Perspective

Process Engineering Research in China: A Multiscale, Market-Driven Approach

Ka M. Ng
Dept. of Chemical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, PRC

Jinghai Li and Mooson Kwauk
Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100080, PRC

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The rapidly evolving Chinese process engineering community and its research are described. A multiscale, market-driven approach is proposed for its future development. In addition to the science and technology, process engineering is broadened to consider the product, sustainability, business and, most importantly, people issues involved. © 2005 American Institute of Chemical Engineers *AIChE J,* 51: 2620–2627, 2005

Introduction

With its GNP growth rate hovering around 8% per year for over the past two decades, China is becoming an important economic partner for the entire world. This growth is expected to continue provided that China can navigate successfully around the potential pitfalls — energy sources, environmental concerns, infrastructure bottlenecks, corporate governance, and intellectual property protection, among others. The Chinese chemical processing industries (CPI) have been growing even faster than the economy as a whole, at over 12% per year. This has contributed to a voracious appetite for raw materials: China is currently consuming 27% of the world's production of steel, 31% of coal, 40% of cement, and 7.4% of petroleum. New chemical plants can be seen everywhere converting all sorts of raw materials into final products. For example, two major petrochemical complexes — a U.S.$2.9 billion joint venture between SINOPEC and BASF in Nanjing, and a US$2.7 billion joint venture between SINOPEC and BP in Shanghai — have started up recently. A US$4.3 billion CNOOC-Shell petrochemical complex northeast of Hong Kong in Daya Bay, Huizhou, will begin operation by the end of this year (see the cover photo). Also, a large number of small and medium sized startup companies have been producing chemical-based consumer products, including dyes and pigments, foods, personal care products, pharmaceuticals, household and office products, etc. Indeed, China is highly competitive in organic synthesis and has become a favorite place for outsourcing the manufacture of organic precursors and intermediates for producing more complex compounds. Investments in China are not limited to manufacturing facilities. Many R&D centers have been set up to take advantage of the local skilled chemists and engineers, including those of multinationals such as General Electric, Rohm and Haas, DuPont, Eli Lilly, and many others. All of this has created enormous opportunities for process engineering research.

Meanwhile, with relatively slow growth, there is a general feeling in developed countries that traditional chemical engineering has reached its maturity, or that the core has lost its relevance particularly in the U.S. (Ottino, 2005). Extensive discussions of the challenges and opportunities facing the CPI have taken place (Harold and Ogunnaike, 2000; Charpentier and McKenna, 2004; among others). High on the recommended list for process engineering R&D include product design, biotechnology, nanotechnology, process intensification, etc. Some detailed roadmaps for action have also been developed (www.chemicalvision2020). (The reader might have noticed that the terms — chemical engineering and process engineering — have been used interchangeably. This is because, we believe, no matter how chemical engineering evolves, and how different industrial sectors might rise and ebb, processing materials of all kinds, be they chemical or biochemical, will remain the heart of chemical engineering.)

With the upgraded facilities and expanded workforce in its CPI, China is certainly in a good position to innovate and to adopt new practices. Should China follow an R&D strategy similar to that of developed countries? If not entirely, how to tailor one that takes into account the needs, wants, competitive advantages, and other circumstantial factors of a China chang-

Correspondence concerning this article should be addressed to K. M. Ng at kekmng@ust.hk.

Table 1. Characteristics of Chemical Engineering Research Institutions in China

- Extensive and continuing reorganization and expansion of universities and research institutions
- Large, integrated chemical engineering colleges
- Young faculty and a huge talent pool
- Extensive collaboration between universities and industry
- Application-specific process development

ing at a rapid pace? Can the rest of the world benefit from China's effort? These questions are examined in this article based on a strategic study carried out by the Chinese chemical engineering community (Li et al., 2004a). We begin with a brief overview of the past and present of process engineering research and the institutions associated with this research in China.

