Nature-inspired chemical engineering processes

Nature is fascinating. It is even more awesome when scrutinised from a scientific, mechanistic angle across length scales, down to the nanoscale, unravelling complex structures and patterns. Natural systems consist of a dynamic, complex assembly of interacting components and systems, leading to emergent behaviour, achieving tasks ultimately aiming at survival, which, very roughly, translates into sustaining current activities. Such activities include processing matter and energy, transporting fluids, changing phase state to obtain products of high quality, and communication. The similarity is striking with what processes in chemical engineering are intended for, since they also deal with the processing of matter, energy and data.

The living environment is sometimes cooperative, but it is usually also competitive. To cope with this, natural processes are sober in their usage of resources, creating little waste as a whole, and they have to be responsive to changes in their environment. These features can be qualified as being performant, efficient and resilient to maintain operation within constraints. In chemical engineering, such attributes are highly desirable as well, especially within the context of sustainable growth. They are indeed key drivers for academics and industry to develop any new process or retrofit existing ones.

Hence, under the auspices of the Editorial Board of the Elsevier journal *Chemical Engineering Research and Design*, we have assembled a special issue on Nature-Inspired Chemical Engineering (NICE) with a particular emphasis on products and processes inspired by nature and related to chemical engineering. The term nature-inspired has been preferred over biomimetics, which often alludes to the superior performance of biological components and systems to justify imitation of particular features without sufficient consideration of a different context in applications.

Mimicking natural objects, tools or processes as a ‘supreme goal’ is misguided, since the constraints and objectives of the natural and chemical engineering domain differ, at least in part. Therefore, NICE questions the goals and desired functions it pursues, in the same way that nature’s most crucial processes and tools relate to aims with strategies to cope with environmental changes. Furthermore, nature and chemical engineering, as conventionally applied, do not rely on the same operating strategies. As recalled by Coppens (2005, 2012) the challenges set by NICE require a fundamental mechanistic understanding of what lies at the core of nature and of how this can be transposed into innovative chemical engineering devices and processes.

The present special issue features seven articles, each with a different focus: review of mechanisms, optimal design of unit apparatuses using these mechanisms, development of structured devices and functional materials, aiming at enhancing transport or reactive phenomena, the development of processes with natural intermediates, and energy applications.

Yu et al. (2020) have reviewed the mechanisms, models and manufacturing processes of an important class of nature-inspired devices: self-cleaning surfaces. These are of industrial importance for chemical engineering whenever adhesion of contaminants is unwelcome, because it reduces functionality or prevents operation. Inspiration comes from a wide range of living systems: geckos, lotus leaves, mosquito eyes, cicada wings, water strider legs, bird feathers, butterfly wings, carp scales, etc. They have identified six key mechanisms that involve a liquid and dry environment. The spreading of self-cleaning devices is correlated with the growing availability of small-scale manufacturing technologies since the mid-2000’s, although some lab techniques cannot be upscaled to a profitable process. Modelling is based on equations frequently encountered in chemical engineering but necessitating numerical techniques, because of the locally complicated structure of surfaces. Both static and dynamical studies are performed, and both Eulerian and Lagrangian approaches are used.

Gerbaud et al. (2020) revisit Coppens’s classification of three published mechanisms underlying nature-inspired engineering, namely hierarchical transport networks, force balancing and dynamic self-organisation (Coppens, 2005, 2012), by setting them in a broader framework supported by nonequilibrium thermodynamics, the constructal law and nonlinear control concepts. This opens new perspectives in the development of nature-inspired devices and processes that would be affected by fluctuations and boundary effects on local properties at a small-scale level. At the process unit level, thermodynamic coupling should be exploited both for nonlinear transport enhancement and resilient behaviour to external constraint changes, in combination with nonlinear control frameworks. At the plant level, they question the opportunity to develop resilient and agile chemical plants based on modular units considered as services and interconnected in a symbiotic network of mass, energy and data exchange. They also discuss the use of optimal control theory and entropy production for nonlinear systems.

Magnanelli et al. (2019) perform a plug flow reactor geometry optimisation by minimising entropy production, a nonequilibrium thermodynamic concept with the help of optimal control theory. In their work, they are inspired by the energy-efficient mass transfer and energy transfer induced by the reindeer nose's complex geometry. Depending on the variables optimised, they find double digit savings, which can be readily realised by a suitable geometry, changing the reactor diameter.

The design of hierarchical porous structures is the scope of the contributions by Cervantes-Martinez et al. (2019), Zhao et al. (2020) and Ye et al. (2019) with the goal of improving transport and/or reactive phenomena in unit operation devices, sometimes by several order of magnitudes. Both meso- and microscale structures are considered. The first two papers study the manufacturing processes, respectively the sol-gel process combined with surfactant templating and crystallisation in a Pickering emulsion, and propose mechanisms and conditions for optimising the structures. Applications of such structures refer to many domains, like electronics, catalysis, adsorption and drug delivery. Ye et al. (2019) develop an analytical method for optimising the hierarchical pore network in lithium-ion battery electrodes.

The development of industrial processes for producing copper selective plated polyimide-based substrates is the focus of the work by Marques-Hueso et al. (2020). The new process reduces waste and toxicity and is taking advantage of a spinach-based visible light sensitive photo-catalyst to induce the fast synthesis of silver nanoparticles on substrates in dedicated areas that can be further plated with copper.

Bearing in mind a noticeable similarity between nature and chemical engineering needs in terms of efficient, low-waste, resilient and performant devices and processes and the potential improvement when implementing natural mechanisms, there is great opportunity and a bright future for nature-inspired chemical engineering.

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