

A VIEW ON CHEMICAL AND BIOCHEMICAL ENGINEERING: WHERE ARE THEY GOING?

A short history of chemical and biochemical engineering is presented, both industrial and educational aspects being considered. The most important trend in the future development of bio/chemical engineering – biological engineering – is pointed out. The current state and near future of biotechnology are described.

Chemical technology and biotechnology have been attracting worldwide attention over the last decades because of their many important contributions to our standard of living. Both of them combine the application of a broad segment of science and engineering, specifically chemistry, biology and chemical engineering, to produce products, such as chemicals, special polymers, semiconductors, biopharmaceuticals etc., or to perform functions that can improve human life, such as the treatment of wastewater or polluted air and the generation of energy [1,2]. The following data are given to illustrate the importance of the two technologies: the worldwide market of chemicals is valued at US\$ 1.3 trillion [3].

When looking for the answer to the question: "Where are chemical and biochemical engineering going?" at the beginning of the new millenium, it seems to the author that it is appropriate to briefly consider how they have grown and developed to the present day. In this paper, chemical and biochemical engineering are primarily considered to be subdisciplines within chemical technology and biotechnology, respectively, that are responsible for translating the discoveries of chemistry and life science, respectively, into practical products, processes or systems capable of serving the needs of human society. Two other terms – process and bioprocess engineering – have also been used with the same corresponding meaning in the last years. By using the term process engineering, it is emphasized that chemical engineering can serve not only chemical technology but also other industries. Similarly, the term bioprocess engineering emphasizes that biochemical engineering serves their all processes involving the action of any biological agent: living organisms or their parts. The term chemical engineering is often used as a synonym for chemical technology [4]. Here, when the term chemical technology or biotechnology is used,

then the author wants to emphasize the chemical or biological process considered.

Beside a short hystory of chemical and biochemical engineering, especially in the 20th century, the development of the education of (bio)chemical engineers is also presented. The most important trends in the futur development of bio/chemical engineering are also pointed out. Furthermore, the current state and near future of biotechnology with an emphasis on bioprocess engineering are reviewed.

HISTORY OF CHEMICAL AND BIOCHEMICAL ENGINEERING

The development of chemical engineering

Although the intellectaul foundation of chemical engineering has undergone a series of great changes, its basic definition has remained the same for the past hundred years. According to the American Institute of Chemical Engineers (AIChE), "chemical engineers take chemistry out of the laboratory and into the factory and the world around us". In other words, chemical engineering has dealt with industrial chemical processes where highly desired chemicals and the materials based on them are produced economically and with no or a minimum adverse effect on the environment [1].

The beginning of chemical engineering is related to the late 19th century and was caused by the need of the society of that time for the mass production of chemicals and materials. At that time, the concept of applied chemistry, originally developed in Germany, was dominant. This concept combined the elements of chemistry and mechanical engineering, and the "chemical engineer" (perhaps designated as better "engineer for chemical technology or "chemical technologist") was either an applied chemist with knowledge of large scale industrial chemical reactions, a mechanical engineer with some knowledge of chemical process equipment or a chemical plant foreman with experience, but little education [5]. The production of each specific product was included in a chemical technology course, and each of these courses had to be

separately studied in detail. It was not easy to educate a "chemical technologist" for a number of different chemical technologies as it was not possible that one person be capable of knowing each of them. Even, their division into specific groups, such as organic or inorganic chemical technology, fermentation technology etc., did not reduce the number of representative technologies which could be successfully studied or led by the same person under industrial conditions [6].

Chemical engineering was first conceptualized in England where George E. Davis, an industrial inspector, presented a series of 12 lectures on the operation of chemical processes (now called unit operations) at the Manchester Technical School in 1887 [5]. The primary evolution of chemical engineering, both educationally and industrially, occurred in the USA. In 1888 the Massachusetts Institute of Technology (MIT) started a four-year chemical engineering program, which largely described industrial operations and was organized by specific products [1]. The program was unique for that time in combining mechanical engineering and industrial chemistry with the emphasis on engineering. Although the program was a step forward, it was similar to the German concept of applied chemistry. A better fundamental intellectual model was required because knowledge about one chemical process most often differed in many details from the knowledge about other processes. In other words, the program did not have a paradigm, that is, an overall concept containing a characteristic set of problems in different chemical processes and systematic methods for obtaining their solution.