Process Engineering Research in China: Past and Present

As in other countries, the development of chemical processing in China started with sulfuric acid, ammonium sulfate, soda ash and caustic soda in the early 1900s. Since then, because of various historical reasons and events, the pace of development and innovation was much slower than that in the U.S., Britain, Germany and Japan (Arora et al., 1998). Nonetheless, being a populous nation, China has made a lot of effort to meet the domestic demand for basic necessities — fertilizers, fuels, plastics, metals, and biochemicals such as antibiotics, with research conducted at universities and various government supported institutions, such as those associated with the Chinese Academy of Sciences (CAS) (Kwauk, 1989).

Along with the transition to a market economy which started in the late 1970s, far-reaching reorganization of these research institutions has been taking place. The characteristics of these organizations are listed in Table 1.

Almost all institutions have been reorganized in one way or another. For one, the former Institute of Chemical Metallurgy with which two of the authors of this article are affiliated was renamed the Institute of Process Engineering (IPE) in 2001, due to the broadening of its research activities and scope to include different levels of process industries with emphasis on temporal-spatial multiscale structures. Similarly, Nanjing University of Chemical Technology was renamed Nanjing University of Technology to reflect its expansion into broader fields. The Petroleum Refining Department of the University of Petroleum was expanded to become the College of Chemistry and Chemical Engineering in 2000. The College of Materials Science and Chemical Engineering at Zhejiang University was formed in 1999 by merging the departments of Chemical Engineering, Materials Science and Engineering, and Polymer Science and Engineering of Zhejiang University with the Polymer Chemistry Division of Hangzhou University. The aim was to intensify the interactions between materials science and chemical engineering.

Research collaborations are encouraged. The National Key Lab in Chemical Engineering was jointly established by Tsinghua University, Tianjin University, East China University of Science and Technology (ECUST) and Zhejiang University to foster fundamental research in chemical engineering. There are also specializations, such as the Laboratory on Manipulable Chemistry at the Beijing University of Chemical Technology. At present, there are 169 institutions engaging in chemical engineering and technology, most of which are being upgraded significantly. These chemical engineering colleges are often made up of separate departments such as chemical engineering, chemical technology, biochemical engineering, applied chemistry, industrial catalysis and powder technology, as well as various research centers and key laboratories. For instance, the college at the South China University of Technology (SCUT) is made up of Chemical and Energy Engineering, Light Industry and Foods, Resources and Paper-Making, Biotechnology, Environmental Engineering, Materials Science and Engineering, Equipment and Control, and Chemistry. This expansive structure makes it easier to deal with large-scale projects that require expertise in areas ranging from process design and equipment design to basic chemistry. This feature is even more pronounced at the CAS institutes such as the Institute of Process Engineering, Dalian Institute of Chemical Physics, and the Institute of Coal Chemistry in Shanxi.

Not surprisingly, most of these colleges have a large faculty and many students. For example, at the School of Chemistry and Chemical Engineering at Dalian University of Technology (DUT), there are 56 professors, 95 associate professors, and nearly 330 PhD students. The number of PhD students in Zhejiang's program is approaching the 500 mark. Many faculty members in leadership positions are in their forties or younger, being the students who entered university after the disruptions of the Cultural Revolution (1966-1975). The youth and depth of this talent pool bodes well for the future development of chemical engineering.

There is extensive collaboration between industry and the chemical engineering colleges. Those industries which used to be state-owned enterprises often sponsor a college to the extent of up to 60% of its R&D budget. Because of all this industry-led research, pilot plant equipment is more common in a university laboratory in China than in the U.S. The advantage of this market-driven approach is that the work is more likely to be put to use immediately. The potential disadvantage is that the research may not be sufficiently fundamental according to the standards elsewhere. However, if executed properly, industry-led development represents an opportunity for China to pursue practical yet fundamental research in process engineering.

