Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Chemical Engineering

Dynamic process intensification

Michael Baldea[1,3] and Thomas F Edgar[1,2]

Most process intensification research and its applications have focused on process and equipment design modifications. In this paper, we present an overview of existing developments and opportunities in dynamic process intensification (DI), which comprises changes to dynamics, operational and control of a chemical process, that result in substantial efficiency improvements. After reviewing a series of examples, we identify several fundamental principles underlying DI, including equipment design and operational approaches. We conclude with a number of challenges and opportunities related to DI system design, operation and control, and fault detection and isolation.

Addresses
[1] McKetta Dept. of Chemical Engineering, The University of Texas at Austin, Austin, TX 78712, United States
[2] Energy Institute, The University of Texas at Austin, Austin, TX 78712, United States
[3] Institute for Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX 78712, United States

Corresponding author: Baldea, Michael (mbaldea@che.utexas.edu)

Current Opinion in Chemical Engineering 2018, **22**:48–53

This review comes from a themed issue on **Process systems engineering: advanced manufacturing**

Edited by **Karen Fletcher**, **Jim Bielenberg**, **Mahmoud El-Hawlwagi** and **Ka Ming Ng**

https://doi.org/10.1016/j.coche.2018.08.003

Introduction

Process intensification is defined as 'any chemical engineering development that leads to a substantially smaller, cleaner and more energy-efficient technology' [1]. While this definition has been interpreted relatively broadly [2,3], to date, most developments in this field have been at the *design* level, focusing on new process and/or device configurations. Such systems typically bring together multiple phenomena (usually associated with individual unit operations) and seek to minimize transport limitations, such that processes are governed by their intrinsic rates. Further, it is typical for such systems to be operated at steady state, largely due to the fact that this approach to intensification leads to a loss of degrees of freedom available for control [4].

We posit that intensification can also be achieved by making *operational and control* changes to a process (whether conventional or intensified by design). In this context, we define *dynamic process intensification* (DI) as '*any change to the dynamics, operation strategy and/or control of a conventional or intensified system, that leads to a substantially more efficient processing path.*' [5].

The purpose of this article is to systematically review existing DI approaches, define future directions and research targets, as well as potential challenges and roadblocks to achieve them. A set of structural/operational process features and elements of DI will be identified, which will then serve to construct a taxonomy of processes and technologies that fall within the realm of DI.

Motivating examples

The focus of this paper is on continuous (rather than batch) processing, implying that the product(s) must be made in a continuous stream. Thus, the dynamically intensified processes considered here operate in a periodic/cyclical fashion. They reach a periodic steady state which, *on the average*, corresponds to the desired production rate(s) and/or product quality. To achieve this, a storage 'buffer' may be required to attenuate any fluctuations in these performance indicators that are associated with the periodic operations. Further, it is expected that some figure of merit (e.g. energy use per unit product) is, all other things being equal, *better* for the dynamically intensified process than for a conventional process of equal capacity, if the latter exists. We begin with reviewing existing dynamically intensified systems and subsequently use this information to extract some generic features of DI systems.

Periodic operation of continuous chemical reactors

The possibility of improving the performance of reaction systems via periodic variation of operating conditions has been observed as early as the 1960s. For example, it was shown that varying the temperature of a CSTR (following either sinusoidal or square-wave patterns) for multiple-reaction systems of the type:

$$2A \rightarrow B \tag{1}$$

$$A \rightarrow C \tag{2}$$

can improve the time-average yield of a product of interest (in this case, B) [6,7].

While it was surmised that this mode of operation exploits the nonlinear influence of temperature on the rates of competing reactions, initial reporting of these improvements was largely based on empirical observations. Further work concentrated on identifying first, the generic conditions that a system must fulfil in order for periodic operation to be beneficial and second, determining the optimal parameters of the cyclic forcing function (i.e. amplitude and period) for maximizing this benefit [7–11].