In producing specifically designed products from raw materials in different chemical processes, chemical engineers experienced both physical operations and chemical reactions necessary for these transformations. The number of these basic unit operations is not that large: filtration, grinding, heat transfer, drying, distillation and so on, and only a few of them are applied in any particular chemical process. Following Davis' blueprint, Arthur D. Little, a chemist, first suggested in 1915 that all industrial chemical processes, on whatever scale conducted, could be viewed as a collection of basic unit operations [1,5]. This concept of unit operations became the first paradigm of chemical engineering, organizing the overall knowledge of chemical engineering in a convenient and effective manner. The capability of chemical engineers to quantitatively describe unit operations appeared around 1920 and provided a reliable tool for the rational design of chemical plants. With the help of the unit operations concept, chemical engineering continued to broaden and move forward. Other classical tools of chemical engineering analysis were added or extensively developed in the first part of the last century; these included material and energy balances, thermodynamics and chemical kinetics.

With the first practical success of the unit operations concept, especially in the petroleum industry, chemical engineering education began to change. Instead of the classical concept of industrial chemical technologies, the concept of unit operations, known as

the American type of chemical engineering, became increasingly accepted all over the world. For the education of chemical engineers, it was more important to teach students the fundamentals of unit operations and how to do them in any chemical process than how to make any specific product. Modern education in chemical engineering at that time began increasingly to include mathematics and physical modelling, such as the theory of similarity and dimensionless analysis. The basis for a more reliable bridging of the gap between laboratory processes and full-scale industrial production was established.

After World War II, displeased with the empirical approach used broadly to define process equipment performance, chemical engineers re-examined the fundamentals of unit operations at the molecular level. As unit operations became better understood, it was apparent that they were not distinct entities, but special cases or combinations of momentum, heat and mass transfer, which were referred to by chemical engineers as the transport phenomena. Unification was the next logical step in the evolution of the unit operations concept. Quantitative mechanistic models were developed for transport phenomena and used to analyze existing and design new process equipment. Any fundamental study of unit operations became a study of momentum, heat and mass transfer. The transport phenomena approach became the second paradigm for chemical engineering [1]. The beginning of the transport phenomena concept was often related [1,7] to the famous textbook of Bird, Stewart and Lightfoot entitled "Transport Phenomena" in 1960, which presented a unified mathematical description of momentum, heat and mass transfer [8]. At the same time, the importance of the mathematical modeling of processes and reactors was emphasized and these models were successfully applied to chemical industries such as commodity petrochemicals [1].

The transport phenomena concept also affected the education of chemical engineers. The unification of unit operations was accepted as being "more efficient in teaching, more economical in time, more adequate in its presentation of the fundamentals and more effective in training toward the definition and solution of broad problems in chemical engineering" [9]. Educated in the transport phenomena concept, chemical engineers were firmer in their understanding of the fundamental principles and more aware of the similarities among many of the unit operations. At that time, the core of the chemical engineering curriculum in its present form was evolved. This core curriculum was based on some basic sciences, such as mathematics, physics and chemistry and on topics central to chemical engineering, such as thermodynamics, chemical kinetics, transport phenomena, unit operations, reaction chemical engineering, process design and control and plant design and systems engineering [1].

Over the last decades, materials science has commanded the attention of many chemical engineering departments. Training programs were based on materials science combined with a core of chemical

engineering courses and chemical engineers were capable of designing and handling the production of different new materials such as ceramics, polymers, composites and electronic magnetic and photonic materials. More commonly, as at the University of Minnesota (Minneapolis, USA), a single faculty taught both parts of the materials science and chemical engineering curriculum [7].

