The Evolution, Structure and Utility of Separations as an Academic Disciplinary Area

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ABSTRACT

The first great unifying concept of chemical engineering was that of unit operations, put forward by Arthur D. Little and colleagues in the early part of the twentieth century. Many of the unit operations were, in fact, separation processes. With the Manhattan Project, unifying aspects of different methods of separation came to be recognized, and in the decades immediately following World War II were developed and codified so as to create disciplinary underpinnings for separations as a distinct field of knowledge. The history of that transition is traced, and a number of unifying concepts of separations are identified. These concepts enable more efficient and powerful approaches to selection, design, improvement and comparison of separation processes. There are many disciplinary approaches for the pertinent elements of the sciences underlying chemical engineering, but there are few for actual engineering activities. Separations is one such area. Finally, a number of current major separations needs provide vivid examples of why the education of chemical engineers needs to be substantially broadened.

INTRODUCTION

As knowledge has inevitably mushroomed over the years, humankind has sought to organize it and distill general concepts. Organization and generalization make knowledge more powerful and facilitate transmission, understanding and application of knowledge. Codification and development of knowledge on a finer scale have been carried out through disciplines and disciplinary sub-areas. Disciplines have been formed around sets of powerful concepts, generalizations and methods that are applicable to many different situations and which gain both efficiency and strong insights in addressing particular needs and for generating further knowledge.

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College degrees in the 19th century tried to cover all of human knowledge, but as knowledge mushroomed there was a move in the early 20th century to combining general education with a specialized major in a discipline. Post-graduate studies then grew, and the idea of general education was largely abandoned in favor of distribution requirements. In engineering, because of the crowded curriculum and the desire to hold the bachelors as the professional degree, general education was largely abandoned, and specialization became almost entirely dominant. I will have more to say about that in the final section of this paper

FROM UNIT OPERATIONS TO SEPARATION PROCESSES[2]

Although chemical engineering as a field arose in the late 1800s[3], the first major unifying concept was that of unit operations, which was put forward by Arthur D. Little and colleagues in an M. I. T. Visiting Committee report in 1915 in the following words.[4] "Any chemical process, on whatever scale conducted, may be resolved into a coordinate series of what may be termed "Unit Operations", as pulverizing, drying, roasting, crystallizing, filtering, evaporating, electrolyzing, and so on. The number of these basic operations is not large and relatively few of them are involved in any particular process. The complexity of chemical engineering results from the variety of conditions as to temperature, pressure, etc., under which the unit operations must be carried out in different processes …"

Subsequent organizations categorized the unit operations by the phases of matter handled or by whether they dealt with fluid flow, heat transfer, mass transfer or particulate solids. Treybal[5] and Sherwood, et al.[6], focused upon mass transfer and those unit operations involving mass transfer.

Many of the unit operations were, in fact, separation processes, the proportion becoming greater as the field narrowed from all unit operations to those involving mass transfer. Still, the different operations were treated individually in books and courses.

The Manhattan Project of the 1940s, which brought with it the urgent need to separate isotopes so as to produce U-235 and deuterium, provided groundwork for recognition that there are common elements among different separation processes and that there are theoretical underpinnings for separations. The extreme difficulty of these separations led to the development of concepts such as cascade theory, theoretical underpinnings for understanding energy consumption of separations and for gaining energy efficiency, and

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[2] Another paper by the author treats the development of unit operations and the transition from unit operations to separation processes in more detail: C. J. King, "From Unit Operations to Separation Processes", *Separation and Purification Methods*, 29 (2), 233-245 (2000).
[3] N. A. Peppas, "The First Century of Chemical Engineering", *Chem. Heritage*, 26 (3), 26-29 (2008).
[4] G. G. Brown, *et al.*, "Unit Operations", Wiley, New York, 1950.
[5] R. E. Treybal, "Mass Transfer Operations", McGraw-Hill, nNew York, 1955, 1968, 1980.
[6] T. K. Sherwood, R. L. Pigford & C. R. Wilke, "Mass Transfer", McGraw-Hill, New York, 1975.

distinctions among inherently different classes of separation processes.[7] In a book that saw only limited circulation, Pratt[8] built upon concepts from the Manhattan Project work and extended them to some other separations, notably binary distillation.

An indirect spur toward the recognition of common elements among separation processes was the introduction of the transport phenomena concept with the book by Bird, Stewart and Lightfoot in 1960[9]. This landmark work put fluid flow, heat transfer and mass transfer on a powerful and common fundamental basis. Courses on transport phenomena appeared soon thereafter, with the result that unit operations, and the separation processes that were included within then, stood apart.

