

Current Trends in Conceptual Process Design

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Abstract

In recent years there has been a marked shift among the chemical companies away from bulk chemicals and towards high-value low-volume products. This shift has presented a number of challenges in applying the existing tools and methods for conceptual process design. Whilst there is some interest in improving existing tools, there is an increased need for the development of new tools that will aid in developing processes for manufacturing specialty chemicals, pharmaceuticals, and microstructured products. In this paper, we will outline the current areas of interest in conceptual process design.

Introduction

Conceptual design or “process synthesis” systematically generates potentially profitable alternatives based on the experimental and mathematical analysis of chemical routes to produce desired product/s from available raw materials. After remarkable progress in the past four decades, process synthesis is now a mature field. An outline of the history of the methods used for process synthesis was recently published in a retrospective article by Westerberg (2004).

The increase in industry capacity globally and the increase in the number of producers has resulted in large excess capacity reducing profitability. Also, rising raw material prices and energy costs have sustained interest in the development of process synthesis tools. The effort at many universities has been supported by the industry, adding to the industrial applicability of the tools developed. Until recently, a substantial amount of work in process synthesis focused on the manufacture of bulk chemicals, partly because these problems were in the immediate interest of the industry, and partly because of an improved understanding of the design and operation of unit operations such as multi-phase reactors, distillation, extraction, absorption, etc., and also the thermodynamic framework to describe the properties of bulk commodity chemicals. Decreasing profit margins in bulk chemicals has forced companies to increase reliance on specialty chemicals and recently towards new products. The stock market appears to disfavor diversified firms with portfolios that include both commodities and specialties, perhaps due to greater difficulties of managing such firms as well as difficulties in evaluating management performance (Arora et al., 1999). Government funding for research is also having a big impact in shifting the direction of academic process synthesis research away from bulk chemicals.

The current challenges to the chemical process industries include quicker development of new products and processes, making existing processes more efficient (by reducing capital and operating costs), and finding new chemical routes to existing products. The challenges will not only require sustaining the existing approaches, but also will demand new approaches to incorporate product design and development. A recent prospective on process synthesis by Barnicki and Siirola (2004) provides useful reading to the practitioners of process synthesis methods. This article will be in a similar spirit, adding to the thoughts published by Barnicki and Siirola (2004). From our viewpoint,

the following areas are likely to be important in the development of conceptual design methods:

New Methods for Existing Tools

Progress in the past four decades have resulted in the development and assimilation of numerous process synthesis tools. Although new tools are slow to come, new methods that improve the performance of the existing process synthesis tools are developed regularly. A few active research areas that aid existing process synthesis tools will be outlined in this section.

Distillation

Design of distillation systems has made enormous progress in the past few decades. The systematic methods for designing distillation systems are widely used in the currently available process synthesis methodologies. Methods for separating mixtures with or without azeotropes, and also for separating heterogeneous mixtures have matured. Nevertheless, useful contributions are still being made to the area. Some of the current research is focussed on the generation of alternatives for distillation systems using a state-task-network representation (Sargent, 1998; Tao et al., 2002), rate based approach to distillation (Taylor et al., 2003), and reactive distillation (Malone and Doherty, 2000).

Hierarchical Decision Making

Heuristics-based methods are often used during industrial process synthesis. A hierarchical procedure for conceptual design published by Douglas (1985) decomposes the design into a series of subproblems such as mole balances at the input-output level, reaction subsystem, separation subsystem, etc. Implementing the hierarchical procedure requires setting-up material balances for evaluating economic tradeoffs, which are used as objectives while proceeding through the decision levels. Manufacture of specialty chemicals is often characterized by complex reaction chemistries, and formulating the mole balances for such chemistries using conventional methods is not easy. Until recently, no systematic procedure to formulate mole balances was available. Systematic

treatment of mole balances must provide for an easy and fool-proof procedure. Mole balances can systematically be written in terms of *reaction invariants*, N_i , which take the same values before, during, and after the reaction. The aim is to generate mole balances that relate the inlet molar flows n_i^0 , with the outlet molar flows n_i . The reaction invariants are determined using the stoichiometric coefficients in the reaction chemistry using matrix notation as below (Gadewar et al., 2001):