Around 1990, it was predicted that the third paradigm for chemical engineering would soon appear in the form of "the explosion of new products and materials", which would "be critically dependent on structure and design at the molecular level" [1]. Today, it is apparent that this prediction has become a reality [7].

The development of biochemical engineering

The central domain of biochemical engineering is the conduction of processes using biological agents such as living or dead cells or cell components on an industrial scale, providing the link between biology and chemical engineering [10,11]. Therefore, the appearance and development of biochemical engineering have been related to the accomplishments of life sciences, as well as to the progress of chemical engineering methodology and strategy.

By the above definition, biochemical engineering is as old as history, for the earliest known document (the "Monument blue", 7000 B.C.) shows beer brewing in Babylon [11]. If restricted only to the production of chemically defined species, biochemical engineering is about a hundred years old. Prior to 1900, only potable alcohol and vinegar were produced on a large scale, and in the early 20th century the main new products were glycerol, citric acid, lactic acid, acetone and butanol, as well as yeast biomass [12]. The major advances during that period were the aeration of yeast culture by air sparging, the addition of a carbon source during the process (fed-batch culturing) and the application of steel vessels that could be sterilized *in situ* by steam.

Complementary developments in biochemistry, microbial genetics and chemical engineering in the 1940s ushered in the era of antibiotics. During the Second World War, the production of penicillin in a submerged culture under aseptic conditions was developed to satisfy the rapidly growing needs for this antibiotic. Process development was also made through the establishment of strain-improvement programs, the introduction of pilot-plant facilities, and the use of large-scale extraction processes. Also, many new bioprocesses were established at an industrial scale, including other antibiotics, vitamins, gibberellin, amino acids, enzyme and steroid transformations. The most significant changes in biochemical engineering probably took place at that time, so its birth as a scientific discipline could be related to this period [11]. One should remember that during the same period of time chemical engineering also developed rapidly.

Research in the area of microbial biomass (as a source of feed protein) in the early 1960s led to some important advances in biochemical engineering. The

economic production of microbial protein with a relatively low selling price was achieved in large-volume bioreactors with efficient aeration and continuous operation, such as a continuous 3,000-m³ pressure cycle fermentor [13]. Aseptic operation over a period of time (more than 100 days) was ensured using high standards of bioreactor construction, the continuous sterilization of feed streams and the computer control of the systems.

Around 1980 progress in biotechnology was initiated by developments in genetic engineering (the *in vitro* genetic manipulation of organisms), which enabled the transfer of genes between unrelated organisms and the precise alteration of the genome of an organism [12]. Genetically-engineered microbial cells became able to produce compounds normally synthesized by higher cells, such as insulin and interferon, or to increase the productivity of common microbial products. Innovative biochemical engineering in the production of these products led to improvements in product recovery, product purification, process safety and reduced overall costs.

The foundation of biochemical engineering training was laid in the 1960s and has remained, more or less, the same until now. It was expected that biochemical engineering would simply be the interaction of two disciplines: chemical engineering and biology, as could be seen in the pioneering book of Aiba and coworkers [10]. The training was based on the basic sciences of chemistry, physics and mathematics, but not on biology. Some biology, including microbiology, biochemistry and genetics, was added to the training program in order to understand the behaviour of biological agents involved in a bioprocess. Attention was focused on the engineering disciplines involved in the design, operation, scale-up and management of bioprocesses and bioprocess equipment. Bioprocesses included not only chemical engineering unit operations, but also unit processes (that is, the reaction mechanisms involved in converting raw materials into valuable products, such as reductions, oxidations, substrate conversions etc). The unit operations concept provided a great analytical tool for the understanding of the behaviour of a bioprocess. Unit-process classification provided a logical approach to the examination of a bioprocess reaction mechanism. Bioprocess design was based on basic chemical engineering courses, such as stoichiometry, reaction kinetics, chemical reaction engineering and process control. Thus, biochemical engineers were capable of exploiting the potentials of a biological agent effectively and economically. Many departments of chemical engineering all over the world have changed their names, becoming departments of chemical and biochemical engineering.

