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Local and global process intensification

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ABSTRACT

The present paper aims at proposing a complementary view of process intensification (PI) based on the concepts of local intensification and global intensification. Local intensification is defined here as the classical approach of PI based on the use of techniques and methods for the drastic improvement of the efficiency of a single unit or device. Some examples are given to illustrate that local process intensification presents several limitations when compared to holistic overall process-based intensification, named global intensification. Indeed, when PI focuses on single units (reactors, separators, hybrid separators, etc.), the strong interactions among all units within the process are ignored and the impact of local intensification of a single unit can be very limited, resulting in weak improvement of the whole process. This paper identifies that process intensification is broader than technical improvement of devices or processes and has to consider several drivers such as economics, safety, eco-efficiency and sustainability to fulfill the key objectives in designing new plants and retrofitting existing units.

1. Introduction

Process intensification (PI), formally regarded as process improvement strategy, consists, according to Stankiewicz and Moulijn [1], in novel equipment, processing techniques, and process development methods that, compared to conventional ones, offer substantial improvements in (bio) chemical manufacturing and processing. It is related to new and innovative technologies which replace large expensive and energy-intensive equipment by devices which are smaller, less costly and more efficient [2–4]. Among the different strategies, a well-established approach is the design of multifunctional devices, which merge several unit operations, e.g. reaction and separation into one apparatus [2]. However, recent approaches in PI predominantly focus on equipment and more specifically on microstructured technologies, providing a high surface-to-volume ratio, hence increasing mass and heat transfer by several orders of magnitude [5]. The revolution-like manners in which microtechnology develops (and as which it is sometimes praised) manifest themselves in the vast number of patents in this field of research. Every year, numerous patents are reported for microtechnology-related areas. Focusing on microreactors, more than 1500 patent publications in different fields of chemical applications already exist, annually rising in number by more than 250 new patents [6]. Then, from the numerous studies published in the literature, it is clear that PI focuses on the equipment improvement, which can be defined as a local approach of process improvement strategy.

On the other hand, process system engineering (PSE), according to Grossmann and Westerberg [7], aims at improving decision-making for the creation and operation of the chemical supply chain, which deals with the discovery, design, manufacturing, and distribution of chemical products. From this definition, PSE can be considered as a global approach of process improvement strategy. Recently, Moulijn et al. [8] felt that it was timely to attempt to better define the place of PI in relation with other chemical engineering disciplines, such as PSE. Based on the preliminary approach by Grossmann and Westerberg [7] and Marquardt et al. [9], they proposed to define PI in conjunction with PSE. The focus and action of PSE take place along the product creation chain, as a top-down approach from the enterprise to the molecules, while the focus and action of PI are on chemical engineering aspects of the process units separately. PI has a more creative than integrating character and primarily aims at higher efficiency of individual steps in that chain, for instance by offering new mechanisms, materials, and structural building blocks for process synthesis.

In addition, the scales considered are different; PSE focuses less on the scale of molecules, sites and (nano-) structure, whereas PI

Abbreviations: API, active pharmaceutical ingredient; CSTR, continuous stirred tank reactor; GHG, greenhouse gases; LCA, life cycle assessment; PI, process intensification; PFR, plug flow reactor; PR, process retrofit; PSE, process system engineering; ROI, return on investment time; RSR, reactor separator recycle.

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explicitly includes this level but often pays less attention to the highest levels. It is clear that PI has consequences for the “longitudinal” action of PSE; for instance, development and application of a reactive separation can influence the PSE over the whole chain, from molecule to site, if not to enterprise.

The improvement of processes must also be examined in the context that a major portion of the chemical industry has matured. Most chemical plants were built at a time when profit margins could be kept large and thus were not typically designed to be the most efficient from an energy and raw material perspective. Nowadays, competitive pressures have greatly increased the need for more efficient processes claiming for the redesign and the modernization of existing facilities. Grossmann et al. [10] estimated that, in the end of the 80s, 70–80% of all process design projects in the western countries dealt with the redesign, i.e. retrofit design of existing facilities.

Also, the successful commercialization of specialty chemicals requires the ability to redesign processes quickly, to respond to changes in new technology and to the short life cycle of new products. According to Grossmann and Westerberg, the development of retrofit design strategies is a more difficult problem than the design of new processes because it includes a far greater number of alternatives than the grassroots problem, due to the need to evaluate and use existing equipment. The nature of the retrofit problem is by nature complex and multidimensional. They propose a list of technical objectives as the increase of the throughput by debottlenecking and by higher conversion of feedstocks, the processing of a new feedstock and the improvement of the quality of the product. Sustainability is also considered by the increase of process safety, the reduction of the environmental impact of an existing process, the reduction of energy input per unit of production, and the higher operability of the process (flexibility, controllability).

