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Conceptual methods for synthesis of reactive distillation processes: recent developments and perspectives

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Jan Harmsen,^e  Megan Jobson^f and Xin Gao^g 

Abstract

Reactive distillation (RD) is a process intensification technique that offers major advantages over conventional technologies by enabling the integration of reaction and separation into a single apparatus. This integration introduces and exploits complex interaction between mass transfer, chemical reaction and hydrodynamics within an RD column; however, these complexities can hinder the adoption of RD by industry. Many approaches have been developed by the scientific community to advance understanding and to expedite the initialization of RD design at the conceptual level. This paper critically discusses recent developments in conceptual methods for synthesizing RD processes. This review paper is the first to consider the range of available approaches for assessing the technical feasibility, controllability, economic viability, and sustainability of RD units by taking into account various configurations in which RD is treated as a new unit operation, and as part of process synthesis in a different way of designing processes based on functions. The review also addresses complex configurations, such as advanced RD technologies. Special attention is paid to process modeling and simulation as well as to education. Knowledge gaps to be filled by further research are indicated.

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Keywords: reactive distillation; conceptual design; process synthesis; technology selection

INTRODUCTION

Purpose of this review article

Over the past 50 years, the number of related research publications in the field of reactive distillation (RD) has notably increased. Malone and Doherty¹ reported that 562 scientific publications about RD were identified in the 30 years before 2000. Then, within the next 11 years, at least 1979 scientific papers were published.² Since then, it seems that the average publications number per year was kept constant at this high level. For instance, Wierschem and Gorak³ reported that >1000 research-based publications produced from 2013 to 2018 aimed to extend the performance of RD. Figure 1 shows the number of scientific papers published in the field of RD and the number of patents in the past decades, with an increased trend. It is evident, therefore, that the field of RD has experienced ongoing and sustained development. However, there is uncertainty about several aspects: first, which findings were included in textbooks for educational purposes and which findings are applicable for industrial engineers in process design; secondly, what specific results can inform process concept design involving RD as a well-established unit operation; and thirdly, which findings are aligned with function-based process design methods or process systems engineering (PSE) approaches, focusing on feasibility, configuration and process optimization.

In order to clarify the state-of-the-art for industrial engineers, for academic teachers and for researchers, we have searched the literature

specifically for methods for conceptual process design, approaches for technology selection and tools to support education in this area. This article reviews the present state-of-the-art for all these subjects. For each subject, scientific literature has been researched in view of

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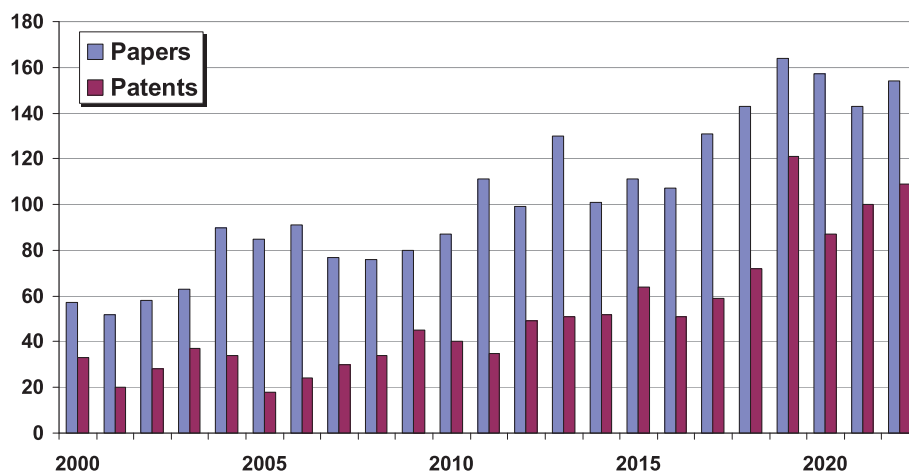


Figure 1. Number of Scopus retrieval of academic papers about RD, and the United States and China authorized patents during 2000–2022.

industrial design and academic teaching. Knowledge gaps are identified and research to fill these gaps is indicated.

There are different ways to categorize RD processes, such as method-based (e.g. heuristics, graphical, optimization-based), evaluation criteria-based, or reaction system-based as shown in several tables afterwards. However, for more clarity, we use the two approaches to conceptual process design in order to structure this article.

The Reactive Distillation Treated as a Unit Operation in Conceptual Process Design section focuses on process intensification (PI) principles, corresponding to new process building blocks that then can be used as a unit operation in conventional process design (based on unit operations). The first step of the operation-based method is researching the new process intensified unit operation. There the new unit operation design description is established. Later, mainly by industrial practitioners, this new unit operation can then be applied in a specific process design containing conventional unit operations and this new PI unit operation, by a process designer. This approach to PI, involving the development of new unit operations, has been broadly explored by Cross and Ramshaw,⁴ Dautzenberg and Mukherjee,⁵ Stankiewicz and Moulijn,⁶ and Franke.⁷ This approach and its results so far, for established PI technologies, are well-explained and described in a textbook by Stankiewicz *et al.*⁸ However, RD is only very briefly described and not suitable for use in education.

The Process Systems Engineering Function-Based Design Leading to Reactive Distillation section focuses on the design of the whole (plantwide) process, based on ‘functions’. Dorst⁹ describes functions as follows: ‘Concentrating on functions you describe what the design has to do in a list of verbs. Each verb easily evokes many possible objects that could fulfil the function. Functions are an intermediate between the problem and its design solution. Thinking in functions is a natural way of thinking when working on a design project.’ The function-based method is applicable to any new process to be designed. In the specific process design, functions are defined connecting input streams to output streams. In a second step, some of the functions are integrated into a function-integrated new design solution. In general, this new design solution is unique and cannot be applied in other process designs, as described in Harmsen and Verkerk.¹⁰ Yet, this function concept has earlier roots. Sirola and Rudd¹¹ introduced conceptual process design using functions, which they called ‘tasks’. A task eliminates a difference between input and output. For example, the task reaction eliminates the difference in molecular type between

input and output, and the task separation eliminates a difference in composition. Combining functions is the next step in process concept design. First, functions needed to get from input to output are identified and then functions are integrated. Process systems engineering (PSE) modeling and simulation methods are crucial in this approach.¹² Process concept feasibility is revealed, and in further cycles between synthesis and analysis the process concept is optimized. The main difference between designing with unit operations and designing with functions is that a unit operation describes how in detail the transformation from input to output occurs, whereas a function only describes what (not how) has to be done to transform the input to output. Modeling, simulation and optimization methods are described as well, along with process controllability. The PSE approach also can generate very complex configurations still in early research.

The Advanced Reactive Distillation Technologies section covers advanced RD technologies for which there are heuristic approaches only and where more systematic methods remain to be developed for these systems. The final sections present conclusions regarding industrial design and academic education, as well as an overview of the knowledge gaps and recommendations for research to fill the gaps. The purpose of this review article is to address the literature gap. Despite the demand for such a comprehensive review from both industry and academia, no article serves this purpose fully.

Research, education and industrial applications of RD: a brief history

Reactive distillation is a process intensification technique that takes advantage of synergistic effects of combining reaction and separation in order to reduce the energy requirements and the capital cost, along with improving the sustainability in distillation process.^{13,14} RD has existed for almost one century both in industry and in the academic world. The first patent was granted in 1921 for the manufacture of esters,¹⁵ while in the following years, several scientific publications reported the application of RD.^{16–18} Industrial interest in RD was renewed in the 1980s, when the company Chemical Research & Licensing patented the first heterogeneously catalyzed process for the synthesis of methyl tert-butyl ether.¹⁹ A few years later, the Eastman Kodak company invented and implemented in 1997 one of the most well-known RD processes for the production of methyl acetate.^{20,21}

The history of the Eastman case has been investigated in some detail by Harmsen and Verkerk.²² They showed that academic

research on process synthesis by Jeff Siirola and academic teaching of Eastman process engineers played an important role in the development of the Eastman design, which is not a simple RD but an extractive RD column of 4 m diameter and 80 m height, in which seven complex sections are combined. Gas streams flowing upwards and liquid streams flowing downward play an active role in this integration. Interaction between industry and academia in education also played an important role. What happened is that Siirola sent some process engineers back to the university (where he did his PhD on process synthesis in 1971), to receive teaching on process synthesis based on functions. After that teaching, the engineers were able to solve the design problem.²² The remarkable thing is that Siirola, together with others from the university had written a textbook on process synthesis,²³ but he considered it insufficient as an educational resource. He probably thought that a stronger interaction between academics and industrial engineers was needed.

This interaction between industry engineers and academics continued in the most-cited RD review paper of Taylor and Krishna,²⁴ which addressed a broad range of topics including practical design considerations, as well as theoretical thermodynamics and mathematical models of RD technology.

Tuchlenski *et al.*²⁵ also focused on process synthesis and design tools, as well as scale-up issues from an industrial point of view. An interesting article about when to select RD was written by Schoenmakers of BASF company.²⁶ That article presents heuristics for the choices of equipment (including RD among others) in a two-dimensional coordinate plane, which are applied for two parameters (reaction rate and relative volatility), considering the use of hetero- or homogeneous catalysts. Thus, a decision method is proposed to decide between various options, for example RD, or conventional distillation with a conventional reactor design. An experienced process concept designer could then quickly decide which option to take. It points to selecting for RD even if there is neither an azeotrope nor a chemical equilibrium reaction present. Notably, all other publications on RD mention that RD is attractive if there is a chemical equilibrium reaction present, or an azeotrope, or both.

Hiwale *et al.*²⁷ reviewed reaction systems that are industrially relevant to the application of RD processes. Their paper particularly highlighted the development of RD technology from 2000 to 2003 considering the rapid growth of studies and research in the RD field during that period.

A review by Harmsen²⁸ of Shell explored drivers and barriers, industrial processes, scale-up methods and available internals for industrial RD application. He also presented >150 industrial implementations. The largest number and the largest scales were hydrogenations implemented in oil refineries. This review emphasizes that RD technology has been successfully applied in industry and is well-known as an established unit operation in process technology.

Given these crucial interactions between academics and industrial engineers advancing the knowledge, on the one hand, and advancing applications, on the other, we will address this interaction for each topic of this review.

REACTIVE DISTILLATION TREATED AS A UNIT OPERATION IN CONCEPTUAL PROCESS DESIGN

Introduction to conceptual process design

Methods for RD design as a unit operation (building block), and process-wide conceptual design methods using RD as a unit

operation are reviewed here. In textbooks on conceptual process design, unit operation selection in several steps is briefly mentioned by Harmsen *et al.*²⁹ and Harmsen and Verkerk.²² Other textbooks on (plant-wide) process design, notably Smith³⁰ and Seider *et al.*,³¹ do not cover RD. The PI textbook on design, by Reay *et al.*³² does not cover RD. However, the book of Gómez-Castro and Segovia-Hernández³³ gives an overview of the present state of RD, covering many recent publications. Keil³⁴ in his very good review on PI also includes a brief overview on RD. The difference from other review articles is that it covers the classical chemical engineering viewpoint and the PSE viewpoint. It also provides an extensive review on PI that includes a temporal description of developments and definitions, and descriptions of a range of PI technologies, with an emphasis on commercially applicable PI units (including RD) that have already brought remarkable impacts on industries. An overview of RD detailing its industrial emergence, advantages and drawbacks, and design approaches are referenced. Rong³⁵ compiles an extensive review of process synthesis and PI including chapters covering RD and integrated design and control.

After the first step scoping the design (in which the design goal and the constraints are defined), process unit operations are selected and sequenced to transform input streams into output streams. Then, the process concept is modeled, and the unit operation parameters are determined through simulation. Also, an assessment is made on the controllability of the process concept. The conceptual design, and its model, is then experimentally validated and subsequently evaluated in the stage-gate process to determine whether it is sufficiently attractive for commercial implementation in the next innovation stages.^{29,31}

This section therefore covers the following: methods for selecting and sequencing process unit operations, design methods for RD; RD configurations; and parameter setting for RD. Process control assessment methods for RD as well as review methods for evaluation in the concept stage-gate are treated in the follow-up section, as these methods are applicable for RD unit operations and for new function-based designs.

Selecting and sequencing process concepts with RD as intensified unit operation

Design selection criteria leading to RD

Chadda *et al.*³⁶ developed a flash cascade model to identify regions of the composition space that can be achieved via reaction and separation. Feasibility is evaluated as a function of the production rate, catalyst concentration and liquid hold-up. The configurations evaluated included single- or double-feed columns, fully reactive or hybrid (stripping-rectifying-reactive) columns. The study is demonstrated in three case studies for esterifications, and although the examples belong to a homologous series, the feasible designs identified are different, which are validated against results from simulation studies. Simplifications that hinder the applicability of this method include dealing with a limited number of permutations and a constant Da number. In addition, operating parameters such as feed ratio, type and location of feeds and side draws, reflux and reboil ratios are not considered.

Reactive distillation design considering rigorous nonlinear models was described by Luyben and Yu.³⁷ They evaluated key design parameters leading to different RD solutions, including hold-up on reactive trays, the numbers of rectifying, reactive and stripping trays, pressure, chemical equilibrium constant, relative volatilities, and reactant feed location. Some counterintuitive

results that are unique for RD were presented. For instance, differently from a conventional distillation column, adding more trays in an RD column does not always reduce the energy consumption. In an RD column, there is an optimum number of reactive trays leading to the minimum vapor boil-up. Furthermore, Luyben and Yu³⁷ used ideal quaternary chemical systems to perform economic comparison of RD with a conventional process and then validated their findings with real reaction systems. The validation using the case of ethyl *tert*-butyl ether production from ethanol and isobutene showed that the RD process would be more economical when the conventional and RD processes have similar operating temperatures. However, Luyben and Yu³⁷ also pointed out that RD, despite its significant advantages, is not always more economically attractive over conventional processes. For instance, producing toluene from benzene using RD technology was found to be less attractive compared to using a conventional process because, to achieve a preferred reaction temperature for that system, an RD column must operate at a high pressure up to 30 bar. In a reactor-distillation column sequence, the temperatures for reaction and separation can be set independently. By contrast, because it has fewer degrees of freedom, RD is not cost-effective for systems where reaction and separation operations involve significantly different temperatures.

Sharma and Singh³⁸ underlined that different process characteristics and parameters lead to different control structures. For instance, to control product purity, the proportional-integral-derivative controller or adaptive controller were found to be suitable for the case of ethyl acetate production via esterification. Conversely, for the same controlled parameter, the non-linear predictive controller was found to be appropriate for the case of methyl acetate production via esterification and the proportional controller was proven to be fit for ethylene oxide hydration producing ethylene glycol.

Evaluation criteria. Reactive distillation containing chemical reaction and compounds separation, is known as a multifunctional equipment. The aim of RD as a multifunctional equipment is to reduce process energy requirements, save on capital investment, and contribute to sustainable resource and environmental development by breaking the limits of chemical equilibrium, improving reaction conversion and product purity, and recycling reaction heat. Therefore, the process design criteria that guide the selection of an RD solution are mainly divided into reaction synthesis and integrated reaction-separation.

Evaluation criteria for process development and applications of RD are similar to other industrial processes. The main evaluation criteria for industrial design process currently include health, safety, economic, environment, social acceptance and sustainability. Researchers use one or more evaluation criteria as objective functions, and use optimization algorithms such as differential evolution and taboo search to obtain optimal processes. Table 1 summarizes the current evaluation criteria used for RD.

