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Review

Coal to Liquid (CTL): Commercialization Prospects in China

Production of fuels/chemicals from syngas ($CO + H_2$) is receiving increased attention with the background of the resource depletion and the unstable prices of petroleum oil. The fuels, especially diesel, obtained from the syngas conversion via Fischer-Tropsch synthesis (FTS), are proved to be of very high quality that will contribute much to environmental protection and raising the energy efficiency in the transportation sector when modern diesel engines are massively applied in vehicles. FTS technologies developed in recent years have reached the stage for the feasibility of construction of large-scale complexes. Under a long-term consideration of developing the field of coal to liquids (CTL), major issues in successfully applying CTL technologies are those controlling the feasibility of all kinds of projects. Points identified are, in general: (1) efficiency advantage over conventional processes (e.g. thermal power generation process); (2) cost and economic benefit; (3) environment advantage. These questions have been better answered using CTL-based poly-generation schemes. Among all the different schemes, in principle, the co-production of liquid fuels and electricity are naturally the main frame. The simple efficiency increase due to the better energy balance in the co-production mode and the environment protection advantage due to the easy-to-apply technology in the pollutant removal and treatment from syngas in a liquid fuel process has projected a bright future even for applying the more capital intensive IGCC + F-T scheme, which can raise the efficiency (to end products) from 43–46 % in either single schemes to about 52–60 %. This new process will guarantee a better solution to environment protection.

Keywords: Coals, Environment protection, Syngas

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1 Introduction

In general, China's confirmed coal reserve is above the magnitude of two compared to that of the oil reserve. It is generally agreed that China has to continuously use coal as the major primary energy source in a long-term consideration. This situation has been stressed recently because of the demand and supply conflict in China's petroleum market.

China is considering to establish a new field using its relatively rich coal resource to partially fill the oil demand and supply gap. This is not only politically but also economically feasible regarding the rapidly increasing liquid fuel demands due to the fast development of the economy of this country. Compared to other options in formulating the energy frame using oil replacements, production of liquid fuels from FTS provides a seeable way that is viable both technologically and economically [1–4].

Fischer-Tropsch synthesis (FTS) can be applied to convert the syngas from various non-petroleum resources, particularly coal in China. In addition, superclean fuels from FTS are believed to contribute to the environmental improvements in comparison with the best fuels available from conventional oil refineries [5]. Recent development in the advanced FTS technology has greatly been enhanced under the frame of the coal utilization program in China. This includes the development of efficient and low-cost synthesis catalysts, the slurry-phase reaction process at a pilot scale, and related process integration on the basis of a systematic development of Fischer-Tropsch reaction engineering [6–18]. These greatly enhance the industrialization of FTS in China.

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2 CTL Processes

2.1 General Features

A typical CTL process using Fischer-Tropsch synthesis is schematically presented in Fig. 1. The above CTL scheme is for the production of hydrocarbons (mainly straight chain olefins and paraffins) with high selectivity to heavy fraction (defined as ICC-HFPT in Synfuels China's CTL technology package; reaction temperature of 250 °C and pressure of 25 bar). This type of FTS process is thus very efficient for high quality diesel production. The experience in the pilot plant test in Synfuels China, Institute of Coal Chemistry (CAS) has shown that using slurry-phase FTS technology with iron catalysts, a well designed process can maximize the diesel selectivity up to 80 %, with small portions of LPG and high quality Naphtha, which can be very good feed stock for steam cracking to produce ethylene, for example. A similar Fischer-Tropsch technology has been demonstrated at the scale of 2500 b/d in SASOL for many years [1] and will be applied in several GTL projects in a few years - mainly by SASOL using cobalt based catalysts.

It should be noted that in a typical CTL process, major conversion steps between energy forms are gasification, converting solid coal to syngas, and FTS, converting the syngas to hydrocarbon products. These two steps are the key points to the total efficiency of the CTL process. This means to get the CTL process improved firstly from these steps.

Among available gasification technologies for large-scale production of syngas, there are actually only a few of them which have commercially been proved: (1) Lurgi fixed bed gasification, (2) Texaco entrained flow gasification using coal slurry, (3) Shell entrained flow gasification using dry powder of coal, and (4) GSP entrained flow gasification.

Lurgi fixed bed gasification has been operated in SASOL's CTL plant. This kind of gasification technology is suitable for gasifying coal with a sufficiently low sticky index and T_2 > 1200 °C. The syngas produced from this kind of gasification technology contains significant methane that must be carefully utilized in a CTL plant design.

