Theoretical Foundations of Chemical Engineering, Vol. 38, No. 2, 2004, pp. 105–111.
Translated from Teoreticheskie Osnovy Khimicheskoi Tekhnologii, Vol. 38, No. 2, 2004, pp. 115–122.

The State of the Art in Chemical Engineering Science and Education

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Received October 20, 2003

Abstract—Chemical engineering education, research, and production are considered as intimately interrelated activities. The current status of the Russian chemical industry is characterized in brief. The tendencies of the development of chemical technology and problems of chemical engineering education are discussed.

In the new context that the chemical industry is facing in the 21st century, some parts of the chemical and petrochemical industries need a new development strategy based on scientific knowledge and high technologies. The current technologies need radical, not superficial, improvements, including a drastic reduction in production cost and a substantial increase in labor productivity. The modern engineering education of chemical engineers must answer these purposes. Much in the chemical industry depends on the skill of the chemical engineer. All the most significant achievements of the 20th century came in our life owing to engineers' creative research and development activity. This specific feature of the development of the chemical industry will persist in the 21st century. Therefore, the 21st century's engineering education should be versatile, combining traditions and novelties.

Unit operations and processes of chemical engineering are part and parcel of many industries. The level of chemical engineering education, progress in chemical technology, and the intellectual level of engineers are important factors in not only the competitive level of production, the standard of living, and the defensive potential of the country but also the status of the country in the world community.

However, modern chemical industry is suffering from the low pace of development of the core subjects of chemical engineering, such as unit operations and chemical reaction engineering.

Probably, only few do not know of the recent changes in some branches of the world chemical industry. There are a lot of publications that explain why these changes have taken place and how chemical engineering should be reoriented to meet the modern trends. Much less attention has been given to the ill effect such reorientation would produce on the core subjects of chemical engineering.

Over the last two decades, researchers have been losing interest in the core subjects of chemical engineering such as unit operations and chemical reaction engineering. At the same time, the range of the topics being researched in chemical engineering research laboratories and university departments is so wide that there is a danger that the core of the subject is being neglected and chemical engineering research will "dissolve" in a variety of applications. Research in chemical engineering may eventually come down to what is more accurately may be labeled as research in applied science.

These circumstances are influencing chemical engineering education. It is often stated that carrying out research at universities is necessary to enliven teaching the students, to update lectures, and to make them more useful. From this standpoint, if the higher school conducted no research in conventional fields of unit operations and chemical reaction engineering, teaching these subjects would be outdated and useless. Therefore, keeping up and strengthening its foundations would invigorate chemical engineering science and the core of the profession.

These are necessary conditions for the development of chemical engineering as an extraordinarily wide area of knowledge. Chemical engineering provides a deep insight in the phenomena and processes in the manufacture of chemical products, which are necessary to meet man's needs for food, clothes, and construction; to protect health; to develop the power industry and information technologies; to create new materials; to protect the environment; and to ensure national security and independence.

CURRENT STATUS OF THE RUSSIAN CHEMICAL INDUSTRY

The chemical industry is steadily developing throughout the world. The range of its products is being constantly widened and renewed. Special attention is being focused on upgrading products; creating new

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materials with desired properties; and developing high-tech branches for producing goods for electronic and medicinal applications, high-quality plastics, and bio-products. However, there are obstacles to the advancement of the chemical industry, among them the growing costs of raw materials and power, inevitable expenditures for waste treatment, increasing expenditures for large-scale research and development (which are necessary to ensure high technical and economic performance of new plants), and rising construction and equipment costs.

In 1960–1985, the USSR chemical industry developed more rapidly than the USSR industry as a whole; in the 1980s, it ranked second in the world and lead the world in some products, e.g., fertilizers. In the years of reforms (1991–1998), the annual output of the Russian chemical industry dropped by 52%. This value far exceeds the 22% drop in production during the Great Patriotic War (1941–1945). Applied science, which formerly provided an efficient link between academic research and industrial practice, is now ruined. Lost are many scientific schools and skilled brainpower in chemical engineering, chemical machine building, and process automation and control.