Generic process concept stage criteria. In industry, process designs are evaluated to decide whether to continue with their development. Industrial evaluation criteria for the designs have been categorized as Safety, Health, Environment, Economic, Technical feasibility, and Social acceptance (SHEETS). For the conceptual design stage, for each criterion, a simplified subcriterion may be defined so that it can be applied with the limited information available at this design stage. Conceptual process design

textbooks, such as Douglas,⁴⁹ Seider *et al.*³¹ and Harmsen *et al.*,²⁹ contain examples of these criteria. More recently, this set has been extended with contributing to Sustainable Development Goals of the UN,⁵⁰ by Harmsen and Verkerk²² and Fernandez-Rivas *et al.*^{45,46} For RD, these categories can be used directly. Almeida-Rivera *et al.*,³⁹ provides evaluation criteria that includes technical feasibility, economic viability, controllability, safety and sustainability. This list contains a new specific criterion for RD, namely controllability, as an aspect of technical feasibility, because controlling a reactive distillation system is more difficult than controlling distillation and reaction sections separately. Thus, the most complete set is then the SHEETS criteria plus those based on sustainable development goals, to which controllability is added as a subset of technical feasibility. Tables 2 and 3 provide an overview of the main dimensions of conceptual RD designs evaluated by earlier methods (up to 2003) and more recent methods (after 2003), respectively.

Sustainability criteria. Sustainable Development Goals set by the United Nations for 2030 and subscribed to by the World Business Council for Sustainable Development, are the only sustainability set of criteria with worldwide consensus. These criteria are relatively recent and are particularly relevant for PI designs, which can contribute to sustainable development, and also highly relevant in education about PI as explained by Fernandez-Rivas *et al.*^{45,46} Jenck *et al.*⁴⁷ interpreted industrial sustainability as employing technologies and know-how to use less material and energy, maximizing renewable resources as inputs, minimizing generation of pollutants or harmful waste during product manufacture and use, and producing recyclable or biodegradable products. In the past sustainability-related criteria have been used for evaluating RD by Harmsen *et al.*^{28,41}

RD consideration in industrial process concept design. Among many PI techniques, RD is a successful example that allows reaction and separation functions to occur in a single column. Owing to these integrated phenomena, an RD process can offer multiple benefits, compared to a classical distillation process. RD columns have been designed and developed for many industrially relevant reaction systems.^{27,28,37,97,98}

The advantages and drawbacks of the application of RD processes have been discussed in depth in literature.^{3,24,99–101} Those advantages include:

- Increased conversion by pulling the reaction pathway to the product side, as well as improved selectivity by avoiding side reactions, because of the continuous removal of products from the column
- Lower costs due to integrated reaction and separation functions in an RD column
- Energy-saving by the use of the exothermic heat of reaction for vaporization of liquid
- Reduced footprint of chemical plants as a consequence of less equipment required
- Improved health (e.g. lower diffusive emissions via flanges), safety and environmental performance because of lower CO₂ emissions and avoidance of hot-spots and runaway reactions
- Circumvented azeotropes by having them reacted away or preventing their presence as a result of simultaneous reaction and separation
- Simplified separation of close-boiling-point components when using a reactive entrainer reacting with one of components to

Table 1. Current evaluation criteria used for reactive distillation

Evaluation criteria	Category	Reactive distillation case	References
Health	Irritation and chronic toxicity	benzene + propylene \Leftrightarrow cumene	39,40
Safety	Mobility, fire/explosion, reaction/decomposition and acute toxicity	propylene glycol monomethyl ether + methyl acetate \Leftrightarrow propylene glycol monomethyl ether acetate + methanol; benzene + propylene \Leftrightarrow cumene	24,39,41,42
Economic	Raw material cost, production cost, investment cost and operation cost	propylene glycol monomethyl ether + methyl acetate \Leftrightarrow propylene glycol monomethyl ether acetate + methanol; ethylene carbonate + methanol \Leftrightarrow dimethyl carbonate + monoethylene glycol; benzene + propylene \Leftrightarrow cumene	28,39–43
Profit	Return on investment and the venture profit	ethylene carbonate + methanol \Leftrightarrow dimethyl carbonate + monoethylene glycol; benzene + propylene \Leftrightarrow cumene; <i>iso</i> -butane + <i>n</i> -butene \Leftrightarrow <i>iso</i> -octane	24,31,40,43–46
Environment	Persistency, air hazard, water hazard, solid waste and bioaccumulation	propylene glycol monomethyl ether + methyl acetate \Leftrightarrow propylene glycol monomethyl ether acetate + methanol; benzene + propylene \Leftrightarrow cumene	31,40–42
Social acceptance	Safety of chemical processes	propylene glycol monomethyl ether + methyl acetate \Leftrightarrow propylene glycol monomethyl ether acetate + methanol	28,42,45
Sustainability	Energy use, raw material efficiency usage and E-factor (amount of waste produced per unit mass of product)	benzene + propylene \Leftrightarrow cumene	40,46,47
Controllability	Robustness and rangeability	methanol + isobutene \Leftrightarrow methyl tertiary butyl ether; ethanol + isobutene \Leftrightarrow ethyl tertiary butyl ether; valeric acid + methanol \Leftrightarrow methyl valerate + water	37,39,48

Table 2. Dimensions of conceptual RD designs assessed by earlier methods (up to 2003)

No	RD design methods	Evaluated dimensions (Feasibility, Viability, Controllability, Sustainability)				References
		F	V	C	S	
1	Residue curve maps	v				51–56
2	Fixed-point algorithm	v				57
3	Phenomena-based approach	v				58
4	Attainable region	v				59,60
5	Statics analysis	v				61,62
6	Thermodynamic-based approach	v				63
7	Conventional graphical technique	v				64–66
8	Reactive cascades	v				59
9	Mixed-integer nonlinear programming	v	v			67
10	Mixed-integer dynamic optimization	v	v	v		68–70
11	Orthogonal collocation on finite elements	v	v	v		71
12	Generalized-disjunctive-programming-based approach	v	v			72
13	Heuristic-based approach for solid-catalyzed RD systems	v				73

- form an intermediate product that is easily separated and reacted to re-form the original component in a second RD column
- Avoidance of chemical degradation because of a boiling system with shorter residence time expected for the operation of an RD column *versus* conventional (batch) reactors
 - Reduced catalyst requirement to gain identical conversion as that in conventional processes

Some drawbacks that are potentially encountered include:

- Reduced flexibility: smaller operating windows (restricted selection of pressure and temperature) and fewer degrees of freedom as a result of the integrated reactions and separations
- Incompatible volatility order between reactants and products
- Difficulties in scaling-up the catalytic packing because of the quantitative matching of reaction and distillation problems in a large column
- Risk of failure when operating RD columns as a consequence of simultaneous phenomena of separation and reaction in the column

Table 3. Dimensions of conceptual RD designs evaluated by recent methods (after 2003)

No	RD design methods	Evaluated dimensions (Feasibility, Viability, Controllability, Sustainability)				References
		F	V	C	S	
1	Element-based approach	v				74,75
2	Stage composition lines	v				76–78
3	Infinite dimensional state-space framework	v	v			79
4	Short-cut method	v				80
5	Memetic algorithm	v	v			81,82
6	Heuristic-based frameworks	v	v			83
7	Feed angle method	v				84
8	Mapping method	v				85–88
9	Extended element-based approach	v		v		89,90
10	Methods for R-DWC	v				91,92
11	Method for RD with side reactor(s)	v				93
12	Method for RD with a pre-reactor	v	v			94
13	Meta-heuristic optimization algorithm based on differential evolution and tabu list	v	v	v	v	95,96

- The presence of reactive azeotropes that cause difficult or infeasible separation¹⁰¹
- The presence of multiple steady states in which diverse conversions and different column profiles might result from an RD column running at specific conditions

The industrially implemented cases presented by Harmsen reveal that the drawbacks did not outweigh the benefits.²⁸ Although degrees of freedom of RDs are indeed fewer, there are sufficient variables to achieve robust control for all RD cases reported, of which the design is not complex.¹⁰² Besides, methods and software facilitating the design are becoming increasingly more sophisticated, and a feasible control design has been solved by dynamic simulation.¹⁰³ The integration of column design and control design would achieve cost savings and increase robustness.¹⁰⁴ Comprehensive simulation packages, pilot plants of modest sizes and validated scale-up knowledge on mass transfer and pressure drop are sufficient to reduce the risk of operating RD columns to acceptable levels, and to explain the quantitative matching of reaction and distillation problems in RD columns.²⁸ Design and simulation tools that include reactions, residence time distribution, mass transfer, heat transfer, momentum transfer and computational fluid dynamic modeling packages integrated with reaction will facilitate the development RD column internals.¹⁰⁵ In conclusion, the increased attention on the design phase reduces the operational difficulty by robust controllable design, whereas the design knowledge is being developed for novel combinations of reaction and separation, such as extractive RD,¹⁰⁶ pressure swing RD¹⁰⁷ and dividing wall distillation columns.^{108,109} The benefits of applying RD will increase, while the barriers for implementing RD will be further reduced owing to increased knowledge by industrial experience and academic research.

These publications on industrial applications of RD show that criteria leading to RD design are the same as for process concept design in general. The publications also show that economics of RD are better than conventional design in all cases.

Selecting RD as a unit operation in conceptual process design by heuristics

Schembecker and Tlatlik¹¹⁰ provided a systematic framework to consider reactive separations in concept design or as they call it,

conceptual flowsheet development. The first step of their procedure involves the analysis of the chemical reaction system in relation to separation. In case of a separation of one or more products, by-products or solvents could benefit the performance of the reactor, the separation behavior of the components must be checked. The chemical reaction, the separation and the design of the apparatus need a defined operating window. When reaction and separation operating conditions can overlap, a reactive separation process may be feasible and could benefit the overall process performance. Schembecker and Tlatlik¹¹⁰ demonstrated by selected cases and modeling that the integration of reaction and separation in one unit may not always bring economic benefits. The overall chemical process always has to be considered to find the best design solution.

Heuristics-based approaches suggest RD design variables based upon knowledge of conventional distillation processes and previously designed RD processes. Subawalla and Fair⁷³ proposed guidelines to design solid-catalyzed RD columns, considering the use of a pre-reactor, operating pressure, location of feed stages and reactive zone, reactant: feed ratio, catalyst mass, number of theoretical separation and reactive stages, reflux ratio and column dimensions. For instance, the reactive zone should be placed where the concentration of reactants is at its maximum. The minimum catalyst loading in an RD column can be determined by simulating a series of isothermal plug-flow reactors and ideal separators in series.⁷³ Shortcut methods for conventional distillation, such as the Fenske method, can give an estimation of the number of non-reactive stages in an RD column. The number of reactive stages is calculated by dividing the height of reactive zone—that depends on the catalyst mass, catalyst density and column diameter—by the height equivalent of a theoretical plate for catalytic section.⁷³

These research results on selection methods did not enter into process concept design textbooks. Even recent textbooks on process concept design such as Seider *et al.*³¹ and Harmsen *et al.*²⁹ cover RD as an option in the design in a very limited way. Harmsen *et al.*²⁹ provides five heuristic rules for selecting RD, but no further detail is provided. Seider *et al.*³¹ has no section on RD.

Kiss¹¹¹ provides a list of industrial applications of RDs. This list can be used as a starting point to conclude whether RD is feasible and attractive. If the reaction under consideration is not in that list, then a simple qualitative diagram with the reaction rate on the

vertical axis and the relative volatility on the horizontal axis, provided by Schoenmakers and Bessling²⁶ of BASF, can be used to assess the potential application (Fig. 2). This diagram shows that, for slow reaction rates, RD is not attractive. For all other conditions RD is attractive, with the exception of a very high relative volatility, where a single stage flash after the reactor can be applied. This pre-selection method has some validity, as hydrogenation reaction in petroleum refineries—reported by Harmsen,²⁸ fulfil this simple criterion. These hydrogenations have the largest number of commercial scale industrial applications of RD (71)—and have typically moderately fast reactions and need several distillation equilibrium stages. The Schoenmakers diagram (as shown in Fig. 2) is however, of limited value for inexperienced designers, as the two diagram axes are not quantified. Inexperienced designers might have difficulties in specifying suitable definitions and boundaries of low/medium/high relative volatilities and reaction rates (e.g. hard to decide whether the reaction rate is too slow for RD). Less experienced designers may require additional time to collect the necessary data for populating the axis before they can effectively apply it to a specific design problem. Nevertheless, such boundaries can be easier defined by experienced designers who do have an intuitive feeling for what slow reaction means in the context of RD, or what a high relative volatility means so that a simple flash separation is sufficient, or have a good impression of the residence time and can estimate whether this is sufficient for the reaction to be completed in the column. For example, if the reaction is too slow, an experienced designer may decide to increase the column pressure and thereby the column temperature by which the reaction rate increases sufficiently to facilitate RD. Nonetheless, this diagram is useful for teaching purposes, to illustrate the need for compatible reaction and separation characteristics (e.g. having one RD column instead of a reactor and a separate distillation column).

Shah *et al.*⁸³ presented a heuristic-based framework for evaluating the feasibility of RD processes by considering types of reactions, reaction kinetics, operating pressure and temperature, heat of reaction, relative volatilities, product purities, equilibrium

conversion and equipment restrictions. The framework is used to evaluate the technical feasibility of RD: if an RD process is potentially feasible, the framework is then employed to check whether the assessed process is economically attractive. When an RD process is considered promising, the technical framework proposed by Shah *et al.*⁸³ can be applied to determine the process parameters and limitations, working regime, internals selection and required mathematical models.

Muthia *et al.*,^{86–88} and Muthia and Kiss⁸⁵ developed a generic heuristic-based mapping method that assists process engineers when making go–/no-go decisions regarding the technical feasibility and (potential) economic viability of RD technology before performing any rigorous simulations. The method represents the reactions by the generic reaction scheme, where one or two reactants react(s) forming two products (with or without equilibrium limitations), and it represents the behavior of the components considering their boiling point order in a map. The maps facilitate rapid assessment of whether RD is technically feasible and economically attractive. The approach works well for zeotropic three- and four-component systems, and it was also extended to systems in which azeotropes form (but it is not as robust in these cases). Nonetheless, the suitability of the mapping method for azeotropic systems is limited when there is more than one relative volatility with the value of 1 (i.e. two or more azeotropes are present in the system).