Texaco gasification has also been commercially demonstrated for quite a long time. It is suitable for gasification of coal with relatively low content and low melting point (< 1350 °C) of ash. Texaco can produce high quality syngas with a (CO + H_2)-content over 96 % after removing the acidic gases.

Shell gasification technology has been successfully applied in Integrated Gasification Combined Cycle (IGCC) plants in Europe and there are tens of installations in the construction stage in China. This gasification technology may work at a temperature a bit higher than that of Texaco's, and the CO + H_2 in raw gas is higher too. Syngas quality is as good as that of the Texaco gasification.

GSP gasification technology developed at DBI (former German Fuel Institute) in former East Germany during the period of 1970–1995 has been buried behind the market in China for many years, although we have found the description in a standard Chinese handbook for ammonia synthesis. This technology used an entrained flow scheme and a simple design to significantly reduce the cost. The very interesting design of the burner ensures the safe operation at very high temperatures (up to 2000 °C). The quality of syngas produced from this technology is the same as those from Texaco or Shell gasification technologies. On the basis of this development, recent open information shows that some new versions have been proposed by two new companies from Germany, Choren and Future Energy.

A gasification technology with high efficiency is expected in CTL processes. In a typical CTL plant, the purified syngas production normally accounts for 60–70 % of the costs of the end products. A critical analysis for balancing between efficiency and economics of the syngas production is therefore very important. Analyses in our CTL study show that gasification technologies with a pressure of about 40 bar (or higher) and a CO + H_2 content as high as possible may be very competitive. Normally this is true if the capital costs for producing syngas for a certain quantity of final Fischer-Tropsch products that can be converted to useful products are at the same level.

Sasol has experienced more than 50 years of applying FTS technology in production of fuels and chemicals. The core synthesis technologies used in Sasol are known as low-temperature Fischer-Tropsch (LTFT) and high-temperature Fischer-Tropsch (HTFT). In LTFT, a precipitated iron catalyst is used in multi-tubular reactors, and spray dried iron and/or cobalt catalysts are used in Sasol's slurry-phase reactors. These reactors are

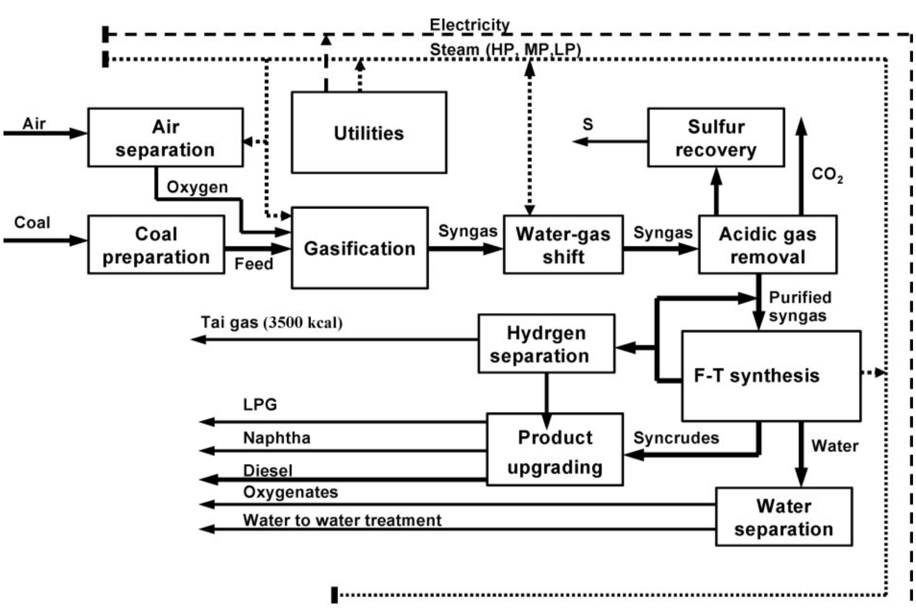

Figure 1. CTL plant frame (Synfuels China, 2004–2005).

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Table 1. CTL diesel properties (Synfuels China®).