In the last decade, the Russian chemical industry was in severe crisis, like the Russian economy as a whole. Its output in 1998 was lower than that in 1990 by a factor of 2.2. However, since 1999, there have been good changes in the chemical industry: the output has grown, its composition has qualitatively changed, and a better use has been made of the production facilities. Since 2000, the output growth rates of the chemical and petrochemical industries have been higher than the industry-wide average. There has been a growth in the production facilities of the Russian chemical industry in the last two years, but there has not been any considerable reequipment as yet.

Today, Russia is falling behind the United States, Japan, and many western European countries in the competitive ability of chemical products (whose range is remarkably wide) and in the implementation of novel technologies because of the high wear and tear of the equipment, the low proportion of small-scale production, the large number of obsolete processes, and the absence of social order.

The level of development of all branches of the chemical industry is an extraordinarily important factor in building a competitive economy, which is our main strategic task. Indeed, in all developed countries, the chemical industry accounts for 12–14% of the total industrial output. This percentage is fairly large.

Scientific and technological renovation of the Russian industry, which is going to take place in the near future, will require that the series of actions serving this purpose be focused on the development of the chemical engineering science.

TRENDS IN CHEMICAL ENGINEERING

The materialization of a new scientific result or invention into marketable goods or services depends on whether there are appropriate new technologies and corresponding market demand and social needs. Note that the formation of an up-to-date chemical industry is being increasingly determined by social needs, which are among the main development factors.

Social needs would be expected to have a much more differentiated and strong effect on the chemical industry in the next 30–50 years. This factor has altered the objectives and problems of chemical engineering. For example, 20–25 years ago, waste disposal facilities were viewed as mandatory elements of the plant design that would raise product cost. Now environmental safety and economy are not considered to be opposing factors. They may overlap and even strengthen each other. The marketability of a product is increasingly dependent on the environmental appropriateness of the product, which determines demand for this product. So, the value system is changing.

The work to be done by a chemical engineer depends on the size scale he deals with. The present-day development of chemical engineering is remarkable for radical changes in the research methods and objects, which are now characterized by an exceptionally wide range of size scales.

The objects of chemical engineering science are various open nonideal systems. They have a complex, multilevel structure, and their size scales range from the atomic–molecular (nanometer) scale to the megameter scale, which is the case when the chemical-engineering system is not confined within the plant and is considered as interacting with the environment and the market. The conjugate time scale of the processes occurring in the system ranges accordingly from 10^{-13} to 10^{8} s.

Over the last decades, decomposition of a unit process has been limited by processes on a catalyst grain, drop, gas bubble, or their ensembles. A specific feature of unit processes in the 21st century is that their size scale is radically shifted to the molecular (nanometer) level.

Consider colloid systems as an example. Nanometer-sized systems have found new technical applications. By progressively reducing the particle size, we can obtain a situation in which quantum effects influence the physical properties of the system. In the design of artificial photosynthesis, which is a novel sensor technology, in data processing, and, particularly, in catalytic processes, nanometer-sized colloid systems stabilized in solids, polymers, or glass can bring us to a new level of technological development.

Another example is the self-organization of molecules into supramolecular aggregates. Earlier, chemistry and chemical engineering science dealt mostly with ionic and covalent interactions resulting in intramolecular bonds. By contrast, supramolecular assemblies are brought about by weak intermolecular forces (hydrogen and van der Waals bonding). They arise from natural interactions, for example, in liquid crystals. Molecular systems with peculiar structures have made possible development of semipermeable membranes for mixture separation, membrane reactors, and organic conducting materials.

Another example is provided by molecular electronics. We are living in the age of informatics and information technologies. Further development of informatics would require a new technological paradigm. Such a paradigm is expected to be soon provided by molecular electronics, which is application of molecules and molecular materials to data generation, reception, and processing. Molecules capable of doing this are conventionally called intelligent or smart. Their fundamental property is bistability, which is the ability to exist in two states and to undergo reversible transitions between these states induced by light, magnetic or electric fields, temperature changes, or chemicals. A single molecule can be a rectifier, switch, or nanoconductor. Such molecular elements are used to synthesize processors.

