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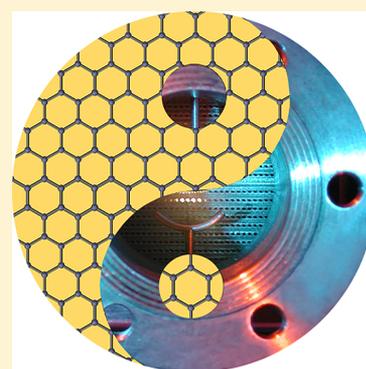
110th Anniversary: The Missing Link Unearthed: Materials and Process Intensification

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ABSTRACT: For many years, process intensification has been seen and considered through the prism of equipment and methods. The current review paper adds a new perspective to it and examines the role of (advanced) materials in process intensification. The discussion is illustrated with numerous examples of various types of materials that have been shown to intensify chemical and catalytic reactions, mass transfer, heat transfer, and momentum transfer processes, respectively. The role of process intensification in manufacturing of new, advanced materials is also discussed. In view of the importance of materials for process intensification, an update of the classical approach to the field of PI is postulated.



1. INTRODUCTION—HISTORICAL NOTES

Process intensification (PI) has attracted much attention in the past 30 years and resulted in numerous publications, including the paper on its fundamentals published in *Industrial & Engineering Chemistry Research* on the occasion of its 100th Anniversary.¹ A popular view on process intensification was introduced nine years earlier by Stankiewicz and Moulijn,² who considered PI as a toolbox encompassing novel types of process equipment and processing methods. Indeed, the majority of research articles published in the field of PI so far have focused on new equipment concepts, e.g., micro-reactors or high-gravity devices, or on innovative processing methods, e.g., hybrid separations or alternative energy forms and transfer mechanisms. Some publications present process systems engineering-derived concepts of PI and focus on the role of process synthesis and computer-aided design in that area.^{3–6} An aspect that, besides occasional mention,³ has been insufficiently addressed in the literature thus far is the role of (advanced) materials in process intensification.

Materials have been shaping humanity through the ages, since the Stone Age until today. Nowadays, (advanced) materials prompt new applications that transform entire industries. The importance of materials for chemical engineering cannot be overestimated. Traditionally, materials used in chemical engineering operations were primarily materials of construction, and one of the first review papers in that area appeared in *Industrial and Engineering Chemistry* in 1932.⁷ Shortly after World War II, *Industrial and Engineering Chemistry* published a series of articles under a common title, “Materials of Construction”, that included aluminum alloys,⁸ cements,⁹ ceramics,¹⁰ wrought copper and copper-based alloys,¹¹

elastomers,¹² fibers,¹³ iron, mild steels and low alloy steels,¹⁴ nickel and high nickel alloys,¹⁵ plastics,¹⁶ hard rubber,¹⁷ stainless steels, and other ferrous alloys.¹⁸ More recently, a chapter on construction materials in the chemical industry was published in *Ullmann’s Encyclopedia of Industrial Chemistry*.¹⁹

On the other hand, enormous developments in the materials science and engineering witnessed in the last decennia have opened new opportunities and possibilities for intensification of chemical processes. In the current paper, we examine the role that (advanced) materials already play or can play in PI. We illustrate the discussion with examples of various categories and types of materials that have been shown to intensify chemical and catalytic reactions, mass transfer, heat transfer and momentum transfer processes, respectively. Last but not least, we take a look at the reversibility of the PI/materials relation, discussing the role of PI in the manufacturing of new, advanced materials.

2. IMPORTANCE OF MATERIALS FOR PROCESS INTENSIFICATION

2.1. Reactions. In chemical reaction engineering, advanced materials offer unique reaction environments, in terms of morphologies and “shape-selective”, perfectly defined pore structures, that result in intensification of catalytic processes. *Zeolites* present a well-established example of shape-selective materials that are widely applied on the industrial scale, for

