Review

Structure, Energy, Synergy, Time#The Fundamentals of Process Intensification

Tom Van Gerven, and Andrzej Stankiewicz

More About This Article

Additional resources and features associated with this article are available within the HTML version:

- Supporting Information
- Access to high resolution figures
- Links to articles and content related to this article
- Copyright permission to reproduce figures and/or text from this article

View the Full Text HTML

100TH ANNIVERSARY
REVIEW

Structure, Energy, Synergy, Time—The Fundamentals of Process Intensification

Tom Van Gerven[†] **and Andrzej Stankiewicz***

Process & Energy Department, Delft University of Technology, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands

Process intensification (PI) is commonly seen as one of the most promising development paths for the chemical process industry and one of the most important progress areas for modern chemical engineering. Often illustrated with spectacular examples, process intensification struggles, however, with its definition and interpretation. Instead of narrowing the scientific discussion down to finding a commonly accepted definition of PI, it is more important to determine its position within chemical engineering and to identify its fundamentals. Accordingly, the paper presents a fundamental vision on process intensification. The vision encompasses four approaches in spatial, thermodynamic, functional, and temporal domains, which are used to realize four generic principles of PI. The approaches refer to all scales existing in chemical processes, from molecular to meso- and macroscale, and are illustrated with relevant examples with special attention given to the molecular scale.

1. Introduction

The 100th anniversary of *Industrial & Engineering Chemistry Research* comes in the period when both chemical process industry and chemical engineering face tremendous challenges. For the industry, these challenges are mainly related to the shrinking availability of nonrenewable feedstocks, rising energy prices, and a broad spectrum of environmental and safety issues. On the other hand, the chemical engineering community is searching for a new paradigm.[1−6]

Process intensification (PI) is nowadays commonly mentioned as one of the most promising development paths for the chemical process industry and one of the most important progress areas for chemical engineering research. However, for more than two decennia, process intensification has been merely considered as a kind of technological "toolbox" containing some spectacular examples of process improvement. Meanwhile, that simplistic view on process intensification as a toolbox only has given room to more in-depth discussions and interpretations. Numerous definitions of PI have been proposed (see Table 1) which, apart from their common focus on innovation, are often quite diverse in nature. Equally diverse is the interpretation of process intensification by various authors. For some, the miniaturization is the fundamental issue of PI,[13,14] with microreactors being the most typical example. For others, process intensification is based on functional integration,[15,16] with reactive distillation as prominent illustration. Arizmendi-Sánchez and Sharatt[17] combine different approaches by identifying synergistic integration of process tasks and phenomena and targeted intensification of transport processes, both on multiple scales, as the main PI principles. On the other hand, Moulijn et al.,[18] in a comparison between PI and process systems engineering, argue that 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". They also see PI acting more on the nano- (molecules) to macroscale (reactors) and less on the mega-scale (plants, sites, enterprises). Finally Freund and Sund-macher[19] have very recently contributed with the suggestion that PI should and does follow a function-oriented approach. As in the previous references, they identify different scales as to which this approach should be undertaken, from phase level via process unit level to plant level (thus not taking the molecular scale into account).

Looking at these valuable contributions cited in Table 1, one feels that most of them only partly grasp the complete picture of what exactly PI is. On the occasion of the 100th anniversary of *Industrial & Engineering Chemistry Research*, the time seems right to attempt a more comprehensive, fundamental vision on process intensification.

Accordingly, in this paper, a fundamental view on process intensification is proposed, which encompasses the underlying generic *principles* and different *approaches* to realize these principles at all relevant *scales*. We introduce and define here four fundamental approaches of process intensification in four domains: spatial, thermodynamic, functional, and temporal. We investigate them in more depth and illustrate with relevant examples on different scales. Finally, we discuss the location of such described process intensification on the multidimensional map of chemical engineering disciplines.

By this, we hope that more clarity can be achieved not only on what process intensification is but also on where chemical engineering should go in order to successfully address the challenges we face.

2. Fundamentals of Process Intensification

2.1. Principles. The PI aim of "drastic improvement of equipment and process efficiency" has been previously translated to "achieve a process that is only limited by its inherent kinetics and not anymore by transfer of mass, heat

* To whom correspondence should be addressed. E-mail: a.i.stankiewicz@tudelft.nl.
† Present address: Department of Chemical Engineering, Katholieke Universiteit Leuven, de Croylaan 46, 3001 Leuven, Belgium.

Table 1. Selected Definitions of Process Intensification over the Last Twenty-Five Years

process intensification...	reference (year)
"[is the] devising exceedingly compact plant which reduces both the 'main plant item' and the installations costs."	Ramshaw (1983)[7]
"[is the] strategy of reducing the size of chemical plant needed to achieve a given production objective."	Cross and Ramshaw (1986)[8]
"[is the] development of innovative apparatuses and techniques that offer drastic improvements in chemical manufacturing and processing, substantially decreasing equipment volume, energy consumption, or waste formation, and ultimately leading to cheaper, safer, sustainable technologies."	Stankiewicz and Moulijn (2000)[9]
"refers to technologies that replace large, expensive, energy-intensive equipment or process with ones that are smaller, less costly, more efficient or that combine multiple operations into fewer devices (or a single apparatus)."	Tsouris and Porcelli (2003)[10]
"provides radically innovative principles ('paradigm shift') in process and equipment design which can benefit (often with more than a factor two) process and chain efficiency, capital and operating expenses, quality, wastes, process safety and more."	ERPI (2008)[11]
"stands for an integrated approach for process and product innovation in chemical research and development, and chemical engineering in order to sustain profitability even in the presence of increasing uncertainties."	Becht et al. (2008)[12]

or momentum (hydrodynamics)".[20] However, this view severely suffers from the drawbacks of using old paradigms such as transport phenomena and unit operations for new challenges. This is mainly the case for the two extreme ends of time and length scales in which chemical engineering is active:[21] the plant and the molecules.

On the macroscale of reactor and plant, the concept of unit operations cannot take into account the often positive effect of integration. In reactive separations, for example, the combination of reaction and separation can increase conversion to 100% in the case of reversible reactions, by taking advantage of the Le Chatelier principle.[22] Freund and Sundmacher[19] quite rightly claim that knowledge of the existing apparatuses that perform unit operations immediately narrows our creativity in search for new solutions. Their proposal to shift from unit apparatuses to unit functions, however, does not completely solve the problem, as the chemical process is still broken down in individual process steps. Whether the advantage of synergy and integration can be also taken into account in the scale levels smaller than the plant level remains to be seen in the (not yet published) second part of their paper.

On the other hand, on the nanoscale of molecules and electrons, the conventional concepts of mass, heat, and momentum transfer become less appropriate. This is the area of quantum chemistry and quantum mechanics. It is, however, the nanoscale where current fundamental research focuses and where substantial increase of chemical and physical knowledge is expected. In agreement with Moulijn et al.,[18] but in contrast to Freund and Sundmacher,[19] we feel that this scale will be the most relevant scale for process intensification in the future.

In view of the above, a question arises concerning the generic principles, on which process intensification is based. We distinguish here four such principles.