Despite the euphoria of growth, one has to remember that the GDP per capita in China is only slightly above U.S.$1,200 a year. Process engineering has been identified as a key component in China's drive to become a competitive manufacturing

Table 2. Challenges to be Addressed through Process Engineering (adapted from Li et al., 2004b)

- Product quality and production capacity cannot meet market demand
- Importing rather than developing its own products and processes
- Most industrial enterprises are too small with obsolete equipment and their technologies are not sufficiently competitive
- Environmental problems and inefficiency in energy usage
- Technology transfer is difficult because research, process design, and manufacturing are not sufficiently integrated

center for the world — moving from textiles, toys and household appliances to other high-end products, thereby improving the standards of living of its people. There are many challenges to be overcome in order to realize this goal (Table 2).

Steinfeld (2004) has remarked that "Chinese enterprises have become extensively linked with the global economy, yet in a shallow manner. They remain stuck in commodity manufacturing, undifferentiated activities for which innovation is absent." While the weakness in developing its own technologies is still true at this moment, China has unique strengths to overcome this problem (Table 3).

The basic sciences in China are advancing rapidly. For example, China ranks fourth in the total number of articles from outside of the U.S. published in ACS journals after Japan, Germany and the U.K., and is projected to replace Japan in the top spot within 15 years (C&EN, 2005). This is hardly surprising because considerable resources from the central, provincial, and city governments have been channeled to the universities, CAS institutes (e.g., Institute of Chemistry, Institute of Physics, and Technical Institute of Physics and Chemistry in Beijing), and research centers. The competition for these funds is fierce. For example, the success rate in the Division of Chemical Engineering and Applied Chemistry, Natural Science Foundation of China (NSFC) is less than one proposal funded out of five applications.

Given that process engineering is expected to play a key role in meeting many pressing needs for high quality products ranging from foods, pharmaceuticals and fuels, to simply clean air and water, how should China allocate its limited resources in process engineering R&D? It is helpful to address this issue from a multiscale, market-driven perspective.

Multiscale, Market-Driven Approach to Process Engineering

Multiscale concepts have been advanced by Villermaux (1995), Sapre and Katzer (1995), Lerou and Ng (1996), and Grossmann and Westerberg (2000) in the West. In China, multiscale methodology was investigated in the chemical engineering community in the early 1980s (Li et al., 1988), and this research has intensified in recent years with the introduction of the concept of complexity science and complex systems (Li and Kwauk, 2003). All of this effort has led to a special issue of *Chemical Engineering Science* (Vol. 59, 2004) entitled *Complex Systems and Multiscale Methodology*. A national project, *Temporal-spatial Multiscale Structures and their Effects in Chemical Engineering*, was initiated in 2004 in China.

The time and length scales of a typical processing plant from this multiscale perspective are shown in Figure 1. The regions

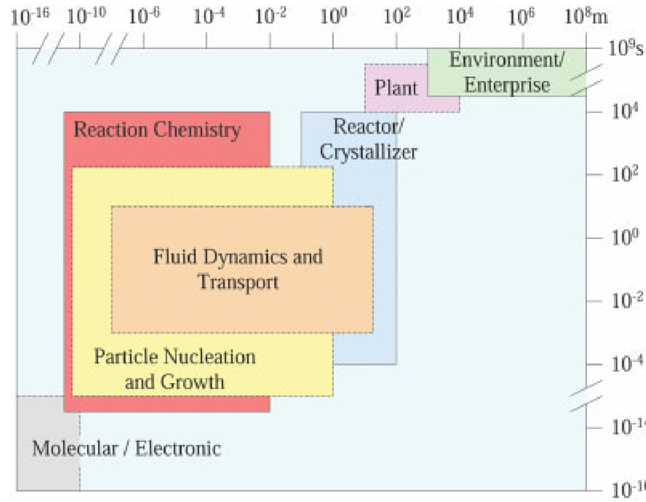

Figure 1. Length and time scales covered in multiscale view of a typical processing plant.

overlap and the locations of the boundaries for each region are not meant to be very exact. Contiguous regions signify the potential for interactions and synergy. The more the regions overlap, the more the scales interact.