In microelectronic and nanoelectronic technologies, heterogeneous interfacial processes are carried out in production of thin-film coatings, doping of semiconductors, and growth of single-crystal epilayers. The principal process of microelectronic and nanoelectronic technologies is high-temperature silicon oxidation, which is widely used in the production of high-performance dielectric–semiconductor systems. The success that has been achieved in producing high-performance $Si–SiO_2$ systems is due to kinetic and physical modeling of the oxidation of semiconductor silicon.

Over the last years, there has been rapid progress in nanotechnology as a part of chemical technology. The main objects of nanotechnology are separate atoms and molecules. At the molecular level, the boundary between chemistry and chemical engineering is indistinct and the main difference is in objectives and the methods to achieve them rather than in the object of research. Here, technology means commercialization of the laboratory-scale synthesis of molecules with desired properties and chemical assemblage of the end product.

Increasingly, the chemical engineering science turn to a new model of development and to a new chemical engineering paradigm based on the laws of elementary processes at the molecular level.

Above, we have provided examples of new, advancing areas of chemical technology. At the same time, marked changes are also observed in the following conventional applications of chemical technology: medical industry, agriculture, production of new materials, energy conservation, chemical processing, and caring for the planet (by which we mean protecting the water resources and atmosphere, employing renewable raw materials and energy sources, and conserving culture antiquities).

The near- and long-term prospects of chemical technology will obviously be determined by progress in the studies in the field of chemical and biochemical synthesis, including investigation of the nature of chemical and biological activity and getting a deeper insight in heterogeneous and homogeneous catalysis. These fields, as well as the separation of chemical mixtures are often mentioned in European scientific publications as key technologies for the sustainable development of society.

Biotechnology. There comes a time when biotechnology plays a significant role in the chemical industry. Microbiological processes are enzymatic reactions occurring in a multiphase, heterogeneous, multicomponent system. These reactions are catalyzed by highly selective enzymes whose activity is variable and can be controlled.

The basic and peculiar step of the microbiological synthesis technology is cultivating a microorganism followed by collecting either the population biomass or the metabolism products of the population. This step involves biological, chemical, mass-transfer, thermal, and hydrodynamic processes. Catalytic processes are very similar to microbiological synthesis. The structure of the mathematical model of a fermenter includes six hierarchical levels: molecule, microorganism cell, microorganism population, element of the fermenter (macroregion), fermenter as a whole, and fermentation plant including product purification and separation units. The first three levels are similar to their counterparts in the kinetic model of catalytic reactors. Likewise, the processes occurring on the last three levels, namely, hydrodynamic, mass-transfer, diffusion, thermal, chemical (biochemical), and biological (microbiological) processes, are similar to those in catalytic reactors. Therefore, in mathematical modeling of bioreactors, one can safely draw on the totality of experience accumulated in the mathematical modeling of catalytic reactions, processes, and reactors.

One of the problems is to find a way of controlling the enzymatic catalytic process. This problem cannot be solved without knowing the laws of the processes occurring at the microlevel. The future of biotechnology depends on the understanding of elementary processes (i.e., biocatalytic act). In many cases, the rate of the overall process is limited by mass transfer owing to the high activity of the biocatalyst. These processes in biotechnological media are poorly studied. Many of these media are non-Newtonian liquids. Of great significance are heat transfer processes, which should be designed so as to obviate the formation of hot zones, which would reduce the activity of the biocatalyst.

Catalysis. Under the assumption that chemistry is focused on the synthesis of all possible kinds of new molecules with various sizes and properties, effective and selective catalysis should be considered one of the most important synthetic means. The practical purposes of catalysis are to control the reaction, attain the maximum yield of the desired product, minimize or obviate the formation of by-products, and decrease the process temperature or pressure in order to reduce power consumption and minimize environmental impact. Catalysis is finding remarkably diversified applications.

Catalytic processes and catalysts are the backbone of the chemical, petrochemical, and petroleum-refining industries. About 75% of the products of these industries are obtained using catalysts. Over 90% of the modern chemical processes are catalytic. The state of affairs and trends in industrial catalysis determine the technological and economical level of the industry. Increasing the selectivity and activity of industrial catalysts is equivalent to raising the capacity of the existing plants without making capital investments. Suppressing the formation of by-products means improving the quality of the end product. An important point is that catalysis does not require any extra energy; moreover, it often cuts down on power consumption.

