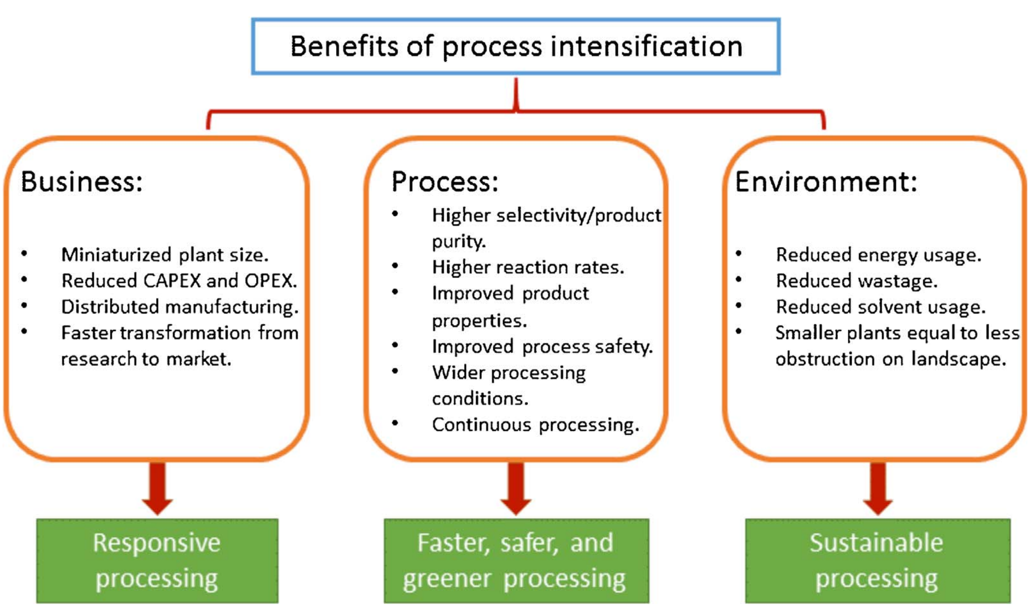

Fig. 1. Business, process, and, environmental benefits of process intensification [4].