One of the primary considerations at the **enterprise scale** is *what to make*, based on market analysis, and the state of art of science and technology. In addition, supply chain management issues such as make-buy decisions and toll manufacturing, and alliances and licensing can have enormous impact on profitability. The **plant/equipment scale** is the traditional area of process engineering which involves process design, equipment design and scaleup, and operations. Here, the key issue is *how to make*. The **particulate/continuum scale** where reactions and transport dominate has been a rich and fruitful research area for chemical engineering sciences. In addition, the recent advances in nanotechnology point to great potential for innovations to emerge from the study of the overlap between chemistry, solid-state physics and process engineering (in terms of reaction and transport) at the nanoscale (Li and Werther, 2005). Considerations at the **molecular scale** are critical for reaction chemistry, etc., but there is normally limited benefit in linking them to enterprise level issues. Clearly, after identifying what to make and working out how to make, it does not necessarily mean that it will be made. The *to-make or not-to-make* decision depends on whether the project meets the relevant financial metrics, as well as the objectives at various levels in the company hierarchy (Ng, 2005). This approach for process engineering is discussed in more detail below.

Table 3. Strengths in Support of the Development of Process Engineering

- Strengths in basic sciences—chemistry, physics and mathematics
- Well-developed education system with a large talent pool
- Rapidly improving national support and infrastructure for research
- Influx of talent from overseas
- Influx of foreign direct investments and technology transfer
- Vast internal market for all kinds of products
- Entrepreneurial spirit

Market-driven Demand-led Product Innovations at the Enterprise Scale

The need for product design and engineering has been stressed by Tanguy and Marchal (1996); Wintermantel (1999); Kind (1999); Seider et al. (2004); Cussler and Moggridge (2001); Wibowo and Ng (2002); Gani (2004), and Hill (2004), and many others. As mentioned, at the enterprise level, one of the primary questions is what to make. To develop innovative and profitable products, we submit that these decisions should be made by working closely with each specific industrial sec-

Table 4. Classification of Processing Industries in China (after Li et al., 2004b)

Processing Industries	Industries with Process Engineering
• Food processing	• Metal surface finishing and thermal treatment
• Food products	• Metal casting
• Paper and paper products	• Powder metallurgy
• Printing	• Insulators
• Petroleum processing and coking	• Integrated circuits
• Chemical raw materials and products	• Electronic components
• Pharmaceuticals	• Tobacco processing
• Chemical fibers	• Raw fiber processing
• Rubbers	• Cotton dyeing
• Plastics	• Wool dyeing and finishing
• Non-metallic minerals	• Silk dyeing
• Ferrous metal smelting and calendering	• Electric power generation
• Non-ferrous metal metallurgy and calendering	• Gas from coal
	• Drinking water

tor. No one knows better about customers' wants and needs than the marketing people in the business. Yet, once the product attributes such as form, function, color, mouth-feel and hand-feel, etc. are specified, it is up to the chemical engineer to select and transform the raw materials into the desired product which might possess a complex structure or configuration to impart the desired functionalities. Indeed, every industrial sector has its own idiosyncrasies in terms of product attributes, processing technologies, equipment type, and product testing procedures. Detailed knowledge in each area is essential in order to realize the full benefits of chemical engineering principles.

Consider the textile and garment industry. A large number of innovative products have appeared on the market, including GORE-TEX,® wrinkle-free, water-repelling, and self-cleaning fabrics. These involve the application of technologies related to membranes, emulsions, polymers, nanoparticles, and catalysts. Also, many processing steps including weaving, dyeing, finishing, and coating are needed to transform natural and man-made fibers into the clothing that appears in the department store. At present, a significant fraction of the product specifications, textile chemicals, and manufacturing technologies come from overseas. Recently, the government approved a US$35 million grant to establish an R&D center at the Hong Kong Polytechnic University to pursue innovations along the entire textile and apparel value chain. China's highly competitive garment industry can serve as the foundation for developments in this area.