Initially, Muthia *et al.*⁸⁷ demonstrated the approach for systems with boiling point order ($T_{b,C} < T_{b,A} < T_{b,B} < T_{b,D}$) where the two products are the lightest (C) and heaviest (D) components in the system, so they are easily separated. Subsequently, the approach was demonstrated for systems with other boiling point orders and provided insights into the optimal feed locations of RD columns. A key innovation of the mapping method is the ‘applicability graph’, which is a plot of reflux ratio *versus* the number of theoretical stages, as illustrated in Fig. 3 (left). A boundary line in an applicability graph identifies the lowest reflux ratios possible for various numbers of theoretical stages. The ‘applicable area’ represents multiple column configurations, each with a certain number of

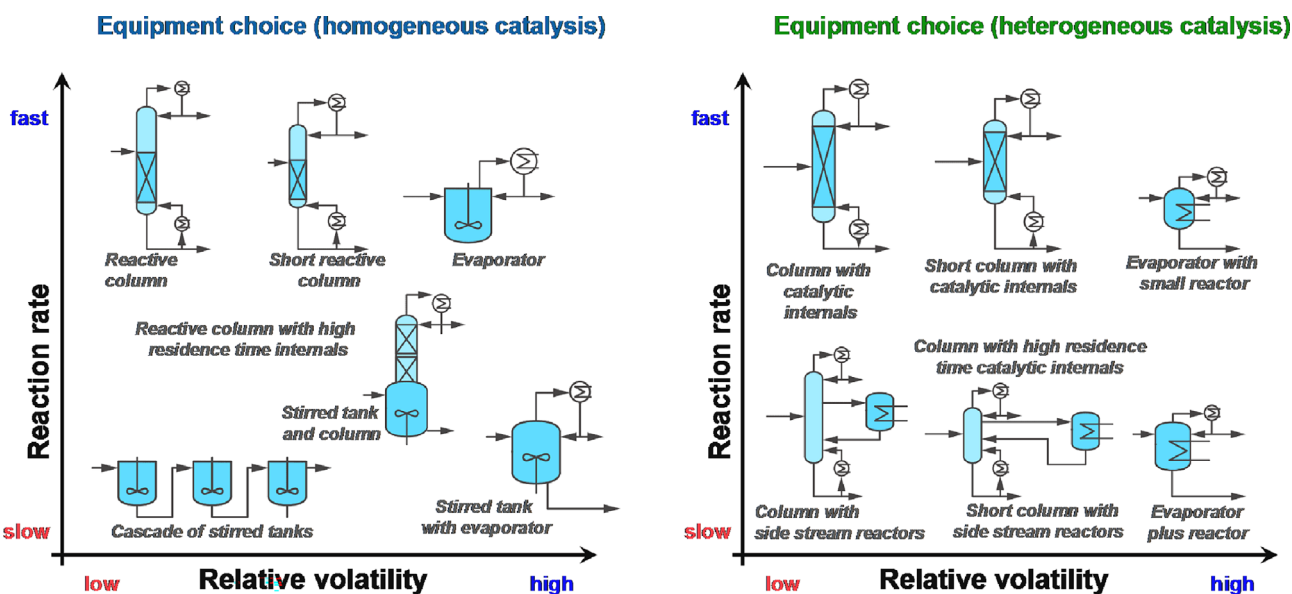


Figure 2. Equipment choices based on the reaction rate and relative volatility.

rectifying, reactive and stripping stages, where some very dissimilar configurations may have similar reflux ratios for an identical number of theoretical stages.

The method of Muthia *et al.*,^{86–88} and Muthia and Kiss⁸⁵ is capable of predicting the applicability area for RD of real systems based only on pre-prepared applicability graphs of generic cases. In these hypothetical generic cases, relative volatilities and chemical equilibrium constants are fixed and independent of process temperatures. However, real (nonideal) systems can also be addressed by the method, in particular for cases involving azeotropes. Figure 3 (right) illustrates the application of the method: the user must select the most relevant generic cases – thus, where representative relative volatilities and chemical equilibrium constants are similar to those of the real system being assessed. The shaded area represents the location in which the actual boundary line is expected to lie. Thus, the user can read from the plot approximate values of the reflux ratio and numbers of stages required in the RD column. Notably, the mapping method predicts the number of theoretical stages and reflux ratio, but not the column configuration. The multiple possible configurations are an opportunity for RD column design.

Further research is needed for multicomponent systems far beyond the three- and four-component method of Muthia *et al.*,^{86–88} and Muthia and Kiss,⁸⁵ such as those occurring in oil refineries with often tens to hundreds of components. Also, more research is needed to enable the Schoenmakers diagram to provide quantitative guidance. The Schoenmakers approach with reaction rates and relative volatility could be a good starting point for this research. The commercially implemented processes reported by Harmsen²⁸ and others could be used to validate the improved map.

RD configuration conceptual design

This section focuses on the design to define the RD column configuration, answering questions such as where to locate the catalytic reaction section, where to locate the feed stage(s), how many stages to use in the top and bottom sections, and what reflux ratio to use. Effective design methods are needed because of the complexity of RD columns and the interdependence of mass transfer, chemical reaction and hydrodynamics within RD columns.

Figure 4 illustrates the classical RD configuration, with a rectifying top section, an RD section and a bottom stripping section. The variations shown in Fig. 4 include those where a decanter or

membrane supplements the overhead condenser and where conventional reactors are used in conjunction with the RD column. These configurations are typical for RD hydrogenations, as noted by Harmsen.²⁸ When azeotropes are involved, the aim is to locate the reactive section in such a way that it prevents azeotrope formation. If equilibrium reactions are involved, the aim is to locate the reactive section such that distillation transfers one or more reaction products from the liquid to the vapor phase, to overcome reaction equilibrium constraints, allowing a high reaction conversion to be achieved.

Luyben and Yu³⁷ provide a simple design method for the simple configurations shown in Fig. 4. RD columns can be designed for 'neat operation' (where stoichiometric amounts of reactants are fed to the RD column) or using an excess of reactant (typically 10–20%), in which case an additional separation unit is required to recover and recycle the excess reactant.

Identifying potentially suitable reactions systems and corresponding RD configurations

Quaternary reaction systems can be classified according to the boiling point order of the compounds. The naming convention defined by Luyben and Yu³⁷ is summarized below.

- Group I_p ($T_{b,C} < T_{b,A} < T_{b,B} < T_{b,D}$)
- Group I_r ($T_{b,A} < T_{b,C} < T_{b,D} < T_{b,B}$)
- Group II_p ($T_{b,C} < T_{b,D} < T_{b,A} < T_{b,B}$)
- Group II_r ($T_{b,A} < T_{b,B} < T_{b,C} < T_{b,D}$)
- Group III_p ($T_{b,C} < T_{b,A} < T_{b,D} < T_{b,B}$)
- Group III_r ($T_{b,A} < T_{b,C} < T_{b,B} < T_{b,D}$)

Figure 5 presents an appropriate RD column configuration for each class of quaternary reaction.⁹⁹ For practical reasons, groups II_p and II_r can be excluded as potential candidates for RD as a result of their unfeasibility from a thermodynamic viewpoint [e.g. two low-boiling reactants (usually with low molecular weight) cannot be converted into two high-boiling products (with larger molecular weight)].

Luyben and Yu³⁷ explored the suitability of RD for these classes of reactions through a theoretical case study. The study assumed equimolar feeds of the reactants, a constant reaction equilibrium constant, K_{eq} , equal to 2 (at 366 K), fixed forward and backward kinetic constants $k_F = 8 \text{ mol s}^{-1}$ and $k_B = 4 \text{ mol s}^{-1}$, and fixed volatilities (relative to the next heaviest component) of LLK/LK/HK/HHK equal to 2. The liquid hold-up was defined from tray

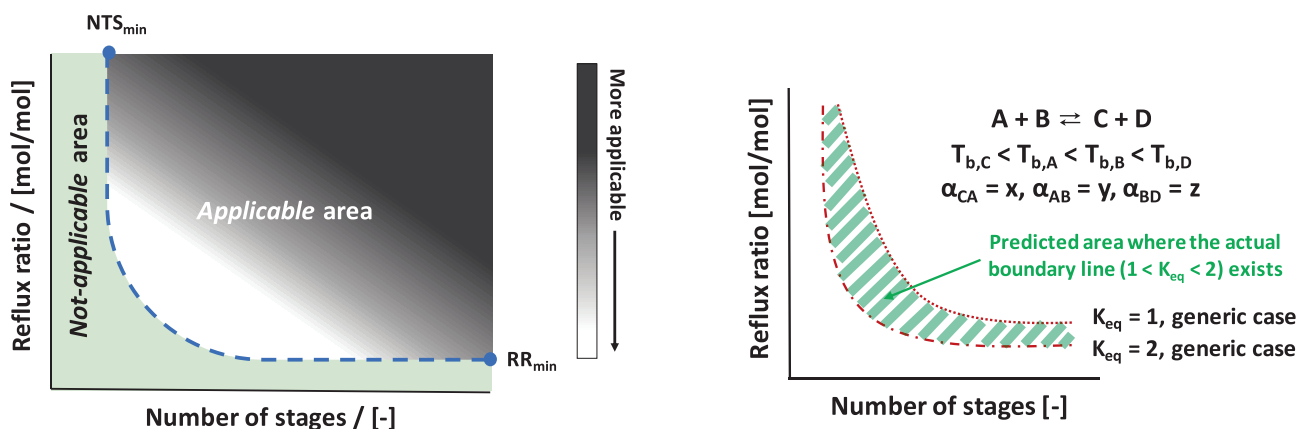


Figure 3. (left) An illustrative applicability graph of reactive distillation (RD) and (right) an illustrative prediction of the applicability of RD to a reaction system, based on generic cases—the actual boundary line is predicted to be within the shaded area.

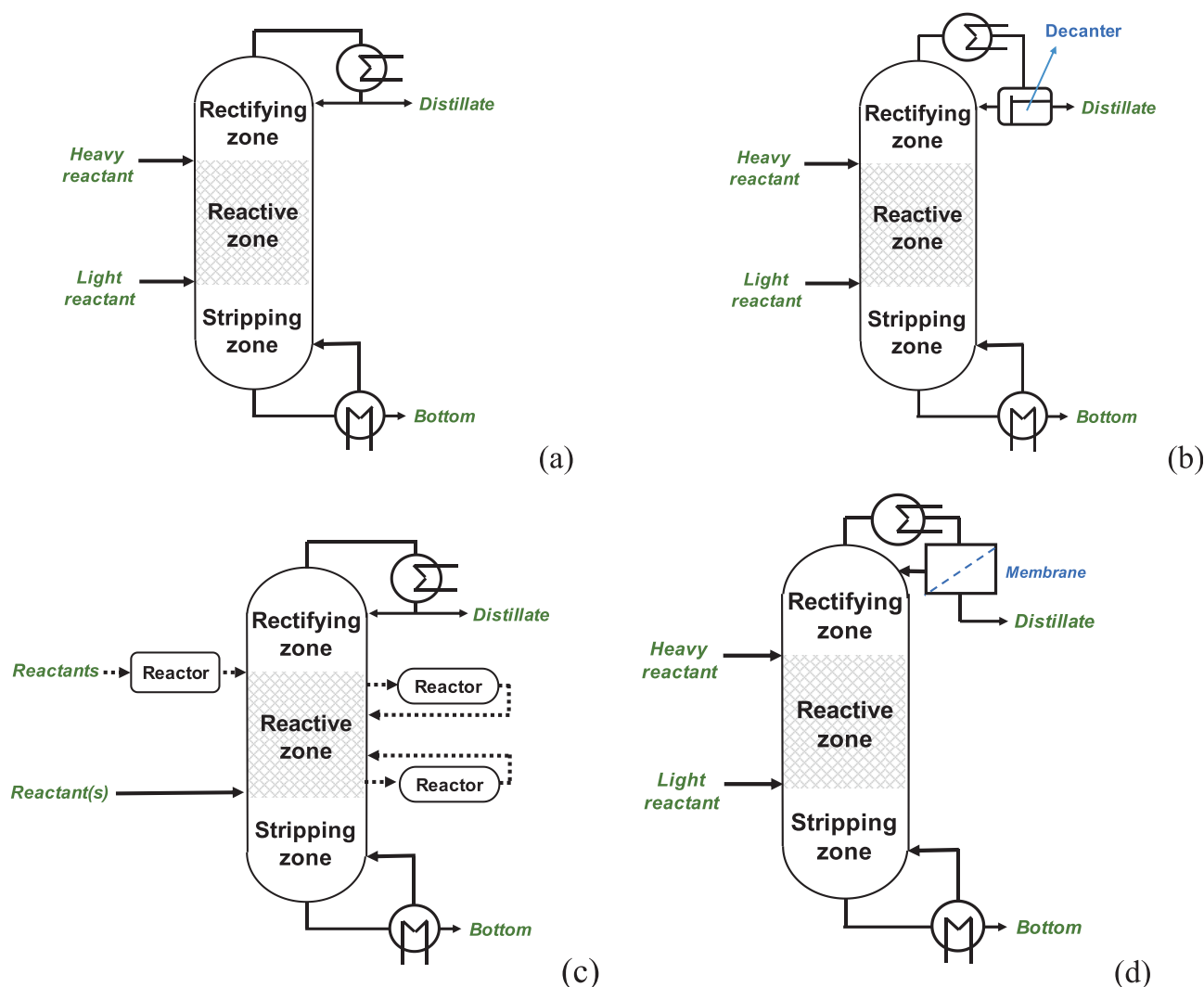


Figure 4. Generic column configurations of: (a) classical reactive distillation (RD), (b) heterogeneous azeotropic RD, (c) RD with pre- and/or side reactors, (d) membrane-assisted RD.

sizing; the kinetic hold-up was set to be ≤ 20 -fold greater than the tray hold-up. The design procedure in their study was iterative and it used some simplifying rules: setting the reactant-feed ratio to unity, placing the reactive zone at the location where the reactants were most abundant, and introducing heavy reactant feed on the top of the reactive zone and light reactant on the lowest tray of the reactive zone. Then, the numbers of rectifying and stripping stages as well as the exact feed location were varied for a fixed number of reactive stages until a configuration with the lowest total annualized cost was obtained. The iterative procedure was carried out for other numbers of reactive stages. The evaluation, to minimize the total annualized cost for the RD column, indicated that group I_p is the most favorable, whereas I_r is the most unfavorable, or specifically: $I_p < III_p < II_p < III_r < II_r < I_r$.

For RD processes with different boiling point order, accelerating the reaction rate has a positive effect on RD synthesis, especially in the presence of strong interactions in the system, such as the presence of a substance that can significantly change the volatility of other substances. Taking the transesterification reaction to prepare isopropanol (group III_p) as an example, the PhD thesis of Geng¹¹² showed the effect of significant difference in reaction

rate on RD processes. They found that as the reaction rate increased, the total annualized cost (TAC) of the RD unit gradually decreased, and as the reaction rate increased, the volatility of various substances in the system significantly increased.