Although catalysis has long been widely used in industry, its potential has not been utilized to the full extent. There are a lot of thermodynamically feasible processes that have not yet been implemented because of the absence of an appropriate catalyst, although they would be welcomed by the industry and would be very profitable. This is especially true for obtaining valuable products from natural gas. Developing and improving catalytic processes demand a fundamental understanding of the mechanism of the reaction steps from the chemical engineer. Industrial catalysis is an interdisciplinary subject that requires the fusion of fundamental and applied sciences. This is why most of the discoveries and inventions in industrial catalysis and catalytic technology have been made by industrial laboratories of companies and by specialized research institutes of the chemical industry.

At the moment, industrial catalysis is being very much challenged by petroleum refining. The most pressing problems in this area are to increase the proportion of secondary processes, raise petroleum conversion, produce antiknock unleaded gasoline, develop hydrofining technologies for straight-run fractions in catalytic cracking, and improve the catalytic reforming and hydrogen cracking processes. Of particular importance is neutralizing the exhaust of internal-combustion engines. Researchers and chemical engineers are taking increasing interest in catalytic polymerization and catalytic synthesis of materials with a desired set of physicochemical properties.

Separation processes. For implementation of a chemical process, it is necessary to deliver the reactants to the reaction zone and draw off and separate the products. Therefore, both today and in the future, much attention is to be given to heat- and mass-transfer processes, their mechanisms, ways of enhancing these processes, and methods of design of high-performance apparatuses.

Separations, including enrichment, concentration, purification and isolation, are the key processes in the process industries and in some branches of the pharmaceutical, food, and microbiological industries. In many cases, separation efficiency determines materials and power consumption in the overall process. A well-designed separation unit often makes the process environmentally quite appropriate and competitive.

Separation processes are characterized by high power and materials consumption. In developed countries, the power annually consumed by separation processes is estimated at about 6% of the total industrial power consumption. In the United States, distillation, evaporation, and drying account for as much as 15.5% of the total power consumed by the process industries.

A reduction in power and resource consumption in separation could be achieved through optimizing the existing processes or designing new, less energy-intensive processes. Note that, as a rule, the separation system should be designed with due regard for the operation of the reactor unit. The best process designs couple chemical reaction and separation in one apparatus.

By way of example, let us consider production of methyl acetate, which is used in large amounts as an intermediate in the manufacture of a number of polyesters, e.g., cellulose acetate, plastics based on cellulose derivatives, the acetate base of textile fiber, etc.

High-purity methyl acetate is obtained by acetic acid–methanol esterification. This reaction is difficult to carry out because of the equilibrium limitations and the existence of methyl acetate–methanol and methyl acetate–water azeotropes. Since the thermodynamic equilibrium constant of this reaction is on the order of 20 and the stream leaving the reactor contains considerable amounts of all of the four components, conventional processes use a liquid-phase reactor with a large excess of one reactant in order to attain high conversions of the other. A conventional separation system includes eight distillation columns, one liquid extractor, and one decanter for decomposition of the azeotropes and tangent pinch present in the mixture. This process requires large capital investments and large amounts of power and solvents.

In 1983, the Eastman Chemical Co. (United States) replaced such a system with a novel reactive distillation unit. With this unit, high-purity methyl acetate is synthesized in a single column, further purification stages are unnecessary, and there are no streams of unreacted reactants to be regenerated. Plus, this unit allows a high conversion to be attained without using a large excess of one of the reactants. This is possible because methyl acetate evaporates from the liquid reaction mixture to raise the conversion.

The column is indeed a complete chemical plant in a single unit producing 400 million pounds of high-purity methyl acetate per year. This process is exceptionally economical: compared to the conventional process, it needs five times smaller capital investments and consumes five times less power. Some time after the plant had been started up, the company put into operation an improved, second-generation, reactive distillation unit. The annual output of the two columns is now nearly 1 billion pounds of methyl acetate.*

Of course, such columns are much more difficult to model and design than conventional apparatuses. Reactive mass-transfer processes show a nonlinear behavior because of the chemical reactions. In recent years, Russian and US researchers have been successfully developing conceptual methods for thermodynamic and topological analysis of distillation. The purpose of this analysis is to select, at the qualitative level, a few near-optimal process flowsheets for subsequent detailed mathematical modeling.