Principle 1: Maximize the Effectiveness of Intra- and Intermolecular Events. This principle describes the aspect of process intensification which until now has received the least attention within the PI community, yet which in our eyes may become the most important one in the future. This principle goes beyond the earlier mentioned statement by Bakker.[20] It is not only about aiming at processes limited only by their inherent kinetics; it is primarily about changing that kinetics. It is about a kind of high-level snooker game
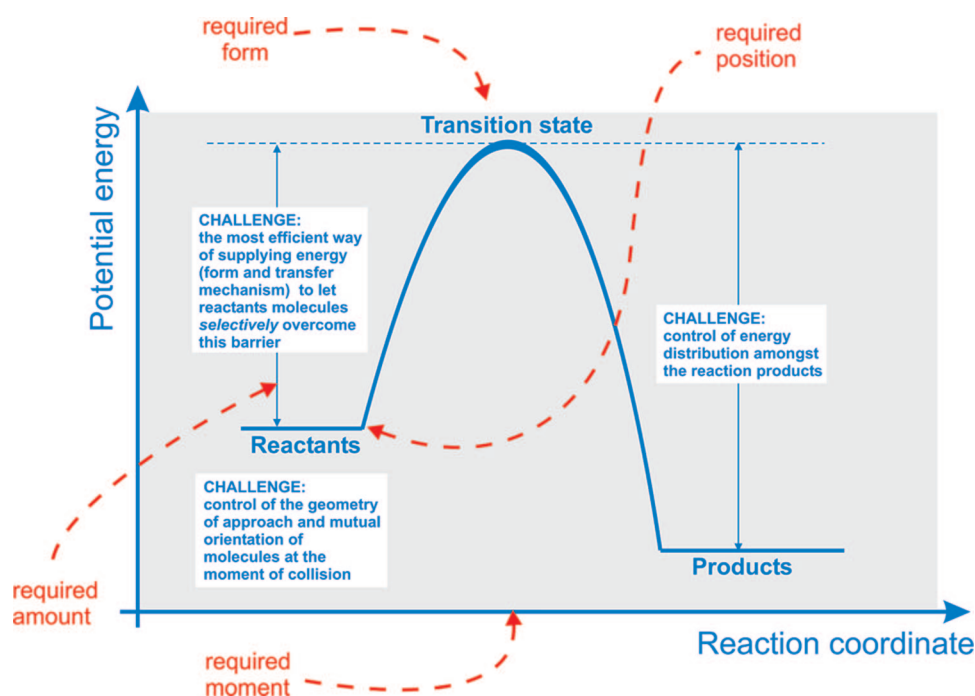

Figure 1. Engineering challenges related to the first principle of process intensification.
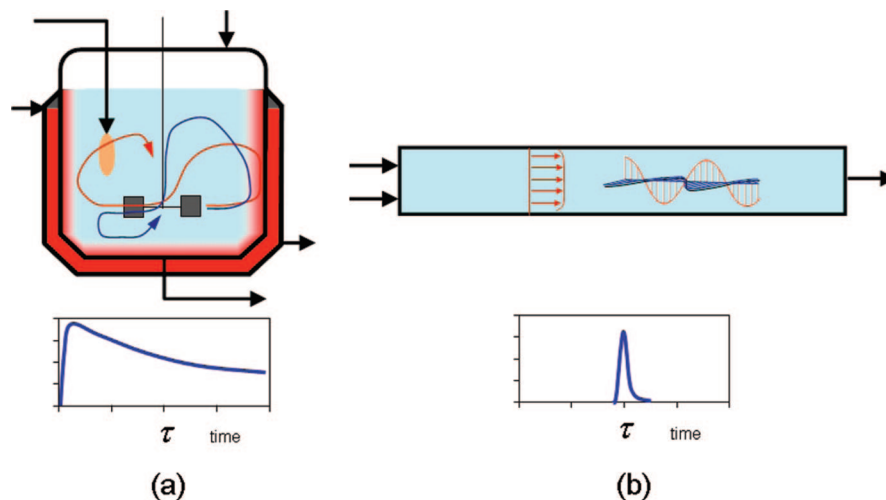
Figure 2. Stirred-tank reactor with a heating jacket (a) contradicting the second principle of process intensification. The residence time of molecules is widely distributed, their trajectories vary, and both concentration and temperature nonuniformities are present. On the other hand, a plug-flow reactor with a gradientless, volumetric (e.g., dielectric) heating (b) enables a close realization of that principle.

on the scale of molecules and electrons. This is where the whole "evil" of low conversions and selectivities, unwanted side-products, etc. has its roots. According to the simplest collision theory, the factors responsible for the effectiveness of a reaction event include: number/frequency of collisions, geometry of approach, mutual orientation of molecules in the moment of collisions, and their energy (Figure 1). Process intensification should and will look for the *engineering* methods to better control these factors. Some fundamental works in that area have already been done by physicists and chemists, and we will take a closer look at it further in this paper.

Principle 2: Give Each Molecule the Same Processing Experience. Processes, in which all molecules undergo the same history, deliver ideally uniform products with minimum waste. Here not only macroscopic residence time distribution, dead zones, or bypassing but also meso- and micromixing as well as temperature gradients play an important role. As illustrated in Figure 2, a plug-flow reactor with gradientless, volumetric heating (e.g., by means of microwaves) will obviously be much closer to the ideal described by the above principle than a stirred-tank reactor with jacket heating.

Principle 3: Optimize the Driving Forces at Every Scale and Maximize the Specific Surface Area to Which These Forces Apply. This principle is about the transport rates across interfaces. The word "optimize" is used here on purpose as not always is the maximization of the driving force (e.g., concentration difference) required. On the other hand, the resulting effect always needs to be maximized, and this is done by the maximization of the interfacial area, to which that driving force applies. Increased transfer areas (or surface-to-volume ratios) can for instance be obtained by moving from the millimeter to the micrometer scales of channel diameters. A circular microchannel of 400 μm in a microreactor delivers a specific area of ca. 15 000 m^2/m^3. The nature, however, still leads the race against the engineering: our capillary veins are ca. 10 μm in diameter, have specific areas of ca. 400 000 m^2/m^3, and (most of the time) do not clog!

Principle 4: Maximize the Synergistic Effects from Partial Processes. It is evident that synergistic effects should be sought and utilized, whenever possible and at all possible scales. Most commonly such utilization occurs in form of

multifunctionality on the macroscale, for instance in reactive separation units, where the reaction equilibrium is shifted by removing the products in situ from the reaction environment. Some interesting possibilities for achieving synergistic effects on molecular or meso-scales will be discussed in the next section.

The above principles, in one form or another, are obviously not entirely new to chemical engineering. In process intensification, however, they are seen as *explicit goals* that an intensified process aims to reach. Besides, the PI interpretation of these principles often goes beyond the boundaries of the classical chemical engineering approach. This can be seen for instance in the first principle, where process intensification basically looks at the methods of *improving* (thus changing) the inherent kinetics of chemical reactions, rather than reaching them. On the other hand, if the second principle had been consequently followed by chemical engineering, we would not have seen any stirred tank reactors in the industry today.

2.2. Approaches and the Scales. A completely intensified process achieves success in realizing all the above-discussed principles, making use of one or more *fundamental approaches* of process intensification. We distinguish four such approaches in four domains: spatial, thermodynamic, functional, and temporal. For simplicity, we name these four approaches here "structure", "energy", "synergy" and "time", respectively.

The above-stated approaches should obviously be applied on all the relevant time and length *scales*. As mentioned before these scales may range from the molecules (down to femtoseconds and -meters) to processing unit or even plant level (up to days and hundreds of meters). Following Westerterp and Wijngaarden,[23] we distinguish three scales in the following paragraphs: the molecular scale (molecular collisions, molecular diffusion), mesoscale (particles, bubbles, films, phases), and macroscale (processing units, processing plants).

