CHEMICAL ENGINEERING EDUCATION

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Summary

Formal chemical engineering education commenced in the late nineteenth century with programs in both the United States and the United Kingdom. Many programs grew out of existing chemistry or mechanical engineering programs. Commencing in the 1920's chemical engineering education focused on the study of unit operations such as separators, reactors and mixers. Following the publication in 1960 of a key textbook education adopted a new paradigm, chemical engineering science. During the 1970's the importance of safety began to be emphasized more in programs while it was not until the 1990's that sustainability and green engineering became more important in undergraduate programs. At the end of the twentieth century the Bologna Declaration saw the first steps in the establishment of a common structure of two degree cycle professional chemical engineering programs within Europe. This article describes the history of chemical engineering education then discusses the critical elements of a

modern undergraduate chemical engineering qualification curriculum. Special attention is given to those subjects that might add breadth and depth to the study of chemical engineering as well as the conduct of the capstone design project normally found in the programs. The important topics of safety, sustainable development and graduate attributes are also discussed. Pedagogical practices in chemical engineering including passive and active learning, collaborative and cooperative learning and problem-led and problem-based learning are discussed. This article concludes with a discussion on professional accreditation of undergraduate chemical engineering programs.

1. Introduction

Chemical engineering is that branch of engineering that processes raw material by physical, chemical or biological means into different products. Today chemical engineers work in a range of industries designing, building and operating processes that transform crude oil into gasoline and plastics, produce a range of specialty products from raw milk and capturing carbon from the smoke stacks of coal-fired power stations.

Chemical engineers need to understand the principles of a range of topics including biological processes, control of processes, fluid flow, heat transfer, mass transfer, material balances, momentum transport, process dynamics, process equipment design, reaction processes, safety, separation processes, solids handling, sustainability and thermodynamics. As well as possessing technical knowledge and skills engineers are problem solvers able to break complex problems into more manageable tasks. Good chemical engineers must be effective communicators, be able to work in teams and have a sound understand of management practices and process economics.

2. History

2.1. Origins of Formal Education

The small scale production of items such as soaps, dyes and glass has occurred for centuries. The coming of the industrial revolution in Europe led to the increased demand for major chemicals such as sulfuric acid, sodium carbonate, sodium hydroxide and bleaching powder. In 1791 Nicholas Leblanc developed a process to produce sodium carbonate from sodium chloride, so winning a prize on offer since 1775 by the French Académie des Sciences. It was in France that the first institutions for technical training and education were established with the founding of the École Polytecnique in 1774. Throughout the nineteenth century the system of Grande Écoles was established within France with several engineers graduating, including Gustav Eiffel, as ingenieur chimiste.

Within the United Kingdom the origins of the chemical engineering profession and chemical engineering education largely arise from the activities of George E. Davis and others in the 1880's. At the age of twenty-eight Davis was appointed to conduct official inspections of chemical plants in order to reduce the amount of gaseous hydrochloric acid released to the atmosphere. As he visited a range of very different sites he observed a pattern of design considerations and operating practices common to most. In 1888 he presented a series of eight lectures at the Manchester Technical School which at the time was proclaimed to be the first chemical engineering lecture series presented in the English language. Later these lectures were collected together into one of the first textbooks in chemical engineering, “A Handbook of Chemical Engineering”. At the same time a course was offered in technical chemistry at the Glasgow and West of Scotland Technical College. Professor Edmund Mills offered a subject that covered topics including gaseous, solid and liquid fuels, refrigerators, evaporators, solids handling equipment and tank design.

It was also in 1888 that the first formal chemical engineering course commenced in the United States. Based in the chemistry department at MIT in Boston the course consisted of existing subjects taken from the mechanical engineering and general chemistry but with the inclusion of a single subject called ‘applied chemistry’. The subject aimed at presenting to its students a discussion of the engineering aspects of the equipment used in manufacturing processes. This was essentially the first course in unit operations although it was not described in that manner at the time. Following on from the success of the MIT program other universities in the USA established chemical engineering programs – University of Pennsylvania in 1892, Tulane University in 1894, University of Michigan in 1898 and Tufts University also in 1898. All these programs grew out of chemistry departments.