With time, the education of biochemical engineers has been affected by the developments achieved in biotechnology. Around 1980 the challenges in learning biochemical engineering were to understand and analyze bioprocesses, which required knowledge on how cells grew and functioned. A microbial cell was seen as "an expanding chemical reactor which took nutrients

Table 1. Review of biochemical engineering courses at Yugoslav universities in 2002

University	Faculty	Option	Course/Duration
Belgrade	Faculty of Technology and Metallurgy	Biotechnology and Biochemical Engineering	Basic Biochemical Engineering (two semesters)
	Faculty of Agriculture	Food Technology of Plant Products; Food Technology of Animal Products	Biochemical Engineering (one semester)
Novi Sad	Faculty of Technology	Microbiological Processes; Pharmaceutical Engineering	Biochemical Engineering (two semesters)
Niš	Faculty of Technology (Leskovac)	Chemical and Biochemical Engineering	Basic Processes of Biochemical Engineering (two semesters)

from its surroundings, grew, reproduced and released products into its environment [11]. The foundation needed for understanding the interactions between the cell and its surroundings was built upon biochemistry, biophysics and cell biology, which were not traditionally included in engineering education. The rates of nutrient utilization, growth and product synthesis became important for a quantitative, most often extremely oversimplified, mathematical representation of bioprocesses. To go beyond qualitative understanding, biochemical engineering training was extended by studying a foundation of mathematical modelling, analysis and the optimization of bioprocesses.

At Yugoslav universities, biochemical engineering was introduced at the faculties of technology in the late 1980s (the 1987/88-school year). Prior to that, at some faculties the basics of biochemical engineering were taught in other courses. The classical biotechnologies, such as beer brewing, had been taught at some faculties of technology and agriculture. As was common at many world universities, biochemical engineering was added to the chemical engineering department but later an independent biochemical engineering department was founded at the Faculty of Technology and Metallurgy of Belgrade University. The biochemical engineering training program was based on modern programs from prestigious world universities. Besides mathematics, physics and chemistry, a chemical engineering "skeleton", composed of fluid mechanics, unit operations, reactor theory, process control, process modelling and simulation and process design) and other engineering disciplines (mechanical and electrical engineering) were established. The training included biology, including microbiology and microbial genetics, biochemistry and enzymology, while the principles of biochemical engineering were taught in a separate course. The training programs were beyond the real possibilities of the Yugoslav faculties of technology for studying biochemical engineering with respect to the available faculty staff, necessary laboratory equipment and textbooks. The lack in the laboratory equipment at some faculties was overcome by a close relationship with domestic pharmaceutical companies. An additional difficulty appeared in the early 1990s, when some of teaching staff left the universities and the country. The first textbooks on biochemical engineering written in Serbian appeared in the early 1990s [14,15]. A review of biochemical engineering courses at Yugoslav

universities and faculties at the present time is given in Table 1.

A TREND IN THE DEVELOPMENT OF CHEMICAL AND BIOCHEMICAL ENGINEERING

Being focused again on developing new products and materials, much like it was one hundred years ago, chemical engineering appears to have come full circle in its development. With the currently emerging paradigm, chemical engineers are concerned with two questions, namely, what products to make (Product Engineering) and how to make them economically and safely (Process Engineering) [16]. To answer the former, chemical engineers should be taught the relations between molecular structure and properties and the manipulation of molecules to attain desired products. The answer to the latter is easier because chemical engineering training programs are still dominated by process engineering. This concept requires that a chemical engineering curriculum include Molecular Product Engineering as a core subject and as a complement to Process Engineering, and subjects how to control products properties in relation to their chemical composition and structure.

