Chemical Engineering in China: Past, Present, and Future

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The need to address ecological problems stemming from China's burgeoning industrial growth is the impetus behind many recent developments in China's surging chemical industry.

The modern chemical industry developed rapidly in the 20th century. Recent chemical engineering milestones — such as the integration of systems engineering methodologies, computer control, and advances in bioengineering and new materials — are at the core of today's chemical industry, and have made enormous impacts on human civilization.

The Chinese chemical industry experienced major changes in the past century as well. A huge and rapidly increasing demand for basic and specialty chemicals has spurred its development, creating a need for advancements in chemical engineering education, research, and development.

According to analyses by the American Chemistry Council (discussed in the Feb. 2011 issue of *CEP*, p. 16), over the next three years, China's chemical industry is expected to grow at a pace four times that of the U.S. chemical industry, and in 2011 China is poised to overtake the U.S. as the largest chemical economy. China's overall economy will inevitably surpass the size of the U.S. economy, currently the world's largest.

However, there is a fundamental difference between the development of chemical engineering in China and in developed countries. As one of the key industries driving the growth of the Chinese economy, the chemical industry experienced its rapid expansion only in the past 30 years, compared to century-long progress in developed nations. While China is now building a world-class chemical economy, it still faces immense sustainability challenges in terms of energy, resources, workforce, and the environment.

The beginnings of the Chinese chemical industry

Until the 1980s, the chemical industry in China was still in its infancy. To meet the basic demand of feeding 20% of the world's population (1.3 billion people) using only 7% of the world's arable land, the chemical industry focused on the production of fertilizers, pesticides, and herbicides to support the rapid expansion of Chinese agriculture. However, while chemical fertilizers should have ensured better crop yield, the insufficient technological foundation in the chemical industry, along with inadequate levels of engineering education, undercut progress. China could not produce enough fertilizers to meet demand, and what was produced created heavy pollution and utilized resources wastefully.

Chemicals and petrochemicals. In the early 1980s, China began to import mature petrochemical process technologies from abroad, which led to its establishment as a competitive force in the petrochemical industry. Today, China leads the world in the production of chemical fertilizers, synthetic fibers, caustic soda, and polyvinyl chloride (PVC), and ranks second in the processing of crude oil and the production of ethylene and synthetic resins (Table 1). While current production of petroleum refinery products, nitrogen and phosphate fertilizers, pesticides, caustic soda, and inorganic salts meets or exceeds domestic demand, the production of ethylene, synthetic fibers and other materials, potassium fertilizers, and methanol is heavily supplemented by imports.

As the capacity for basic chemicals increased, technical indicators of capital efficiency, such as plant capacity in the petrochemical industry, have also been continuously improving. In addition, novel refining technologies for clean gasoline production with high-value olefin byproducts have been introduced, including a two-stage fluid catalytic cracking (FCC) technology that combines the functions of refining and propylene production.

Increased productivity, energy savings, and reduced CO_2 emissions have become central goals of the petrochemical industry and are driving science and technology development.

Meanwhile, limited resources remain a critical constraint to the development of the Chinese petrochemical industry. For example, in 2007, petroleum production in China was about 18.7 Mt and imports were about 16.3 Mt. This dependence on imported fuel continues to increase.

A coal-based chemical industry. In 2006, coal supplied 70.2% of the energy consumed in China, oil and natural gas supplied 23.5%, and the remaining 6.3% came from other sources. This is in sharp contrast to energy consumption in the rest of the world, where coal provided 28.4% of the energy. Since coal is an abundant natural resource in China, coal-based chemistry is a major factor in the development of the chemical industry, with large-scale clean-coal projects becoming the focus of development efforts.

The conversion of coal to methanol is increasing dramatically. New coal chemistry technologies, such as methanol to olefins (MTO), methanol to propylene (MTP), methanol to aromatics (MTA), and coal to synthetic natural gas (SNG), are being developed at the pilot scale. Moreover, the pilot use of methanol and dimethyl ether (DME) as alternative fuels aims to mitigate China's urgent demand for oil.

