Chinese Journal of Chemical Engineering 24 (2016) 553–557

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJChE

Perspectives

A paradigm-based evolution of chemical engineering

Alexandru Woinaroschy

Department of Chemical and Biochemical Engineering, Politehnica University Bucharest, Bucharest 011061, Romania

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 23 November 2015
Accepted 10 December 2015
Available online 4 February 2016

Keywords:
Paradigms
Unit operations
Transport phenomena
Product engineering
Sustainable chemical engineering

ABSTRACT

A short presentation of chemical engineering evolution, as guided by its paradigms, is exposed. The first paradigm – *unit operations* – has emerged as a necessity of systematization due to the explosion of chemical industrial applications at the end of 19th century. The birth in the late 1950s of the second paradigm – *transport phenomena* – was the consequence of the need for a deep, scientific knowledge of the phenomena that explain what happens inside of unit operations. In the second part of 20th century, the importance of chemical product properties and qualities has become essentially in the market fights. Accordingly, it was required with additional and even new fundamental approaches, and *product engineering* was recognized as the third paradigm. Nowadays chemical industry, as a huge materials and energy consumer, and with a strong ecological impact, couldn't remain outside of sustainability requirements. The basics of the fourth paradigm – *sustainable chemical engineering* – are now formulated.

1. Introduction

The aim of this paper is to present the evolution of chemical engineering pointed to its general *paradigms*. We will start from the paradigm definition given by The American Heritage Dictionary of the English Language: "Paradigm is a set of assumptions, concepts, values, and practices that constitutes a way of viewing reality for the community that shares them, especially in an intellectual discipline". An overuse of the word paradigm has led to some confusion over the meaning of the term. Villermaux [1] has considered paradigms as: mass, heat, momentum analogies, reaction-transfer coupling, effective media and properties, population balance, residence time distribution, axial dispersion, continuous stirred tank, non-linear dynamics, energy and entropy management, structure of condensed matter, *etc.* Nevertheless, specific techniques for solving various classes of chemical engineering problems are not new paradigms, they fall within the current chemical engineering way of thinking. Related to the overuse and confusion over the meaning of word paradigm, Hill [2] refers the Dilbert comic strip where every engineer says his project is a paradigm, but no one seems to know what that means!

For the evolution of chemical engineering, the definition given by The American Heritage Dictionary of the English Language [3] is useful to be linked with that proposed by Kuhn [4], which defines a scientific paradigm as: "universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of practitioners".

From the ancient times applied chemistry meant an art, a trade for obtaining salt, caustic soda, soap, sulfuric acid, sugar, and glass-things in rudimentary workshops. Traditional recipes have been transferred with minor, empirical improvements gained from observation. This period can be considered as the *empirical stage* of chemical engineering.

The development of the variety and the amounts of the chemical products, mainly in the last quarter of the 19th century, imposed a new stage, respectively the *rational stage* of chemical engineering. The empirical rules and practices were abandoned for rational scientific methods. The transition to this stage is especially owing to the great progresses of physical chemistry. In 1885 prof. H.E. Amstrong has taught at Central College of London the first chemical engineering course. In this course fundamental scientific training was combined with technical practice for the design of chemical industry equipment. It may be considered that at this moment the rational stage of chemical engineering begins.

In 1887 prof. Geoge Davies from Manchester Technical College has taught a lot of chemical engineering lessons. These lessons were the roots of his further Handbook of Chemical Engineering published in 1901 and next in a second edition consisting in two volumes in 1904. The practical value of Davies lessons from this book consists in the variety and abundance of the technical end economical data. Due to the lack of scientific explanations, in fact this book belongs to empirical stage and is a document of what meant chemical engineering at that stage [5].

2. The first paradigm: unit operations

The Davies' book contained a novelty, which subsequently it appears to be more important as it incipiently looked: instead to describe each technological process existent at that time, Davies regards an industrial chemical process to be composed by distinct sections which are present – in different sequences and conditions – in many other processes. As this Davies' priority was not explicitly

E-mail address: a_woinaroschy@chim.upb.ro.

http://dx.doi.org/10.1016/j.cjche.2016.01.019
1004-9541/

announced, it was assigned to Arthur D. Little, which in a report to Massachusetts Institute of Technology has introduced the notion of *unit operations*. Much more lately, in 1958, Davies' priority about the concept of unit operations has been recognized [5]. This concept and its application can be assumed to be the first paradigm of chemical engineering, namely *the unit operations paradigm*. Therefore, the explosion of chemical industrial applications at the end of 19th century and at the beginning of the 20th century imposed the requirements of the process details knowledge systematization. It can be considered that the first paradigm has appeared as a necessity of systematization. The representative book of this paradigm is "Principles of chemical engineering", written by Walker *et al.* [6].

The tens of thousands of industrial chemical processes can't be individually treated to the detailed scale as imposed by design and operation of the corresponding plants. Nonetheless, these processes are made from a much smaller number (about 80) of unit operations. Based on unit operation paradigm, an enormous amount of information concerning both theoretical and experimental studies, as well as results about unit operations is systematized, in a huge literature (books, papers, and patents).