The life sciences, combined with chemical engineering, are more conducive to the product engineering concept because unit operations – the necessary tools and processes – are not yet well established [7]. New biology, based on the sequencing of genomes, has had a profound impact on biotechnological and biomedical research, bearing a broad spectrum of new products. The most obvious changes emerge from the availability of genes and intergenic control elements, all important components for genetic engineering. The realization that genes, enzymes and proteins function through a complex network of interactions, not separately from one another, is a well-known concept. Genomics and associated emerging technologies allow for the first time that such interactions can be identified and, in some cases, measured quantitatively at the molecular level [17]. Chemical engineering, with integration and quantification as its key elements, can help both in the understanding how a complex biological system (the human body being the most important biological system today) functions and in designing a new biological system by modifying some reaction pathways to

improve its properties for industrial or medical applications. Because of both the presence of chemical reactions underlying almost all cellular functions and the specific biological properties of cells and organisms, chemical-biological engineering is a powerful tool in the realization of potentials of systems biology [17]. Chemical-biological engineers will have promising opportunities for designing, developing, manufacturing and processing valuable products, including synthetic materials, chemicals, pharmaceuticals, biopolymers, food products, human tissue, etc.

In 2001 the Chemical Engineering Department at Tufts University, Medford, Massachusetts, USA, changed its name into Chemical and Biological Engineering, reflecting the growing component of biological systems engineering in chemical engineering. The word biological emphasizes that complex biological systems, such as, for instance, the human body, which include both chemical reactions and biological information, are exposed to study. The mathematical and systems oriented courses of chemical engineering curricula, applied to design and optimization problems, should also have the major role in the biological engineering training program.

The undergraduate chemical engineering program at Tufts University is given in table 2. A variety of primary courses covers mathematics, physics, chemistry, biology as well as engineering and engineering science. The chemical and biochemical engineering courses provide the more specific foundation material necessary to solve complex engineering problems and

to develop production and purification at any scale under economic and environmental constraints.

BIOTECHNOLOGY: AT THE TURN OF CENTURY

The prospects for biotechnology and bioprocess engineering at the turn of the century have never looked better because of the breakthroughs in genomics, combinatorial and other lead optimization techniques, enhanced bioreactors and separations technologies and developments in laboratory computer platforms [19]. This remarkable progress in biotechnology can be illustrated by data, given in Table 3, concerning the total number of biotechnology companies and employees and their revenues in the leading countries in 1998. A biotechnology revenue of approximately more than US\$ 35 billion in 1998 surpassed the prediction from the early 1990s (US\$ 24 billion) and was more than 7 times greater than that from 1986 (about US\$ 5 billion) [15]. A permanent increase of biotechnology revenue has been characteristic for the USA and Japan, and a spectacular progress has been made in German biotechnology at the end of the 1990s. In a few years (from 1997 to 1999) the number of biotechnology companies in Germany dramatically increased about a hundredfold (a total of 279 companies), their combined sales were up nearly 40% (roughly US\$ 380 million), and their research spending was up to US\$ 240 million (up 77 %) [21]. Three major factors caused the dramatic growth of the German biotechnology industry: an amendment in Germany's genetic engineering law (in 1993), the

Table 2. Chemical engineering curriculum for undergraduate study at Tufts University (accredited program) [18]

First-Year	Sophomore Year	Junior Year	Senior Year
<i>Fall term</i>			
Introduction to Computers in Engineering	Physical Chemistry with laboratory	Unit Operations and Transport Phenomena I and II	Unit Operations and Transport Phenomena IV
Engineering elective	Calculus III	Applied Mathematics and Software for Chemical Engineers	Chemical Engineering Projects Laboratory
Calculus I	Structure and Strength of Materials	Organic Chemistry with laboratory	Process Dynamics and Control
Chemical Foundations	Thermodynamics and Process Calculations I	Introduction to Electrical Engineering	Chemical and Biological Engineering elective or undergraduate research
Expository Writing	Free elective	Humanities and social sciences elective	Humanities and social sciences elective
<i>Spring term</i>			
Engineering Graphics	Thermodynamics and Process Calculations II	Unit Operations and Transport Phenomena III	Chemical Engineering Projects Laboratory
Engineering elective	Differential Equations	Reactor Design	Chemical Process Design
Calculus II	Introduction to Biology	Advanced Chemistry elective	Chemical and Biological Engineering elective
Chemical Principles	Advanced Chemistry elective	Chemical and Biological Engineering elective	Chemical and Biological Engineering elective
General Physics I	Free elective	Humanities and social sciences elective	Humanities and social sciences elective
Humanities and social sciences elective			