Indexes	Hydrogenated Fraction Refinery $Co\text{-}MoS_2$ catalyst	Hydrocracked $Co\text{-}MoS_2$ catalyst	Hydrogenated Fraction S-free catalyst
Density kg/L	0.7684	0.7782	0.7664
Viscosity / mm^2/s, 20 °C	3.172	3.957	3.276
Initial boiling point / °C	150	130	185
Final boiling point /°C	370	385	330
Disti. Range / °C	–	–	–
5%	–	–	185–206.2
10%	154–188	138–184	213.7
30%	257	231	232.7
50%	278	272	252.7
70%	293	305	278.2
90%	323	332	310.2
95%	330	341	322
Dried	337	349	331.8
Flash point /°C	64	66	>70
Cetane number	74.1	66	75–90
Total aromatics %	0.4	0.7	–
Olefin /%	0.5	–	–
Sulfur / ppm	<4	<5	<0.5
CFPP / °C	–3	–34	–2

operated at 200–240 °C and 25–45 bar, favoring production of heavy hydrocarbon products with a low methane selectivity of typically about 4 %. In HTFT, a melted iron catalyst is used in gas-solid fluidized bed reactors at 25 bar and 340 °C to produce light fractions consisting of mainly unsaturated hydrocarbons with a methane selectivity of typically 6–7 %. The total capacity of Sasol CTL complexes is well above 160000 barrels/day. Recent open domain news shows that Sasol is expanding application of its LTFT (cobalt catalyst) for converting natural gas into typically clean diesel fuels in Africa and the Middle East.

Shell has been working on the commercialization of its SMDS technology of Fischer-Tropsch synthesis using the cobalt catalyst in multi-tubular fixed bed reactors. An about 12500 barrels/day-plant was put into operation using natural gas-derived syngas in Malaysia in 1993. The SMDS technology produces as much clean diesel fuels as possible from heavy synthetic crude from FTS. This technology can, in principle, be applied to CTL purposes as well.

There are quite a few other companies in the world claiming their FTS technologies. However, it seems that all are in the development stage, projecting more and more FTS technologies for the CTL plant owners to select in the future.

The diesel product properties from the CTL pilot plant of Synfuels China are summarized in Tab. 1. It is clear that CTL diesel has several advantages over existing diesel fuels in China's market:

- extremely low sulfur content
- very high cetane number
- very low aromatics content
- 8 %-fuels saving and significant emission reduction on a normal diesel engine test [5].

2.2 Efficiency Analysis of the CTL Process

Fig. 2 is a simplified form of Fig. 1 by dividing the CTL process into two parts: the syngas production and the FTS to final products. This figure is thus designed to easily see the overall input and output streams of materials and energy. The streams are defined according to the results from process simulation with HFPT process technology conducted in Synfules China, assuming that a dry-powder fed entrained flow gasification technology with heat recovery from the high-temperature syngas stream out of the gasifier.

Within Fig. 2, one may conduct a general analysis on the efficiency distribution in a typical CTL process. If this process is considered, the oil efficiency is a very good measure of the efficiency level of the CTL process to desired products that can be sold to the market. This can easily be obtained by using the tonne of coal equivalent (tce) quantities for different streams by applying:

$$\text{Eff (oil)} = \text{tce (8)/tce ((1)+(2)+(3)+(4)+(5))} = 528.183/1179.64 = 44.8\,\% \quad (1)$$

It is clear from Fig. 2 that major energy losses (if we cannot properly consider recovery of energy) are:

$$\text{Eff}_{\text{loss}}\text{(gasification boiler)} = 117.857/1179.64 = 10\,\% \quad (2)$$

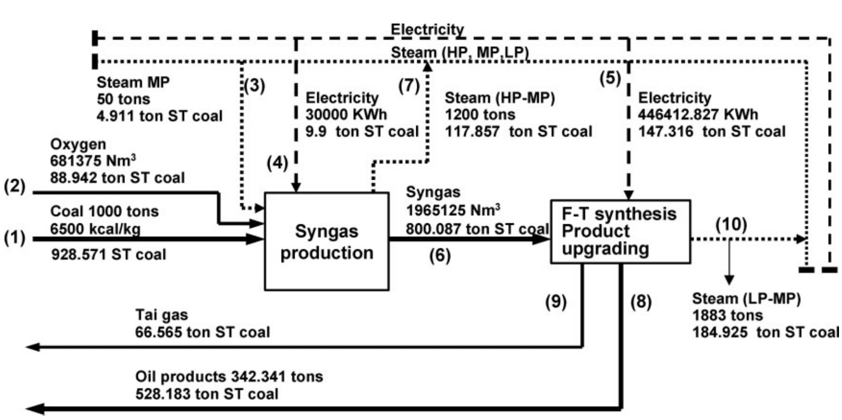

Figure 2. Main frame of the in-out diagram of a HFPT CTL process.

