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Book review: "Process intensification – breakthrough in design, industrial innovation practices, and education"

By Jan Harmsen and Maarten Verkert De Gruyter

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Process intensification is often defined as the improvement of a process at a molecular, functional, and operational levels to design breakthrough, cost-effective, and integrated chemical technologies. This discipline, that has emerged in its full splendor only in recent years, is considered to be one of the most promising paths for developing circular processes and is attracting great scientific and technological interests. Miniaturized continuous-flow reactors for century-old batch processes, lean operations, and synergistic reaction-separation methods are today essential elements of the industrial practice. Written by Jan Harmsen and Maarten Verkert, *Process Intensification - Breakthrough in Design, Industrial Innovation Practices, and Education* is a timely contribution to the field and presents a concise, complete, and systematic overview of the sustainability aspects encountered in process intensification. In particular, taking the steps from the discipline theoretical foundations, the book moves to more advanced topics, covering real applications that the authors have seen in their life-long industrial experience. Dr Jan Harmsen is, in fact, a chemical engineer who has held professional positions in process research, process development, reaction engineering, process concept design, and process intensification at European and Asian manufacturing sites of Shell. He was also a professor of Sustainable Chemical Technology at TU Delft and Groningen University. On the other hand, Dr Maarten Verkerk is a material scientist that has worked for more than 15 years at Philips, before returning to academia, teaching innovation, sustainability, philosophy, and ethics at Maastricht University and TU Eindhoven.

One of the goals of *Process Intensification - Breakthrough in Design, Industrial Innovation Practices, and Education* is to provide practical guidelines to chemical engineers on how to design in a very systematic manner sustainable processes for the next century. Thus, the book covers several topics: process design, function integration, process value, equipment sizing and costing, economic evaluation, process optimization and validation, process feasibility and development stages, engineering procurement, start-up, and societal values. The book briefly details the usage of specific unit operations such as reactive distillation, oscillatory baffled reactor networks, as well as the role of emerging process windows.

The text is divided into 19 chapters, which are split into four sections. The first, entitled "Theory", gives a general introduction to the topic of process intensification, clarifying the difference between conventional process design based on established unit operations and design based on process-intensified principles. After defining what process intensification is, it enumerates the four domains of process intensification (i.e., structure, synergy, time, and energy), bringing multiple examples of chemical process units to clarify the concepts. This section then describes the role of sustainability as a gate for chemistry and chemical engineering innovation, through the eyes of managers and engineers, and how these values, interests, and beliefs can be applied in industrial innovation practices. This section ends with a holistic overview of intensification practices at various levels (e.g., R&D, operations, marketing, and sales), convincingly showing with memorable examples from the author's experience at Shell Chemicals how the different perspectives on process improvement are integrated into project plans and decision-making stage.

Section two, consisting of six chapters, goes deeper into the application of this theoretical framework, pointing to the steps that facilitate inventors to get process ideas to the development stage. This section opens with a description of the discovery stage, which is about obtaining concepts (i.e., scoping, design synthesis, simulations, trial-and-error experiments) and validating them (i.e., analysis, proof-of-concept, and gate evaluation). It also highlights the role of creativity and multidisciplinarity in breaking current barriers. The following chapters detail concept and feasibility stage, where a process design is provided and where the feasibility of the most critical steps is assessed, prior to make a decision regarding the development stage. Here, a proven pilot design is realized to take the decision about entering the commercialization stage. The final two chapters are about project procurement, realization, start-up, and normal operation. To this end, this whole section gives an excellent description to get an idea of the tools needed to improve an industrial process and how these can be applied, successfully laying a foundation for the topic of process improvement as a whole. In a sense, this section suits not only Chemical and Process Engineering students, but also scientists and line managers that are already working in the private sector and are implementing sustainability development goals in the chemical, materials, and process sectors.

The third section focuses on selected industrial cases. Each topic is motivated by introducing the main characteristics and relationships

that must be ensured so that a new process can truly reach commercial scale and can be greener, leaner, safer, and more efficient. The authors introduce the use of rotating cone reactor for the pyrolysis of biomass, the multifunctional integration of unit operations for the synthesis of methyl acetate at Eastman, the Shell OMEGA monoethylene glycol process, the use of cyclic reactive distillation for intensified ethanol production, and the implementation of intensified-principles in pharmaceutical drug discovery and development. In doing so, this section covers important industrial and research results in the field of process intensification. The reader is hooked by the mole of the information provided, and the two authors successfully convey their passion for the field as well as a sense of how exciting and far-reaching process intensification can be.

The final section is about the critical role that teaching (at B.Sc., M.Sc., and Ph.D. level) can have in advancing the field, creating a competent and dedicated workforce to enhance the industry expertise and its competitivity. Overall, the last chapters contain excellent advice for scholars and all those working in the education field.

Several chapters have an "exercise" section near the end. Here, Harmsen and Verkerk provide a few research questions and challenges that need to be addressed in order to make advances in a particular area. These questions give the reader a piece of direct evidence that process intensification is a dynamic, still-developing field that needs continuous contributions. The questions presented are also an outstanding resource for instructors looking for topics for class discussions. Overall, conscious of the spiraling advances in this multidisciplinary field, the authors undertook the commendable task of writing a short and unified text that would serve as a guide for activities in this area. The extensive bibliography provided at the end of each chapter is superb, containing a list of further reading to key papers and review articles. Students and readers new to the field of process intensification can only appreciate this comprehensive bibliography because they can readily find articles to learn more on a particular topic that catches their interest. Thus, I am sure that this book will endure as a reference in the field of Process Intensification for the decades to come.

It is important to recognize that this work by Harmsen and Verkert builds on other outstanding texts (Reay, Ramshaw, Harvey, *Process Intensification - Second Edition*, *Engineering for Efficiency*, *Sustainability and Flexibility*, Elsevier 2013; Stankiewicz, Van Gerven, Stefanidis, *The Fundamentals of Process Intensification*, Wiley 2019; Hessel, Kralisch, Kockmann, *Novel Process Windows: Innovative Gates to Intensified and Sustainable Chemical Processes*, Wiley 2014; Segovia-Hernández, Bonilla-Petriciolet, *Process Intensification in Chemical Engineering*, Springer 2016). While the above-mentioned texts introduce the mechanisms of process intensification and detail the design principles of compact microheat exchangers, reactors, separators, and micromixers, serving as a valuable resource for those entering the field for the very first time, this book extends and revisits the topic drastically, including recent evolutions in the understanding of how process intensification must be integrated with modern sustainability principles. For this reason, the authors go beyond the theoretical foundations, explaining how to apply process intensification principles in real industrial processes and, for the very first time, how to complement those principles with best green chemistry practices. Also, how those principles are applied when multiple stockholders (i.e., R&D, operations, marketing, and sales) are involved. Another real asset of the book compared to the others is its dynamic structure, which enables the reader to engage with the content at almost any point without knowledge of the preceding sections.

In conclusion, *Process Intensification - Breakthrough in Design, Industrial Innovation Practices, and Education* by Harmsen and Verkerk succeeds in its aim of equipping the reader with interconnected and state of-the-art concepts in sustainable process intensification. The result is admirable. The didactic writing style ensures that the book will be an excellent learning resource, both for advanced graduate students wishing to apply modern concepts in process definition, and certainly for scholars, scientists, engineers, and managers in large firms and startups.

AUTHOR CONTRIBUTIONS

Gianvito Vilé: Conceptualization; formal analysis; investigation; methodology; writing-original draft; writing-review and editing.

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