$$N_i^0 = n_i^0 - \boldsymbol{\nu}_i^T (\boldsymbol{\nu}_{Ref})^{-1} \mathbf{n}_{Ref}^0, \quad i = 1, \dots, c - R \quad (1)$$

$$N_i = n_i - \boldsymbol{\nu}_i^T (\boldsymbol{\nu}_{Ref})^{-1} \mathbf{n}_{Ref}, \quad i = 1, \dots, c - R \quad (2)$$

where $\boldsymbol{\nu}_i^T$ is the row vector of the stoichiometric coefficients of component i , and $\boldsymbol{\nu}_{Ref}$ is a submatrix of the stoichiometric coefficient matrix corresponding to chosen reference components. N_i^0 are the reaction invariants based on the inlet molar flow rates and N_i are the reaction invariants based on the outlet molar flow rates. When we equate these reaction invariants, the stoichiometric mole balances for the reacting system are simply:

$$N_i^0 = N_i, \quad i = 1, \dots, c - R \quad (3)$$

The method of reaction invariants simplifies substantially the effort required to formulate mole balances during the conceptual design stage.

New methods that augment the effectiveness of existing methods for conceptual design (such as the hierarchical procedure) will include process models for considering novel equipment in the decision making process (e.g., reactive distillation, simulated moving beds, inorganic membrane separation, etc.), and adapting the existing methods for high-value products, for e.g., microstructured materials (Meeuse et al., 2000). A computer-aided methodology for process development using limited amount of data was published by Schembecker et al. (1994). The expert system, PROSYN, based on this methodology uses rules and heuristics together with numerical calculations to generate alternatives. We find the methodology especially useful in the early stages of process synthesis when limited amount of experimental data is available. The methodology is regularly updated with new developments, and most recently we have added methods for generating and evaluating crystallization-based alternatives.

Optimization

Combinatorial and algorithmic methods are required to explore more alternatives than what is possible with methods requiring significant human input, such as the hierarchical decision making process. Optimization is therefore evolving as a useful tool in process synthesis. Studies based on optimization methods, such as those described by Grossmann and co-workers (1983, 1997), can be used to include quantitative economic objectives in process synthesis. In optimization-based methods, a superstructure is typically used as a basis to include process alternatives. The presence or absence of certain devices, as well as their interconnections, can be modeled using discrete binary variables. The solution of a mixed-integer nonlinear program gives the optimum flow-sheet structure and design variables for a defined objective. It is essential for this or similar approaches to determine the appropriate superstructure for a large class of process flow sheets. An important aspect of successfully implementing optimization-based process synthesis is the generation of a superstructure that contains all potentially profitable alternatives. Also, optimization problems even for a simple flowsheet are extremely difficult to solve. Significant progress is currently being made in devising new concepts and algorithms to solve increasingly complicated optimization problems. It can however be said that the methods have not yet reached a point where practitioners in the industry can implement them with ease for process synthesis problems. Biegler and Grossmann (2004) in their retrospective article give a very good description of the state-of-art on the mathematical methods for optimization. We expect that the development in optimization algorithms to continue, along with methods that can combine the superstructure generation aspects of heuristics-based tools with the alternatives generation and screening aspects of optimization-based tools (e.g., Daichendt and Grossmann, 1997).

New Areas for Conceptual Design

Process flowsheets for producing low-volume high-value products are usually less complicated than those for bulk chemicals, partly due to their limited mass and energy integration. The physical and chemical characteristics (chemistry, phase behavior, etc.) however are much more complex. Also, batch processes are often preferred over continuous processes due to the requirement of faster time

to market, flexibility of operation, and lower volumes. Many unit operations used are different from bulk commodity manufacturing, e.g., high shear agitators, wet millers, crystallizers, etc. The requirement of product performance over purity, and complexity of the physical and chemical phenomena make the conceptual design task challenging. A few new areas for research to deal with the challenges are outlined in this section.