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$$\mathrm{Eff}_{loss}(\text{FT tailgas}) = 5.6\,\% \quad (3)$$

$$\mathrm{Eff}_{loss}(\text{FT reaction heat}) = 15.7\,\% \quad (4)$$

However, in a CTL process, the above defined efficiency losses can be reasonably recovered. For example, the HP/MP steam from gasification can be converted into electricity or simply used as the power for air compression, leading to saving input energy and thus increasing total efficiency by 3–4 %. However, recovering this part of the energy needs the input of significant capital investment. This is very crucial in evaluation of the gasification options in a CTL project. A similar situation holds for efficiently using the tail gas from the FTS loop if IGCC is applied, in which major concern may become significant increase in the capital cost for constructing the IGCC system.

The last part of the energy loss in FTS reaction heat has not sufficiently been noted because all recent effort in FTS technology development has been devoted to improving the catalyst and reactor performances. It is apparent that the latest FTS technologies using low-temperature synthesis conditions cannot meet the efficiency requirements in recovering the largest part of the loss in a CTL process. Typically for a cobalt catalyst, which seems to be a favorable choice for GTL processes, the operation temperature of the FTS reactor is typically about 190–220 °C, leading to large quantity of low grade steam (10–15 bar) from reaction heat removal. For meeting both this requirement and FTS performance, Synfuels China has successfully developed the LFPT process (reaction temperature 270 °C) using an iron catalyst in the slurry-phase reactor with low constructing and operation costs. The major benefit of applying the LFPT process over others is that the steam generated from the reaction heat can be upgraded to 25–30 bar due to the high-operation temperature (270 °C), keeping the methane selectivity at the level similar to those with low-temperature FTS.

3 CTL and China

3.1 Oil Supply Gap

The oil supply in China has been in a stage where the gap between the demands and the domestic production is expanding rapidly. According to open domain data, imported oil has reached the level of about 120 million tons in 2004. This number will certainly increase in the next decades in order to keep the economic development. Fig. 3 shows the case study of China's oil demand and supply from domestic oil fields [19]. It is predicted that the demands for the oil supply will reach the level of about 500 million tons annually by the year 2020. However, the supply from domestic oil fields will only meet less than 40 % of the demand and will decline afterwards.

Under the pressure from the dilemma of oil supply, developing oil replacements has been a focus in China. Ethanol produced from wasted foodstuff has been used in gasoline in several areas of China for demonstration, for which financial support from governmental organizations has been commissioned since 2001. Development of biomass-derived liquid fuels has received much attention. However, the technological development and energy policy system still need to be enhanced in order to systematically form a workable system that can notably reduce the demands for oil supply by using biomass resources.

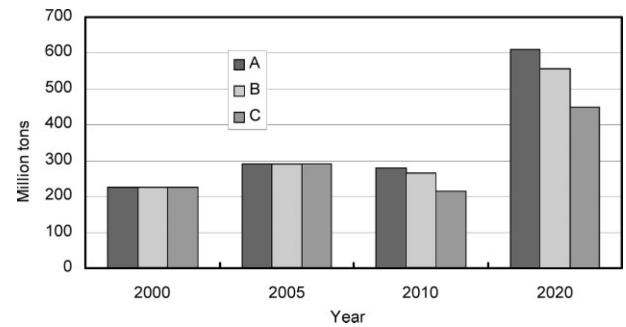

Figure 3. Study of three cases for China's oil demands (columns) and oil supply from domestic oil fields Case A: the current situation extrapolation of oil demands. Case B: the limited extrapolation with consideration of a strategy for reducing oil consumption. Case C: the limited extrapolation with consideration of a strategy for reducing oil consumption.

Coal with rich reserves is the major primary energy resource in China. About 5500 billion tons of coal resources exists as estimated in China Coal Industry Yearbook 1996, although confirmed recoverable coal reserves are 115 billion tons; about 40 times as much compared to oil reserves in the country [20]. It can therefore be concluded that developing oil replacements by using coal resources may constitute a feasible solution with consideration of both scale and technological factors, namely CTL will play dominant practical roles in a short and medium term for oil replacement production.