As a personal aside, starting in 1963 I was working on my own book, "Separation Processes".[10] Initially, it was to be co-authored with Donald Hanson and to build upon his own class notes on distillation and his work on computer calculations for distillation and extraction.[11] Early on, we addressed the question of whether this should be a book on distillation and possibly some other separation processes, or whether it should be a book on separation processes in general. Without much thought at all, perhaps characteristic of the naivety of a new Assistant Professor, I opted for separation processes in general. Shortly thereafter, Hanson withdrew from the project because of administrative duties and the press of time, and so I went ahead on my own. `As I got further and further into the project over the next several years, I recognized that there are many similarities among different separation processes, along with opportunities for classification and for common means of analysis and synthesis for different separation processes. Consequently, I oriented the book more and more toward separations in general and the concepts that unify them.

I endeavored to establish the common features and functions of separation processes, the factors governing separation factors and selectivity, and the rationales for staging and countercurrent, cross-current, co-current, and fixed-bed designs. Following leads from Hengstebeck[12], I pursued general uses of the McCabe-Thiele (y-x) diagram to illustrate patterns of compositional change and avenues toward improvement of separation processes, including multi-component distillation and non-distillative separation processes. I explored and contrasted which features of various separation processes warranted what analytical, graphical and numerical computation methods. I built forward on the aforementioned work of Cohen, Benedict and Pigford, and Pratt, on energy consumption and treated as relatively new subjects the logic of identifying candidate separation processes and selecting among them, choosing sequences for multi-step

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[7] K. Cohen, "The Theory of Isotope Separations", National Nuclear Energy Series, Div. III, Vol. 1B, McGraw-Hill, 1951; M. Benedict & T. H. Pigford, "Nuclear Chemical Engineering", McGraw-Hill, New York, 1957.
[8] H. R. C. Pratt, "Countercurrent Separation Processes", Elsevier, 1967.
[9] R. B. Bird, W. E. Stewart & E. N. Lightfoot, "Transport Phenomena", Wiley, New York, 1960.
[10] C. J. King, "Separation Processes", McGraw-Hill, New York, 1971, 1980.
[11] D. N. Hanson, J. H. Duffin & G. F. Somervillee, "Computation of Multistage Separation Processes", Reinhold, New York, 1962.
[12] R. J. Hengstebeck, "Distillation: Principles and Design Procedures", Reinhold, New York, 1961.

separations, and optimizing designs. For the second edition, I dropped the optimization methods and included a chapter on pertinent mass-transfer concepts.

Subsequently, we have seen additional texts and handbooks on separations and separation processes, Engineering Foundation conferences, a National Research Council study, and, significantly, the formation of a Separations Division within the American Institute of Chemical Engineers (AIChE) in 1990 and the reorganization and renaming of Group II of the AIChE Program Committee from Unit Operations to Separations, corresponding to the division that was formed.

UNIFYING CONCEPTS FOR SEPARATION PROCESSES

Here are some of the important unifying features of separation processes.

1. Separation processes can be divided into those that utilize equilibration and those that are rate-based. Equilibration processes can use either energy or mass separating agents.

2. Chemical and/or structured separating agents can be used in the implementations of various mass-separating-agent and rate-based processes. Selection of appropriate chemical agents can be based upon knowledge of solution, complexation, hydrogen-bonding, and solid-state chemistry. Micro- and nano-structures enabling separation can be implemented as holes, pores, cages, chelates, micellar structures and the like, and can be tuned in through control of structural sizes.

3. One can enhance the fundamental degree of separation through counter-currency and staging, generation of reflux, addition of agents at appropriate points, differential migration, and the integration of separation and chemical reaction, such as in distillative esterification processes.

4. The progress of any countercurrent or staged separation can be analyzed by the McCabe-Thiele y-x diagram, which gives direct insights for design improvements.

5. The energy consumption of a separation process is associated with the quantity of separating agent and its ease of regeneration. Energy consumption can be reduced through appropriate concepts of staging, y-x “pinch” alleviation, secondary additions of agents, cascading, appropriate sequencing, and use of the multi-effect concept.

6. Computational methods for different separation processes have common features with the most effective sequencing of calculations and convergence methods depending on physical characteristics of the process.

7. There is logic for selecting among different methods of separation for a particular application.

8. A general understanding of separations facilitates generating entirely new methods of separations. Examples from the past include the development of azeotropic and extractive distillation by Othmer and associates and the development of field-flow methods of separation Giddings and associates, both of which were based upon extensive intuitive insights.

SEPARATIONS AS AN ENGINEERING DISCIPLINARY AREA

As noted earlier, disciplines and sub-disciplines with powerful, unifying concepts make the organization, transmission and application of knowledge more efficient and effective. Chemical engineering has a number of sub-disciples with those characteristics. Examples are transport phenomena, chemical kinetics, thermodynamics, and allied areas such as physical chemistry and organic chemistry. These other sub-disciplines are all sciences, however. They do not convey the essential engineering aspects of the profession.