The concept of principles, approaches, and scales is schematically shown in Figure 3. In the present paper, special attention will be given to the molecular scale since this is the least documented scale so far in the process intensification literature.
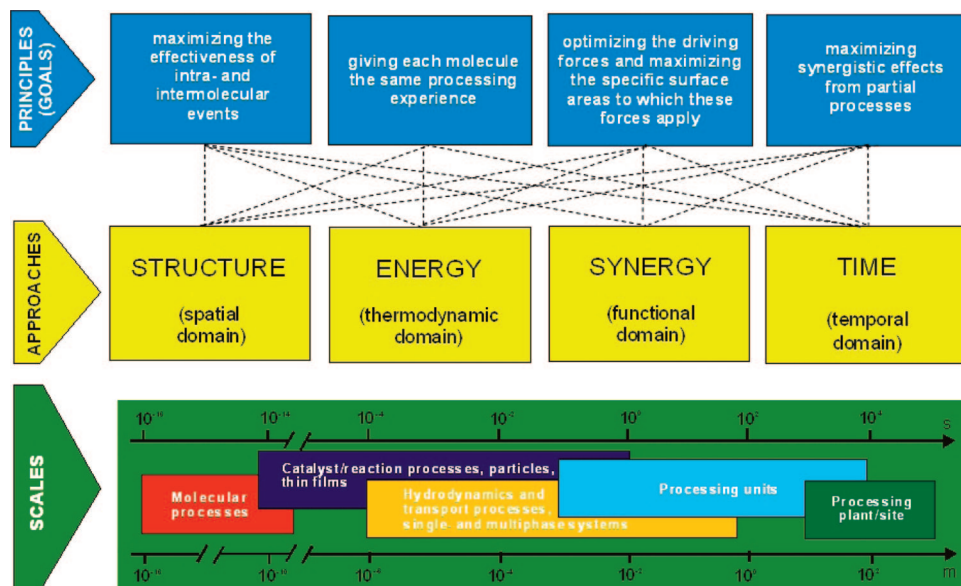
Figure 3. Fundamental view on process intensification.

2.2.1. Structure: PI Approach in the Spatial Domain. In general, a structure is introduced to avoid spatial randomness. Although a chemical process can sometimes benefit from the randomness (e.g., making use of the Brownian motion, which is essentially a random phenomenon), it should in general be harnessed by structure in order to be able to control it and to direct it toward the preset goal. Secondary liquid maldistribution and insufficient particle wetting in trickle-bed reactors present a typical example of poorly controllable unwanted phenomena in a random system. A "side-reason" for structuring is to simplify the scale-up.[24]

For process intensification spatial structuring can be employed to realize any of the four PI principles. On the molecular scale, the effectiveness of reaction events can be affected (improved) by structural measures. Examples here are the molecular reactors, which are miniature reaction vessels that spatially control the assembly of reagents to affect the outcome of chemical transformations at the molecular level.[25] As they are themselves not altered through the chemical transformation, by definition they are operating as catalysts. A wide range of these molecular reactors are being studied, such as cyclodextrins[25,26] and zeolites (aka molecular sieves).[27,28]

The activity of molecular reactors is highly affected by their structure. The toroid structure of cyclodextrins with hydrophilic exterior and hydrophobic interior accepts molecules only in specific orientations. The geometrical preference of cyclodextrins can change depending on the state they are in. Figure 4 shows as an example the entrance of nitrophenol in a permethylated α-cyclodextrin in solution and in the solid state.[26] These properties can obviously be used to affect selectivities of reactions. Another striking example is the reaction of indoxyl and isatinsulfonate which gives in the absence of cyclodextrins a mixture of indigo and indirubinsulfonate in yields of 25 and 1.4%, respectively. In the presence of a cyclodextrin dimer the yields change to <0.1 and 22%, respectively.[25] A ratio change by a factor of more than 3500! In zeolite science, the occurrence of shape-selective catalysis has been well described, e.g., refs 28−30. It consists of the effect of the zeolite structure on reactant selectivity, product selectivity, and restricted transition state-type selectivity. Related phenomena include the inverse shape-selectivity, where restricted transition state-type selectivity
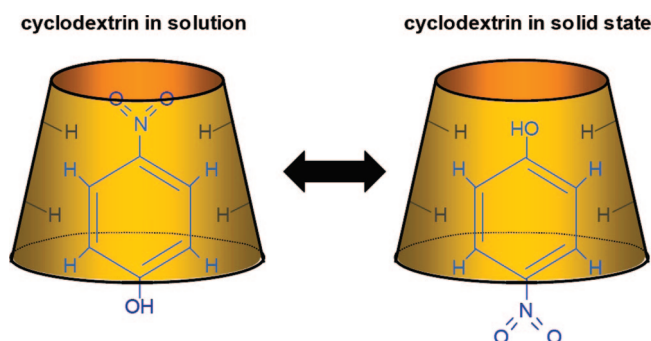

Figure 4. Phase-dependent orientational preference of cyclodextrins (on the basis of the work of Dodziuk[26]).

arises from a positive discrimination of specific transition states, and the cage or window effect, where products are trapped in the cages or at the pore mouth of the zeolites and are not observed as products.

Also the principle of molecularly imprinted systems, which are nowadays investigated mainly in relation to racemic or biomolecular separations, can be potentially applied for improving the stereoselectivity of the reaction events. Molecularly imprinted systems are highly selective due to three structural characteristics of the cavities they incoporate: size, shape, and functional group orientation.[31] In theory use of such systems should lead to 100% yield in separation and synthesis processes. In practice, however, there are still several problems associated with synthesis and use of molecularly imprinted systems such as the difficult removal of the template during synthesis, imperfect cavities, the overall lack of understanding in the design and synthesis, etc.[32] Nevertheless, promising advances have recently been made. Trotta et al.[33] report on preferential separation of tetracycline hydrochloride over a similar compound by a molecular imprinted membrane. Mosbach[34] opens up the domain of selective synthesis by imprinting techniques such as double imprinting and direct molding.

From the above, it is clear that further development of molecular-scale structuring and its applications on the commercial scale needs a multidisciplinary approach involving chemical engineering, chemistry, and materials science.
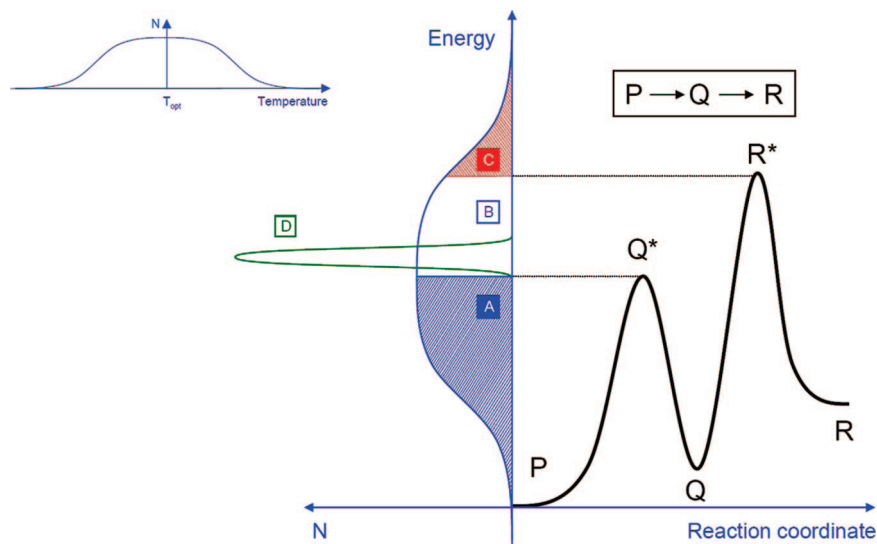
Figure 5. Illustration of the energy distribution problem in molecules in relation to the yield of consecutive reactions. (A) Molecules have insufficient energy to cause a reaction to occur. (B) Molecules have enough energy to form the required product Q. (C) Molecules have enough energy to form unwanted byproduct R. (D) Desired level and distribution of the energy provided to molecules.