Despite other routes in CTL options, production of clean diesel fuel from FTS is obviously an advantageous solution for China: CTL via FTS has successfully been applied commercially at large scale. FTS using coal-derived syngas will have seamless connection with the future biomass feed stocks via gasification. FTS has been proved at large scale in producing high-quality liquid fuels and chemical feed stocks. The main products of FTS can be directed to super-clean diesel that can be combined with modern diesel engine technologies to formulate an energy system for the transportation sector with high efficiency (30 % reduction in fuel consumption compared to gasoline engine systems) and high environmental standards. FTS products will therefore provide a completely new and efficient transportation system by encouraging the use of diesel cars and burning superclean FTS diesel, regarding the rapid growth of the number of private cars and the population of the country. FTS products can be seamlessly bounded to existing infrastructures, projecting a better mines-to-wheels and life cycle economy than any other CTL options.

For a long-term sustainable consideration, a road map regarding resource availability and product demands is shown in Fig. 4. Apparently, the current major use of coal is in the power plants that use combustion boilers, and using coal for electricity generation will continue but will gradually transfer to using IGCC-type technology in power plants. FTS will seamlessly come into the chain to convert syngas, currently

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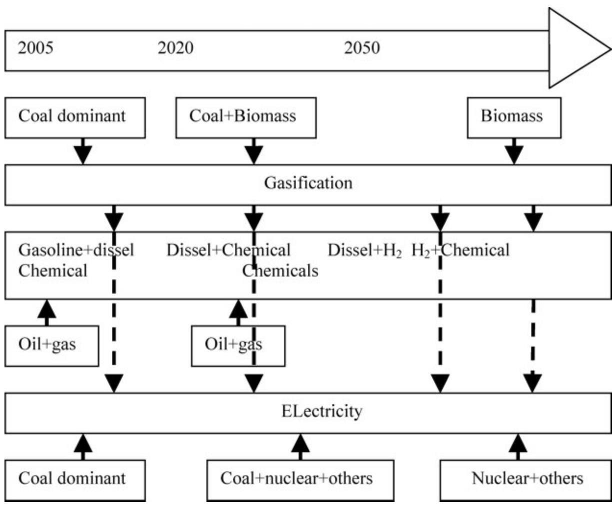

Figure 4. Road map of China's energy resources and demanded products.

from large-scale gasification systems, into clean diesel fuel and chemicals. For a very long-term consideration, biomass-derived syngas can be converted to chemicals and if necessary, to fuels via Fischer-Tropsch technology, implying a long span of FTS technologies.

3.2 Fischer-Tropsch Synthesis: Technology Status in China

3.2.1 Brief History: FTS in China

Development of FTS technology has mainly been conducted in the Institute of Coal Chemistry under the Chinese Academy of Sciences. This can be divided into two different stages. Before 1997, focus was placed on the iron catalyst to be used mainly in fixed bed reactors. Slurry-phase FTS was studied in the laboratory. In that stage, tracking back to the early 1980s, ICC had not systematically focused on the fundamental investigation, leaving many basic questions beyond a better understanding. Only a few international publications in fundamental studies appeared in that period [21, 22]. The fixed-bed FTS, called the MFT (modified Fischer-Tropsch) technology, using precipitated iron catalysts was scaled up to a demonstration plant of about 40 barrels/day in 1993, and that project did not run well because no support was gained due to the extremely low oil price at that time and some deficiencies in the economic aspects of the fixed-bed FTS using iron catalysts.

After 1997, FTS development in the ICC was assigned to go back to emphasis on the fundamental investigation of the FTS process technologies with a focus on the slurry-phase FTS. The starting point was the reaction engineering investigation on the basis of detailed kinetics studies together with catalyst development for slurry-phase FTS with the view of the process technology. In 2000, two iron catalysts were tested in laboratory-scale reactors with detailed kinetics investigation. Later, modeling of reactors and processes was conducted accompanying process analyses [9, 11, 12, 16], forming the basis of current scaling-up efforts.