Graphical design methods for column configuration

Daza *et al.*⁷⁴ provided a set of three graphical methods and a stage-to-stage computation method enabling feasibility assessment for RD columns based on approaches similar to those employed for non-RD columns. The methods apply the 'element' concept.¹¹³ The term 'element' is used for molecular groups, rather than for single chemical components. For binary element systems, which may consist of three or more compounds, Daza *et al.*⁷⁴ developed reactive McCabe–Thiele- and reactive Ponchon–Savarit-type diagrams. For multi-element systems, which usually correspond to reactions with four or more compounds, a stage-to-stage computation method adapted from the Lewis–Matheson approach¹¹⁴ is applied for reactive systems. For RD columns comprising both reactive and nonreactive stages, the computation of bubble points is required within reactive and

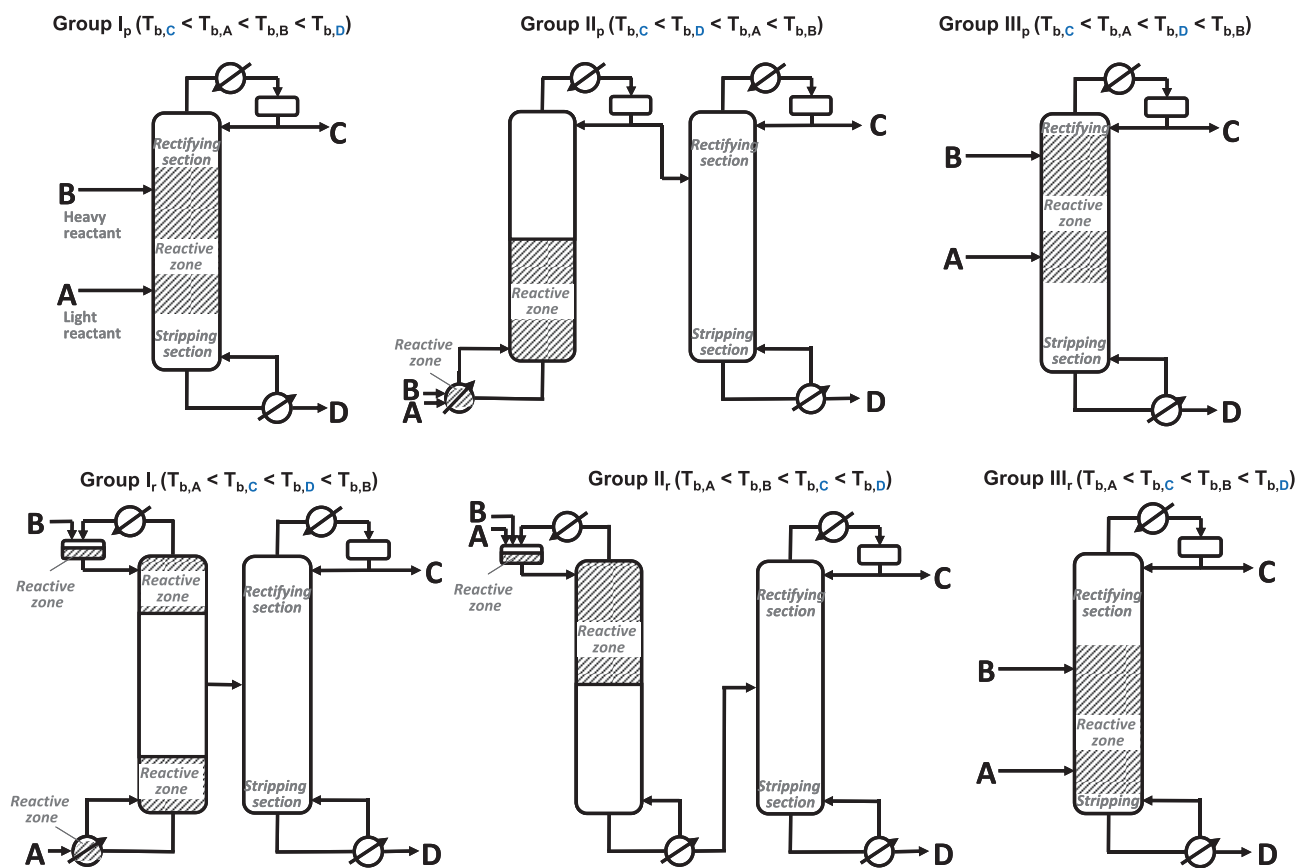


Figure 5. Reactive distillation groups for quaternary reversible reactions ($A + B \rightleftharpoons C + D$), based on various order of relative volatility between components.

nonreactive stages in order to estimate composition and temperature profiles.

Groemping *et al.*⁷⁸ presented a graphical method applying stage composition lines (SCL) – and, by analogy, reactive stage composition lines – where a SCL is the locus of compositions leaving a reactive stage at any reflux or boil-up ratio.¹¹⁵ The objective was to assess the feasibility of RD processes, based on the assumptions of reaching reaction and vapor–liquid equilibrium on all stages. The proposed method is capable of generating multiple RD designs. However, the method is restricted to RD processes with two degrees of freedom, following the Gibbs phase rule for isobaric systems, and it is only applicable for single-feed columns with two products. Dragomir and Jobson^{76,77} extended the scope of the method of Groemping *et al.*⁷⁸ for single-feed columns with different types of hybrid configurations, including for single-feed kinetically-controlled RD processes.

Jantharasuk *et al.*⁷⁵ extended the element-based approach⁷⁴ and coupled it with a driving force diagram¹¹⁶ to enable the feasibility assessment of a multicomponent RD column. The approach applies an equivalent binary element concept, which treats multicomponent mixtures as a system comprising a pair of heavy and light key elements. Based on this simplification, RD design parameters, such as the number of theoretical stages, feed stages and minimum reflux ratio, can be assessed using a graphical approach similar to that often applied for nonreactive systems containing two components. The element concept has also been demonstrated for optimization and control of RD.^{89,90}

Almeida-Rivera *et al.*³⁹ thoroughly discussed available methods for conceptual design of RD columns. They identified three classes

of approaches: heuristic methods, graphical methods (e.g. residue curve maps) and simulation-based methods. Table 4 gives a summary of the strengths and weaknesses of these methods for synthesizing RD processes.

Conceptual design of RD using residue curve maps

Graphical methods are among the oldest attempts to develop systematic methods for the design of RD processes. Slightly more than 38 years ago, the scientific community initialized attempts to generate graphical methods for synthesizing RD columns. Barbosa and Doherty^{51,52} for the first time employed residue curve maps and developed a set of transformed composition variables to assess RD feasibility. This approach enabled calculation of minimum reflux ratios for single- and double-feed RD columns. The fundamentals and applications of residue curve maps (RCM) for RD were further explored by Fien and Liu,⁵⁴ Ung and Doherty,⁵⁶ Espinosa *et al.*⁵³ and Qi *et al.*⁵⁵

The structure of a residue curve map depends on thermodynamics that strongly affect the shape of composition profiles and therefore which products can be obtained from an RD column. Residue curve maps remain invaluable tools for assessing the applicability of RD columns. However, reactive RCM (quaternary plots) are challenging to set up and use in practice, and only some commercial and free software supports their generation or use (e.g. ASPEN PLUS, DORTMUND DATABANK, CHEMSEP).

A fixed-point algorithm screens feasible column designs based on the use of RCM techniques.⁵⁷ Fixed points that belong to pure components and azeotropic compositions are assessed. Their locations change when reflux ratio and external reboil ratio

and/or the Damköhler number are modified. In contrast to stable and unstable nodes, the location of fixed points relies on process parameters. Li *et al.*¹¹⁷ developed a modified fixed-point methodology that overcomes the limitations of the original approach originated by Buzad and Doherty.⁵⁷ The modified method includes the effects on temperature within an RD column and it also expands the approach from ternary to quaternary mixtures.

Attainable region method

A method called the attainable region technique enables the identification of feasible reactor networks based on graphical properties of plug flow and continuous stirred tank reactors.¹¹⁸ An attainable region means a segment of a concentration space that can be obtained from a given feed composition by the combination of reaction and mixing. This method considers two attainable product compositions and the vector joining those two points by mixing. Conditions are defined for the boundary of an attainable region, to help construct the region. The attainable region approach was extended to address RD.^{59,60}

Giessler *et al.*^{61,62,69} proposed a method called *statics analysis* to estimate the number of theoretical stages of an RD column based on thermodynamic-topological analysis of distillation diagrams. Statics analysis treats an RD column as a succession of reaction and distillation units, where the feed is transformed to a pseudo-initial mixture – with certain compositions and a certain degree of reaction – and separated in a distillation unit. The method relies on assumptions of infinitely large vapor and liquid flow rates in the column and an adequate capacity of the reactive zone for a given conversion. The number of theoretical stages is estimated from the distillation line, and the number of reactive stages is calculated based on the intersection of the distillation line and the boundary between the forward and backward reactions that is called the chemical equilibrium manifold. Nevertheless, the method is limited because multiple feeds, multiple products and multiple azeotropes cannot be handled.

A phenomena-based approach⁵⁸ characterizes mixing, separation and reaction in an RD column as the phenomena vectors in a composition space. The presence of a kinetic fixed point, which is undesired, is indicated by the summation of these vectors as it describes flat concentration profiles. Therefore, some actions to move away from that point are employed (such as changing design parameters and operating conditions).

Frey and Stichlmair⁶³ proposed a thermodynamic-based approach to identify the applicability of RD based on the existence of RD lines and potential reactive azeotropes. Possible 'distillation regions' are determined based on distillation lines (analogous to residue curves). This method can be applied to reactions reaching equilibrium fast and slow, but the analysis needs detailed knowledge about the phase equilibrium, reaction kinetics and the residence time within the column.

Conventional graphical techniques, which are based on the McCabe–Thiele and Ponchon–Savarit methods, enable the distribution of reactive zones within an RD column for a specified extent of reaction by adjusting the catalyst hold-up.^{64–66} Some assumptions applied are constant molar overflow, a single reaction for a binary system and attainable vapor–liquid equilibrium.

The reactive cascades method assumes rectifying, reactive and stripping sections as a cascade of flashes in either co-current or counter current flow,⁵⁹ taking into account reaction kinetics, rather than assuming chemical equilibrium – phase and reaction equilibrium – on every stage. An RD configuration is obtained for a given normalized Damköhler (Da) number – defined as the ratio of characteristic residence time (H_0/V) to characteristic reaction time ($1/k_f$) – based upon the specification of the product separation.¹¹⁹ The fixed-point algorithm assumes a fixed residence time for every flash stage and an identical fraction of feed to be vaporized in each stage. Note that for low values of Da number ($Da < 0.1$), where the reaction rate on each stage is relatively slow compared to the residence time on each stage, the system is dominated by phase equilibrium. For large values of Da ($Da > 10$) the reaction rate is fast and chemical equilibrium is approached on the reactive stages. If the Damköhler number is in the range in between these values ($0.1 < Da < 10$), then the process is kinetically controlled.

A short-cut method by Carrera-Rodríguez *et al.*⁸⁰ enables the calculation of the number of theoretical stages, reflux ratio, feed-tray location and top or bottom flow. The application of this graphical method is based on RD lines and tray-to-tray calculations. To ensure that product compositions are met, material balances are quantified using reaction-invariant composition variables and they used tray-by-tray calculations and solved from the outside (i.e. top and bottom) to the inside of an RD column (i.e. feed stage) to ensure that the product compositions are met. Although the method allows reduced computational effort in a conceptual study by eliminating the need for rigorous and many trial-and-error calculations, its application is demonstrated only in etherification cases that are specifically limited to ternary reaction systems.

Avami *et al.*⁸⁴ developed a variant of the so-called feed angle method for shortcut design of single- and double-feed RD columns. The feed angle method, which was originally generated for heterogeneous azeotropic distillation,¹²⁰ uses pinch-point analysis to estimate the minimum energy demand of an RD column based on the calculation of a tray at the feed pinch. The method is both graphical and optimization-based using residue curve maps. The minimum energy demand is calculated using an optimization method considering mass and energy balances of the stages adjacent to pinch points. This method offers simplicity by enabling the design of a simple column model from the

Table 4. Key strengths and weaknesses of methods for synthesizing RD processes

	Graphical methods	Optimization-based techniques	Heuristic approaches
Key strengths	Able to provide visual insights into the feasibility of RD columns	Accounts for viability and controllability	Estimates key design variables of RD columns using straightforward rules of thumb
Key weaknesses	Limited to their graphical nature	Complex models and lengthy assessment	Requires rigorous computations of pre-defined real processes

calculation of the relevant pinches and the compositions on a tray above or below the feed pinch, but is not proven suitable for the design of columns for multicomponent systems.

Parameter setting of RD

The main parameters that affect the design of an RD process include:

- Integer variables: the number of reactive and nonreactive stages and their location, location of the feed(s).
- Continuous variables: operating pressure, reflux and boil-up ratios, distillate and bottom rates, condenser and reboiler duty, feed ratio of reactants, liquid hold-up or solid catalyst loading.

In contrast to the conventional non-RD, some of these parameters are counterintuitive owing to the complex interaction of reaction and separation. One of the most notable examples, which has been validated by experimental results, is that the production rate of methyl acetate by an RD process will first increase and then decrease when the reflux ratio keeps raising.^{121,122} In this RD process, a higher reflux ratio will enhance the separation effect, promoting the heavy product being enriched in the bottom of the column and the light product being enriched in the top of the column, resulting in a higher conversion. Meanwhile, the improved separation effect will cool the column, hence a drop in the temperature profiles will reduce the reaction rate. The interaction of these two effects limits each other, which give rise to the observed phenomenon.

The operating pressure influences the temperature profiles, and temperature impacts both reaction and separation: reaction rates, equilibrium constants and existence of side reactions; saturated vapor pressure, binary interaction parameters and enthalpy. The life of a catalyst is also affected by temperature, and a higher pressure needs a higher equipment investment. Therefore, the influence of one single parameter on the RD process is nonlinear and potentially nonconvex, making conventional sensitivity analysis not suitable for RD design.

The design degrees of freedom include pressure (which fixes temperatures), reactive tray hold-up (residence time), number of reactive trays, location of reactant feed streams, number of stripping trays, number of rectifying trays, reflux ratio and reboiler heat input.³⁷

The design of RD columns is much more sensitive to pressure than a conventional distillation column. Both liquid and vapor phases must coexist (which is why temperature and pressure are not independent variables). The reaction will be strongly dependent on temperature and therefore temperature and pressure need to be selected carefully to ensure feasibility of RD. As both reaction and distillation operations occur in a single vessel that operates at a single pressure, the temperatures in an RD column are set by vapor–liquid equilibrium and stage compositions, and they affect both phase equilibrium and the reaction kinetics in the phase of interest (liquid phase). At low temperatures, the reaction rates are low and large hold-ups (large amounts of catalyst) will be required. However, at high temperatures it may be difficult to achieve the desired conversion in case of small chemical equilibrium constants (e.g. exothermic reversible reactions), and undesirable side reactions might be promoted also.³⁷ Also, volatilities in general will decrease at higher pressure, which means more stages, and more reflux needed to achieve desired separation. Higher pressure means higher capital costs. Therefore, simulations and optimizations including capital cost will be needed to

find the optimal solution, and also a comparison with a separate reactor and distillation design will have to be made.

Similar to classic distillation, the number of theoretical stages indicates how tall an RD column is. The column diameter is determined from maximum vapor load, given the vapor and liquid flow rates required for the desired separation. Hold-up is crucial in RD design as the extent of reaction directly depends on the hold-up or the amount of catalyst on each tray. Hence the hold-up must be known before the RD is designed and before the column diameter is known. Thus, the design procedure for RD columns is iterative.

An initial stage hold-up is assumed, and the RD column is designed to achieve the desired conversion and product purities. The diameter of the RD column is calculated from maximum vapor-loading correlations, and then the height of liquid on the reactive trays is calculated to give the assumed hold-up. Liquid heights between 10–15 cm are typical, as higher values may lead to pressure-drop limitation.³⁷ If the calculated liquid height is unacceptably large, a new smaller hold-up is assumed, and the design calculations are repeated. The total number of reactive trays will increase when the hold-up per stage is reduced. An alternative to avoid this is to make the diameter larger than that dictated by vapor-loading considerations.³⁷

After the location of the reactive section is decided based on the RD type, the optimization step begins for process design. Usually, the maximum economic benefit is chosen as the major objective variable under the target conversion of reactants, but sometimes the controllability, safety, and environmental performance are selected as secondary objective variables. The sequential approach used in the optimization stage is likely to get trapped in the local optima, hence deterministic optimization algorithms are applied in the design of RD processes, for example, generalized Benders decomposition algorithm, branch and bound algorithm, outer-approximation/equality relaxation/augmented-penalty algorithm, and sequential quadratic programming algorithm. Recently, derivative-free stochastic optimization algorithms, such as simulated annealing algorithm, differential evolution algorithm, genetic algorithm and nondominated sorting genetic algorithm II, are employed to reduce additional calculation time.^{39,123,124} The application of optimization algorithms will be discussed in detail in a later section.

Nowadays, homogeneous RD processes are still commonly used in the chemical industry, such as self-catalyzed ethylene oxide hydrolysis, and transesterification between dimethyl carbonate and ethanol catalyzed by sodium methoxide. The liquid hold-up is the key parameter of the design of homogeneous RD processes, controlled by the column diameter, weir height of tray columns, or inclination angle of packed columns. Higler *et al.*¹²⁵ and Gómez *et al.*¹²⁶ studied geometrical parameters of column trays, which determine liquid hold-up. Ciric and Gu,⁶⁷ Buzad and Doherty,¹²⁷ and Melles *et al.*¹²⁸ studied the nonuniform distribution, which will increase the conversion.