In Germany at the close of the nineteenth century an extensive network of technical institutions existed alongside the well-established universities. These technical institutions were both well-funded and very well supported by industry. The chemical industry in particular recruited graduates from the chemistry and industry chemistry programs however chemical engineering programs did not initially evolve in this environment. It was not until much later that separate chemical engineering programs emerged from the well-established mechanical engineering programs.

2.2. The First Paradigm – Unit Operations

In 1908 the recently formed American Institute of Chemical Engineers established a committee on Chemical Engineering Education with the task of determining what a chemical engineer should be educated in. The report of the committee in 1913 was inconclusive and with other pressing demands on the young and very small AIChE the committee did not reconvene until 1920 under the chairmanship of Arthur D. Little. Little had graduated with a degree in chemistry from MIT in 1885 and went on to found the company that came to be known as Arthur D. Little Inc. In a report to the President of MIT prepared in 1915 Little coined the phrase ‘unit operations’, suggesting that chemical engineering education be framed around the different types of unit operations found in industry.

The Chemical Engineering Education Committee chaired by Little conducted a comprehensive survey of the syllabus of the chemical engineering programs offered by 78 institutions. The committee was amazed by the wide range of subjects and topics covered by the diverse programs and found that there was almost no evidence of anything like a standard course in the discipline. The final report in 1922 declared that:

> *‘Chemical engineering … is not a composite of chemistry and*

> *mechanical and civil engineering, but a science of itself, the basis of which is those unit operations which in their proper sequence and co-ordination constitute a chemical process as conducted on the industrial scale'.*

A new Chemical Engineering Education Committee was constituted in 1922 to set out in further detail what topics should be included in an undergraduate program. In 1925 the Committee listed fourteen programs that met its standards and recommended that a permanent committee of the AIChE be established to conduct what were essentially accreditation activities.

With the spread of a more standardized curriculum across schools in the USA demand quickly developed for appropriate textbooks. At that time MIT was at the forefront of curriculum development and one of the most important textbooks of the period came out of that department, "Principles of Chemical Engineering" by William Walker, Warren Lewis and William McAdams and published in 1923. The book was squarely based on a unit operations approach to chemical engineering education. Some of the other important books that followed in the next two decades were:

- Chemical Process Principles in 1930 by Hougen and Watson
- Der Chemie-Ingenieur as 12 volumes from 1932 to 1940 by Eucken of Gottingen
- Perry's Chemical Engineer's Handbook in 1934 by Perry of DuPont
- Chemische Ingenieur-Technik in 1935 by a range of many authors drawn from industry

The number of chemical engineering programs offered around the world grew significantly from 1920 onwards as the process industries boomed. In Canada the first chemical engineering programs were offered at Queen's University (1902) and then at the University of Toronto (1904). In Australia chemical engineering topics had been offered as early as 1915 at the Sydney Technical College but it was not until 1948 that a formal degree course was offered at the University of Sydney. Chemical engineering education commenced in India in 1921 at the Bengal Technical Institute while a year later courses at the University of the Witwatersrand and the University of Cape Town began in South Africa. In the first decades of the twentieth century Japan had a very modest chemical industry and consequently no strong demand for chemical engineers. It was only in 1940 that chemical engineering programs commenced at the Tokyo Institute of Technology and Kyoto University. In the United States and the United Kingdom this period also saw a rapid increase in the number of programs offered. In the US chemical engineering programs spread from initially offerings on the east coast across to the west coast, while in the UK programs opened at Imperial College (1937), University College London (1937), University of Cambridge (1945) and the University of Leeds (1945).

2.3. The Second Paradigm – Chemical Engineering Science

During the 1950's there was a growing realization that there was a need to identify and study the scientific principles underlying the unit operations. Chemical engineering science emerged as a new paradigm in understanding chemical engineering principles. This was a shift from what might be considered the first paradigm of the unit operations approach. By identifying the underlying physical, chemical and/or biological principles of unit operations, proponents of chemical engineering science sought to extend the application of these principles beyond the realm of just unit operations.

Arguably one of the most important chemical engineering textbooks ever published laid the foundations for the chemical engineering science approach to momentum, heat and mass transport. In the late 1950's three academics from the University of Wisconsin, R.Byron Bird, Warren Stewart and Edwin Lightfoot, developed a course that adopted the chemical engineering approach. The book that developed out of that course, "Transport Phenomena" published in 1960, was the first of a number of books to consider the principles that underpin unit operations. The book was so well written that a second edition was not released until 2002, some forty years later.