Crystallization

The final product of organic fine chemical processes is often a crystalline solid or a formulation that includes crystals. Along with the purity of the crystals, their size, size distribution, and shape are additional factors that affect product functionality and quality, process design, and economics. Shapes that are needle- or plate-like are generally less desirable for processing reasons than equant, low aspect ratio crystals. Crystal morphology also influences material properties such as bulk density and mechanical strength that play a major role in storage and handling. It also affects agglomeration and mixing characteristics (important in formulation), as well as their re-dissolution properties. Solid dose pharmaceuticals are an important class of organic chemicals where shape is of vital interest. Remarkable progress has been made recently in developing shape prediction models that account for lattice geometry, intermolecular bonds, interplanar spacing and also the solute–solvent interaction (Winn and Doherty, 2000).

It is well known that crystals grow in a variety of shapes in response to both internal and external factors. Some of these factors can be manipulated (e.g., solvent type, solution temperature and supersaturation, etc.) by crystal engineers to steer crystals towards a target shape or away from undesired shapes. In spite of more than a century of research on crystallization, there is relatively little known on the dynamics of the evolution of crystal shape from a seed to a steady state shape. Gadewar and Doherty (2004) developed a mathematical model to track facets appearing and disappearing during the evolution of crystal shape. The model also gives the crystal shape at steady state that is consistent with the predictions from the commonly used Wulff–Chernov approach (Chernov, 1963). For crystals that have a dominant face, the shape can be tracked by

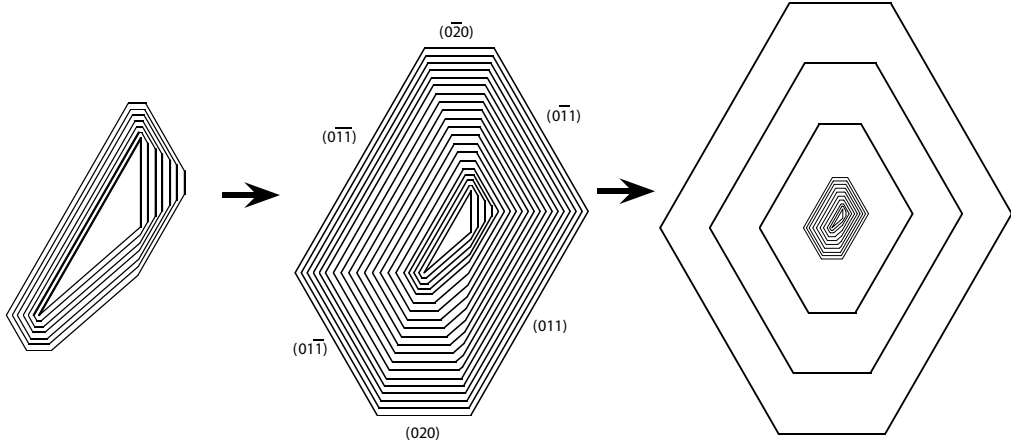


Figure 1: Predicted Shape Evolution of Succinic Acid.

the projection in two-dimensions using the following dynamic equations:

$$\frac{dx_i}{d\xi} = u_i - x_i, \quad i = 1, \dots, N - 1 \quad (4)$$

$$L = L^0 \exp(\xi) \quad (5)$$

where $x_i = \left(\frac{l_i}{L}\right)$ is the relative length of face i to the perimeter, $u_i = \left(\frac{v_i}{V}\right)$ is the relative velocity of face i to the sum of tangential velocities of all faces (for given perpendicular growth rates, u_i has a constant value during crystal growth), $L = \sum_{i=1}^N l_i$ is the perimeter of the crystal at any time, L^0 is the perimeter of the seed crystal (time $t = 0$), and $V = \sum_{i=1}^N v_i$ is the sum of tangential velocities of all faces. Here, ξ represents a dimensionless warped time, and is related to the real time t by $\xi = \ln(1 + Vt/L^0)$. Figure 1 shows the predicted shape evolution for succinic acid grown out of water from a random shaped seed. The shape evolution results in appearance and disappearance of faces, finally settling to a steady state shape resembling a hexagonal plate.