The first patent of RD is methyl acetate production catalyzed by sulfuric acid. Even though soluble catalysts possess high catalytic activity, homogeneous RD has several disadvantages for industrial applications: the corrosivity increases the capital investment, fouling on column trays, separating and recycling soluble catalysts complicate the process. Nowadays, cation exchange resin could replace sulfuric acid for a majority of mild reactions catalyzed by the acidic catalyst. Heterogeneous RD process will avoid fouling and the separation and recycling of the liquid catalyst. The resin bag was initially placed in the downcomer or on the plate, which

increases the pressure drop and has a low catalyst loading. The development of catalytic packing, which combined the catalyst bags and structured packing sheets, allows loading the packed reactive column with more solid catalysts than the traditional tray reactive column while keeping a low pressure drop. Baur and Krishna¹²⁹ and Klöcker *et al.*^{130,131} compared the performance of different types of catalytic packings. Gao *et al.*¹³² and Wang *et al.*¹³³ studied the impact of geometric parameters of catalytic packings. These studies facilitate the design of heterogeneous RD process.

Tang *et al.*¹³⁴ assumed that the solid catalyst occupies half the volume of the liquid hold-up on the column tray, whereas the column diameter is obtained from the vapor load. González-Rugiero *et al.*¹³⁵ used the F-factor under maximum vapor load to calculate column diameter. These two methods ignore the influence of liquid load and use a fixed value of catalyst volume fraction, which is inappropriate for the design of the RD process. Shu *et al.*¹³⁶ proposed a universal method to obtain column diameter for variable catalyst volume fraction, using the concept of vapor velocity at flooding point to consider the influence of both vapor and liquid load. Yang *et al.*¹³⁷ explored the influence of residence time distribution on the performance of RD by process optimization and experimental validation, in which for a specific system, a nonuniform and optimized residence time (or liquid hold-up) distribution will increase the conversion of reactant under the same total residence time.

The height of the reactive section is equal to the product of the tray number and tray spacing, or the product of the theoretical stage and HETP (height equivalent to a theoretical plate). According to Shu *et al.*,¹³⁶ a higher reactive section and a suitable reflux ratio will enhance the separation effect, promote the forward reaction, and reduce the catalyst demand to achieve target conversion. Therefore, the catalyst volume fraction and the tray number or the theoretical stage shall be optimized simultaneously, which is implemented by stochastic optimization algorithms. Meanwhile, the nonuniform distribution of the catalyst is implemented by the segmentation of the reactive section, which will reduce both catalyst demand and energy consumption for certain systems.

In conclusion, the column size (diameter and height) is the key parameter of RD design problem for industrial designer, and these parameters shall be optimized simultaneously and iteratively. The logic for flowsheet design is important for educators, which allows students to train in design thinking and methods. The RD design goals and development ideas are important to researchers to further develop better design methods and RD processes.

PROCESS SYSTEMS ENGINEERING FUNCTION-BASED DESIGN LEADING TO REACTIVE DISTILLATION

Introduction to PSE and function-based design

Keil³⁴ describes, in his comprehensive review on PI, two approaches. In one approach, new PI technologies are researched and developed as building blocks in conventional process concept design. The other approach is a PSE approach in which processes are designed based on functions rather than pre-defined building blocks or unit operations. The first step is identifying process functions, followed by integration functions. Reactive distillation is one of the potential results of this function-based design. The functions (tasks) in conceptual process design have seven

categories in the chemical process industry, which are molecular identity change (chemical reaction), amount change (add component), composition change (separate, mix), phase change (evaporate), temperature change (cool), pressure change (pumping) and form change (extrusion).⁴¹ The functions can be included in modeling, which is an essential element in this approach to determine the feasibility of the integration function and determine the best function configuration and integration. Later, simulation is used to optimize the design. Harmsen and Verkerk¹⁰ propose a hybrid approach to achieve PI in chemical industries. This approach combines the building blocks and function design methods with an adaptation of the values, interests and beliefs model to account for hard (physical, technical, economic) and soft (psychological, social, moral) factors for decision making. This approach intends to unify research and development, marketing and operations departments. Nevertheless, there is still a gap to fulfill for a methodology that integrates PI for reactive separation systems that includes synthesis, operability, safety and control, as well as computational tools that can support the development of PI.¹³⁸ Notably, Iftakher *et al.*¹³⁹ proposed an integrated computer-aided tool that performs simulation, design, optimization and control systematically for RD.

Function identification and integration

Function-based process design methods

Function design methods are systematic approaches used to identify, analyze, and integrate process functions to achieve desired process objectives (i.e. smaller, cleaner, more energy-efficient technology). In a chemical process, the typical function units include reaction, separation, heat and mass transfer. The incorporation of such functions helps develop novel process options. Taking the potential RD device (multifunctional reactor and separator) as an example, its application is mainly divided into two aspects. On the one hand, separation by distillation is used to promote reaction conversion, resulting in breaking through the chemical equilibrium, achieving maximum conversion and selectivity. On the other, the reaction is used to enhance the distillation separation to complete the separation of azeotrope or high precision purification of trace substances. Based on the identified functions in the process and their interactions, options for integrating the function units need to be evaluated by optimization techniques. This involves considering factors such as investment costs, operating costs, energy consumption, environmental impact, exergy and responsiveness to balance various objectives and make decisions.^{140,141}

Results of function design methods

Reactive distillation with pre- and/or side reactors. Function-based design with PSE methods has resulted in several options that need further detailed design on configuration and parameter setting. Options already published are: distillation with a pre- and/or side reactors. The input and output of a side reactor are connected to a distillation column. If only the output is connected to the distillation column that it is just classic process design. If the reactor output is connected to an RD column that unit is called a pre-reactor.

Daniel and Jobson⁹⁴ provided an approach to obtain the optimum distribution of the reaction extent between a pre-reactor and an RD column, where chemical equilibrium is assumed. For a range of pre-reactor temperatures, the cost for the reactor and the heat exchanger upstream of the reactor are calculated. A graphically-based boundary value method is used to identify

the design of the RD column for each pre-reactor temperature. Then, the duty and costs for the feed pre-heater, upstream of the RD column, are included. The overall cost of the flowsheet is considered to rank the designs. Notably, their work focuses on the RD process optimization method rather than the RD column itself.

Hussain *et al.*⁹³ presented a method for a technical feasibility evaluation of side-reactor column configurations for both conventional and RD processes. Their proposed framework needs as input, for the reaction systems, operating pressure and temperature, boiling point orders, catalyst loading and hydraulics. The output is a yes/no decision regarding the application of a side-reactor column.

Modeling, simulation and optimization

Modeling and simulation are presented by many researchers. Some focus on modeling and simulation to determine the technical feasibility of a design option, whereas others focus on optimizing the designs for cost, energy and environmental impact. The methods are in most cases applicable to RD as a unit operation and in function-based process synthesis and design.

Jeff Siirola obtained his PhD on computer-aided synthesis of chemical process design, and he summarized that in a paper and a textbook publication with Rudd.^{11,23} In 1995 and 1996, he published two papers on industrial perspectives on process function synthesis, in which he describes his method in detail and illustrates it with the methyl acetate case.^{21,142} The synthesis method is based on functions (addressed as tasks) and not based on unit operations. Siirola can therefore be seen as the founding father of process synthesis with functions. His main method consists of a hierarchy of heuristic design steps. The first step is defining input and output streams of the whole process to be designed. Then, functions are generated by a hierarchy of steps, molecular identity, amount, composition, phase, temperature and pressure, and form. In each of those steps the property difference between input and output is removed by a function. Molecular differences between input and output for instance are resolved by reaction functions. Differences in compositions between input and output streams are resolved by separations. His method is supported by Residue Curve Maps to synthesize the separation scheme. Siirola's method is based on block-flow diagrams in which each block represents a function. After function identification, functions are

integrated as much as possible, or as optimal, in a single piece of equipment. His method resulted in the methyl acetate RD design, consisting of six functions integrated in one RD column (see Fig. 6). The design was developed and implemented on a commercial scale. Details of the development and of the final column dimension and scale are provided by Agreda *et al.*²⁰ and by Harmsen and Verkerk²² by interviewing Siirola. The details reveal that computer-based modeling and simulation played an important role in the rapid and successful development. In summary, Siirola's process synthesis is based on heuristics for function identification and integration, graphical residue curve mapping, and computer modeling and simulation.

They *et al.*¹⁴³ introduced a procedure that combines synthesis, technical feasibility analysis and design of RD columns. It relies on a progressive introduction of the process complexity. From minimal information concerning the physicochemical properties of the system, three steps lead to the design of the unit and the specification of its operating conditions. This procedure can be applied to equilibrium-limited reactive systems where the number of degrees of freedom is equal or less than two. The methodology provides a reliable initialization point to optimize the process, and it was applied with success to the production of MTBE and methyl acetate. This means that the procedure can reproduce process designs reported for these applications. The procedure is applicable to simple equilibrium systems where it helps to find initialization points for the simulation and optimization models.

Li *et al.*¹⁴⁴ proposed a generalized method for the synthesis and design of RD columns. The method starts with a simple process design with all feeds of reactants at the middle of the RD column and all stages as reactive ones. This evolves into an optimum process via sequential structure adjustments, including reactive section arrangement, feed stage relocation, feed splitting and catalyst redistribution. The proposed generalized method is known for its simplicity and robustness to the initial guess of process configuration and the thermodynamic properties of the components to be separated.

Burri and Manousiouthakis⁷⁹ proposed an infinite dimensional state-space framework (IDEAS) that allows the global optimization of RD networks, especially regarding the minimum reactive hold-up and the total capacity. In a wider context, this approach allows optimal process networks by decomposing them into: (i) an

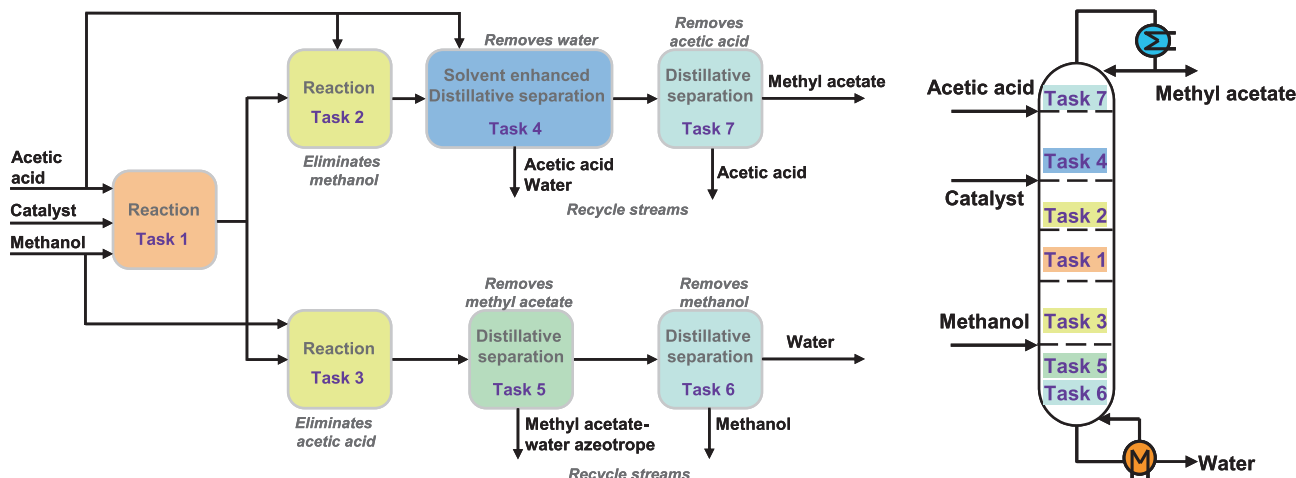


Figure 6. Methyl acetate production: task/function based design of reactive distillation.

operator network, such as reactors, distillation columns and heat exchangers, and (ii) a distribution network, such as mixing, splitting and recycling. Within the framework, network synthesis is prepared as an infinite dimensional linear programming problem. This process representation gives rise to a linear feasible region for RD networks. A hybrid approach to the design of an RD system based on the IDEAS framework includes PDS to overcome pressure-dependent azeotropes. Synergies in the operation are found as both reductions in catalyst requirement and total flows are identified when compared to the operation of RD or PSD separately.¹⁴⁵

Nezhadfarid *et al.*¹⁴⁶ proposed a method for synthesizing reactor-distillation sequences now including RD. The method consists of sequences generation, simulation, optimization using TAC as the objective function. Two case studies are presented where RD appears to be economically more attractive than conventional configurations.

Process-function synthesis methods, which include RD synthesis, are still limited. Comprehensive methods containing heuristics based on industrial experiences and design studies, computer modeling for rapid technical feasibility testing, including controllability, and methods for applying evaluation criteria for the conceptual stage are still not available and require further research. Teaching process function synthesis resulting in RD can be done with block flow diagrams and using the industrial cases published in literature. Residue curve mapping for azeotropes and equilibrium reactions can also be applied.

Modeling for feasibility

The technical feasibility of an RD column is performed at the conceptual level in order to assess whether the application of RD is practically attractive. The scientific community has developed various methods to model different aspects, such as column configurations, stream effects and effects of the heat of reaction.

Okasinski and Doherty¹⁴⁷ developed a steady-state design method for kinetically controlled, staged RD columns based on the fixed points of material and energy balances and their associated eigenvectors. The application of the proposed method provides insights into a feasible column design by considering a single isomolar or non-isomolar liquid-phase reaction, heat effects, nonideal vapor-liquid equilibrium, and the distribution of liquid hold-ups within the reactive section. Given feed and product compositions along with several variables – reboil ratio and Damköhler number – a feasible rectifying or stripping profile is projected onto a composition plane. The design methodology is favored as it is capable of handling realistic models of vapor-liquid equilibrium and heat effects. However, it was only proven to be suitable for pseudo-homogeneous reaction models, whereas many reactions commonly require more complex models.

Huang *et al.*¹⁴⁸ proposed an approach for the reinforcement of internal heat integration during the synthesis and design of an RD column. The approach, which can be applied for chemical reaction systems involving highly thermal effect, is a sequential procedure considering extending the reactive section to either the rectifying section or the stripping section, selecting the feed location within the reactive section, and determining catalyst distribution to achieve further internal heat integration within an RD column. Further heat integration between reaction and separation operations leads to the enhancement of thermodynamic efficiency; therefore, reducing costs and saving energy. However, numerous trial-and-error attempts are required to seek desired

configurations, which make the approach time-consuming and rather unfavorable to be applied for a preliminary a design.

Huang *et al.*¹⁴⁹ proposes systematic procedures for process synthesis and design of RD. For RD systems involving reactions with high thermal effect, there must be an exclusive consideration of internal energy integration between the reaction operation and separation operation involved. In case of a highly endothermic reaction with an extremely low reaction rate and/or small chemical equilibrium constant, internal mass integration also has to be considered between the reactive section and stripping section. For RD systems involving reactions with moderate thermal effect, a careful trade-off between internal mass and energy integration should be considered. For RD columns involving reactions with negligible or no thermal effect, an exclusive consideration of internal mass integration is sufficient.