Table 3. Review on biotechnology revenues in the most developed countries in 1998*

Country	Number of companies	Number of employees	Revenue, in billions of US\$
USA	about 1300	153 000	19.6**
EU	1178	45 000	3.7
Japan	–	–	10.0***
Canada	282	1000	1.1

* Adapted according to [20].

** Sales represent US\$ 13.4 billion

*** Sales

investments of large pharmaceutical and chemical companies in biotechnology research in the country (these activities had been based outside Germany) competition and the "Bio-Regio" competition among the regions of Germany (in 1995), sponsored by the Federal Minister of Research, encouraging regions to form networks to spur joint research, the start-up of new companies and so on [21]. The German biotechnology industry has another unique characteristic: its companies have been small companies (about 50% of the companies have less than 10 employees, 30% have 11 to 20 employees and only 2% have more than 80 employees) [21]. By contrast, small companies were non-existent in Japan, where research and development was conducted primarily in large companies [2]. In Europe as a whole [21] and the USA [2], new biotechnology was pursued by both large and small (startup) companies.

The success of biotechnology and biochemical engineering is seen in the effect of new products and bioprocesses; these include biopharmaceuticals, specialty products and industrial chemicals. The application of biotechnology on an environmental scale, including pollution control, bioremediation and mining, is also important.

Biopharmaceuticals include therapeutic proteins, polysaccharides, vaccines, diagnostics and low-molecular-weight pharmaceutical chemicals. Biotherapeutics have mainly resulted from the recombinant-DNA and hybridoma technologies, the most important being insulin, growth hormone, α -interferon, monoclonal antibody, tissue plasminogen activator, hepatitis vaccine and erythropoietin. Despite the numerous options, most of the products are made either in recombinant *E. coli* or in animal cells (Chinese hamster ovary or hybridoma cells). The use of *E. coli* is based on its capability to produce a number of products at high level. The critical and often most expensive (50% or more of the total production cost [2]) part of the process is the isolation/purification of the desired protein. Biotechnology companies hide much of their knowledge about protein purification, but the type and order of process steps are known. Attention is focused on the integration of individual purification steps into a production system as it moves from the laboratory to the plant. In many cases, an important production step is the refolding protein process. The key to a commercial

protein recovery process lies in improving the renaturation yields by minimizing aggregation and reducing the costs of the chemicals needed [22].

Based on the advanced techniques of molecular biology, such as protein and metabolic engineering, rational approaches to the design of therapeutic drugs have been developed. Protein engineering (the designing of drugs with computer-assisted molecular modelling) has been used to modify the primary sequence of a protein at selected sites to improve some of its properties (stability, pharmacokinetics or bioactivity) or to design hybrid proteins that contain regions that aid its isolation/purification. The integration of metabolic engineering and fermentation technology is necessary for the successful commercial production of chemicals [23]. Metabolic pathway engineering could be useful in shifting metabolic flow toward a targeted product, creating arrays of enzymatic activities for the synthesis of new structures and accelerating rate limiting-steps. The mathematical modelling of metabolism, including both the stoichiometry and kinetics of bioprocesses, can contribute to metabolic engineering in improving existing bioprocesses and developing new ones [24].