Another example is traditional Chinese medicines and dietary supplements. China has a long history and rich experience in using herbal products. The compounds in these natural products are not as well characterized as the organics in the petrochemical industry, yet it is not unusual to have a concoction that contains five or more active ingredients derived from a number of herbs. To formulate and produce such products with acceptable quality assurance is an interesting and challenging problem that requires close collaboration between chemists, biologists, chemical engineers, pharmacologists and medical personnel (Ko and Ng, 2004).

Our proposal here is in agreement with Landau's view (1997). Fearing that there is excessive science and not enough engineering in the academic arena, Landau has argued that ". . . chemical engineering's third paradigm, if there is one, is to return the discipline closer to the practices in industry and to strengthen interdisciplinary ties . . .". Observing that a business graduate can earn more money than a PhD chemical engineer, Landau also commented that "the rigorous training in the systems approach of chemical engineering often can qualify able chemical engineers to go into general management". While we may not want to be a manager or a financial officer, a better understanding of the business at the enterprise level can certainly amplify the impact of process engineering in a given industrial sector.

Electronic materials engineering and pharmaceutical engineering have already taken hold in the U.S. chemical engineering community. It is up to the researchers and industrialists in China to choose which of the processing industries to emphasize. Table 4 shows the primary processing industries as well as those processing industries with extensive process engineering in China. It is estimated that these processing industries account for 16.6% of China's GDP. One can refine this table by adding other sectors and subsectors, such as personal care products, biofuels and other bioproducts. However, most important is to come up with high quality, high value-added and innovative products that can meet market needs.

Product-centered Process Development at the Plant and Equipment Scale

In this era of globalization, there is relentless pressure to shorten time-to-market. For consumer products, such as personal care, office and home products, the response time is measured in months. The primary concerns are technology transfer and management of existing plants. If a large-scale grassroots plant is needed to manufacture commodity chemicals, it is highly desirable to be able to build such a plant with minimum investment in three years or less, beginning with the chemistry recipe. To achieve such technical goals, the necessary experiments and calculations for process design must be identified and executed systematically and expeditiously, using the proper facilities and software tools. On the management side, a team must be assembled with the requisite technical skills, and it is important to be realistic about what is achievable in the specified time, with the available human and monetary resources, and technology. China has little choice but to learn to move fast and to innovate.

For truly new products and their corresponding new processes, typically little physical or chemical information is known in the early stages of conceptual design. In fact, in **process research and innovation**, effective collaboration be-