Experimentally measured shape evolution of succinic acid grown out of water is shown in Figure 2. Fig. 2a shows that the seeds are of random shapes. At a time interval of 1 hour, the crystal has evolved to the shape shown in Fig. 2b. After 2:15 hours in the crystallizer, most of the crystals reach steady state shape, however, some of the shapes are still evolving as shown in Fig. 2c. The steady state shape of the crystals was achieved after approximately 3:30 hours as shown in Fig. 2d. Some agglomeration begins to appear at larger time periods in the crystallizer (>3 hours). The experiments were repeated with another set of random seed crystals, and the steady state shape from the new set of experiments is shown in Fig. 2e, which matches with the predicted shape.

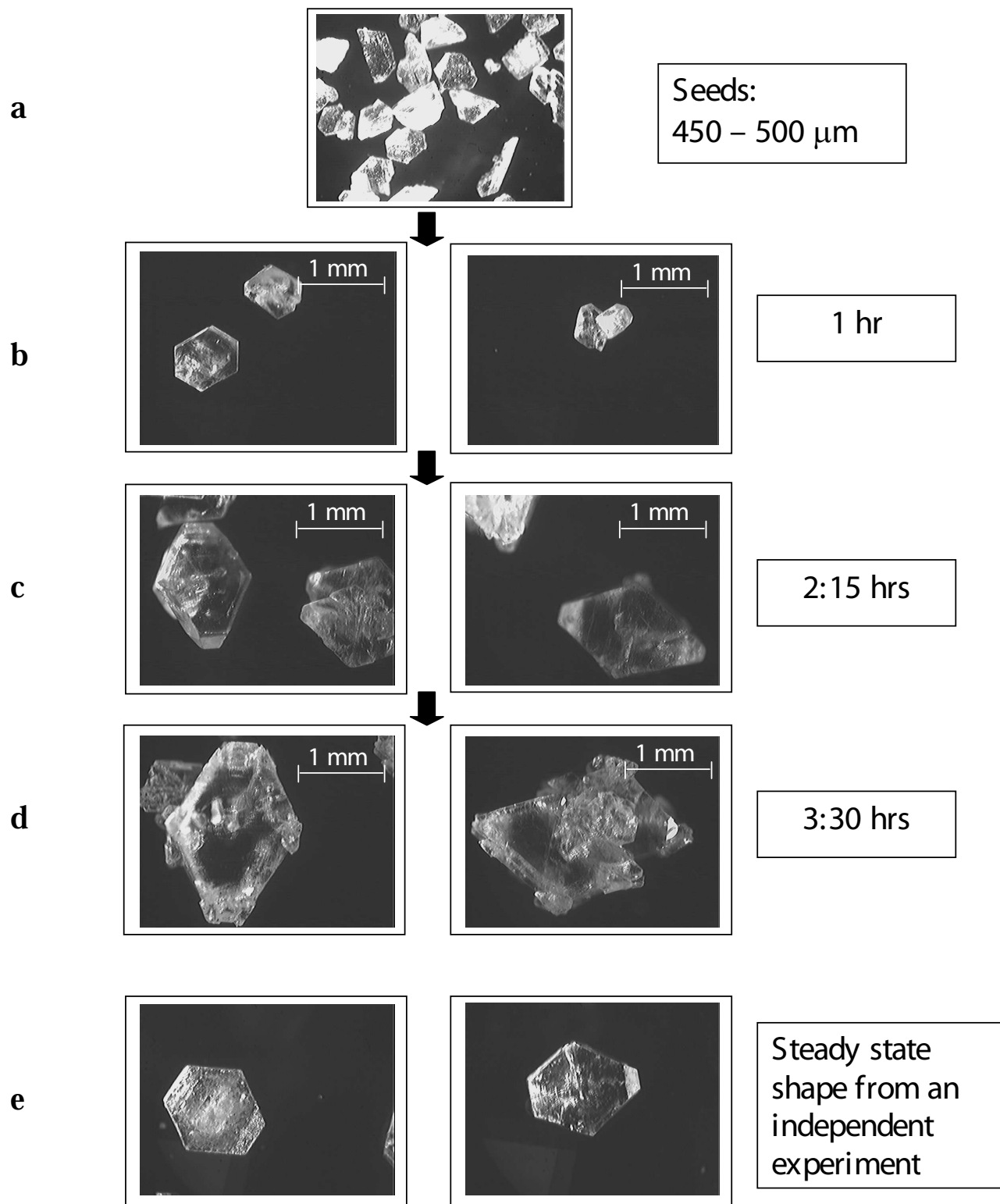


Figure 2: Experimental Shape Evolution of Succinic Acid.