Until recently, more than 95% of China's needs were met by domestic energy resources. For exported products such as coke, calcium carbide, ferrosilicon, ferroalloy, aluminum ingot, and polycrystalline silicon, the amount of energy needed to manufacture each unit of product is rather large — so export of these materials implies an embedded energy export. It is estimated that, from 1997 to 2007, the total amounts of imported and exported energy in China were roughly balanced. However, due to the high rate of industrial development, China's environmental burden has been increasing at substantial rates because of heavy pollution.

Specialty chemicals and materials. Concurrent with developments in the petrochemical and coal-based chemical industries, the production of specialty chemicals such as pesticides, paints, and additives has also seen high rates of growth. However, these products are of lower added value and are produced using less-advanced technologies.

Still, current Chinese R&D capabilities cannot meet the anticipated demands for future mass production of specialty chemicals. This weakness creates excellent opportunities for collaboration between Chinese specialty-chemical manufacturers and foreign chemical companies, technology developers, and product formulators.

Table 1. China is now a world leader in production volume for many major chemical and petrochemical products (10^4 t).

Product	2000	2007	World Rank
Tires	12,158	55,638	1st
Refined oil	20,238	32,679	2nd
Fertilizers	3,091	5,696	1st
Sulfuric acid	2,365	5,391	1st
Nitrogen	2,398	4,187	1st
Synthetic resins	1,079	3,038	2nd
Soda	834	1,772	1st
Caustic soda	668	1,759	1st
Calcium carbide	340	1,482	1st
Phosphate	663	1,257	1st
Methanol	199	1,076	1st
Ethylene	470	1,048	2nd
PVC	240	972	1st
p-Phthalic acid	202	933	N/A
p-Xylene	130	350	N/A
Potassium	30	250	N/A
Synthetic rubber	84	222	3rd
Pesticides	65	173	1st
Engineering plastics	4	56	N/A

Innovations in clean energy and low-carbon techniques

Pollution control is one of the biggest challenges faced by the Chinese chemical industry. For the period 2006–2010, the government issued guidelines requiring the SO_2 emissions index and the chemical oxygen demand (COD) index to be reduced by 10%. At the same time, it is accepted that the most rational route to implementing pollution control would be through innovative production technologies that lead to zero-emission process designs, especially for the coal-based segment of the chemical industry.

The ENN Group, a private enterprise in China, has established a research center where it has been pursuing the integration of novel technologies and engineering methodologies, and in 2009 it unveiled a coal-based clean energy, zero-emission production technology at the pilot scale (Figure 1). It is anticipated that this integration of low-carbon technologies will lead to the successful incorporation of solar energy, wind energy, and biotechnology with the coal-based chemical industry, providing an effective solution to the CO_2 emission problem. Furthermore, underground processes based on steam-oxygen gasification, catalytic gasification, and methanation technologies are directed toward the development of clean and low-carbon processes that convert dirty coal to clean and low-cost energy.

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Another series of innovations is targeting the clean production of PVC resins. In 2009, the annual production of PVC in China was about 12 Mt, and was mainly based on the conventional carbon calcium route, which uses mercury as the major component of the catalyst that converts acetylene and hydrochloric acid to vinyl chloride monomer (VCM). This creates severe environmental pollution in terms of waste gas, dust, mercury, and wastewater.

As a remedy, China has been exploring coal pyrolysis to produce acetylene in thermal plasma reactors. In this process, pulverized coal is injected into hydrogen plasma at ultrahigh temperatures and supersonic flow velocities. Byproducts of the coal-to-acetylene conversion include hydrogen, ethylene, methane, and carbon monoxide. The clean, coal-based process is also attractive because it is a one-step conversion technology that does not produce direct emissions of CO_2 and does not need water as a feedstock.

Acetylene is a major feedstock for the synthetic chemicals industry. Technological breakthroughs in coal pyrolysis using plasma would revitalize the acetylene industry — an attractive prospect considering the increasing prices and scarcity of oil resources.