For each unit operation, the following are investigated: (1) the fundamental theoretical principles needed by the formulation of phenomena equations; (2) the laboratory and pilot experimental methods needed by the equations which cannot be theoretically formulated; and (3) the ways to equipment scale-up from laboratory or pilot scale to industrial scale.

To achieve the results imposed by process research, design, and operation the unit operation paradigm use the following general theoretical principles: (1) momentum, energy and mass balances; (2) thermodynamic phase equilibrium relations; (3) momentum, energy and mass physical kinetic relations (transfer equations); and (4) financial conditions and the corresponding equations. In this way, if the material physical properties are defined, as well as technological and economic constraints, it is possible to obtain a quantitative solution for each specific industrial chemical process. It may be said that if the chemist is thinking in chemical reactions, the chemical engineer is thinking in unit operations. Subsequently, the paradigm of unit operations was adopted by other process industries, such as food industry or light industry.

3. The second paradigm: transport phenomena

While still useful to the present day, the unit operation paradigm proved inadequate for solving some important classes of problems [2]. This awareness led to the emergence of chemical engineering science as a second paradigm in the late 1950s, as best exemplified by the Birds' textbook Transport Phenomena [7]. This is the *transport phenomena paradigm*, an upper systematization and synthesis evolution. At the moment of issue of this book, the field of transport phenomena has not been yet recognized as a distinct engineering subject. The authors have considered that it is important to put more emphasis on understanding basic physical principles, than on the blind use of empiricism. Their thought has been that the subject of transport phenomena should rank along thermodynamics, mechanics, and electromagnetism as one of the key "engineering sciences". The paradigm of transport phenomena approaches the three elementary physical processes, which take place in any kind of unit operation: momentum, energy, and mass transport. Thus, unit operations can be considered as specific applications of these three fundamental processes. As combinations of unit operations give technologies, combinations of transport processes give unit operations.

The paradigm of transport processes presses for the mechanisms of these processes, on the phenomena, which take place close to the border of two physical phases; the aim of the paradigm consists in the deep understanding of the elementary causes and effects which explain the features and applications of each unit operation. The transport phenomena paradigm extends the content of chemical engineering to a fundamental, theoretical science, closely linked with physics, mathematics, mechanics, thermodynamics, electromagnetism *etc.* The birth of the second paradigm was, therefore, the consequence of the need for a deep, scientific knowledge of the phenomena which explain what happened inside of unit operations.

Engineering, in the last analysis, depends heavily on heuristics to supplement incomplete knowledge. Transport phenomena can, however, prove immensely helpful by providing useful approximations, starting with order of magnitude estimates, and going on to successively more accurate approximations, such as those provided by boundary layer theory [8].

At last, it appears the trend to gather all the three transport phenomena in a single concept, respectively the property transport [9]. This very high systematization is justified by the analogy of the transport phenomena, respectively the structural similitude of differential equations and boundary conditions which describe them. In this treatment, each fundamental transport process becomes a specific case.

4. The third paradigm: chemical product engineering

In the second part of 20th century the diversity of industrial products (in many cases with close properties and with the same utilization) has a huge growth, and correspondingly, very strong market fights have evolved between producer companies. The same things happened with chemical products. The importance of properties and qualities of chemical products has become essential. Until recently, the main purpose of chemical engineering has been to obtain the lowest cost process. Even process related issues like reliability, product purity, pollution control, *etc.* have been ultimately translated into costs that must be minimized. In contrast, chemical product design tries to obtain the most added values for a product through enhanced product properties. This is a more complex task than a mathematical treatment to maximize profit. The profit depends in some unidentified way upon the complex set of product properties. Therefore, product engineering problems can't be solved by traditional chemical engineering approaches. Their solution requires not just additional chemical engineering approaches, but even more fundamentally, and that is why *product engineering* should be recognized as a *third paradigm* of chemical engineering, as first hinted in 1988 [10]. Hill [2] substantiated the product engineering as a new paradigm, respectively the third paradigm of chemical engineering. Hill has considered that, "while the design of a chemical product and its manufacturing process is analogous, some critical differences are so fundamental that a new paradigm and new approaches are needed to successfully solve product design problems".

It can be assumed that the third paradigm was imposed by the fight for technical and economical product performances generated by a strong competitive market environment. Nowadays, it is far more important what and how much is sold, than what and how much is produced.

New chemical products have been created by combining a wide knowledge of existing chemical products with a big amount of scientific experimentation. A combinational explosion of product options will limit all experimental techniques. Therefore, it is desirable to minimize experimentation through a systematic consideration of product formulation prior to experimentation. Product engineering techniques is largely based on heuristics when data are limited, followed by detailed calculations when data become available, this being the essence of the third paradigm. The basics of the third paradigm have been stated in the book of Cussler and Moggridge (1st ed. [11] and 2nd ed. [12]). The general steps of product engineering propose by Cussler and Moggridge [12], followed by the general stages of process engineering are presented in Fig. 1, where we put into evidence the distinction between the steps of product and those of process engineering. We consider that this distinction may be useful for a better discrimination between the terms "product" and "process" engineering, very frequently used nowadays in chemical engineering literature.

Cussler and Moggridge [12], have proposed a generic framework for chemical product design, based on a 4-step algorithm: the first three