Details on the experimental set-up are given in Gadewar, Hofmann and Doherty (2004). Figure 2 shows that the steady state shape of the crystals is unique and independent of the shape of the seed crystals, as predicted by the theoretical model. The experimentally measured steady state shape is also in excellent agreement with the theoretically predicted shape shown in Figure 1.

Further work in the field of shape prediction can be expected in the area of prediction of simultaneous shape and size distribution, study of polymorphs where the properties and uses depend on the polymorph, and chiral separation of enantiomeric pharmaceutical products. The developments in the predictive methods will also result in the development of better process models for the design of crystallizers.

Property Prediction

Description of the physical properties is an important prerequisite of the conceptual design exercise. An excellent review article on the developments in the thermodynamics of fluid-phase equilibria was recently published by Prausnitz and Tavares (2004). They suggest that among the emerging areas of thermodynamic property prediction, the use of molecular simulations, and quantum mechanics (possibly coupled with the existing models such as UNIFAC) look promising, given that the computation power is expected to rise even as the computation costs are projected to decrease. Development in property prediction methods in the near-supercritical and supercritical regions are required for the design of processes based on supercritical fluids (e.g., use of supercritical carbon dioxide as a solvent for extraction). Computer aided molecular design (CAMD) determines a molecule or molecular structure for a given set of building blocks and set of target properties (Gani et al., 2003). Reliable prediction of the pure component and mixture properties is necessary for the success of CAMD, and will require combination of approaches (both empirical and non-empirical) to describe all the requisite properties. CAMD can be coupled with the conceptual design methods for the generation of alternatives (e.g., solvent selection for extractive distillation).

Gani and Christensen (2003) use a UNIFAC-based approach to determine a solvent for a pesticide formulation. Formulations in the agrochemicals market consist of complex mixtures of surfactants, dispersants, emulsifiers, polymers, buffer agents, antifoams, oil concentrates and inorganic

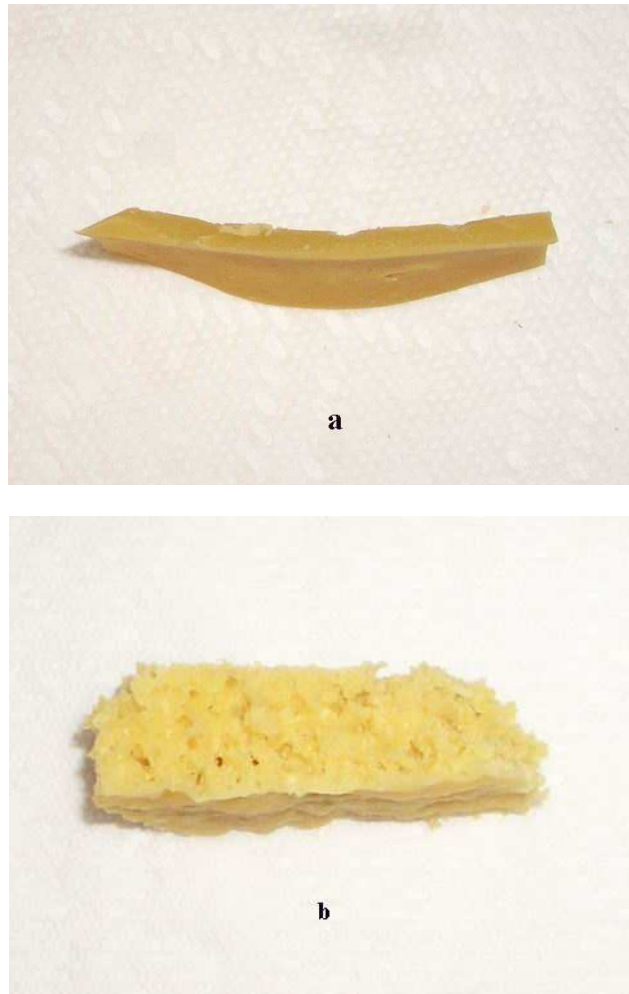


Figure 3: Effect of microstructure on a food product.

salts (Cordiner, 2003). Models to predict the thermodynamic behavior of such electrolytic systems are not available currently, and the development of such models will aid the faster design of new formulations in agrochemicals.