On the other hand, separations is a sub-discipline that pertains directly to the engineering aspects of chemical engineering. It relates directly to the identification of candidate separation processes for a given need, selection among candidate processes, designing for efficiency and minimum cost, analysis and improvement of process designs, and trouble-shooting of existing processes – all of which are engineering functions. Chemical engineering education tends to emphasize the underlying science over engineering itself. Well designed courses in separation processes teach engineering.

Our profession needs to seek additional sub-disciplinary structures that teach the engineering aspects of the profession. In that way we can boost the engineering end of the curriculum and better prepare our graduates for undertaking engineering functions.

EDUCATING ENGINEERS FOR NOW AND THE FUTURE

Gaining efficiency in the curriculum through inclusion of courses on separations and identification of additional engineering sub-disciplinary areas will help, but it will not do the full job of preparing engineering graduates for their needs and opportunities and rapid changes in today's and tomorrow's worlds. More and more, engineers deal will complex issues and problems that have vital non-engineering and non-scientific dimensions, often with much public interaction and concern. Engineers in the United States will need to be global citizens with awareness of cultures and customs of other countries. Engineers will be well placed to move into management, government, and other, highly multidimensional functions, *if* they can move beyond the elements of science and engineering themselves.

One can recognize these needs even in the more specific context of separations. Think of what will be needed in terms of policies, politics and public education to implement carbon sequestration for ameliorating global warming. Think the same way of the issues of water supply for the population of both the world and parts of the United States, with more and more needs for reclaiming waste and contaminated waters and creating fresh water from sea water. Think of the growing social issues of alleviating contamination of foods, beverages and products of biotechnology. Couple that with the need for cost-efficient and reliable separations associated with the recovery of biologically produced fuels and chemicals from complex and relatively dilute mixtures. Think of the social and policy aspects of controlling worldwide air pollution from many sources beyond just carbon dioxide emissions.

To meet these needs, achieve these opportunities, and lead the most fulfilling lives, engineers in the United States must have a much broader education than is now the case. I have written elsewhere on this subject[13], as have others[14]. Other professions, such as medicine and law, have recognized the value of building upon a general undergraduate education, rather than actually being that undergraduate education. Engineers deserve a similar structure, with breadth in undergraduate education to include the same general-education and distribution requirements as are typical of a liberal arts or College of Letters and Science, education.

These needs are too great to be squeezed into a bachelors-degree education along with the growing body of scientific and engineering knowledge. Engineers should proceed through to a Masters degree for a sufficient professional education, and the Masters should thereby become the accredited professional degree. Engineers even deserve the opportunity to take an undergraduate major that is something other than engineering, as long as they can incorporate sufficient pre-engineering requirements. The "pre-med" concept has served medical education well over the years. It would do the same for engineering, through a more flexible and general bachelors degree that includes the requirement of certain courses specific to preparation for the graduate engineering degree.

It will be argued that industry readily hires engineers at the bachelors level, and so they do in most cases. But this is a place where the interests of the individual engineer diverge from those of corporations. There are many entry-level jobs for which the current bachelors-level engineering education may be sufficient, but the opportunities for engineers to move ahead and have more, and more fulfilling, options open to them are greatly enhanced by a broader and longer education.

Things are happening along these much-needed lines. The civil engineering profession has recognized needs of this sort by defining a Body of Knowledge needed for the profession and launching a move to the Masters degree as the professional and accredited

[13] C. J. King, "Let Engineers Go to College", *Issues in Science and Technology*, 22, No. 4, 25-28 (2006). http://www.issues.org/22.4/p_king.html.

[14] J. J. Duderstadt, "Engineering for a Changing World", The Millenium Project, University of Michigan, Ann Arbor MI, December 2007. http://milproj.dc.umich.edu/publications/EngFlex_report/

degree[15]. A recent National Academy of Engineering report[16] recommended that "the baccalaureate degree should be recognized as the "preengineering" degree or bachelor of arts in engineering degree, depending on the course content and reflecting the career aspirations of the student" and that "ABET should allow accreditation of engineering programs of the same name at the baccalaureate and graduate levels in the same department to recognize that education through a "professional" master's degree produces an AME, an accredited "master" engineer". After much debate, ABET has now removed their restriction against accreditation at more than one degree level. This is an important step that enables a transition over time to primary accreditation at the Master's level.

[15] http://www.asce.org/professional/educ/

[16] National Acedemy of Engineering, "Educating the Engineer of 2020: Adapting Engineering Education to the New Century", National Academy Press, Washington DC, 2005.