Chemical engineering systems are open and often nonlinear, and processes in these systems are far from the thermodynamic equilibrium. Therefore, the chemical engineer should be familiar with the theory of open systems. In these systems, there can be multiple steady states, both stable and unstable, and spatiotemporal dissipative structures. For example, the study of the dynamics of origination and development of unstable steady states is of considerable importance in the theory and practice of industrial catalysis. This study has demonstrated the great role of fundamental knowledge. It has been established and recognized that unpredictable variations in the reaction rate—chaotic self-oscillations or chemical turbulence—originate in comparatively simple catalytic reactions such as CO oxidation over platinum-metal catalysts.** This regime is observed in catalytic neutralizers of the exhaust of internal-combustion engines. The strange attractor has become a mathematical counterpart for sustained chaotic oscillations in low-dimensional deterministic systems. Note that chemical turbulence is not an exotic phenomenon. It is more frequent in chemical engineering practice than was previously believed.

In a chemical engineering system, there can be a reverse process, specifically, transition from an unstable to a stable state. This would result in microflow self-organization, which is the spontaneous origination of stable structures. The Benard cells are a classical example of spatial dissipative structures. At a small temperature gradient, we have an ordinary heat-conduction problem: heat supply results in some temperature field, the liquid remaining quiescent. Raising the temperature gradient brings about a bifurcation, and ordered motion begins in the liquid. Further increasing the temperature gradient makes the motion unstable and chaotically turbulent. Chaos is observed at a high heat-supply rate.

* Doherty, M.F. and Malone, M.F., *Conceptual Design of Distillation Systems*, New York; McGraw-Hill, 2001.

**Slinko, M.M., Ukharskii, A.A., Peskov, N.V., and Jaeger, N.J., Chaos and Synchronization in Heterogeneous Catalytic Systems; CO Oxidation over Pd Zeolite Catalysts, *Catal. Today*, 2001, vol. 70, p. 341.

The thin layer of adsorbed matter on the catalyst surface is an example of an open nonideal system exchanging matter and energy with the gas and solid phases. Spatiotemporal self-organization is possible in such a system.

Dynamic chaos, which is due to nonlinearity and the rather large number of degrees of freedom, is inherent in many chemical engineering systems. However, it is hardly observable if it is weak, sets in after a long time, or takes place in a narrow range of system parameters.

It is necessary to familiarize students with nonlinear dynamics, spatiotemporal self-organization, and dynamic chaos, since, as was mentioned above, seemingly all chemical engineering systems are nonlinear and open and the processes occurring in these systems are essentially nonequilibrium.

Self-organization is also observed at the liquid/gas and liquid/liquid interfaces in absorption and extraction. In this case, it is caused by local gradients of surface tension (Marangoni effect) that have resulted from temperature and concentration gradients or by density gradients (Rayleigh convection).

The discovery of self-organization and of the formation of spatiotemporal dissipative structures in various kinds of deterministic nonlinear dynamic system (e.g., chemical, biological, and technical systems) is among the greatest achievements of the last three decades.

The works of Mandel'shtam's, Prigogine's, and Haken's schools laid the foundations of new disciplines: nonlinear dynamics; synergetics, which is the science of self-organization; and the theory of open nonlinear dissipative systems. Studying open nonlinear chemical engineering systems, which is expected to explain and predict the spatiotemporal self-organization of structures, is a promising approach to the intensification of unit operations.

The theory of the basic unit operations of chemical engineering and chemical reaction engineering consists of a large number of mathematical models. The models are formulated in terms of nonlinear equations of mathematical physics and physicochemical kinetics. Nonlinear dynamics is the key for the analysis and understanding of chemical engineering systems. It has already provided the following new fundamental results: it has been found that processes near and far from equilibrium occur by different mechanisms, a system can have multiple steady states (both stable and unstable), and chemical turbulence (deterministic chaos) can develop.