Modeling for parameter setting and optimization

Optimization-based techniques rely on mathematical relationships among the objectives or performance criteria to be optimized, the type of decision variables and the presence of several constraints in RD processes.¹²³ Mixed-integer nonlinear programming aims to provide fully or partially optimized solutions for the design parameters of RD, such as the optimum number of theoretical stages, feed stage locations, reflux ratio, condenser and reboiler duties and liquid hold-ups.⁶⁷ This method is based on rigorous calculations with functions consisting of master- and sub-problems. The objective functions are related to annual operating cost and annualized investment. The constraints of the rigorous calculations are taken into account from the mass, equilibrium, summation and heat (MESH) equations, kinetics and thermodynamics and/or rational connections between process parameters.

Mixed-integer dynamic optimization deals with problems to operate RD columns with the minimum economic cost and with an acceptable dynamic performance owing to the existence of disturbances.^{68,70,150} It involves finding continuous, tuning and integer parameters. These include continuous parameters, such as column diameter, reboiler, condenser, tuning parameters and integer parameters, such as the presence of catalyst on different sections of RD columns.

Orthogonal collocation on finite elements converts the discrete number of stages in an RD column into a continuous variable and makes compositions and temperature as functions of position.⁷¹ In this approach, the column is divided into several sections that are subsequently partitioned into smaller fine elements. For each finite element, a number of collocation points is determined, and mass and energy balances are fulfilled. These collocation points are selected as the roots of the discrete Hahn family of orthogonal polynomials. The orthogonal collocation method is mainly a modeling approach that assists optimization, and not a stand-alone design method for RD processes.

Jackson and Grossman⁷² developed a new method based on the Generalized Disjunctive Programming approach¹⁵¹ that uses rigorous models, including tray-to-tray calculations, phase equilibrium and kinetic-based models, to assess the optimum designs of RD columns for kinetically controlled reactions. This technique employs disjunctions for conditional trays to apply the MESH and kinetics formula with the aim of minimizing the size of the nonlinear programming sub-problems.

Segovia-Hernández *et al.*¹²³ provided an overview of RD design methods that are based on optimization techniques including both deterministic and stochastic approaches. The paper

concluded that despite the attractiveness of RD technology, designing RD columns remains a complicated task. It is mainly caused by the difficulty associated to the modeling by using non-linear and multivariable equation systems of these processes and the parametric uncertainty of the model parameters. Some deterministic methods are able to provide the global minimum on energy consumption, but they usually demand complex mathematical algorithms, and therefore, their usage can be difficult and time-consuming. Regarding the convergence properties and the reliability of the methods, the paper of Segovia-Hernández *et al.*¹²³ identified that stochastic optimization methods are promising tools, but it is essential to develop new methods with better convergence properties for solving multivariable and non-convex RD design cases.

Linan *et al.*¹⁵² presented the optimal synthesis and design of a reactive/catalytic distillation column, by explicitly considering the multiscale and multiphase nature, and by using a rate-based model that couples micro- and macroscale events taking place inside the column. Solving this intensive optimization problem is challenging as a consequence of nonlinearities introduced by the heterogeneously catalyzed reactions, transport phenomena, and interactions between discrete and continuous variables. A discrete-steepest descent-based optimization framework was used to address the optimal synthesis and design. The results show that multiscale events cannot be ignored as they can lead to process designs that are infeasible or different than those obtained using an equilibrium-based model.

Thus, there is a critical need to systematically consider the multiscale and multiphase events in RD columns for the optimal design of realistic, cost-effective, and attractive PI systems.

Vázquez-Castillo *et al.*⁹⁶ employed a multi-objective meta-heuristic optimization algorithm based on differential evolution and tabu list (MODE-TL) proposed by Sharma and Rangaiah⁹⁵ to optimally design an RD process for the production of ethyl levulinate. The method includes multiple objectives such as the total annual cost of the RD process Eco-indicator 99 result, representing the environmental impact, and an individual risk index indicating process safety. The latter are minimized. The objectives are weighed equally, and the mass flow rates and purity constraints are maintained as constraints.

Tsatse *et al.*¹⁵³ described the optimal design and operation of RD systems based on a superstructure methodology. The proposed method considered a cost-based objective function and used MILP optimization to obtain solutions for different case studies with varied reaction and separation characteristics. Their findings suggested that the capital costs of the column design are mainly sensitive to relative boiling-point rankings. Furthermore, the impact of system characteristics on the optimal design and operation is extended due to relative contributions from separation performance and kinetics.

MINLP design for plant-wide concept design

Burri and Manousiouthakis⁷⁹ are perhaps the first to propose a linear programming optimization technique in combination with a network of process units. First, a process network is set up containing all conceivable building blocks, such as reactors, distillation columns and heat exchangers. It is called a network because all units are connected to each other in any different conceivable way by mass flows using simple mixing, splitting and recycling of streams. Since then, this field has been advanced enormously.

Controllability assessment

An RD process is considered technically feasible when targeted design specifications can be successfully achieved; therefore, the process can be applied and is useful to deliver desired chemical products. Technical feasibility also means that the process is controllable. The objectives of a controllability analysis at the conceptual stage are to determine whether the concept design is controllable, such that product quality and safety constraints are met all the time over a wide range of anticipated disturbances.¹⁵⁴

Noeres *et al.*¹⁵⁵ presented a rigorous model to represent the pseudo-steady-state and dynamic behavior of an RD column. The validation is performed using an experimental set-up which was subject to several tests including perturbations. With simplifications, an extended equilibrium stage model was used to derive the control strategy and optimization. Initially, a linear controller was verified using the complex rate-based model. This research contributes with a rate-based model that takes into account the catalyst phase and nonideal flow behaviors in the liquid phase to accurately describe the hydrodynamics in the column.

The occurrence of multiple steady states is a challenging feature of RD owing to the complexity and high nonlinearity of the models describing its behavior, which at the same time complicates the selection of the control strategy. Pavan Kumar and Kaistha¹⁵⁶ proposed a new metric, rangeability, to assess the controllability of an RD system. Also, this research provides insights into selecting a control policy that is more suitable to avoid steady-state multiplicity. Additionally, it offers guidance to identify the most appropriate control variable that enables prompt and effective control actions without a significant lag.

Luyben and Yu³⁷ provide methods for this control assessment of a number of specified RD systems. They explored RD control design in detail covering cases of both ideal and nonideal systems. For ideal quaternary reversible systems ($A + B \rightleftharpoons C + D$), a one-column process for a neat operation was shown to be significantly less expensive than a two-column process for an operation with an excess of one of reactants. However, the one-column is typically more difficult to control as it needs a control system that can obtain the required precise balancing of the fresh feed streams and, therefore, can avoid the gradual buildup of one of reactants. The one-column system also possesses a drawback of having fewer manipulated variables to control disturbances. For ideal ternary reversible systems with two reactants and one product ($A + B \rightleftharpoons C$), major impacts on both the control structure and vapor-liquid equilibrium caused by the presence of an inert component were observed. For the esterification of alcohols, ranging from methanol to amyl alcohol, Luyben and Yu³⁷ showed that workable temperature control could be obtained with simple control. The authors also demonstrated the performances of RD columns for the production of methyl *tert*-butyl ether and ethyl *tert*-butyl ether, which were significantly influenced by different control scenarios of incoming methanol or C4.

Sharma and Singh³⁸ evaluated control structures of RD columns for different industrially relevant reaction systems and reviewed types of RD controllers from literature. Different control methodologies for RD columns are classified into: (i) simple proportional-integral (PI) controllers, and (ii) advanced model predictive controllers (MPC), such as dynamic matrix control (DMC), quadratic dynamic matrix control (QDMC), robust multivariable predictive control technology (RMPCT) and generalized predictive control (GPC). The proportional-integral-derivative (PID) controller has been applied widely to many chemical processes because of

its simplicity and robustness, but it cannot be effective enough to control complex systems such as RD. The use of advanced model predictive controllers, such as nonlinear MPC, is appropriate for systems with the presence of multiple steady states and the highly nonlinear nature.

Mansouri *et al.*^{89,90} provided a framework that integrates the evaluation of process design and control of RD processes for multicomponent systems. The approach represents a multicomponent system as two key components, light- and heavy-boiling key components; the rules for selecting the key components are given by Jantharasuk *et al.*⁷⁵ Analytical, steady-state and closed-loop dynamic analysis showed that the control structure, disturbance rejection and energy requirement of an RD column designed to maximize the driving force is better than any other operating point.

Tsatse *et al.*^{157,158} proposed a framework to evaluate how uncertainty affects the design and operation of RD systems. They also investigated the interactions between characteristics of the system and controllability of RD. The framework is useful for an early design stage to quantify the impact of specific input parameters on process performance and costs. Three case studies with more/less favorable kinetics and relative volatilities were evaluated, leading to a key remark that an economically optimal RD process may be inefficient when design and operational uncertainties are considered; therefore, different mitigation approaches, depending on the reaction and separation characteristics of a process, may be applicable to improve the system's robustness. Furthermore, the presented case studies showed that uncertainty in the rate constant has a more significant impact on the system performance compared to a similar uncertainty in chemical equilibrium.

Apart from the framework of Tsatse *et al.*^{157,158} and the presented findings by other researchers discussed above, further studies could be performed to account for the nonideal reaction and separation characteristics commonly found in industries, for instance, owing to the presence of azeotropes that make the separation performance less/more challenging. Another example is the importance of mitigation strategies in minimizing the risk of the formation of unwanted products as a result of potential parallel or consecutive reactions due to the process sensitivity to the temperature changes along the column. Kiss *et al.*¹⁵⁹ triggered the generation of conceptual methods and frameworks to assess the operability of those different configurations. The availability of such methods could indeed accelerate the adoption of various RD configurations (configurations other than classical RD technology) by the chemical industries. Nevertheless, there is plenty of room for further studies to synthesize and develop a framework that accounts for the operability of multiple alternatives of RD columns and helps end-users to quickly obtain insights into the most potential RD configurations. Focusing on a plant-wide operation that involves recycling streams owing to unconverted reactant or by-products that need to be reprocessed, Moraru *et al.*¹⁶⁰ proposed a design philosophy, rather than a design methodology, that starts with simple calculations based on simplifying assumptions which then becomes more rigorous as more information is available. As a result, the topology of the full process and the mass and energy balance are obtained. In addition, a control strategy to achieve the material inventory applicable to the plant-wide operation is obtained.

The next section presents recent developments focusing on synthesis and early-stage design of advanced RD technologies. A fully generic method for process controllability assessments in

process concept design covering both nearly ideal and nonideal reaction systems has not been published thus far. Further research is needed in this area.

ADVANCED REACTIVE DISTILLATION TECHNOLOGIES

Research studies in the RD field, in particular when applying function synthesis approaches, lead to the development and potential application of advanced configurations. A recent publication by Kiss *et al.*¹⁵⁹ provided insights into promising options for potential applications in industry, including reactive dividing-wall column (R-DWC), catalytic cyclic distillation (CCD), reactive high-gravity (R-HiGee) distillation, reactive heat-integrated distillation column (R-HIDiC), and membrane-, microwave- or ultrasound-assisted RD. Figure 7 illustrates selected advanced RD configurations^{159,161} that are described in detail elsewhere.^{111,162–169} Notably, commercially applied RD described in the literature covers mostly the conventional RD configurations (Fig. 4) which are fairly well-explored. Only recently a few studies have focused on the conceptual process design and synthesis of advanced RD technologies.^{170,171} Pazmiño-Mayorga *et al.*¹⁷¹ proposed the use of operating windows to identify suitable operating limits for advanced RD technologies. The dataset required to construct such operating windows include thermodynamic properties, kinetic parameters, constraints of materials and experimental methods, and heuristics. Using two new concepts – representative components and a sliding window – they demonstrated how complex features in three case studies can be assessed in an operating window. For instance, an identified side reaction for the case of methyl acetate production is not likely to happen at the operating conditions identified. Pazmiño-Mayorga *et al.*¹⁷⁰ presented a synthesis methodology to qualify advanced RD technologies as advantageous, technically feasible, or not applicable, by considering four aspects consecutively: compositions and splits, basic properties and operating windows, kinetics, and phase equilibria. This synthesis methodology relies on the use of heuristics and first principles, aiming to reduce computational effort compared to mathematical programming-based methods. Although advanced RD technologies lack specific heuristics, Pazmiño-Mayorga¹⁷² adapted heuristics proposed by Kiss¹¹¹ and those obtained from case-specific investigations to support the development of synthesis methodologies for advanced RD, such as the one presented in Pazmiño-Mayorga *et al.*¹⁷⁰ Further studies could be performed to include the interplay of mass and heat transfer and miscibility gaps in advanced RD technologies.

These new RD technologies are very promising, yet they are in different stages of development, with various niche applications typically driving the research. Some of these complex configurations have already received a defined status and are treated below.

Reactive dividing wall column

Studies in the field of RD technology have also contributed to the development of design methods for configurations other than classical RD columns, such as the R-DWC. Literature reports go from equilibrium-stage models based on MESH equations, rate-based modeling and simulation of R-DWC processes, to broad analysis of R-DWC, its minimum energy demand and the potential for energy savings.^{159,169} In chemical systems with multiple products or that require recycling excess reactants, R-DWC provides a notable advantage by efficiently removing middle-boiling

products as side streams.¹⁶⁷ This feature is crucial for handling multiple splits and outlet streams in a reaction-separation system. Nevertheless, it is important to note that an R-DWC operates at a fixed pressure, in contrast to separate columns where the pressure can be adjusted independently, resulting in a reduction of degrees of freedom. The R-DWC has been modeled using rate-based approaches, and its performance has been theoretically studied for various chemical systems. Schröder *et al.*⁹² proposed a method to determine the minimum vapor demand of R-DWC by accounting for the summation of the minimum vapor demand of both the prefractionator (that acts as a reactive section) and main column. In their work, the characteristics of an optimal reaction system for an R-DWC and an approach for quantifying the minimum vapor demand were developed through the formulation of hypotheses that were validated by rigorous simulations. The method enables the comparison of energy demand between the application of R-DWC and less integrated process alternatives at the process synthesis level; therefore, it allows process engineers to quickly gain insights into the promising potential of the R-DWC application early on. Sun and Bi¹⁷³ extended the application of the minimum vapor flow method (based on the Underwood equations) and the minimum-energy mountain diagram to the R-DWC taking into account the effect of the reaction. Daniel *et al.*¹⁷⁴ applied the boundary value method (compositions set at the ends of the column) for the conceptual design of an R-DWC. Pazmiño-Mayorga *et al.*¹⁷⁵ used a decomposition approach for the conceptual design of a dual R-DWC, where two reactions – esterification and hydrolysis – take place in the same column.

Kang and Lee⁹¹ introduced a graphical approach to visualize the composition trajectories along the reactive section of a reactive dividing-wall column. Using the graphical tray-by-tray calculation, one estimates the number of theoretical stages, liquid and vapor compositions, and minimum reflux and reboiler ratios before performing rigorous computations. The proposed approach was validated only by a ternary decomposition reaction, $A \rightleftharpoons B + C$, (i.e. the synthesis of dimethyl ether from methanol dehydration). Therefore, it is necessary to validate the approach further for other ternary and quaternary reaction systems that are frequently encountered for the application of RD in the chemical industry.

