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Dedicated to the memory of
Academician Dr. Eng. Emilian BRATU (1904–1991)

THE PARADIGMS OF CHEMICAL ENGINEERING

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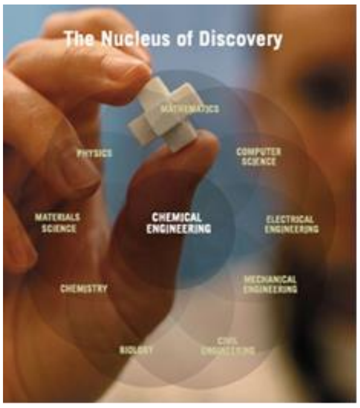
For the evolution of chemical engineering is useful the definition proposed by Kuhn, which defines a scientific paradigm as: "universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of practitioners" (Kuhn, 1996).[11] From the ancient times applied chemistry meant an art, a trade for obtaining salt, caustic soda, soap, sulfuric acid, sugar, 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 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.
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 Bratu.[1]



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 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 later, in 1958, Davies' priority about the concept of unit operations has been recognized Bratu.[1] This concept and its application can be assumed to be the first paradigm

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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.*[2]

The tens thousands 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 operations 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, patents).

For each unit operation there are investigated:

– the fundamental theoretical principles needed by the formulation of phenomena equations;

– the laboratory and pilot experimental methods needed by the equations which can not be theoretically formulated;

– 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:

– momentum, energy and mass balances;

– thermodynamic phase equilibrium relations;

– momentum, energy and mass physical kinetic relations (transfer equations);

– financial conditions and the corresponding equations.

In this way, if the materials 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.

THE SECOND PARADIGM: TRANSPORT PHENOMENA

While still useful to the present day, the unit operations paradigm proved inadequate for solving some important classes of problems Hill.[3] 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 Bird *et al.*[4]

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 press 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 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 Bird *et al.*[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 producers companies. The same things happened with chemical products. The importance of properties and qualities of chemical products have become essentially. 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 try to obtain the most added value 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 Committee on Chemical Engineering Frontiers[5]. It can be assumed that the third paradigm was imposed by the fight for technical and economical products performances generated by a strong competitive market environment.

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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 were stated in the book of Cussler and Moggridge.[6,7] (1st ed., 2001 and 2nd ed., 2011). Here they have proposed a generic framework for chemical product design, based on a 4-step algorithm: (1) identify customer needs, (2) generate ideas to meet those needs, (3) select among the ideas, and (4) manufacture the product. The step four of chemical product design contains all the following four steps of chemical process design: (1) batch vs. continuous process, (2) inputs and outputs, (3) reactor and recycles, and (4) separations and process integration. The authors admit that this four step algorithm is a major simplification that affects effectiveness in specific cases. But, this procedure can be an excellent starting point, very useful to expand each specific case.

Related to the controversy of the key to product design, management or technology, Cussler and Moggridge consider that the application of technology is central to chemical product design. Due to major changes in the chemical industry the product design role and merits are continuously increasing, but this is not an argument that process design should disappear. Product design and process design must be used together, in agreement with these changes in the chemical industry.

THE FOURTH PARADIGM: SUSTAINABLE CHEMICAL ENGINEERING

Nowadays the concept of sustainability is imposed in al human activities fields, especially in industrial domains. Chemical industry, as a huge materials and energy consumer, and with a strong ecological impact, could not remain outside of sustainability requirements. The basics of the fourth paradigm – sustainable chemical engineering – are now formulated. This new paradigm is set on the recognition of limitation of resources, the requirement for inter and transgenerational equity within human society and the need for preservation of life supporting natural systems Narodoslawskty.[8] The contemporary discussion around the concept of sustainability started with Brundtland report – World Commission on Environment and Development[9]. In this report, sustainability or sustainable development is defined as "the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs". This report clearly frames the challenge of sustainability: it requires human society to live within the limitation of our planet in a way that allows infinite development in temporal terms. Sustainability becomes more and more important in the modern economy, and in 1999 the Dow Jones Sustainability Indices were started. Corporate sustainability is considered a business approach that creates long-term shareholder value by embracing opportunities and managing risks deriving from economic, environmental, and social development. Nowadays, these three dimensions constitute sustainability and are considered the three pillars carrying this concept. All these three parts are equally important in sustainable development. They are not independent of each others; on the contrary, there is manifold interaction between them. For the economic assessment there are already a number of books, especially in the chemical engineering field, that cover cost and profitability subjects in detail. There are published many methods for environmental assessment. Chemical engineering, with its strong systemic orientation and its function to link natural sciences, engineering and industrial practice, is in "pole position" among many other engineering sectors to meet the challenges of sustainable development. It is a key engineering discipline for adapting human society towards sustainability Narodoslawskty.[8]

A main task of chemical engineering during its entire evolution was to reduce material and energy consumption. Chemical engineering is placed on the first positions among other engineering sectors related to these consumptions. Before sustainability era, reducing of material and energy consumption was imposed by economical reasons (increasing profitability, decreasing products cost). Environmental assessment modifies drastically the material and energy consumption, now these amounts are not the unique objective. The main feature consists in the change of material and energy resources base both in order to preserve the frequently used resources, but also to involve new sources, especially environmentally friendly ones. Related to the use of new raw materials an example in this direction is the book Bioprocessing for Value-Added Products from Renewable Resources.[10] Related to energy resources the limitation of fossil resources adds to the pressure on society to look for other sources. A particular challenge for chemical engineering is providing energy storage in a sustainable way. Renewable sources for energy and material will become more important and will require a massive re-structuring of industrial processes Narodoslawskty.[8]

CONCLUSIONS

Related to the paradigms role in the evolution of chemical engineering, it is relevant the Kuhn conception Kuhn,[11] respectively that even when paradigms are known to be inadequate, their inadequacies are frequently minimized, or even ignored by the scientific community. Nevertheless, if and when a paradigm reaches a crisis where its technical inadequacies are brought into focus, perhaps driven by social requirements, a new paradigm will arise to explain what the prior paradigm could not. During the evolution of chemical engineering each new paradigm was a step forward which has extended the manifold of the tasks that can be solved. However, no older paradigm is derelict. In fact, almost all paradigms must be used together in order to solve the complex chemical engineering problems.

Of course, the discussion about paradigms of chemical engineering cannot avoid the subjectivity. Some personal ideas of the author and the references selection are, doubtlessly, questionable. There are hundreds works that deal with the fundamentals of chemical engineering, with its past, present, and future. Here, we have tried, very briefly, to emphasize the importance of the basic paradigms in chemical engineering evolution.

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