The performance of chemical plant equipment can readily be improved using computational fluid dynamics. This approach is particularly efficient for multiphase systems and for apparatuses with complicated geometry. Computational fluid dynamics is supplemented by tomography and nuclear magnetic resonance spectroscopy, which provide insight into transfer processes and the internal structure of flows in the apparatus.

It is now obvious that no progress in chemical engineering is possible without widely using mathematical modeling and automated research systems. The processes involved in chemical technology are extremely sophisticated, so heuristic approaches cannot ensure further technological development of most of the segments of the chemical industry.

The present days are critical for mathematical modeling, automated research systems, and computational and field experiments. The coming years will show whether we have been able to ensure favorable conditions for progress in these areas. If it appears that we have not succeeded to a large enough extent, the consequences of our inattention to modern research methods and of our incomprehension of the essence of things will be exceptionally detrimental.

Nowadays, the interests of chemistry and the needs of technology at the molecular level are converging. Chemical design of compounds and materials with desired properties has become a practical problem for the technologist. Furthermore, chemical and biological means and methods are increasingly interpenetrating and enriching each other, promising new discoveries, novel processes, and useful compounds and materials.

At the turn of the 21st century, we are facing the formation of new chemical technology, which will demand from the researcher and chemical engineer a knowledge deeper and more versatile than in the last quarter of the 20th century. In European universities, as well as in Russia, the need for the reforming of chemical engineering education is felt.

PROBLEMS OF CHEMICAL ENGINEERING EDUCATION

The main tasks in improving chemical-engineering education are to give the students more fundamental knowledge and to stay ahead of the developing chemical technology, taking into consideration its prospective problems. Chemistry and chemical-engineering science are developing so rapidly that part of the students' knowledge may become obsolete before graduation. Giving students more fundamental knowledge means paying more attention to teaching fundamental laws of nature, new instrumental experimental methods, informatics, and economics. Education should firmly rest upon scientific knowledge and high moral principles.

Learning chemical-engineering theory should make the student understand that the engineer always needs theory when it comes to making an important decision as to the design or operation of a chemical plant. First of all, when studying a new process on a laboratory scale, the research engineer should be sure that his measurements are suitable for extrapolation to an industrial scale. Therefore, he should know the principles of modeling aimed at scaling-up the process. He should comprehensively master theory, understanding that measurements alone provide only data, not knowledge. Knowledge is contained in a model, which must be able to predict the behavior of the process under given conditions. Mathematical education should demonstrate to the student that mathematical concepts and methods, though abstract, will not take him away from the problems of chemical engineering and industrial practice; rather, they will be necessary to study processes in terms of quantitative laws, logical connection, and geometric shape. Russian engineering education has been renowned for combining proper teaching of fundamental disciplines with a high level of special and field training.

Skilled specialists are required to carry out modern research. Chemical-engineering education has never had so pressing a need for broad-minded pedagogues whose mental outlook is not confined within some area of engineering and goes far into science, technics, and chemical technology. Specialized education is always easier and cheaper than fundamental, comprehensive education. Versatile education of chemical engineers is a Russian tradition.

The reader can find the following words in the preface to a textbook published in 1913 by I.A. Tishchenko,* the founder of the Moscow school of chemical engineering: "At present, teaching applied chemistry at higher technical schools is based on specializing the students in some narrow areas of chemical engineering. Formerly comprehensive courses of chemical engineering are now divided into more special ones, and, increasingly, the common essentials of typical unit operations escape the student's attention. Specializing in some area, the student takes a specific view of all the processes he deals with, his mind being forcedly narrowed. In his future practice, he usually has to work hard to do away with once adopted one-sided views.