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Table 1. Examples of Material-Related Intensification Effects in Chemical and Catalytic Reactions

property/mechanism	Material category	example	process	reference technology	intensification effect
structural shape selectivity	metal-organic frameworks (MOF)	IRMOF-1 ²¹	toluene alkylation	AlCl ₃ catalysts	1.8 times higher <i>para</i> -alkylation selectivity
	liquid crystals (LC)	IRMOF-1 ²¹ cholesteric LC ²⁵	biphenyl alkylation photochemical dimerization of acenaphthylene	AlCl ₃ catalysts reaction in benzene (no LC)	1.9 times higher <i>para</i> -alkylation selectivity 38.8 times higher ratio between <i>trans</i> - and <i>cis</i> - isomers at 2.45 times higher conversion
	hierarchically structured catalysts	hierarchical SAPOs-supported Pt catalyst with spongelike architecture ³⁶	hydroisomerization of <i>n</i> -heptane	nanoporous SAPOs-supported Pt catalyst	2 times higher isomer yield
mesoporosity	carbon nanotubes (CNT)	multivalled carbon nanotubes ²⁹	methanol synthesis from H ₂ /CO/CO ₂	catalyst without CNT	44% higher CO conversion and 25% higher methanol formation rate, at 15–20 °C lower reaction temperature
		CNT-supported Co catalyst ⁴²	Fischer–Tropsch synthesis	activated carbon-supported Co catalyst	50% higher CO conversion and 62.6% higher selectivity to C ₅ +
selective permeability	carbon molecular sieves (CMS)	SiO ₂ –Al ₂ O ₃ catalyst integrated with carbon molecular sieves ³⁰	ammonia reaction with methanol yielding monomethylamine (MMA), dimethylamine (DMA), and trimethylamine (TMA)	same catalyst without CMS	2.7-fold increase in the (MMA+DMA) to TMA ratio
	metals/alloys	Pd-based membrane reactor ^{43,44}	water-gas shift reaction	conventional process of HT-WGS, LT-WGS, and purification stage	2 times higher CO conversion, >90% reduction of reaction volume
large surface area and adsorption capacity	graphene-based	graphene oxide ³³	CO ₂ hydrogenation to methanol	GO-free catalyst	39% higher space time-yield of methanol
solvophobicity	ionic liquids (IL)	[BMIM][Br] ²⁷	pharmaceutical intermediate production: 3-aminoimidazo[1,2-a]pyridines production	no IL present	2.5–3 times higher conversion
superwettability	hydrophilic catalytic materials	hydrophilic TS-1 zeolite ³⁵	oxidation of 1-hexene with H ₂ O ₂	conventional TS-1 zeolite	8 times higher reaction rate
responsiveness to microwave heating	dielectric catalysts	chitosan-supported palladium catalyst ³⁷	Suzuki reaction	same catalyst, no MW heating	12 times shorter reaction time to reach the same conversion (93%)
responsiveness to induction heating	supramagnetic materials	silica-coated manganese ferrite nanoparticles in flow reactor ⁴⁰	hydrogenation of aromatic alkene	batch reactor with oil bath heating	reaction time shortened from 10 h to 8 min

Table 2. Examples of Material-Related Intensification Effects in Mass-Transfer Processes

Material		reference technology	intensification effect
property/mechanism	category	process	reference technology
molecular/ionic sieving	zeolites	ethane and ethylene separation	reference distillation
	MOFs	propylene and propane separation	cryogenic distillation
	graphene-based	water and Methyl Red separation	commercial NF270 membrane
	porous organic cages (POCs)	dye-wasted water treatment	commercial nanofiltration membrane
	polymers of intrinsic microporosity (PIMs)	H ₂ /N ₂ gas separation	conventional Matrimid S218
porosity/capillary action	SiC	<i>n</i> -heptane and hexaphenylbenzene separation	commercial Starmem 240
	carbon	distillation	conventional sieve tray
structural shape selectivity	liquid crystals (LC)	distillation	conventional Raschig ring random packing
surface renewal	liquid membrane	separation of C60, and C70 fullerenes	Develosil ODS-5
	magnetic materials	Cu ²⁺ ion recovery	PVDF hollow fiber membrane extraction
responsiveness to magnetic field	magnetic materials	cell separation	conventional centrifugation
		liquid (5 wt % acetic acid) – liquid (toluene) extraction	in the absence of nanoparticles and the oscillating magnetic field

ethylene separation selectivity from ethane of ~100; potentially tremendous energy saving
complete exclusion of propane from propylene, potentially 90% less energy consumption
9 times higher water permeability with comparable retention of Methyl Red
two orders of magnitude higher water permeance with similar rejection

1 order of magnitude higher permeability; selectivity is still an issue
two orders of magnitude higher permeance with similar rejection of hexaphenylbenzene

up to 60% higher tray efficiency
up to 30% lower HETP; up to 40% lower pressure drop; 20% higher flooding point,
separation factor is 3.00 compared to 1.84