A mercury-free process to synthesize VCM is also being explored, and is expected to be commercialized within five to ten years. Successful development of this and the acetylene process would revolutionize the production of PVC, a process that started from coal.

A novel gas-solid contacting process to make chlorinated PVC (CPVC) using cold plasma to initiate the chlorination process is in development. This process generates significantly less pollution than the conventional aqueous-suspension method.

These examples illustrate the guiding principle behind present-day R&D in the Chinese chemical industry: addressing ecological problems through technological innovation. This principle is expressed in the scope and content of China's educational and research programs.

Furthermore, the government encourages the establishment of industrial clusters, which through innovative integration of production facilities can reduce net pollution and the environmental impacts of the cluster's effluents. More than 100 so-called eco-industrial demonstration parks have been established so far. Within each of these, the factories can optimally allocate the flows of materials, energy, effluents, value streams, and information streams — for example, waste streams and waste heat from Plant A can be utilized by Plant B. In this manner, the industrial chain is extended, the network of integrated operations across different processing plants is expanded, and the entire system is well integrated to achieve the best efficiency.

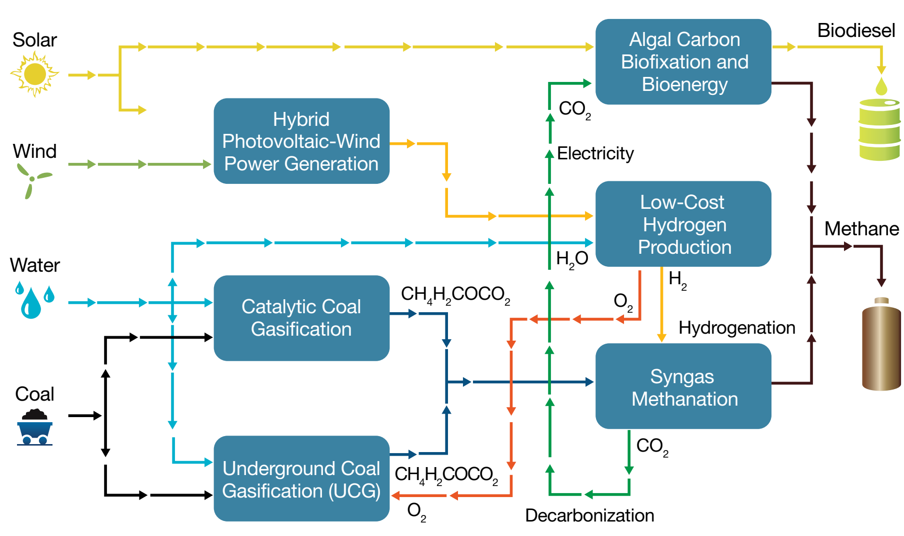
Broadening chemical engineering education

The rapid development of its chemical industry is driving the growth, in terms of both size and quality, of China's chemical engineering education and research.

In 2007, 2,073 universities offered courses in engineering, and most of them offered degrees in chemical engineering. With the most engineering students in the world (891,000 students entered engineering schools in 2007), China would be expected to have the largest population of chemical engineering students. Yet, the role of chemical engineering as a discipline is not fully appreciated in Chinese society — a reality incompatible with the need for rapid development of the national chemical industry. This attitude may be attributed to historical perception of the chemical industry in China — one involving pollution, safety issues, and harsh working conditions.

In an effort to guide high school students into chemical engineering, educators are redefining what it means to be a chemical engineer and better explaining the pivotal role that the discipline will play in advancing China's economy and quality of life. Educators want students to see chemical engineering as an innovation area where one can become an inventor and entrepreneur, derive satisfaction from professional success, and make a positive impact on society.