The importance of microstructure in food products became evident by a cooking experiment that went wrong. Dhokla is a popular snack in western India, and is prepared by steaming a batter made of lentil flour. The most important step is the creation of the microstructure when the batter is prepared. Figure 3a shows the side view of a slice when the microstructure during the batter preparation was disturbed by intentionally adding water and stirring after the microstructure was established. The image shows that there are no pores in the slice which causes undercooking, making the taste undesirable. Figure 3b shows the side view of the slice when the microstructure

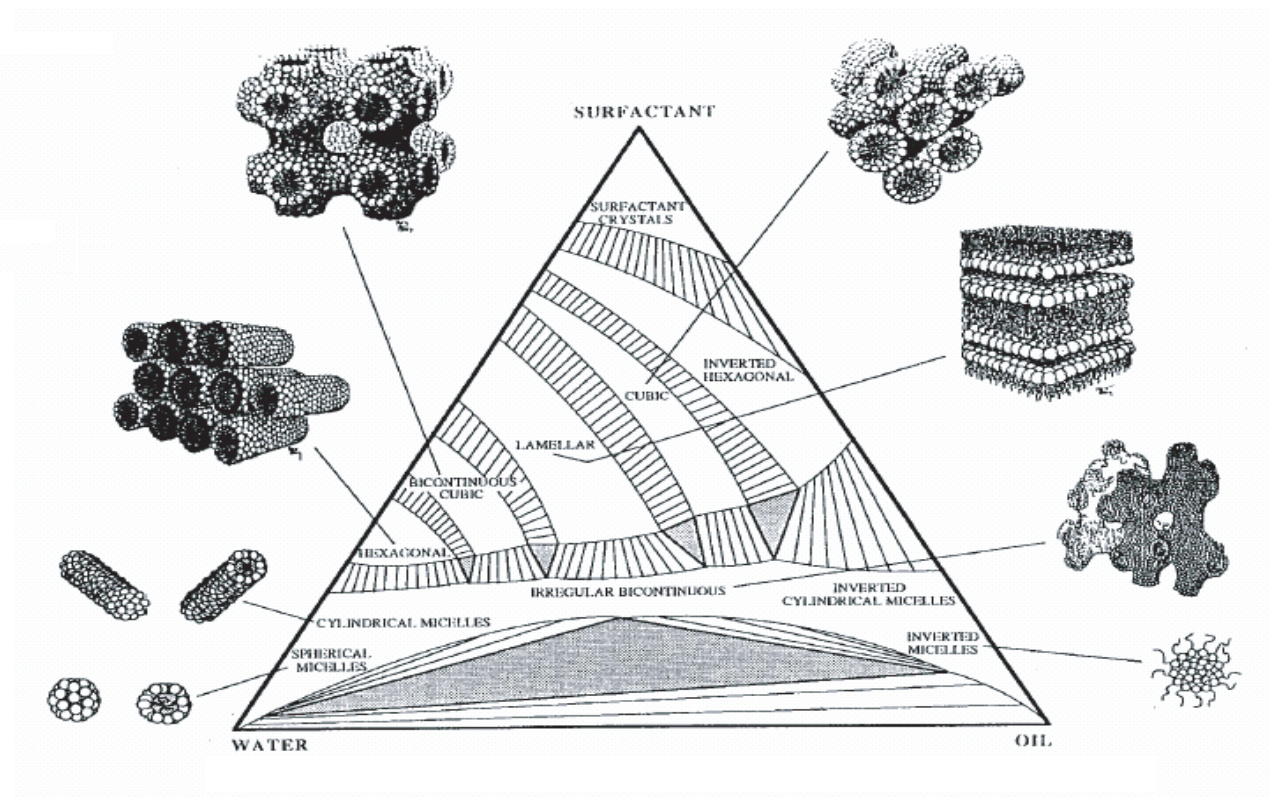


Figure 4: Schematic of oil-water-surfactant phase diagram with corresponding microstructures.