3.75 times higher mass transfer coefficient
1 order of magnitude higher efficiency of cell recovery
up to 2.6-fold mass-transfer enhancement

instance, in fluidized catalytic cracking (FCC). Another, more recent family of materials that can be used for shape-selective catalysis, are *metal–organic frameworks* (MOFs). These are crystalline hybrid materials whose crystal structure is built from a three-dimensional (3D) network of metal ions or small discrete clusters connected by multidentate organic molecules. The pore size and geometry of MOFs can be tuned to suit various applications, including catalysis.^{20–22}

Liquid crystals miss the rigidity of a solid matrix. At the same time, however, the order of the crystalline phase restricts the randomness in motion of the dissolved molecules. Because of that feature, liquid crystals can influence the behavior of the chemical reactions performed in those media (for instance, photodimerizations, where clear effects of the liquid crystal and its type on the selectivity of the reaction were observed).^{23–25} Also, *ionic liquids* (ILs) present an interesting environment for carrying certain “green” chemical reactions with clear intensification effects.^{26,27} A separate group of advanced materials that have been reported to significantly improve the reaction performance are carbon-based materials, including *carbon nanotubes*,^{28,29} *carbon molecular sieves*,³⁰ and *graphene oxides*.^{31–33}

Some specific properties of advanced catalytic materials can be utilized for intensification of chemical reactions. For instance, adjusting the wettability of catalysts can lead to enhanced catalytic performance, as shown by Wang and Xiao.^{34,35} Also, catalytic materials that allow adjusting pore structure from a purely nanoporous structure to a hierarchical structure can result in enhanced yield.³⁶ Very interesting challenges for materials are seen in the field of chemical and catalytic reactors driven by electromagnetic energy, such as microwave (MW), radio frequency (RF), or inductive heating. Those types of heating allow a dramatic increase in reaction rate and/or product yield, compared to conventional heating.^{37–41} In MW and RF catalytic reactors, the control of local temperature in the catalyst bed is of paramount importance and can only be achieved via a careful choice of *materials with the right dielectric properties*. In reactors based on induction heating, *core–shell superparamagnetic nanoparticles* can be used to intensify the energy transfer and shorten reaction times.^{40,41}

Table 1 provides some examples of material-related intensification effects in chemical and catalytic reactions.

2.2. Mass Transfer. Similarly, in mass-transfer processes, advanced materials can provide remarkable advantages. For instance, a finely tunable design in pore aperture and structure, and/or molecule–surface interaction by surface functionalization, results in process intensification of molecular-scale separation (“molecular sieving”). *Zeolites* and *metal–organic frameworks* (MOFs) exhibit excellent performance in gas separation, especially in the case of close-boiling mixtures, with a high potential of attainable 90% energy savings, compared to conventional energy-intensive cryogenic distillation methods.^{45–47} *Covalent-organic frameworks* (COFs), *porous organic cages* (POCs), and *polymer of intrinsic microporosity* (PIMs) have also been developed for mass-transfer operations and deliver excellent intensification effects, compared to conventional technologies.^{48–52}

Different from MOFs and zeolites, which belong to molecularly 3D porous materials, *graphene* is a type of two-dimensional (2D) material of atomic thickness. Graphene-based materials show high flexibility and tunable interspacing property.^{53,54} This provides another pathway for molecular

sieving with microporosity and potentially breaks the tradeoff between permeability and selectivity,⁵⁵ for instance, in the organic waste filtration in water treatment processes.^{56,57}

SiC and *carbon* foams, because of their high porosity and good liquid spreading facilitated by capillary forces, redefine equipment internals for the otherwise very mature distillation technology.^{58,59}

Liquid crystals, as a special phase of materials, provide high potential for separation of other functional materials (for instance, fullerenes (C60 and C70)), because of good molecular shape recognition capability.⁶⁰ Also, *ILs* with well-defined cationic ligand and anionic ligand offer selective separation transport in lignin separation.⁶¹ *Liquid membranes*, which are a combination of liquid solution as the selective agent and a membrane as the support, present an opportunity for a more-efficient ion separation or recovery.^{62,63}

Soft matter, which is a term established by Pierre-Gilles de Gennes, the Nobel Laureate in Physics in 1991, comprises a huge materials library. Composite *hydrogels*, which are an example of soft matter, possess the features of interlinked networks and matrix. They can be used, for instance, to form a confined and elastic space for controllable crystallization with tunable crystal size and desirable crystalline form. A hydrogels-based crystallization reactor presents an alternative method to intensify conventional crystallization process.^{64,65}