Concerning economics and the major constraints of process retrofit (PR), several approaches can be developed. The change of the operating conditions of the process can enable to keep the same implemented equipment which is obviously the least costly in terms of investment. The change of architecture of the process by changing the piping that connects the devices is another alternative. For example, with respect to the cost of purchasing a new column, repiping typically incurs very modest costs. It is also possible to keep the process flowsheet intact but to change the equipment sizing, sometimes in ways that the external physical dimensions of the equipment are not altered. Such changes could include installation of new tube bundles inside existing heat-exchanger shells, closer packed trays or even packing inside columns. And finally, the last approach is the addition of new equipment to reach the objectives.

From the definition proposed by Grossmann et al. [10], it is obvious that PR shares numerous keywords (improvement of conversion and yield, reduction of energy consumption and environmental impact, safety considerations, etc.) with process system engineering and process intensification. This large overlapping between those three concepts shows also that PR is concerned by local and global intensification and that synergies between them may exist.

However, as stated by El-Halwagi and co-workers [11], there are some limitations in most of the previous works focused on unit-based intensification when compared to holistic overall process-based intensification.

El-Halwagi and co-workers identified process integration as a holistic and systematic framework for intensification where, however, process intensification has a broader scope. They defined two main classes for intensification: single-unit intensification and plant intensification. Unit intensification refers to the previous definition of process intensification. On the other hand, plant intensification focuses on the improvement of the global process: maximize the throughput, minimize inventory, or minimize utility materials and feedstock. In case of plant intensification, units that will be intensified are not pre-specified and more than one unit can be intensified simultaneously.

The present paper aims at proposing a complementary view of process intensification based on the concepts of local intensification and global intensification. Local intensification is defined here as the classical approach of PI based on the use of techniques and methods for the drastic improvement of the efficiency of a single unit or device (reactors, separators, mixers, exchangers, etc.), to overcome specific limitations that can be related to thermodynamics, kinetics, heat or mass transfer and energy supply. It mainly focuses on the technical improvement of the performances of equipment but the interactions among all units within the process are ignored and the impact of intensifying a single unit on the rest of the process is not considered.

First, global (or overall) intensification has a more general view on the whole process, considering first a multi-dimensional approach consisting in the simultaneous improvement of several units. The process is improved by inventory and utility minimization and by throughput maximization. Process intensification is achieved using the classical methods of local intensification and heat and mass integrations meaning that a complex flowsheet or architecture should be designed to increase the overall process efficiency. The impact of a local change will have an effect on the entire process due to the strong interactions between units and should therefore be studied at the whole process scale.

Secondly, global intensification possesses a multi-dimensional aspect where different drivers (economic, safety, eco-efficiency and sustainability) are included in the strategy. There are some limitations in most of the previous PI works as they focused mainly on technical drivers but did not develop an holistic view, omitting to include the different drivers. This is not the case with retrofit design that recently included various methods to evaluate and reduce the environmental impact of chemical processes. Sun et al. [12] proposed the formulation of a multi-objective optimization problem to determine sustainable chemical process designs taking into account economic, environmental and societal aspects. El-Halwagi and co-workers [13] presented a multi-objective optimization procedure for the recycle and reuse networks including the environmental implications of the discharged wastes using life-cycle assessment. More recently, they developed [11] a first attempt to couple an intensification strategy with a multi-objective optimization problem, but the mathematical functions used to represent intensification lacked for realism. In a recent study, Gani and co-workers [14] presented the development of a software tool and its application to chemical processes, based on the implementation of an extended systematic methodology for sustainable process design.

Further work is still needed to combine process retrofit, process intensification and process system engineering to define an intensification strategy which takes into account both the local approach of PI and the global approach of PSE considering the whole process by multi-objective optimization to propose sustainable and intensive chemical process designs. The strategy should answer the following questions. Which equipment should be intensified in a process? What is the impact of local process intensification of a device on the overall process performance? How should new process architecture be achieved? Which optimization criteria should be chosen? What are the criteria of safer processes?

In the present paper, some examples will be given to illustrate that the classical approach of process intensification based on single-unit intensification presents several limitations when compared to holistic overall process-based intensification.