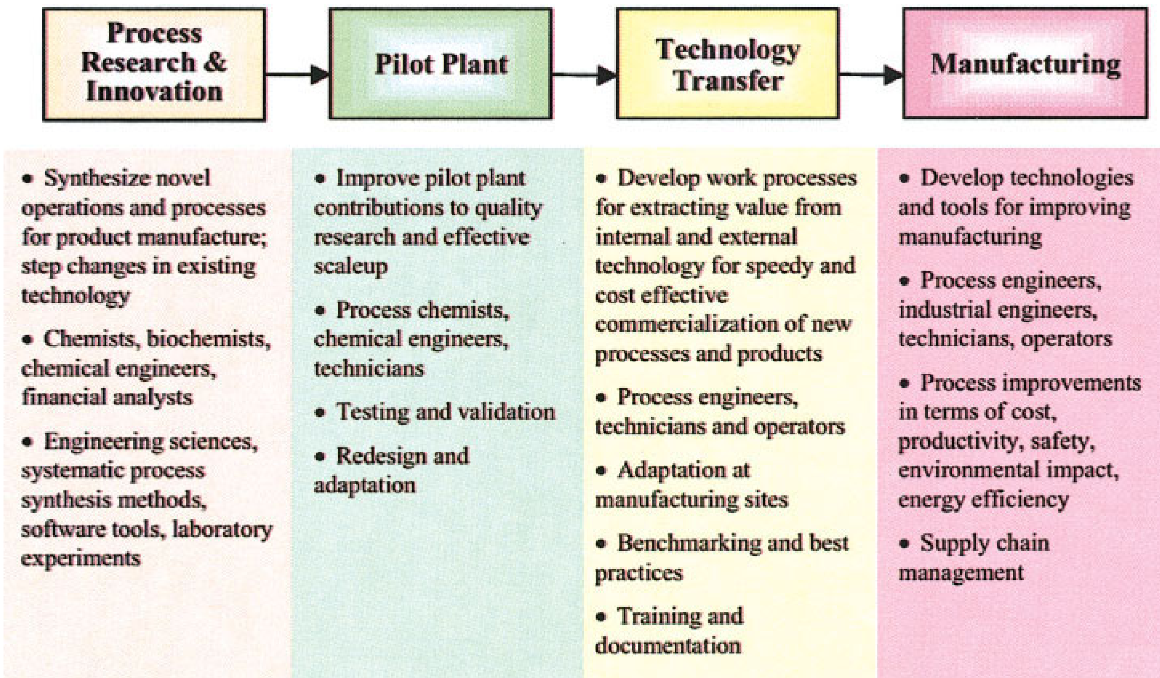

Figure 2. Objective, stakeholders, and tasks in the four areas of process development (after Ng and Wibowo, 2003)

tween chemists and chemical engineers in the concurrent development of chemistry and engineering has been identified as the key for shortening time-to-market and designing a better process. Another important element is scale-up. **Pilot plants** are often indispensable in scaling up small scale experiments to the commercial plant, and a process involving units, such as multiphase reactors, crystallizers, and in general any solids processing units cannot be reliably designed without pilot-plant testing (Bisio and Kabel, 1985; Ng, 2002a). Third, many companies conduct contract research, and custom manufacturing, and have R&D centers and manufacturing sites in China. Chinese firms have also started to acquire foreign assets as is evident from the highly publicized bid for Unocal by CNOOC. Thus, research collaboration can now involve people with different technical backgrounds and cultures in laboratories all over the world. Effective **technology transfer** is a crucial element in successful commercialization. Fourth, **manufacturing** excellence through process development and supply chain management is needed. SINOPEC, for example, has been making major efforts in developing IT for improved competitiveness (Wang, 2003). There is a widespread perception that manufacturing is important only for commodity chemicals. However, according to one estimate, savings of US$500 million can be realized over the patented life of a typical blockbuster drug on the market if the manufacturing process is properly designed.

Recently, this movement toward effective process development has culminated in the formation of a new Division of the American Institute of Chemical Engineers (AIChE) — the Process Development Division (www.pd-aiche.com). It consists of four areas: Process research and innovation, pilot plants, technology transfer, and manufacturing. Figure 2 shows the four areas of process development, along with a brief description of the associated vision, the stakeholders, and examples of activities and tools involved.

With their close collaboration with industry, research institutions in China are well positioned to develop workflow for every phase of process development (Wibowo et al., 2003). Workflow refers to a set of activities and the corresponding flow of information among stakeholders to achieve a clearly defined set of technical and managerial objectives. *It is absolutely critical to take into consideration the human factor in workflow.* It is not unusual to find well-designed experimental setup and highly sophisticated software that is underused or idle in an industrial laboratory. The engineer does things the old fashioned way because the new tools simply do not fit in well. To achieve excellence in process development, and thereby a shortened time for product launch, systematic planning and execution of a process development project through workflow is essential.

Another opportunity lies in the development of low-cost, high-performance equipment for process research, pilot-plant and manufacturing. With extensive experience in pilot plants, Chinese research institutions are well placed to innovate in equipment design. Developing specialized equipment for nanomaterials and bioprocessing is a particularly fertile area in need of new ideas.

Expansion of Chemical Engineering Sciences

China can afford to engage in a broad spectrum of chemical engineering science areas because of the sheer size of its research community. Table 5 shows a collection of topics identified by leading Chinese researchers looking forward into the future of chemical engineering. Similar topics have been and are being pursued in developed countries.