Throughout the last decades of the twentieth century enrolments in chemical engineering programs increased. At the same time chemical engineering science principles began to be applied in to biological processes. The sub-discipline called variously biochemical, biomolecular or bioprocess engineering began to emerge. During the late 1970's and early 1980's fundamental principles of biology, genetics and microbiology began to appear in chemical engineering curricula worldwide. The increasing incorporation of bio-related topics continues to grow to this day.

2.4. Developments Since 1990

The early 1990's saw the introduction of combined degree programs in Australia. In the Australian model students enrolled into two complete undergraduate degrees simultaneously. At the completion of their five or six year course of studies the students would then have two undergraduate degrees, not a major and a minor degree. The most popular combinations for chemical engineering students were the science disciplines of chemistry, biology, microbiology, genetics and physics, with commerce, economics and law also being popular. By the middle of the first decade of the twenty-first century some Australian chemical engineering programs had two-thirds of their students undertaking some form of combined degrees.

In 1999 government representatives from 28 European countries signed the Bologna Declaration, aimed at creating the European Higher Education Area. Two of the main aims of the process were to establish a common structure for higher education across the region based upon a two degree cycles – Bachelor and Masters – and to promote mobility of students and mutual recognition of degrees between the signatory countries. The Bologna Model for education involves a three-year Bachelor degree followed by a two-year Masters degree with professional recognition based upon the attainment of the Masters degree. In 2005 the European Federation of Chemical Engineering Working Party on Education released non-binding guidelines for the minimum expectations with respect to learning outcomes and transferable skills development for graduates from the three-year Bachelor, two-year Masters programs. The guidelines note that typically a first cycle program should contain 20 to 30 % mathematics and science content, 40 to 50 % engineering courses, and up to 10% non-technical topics. A key element of the first cycle program is a chemical engineering capstone project. The second cycle should contain further chemical engineering studied to a greater depth as well a second, more substantial project.

At the beginning of the twenty-first century there is a growing recognition that chemical engineers will have to play leading roles in addressing some of the crucial issues associated with climate change and sustainable development. Emission reduction technologies such as carbon capture and sequestration, waste minimization and green engineering are all underpinned by sound chemical engineering principles. Undergraduate chemical engineering programs increasingly are making their students aware of sustainable development and their responsibilities to society for these concerns. In some programs sustainable development and aspects of green engineering are available as separate units or subjects while in other programs these important topics are embedded throughout the curriculum.

3. Modern Curriculum Content

The undergraduate chemical engineering curriculum has evolved significantly over the last 120 years. Over the last thirty years there has been a growing emphasis on bioprocesses, safety and the environment. As the proportion of graduates commencing work in the traditional petrochemical industries has declined in favor of the biotechnology sector, the food and beverage, pharmaceutical, minerals processing, and pulp and paper industries so the curriculum in many institutions has refocused to cover unit operations and industry practices in these particular sectors. Some institutions offer programs having a particular focus which is relevant to the local economy and which may be supported by local industries, e.g., coal processing, pulp and paper, minerals processing.

Following its review of chemical engineering curricula in Europe, the European Federation of Chemical Engineering (EFCE) working party released its recommendations for what first and second cycle chemical engineering programs should have as their learning outcomes, i.e, what knowledge students should have and what they should be able to do immediately after graduation.

According to the EFCE after graduation, a first cycle degree chemical engineer should

- Have a knowledge of relevant basic sciences (mathematics, chemistry, molecular biology, physics) to help understand, describe and deal with chemical engineering phenomena
- Understand the basic principles underlying chemical engineering:
    - Material, energy, momentum balances
    - Equilibrium
    - Rate processes (chemical reaction, mass, heat, momentum transfer)
- And be able to use them to set up and to solve (analytically, numerically, graphically) a variety of chemical engineering problems;
- Understand the main concepts of process control;
- Understand the principles underlying methods of process/product measurements;

- Be able to plan, perform, explain and report simple experiments;
- Have a knowledge of relevant literature and data sources;
- Have a basic understanding of health, safety, and environmental issues;
- Understand the concept of sustainability;
- Understand basic concepts of chemical product engineering;
- Have knowledge of some practical applications of process and product engineering;
- Have an ability to analyze complex problems in the chosen orientation;
- Have some experience in using appropriate software;
- Be able to perform appropriate design in the chosen orientation; and,
- Be able to calculate process and project costs.