3.2.2 Laboratory Investigation

FTS development in the laboratory has been extensively enhanced in Synfuels China (the research & engineering center of synthetic fuels) located in the ICC since 1997. Two types of iron catalysts have been developed for slurry-phase FTS (the co-precipitated Fe-Cu-K catalyst and the Fe-Mn catalyst) [7, 8]. Both catalysts are now scaled up accompanying the pilot plant mission. Using specific preparation procedures, including shaping with spray drying techniques developed in Synfuels China, the catalysts prepared have reached the level for long-term run in severe slurry conditions. Long-term runs both in the laboratory and the pilot plant reactors indicate that the catalysts named as ICC-IA for the Fe-Cu-K catalyst and ICC-IIA for the Fe-Mn catalyst have excellent performances under severe slurry FTS reaction circumstances.

For basic understanding of these catalysts, systematic study of long-terms run has been conducted in the laboratory. Runs for 4200 hours for the ICC-IA catalyst and for 4800 hours for the ICC-IIA catalyst were accomplished. Under laboratory conditions, experimental data show that these catalysts have very good stability for long-term run in slurry reactors. Kinetic

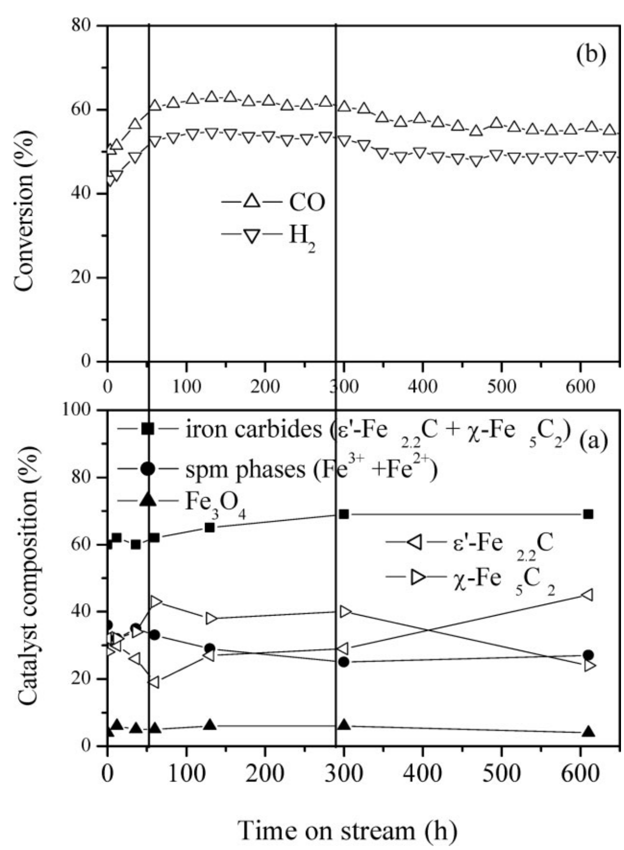

Figure 5. Correlative studies of phase transfer and activities of an ICC-IA model catalyst during FTS reaction.

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models have been developed for these model catalysts and will be optimized in the pilot plant tests. In order to improve the catalysts even further, the characterization using typically XRD, SEM, and MES is continuously performed to accumulate fundamental information on the FTS catalysis over these catalysts. One example of this type of studies conducted is continuously tracing the phase change in a model catalyst of ICC-IA using MES. As shown in Fig. 5, the phase status of the catalyst can be clearly correlated with the formation and transfer of iron carbides. More in detail, the Fe_5C_2 phase plays essential roles in FTS activity, while carbide phase with a bit more carbon ($Fe_{2.2}C$) have lower FTS activity than Fe_5C_2, and the Fe_3O_4 phase is apparently not positive for FTS in the reaction stage. More detailed MES parameter analyses show that FTS activity is also closely correlated to the dispersion of the active phases.

Kinetic studies are divided into two stages, the laboratory stage and the engineering scale-up stage. Most of the work conducted in the laboratory stage is focused on obtaining detailed mechanisms based on kinetic models, in which non-intrinsic effects normally implied in the experimental data were avoided in order to get the fundamental understanding of the kinetic behaviors of the pre-assumed surface steps involved in FTS. As many as possible mechanism possibilities are surveyed on the basis of the fundamental information available, as well as the information newly obtained through quantum mechanical calculations of the reaction steps over solid catalyst surfaces [23].