The use of recombinant microorganisms has resulted in the favorable conditions and the successful techniques for applying higher organisms, such as mammalian, insect or plant cells, and transgenic animals and plants for producing recombinant proteins. In these cases, large-scale processes have usually settled on using suspension cultures in stirred-tank bioreactors with some form of controlled feeding [25]. Transgenic animals can also be used not only as production vehicles for safely obtaining biotherapeutics, such as producing human proteins in cow's milk, and sources of tissues and organs for use in transplantation patients but also in the breeding industry [26]. In response to the growing need for tissues and organs for transplantation, tissue engineering, i.e. the artificial manipulation of cells to promote tissue and organ regeneration, as a biomedical technique has been developed. Currently, tissue-engineered skin is commercially available, and cartilage, temporary liver-assistance devices and tissue-engineered bone are in clinical testing [27]. Combined with genetic and metabolic engineering and with developments in the area of bioreactor design, plant-cell culture technology shows promise for the large-scale production of valuable plant products, and a good example is Paclitaxel (Taxol), an anticancer agent. Both the achievement of reproducible product yields and the increase in volumetric productivity are crucial for potential commercialization [28]. Plant-cell tissue culture is used commercially in Japan to produce the pigment shikonin and ginseng as a health food [2].

Specialty products include chemicals, proteins, microbial biomass and other products the annual use of which is measured in tons. The world market for these bioproducts is several billions of US\$ per year. Here, the focus is on some bioproducts of special interest, such as antibiotics (about US\$ 23 billion), non-antibiotic agents (for instance, sex hormones, ionophores etc.;

more than US\$ 1 billion), amino acids (US\$ 1.6 billion), citric acid (US\$ 1.4 billion), nucleotids (US\$ 450 million) and others [20].

The environmental application of biotechnology (ecobiotechnology) encompasses pollution control, bioremediation, biocatalysis and biomaterials for "green" chemistry, agricultural biotechnology (agrobiotechnology or "green" biotechnology), mining (geobiotechnology; biohydrometallurgy) and microbial-enhanced oil recovery. The problem of pollution control is tremendous and estimated to be about \$ 115 billion only in the USA in 1990 [2]. Because of the needs of society to maintain clean soil, air and water, ecobiotechnology will continue to expand. Advances in biological wastewater treatment have been achieved by the better understanding of mixed microbial populations and by choosing a proper bioreactor design [29] and also, by increasing the knowledge about the biotransformation of some toxic substances, such as chlorinated solvents, perchlorate, nitroaromatic compounds, metals and radionuclides [30–32]. As the microorganisms that clean up contaminated environments are the key factor, a deeper understanding of their metabolic activities is therefore necessary for further improving bioremediation processes [33]. It is worthwhile to emphasize the use of microorganisms either as live biocatalysts for pesticide toxification [34] or pesticides (for instance, the use of *Bacillus thuringiensis* for the selective control of insect pests) [35], removing sulphur from fossil fuels [35] and waste air treatment in biofilters [36]. The utilization of biowaste as a resource for bioproduct development can be a useful approach in managing wastes [37]. Beside traditional uses, biowastes can be used for obtaining "pure" energy, as in the case of the methane fermentation technology [38]. Biogenic hydrogen can also be a source of alternative energy [35]. Microbial leaching (bioleaching) has been used for recovering some metals (copper, uranium and gold) from low-grade ore and mineral concentrates [39, 40].

The development and application of novel bioreactor designs have also contributed to the recent progress of biotechnology. Most innovations address oxygen transfer, shear induced by stirring, the control of water activity in organic phase systems, the *in situ* recovery of the main or by-pass product and waste biotreatment. Of the new bioreactors, the following should be mentioned: bioreactors for better mixing (or oxygen transfer) and lower shear stress, bioreactors for two-phase reactions and environmental bioreactors [41]. The application of integrated fermentation and product recovery (extractive bioconversion) continues to be improved for many products [42, 43].

THE PROSPECTS OF BIOCHEMICAL ENGINEERING

Advances in bioprocesses and biotechnology are considered to be critical to the industry if it should maintain and improve competitiveness [3]. The discovery of new biocatalysts, the improvement of biocatalyst performance and improved biochemical engineering hold great promise for bioprocesses and biotechnology.