Because there are no commercially available simulators that include an R-DWC module, or even one for a DWC, a decomposition method is commonly employed for simulation. The R-DWC is decomposed through the dividing wall in a sequence of conventional and RD columns with interconnecting streams. The arrangement is thermally and hydraulically equivalent to an R-DWC.^{92,169} In addition, the mass-transfer resistances of all components are assumed to be identical, and heat transfer through the wall is assumed to be negligible.¹⁷⁶

According to Weinfield *et al.*,¹⁶⁹ R-DWC is most promising for reversible reactions with the components sharing suitable boiling-point characteristics, allowing simultaneous separation and reaction, and when more than two outlet streams are expected, as noted by Pazmiño-Mayorga *et al.*¹⁷⁰ Weinfield *et al.*¹⁶⁹ were the first to review experimental, modeling and dynamic control studies and research in the field of R-DWC, while also identifying knowledge gaps that should be addressed to bring the technology to commercial scales. Liu *et al.*¹⁷⁷ proposed control strategies using intelligent fuzzy logic and model predictive control, and demonstrated that overshoot and transition time are mitigated when compared to PID control. Unlike DWC industrial implementation, starting with the first documented industrial

installation at a BASF site in 1985^{178,179} and a range of retrofits, with Montz as one of the leading DWC technology providers,¹⁸⁰ R-DWC has not been implemented at a similar pace. Several challenges remain to be further developed regarding the modeling and simulation of R-DWC as there exist uncertainties about the decomposition methods, and complex control schemes for the improvement of dynamic models, shortcut design and experimental demonstrations (currently limited to only five chemical systems, two laboratory-scale and two industrial-scale units) that have slowed proof-of-concept for industrial implementation.^{169,181} The design and control of R-DWC can draw on the extensive experience of RD and DWC, respectively. Other limitations of R-DWC relate to catalyst formulation, hold-up and residence time, pressure drop and flooding, and the need for equal pressure drop on the two sides of the dividing wall.¹⁵⁹

Catalytic cyclic distillation

CCD uses separate phase movement, which is achieved with technology-specific internals and a periodic operation mode.¹⁵⁹ One operating cycle consists of a *vapor flow period* (when the thrust of rising vapor prevents liquid downflow) followed by a *liquid flow period* (when the liquid flows down the column, dropping by gravity from one tray to the tray below). The internals used for cyclic distillation allow the control of the amount of liquid on the tray, and thus the reaction time.¹⁸² CCD offers the advantage of significantly higher liquid hold-up and catalyst per tray compared to conventional RD systems. This feature makes CCD suitable for relatively slower reactions occurring at lower temperatures, allowing for longer residence times. Consequently, this enables efficient use of the column shell given the high ratio of catalyst volume and liquid hold-up to the space available for vapor flow, thus extending the range of applicability of RD. Hence, the time available for reaction and the amount of liquid on a tray can be manipulated during the vapor flow period.¹⁸²

Pătruț *et al.*¹⁶⁸ proposed a rigorous model and simulation study for the production of DME, which included mass and energy balances for each period. The results showed that CCD achieved higher purity than a conventional RD and used lower vapor flow-rate and fewer stages, resulting in reduced energy consumption. To complement the model of Pătruț *et al.*¹⁶⁸ that accounted for mass transfer only, Rasmussen *et al.*¹⁸³ proposed a model that described heat transfer. Compositions found in both studies presented similar trends. However, temperature profiles were different because of the variations observed during the vapor flow period when taking into account heat transfer. In an effort to simplify the process, Rasmussen *et al.*¹⁸⁴ applied the previously proposed model in a well-known case study involving MTBE production, assuming chemical equilibrium. Their findings revealed that the cyclic operation had a beneficial impact on the stage performance within the reactive section as a result of decreased back mixing, resulting in improved separation efficiency. Rasmussen *et al.*¹⁸⁵ introduced three quantitative metrics to assess CCD performance: distance from equilibrium (indicating how quickly chemical equilibrium is achieved during the vapor flow period), the total production over a cycle, and the mean Damköhler number over a cycle. These metrics were employed in three case studies for the production of methyl acetate, MTBE and DME, and the mean Damköhler number over a cycle was suggested as a valuable indicator of the viability of CCD.

Simulation of cyclic distillation, both for the steady-state model and for the dynamic vapor flow periods, has been carried out in MATLAB.¹⁸⁴ However, commercial software for chemical process

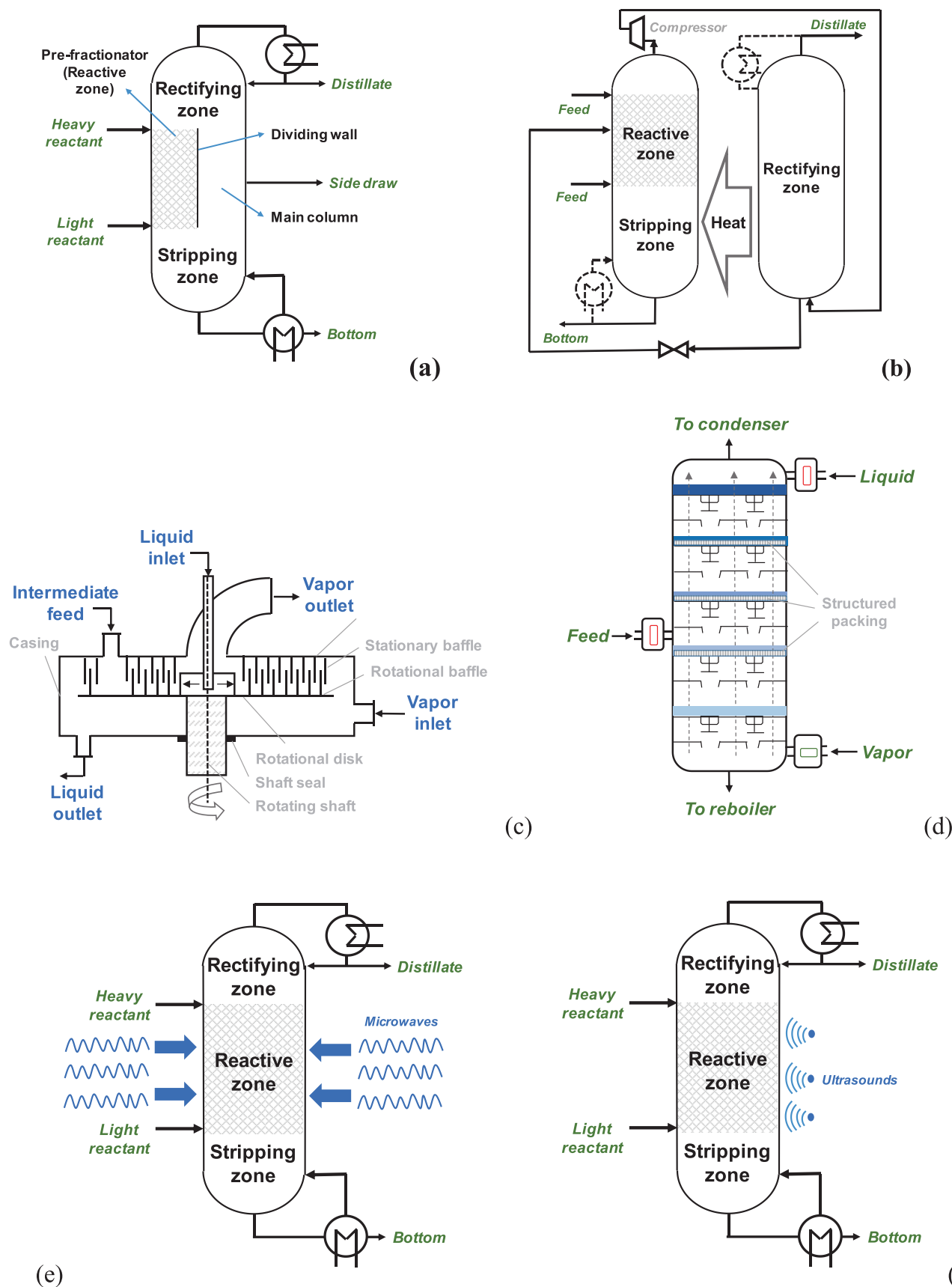


Figure 7. Advanced RD column configurations: (a) reactive dividing-wall column, (b) reactive HIDiC, (c) rotating zig-zag bed for (reactive) HiGee distillation, (d) catalytic cyclic distillation by alternating a vapor-flow period with a liquid-flow period, (e) microwave-assisted reactive distillation (RD), and (f) ultrasound-assisted RD.

design cannot be adapted for simulating cyclic processes because the hydrodynamic limitations seen in operation are not reflected. This issue arises from the fact that data about internals included in such software are not suitable for cyclic distillation, as pointed out by Kiss and Maleta.¹⁸⁶ Additionally, the synthesis and design methods for dynamically intensified technologies encounter substantial challenges related to modeling, simulation and optimization, as discussed by Baldea and Edgar.¹⁸⁷ Operational challenges involve the use of moving parts, particularly in the presence of catalyst particles, to achieve effective mixing and turbulence in the liquid phase to enhance the reaction without affecting the catalyst particles. This potential damage could be reduced by adding structured catalytic packing or catalytic internals on the trays. Therefore, further research is needed to develop and validate methodologies for synthesis and conceptual design, simulation tools, control strategies, and optimization in order to enable the industrial implementation of CCD.

Reactive HiDiC

The R-HiDiC combines heat integration and PI by merging a HiDiC with an RD unit.^{159,188} In a nonreactive HiDiC, energy is transferred from a higher-pressure, higher-temperature rectifying section to a lower-pressure, lower-temperature stripping section using mechanical work (e.g. compression) based on the heat pump concept.¹⁸⁹ In an R-HiDiC, a reactive section can be placed in either the stripping section (for endothermic reactions) or the rectifying section (exothermic reactions). The exothermic heat of reaction can partially support vapor traffic, while endothermic reactions aid in condensation in the rectification section, generating additional liquid reflux.^{159,188,190} However, note that the need for a compressor can increase electricity and capital costs.¹⁸⁸

Review papers by Kiss and Olujic¹⁹¹ and Fang *et al.*¹⁹² offer comprehensive information on HiDiC, covering its working principles, modeling, simulation, optimization, design, dynamics, control and applications, which can offer valuable insights for R-HiDiC.

The main advantage of R-HiDiC lies in its internal heat integration, which lowers the demand for hot and cold utilities, potentially complemented by the heat of reaction. This reduction in reboiler and condenser duties – and the associated utility requirements – results in improved energy efficiency.^{111,193–195}

The industrial application of the nonreactive HiDiC, commercially known as SUPERHiDiC and implemented by Toyo Engineering, has proven to be energy-efficient,^{196,197} yet there is no information available regarding commercial applications of R-HiDiC.

Modeling R-HiDiC is based on approaches for HiDiC that assume either a uniform heat transfer area or a uniform heat load distribution.^{198,199} When designing R-HiDiC, factors to consider include location of the reactive section, the number of rectifying and stripping stages, the feed location, the vapor fraction of the feed stream, the compression ratio (between the rectifying and stripping section) and the number of heat exchangers.²⁰⁰ Among these, the number of heat exchangers and the compression ratio are the most critical.²⁰¹ A small compression ratio between 1.3 and 3 is preferred to avoid a high-pressure difference between the rectifying and stripping sections.^{191,199} Hence, keeping energy costs down, particularly for equilibrium-limited reactions involving mixtures of chemicals that boil at similar temperatures. However, the range of applicability is likely to be narrower than that for conventional RD.¹¹¹ Concerning heat exchangers, the SUPERHiDiC concept offers valuable insights for design, such as using

side heat exchangers to transfer heat between different parts of the system at various heights,¹⁹⁷ which can also be applied to R-HiDiC.

Pulido *et al.*²⁰² simulated an R-HiDiC using the RadFrac model within ASPEN PLUS. Their model featured a concentric design with energy exchange taking place through stage-to-stage interconnections. However, the study provided limited information about the specifics of these stage connections and the results obtained.

However, Babaie and Nasr Esfahany²⁰⁰ introduced an optimization approach for the integrated operation of R-HiDiC combined with pervaporation. The simulation of R-HiDiC was carried out using ASPEN HYSYS. Compared to conventional RD, the optimized outcomes demonstrated a reduction of 29% in energy consumption and 12% in TAC – despite the addition of five heat exchangers and one compressor. Eyvazi-Abbari *et al.*²⁰³ proposed a modified reaction/distillation algorithm to synthesize heat-integrated columns, including internal HiDiC, external HiDiC and R-HiDiC.

The outlook for R-HiDiC is positive, driven by the significant energy-saving potential of HiDiC, which provides strong incentives. The existing commercial adoption of SUPERHiDiC could catalyze further advancements and foster industrial interest in R-HiDiC.¹⁵⁹ Nevertheless, design and control of R-HiDiC need further investigations, given the interactions between vapor and liquid streams and the reaction in heat integration.^{188,190}

Simultaneously, optimizing the operation of R-HiDiC, including economic assessments, becomes crucial in assessing the balance between energy savings and capital costs.²⁰⁰ Additionally, the development of methodologies for simultaneous process synthesis and integration becomes essential to uncover the potential of R-HiDiC during flowsheet development, such as the one described in Pazmiño-Mayorga *et al.*¹⁷⁰

Reactive HiGee

Reactive high-gravity distillation combines high-gravity distillation (HiGee) and rotating packed-bed reactors (RPB),²⁰⁴ providing a potential for solid-catalyzed gas–liquid reactions. This potential mainly results from the intensified gas–liquid mass transfer rates and the good catalyst wetting at high gravity.¹⁷⁸ Owing to the high rotational speed, the residence time and hold-up volume decrease, resulting in smaller equipment.¹⁵⁹ This reduction in liquid hold-up, coupled with rapid mass transfer, helps avoid undesired series reactions that might otherwise reduce selectivity towards the desired product. The rapid removal of the main reaction products facilitates enhanced selectivity and ensures low yield losses.^{159,170} However, it is important to note that the range of applicability of R-HiGee is limited to liquid-phase reactions only, particularly those involving fast reactions with competing serial reactions.²⁰⁵ In addition, prolonged operation at high gravity also results in erosion of the catalyst trapped in the internals (e.g. wire mesh). Although specific studies have demonstrated the effective heat dissipation in HiGee distillation,²⁰⁶ Rao²⁰⁷ suggests that HiGee may not be suitable for reactive separations with significant heats of reaction owing to challenges in achieving *in situ* cooling or heating. To mitigate hotspots in rotating packed beds, alternatives such as the use of coils for heating and cooling have been explored, particularly in the context of gas absorption.²⁰⁸ The limited heat dissipation can be attributed to unfavorable geometries and reduced contact time between the vapor and liquid phases. Consequently, R-HiGee is primarily suited for systems with lower heat effects.²⁰⁷

HiGee devices, owing to their operational flexibility and compact design, find potential applications in scenarios characterized by movement or space constraints, such as offshore platforms and spacecraft.^{32,204,209} Niche uses for R-HiGee include scenarios involving high-viscosity fluids or fast reactions controlled by mass transfer.^{207,209,210} One notable industrial application of R-HiGee is in cases where one of the reactants is a gas, similar to gas stripping, but with the unique feature of the gas reacting with the liquid phase and catalyst. This application was successfully employed for the industrial production of hypochlorous acid at Dow Chemical.^{204,211} Reports exist regarding the industrial utilization of reactive HiGee for nanoparticle preparation²¹² and HiGee distillation, stripping and gas cleaning in China.²⁰⁷ However, information on industrial applications of R-HiGee in the open literature is limited.