Other specific properties of advanced materials, such as superwettability or magnetic response, can be utilized for intensification of mass-transfer processes. *Superwettability*, which is a special interfacial property resulting from the interplay between the micronano hierarchical structure and the lower-energy surface, is applicable in mass-transfer operations. For example, superoleophobic ZIF-8 coating on steel mesh exhibits 99.9% separation efficiency and extremely high flux in water–oil separation by selective affinity and capillary force.^{66,67} The possibility of gravity-driven operation, without additional energy input, together with the extraordinary separation efficiency, promises to result in a highly energy-efficient process.⁶⁸ In addition, superwettability can also facilitate nonfouling and long-lasting stable operation of membranes, which is of paramount importance for industrial practice.^{69–73} As already mentioned in the reaction part, interesting material-related challenges are seen in the processes driven by electromagnetic energy. *Materials that are responsive to magnetic field* are one example, which, coupled with proper surface modification, provide a remarkable opportunity for intensification.^{74,75}

Selected examples of material-related intensification effect in mass-transfer processes are listed in Table 2.

2.3. Heat Transfer. Selected *ceramics and metals* play a key role in intensifying heat-transfer operations, because of their excellent thermal conductivity. For example, *silicon carbide* is used to fabricate heat-exchanger reactors for extremely efficient heat removal/supply.⁷⁶ Similarly, *aluminum foam* can be used as a reactor packing to eliminate the danger of thermal runaway, in the case of highly exothermic reactions.^{77–79} On the other hand, similar to mass-transfer operations, *nanoparticles-based nanofluids* deliver a significant improvement of thermal conductivity.^{80,81} In principle, the application of nanofluids as a replacement for conventional cooling/heating agents should not require a major modification in the existing process.

Metamaterials own unusual electromagnetic properties that are not found in naturally occurring materials.⁸² They are

Table 3. Examples of Material-Related Intensification Effects in Heat-Transfer Processes

property/mechanism	Material		process	reference technology	intensification effect
	category	example			
thermal conductivity	ceramics	SiC ⁷⁶	exothermic process in heat exchanger-reactor	Plexiglas	6–20 times more efficient in terms of thermal exchange capacity
	metal	aluminum ⁷⁹	Fischer–Tropsch synthesis	alumina-based catalyst particles	ca. 650 times higher thermal conductivity; no thermal runaway
	nanofluids	Cu nanoparticles ⁸⁰	general heat/energy transfer	water	1.78-fold increase of thermal conductivity
responsiveness to magnetic field	magnetic materials	magnetite nanoparticles ¹⁰⁰	general heat/energy transfer	deionized water	4-fold enhancement of local heat-transfer coefficient
		magnetite nanoparticles ⁹⁰	general heat/energy transfer	barium ferrite, cobalt ferrite or maghemite	more than 3-fold increase of heating rate
responsiveness to microwave heating	dielectric materials	Fe ₃ O ₄ -petalite composite ⁹¹	general heat/energy transfer	petalite foam without Fe ₃ O ₄	7 times higher heating-up rate
superwettability	superhydrophilic materials	superhydrophilic TiO ₂ coating ⁹⁴	pool boiling	hydrophilic copper	2-fold increase of maximum heat flux

Table 4. Examples of Material-Related Intensification Effects in Mixing and Momentum-Transfer Processes

property/mechanism	Material		process	reference technology	intensification effect
	category	example			
elongational viscosity; molecular stretching	polymer	general linear polymer of molecular weight above 100 000 ¹⁰³	single-phase flow	no additives	up to 70%–80% drag reduction
		poly isobutylene ¹⁰²	multiphase flow (air-crude oil)	no additives	up to 40% drag reduction
micelle-forming; wall slip	surfactant	APG1214 ¹⁰⁴	water flow through the microchannel	surfactant-free deionized water	up to 30% drag reduction
superwettability; boundary slip	superwettable materials	PTFE nanofiber forests coating ¹⁰⁵	laminar flow	no coating	55~65% higher mass flow rate at the same applied pressure
		microstructured Teflon coating ¹⁰⁶	turbulent flow	no coating	75% turbulent drag reduction
		organically modified SiO ₂ particles coating on the foam SiC ¹⁰⁷	flow through a distillation tray	no coating	up to 43% less pressure drop
responsiveness to magnetic field	ferrofluids	Fe ₃ O ₄ ferrofluid ¹⁰⁹	mixing in microfluidic channel	same fluid, no magnetic field	up to 6-fold shortening of the mixing length

usually made from assemblies of multiple elements fashioned from composite materials such as metals or plastics and arranged in repeating patterns. As stated by Raman et al.,⁸³ their specially designed structures give them smart properties capable of manipulating electromagnetic waves, by blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials. The properties may offer opportunities to intensify chemical processes.