The remaining three PI principles are realized by introducing structures on meso- and macroscale. For instance, the static mixer, a classical PI example, greatly improves the uniformity of the processing experience of the molecules by offering an almost-ideal plug-flow with very intensive mixing, at the same time significantly enhancing the specific interfacial area for the mass transfer. Similar effects in transport processes are seen also in various types of other structured reactors,[35] including monoliths, gauzes, foams, and a variety of milli- and microchannel systems. Spatially structured environments also enable combination of various functions to achieve synergy of the partial processes (thus realizing the fourth PI principle), as it happens for example in the reactive distillation units or in (catalytic) membrane reactors.

Fractal structures need a separate mentioning here as they present in our eyes a very specific type of spatial structuring with a high potential to intensify chemical processes. Fractals are self-similar objects whose pieces are smaller duplications of the whole object. Numerous systems found in the nature, such as tree leave nerves or our lungs, have a fractal structure. Such structures allow for uniform, energy-efficient, and very intensive transport processes. In chemical engineering, fractal concepts are found so far in the catalysis engineering[36,37] and in transporting/distributing fluids. Fractal distributors provide a uniform fluid distribution, enable reliable scale-up, and exhibit a very low sensitivity to changes in feed flow rate.[38-40] The application of a fractal ion exchanger in the juice softening process in the sugar beet industry has led to substantial improvements compared to the use of a conventional lateral orifice distributor: lowering of the resin bed depth by a factor of 7, decrease of the pressure drop over the bed by a factor of more than 35, and overall capital cost reduction by a factor of 2.5–3.[41]

2.2.2. Energy: PI Approach in the Thermodynamic Domain. Energy is the focus of the PI approach in the thermodynamic domain. The basic question here is how energy can be transferred from source to recipient in the required form, in the required amount, on the required moment, and at the required position. All energy that does not fit the requirements (unable to be absorbed, more than needed, "wrong" form, too early or too late, too far away) is not used optimally and (partly) dissipates. Although heat is a major type of energy, the term energy is by no means restricted to it. Pressure and movement are examples of other forms of energy that often need to be present at some stage in a chemical process.

Similar to spatial structuring, the thermodynamic approach addresses all four principles of process intensification. On the *molecular scale*, interesting works are reported in physics and chemistry aiming at the control of the molecular orientation by using magnetic fields,[42,43] strong electric fields,[44-46] or laser fields.[47-49] These works are still very fundamental in nature but the ideas and methods there reported need to attract more attention of the process intensification community.

The energy of molecules during collision is another factor which determines the effectiveness of a chemical reaction event. Improvement of the Maxwell–Boltzmann distribution in order to bring more molecules at the energy levels exceeding the activation energy threshold occurs conventionally via conductive heating. However, conductive heating is nonselective in nature, and so, other, nonreacting (bulk) molecules heat up together with the reacting ones. From the PI point of view, it is of paramount importance to deliver and remove exactly the required amount and form of energy. We illustrate it with a simplified example shown in Figure 5 inspired by the work of Schwalbe et al.[50] In a conventional system, such as one with significant temperature gradients, the energy of molecules is widely distributed. In case of a consecutive reaction of the type shown in the figure, where Q is the required product, a part of molecules (A) has energy insufficient to pass the transition state. Another part (B) has sufficient energy to get over the threshold and form product Q. A large portion of these molecules has in fact more energy than it is needed to form Q. Finally, there are molecules in our pool that possess enough energy to generate also the transition state R* which eventually leads to the formation of the unwanted product R. Ideally, one should provide the molecules with a narrowly distributed amount of energy, just exceeding the potential energy level of Q*, as it is illustrated by the curve D.

Furthermore, the energy is ideally delivered to the reactants only and not to other molecules, and remains with those reactants until they collide. Microwaves provide an example of a specific energy form which at least partially addresses that problem. Materials couple with microwave energy mainly by two mechanisms: dipole rotation and ionic conduction.[51,52]
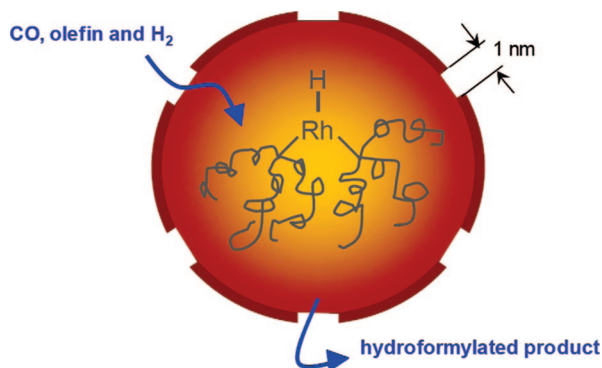
Figure 6. Homogeneous Rh catalyst encapsulated by a porous and hollow silica microsphere causing deliberate diffusion-limited input of reactants leading to enhanced product selectivity (on the basis of the work of Dautzenberg and Mukherjee[15]).

Both mechanisms generate movement, and therefore molecular friction, collisions, and heat. Because of the uptake of microwave energy by specific components in a reaction mixture, it is theoretically possible to heat up only the required reactants and/or catalytic nanoparticles without heating the bulk solvent or catalyst.

On the other end of the temperature scale, research groups in the domain of atomic physics are investigating cooling of molecules down to a few (milli)kelvin by using laser fields.[53] Unprecedented possibilities come into sight if these methods could be scaled up and utilized in chemical reactions.

This brings us to localized energy transfer in the area of photochemistry. Photochemical reactions are activated by the energy of light. Because of this specific form of activation, the selectivity of photochemical reactions can reach 100%.[54] A specific engineering problem for this type of reactors is the photon transfer from illumination source to the molecules that need to be activated.[55] Optical fibers, light emitting diode (LED) sources, and luminescent materials are currently investigated.

On the *meso- and macroscale*, alternative energy forms and alternative ways of transferring the energy have been shown to enhance mass and heat transport and to improve contact between phases.[54] Several energy forms appear promising such as electric fields, e.g., refs 39 and 54, magnetic fields, e.g., refs 56−58, and acoustic fields, e.g., refs 59−61. As mentioned earlier, microwave irradiation results in the gradientless, volumetric heating without heat-transfer surfaces, hence realizing the second PI principle. Also, the energy transfer by creating artificial gravity fields in the so-called high-gravity equipment, such as spinning disc reactors or rotating packed beds, is reported to deliver spectacular intensification effects, both on the research and commercial scale, e.g., refs 62−64.

2.2.3. Synergy: PI Approach in the Functional Domain. As stated earlier, looking for and maximizing the synergistic effects from partial processes presents one of the four generic principles of process intensification, and multifunctionality is the key term here.[15,16] Bringing multiple functions together in one component (a molecule, a phase, or a reactor) often leads to significantly better performance than the separate functions executed sequentially.