Modeling approaches for R-HiGee include both equilibrium and nonequilibrium methods. Detailed models account for changes in mass transfer coefficients along the radius due to the gravity field, interphase mass transfer, and interactions with the packing, rotor and casing.²⁰⁴ The ability to adjust the rotational speed provides an additional degree of freedom, offering further opportunities for design and optimization.²¹³ Although models for HiGee and R-HiGee are not readily available in commercial simulation software, Krishna *et al.*²¹⁴ used the RadFrac module in ASPEN PLUS for rigorous rate-based calculations by discretizing the R-HiGee unit into segments, converting them into a series of attached cylinders. The method produced satisfactory results for a nonreactive HiGee, and a conventional RD was modeled and validated independently. However, its broader application remains limited as a consequence of insufficient data for validation, as highlighted by Hilpert *et al.*²¹⁵ Other tools employed in the study of R-HiGee include FORTRAN, EXCEL and COMSOL MULTI-PHYSICS.^{210,214}

Complex interactions between hardware, operating conditions and simultaneous phenomena make the development of generic widely applicable models out of reach.²⁰⁶ This limitation hinders the integration of such process options into frameworks for process synthesis. Neumann *et al.*²¹⁶ report that the industrial production of hypochlorous acid, previously introduced, has attained a technology readiness level of 9, indicating that it is a proven technology. However, systematic design procedures for extending the application of this technology to other systems are currently unavailable. To extend the range of applicability of R-HiGee technology, further research on suitable packings is necessary to achieve longer residence times,¹⁵⁹ for example, using 3D printed configurations for the rotor to enhance heat dissipation.²⁰⁷

Membrane-assisted RD

Membrane-assisted RD processes are similar to azeotropic RD systems. The main difference is that MA-RD uses a membrane instead of a decanter for separation and thus is not limited to systems forming two-liquid phases. The membranes introduce advantages when coupled to an RD column to aid separation, as the rate at which one species passes through the membrane is much larger than that of the other species, thereby overcoming thermodynamic limitations such as azeotropes.¹⁶⁶ The combination of membrane and RD in one unit and/or series arrangements has excellent potential to further intensify the performance of RD, particularly where the timely removal of water by-product is crucial (e.g. production esters and ethers).¹⁵⁹

Industrial applications of membrane-assisted distillation, focusing on azeotrope separation, are reported.²¹⁷ However,

applications of MA-RD have been only investigated experimentally and in simulation.²¹⁸ For MA-RD, the membrane and the RD column are modeled independently. Each model is either compared to the results of other simulations or validated through laboratory or pilot-scale tests. RD columns are commonly represented using the RadFrac module in ASPEN PLUS. Physico-chemical interactions between components and the membrane are typically described by empirical and semi-empirical models, which can be implemented in ASPEN CUSTOM MODELER and as a User2 subroutine in ASPEN PLUS.^{166,219} However, particular emphasis is placed on membrane modeling and optimization, including economic considerations, during process design owing to the substantial costs associated with the membrane.²²⁰

Scharzec *et al.*²²¹ proposed a methodology for early-stage synthesis and design of processes with pervaporation units. The approach starts with ideal models, progressing to economic considerations. Using thermodynamic insights from Jakstrand *et al.*,²²² it evaluates the applicability of pervaporation based on pure component information, considering solubility and molecular weight. Residue curve maps identify distillation boundaries, providing opportunities for hybrid operations. Shortcut and ideal models, along with NLP optimization, minimize energy use in various configurations. If improvements are possible, a suitable membrane is sought. Finally, superstructure optimization, incorporating sizing and costing, is used to minimize TAC using ideal models for pervaporation.

Models and simulation tools for RD are well-established,¹²⁴ yet the field of membrane modeling and design encounters challenges. The separation characteristics of membrane materials are typically studied on a case-specific basis for a given chemical system, often requiring laboratory-scale experiments for validation.²¹⁸ Consequently, the development of generic methods and model-based tools for widespread application relies heavily on precise molecular models to describe membrane separation and its integration with distillation, as emphasized by Liu *et al.*²¹⁷ This limitation can be extended to the domain of RD.¹⁷⁰

Microwave-assisted reactive distillation

Microwaves have the potential to improve reaction and separation performance by enhancing the relative volatility of substances, particularly, the evaporation of water is stimulated causing an instantaneous shift in equilibrium.^{162,223} These characteristics may extend the range of RD applications in MW-RD.²²⁴

MW-RD is particularly promising for reactions involving chemical products with high dielectric constants, allowing efficient absorption of microwaves and easy separation from the reactive system. Unlike conventional heating, microwave-induced dielectric heating operates through volumetric heating, resulting in an inverted temperature gradient across the entire volume. This heating mechanism is primarily influenced by dipolar polarization and ionic conduction.²²⁵ The effect of microwaves on VLE is still a debated topic as the underlying science is not fully understood.

Temperature was identified as the primary influencer for liquid-phase reactions when investigating the impact of reaction temperature and microwave power density on conversion. Microwave-assisted processes outperformed conventional heating, as evidenced by a lower apparent activation value.²²⁶

Werth *et al.*²²⁵ carried out preliminary experiments of microwave-assisted evaporation of pure components, showing a relatively small superheating of the liquid phase. However, no discernible impact of the applied microwave field on separation efficiency at the macroscopic distillation scale was observed for

binary mixtures. A model-based process analysis of MW-RD demonstrated no significant enhancement in conversion or selectivity.²²⁵ A later study that evaluated MW-RD in batch mode experimentally and in simulation found that the application of microwave fields intensified the performance of RD, showcasing the potential for high efficiency and energy savings.²²⁷ Another study for continuous MW-RD showed increased purity of the main product on account of the application of microwaves compared to conventional continuous RD.²²⁸ MW-RD simulations were carried out in ASPEN CUSTOM MODELER, ASPEN BATCH DISTILLATION and in ASPEN PLUS.^{225,227,228} A pilot-scale test for microwave-assisted continuous reaction distillation process for acetic acid esterification applied microwave RD equipment including specialized packing called MRDPAK, designed to be transparent to microwaves and ensure sufficient residence time for liquid reaction and mass-transfer efficiency.¹⁶²

Considering the uncertainties of measuring the microwave effect on separation efficiency at a macroscopic distillation scale, investigation of the influence of microwaves on the separation efficiency require dedicated microwave equipment.²²⁵ Currently, the lack of mature devices to facilitate microwave use at large scales and to increase the microwave penetration depth is a key barrier to commercial uptake of MW-RD technology.¹⁵⁹

The lack of established methods for screening, design and economic evaluation further adds to the challenges. Advancements in this field demand comprehensive research encompassing design synthesis, advanced modeling, simulation, and experimental validation—a holistic PSE approach is vital for the development of MW-RD technology.

Ultrasound-assisted reactive distillation

The use of ultrasound (US) into RD, specifically enzymatic RD (ERD), has demonstrated its ability to boost chemical activity and accelerate reaction rates.^{164,165} A techno-economic analysis conducted by Wierschem *et al.*,²²⁹ studied the advantages of US-RD, revealing that faster reaction rates resulted in a reduction in size of the reactive section, and the column overall, compared to ERD without ultrasound. While installation costs of the ultrasound equipment are high, they are compensated by the reduced height of RD column associated with a shorter reactive section. Cost advantages are expected when the increase in the reaction rates achieved through the application of US surpasses the additional costs associated with US equipment. In such cases, the process improvements resulting from US utilization outweigh the equipment expenses, leading to overall cost savings.

Simulation of US-RD has been carried out in ASPEN PLUS, using kinetic parameters obtained from experiments applying ultrasound. However, no comparison against conventional operation is presented and the results found are trivial.²³⁰

In processes with significant economic potential, it is imperative to implement process control mechanisms for automatic adjustment of conditions and compensation for feed fluctuations.^{164,165}

However, to fully harness the advantages of ultrasound, a comprehensive understanding of its precise effects on reaction rates and physical phenomena is essential. Consequently, addressing the following aspects is crucial for advancing knowledge in this domain: equipment design, scale-up procedures, field uniformity considerations and penetration depths.^{164,165} Application of US-RD remains limited owing to the lack of large-scale US devices, although a roadmap was proposed for industrial implementation.^{164,165}

CONCLUSIONS AND RECOMMENDATIONS

Conclusions on industrial design

Reactive distillation offers significant advantages over conventional technologies, yet designing RD columns requires more challenging tasks considering integrated reaction and separation occurring in a single apparatus. A trade-off in determining design parameters is usually necessary, as, for instance, either low- or high-temperature cases may not be technically feasible and economically viable. For engineering from industry, the conceptual design methods are required and used to evaluate whether RD is a worthwhile process based on certain evaluation criteria: safety, health, environment, economic, technical feasibility, social acceptance, controllability and sustainability. Although the development of RD design methods initiated over 30 years ago, it is exciting to observe that the conduct of research in this subject is alive and progressive to date considering RD as an intensified unit operation or as a part of the result of function-based process synthesis and design. This paper provides remarks concerning industrial design to fill the identified gaps between the industrial designer and RD processes.

The historic overview of the development of RD technology underlined the importance of a strong interaction between academia (both research and teaching) and industry in gaining successful applications of RD technology; the famous story of the RD application in the Eastman design was discussed as an example. Most of the developed RD design methods are useful for the initialization of column models as they have been validated using different chemical reaction systems. However, rather than using some theoretical case studies, the validation of RD design methods needs to include existing column designs that have been industrially applied. Participation from industrial players, such as providing sufficient data of existing industrial column designs, is indeed advantageous as in most cases access to such information is limited. Moreover, the investigation about design of RD column internals lacks significantly, which severely restricts industrial application for RD process. With those stronger collaborations between academia and industry, design methods for RD columns can be expected to be truly useful in the chemical industries.

Conclusions on education

Reactive distillation has been recognized as a primary example of PI techniques for teaching activities at universities. The status of teaching PI is summed up in two articles by Fernandez-Rivas *et al.*^{45,46} It is of interest to note that the UN SDG's prominently figure in those articles as part of teaching methods for PI. However, in these articles no specific attention is paid to RD. Sitter *et al.*²³¹ reviewed different approaches to synthesize an intensified process, yet most are based on methods from Process Synthesis and Process Optimization. For education on RD several textbooks are available, such as Luyben and Yu³⁷ and Sundmacher and Kienle²³² or RD book chapters in other established textbooks.^{2,111,233,234} These books strongly lean on equilibrium reactions and azeotrope formation such as in esterification cases. The much simpler cases of nonequilibrium reactions and no azeotropes (such as hydrogenations) are not treated. This is more remarkable as the latter are some of the most applied industrially^{28,235} and are easier to teach. It is recommended to extend teaching methods for nonequilibrium reactions and (no-n)azeotrope design problems. Teaching materials could be extended to cover RD evaluation criteria and more industrial RD cases, such

as those for nonequilibrium reactions and (non-)azeotrope systems, in order to allow students to gain a real-world understanding of the applications, needs, challenges and trade-offs faced by industry.

For the process concept design which includes RD as one of the unit operations to select from, there is no textbook available for education. For a detailed configuration of RD, the textbook by Luyben is available. Luyben and Yu³⁷ provide conceptual process design methods for RD columns treated as unit operation. Lutze and Gorak¹⁶⁶ also describe the conceptual design and modeling methods for RD, but in less detail than Luyben and Yu.³⁷ Harmesen²⁸ provides many methods for design and selection of catalytic packings for RD. In addition, teachers in the field of RD should extend the design methods and the principles and concepts of RD to other processes with enhanced coupling of functions (such as: reactive absorption, reactive adsorption, reactive extraction, reactive crystallization, reactive chromatography and membrane reactors), so as to inspire, guide and train students in design and research training in related fields.

Conclusions on academic research

Reactive distillation has been recognized as a primary example of PI, revealing numerous advantages and potential applications in the literature. However, the recognized limitations of RD, particularly the need for overlapping reaction and separation windows, persist even at the synthesis and conceptual design level. The prospect of overcoming these limitations and expanding the applicability of RD lies in the additional intensification offered by advanced RD technologies, as proposed in Pazmiño-Mayorga *et al.*^{170,171} Despite their potential, there is a limited body of literature addressing how these advanced technologies can be incorporated into a process flowsheet during the synthesis stage.

These advanced RD technologies show promise for industrial implementation, as acknowledged by Kiss *et al.*,¹⁵⁹ yet their technical maturity remains low, making their practical application risky. The absence of widespread industrial applications and limited pilot tests contributes to the lack of ready-to-use models in commercial simulators, further complicating the validation of design models. Process simulation software tailored for the development of advanced RD technologies is currently unavailable. However, adaptations in ASPEN PLUS and proprietary models in MATLAB or ASPEN CUSTOM MODELER have been employed in certain cases. These adaptations, however, present challenges in terms of model reusability and validation owing to the limited sharing of implemented models in the literature. Moreover, the existing process simulation software lacks comprehensive coverage of the additional intensification features associated with advanced RD technologies, such as cyclic operation, high-gravity fields, internally heat-integrated distillation, and reactions combined with dividing wall columns, as highlighted by Kiss and Smith.¹³ In terms of hardware components, commercially available catalytic packing or internals used for cyclic operation have not been integrated into widely used simulation software, posing challenges for modeling and validation efforts.

In conclusion, while the potential of advanced RD technologies is promising, their journey to industrial implementation faces challenges related to technical maturity, limited literature on synthesis methodologies, and the absence of comprehensive process simulation software accommodating their unique features and hardware components. Research about the internal mechanism of the interaction between reaction and vapor–liquid mass transfer is needed to understand the enhancement achieved by the

simultaneous phenomena. Currently, this understanding is confined to roughly qualitative analysis. Objective variables varying with decision variables require detailed analysis from the view of interaction mechanisms. Addressing these challenges is crucial for realizing the full potential of these technologies in enhancing chemical processes.

Recommendations

Recommendations for further research to fill knowledge gaps

Research performed by the scientific community takes significant roles in bringing conceptual RD design closer to its application in industry. The conduct of research has successfully delivered many conceptual methods for the synthesis of RD processes. The next level of challenges that needs to be addressed by further research is the development of new or modified design methods that can outperform the capability of existing methods in designing RD columns at the conceptual level. The provision of methods allowing the performance of RD design tasks to become quicker and cheaper will be significantly advantageous for industrial and academic end-users.

The application of advanced RD including reactive dividing-wall column, catalytic cyclic distillation, high-gravity RD, heat-integrated distillation column, and membrane-, microwave- or ultrasound-assisted RD is very promising. Yet, those technologies are in different stages of development. Although research in developing conceptual designs for case-specific applications shows progressive milestones, methods for synthesis and design are limited. A deeper understanding of multiscale phenomena and interactions is needed for simultaneous reaction and distillation in the presence of additional intensification features. Future research can focus on the development of reliable models to describe the behavior of advanced RD technologies, including dynamic operations and control strategies, enabling performance evaluation that becomes an interesting, yet challenging subject to explore in the future. The knowledge gaps are mainly screening criteria for selection, design methods, and quantified economic advantages compared to conventional reference designs. Future research can further expand the application fields of RD, especially the production of high value-added products in fine chemicals. In addition, the direction of RD can be expanded to the field of catalytic reactions, not just in the field of distillation and separation. For example, coupling the photocatalytic reaction process with distillation, developing photocatalytic RD and enzyme catalytic RD.²³⁶

Recommendations for co-operation academia and industry

The interaction between academia and industry played an important role in the development of the knowledge field of RD. For further development of this field, it is important to organize this interaction. We want interactions and collaboration to take place; we want mechanisms that promote collaboration; we need mind-sets in academia and industry that enable fruitful development of fit-for-purpose design approaches. In that vein, we point to several productive EU-funded projects (e.g. BioCatPolymers, Brite Euram, INTINT and INSERT) or projects from the Bio Base Europe Pilot Plant (e.g. ReSolve).

DATA AVAILABILITY STATEMENT

Upon reasonable request from corresponding author.

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