To this end, Chinese professors have proposed a new chemical engi-



▲ **Figure 1.** China's ENN Group has proposed a coal-based low-carbon emission technology that aims to integrate solar energy, wind energy and biotechnology with the coal-based chemical industry.

neering paradigm, defining it as the *transfer and transformation of materials, energy, and information* — a definition that integrates the three key elements of any chemical process and, by extension, of the chemical engineering discipline. This definition embodies the fusion of chemical engineering with other disciplines, such as chemistry, physics, and biology. With this mindset, the latest discoveries in other disciplines can be readily introduced into chemical engineering — an approach that allows developments in these areas to become starting points for further growth and knowledge sharing.

Advances in research and technology

Today, China's national science and technology development strategy serves as a guide for setting the country's technological priorities, with universities conducting fundamental research according to the needs articulated by the chemical industry. The result has been a series of new technologies that have fueled a revolution in the Chinese chemical industry. This approach has also led to the extensive licensing of major technologies — developed in China — by chemical companies from other countries, including FCC technologies with olefins as byproducts, deep catalytic cracking (DCC) processes, and large-scale gasification technologies using opposed multi-burner (OMB) gasifiers.

Another reflection of China's new competitiveness can be found in its published research. A 2007 report of the U.S. National Research Council, "International Benchmarking of U.S. Chemical Engineering Research Competitiveness," noted a tenfold increase in Chinese publications from 1990 to 2006. Today, the number of peer-reviewed articles by Chinese researchers in Science Citation Index (SCI)-listed journals is the third-highest in the world.

Despite this progress, China still lacks core innovations with significant impact on the emerging areas of science and technology. Furthermore, the efficiency and success rates of technology transfer from R&D labs to commercial applications are still relatively low. To overcome these weaknesses, the government has offered incentives to encourage the establishment of strategic R&D alliances for new technologies, such as in iron-and-steel-related processes and products, new generations of clean-coal technologies, and others.

Wrapping up

Although the Chinese chemical industry is now a major part of the world's chemical economy, it remains a very young industry. It grew at dramatic rates over the last 30 years, initially through large imports of process technology packages and then gradually through homegrown technologies based on Chinese research. Today, China, with the world's largest population, must rely on its own abilities to innovate and establish advanced, sound chemical industry systems with a strong foundation in education, research, and development, in order to fulfill the national demand for sustainable development.

China's openness to the world creates many opportunities for chemical engineers, from both China and overseas. In other words, China is developing economically with a global vision, but is acting locally. In a sense, China is creating a unique model for social and economic development that is different from what is typical in Europe and North America. Opportunities and challenges are vast, attractive, and exciting, and offer synergistic interaction between China's development in the chemical industry and advancement of the chemical engineering discipline in terms of education, research and development, and growth in professional effectiveness and satisfaction. CEP

Further Reading

Cheng, Y., *et al.*, "Inlet Effect on the Coal Pyrolysis to Acetylene in a Hydrogen Plasma Downer Reactor," *Candian Journal of Chemical Engineering*, **86** (3), pp. 413–420 (2008).

Chen, J. Q., and Y. Cheng, "Process Development and Reactor Analysis of Coal Pyrolysis to Acetylene in Hydrogen Plasma Reactor," *Journal of Chemical Engineering of Japan*, **42** (Supplement 1), pp. 103-110. (2009).

Wu, C. N., *et al.*, "Thermodynamic Analysis of Coal Pyrolysis to Acetylene in Hydrogen Plasma Reactor," *Fuel Processing Technology*, **91** (8), pp. 823–830 (2010).

Wu, C. N., *et al.*, "Analysis of Key Techniques and Economic Feasibility for One-Step Production of Acetylene by Coal Pyrolysis in Thermal Plasma Reactor," *CIESC Journal*, **61** (7), pp.1636–1644 (2010).

Acknowledgments

This article is based on a Perspective article of the same title published in the March 2011 issue of *AIChE Journal* (vol. 57, no. 3, pp. 552–560). The authors express heartfelt gratitude to Pablo G. Debenedetti of Princeton Univ. and George Stephanopoulos of MIT for their invitation to write that article and their editorial efforts to improve the manuscript.

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