The potential for discovering new biocatalysts is large, since most part of the microbial world has not yet been studied. The DNA of industrially important microorganisms and plants should be sequenced and gene structures defined, while metabolic pathways are expected to be quantitatively modelled and thoroughly understood. Biocatalysts with improved properties are needed for producing more efficiently targeted products at lower cost. The improvement of known biocatalysts will be achieved through the application of molecular biology, genome sequencing and metabolic pathway engineering. Improved biocatalysts will increase the yield, rate and/or selectivity of bioprocesses and allow the better use of cheaper raw materials from biomass. These novel bioprocesses will not only improve the protection of human health, safety and the environment [3], but also support sustainable development [44]. To reach the goal of sustainability, biotechnology can be very important in the areas of food production, renewable materials and energy, pollution prevention and bioremediation, providing that some technical and economic problems be solved [44]. Important preconditions for achieving improvements in bioprocessing are enhancements in biochemical engineering, including innovative bioreactor designs, continuous bioreactor systems, on-line measurements and process control, the more effective isolation and purification of bioproducts and processes that integrate biological reaction and product recovery.

Industry, academia and government must take part in advancing the use of bioprocess engineering and biotechnology, by supporting "the research and education that will lead to broader economic viability and public acceptance of bioprocesses as the source of sustainable, higher performance chemical products" [3]. This requires that industry clearly define the research tasks that will result in more powerful and more efficient biocatalysts, more effective bioprocess technology and very cheap raw materials, such as renewable ones. On the other hand, the basic task of universities is to broaden the knowledge about industrial bioprocesses, such as metabolic pathway engineering, the quantitative modelling of metabolisms, reaction and separation technology etc. The education of biochemical engineers should, therefore, involve many more biological disciplines, including biochemistry, molecular biology, cell biology and genetics.

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IZVOD

POGLED NA HEMIJSKO I BIOHEMIJSKO INŽENJERSTVO: KUDA IDU?

(Stručni rad)

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U ovom radu, na hemijsko i biohemijsko inženjerstvo se gleda kao na subdiscipline hemijske tehnologije i biotehnologije ali i u širem značenju, tj. kao hemijska tehnologija i biotehnologija. Hemijska tehnologija i biotehnologija podrazumevaju kombinovanu primenu otkrića prirodnih nauka, specifično hemije i biologije, i inženjerstva, naročito hemijskog inženjerstva, u cilju dobijanja proizvoda i vršenja određenih funkcija koji mogu biti od koristi ljudima. Kao subdiscipline hemijske tehnologije i biotehnologije, hemijsko i biohemijsko inženjerstvo su odgovorni za prevođenje otkrića hemije, biohemije i bioloških nauka u praktične proizvode, procese ili sisteme koje mogu služiti potrebama društva.

U radu je dat sažet istorijat razvoja hemijskog i biohemijskog inženjerstva do današnjih dana i, paralelno sa njim, kraći osvrt na razvoj obrazovanja hemijskih i biohemijskih inženjera. Istaknuto je da se hemijsko i biohemijsko inženjerstvo nalaze na početku nove paradigme, koja označava razvoj i dobijanje novih proizvoda (product engineering).

Ukazano je na najvažnije trendove razvoja hemijskog i biohemijskog inženjerstva, a posebno je naglašeno novo multidisciplinarno biološko inženjerstvo. Učinjen je i osvrt na stanje biotehnologije na prelazu između dva veka i naglašene njene perspektive u bliskoj budućnosti. Otkriće novih biokatalizatora, poboljšanje performansi postojećih biokatalizatora i razvoj biohemijskog inženjerstva obezbediće dalji napredak moderne biotehnologije.

Ključne reči: Hemijsko inženjerstvo • Biohemijsko inženjerstvo • Biološko inženjerstvo • Hemijska tehnologija • Biotehnologija •
Key words: Chemical engineering • Biochemical engineering • Biological engineering • Chemical technology • Biotechnology •