On the *molecular scale*, the catalytic function can be combined with a secondary or even tertiary function such as an additional catalytic function (bifunctional catalysts, e.g., refs 65 and 66) or adsorption, e.g., refs 66−68. The cases of encapsulating a homogeneous catalyst, e.g., ref 69, adhere closely to the structural approach using molecular reactors, described earlier, as shown in Figure 6. Catalytic functions can

also be synergistically coupled with an input of acoustic or electromagnetic energy. Catalysts operating in ultrasound field undergo *in situ* rejuvenation,[70] while application of microwave irradiation has been shown to selectively increase the temperature of the active metal nanoparticles, leading to higher conversions and selectivities at lower bulk temperatures.[71,72]

Interesting synergistic effects on *molecular* and *mesoscale* are observed when combining two different forms of energy. For instance, a combination of high-gravity field and photochemical processing was investigated. The spinning disc reactor was studied for UV-initiated polymerization of butyl acrylate,[73,74] as well as for TiO$_2$-based photocatalytic oxidation processes.[75,76] Microwave-assisted photochemical processes were also investigated. Kataoka et al.[77] observed an almost 2-fold increase of conversion when a photocatalytic reactor for ethylene oxidation has been subjected to microwave irradiation. Also sonophotocatalytic reactors were investigated, basically in application to wastewater purification.[78] The role of ultrasound in such reactors is not only to activate the reactions by implosions of microcavities, but also to clean and sweep the catalyst surface (fouling prevention) and to facilitate the reactants transport to it. Last but not least, effects of simultaneous irradiation by microwaves and ultrasound ("microwave sonochemistry") were also studied.[79−81] The application for example of microwave sonochemistry to pyrolysis of urea resulted in 25% increase of the product yield (cyanuric acid) as compared to both the conventional method and to the microwave-only method. In case of the esterification of propanol with acetic acid the corresponding improvements were 24% and 9%, respectively.[80]

On the *macroscale* search for synergy can be performed at the reactor level by introducing multifunctional reactors. Process intensification is achieved when the functions are integrated in such a way that one or both of them benefit from the interaction effect, for instance a shift of the reaction product composition beyond the equilibrium by an in situ separation/removal, or an enhancement of the separation efficiency by a chemical reaction.[82] Reactions are also combined with heat exchange (heat exchanger (HEX) reactors), power generation (fuel cells), or phase transition (reactive extrusion). Separations in turn can be integrated with heat exchange[16,83] or with each other that leads to so-called hybrid separations.[82,84]

2.2.4. Time: PI Approach in the Temporal Domain. The process intensification approaches in the temporal domain are basically twofold and involve either manipulations of the time scales at which different process steps proceed or the introduction of dynamic states into a process, usually in form of periodicity. Obviously, both these approaches have important consequences not only for process intensification itself but also for a number of enabling chemical engineering disciplines, such as process modeling or process systems control.

Manipulation of the time scales may mean for instance bringing molecules under extreme temperature conditions for a very short time, such as in the so-called millisecond reactors[85−87] or sonochemical reactors.[60,88,89] It may also mean a drastic shortening of the mixing times, as it is done in microfluidic systems using high-gravity fields where mixing times are reportedly reduced by 2 orders of magnitude.[90]

Periodicity, on the other hand, can be found on multiple timescales in nature, varying from seasonal changes to the pulsing flow in our lungs and veins. Also, a lot of "natural" periodicity can be found in chemical processes operated in stationary state in macroscopic sense. Among those "natural" periodicities are processes taking place at active catalytic sites,
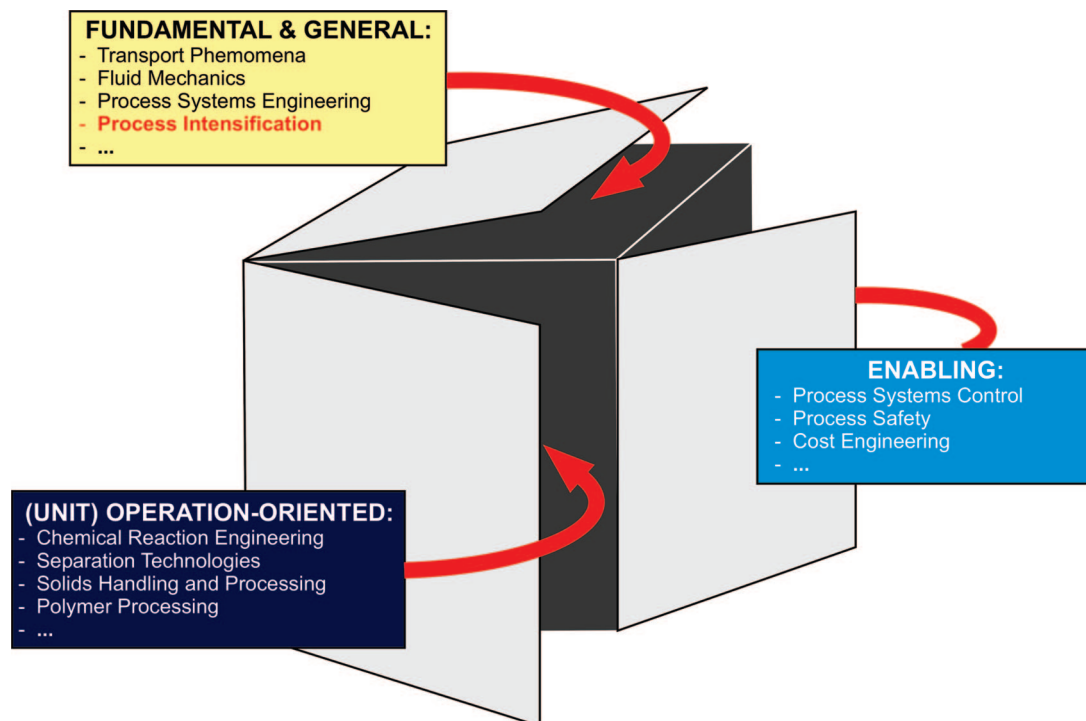
Figure 7. Disciplines constituting the magic box of chemical engineering.

Table 2. Comparison between Process Systems Engineering and Process Intensification

	process systems engineering	process intensification
aim	multiscale integration of existing and new concepts	development of new concepts of processing methods and equipment
focus	model, software, numerical method	experiment, phenomenon, interface
interdisciplinarity	modest (interface with applied mathematics and informatics, chemistry)	strong (chemistry and catalysis, applied physics, mechanical engineering, materials science, electronics, etc.)

formation, coalescence, and break-up of bubbles and droplets, and various circulation phenomena in the equipment.

Also many of the PI methods exhibit "natural" periodicity. Oscillations of molecules or ions induced by microwaves, was already described in the section Energy. Microcavities produced by the acoustic fields are also periodic in nature, with lifetimes of around 50 μs.

Introducing an "artificial", purposeful periodicity on the other hand can enable realizing all four principles of process intensification.

- It can influence kinetics of the adsorption—reaction—desorption processes on the catalyst surface and, hence, help in realizing the first PI principle. The so-called periodic forcing of catalytic processes (by oscillating pressures, concentrations, or temperatures) has been widely described in the literature, e.g., refs 91—93. It can also influence the effectiveness of biochemical reactions, like those taking place in algae subjected to a flashing light.[94]

- It can change and improve mixing characteristics of the system and, hence, help in realizing the second PI principle. For example, the so-called variable-volume operation, i.e. oscillating the liquid volume inside a continuous stirred-tank reactor, brings its mixing characteristics close to those of a plug-flow reactor.[95] The so-called oscillatory baffled flow reactor allows for a near-plug flow operation at low overall flow velocities, thus long reaction times, by changing a pipe into a large number of stirred tanks in series.[96,97]

- It can increase interfacial mass transfer rates and, hence, help in realizing the third PI principle. For instance, purposeful pulsing of the feed in trickle-bed reactors has been shown to bring significant improvement in the mass transfer rates, in catalyst wetting, and in the radial uniformity of liquid flow.[98]

- It can shift the process beyond the equilibrium limitation, or it can improve heat management in multifunctional systems and, hence, help in realizing the fourth PI principle. Flow reversal in the reversed-flow reactors is a typical example here.[99,100]

A particular application of the temporal approach of process intensification is the switch from batch to continuous processing.[13,101] The temporal aspect lies in the fact that the residence time distribution is reduced substantially as near-plug flow is achieved.[102,103] A significant problem with stirred tank reactors is the occurrence of transport limitations, especially in scale-up, leading to poor mixing and low efficiency at larger scales.[13] Heterogeneous mixing patterns have been shown extensively in tank reactors. Switching to continuous processing may therefore result in realization of the second and third PI principles.

