Editorial: Voices of the next generation of Process Intensification

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Process Intensification (PI) can shape the modern chemical, pharmaceutical and energy industries, by moving away from the traditional unit-operations approach, exploiting the synergetic value of integrating various phenomena at different scales. In this special issue, we bring the perspectives of early-career scholars from all over the globe on the future of process intensification. While the classification of PI into the energy, structural, functional, and temporal domains is well-established [1], most PI technologies effectively combine phenomena and principles related to multiple domains. The synergistic combination of multiple domains paves the way to develop more efficient, sustainable, and adaptable processes to address global challenges in the fields of chemical manufacturing, the energy transition, and environmental protection. One of the main challenges pointed out by many of the authors is the development and deployment of solutions to create a sustainable economy. Some contributions address the prospects of a specific novel PI technology and its potential realization. Many authors highlight novel energy utilization methods and functional structures as means to address these challenges. Another theme of focus is new tools, models, and characterization techniques, to support the development of PI technology. Lastly, some perspectives focus on the potential of practical (economical) implementation of PI technologies at scale. The contributions are thus classified as: a) Novel energy utilization methods, b) novel functional structures, c) new development tools, and d) PI at scale.

Novel energy utilization methods

Both hydrodynamic and acoustic cavitation are viewed as energy efficient, cost effective and scalable methods for process intensification of various industrial applications, such as wastewater treatment, nanoparticles and nano emulsion synthesis, water disinfection, increasing rate of reactions etc. Regarding this, Badve and co-workers [2] have studied the novel approach of starch nanoparticle synthesis via cavitation. The authors state that cavitation devices can be operated at ambient conditions, requiring minimal energy to operate compared to conventional methods of nanoparticle synthesis. This work demonstrates the effective use of cavitation technology for nanoparticle synthesis via a top-down approach.

Saharan and co-workers [3] have communicated the intensification and optimization of catechin extraction from the bark of the *Syzygium cumini* tree using a stirred reactor, Soxhlet, ultrasonic bath, and ultrasonic horn. Compared to conventional extraction techniques, ultrasonication based extraction resulted in faster extraction rate, lowest energy requirement and highest yield. This work illustrates the use of ultrasonication as a promising tool to enhance the efficiency of conventional extraction processes, based on yield, energy, and cost savings.

Microwave-assisted intensification is a promising approach to achieve efficient pyrolysis of organic wastes to produce aviation oil. However, microwave pyrolysis of organic wastes for aviation oil production still faces some challenges to reach satisfactory process intensification performance. For this reason, Zhang et al. [4] present some perspectives on the intensification of aviation oil production from microwave pyrolysis of organic wastes, where three main problems, namely, poor heating, microwave energy loss, and low oil quality are discussed, and four possible solutions, namely, feedstock screening, heating process intensification, pyrolysis process intensification, and products upgrading are proposed.

Microwave heating has been proposed as well to electrify and intensify the production of some of the key chemical compounds towards sustainable manufacturing. In this view, Goyal reports an overview of the status of microwave-assisted technologies in the context of multiphase reactors along with a discussion of the application examples, current technological challenges and possible future research directions [5]. This perspective demonstrates the potential in improving process yield and selectivity, productivity and energy efficiency revealing its importance for sustainable chemical processes.

Carbon capture and utilization are acknowledged as crucial technologies for the mitigation of the environmental impact of the chemical industry. Pahija et al. [6] review the possible routes towards intensification of the carbon capture process through advanced technologies (e.g., rotating packing beds, membrane reactors) and materials (e.g., metal-organic frameworks, new solvents). Moreover, the potential of the further utilization of the captured CO_2 to produce value-added materials via biological, catalytic, and electrochemical processes is critically discussed.

Murmura and Brasiello discuss the challenges and opportunities of electrochemically converting waste CO_2 to high-value chemicals or synthetic fuels [7]. In their perspective they review technologies for CO_2 capture, discuss traditional versus novel CO production routes, with focus on low and high temperature electrolysis, and elucidate CO and direct CO_2 reduction processes to C_{2+} products. It is concluded that a net zero CO_2 emissions energy sector is possible through a synthetic fuel-based economy which would use existing infrastructure, as opposed to invest in a new one. The key to this, in their view, is to treat CO_2 as a resource rather than as waste.

Alternative sources of energy can provide critical contributions toward the intensification of process sustainability. Ambrosetti provides an overview of the power-to-heat technologies for the decarbonization of chemical and catalytic processes [8]. The main available technologies (i.e., microwave, Joule and induction heating, and roto-dynamic reactors) are reviewed and typical applications are critically discussed. The perspective highlights the potential of electrically heated systems in chemical and catalytic reaction engineering demonstrating that power-to-heat is a crucial tool for increasing energy efficiency and reducing the environmental footprint of the chemical industry.

Moioli analyses process intensification approaches required in the development of chemical reactors to effectively enable the energy transition [9]. He argues that such approaches should focus on three process attributes: size (miniaturization), efficiency and flexibility. Moioli argues that PI approaches will be extremely important to enable new reactor designs resulting in smaller, but more efficient and flexible process units. In this perspective Moioli analyses and compares various CO_2 sources, H_2 production routes from renewable energy sources, and synthetic methane production strategies.

Chemical looping and sorption-enhanced gasification are viewed as promising technologies to improve energy efficiency and simplify processes to produce renewable hydrogen, synthetic fuels, and chemicals. Therefore, Dai and Whitty [10] summarize the state-of-the-art of reactors, functional materials, and modeling works for chemical looping and sorption-enhanced gasification of biomass feedstocks, where the effects of essential process parameters, including temperature, solid circulation rate, steam-to-biomass ratio, and reactor configuration are emphasized. This perspective highlights that chemical looping and sorption-enhanced gasification are very good ways to develop compact operation technologies for energy conversion.