Magnetocaloric materials gain increasing interest as an energy-lean technology for alternative cooling and refrigeration systems. Compared to the conventional vapor compression technology, in magnetocaloric materials, the intensified cooling is achieved by a repeated cycle of magnetization and demagnetization in magnetic fields. As claimed in the literature,^{84–86} its Carnot efficiency can even approach 100%, while the conventional technology can only reach 40%. Also, other *materials responsive to external fields*, including electric fields, magnetic fields, and microwave fields, can achieve rapid heating rates, significantly higher energy efficiency, and more homogeneous temperature distribution, compared to the conventional heating.^{40,87–91}

Similarly to reactions and mass-transfer operations, *superwettability*, which is a specific property of some advanced materials, can be utilized to intensify heat-transfer operation.^{92,93} For example, a superhydrophilic surface can intensify pool boiling by increasing the critical heat flux (CHF);⁹⁴ a superhydrophobic surface can turn film condensation into the perfect dropwise condensation, achieving an order-of-magnitude intensification effect.⁹⁵

Coking is a common phenomenon in petrochemical cracking processes, which results in rapid deterioration of the heat-transfer performance of cracking tubes. Some *inorganic coatings* can significantly reduce the coking rate and, although they do not intensify the process as such, they enable the retaining of very intensive heat transfer through the tube wall.^{81,96–99}

Some examples of the material-related intensification effects in heat-transfer processes are listed in Table 3.

2.4. Momentum Transfer. *Polymer or surfactant additives* can change the boundary phenomena near the wall and the interaction between liquid and solid, resulting in drastic reduction of the hydraulic resistance, whether it is a single-

phase or a multiphase flow, a macroscale or a microchannel flow, oil or water.^{101–104}

Similar to the role of superwettability in reactions, mass transfer, and heat transfer, a *superwetable surface* can also significantly reduce the energy consumption, via the drag reduction in laminar flow,¹⁰⁵ turbulent flow,¹⁰⁶ and also bubbling flow process.¹⁰⁷

Mixing is the fundamental phenomenon playing a role in reactions, mass transfer, and heat transfer, and is of significant importance, particularly for liquid-phase process. Tremendous mixing intensification effects can be achieved by the addition of *particles responsive to magnetic fields*.^{99,108} Several examples of material-related intensification effects in mixing and momentum transfer are provided in Table 4.

3. THE 'YIN AND YANG': MATERIALS FOR PI – PI FOR MATERIALS

In the previous sections, we presented the importance of (advanced) materials for process intensification. Advanced materials, such as carbon materials (graphene, CNT), molecularly porous/structured materials (zeolites, MOFs, COFs, POCs, PIMs), nanoparticles or nanofluids, soft matter (hydrogels, ionic liquids, polymers, liquid crystals), selected ceramics and metals, superwetable materials, electromagnetic-responsive materials, all were shown to play an important role in intensifying reactions, as well as mass-, heat-, and momentum-transfer processes.

According to the old Chinese philosophy, the two opposite elements, Yin and Yang, interact, attract and complement each other. The relationship between materials and process intensification has that “Yin and Yang” nature. Materials are used to intensify processes, while process intensification (PI) technologies are used to manufacture materials. Accordingly, in each of the four elementary domains of PI, first introduced by Van Gerven and Stankiewicz in their article published on the 100th Anniversary of I&ECR,¹ intensified technologies are found that have been or can be applied in the manufacturing of advanced materials. For example, in the *spatial* (“Structure”) domain, various polymers are synthesized in a highly controlled way using *microchannel* or *millichannel reactors*. Microfluidic systems are also used for the synthesis of hydrogels and crystal polymorphs. In the *thermodynamic* (“Energy”) domain, acoustic (ultrasound) or electromagnetic (e.g., light, microwaves) fields are applied for the synthesis and processing of (bio)polymeric, ceramic, crystalline, or carbon materials with specific properties. HiGee technology, based on centrifugal force, shows faster mixing performance that leads to improved product quality in the nanoparticle synthesis and polymer, compared to conventional technology. In the *functional* (“Synergy”) domain, membrane crystallization allows for a better control of crystal polymorphism, while *reactive extrusion* simplifies the polymerization process and deliver better polymer performance. Finally, in the *temporal* (“Time”) domain, *oscillatory flow reactors* can be applied in the continuous production of polymers or crystalline materials, while *pulsed plasmas/laser* are used in the synthesis of nanoparticles and thin-film materials. Table 5 provides a brief, nonexhaustive overview of PI technologies applied in the synthesis, manufacturing, and processing of advanced materials. As one can see, the technologies in the Energy domain dominate the field.