was undisturbed after the batter preparation. The pores in the slice seen in Figure 3b allow better steaming and therefore desirable taste. Many examples exist in the consumer products industry where the quality of a product depends substantially on the microstructure (e.g., ice cream, margarine, soaps, toothpaste, etc.). Thermodynamic models must be capable of describing the phase behavior for such mixtures. A phase diagram for the oil in water emulsion in the presence of a surfactant published by Davis (1991) is reproduced in Figure 4. The figure shows the complexity of describing such systems due to the presence of multiple phases (and topologically different microstructures). Further progress in predictive and experimental methods will allow a more reliable description of the phase behavior, and form a basis for the application of systematic tools for conceptual design.

Product and Process Design

In the past decade, a shift towards products based on performance and properties is seen among the process industries. A part of this shift is accomplished by acquisitions (e.g., acquisition of Shipley Company by Rohm and Haas in the early nineties), while sometimes companies opt for realigning their businesses by selling or spinning-off divisions not aligned with their growth strategy (e.g., Dupont's sale of their textile fibers division to Koch Industries in 2004). Product design can be defined as the generation and implementation of ideas leading to either a new product or an improvement in an existing product. Product design requires multidisciplinary work involving both the business side (market research, business development, etc.) and the research side (chemists, biologists, engineers, etc.). Tools must be developed for systematically designing products in collaboration with other disciplines. A typical product design exercise for structured products follows the following steps (Hill, 2004): 1) Idea generation, 2) Technical target, 3) Identifying active ingredients, 4) Physical prototype, 5) Prototype assessment, 6) Prototype refinement. In the above mentioned steps for product design, there is no room for process design, since the flowsheet is often fixed by the product formulation recipe. This is also true in the process development of pharmaceuticals, where the flowsheet is fixed before the regulatory approval. The question therefore is, what is the scope of conceptual process design in the field of structured products and pharmaceuticals?

Conceptual design can not only help the development of an economically desirable manufacturing process, but also can provide key competitive advantage. Examples where process design plays an important role in faster time to market as well as in new product formulation are described by Pisano (1997) and Hill (2004). A successful conceptual design procedure requires a description of the properties and its relation to the product performance and value. The methodology must also incorporate the relevant chemistry (including reaction chemistry, colloid chemistry, solid state chemistry, etc.), and the decisions should be based on economics (Doherty, 2002). Progress in developing systematic methodologies for conceptual design of processes for structured products has been limited. An approach based on Douglas's hierarchical procedure was published by Meeuse et al. (2000) for the conceptual design of microstructured liquids. Dhingra and Malone (see Dhingra, 2001) used the attainable region theory to a laminar emulsion for determining feasible drop size distributions that are independent of the mixing equipment used. The feasible drop size distributions

provide targets for the mixing equipment configuration and also helps in generating system alternatives. Developments in applying conceptual design methods to structured products will mirror the development in property prediction methods for microstructured products and complex molecules. In our experience, we have found process synthesis methods to be very effective in developing economically attractive process alternatives for the production of complex organic molecules, and microstructured products when it is possible to reliably predict the physical properties and phase behavior. Further progress is expected in using new process models for operations commonly used in manufacturing structured products together with the improved understanding of the thermodynamic and chemical description of microstructured materials for simultaneous product and process design. The progress will have a significant impact on developing better-faster-cheaper processes for new products.

Concluding Remarks

There has been remarkable progress in the methods and tools for conceptual process design in the past three decades. Much of the activity has focussed on the production of bulk commodity chemicals. However, there is increasing interest among the process industries as well as in academia for developing new design methodologies for chemical products that are defined by their properties and performance. A common feature among value-added chemical products is the complexity in the physico-chemical behavior represented by complex chemistries, microstructures and intricate phase behavior. New developments are expected in the process models for unit operations, prediction of property-structure-value relationships, phase behavior, and systematic methods for simultaneous product and process design.

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