However, with its late industrialization, China has to focus on selected fields. It is important that China pursues engineering science research which will have a real impact on industrial practice in its manufacturing industries. One way to ensure that

Table 5. Frontiers and Needs—Topics Discussed by Li et al. (2004a)

- Nano Scale Technology, Process, Equipment and Products
  - ○ Molecular engineering and process engineering
  - ○ Surface and interface
  - ○ Micro chemical engineering systems
  - ○ Biodiesel research and applications
  - ○ Enzyme catalysis, enzyme engineering and genetic engineering
  - ○ Nanomaterials and surface modification
  - ○ Microencapsulation
- Complex Systems/Nonlinearity/Multiscale Structure
  - ○ Multiscale structure of copolymers and surface active agents
  - ○ Emulsions and micro-emulsions
  - ○ Polymer engineering
  - ○ Biosystem complexity and process engineering
  - ○ Reactor scaleup
  - ○ Complex systems and multiscale methodology
- Computer Simulation and Integrated Systems
  - ○ Molecular simulation
  - ○ Statistical mechanics and density functions
  - ○ Computational fluid mechanics and parallel computing
  - ○ Integrated systems (process synthesis/integration) and industrial ecology
  - ○ Computational mass transfer
  - ○ Multiobjective optimization
  - ○ Computational molecular science
- Resource-related Chemical Engineering
  - ○ Coal processing
  - ○ Biomaterial utilization—fundamentals of effective transformation of straw to liquid fuel
  - ○ Traditional Chinese medicine modernization and natural pharmaceutical product extraction—chemical engineering fundamentals
  - ○ Non-metallic minerals
  - ○ Metallic minerals
  - ○ Ecological resources utilization
  - ○ Petroleum—catalysis, reactors and technology
  - ○ Catalytic transformation of natural gas
  - ○ Gas hydrates
- Molecule and Super Molecule Design, Products for Chemical Engineering
  - ○ Product engineering
  - ○ Fine chemicals
  - ○ Drug release systems
  - ○ Fine chemicals and photonic materials
  - ○ Biomaterials
  - ○ Strategy for developing pharmaceutical engineering
  - ○ Ceramic materials and electrode processes
  - ○ Membrane materials and processes
- Special and Multifunctional Chemical Engineering Process
  - ○ Supercritical fluid technology
  - ○ Plasma green synthesis technology
  - ○ Intensification of external fields
  - ○ Life processes
  - ○ Process intensification and coupling
  - ○ Reactor dynamics
  - ○ Special processes
- Data Determination, Utilization and Measurements
  - ○ Data mining
  - ○ Measurement technology

this happens is to demand industrial participation in and contributions to the research project. Nonetheless, the topics have to be selected in a balanced manner to allow room for curiosity-driven research.

A particularly important topic is energy-related research, including energy savings in chemical processes, coal liquefaction, biodiesel, and enhanced oil recovery. In 2002, the ratio of oil use to GDP in China was 0.17 (arbitrary units) while it was 0.1, 0.06, and 0.05 in the U.S., EU and Japan, respectively (The Economist, 2005), indicating considerable room for improvement.

Note that the multiscale, market-driven perspective is by and large applicable to the areas recommended by the task force on developing process engineering in China (Table 6).

Conclusions

Many opportunities in process engineering await China's participation and contribution — chemical-based consumer products, products based on nanotechnology and biotechnology, etc. The focus on innovative products by no means implies that the traditional petrochemical sector is less important. If one assumes an annual growth rate of 12% for the Chinese CPI for another decade, plant capacity must increase by three-fold in China. A similar prediction was made by Siirola (2004) in a wider context. Worldwide plant capacity must increase by more than five-fold by 2050 if a growth rate of 4% is assumed. With such high volume of production, any innovation translates into large economic impact. A special challenge for China is to develop its manufacturing capabilities while creating a knowledge-based economy in a much more compressed time frame compared to what was available to developed countries.