3. Process Intensification and Modern Chemical Engineering

After defining the fundamentals of process intensification, it is worthwhile to briefly look at its position within the broader field of modern chemical engineering. That field can in our opinion be seen as a three-dimensional matrix comprising three classes of (sub)disciplines, as illustrated in Figure 7. First, we have *unit operation-oriented disciplines* such as separation technologies, chemical reaction engineering, or solids handling and processing. These disciplines are the most "classical" ones

as they originate from the age of the unit operations paradigm in chemical engineering. The second class comprises *fundamental and general disciplines* such as transport phenomena, engineering thermodynamics, fluid mechanics, or process systems engineering. These are the disciplines which are not unit-operation-bound and which address issues or phenomena occurring in various process stages and operations. Process intensification also belongs to that category. Finally, *enabling disciplines* such as process systems control, process safety, or cost engineering provide auxiliary knowledge and tools necessary for proper process design and operation.

Of special importance is here the synergistic relation between process intensification and process systems engineering. Despite clear differences in aim, focus, and interdisciplinary aspects (Table 2), these two disciplines complement each other to a large extent, with process intensification playing the role of a "provider of building blocks" from which the process systems are further developed. In this sense, process intensification opens up new interesting opportunities for process systems engineering in terms of model development and inclusion of innovative types of equipment and processing methods in process and plant design and optimization.

4. Conclusion

Process intensification presents a quickly developing field of chemical engineering, characterized so far by a great variety of definitions and interpretations. Instead of proposing one more definition of process intensification, in this paper we have tried to define its fundamentals. These fundamentals are in our opinion based on four generic principles and include four approaches within the spatial, thermodynamic, functional, and temporal domains.

The PI approaches described in this paper refer to all scales existing in chemical processes, from molecular to meso- and macroscale. During the last two decennia, the meso- and macroscale have been receiving the most attention within the PI community. In our opinion, however, it is the molecular scale where the research interest of PI in the coming years should turn to and where the most crucial technological challenges are waiting. Because of its strongly interdisciplinary character, process intensification is perfectly fitted to meet those challenges collaborating with other disciplines, such as chemistry, catalysis, applied physics, materials engineering, electronics, etc.

Process intensification may never find a single, commonly accepted definition. Many other fields of contemporary science encounter the same problem—just to mention product engineering or nanotechnology. But, it is not the definition that will eventually determine the importance of process intensification in the history of chemical engineering. It is rather the societal relevance of the issues it addresses when taking chemical engineering on a creative journey beyond its established boundaries. Because, as Professor Keil[104] rightly wrote, in process intensification the journey is the reward.

Literature Cited

(1) Villermaux, J. Basic chemical engineering research. Where are we going. *Trans. Inst. Chem. Eng. A* **1993**, *71*, 45.

(2) Villermaux, J. Future challenges in chemical engineering research. *Trans. Inst. Chem. Eng. A* **1995**, *73*, 105.

(3) Astarita, G.; Ottino, J. M. Thirty-five years of BSL. *Ind. Eng. Chem. Res.* **1995**, *34*, 3177.

(4) Wei, J. A century of changing paradigms in chemical engineering. *CHEMTECH* **1996**, *26* (5), 16.

(5) Stankiewicz, A.; Moulijn, J. A. Process Intensification. *Ind. Chem. Eng. Res.* **2002**, *41*, 1920.

(6) Batterham, R. J. Sustainability—the next chapter. *Chem. Eng. Sci.* **2007**, *61*, 4188.

(7) Ramshaw, C. Higee distillation—an example of process intensification. *Chem. Eng. London* **1983**, *389*, 13.

(8) Cross, W. T.; Ramshaw, C. Process Intensification - laminar-flow heat-transfer. *Chem. Eng. Res. Des.* **1986**, *64*, 293.

(9) Stankiewicz, A.; Moulijn, J. A. Process intensification: transforming chemical engineering. *Chem. Eng. Progr.* **2000**, *96* (1), 22.

(10) Tsouris, C.; Porcelli, J. V. Process Intensification - Has its time finally come? *Chem. Eng. Progr.* **2003**, *99* (10), 50.

(11) ERPI. European Roadmap for Process Intensification. Creative Energy - Energy Transition. www.creative-energy.org (accessed September 2, 2008).

(12) Becht, S.; Franke, R.; Geisselman, A.; Hahn, H. An industrial view on process intensification. *Chem. Eng. Process.: Process Intens.*, available online April 26, 2008,http://dx.doi.org/10.1016/j.cep.2008.04.012.

(13) Stitt, E. H. Alternative multiphase reactors for fine chemicals. A world beyond stirred tanks? *Chem. Eng. J.* **2002**, *90*, 47.

(14) Mae, K. Advanced chemical processing using microspace. *Chem. Eng. Sci.* **2007**, *62*, 4842.

(15) Dautzenberg, F. M.; Mukherjee, M. Process intensification using multifunctional reactors. *Chem. Eng. Sci.* **2001**, *56*, 251.

(16) Huang, K.; Wang, S. J.; Shan, L.; Zhu, Q.; Qian, J. Seeking synergistic effect - a key principle in process intensification. *Sep. Pur. Technol.* **2007**, *57*, 111.

(17) Arizmendi-Sánchez, J. A.; Sharatt, P. N. Phenomena-based modularisation of chemical process models to approach intensive options. *Chem. Eng. J.* **2008**, *15*, 83.

(18) Moulijn, J. A.; Stankiewicz, A.; Grievink, J.; Górak, A. Process intensification and process systems engineering: a friendly symbiosis. *Comput. Chem. Eng.* **2008**, *32*, 3.

(19) Freund, H.; Sundmacher, K. Towards a methodology for the systematic analysis and design of efficient chemical processes - Part 1: From unit operations to elementary process functions. *Chem. Eng. Process.: Process Intens.* **2008**, *47*, 2051−2060.

(20) Bakker, R. A. Process Intensification in industrial practice: methodology and application. In *Re-engineering the Chemical Processing Plant: Process Intensification*; Stankiewicz, A., Moulijn, J. A., Eds.; Marcel Dekker: New York, 2004; p 447.

(21) Lerou, J.; Ng, K. M. Chemical reaction engineering: a multiscale approach to multiobjective task. *Chem. Eng. Sci.* **1996**, *51* (10), 1595.

(22) Schmidt-Traub, H.; Górak, A. *Integrated reactor and separation operations*; Springer-Verlag: Berlin, 2006.

(23) Westerterp, K. R.; Wijngaarden, R. J. Chemical Reactor Engineering. In *Ullmann's Encyclopedia*; 2005.

(24) Coppens, M.-O. Structuring catalyst nanoporosity. In *Structured catalysts and reactors*, 2nd ed.; Cybulski, A., Moulijn, J. A., Eds.; CRC Press, Taylor and Francis Group: Boca Raton, FL, 2006; p 779.

(25) Easton, C. J. Cyclodextrin-based catalysts and molecular reactors. *Pure Appl. Chem.* **2005**, *77* (11), 1865.

(26) Dodziuk, H. Molecules with holes — cyclodextrins. In *Cyclodextrins and their complexes*; Dodziuk, H., Ed.; Wiley-VCH Verlag GmbH & Co.: Weinheim, 2006; p 1.

(27) Davis, R. J. New perspectives on basic zeolites as catalysts and catalyst supports. *J. Cat.* **2003**, *216*, 396.

(28) Stöcker, M. Gas phase catalysis by zeolites. *Microporous Mesoporous Mat.* **2005**, *82*, 257.