Novel functional structures

Wehinger discusses recent advances in heat and mass transfer in structured reactors [11]. Particle shape modification of randomly packed beds, foams, monoliths, and periodic open cellular structures are discussed. Specifically, the author highlights that structured reactors could be tailored with 3D printing and inductively heated for sustainable and low footprint chemical products. It is concluded that development and manufacturing costs should be quantified to elucidate the economic benefits of these approaches.

Among the most promising approaches to process intensification, microreactor technology has emerged as a critical method that aligns with green chemistry and engineering principles, offering significant opportunities for sustainable chemical synthesis. Yue's perspective article [12] provides an overview of process intensification principles behind microreactors and highlights their merits, typical application examples, and future research directions. The perspective convincingly demonstrates that the miniaturization of traditional chemical reactors improves energy efficiency, reduces waste, and enhances reaction control, making microreactor technology an essential tool for sustainable chemical synthesis, particularly to produce value-added chemicals and fuels from biomass.

Francia discusses novel reactor concepts to increase the efficiency of contact between gases and solids [13]. The author emphasizes the role of structured fluidization focusing on two pathways: dynamically structured oscillating fluidized beds and vortex devices, which may evolve into rotational moving beds working at high interfacial velocity. It is suggested that these strategies may offer improved adaptability and control to become a broad large-scale technological platform, for highly efficient gas-solid operations.

Boczkaj and co-workers [14] have studied the decolorization of tartrazine, Ponceau 4R, and Coomassie brilliant blue dyes using conventional oxidation in combination with hydrodynamic cavitation. The use of oxidants, such as persulfate and hydrogen peroxide with cavitation conditions revealed a synergetic effect on dye decolorization. The authors have convincingly demonstrated the use of hydrodynamic cavitation as one of the promising process intensification options for dye decolorization in wastewater treatment strategies.

New development tools

Operando measurements can provide tremendous insights into the reaction mechanism and process behaviors fostering fundamental understanding and providing rational strategy for technological advancements and intensification. The Perspective by Pesch discusses operando nuclear magnetic resonance imaging for the investigation of catalytic reactions and reactors describing typical applications, current challenges and highlighting the potential for process intensification [15].

Jin et al. [16] give a perspective on supercritical water gasification of fuel particles in chemical reactors focusing on multi-component resistance analogy analysis. Process intensification from the aspects of interfacial reaction, boundary layer, and vertex diffusion is discussed to show the current research progress and outstanding issues for supercritical water gasification of fuel particles in chemical reactors. Based on this perspective, the authors present some suggestions to use multi-component resistance analogy analysis for reactor optimization design and scale-up.

Computational tools can also be important for intensified applications. In this context, Bracconi [17] presents a computational tool for the intensification of catalytic reactors to enhance the understanding of catalyst functionality in reactive environments through multiscale modeling. The paper discusses the use of machine learning to reduce computational costs, the integration of physics-based machine learning models to develop innovative solutions for chemical reactors, and the potential of additive manufacturing for manufacturing unconventional reactors.

Advanced modeling techniques coupled with *in situ* measurements can play a major role in the development of intensified technologies. Ouyang et al. discuss the combination of lab-scale fundamental experiments and detailed multiscale simulations and optimization with process simulations as an effective strategy for equipment intensification [18]. As a result, a generic methodology for the development of chemical reactors is proposed to accelerate PI implementation and increase its technology readiness level.

Baltussen [19] gives a perspective on how bubbly flow reactors can be enhanced by in-depth understanding of mass transfer at the bubble scale. It is emphasized that fluid dynamics should benefit the intrinsic reaction kinetics, which can only be done when each molecule has exactly the same experience. As local concentration is confined by the hydrodynamic wake of bubbles, it is quite difficult for molecules in the liquid to have the same or a similar experience in the reactor. Thus, this perspective shows the importance of developing methods to enhance local mixing.

PI at scale

Despite the tremendous attention and research efforts PI has gained in the last two decades, industrial implementations remain scarce. One of the main reasons for that are the cost drivers (the economy of scale) and the conservative nature (due to the high risk of retrofitting) of the chemical industry. Patel and Pereira discuss the challenges process intensification technologies face in achieving commercial readiness [20]. They give a few representative examples of commercially deployed and relatively mature PI technologies. However, they recommend that to fully exploit the promise of PI, sustained engagement between the research community and industrial process engineers is critical. They emphasize that knowledge exchange through collaborations and consortia are of utter importance to educate process engineers about the PI technologies and tools, and to penetrate industry.

Patrascu suggests that PI may have a great impact on decentralized (distributed) production [21]. A few key processes to produce commodities (hydrogen and ammonia) and for CO_2 utilization are discussed, which, if distributed, would create an industrial incentive to implement PI technologies. Patrascu argues that PI advances have great potential to enable the transition from large-scale centralized production to a distributed production, by significantly improving the cost function at small scale compared to traditional process technologies.

Concluding remarks

This special issue contains the original perspectives of 20 early-career scholars and leaders in process intensification. We hope that this collection will inspire readers to explore the potential of process intensification in process design. The methodologies included herein offer a promising avenue for reducing the environmental impact of chemical synthesis. Increasing interaction between academia and industry is vital to enable process intensification at scale, globally. It is important to understand the key industrial cost drivers (including the cost of environmental impacts) to promote relevant innovation based on process intensification principles.

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