The Department of Chemistry of the Imperial Moscow Technical College believes that, in principle, the differentiation of the engineering course is obviously beneficial, for it makes training the student in the area he chose more intensive and fruitful. However, the Department has found it timely to counterbalance the tendency to unreasonably narrow specialization with a new course that is expected to broaden the students' knowledge in the field of general chemical engineering. This course has been given the name *Basic Unit Operations and Equipment in Chemical Engineering* …. This course should comprise all general information concerning the processes and apparatuses that is pertinent to most, if not all, of the areas of chemical engineering …. A specific feature of generalization in engineering science is that, of the totality of scientific facts and inferences, only those are used in engineering which are most profitable in given time and place contexts. Therefore, the idea of economical technology

* Tishchenko, I.A., *Osnovnye protsessy i apparaty khimicheskoi tekhnologii* (Basic Unit Operations and Equipment of Chemical Engineering), Moscow: Tipo-Litografiya I.Kh. Kavykina, 1913.

should be both the starting point and the clue in the new course."

The chemical engineer should not only know the subject well but, based on fundamental principles of chemistry, physics, and mathematics and on accumulated engineering experience, also be able to explain, in unified terms, the processes and phenomena occurring in apparatuses and chemical plants. Departments of processes and apparatuses in chemical engineering must be susceptible to the new for their graduates to be aware of the challenging problems that are expected to determine the development of the chemical industry and chemical engineering for some time.

Today, like in the years of the formation of process and apparatus science, savings in energy and resources is the main concern of chemical engineering. In this connection, necessary conditions for progress in the scientific foundations of chemical engineering are a deeper insight in the mechanism of conventional unit operations (such as distillation, gas absorption, liquid extraction, adsorption, and membrane separation) coupled with a reactor unit and the ability to control these processes.

However, over the last three decades, the higher school course of the theoretical foundations of chemical engineering, including industrial catalysis, chemical reactors, and basic industrial unit operations and equipment, has not kept pace with the rapidly developing technology.

Nowadays, only few prominent researchers, designers, and industrial engineers participate in lecturing on the processes and apparatuses of chemical technology and chemical reactors. The student is usually taught not by a researcher or a skilled engineer but by a teacher on the staff whose research activity in recent years has been restricted by the lack of material procurement. Education should easily be adaptable to current trends in science and technology. This is possible only when the teacher himself is at the frontier of chemical technology and the chemical industry.

It is in this way that Russian education developed in the prewar period (1920–1940). A great contribution to chemical engineering education was made by Tishchenko as Director of the Mendeleev Institute of Chemical Technology (MICT) in 1922–1929. It is in this period that the Moscow school of chemical engineering was founded. Tishchenko recruited N.F. Yushkevich, B.G. Shvetsov, N.N.Vorozhtsov, and other specialists who were very much engaged in the industry, and fell into improving engineering education. In those years, chemical-engineering education in Russia was advancing more rapidly than that in the United States and Europe. The US authors Walker, Lewis, and McAdams published their famous book *Principles of Chemical Engineering*[*] only 10 years after the aforementioned book by Tishchenko appeared.

In postwar years, MICT pedagogues that had actively participated in the foundation of the Moscow school of processes and apparatuses established their own prominent schools faithful to Tishchenko's views, among them A.G. Kasatkin at MICT, N.I. Gel'perin at the Lomonosov Institute of Fine Chemical Technology, and A.N. Planovskii at the Moscow Institute of Chemical Machine Building.

Improving the teaching of the scientific foundations of chemical engineering now requires radical changes in the curriculum. It is necessary to start a new stage of development of the main course. At present, the course of processes and apparatuses in chemical engineering is the key engineering discipline serving as a basis for general chemical-engineering education. This basis must be matched to modern chemical technology.

An updated course of processes and apparatuses in chemical engineering should be free of the gap between physical processes (hydrodynamic ones and heat and mass transfer) and chemical processes that is now typical of Russian chemical-engineering education. It has long been necessary to give a course of transport phenomena before lecturing on processes and apparatuses. The theory of transport phenomena in reactive media should make up a theoretical basis in educating a chemical engineer.

A new course of processes and apparatuses of chemical technology should contain a chapter devoted to chemical and biochemical reactors and set forth the basic principles of conceptual design of processes involving multiphase and multicomponent systems.

New ideas need a new generation of engineers and researchers, so the most important task of the Russian higher school and the Russian scientific community is graduating skilled and active brainpower capable of solving the great problems that are challenging world science and the Russian industry.

[*] Walker, W.H., Lewis, W.K., and McAdams, W.H., *Principles of Chemical Engineering*, New York: McGraw Hill, 1923.