(29) Davis, M. E.; Katz, A.; Ahmad, W. R. Rational catalyst design via imprinted nanostructured materials. *Chem. Mater.* **1996**, *8*, 1820.

(30) Attfield, M. P. Microporous materials. *Sci. Progr.* **2002**, *85* (4), 319.

(31) Janiak, D. S.; Kofinas, P. Molecular imprinting of peptides and proteins in aquous media. *Anal. Bioanal. Chem.* **2007**, *389*, 399.

(32) Kandimalla, V. B.; Ju, H. Molecular imprinting: a dynamic technique for diverse application in analytical chemistry. *Anal. Bioanal. Chem.* **2004**, *380*, 587.

(33) Trotta, F.; Baggiani, C.; Luda, M. P.; Drioli, E.; Massari, T. A molecular imprinted membrane for molecular discrimination of tetracycline hydrochloride. *J. Membr. Sci.* **2005**, *254*, 13.

(34) Mosbach, K. The promise of molecular imprinting. *Sci. Am.* **2006**, October, 87.

(35) Cybulski, A., Moulijn, J. A., Eds.; *Structured catalysts and reactors*, 2nd ed.; CRC Press, Taylor and Francis Group: Boca Raton, FL, 2006.

(36) Coppens, M.-O.; Froment, G. Catalyst design accounting for the fractal surface morphology. *Chem. Eng. J.* **1996**, *64*, 69.

(37) Phillips, C.; Ben-Richou, A.; Ambari, A.; Fedorov, A. Catalyst surface at a fractal of cost—a quest for optimal catalyst loading. *Chem. Eng. Sci.* **2003**, *58*, 2403.

(38) Kearney, M. Control of fluid dynamics with engineered fractals—adsorption process applications. *Chem. Eng. Commun.* **1999**, *173*, 43.

(39) Coppens, M.-O.; van Ommen, J. R. Structuring chaotic fluidized beds. *Chem. Eng. J.* **2003**, *96*, 117.

(40) Coppens, M.-O. Scaling-up and -down in a Nature-inspired way. *Ind. Eng. Chem. Res.* **2005**, *44*, 5011.

(41) Kochergin, V.; Kearney, M. Existing biorefinery operations that benefit from fractal-based process intensification. *Appl. Biochem. Biotechnol.* **2006**, *129−132*, 349.

(42) Alnis, J.; Auzinsh, M. Alignment-orientation conversion in molecules in an external magnetic field caused by a hyperfine structure. *Eur. Phys. J. D.* **2000**, *11*, 91.

(43) Shestakova, A. K.; Makarkia, A. V.; Smirnova, O. V.; Shtern, M. M.; Chertkov, V. A. Orientation of molecules by magnetic field as a new source of information on their structures. *Russ. Chem. Bull. Int. Ed.* **2006**, *55* (8), 1359.

(44) Brooks, P. R. Reactions of Oriented Molecules. *Science* **1976**, *193* (4247), 11.

(45) Friedrich, B.; Herschbach, D. R. Spatial orientation of molecules in strong electric fields and evidence for pendular states. *Nature* **1991**, *353*, 412.

(46) Dion, C. M.; Keller, A.; Atabek, O. Orienting molecules using half-cycle pulses. *Eur. Phys. J. D* **2001**, *14*, 249.

(47) Zare, R. Laser control of chemical reactions. *Science* **1998**, *279*, 1875.

(48) Sakai, H.; Minemoto, S.; Nanjo, H.; Tanji, H.; Suzuki, T. Controlling the orientation of polar molecules with combined electrostatic and pulsed, nonresonant laser fields. *Phys. Rev. Lett.* **2003**, *90* (8), 083001.

(49) Cong, S.-L.; Han, K.-L.; Lou, N.-Q. Controlling the orientation and alignment of reagent molecules by a polarized laser. *Chin. Phys. Lett.* **2003**, *20* (7), 1038.

(50) Schwalbe, T.; Autze, V.; Hohmann, M.; Stirner, W. Novel innovation systems for a cellular approach to continuous process chemistry from discovery to market. *Org. Proc. Res. Dev.* **2004**, *8*, 440.

(51) Strauss, C. R.; Trainor, R. W. Invited review: Developments in microwave-assisted organic chemistry. *Aust. J. Chem.* **1995**, *48*, 1665.

(52) Lidström, P.; Tierney, J.; Wathey, B.; Westman, J. Microwave assisted organic synthesis—a review. *Tetrahedron* **2001**, *57*, 9225.

(53) Viteau, M.; Chotia, A.; Allegrini, M.; Bouloufa, N.; Dulieu, O.; Comparat, D.; Pillet, P. Optical pumping and vibrational cooling of molecules. *Science* **2008**, *321*, 232.

(54) Stankiewicz, A. Energy matters, alternative sources and forms of energy for intensification of chemical and biochemical processes. *Trans. Inst. Chem. Eng.: A, Chem. Eng. Res. Des.* **2006**, *84*, 511.

(55) Van Gerven, T.; Mul, G.; Moulijn, J. A.; Stankiewicz, A. A review of intensification of photocatalytic processes. *Chem. Eng. Process.: Process Intens.* **2007**, *46*, 781.

(56) Nuyens, J.; Martens J. *Emulsification method for producing emulsion for use in, e.g. detergents, involving flowing, conducting, or circulating premix of at least two immiscible liquids through magnetic field(s) under conditions to emulsify the pre-mix.* Patent WO2004043580, 2004.

(57) Van den Mooter, G.; Martens, J.; Nuyens, J. *Reduction of an average size of biologically active compound particles or agglomerates suspended in a fluid involves flowing at least one time the fluid through at least one magnetic field.* Patent WO2005018611, 2005.

(58) Munteanu, M. C.; Iliuta, I.; Larachi, F. Process Intensification in artificial gravity. *Ind. Eng. Chem. Res.* **2005**, *44*, 9384.

(59) Neis, U. Intensification of biological and chemical processes by ultrasound. *TU Hamburg−Harburg Rep. Sanit. Eng.* **2002**, *35*, 79.

(60) Gogate, P. R. Cavitational reactors for process intensification of chemical processing applications: a critical review. *Chem. Eng. Process.: Process Intens.* **2008**, *47*, 515.

(61) Wu, J.; Graham, L. J.; Noui-Mehidi, N. Intensification of mixing. *J. Chem. Eng. Jpn.* **2007**, *40* (11), 890.

(62) Ramshaw, C. The spinning-disc reactor. In *Re-engineering the Chemical Processing Plant: Process Intensification*; Stankiewicz, A., Moulijn, J. A., Eds.; Marcel Dekker: New York, 69, 2004.

(63) Trent, D. Chemical processing in high-gravity fields. In *Re-engineering the Chemical Processing Plant: Process Intensification*; Stankiewicz, A., Moulijn, J. A., Eds.; Marcel Dekker: New York, 2004; p 33.

(64) Rao, D. P.; Bhowal, A.; Goswami, P. S. Process intensification in rotating packed beds (HIGEE): an appraisal. *Ind. Eng. Chem. Res.* **2004**, *43* (4), 1150.

(65) Gunn, D. J. The optimization of bifunctional catalyst systems. *Chem. Eng. Sci.* **1967**, *22*, 963.

(66) Grünewald, M.; Agar, D. W. Enhanced catalyst performance using integrated structured functionalities. *Chem. Eng. Sci.* **2004**, *59*, 5519.

(67) Agar, D. W. Multifunctional reactors: old preconceptions and new dimensions. *Chem. Eng. Sci.* **1999**, *54*, 1299.

(68) Dietrich, W.; Lawrence, P. S.; Grünewald, M.; Agar, D.W. Theoretical studies on multifunctional catalysts with integrated adsorption sites. *Chem. Eng. J.* **2005**, *107* (1−3), 103.