To meet this challenge, a multiscale, market-driven approach is proposed for the further development of China's processing industries. The stakeholders at each level have different skill sets ranging from managerial, to technical and scientific. The key is that decisions, technical or otherwise, be made in a hierarchical manner, from the enterprise scale down to the molecular scale. The decisions at each level should be made as transparent as possible to all stakeholders. This seemingly simple idea, if applied consistently, is expected to help guide the formation of a seamless academic-industrial structure for efficient product and process development. "Multiscale" opens a way to cope with complex systems in chemical engineering while "Market-driven" ensures its role in developing the economy.

In this market-driven approach, the measure of whether or not our profession is successful is the availability of job opportunities for chemical engineering graduates, which in turn depends on whether the research and teaching in our universities meet market needs. *The core of chemical engineering*

Table 6. Recommended Mid to Long Term Technological Goals (after Li et al., 2004b)

- Develop innovative technologies and processes that are suitable for national resources and needs
- Develop nontraditional conversion processes and those under extreme conditions
- Emphasize high performance computations and modeling of complex processes for use in process scaleup and control
- Strengthen the overlap between process engineering and process systems engineering, with emphasis on various process industries and industrial ecology
- Identify common features and problems among the various industries within the CPI, and develop general methods for each level of the hierarchical approach
- Develop core technologies as driver for strengthening the structure of the process industries
- Integrate research, design, and manufacturing

Table 7. Five Generic Skills/Abilities Least Fostered at University vs. Demands of Work (after Lin, 2004)

- Ability to communicate effectively
- Knowledge of methods for total quality management
- Knowledge of methods for project management
- Management skills
- Business oriented thinking/Business approach

should be decided, not only by what we think the science and engineering principles should be, but also by what our graduates, particularly those who decide to enter the workforce with a bachelor's degree, need in the workplace. Recently, the World Chemical Engineering Council conducted a survey on "How does chemical engineering education meet the requirements of employment?" Answers were received from 2,158 young chemical engineers in 63 countries (WCEC Secretariat, 2004). As pointed by Lin (2004), a better understanding of management and business issues can be beneficial (Table 7). This multiscale, hierarchical approach, along with a revitalization of the chemical engineering curriculum, should help. In a way, the demarcation between process engineering and business has become blurred. We have to understand technology-related managerial and marketing issues to be effective at work. In fact, business students are also learning more about chemical engineering (Ng, 2002b) and an engineering-business dual degree is now being offered at the Hong Kong University of Science and Technology (HKUST).

This multiscale perspective fits well with research in sustainable development, in which global objectives, industry strategy, enterprise targets, specific projects, individual actions/measured outcomes are viewed in an integrated manner (Batterham, 2004). Tools for dealing with sustainability issues such as stakeholder analysis, life-cycle analysis, indicators and decision analysis are now covered in courses for engineering students (Darton, 2004).

Finally, let us briefly touch on the inevitable question. Is the emergence of China's CPI a threat or an opportunity from the perspective of other countries? While many new plants are being built in China, most rely on imported technologies. China's technical know-how, managerial skills and industrial infrastructure lag behind those of developed countries. China can greatly benefit from an infusion of ideas and talent from developed countries and from its neighbors to accelerate its industrialization and its transition to a knowledge-based economy. In fact, similar issues are faced by various economies in Asia with significant growth in their respective CPI (Anonymous, 1997). Many reforms and developments in chemical engineering are taking place in Japan, Korea, Singapore, Malaysia, Thailand, and other Asian countries. For example, the creation of new business models has been a major focus in Japan (Hasatani, 2004). It is our hope that this article, in addition to the description of the multiscale, market-driven approach, will plant seeds for collaborations in this ever more open global village. We anticipate an increasing flow of information, people and capital among different countries, an accelerated pace of product and process innovation, a revitalized curriculum for process engineering, and a more versatile chemical engineer in the coming years.

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