Table 5. Process Intensification (PI) Technologies for the Synthesis, Manufacturing, and Processing of Advanced Materials

PI technology	materials addressed
PI Domain: Structure	
microstructured/microfluidic reactor	polymers (various types) ^{110–112} hydrogels ^{113–115} crystals/polymorphs ^{116–118} nanoparticles ^{119,120}
millireactor static mixer	polymers ¹²¹ polymers ¹²²
PI Domain: Energy	
electric field microwaves	(bio)polymers ^{123,124} polymers ^{125,126} polymeric biomaterials ¹²⁷ ceramics ^{128–130} glasses ^{128,129} composites ¹²⁹ metallic materials ¹²⁹ graphene and graphene-based products ^{131,132} carbon nanotubes ¹³³ quantum dots ¹³⁴
plasma	carbon nanotubes ^{135,136} biomaterials ¹²⁷
γ -ray irradiation light; coherent (laser)	hydrogels ¹³⁷ hydrogels ¹³⁷ colloids ¹³⁸ structured biomaterials ¹²⁷ carbon nanotubes ¹³⁶
light; noncoherent (visible, UV)	polymers ^{139–143} biomaterials ^{127,144}
ultrasound	polymer nanocomposites ¹⁴⁵ hydrogels ¹⁴⁶ (nano)biomaterials ¹²⁷ graphene ^{147,148}
HiGee: rotating packed bed	nanoparticles ^{149,150} polymers ¹⁵¹
HiGee: spinning disk reactor	polymers ^{152,153} nanoparticles ^{153–155}
PI Domain: Synergy	
reactive extrusion heat exchanger (HEX) reactor membrane crystallization	polymers ^{156–158} polymers ¹⁵⁹ crystal polymorphs ^{160,161}
PI Domain: Time	
oscillatory flow reactor	crystalline materials ¹⁶² polymers ¹⁶³
pulsed plasma pulsed laser	nanoparticles ^{164–166} nanoparticles ¹⁶⁷ thin-film materials ¹⁶⁸

4. CONCLUSIONS

For many years, process intensification has been seen and considered through the prism of equipment and methods.² The current paper adds new insights and another perspective to it. Based on the above-discussed examples, we can clearly see that (advanced) materials present an important, third way of intensifying (catalytic) reactions, as well as heat-, mass-, and momentum-transfer processes. They carry two main ingredients of PI, which are the innovation and the significant scale of the effects achieved. Because of that fact and because of the “Yin-Yang” interrelationship between PI and materials, the

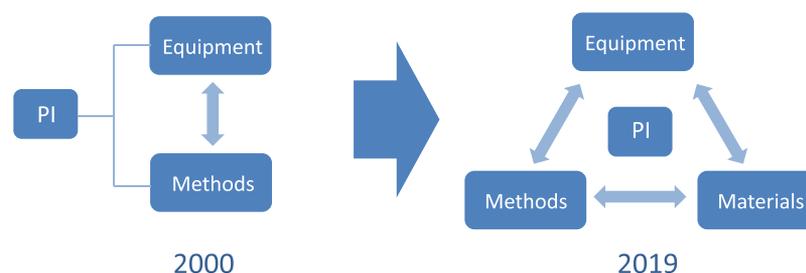


Figure 1. Field of process intensification, as it was seen in 2000² and as it should be seen today.

almost-20-years-old “toolbox” approach to process intensification² should now be updated, as proposed in Figure 1, and materials should be given a place in the field that they fully deserve.

Only a few of the materials discussed in this paper have already been seen in industrial-scale applications. These include, for instance, zeolites in catalytic reactors and in mass-transfer processes, silicon carbide in heat-transfer equipment and in distillation columns, or drag-reducing polymers in petroleum pipelines. The vast majority of the reviewed materials, however, have so far been synthesized and investigated only on the laboratory/bench scale. In order to implement them in commercial processes, important hurdles must be overtaken, which obviously include the cost and, in many cases, also the lack of the large-scale manufacturing technologies for those materials. We expect that the “Yin-Yang” relation between materials and process intensification will help overtake those hurdles and that the low-cost, PI-based technologies for manufacturing those materials will be developed in the years to come.

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Notes

The authors declare no competing financial interest.

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