Cyclic distillation

Research carried out in the 1960s [12–15] also revealed the possibility of operating distillation systems in a cyclic fashion. Cyclic distillation in this case involved segregating the fluid traffic in the distillation column, with fast (i.e. in the order of seconds) switching between (downward) liquid flow and (upward) vapor flow. Segregation reduces unnecessary mixing between the vapor and liquid phase, and between the liquid material on adjacent trays. Literature reports claim increases in stage efficiency and throughput compared to conventional columns [13–15], as well as improvements in energy use [16]. Columns intended for cyclic operation use customized/dedicated internal components (including special trays that have no downcomers). The concept of cyclic operation was also applied to extraction columns [17]. In general, adding such technology to a chemical plant is likely acceptable for new investments, but retrofits of existing distillation or extraction towers may prove costly and problematic.

Periodic distillation based on output multiplicity

Early research [18,19] demonstrated that (binary) distillation columns exhibit steady-state multiplicity. Of particular interest is output multiplicity, where a column can produce distillate of two different purities with the same reboiler duty. A recent development in the dynamic intensification of distillation processes relies on exploiting this nonlinearity [5] to lower column energy use (defined as the sum of reboiler and condenser duties) for a distillate stream of desired purity. This dynamic intensification approach relies on the observation that the target product can be obtained as a blend of two auxiliary products (one of higher purity, the other of lower purity than desired), both of which have *lower* specific energy consumption. Thus, the operating conditions (column pressure, boilup rate) are periodically switched between the operating points corresponding to the two auxiliary products, and the distillate stream is collected in a buffer tank whose average composition equals that of the desired product. The control signals may be continuous or step-wise, with periods in the order of magnitude of the time constant of the column itself (minutes to hours). Importantly, this concept relies on a conventional distillation column and does not require any dedicated hardware.

Reverse-flow reaction systems

Reverse-flow reactors (RFRs) have been proposed as an intensified design for carrying out endothermic reactions [20]. The system comprises a tubular reactor whose operation consists of two separate, discrete steps: a heating step, whereby a fuel is (catalytically) combusted to heat the catalyst bed, and a reaction step, where the process stream (typically fed to the reactor at he opposite end) passes over the hot catalyst and undergoes the desired reactions. Pressurization/depressurization, purging, or other steps can be inserted in the operating cycle as needed, and multiple reactors can be operated in parallel to ensure a (relatively) constant flow of product. The reaction system reaches a cyclic/periodic steady state, rather than having a single steady-state operating point as is the case with most continuous processes. Several applications of reverse flow reactors have been reported, including the production of syngas [21], SO_2 oxidation [22], and the mitigation of volatile organic compound emissions [23]. Operational complexity notwithstanding, it is argued that reverse-flow systems have capital expenditure advantages compared to a conventional system of equivalent capacity. The latter would require, for example, a separate heating furnace and a feed-effluent heat exchanger to maintain the required thermal regime.

Oscillatory baffled reactors (OBRs)

OBRs are tubular reactors that diverge from the conventional plug-flow design in two important ways. From a design perspective, the flow encounters resistances (baffles) placed at equally spaced intervals along the flow path. From an operational perspective, an oscillatory motion is imposed over the net flow by means of a secondary pump/actuator. Combined with the baffled structure, the oscillatory fluid motion simulates the operation of a cascade of CSTRs, effectively achieving a desirable plug flow profile. OBRs provide an intensification opportunity for reactions that require long residence times and where a conventional plug-flow reactor would have an impractical length. We note that the idea of oscillatory mixing has been used for the intensification of other processes; see Ni *et al.* [24] for a review.

Cyclic adsorption processes

Pressure swing adsorption (PSA) is a widespread technique for separating gas mixtures, and has been applied to, for example, air separation (to generate oxygen or nitrogen) and the separation of hydrogen from syngas. Fundamentally, PSA relies on the difference in adsorption rates between the components of the mixture on a given solid adsorbent, as well as on the influence of pressure on the amount of adsorbed component. A PSA system comprises of two (or more) adsorbent-packed beds, which are operated in a cyclic fashion, in a carefully choreographed sequence of discrete steps that are implemented in practice by changing the positions of several automatic valves that control the flow and feed/extraction