The EFCE recommends that after graduate second cycle degree chemical engineers should

- Be able to communicate effectively, including in English, using modern presentation tools as appropriate;
- Be able to work in multidisciplinary teams;
- Have an understanding of the impact of engineering solutions in an environmental and societal context;
- Have an understanding of professional end ethical responsibility; and,
- Be able to learn on his/her own, and have a recognition of the need for life-long learning.

These learning outcomes are in general accord with those of a number of national accrediting agencies.

The VCI – Society for Chemistry and Process Engineering of Germany has proposed recommendations for the development of consecutive first and second cycle chemical engineering programs. In their document 'Qualification Frames and Curricula for Degree Courses for Process, Chemical Engineering and Biomolecular or Bioprocess Engineering at Universities and Fachhochschulen (Universities of Applied Sciences)' they outline program outcomes in six broad areas:

- Knowledge and understanding
- Engineering analysis
- Engineering design
- Investigations
- Engineering practice
- General skills.

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Bibliography

Azapagic A., Perdan S., Clift R. (2004) Sustainable Development in Practice – Case Studies for Engineers and Scientists, 446 pp. John Wiley and Sons, Chichester, UK [Textbook containing introduction to concepts of sustainable development and green engineering followed by eleven different well developed case studies].

Barkley E.F., Cross K.P., Major C.H. (2005) Collaborative Learning Techniques – A Handbook for College Faculty, 303 pp. Jossey-Bass, San Francisco, USA [A useful guide book for any educator wishing to adopt collaborative and/or cooperative learning techniques in the classroom].

Bird R.B., Stewart W.E., Lightfoot E.N. (2002) Transport Phenomena, 2nd edition, 894 pp. John Wily and Sons, New York, USA [The first edition of this textbook ushered in the era of Chemical Engineering Science].

Darton R.C., Prince R.G.H., Wood D.G. (2003) Chemical engineering: visions of the world, 129 pp. Elsevier, Amsterdam, The Netherlands [This book includes a comprehensive history of the chemical engineering profession and chemical engineering education].

Felder R.M., Silverman L.K. (1988) Learning and teaching styles in engineering education, *Journal of Engineering Education*, 78(7), 674-681 [Significant paper looking at learning styles in chemical engineering education].

Institution of Chemical Engineers (2008) Accreditation of chemical engineering degrees - a guide for university departments and assessors based on learning outcomes, 75 pp. Institution of Chemical Engineers, Rugby, UK [A useful guide to the chemical engineering accreditation standard currently being used in several countries around the world].

Kentish S.E., Shallcross D.C. (2006). An International comparison of final year design project curricula, *Chemical Engineering Education*, 40(4), 275-280 [This work presents the results of an international survey on the final year capstone chemical engineering design project].

Prince M.J., Felder R.M. (2006). Inductive teaching and learning methods: definitions, comparisons, and research bases, *Journal of Engineering Education*, 95(2), 123-138 [This paper reviews several different teaching styles including problem based learning].

Shallcross D.C., Parkinson M.J. (2006) Teaching ethics to chemical engineers: some class room scenarios, *Education for Chemical Engineers*, 1, 49-54. [This work describes in detail the structured controversy technique and presents three scenarios on professional chemical engineering ethics].

Biographical Sketch

Associate Professor David Shallcross is Head of the Department of Chemical and Biomolecular Engineering at the University of Melbourne. He is also Associate Dean (Teaching and Learning) for the Melbourne School of Engineering. David has won several national and international awards recognizing his excellence and leadership in chemical engineering education including the 2006 Frank Morton Medal of the Institution of Chemical Engineers and a Carrick Citation from the Carrick Institute in Australia. He is the Founding Editor of the international peer-reviewed journal, Education for Chemical Engineers, and is a corresponding member of the European Federation of Chemical Engineering Working Party on

Education. He is an experienced chemical engineering program accreditation assessor for the Institution of Chemical Engineers and is also an assessor trainer. He was recently appointed to the Council of the Institution of Chemical Engineers in which he is the Vice-President – Qualifications. He is the Founding Chair of the Australia-based Education Subject Group for the IChemE and has run several international workshops on aspects of chemical engineering education. He is also the author of the book "Physical Property Data Book", a reference book used by chemical engineering students in many universities.