(69) Davis, M. E. Reaction chemistry and reaction engineering principles in catalyst design. *Chem. Eng. Sci.* **1994**, *49*, 3971.

(70) Mikkola, J.-P.; Salmi, T. In-situ ultrasonic catalyst rejuvenation in three-phase hydrogenation of xylose. *Chem. Eng. Sci.* **1999**, *54* (10), 1583.

(71) Zhang, X.; Hayward, D. O.; Mingos, D. M. P. Microwave dielectric heating behavior of supported MoS2 and Pt catalysts. *Ind. Eng. Chem. Res.* **2001**, *40*, 2810.

(72) Will, H.; Scholz, P.; Ondrushka, B. Heterogeneous gas-phase catalysis under microwave irradiation — a new multi-mode microwave applicator. *Top. Cat.* **2004**, *29* (3−4), 175.

(73) Dalglish, J.; Jachuck, R.; Ramshaw, C. Photo-initiated polymerization using spinning disc reactor. In *Process Intensification for the Chemical Industry*; Green, A., Ed.; Professional Engineering Publishing Limited: Bury St. Edmunds, UK, 1999; p 209.

(74) Boodhoo, K. V. K.; Dunk, W. A.; Jachuck, R. J. Spinning disc reactor for photopolymerization. *Polym. Prepr.* **2001**, *42* (2), 813.

(75) Yatmaz, H. C.; Wallis, C.; Howarth, C. R. The spinning disc reactor - studies on a novel TiO$_2$ photocatalytic reactor. *Chemosphere* **2001**, *42*, 397.

(76) Dionysiou, D. D.; Burbano, A. A.; Suidan, M. T.; Baudin, I.; Laîné, J.-M. Effect of oxygen in a thin-film rotating disk photocatalytic reactor. *Environ. Sci. Technol.* **2002**, *36*, 3834.

(77) Kataoka, S.; Tompkins, D. T.; Anderson, M. A.; Zorn, M. E.; Zeltner, W. A. Microwave-assisted heterogeneous photocatalytic oxidation. *Ceram. Trans.* **2001**, *111*, 225.

(78) Gogate, P. R.; Pandit, A. B. Sonophotocatalytic reactors for wastewater treatment: a critical review. *AIChE J.* **2004**, *50* (5), 1051.

(79) Maeda, M.; Amemiya, H. Chemical effects under simultaneous irradiation by microwaves and ultrasound. *New J. Chem.* **1995**, *19* (10), 1023.

(80) Chemat, F.; Poux, M.; Di Martino, J.-L.; Berlan, J. An original microwave-ultrasound combined reactor suitable for organic synthesis: application to pyrolysis and esterification. *J. Microwave Power Electromagn. Energy* **1995**, *31* (1), 19.

(81) Cravotto, G.; Cintas, P. The combined use of microwaves and ultrasound: improved tools in process chemistry and organic synthesis. *Chem.−Eur. J.* **2007**, *13*, 1902.

(82) Stankiewicz, A. Reactive separations for process intensification; an industrial perspective. *Chem. Eng. Processes* **2003**, *42*, 137.

(83) Olujic, Z.; Fakhri, F.; de Rijke, A.; de Graauw, J.; Jansens, P. J. Internal heat integration - the key to an energy-conserving distillation column. *J. Chem. Technol. Biotechnol.* **2003**, *78*, 241.

(84) Buchaly, C.; Kreis, P.; Górak, A. Hybrid separation processes - Combination of reactive distillation with membrane separation. *Chem. Eng. Process.: Process Intens.* **2007**, *46*, 790.

(85) Goetsch, D. A.; Schmidt, L. D. Microsecond catalytic partial oxidation of alkanes. *Science* **1996**, *271*, 1560.

(86) Deluga, G. A.; Salge, J. R.; Schmidt, L. D.; Verykios, X. E. Renewable hydrogen from ethanol by autothermal reforming. *Science* **2004**, *303*, 993.

(87) Stefanidis, G. D.; Vlachos, D. G. Millisecond methane steam reforming via process and catalyst intensification. *Chem. Eng. Technol.* **2008**, *31* (8), 1201.

(88) Thompson, L. H.; Doraiswamy, L. K. Sonochemistry: science and engineering. *Ind. Eng. Chem. Res.* **1999**, *38*, 1215.

(89) Cravotto, G.; Cintas, P. Power ultrasound in organic synthesis: moving cavitational chemistry from academia to innovative and large-scale applications. *Chem. Soc. Rev.* **2006**, *35*, 180.

(90) Ducrée, J.; Haeberle, S.; Brenner, T.; Glatzel, T.; Zengerle, R. Patterning of flow and mixing in rotating radial microchannels. *Microfluid Nanofluid* **2006**, *2*, 97.

(91) Cutlip, M. B. Concentration forcing of catalytic surface rate processes: Part I. Isothermal carbon monoxide oxidation over supported platinum. *AIChE J.* **1979**, *25* (3), 502.

(92) Silveston, P. L.; Hudgins, R. R. Periodic forcing of temperature of catalytic reactions. *Chem. Eng. Sci.* **2004**, *59*, 4043.

(93) Zhdanov, V. P. Periodic perturbation of the kinetics of heterogeneous catalytic reactions. *Surf. Sci. Rep.* **2004**, *55*, 1.

(94) Katsuda, T.; Shimahara, K.; Shiraishi, H.; Yamagami, K.; Ranjbar, R.; Katoh, S. Effect of flashing light from blue light emitting diodes on cell growth and astaxanthin production of Haematococcus pluvialis. *J. Biosci. Bioeng.* **2006**, *102* (5), 442.

(95) Zwijnenburg, A.; Stankiewicz, A.; Moulijn, J. A. Dynamic operation of chemical reactors: friend or foe? *Chem. Eng. Progr.* **1998**, *94* (11), 39.

(96) Ni, X.; Pereira, N. E. Parameters affecting fluid dispersion in a continuous oscillatory baffled tube. *AIChE J.* **2000**, *46*, 37.

(97) Pereira, N. E.; Ni, X. Droplet size distribution in a continuous oscillatory baffled reactor. *Chem. Eng. Sci.* **2001**, *56* (3), 735.

(98) Boelhouwer, J. G.; Piepers, H. W.; Drinkenburg, A. A. H. The induction of pulses in trickle-bed reactors by cycling the liquid feed. *Chem. Eng. Sci.* **2001**, *56* (8), 2605.

(99) Matros, Y. S.; Bunimovich, G. A. Reverse-flow operation in fixed bed catalytic reactors. *Cat. Rev.* **1996**, *38* (1), 1.

(100) Eigenberger, G.; Kolios, G.; Nieken, U. Thermal pattern formation and process intensification in chemical reaction engineering. *Chem. Eng. Sci.* **2007**, *62*, 4825.

(101) Wheeler, R. C.; Benali, O.; Deal, M.; Farrant, E.; MacDonald, S. J. F.; Warrington, B. H. Mesoscale flow chemistry: a plug-flow approach to reaction optimisation. *Org. Process Res. Dev.* **2007**, *11*, 704.

(102) LaPorte, T. L.; Wang, C. Continuous processes for the production of pharmaceutical intermediates and active pharmaceutical ingredients. *Curr. Opin. Drug Discovery Dev.* **2007**, *10* (6), 738.

(103) Luyben, W. L. *Chemical reactor design and control*; John Wiley & Sons: Hoboken, NJ, 2007.

(104) Keil, F. J. Modeling of Process Intensification - An introduction and overview. In *Modeling of Process Intensification*; Keil, F. J., Ed.; Wiley-VCH: Weinheim, 2007; p 1.