Advances in kinetic studies are ongoing, and improvements in established laboratory kinetic models [15] and expansion in the mechanism-searching domain are stressed. Even at this stage, it is understandable that our knowledge in the detailed FTS mechanism and the possible changes of the mechanism along the catalyst life cycle is still very limited, regarding the complexity of both FTS reactions and catalyst phases. In addition to the extensive detailed kinetics experiment and modeling analyses covering the formation rates of hydrocarbons and the WGS reaction rate, recent kinetic modeling has expanded to the selectivities of oxygenates. Oxygenates are in relatively small quantities compared to hydrocarbon products, but it is essentially important to understand the kinetics of the reactions producing them in view of further scaling up of the process. As in the kinetics study of the FTS main reactions, the kinetics model for the formation of oxygenates is on the basis of sets of pre-assumed mechanisms [24]. It can be seen that the surface steps listed may have totally different chemical forms in actual FTS reaction situations, keeping in mind that formation of most of the surfaces species defined in the mechanism description is lacking of experimental support. Especially for oxygenate formation over FTS catalysts (iron based), little information is available in the fundamental domain. It is even true for main FTS reactions. Nevertheless, the detailed kinetic models can predict the selectivities in an even better way. As an example, in the recent kinetics modeling of oxygenate formation, selectivities for major oxygenates detected in FTS products are well-described by the detailed kinetics model (see Fig. 6).

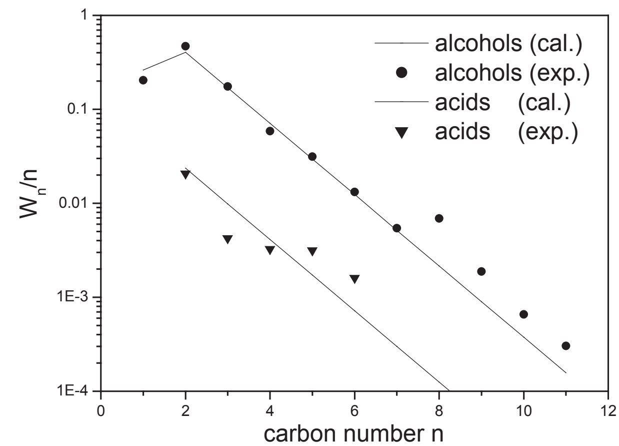

Figure 6. Selectivities of oxygenates in FTS.

With the increasing demand and importance of FTS technology, it is necessary to promote the activity of iron-based catalysts. This requires the understanding of the detailed FTS mechanism. However, the complexity of co-existing phases on catalyst surfaces hinders the detailed definition and understanding of the active phases with the analytical methods. In contrast, quantum-chemical study on FTS mechanisms with definite information from experimental characterization can provide the theoretical basis for technological development of catalysts and kinetic simulations of catalytic processes. Recent success using quantum mechanics/chemistry tools to study the molecular and atomic nature of various kinds of catalytic chemical processes in Synfuels China [25–31] has encouraged us to consider the catalytic processes on the phases of iron catalysts by using these mentioned theoretical tools. The first phase chosen is naturally the Fe_5C_2 with the strongest correlation with FTS activity. Preliminary study was on the quantum mechanical calculations (CASTEP [32, 33]) of CO adsorption on the (001), (110), and (100) surfaces of the Hägg iron carbide (Fe_5C_2), as shown in Fig. 7. Over these surfaces, CO molecules were positioned on various kinds of sites, and the adsorption modes and energy were carefully scanned. Calculations for adsorption modes of CO over these surfaces

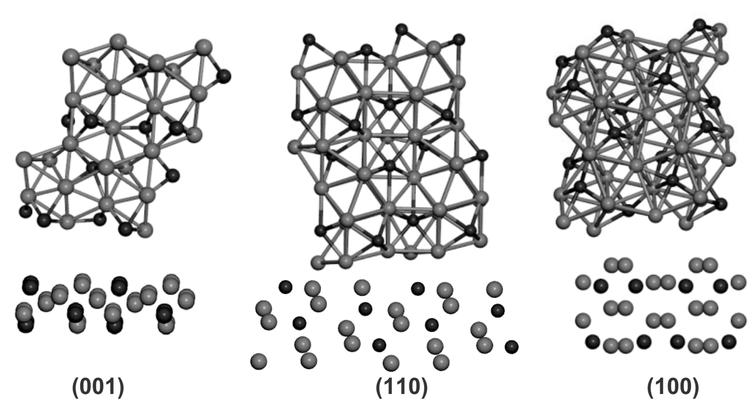

Figure 7. Schematic top and front views of $Fe_5C_2(001)$: (a) top and side views of (110), (b) top and front views of (100), (c) in a p(2_2) unit cell.

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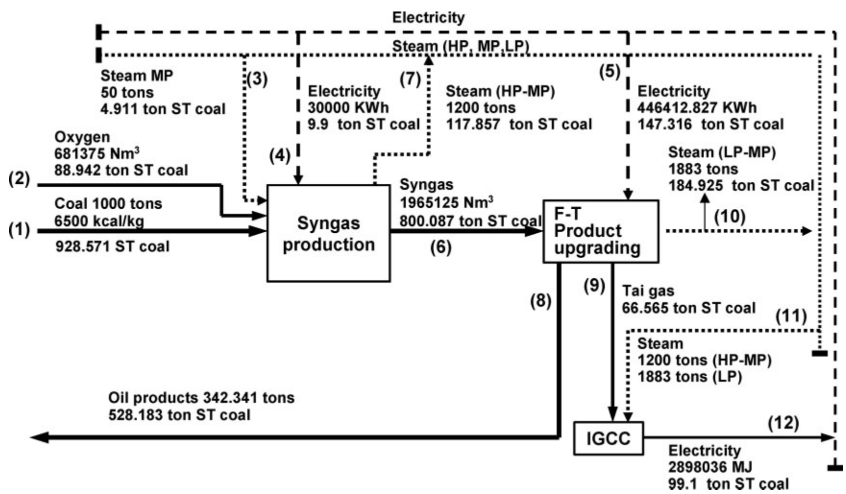

Figure 8. CTL combined with IGCC power generation.

under the coverage up of to 1/2 were performed. Twenty adsorption modes were identified, implying a complexity in CO adsorption on iron carbide phases [34]. The results from this kind of investigation are expected to be used for a comprehensive understanding of the mechanisms of FTS reactions over iron catalysts. For this purpose, further investigation of the interaction of the surfaces of several phases with CO and H_2, as well as other FTS molecules, are ongoing.

Most reaction engineering studies on FTS over iron catalysts are based on detailed kinetic results along with understanding the hydrodynamics of bubble column reactors through cold mode tests and CFD calculations. For this purpose, cold mode facilities were built in 1999 for mimicking the pilot plant reactor system. These before-head investigations have been shown to be very helpful in reducing the risk in the real pilot plant operation. In addition, process analysis (using ASPEN Plus simulation) imagined under different backgrounds have successfully assisted the implementation of the complete pilot plant that just constitutes all key parts necessary in industrial plants.

In summary, laboratory studies of the catalysis and catalysts, kinetics and reactors, and other fundamental aspects of FTS formed all the important concepts of the further scaling-up efforts. These studies with more and more enhancement are continuously playing the most important roles in the development of FTS technology initialized in ICC.

3.2.3 Pilot Plant Tests

The pilot plant for slurry-phase FTS process development was founded in 2001, 5 years after the last pilot plant operation for the fixed-bed MFT technology. Construction of the new pilot plant with the capacity of 15–20 barrels/day lasted about one year. The first run was conducted in September of 2002. That was not a completely successful run, but it lasted about 25 days and did produce syncrude samples, showing good prospects of this slurry-phase FTS system. After a major equipment modification in the winter of 2002, three runs were conducted in 2003 accompanying a close feedback between the pilot plant and laboratory, leading to major improvement of several key technologies making the FTS workable. In 2004, two successful long runs were carried out with the ICC-IA catalyst. Each lasted around 1500 hours for testing catalyst life; some key parameters for scaling-up. At the same time, a large quantity of syncrude samples was produced for further upgrading. During the whole pilot plant study, the process model based on a detailed kinetics model and slurry reactor model was build with an ASPEN Plus software package. Before experiment, based on the calculations of the process model for pilot plants, an experiment scheme was suggested for pilot plant study. During the run, the process model can analyse the results in time for changing the experiment scheme. With the results of the pilot plant, the kinetics model and reactor model were validated.

In addition to the key technology development, Synfuels China has been cooperating with industrial partners to develop the syncrude upgrading process technologies, for which the existing technologies used in oil refineries are examined, and new specific technologies are developed to maximize the middle distillate yields from the syncrude and minimize the upgrading cost. In most cases, FTS crude has first to be hydrogenated to saturate the double bonds and to remove oxygenates. The hydrogenated products are separated to naphtha and diesel range fuel products, and the heavy products extracted from the bottom of the distillation facilities are hydrocracked into the desired fractions. The nature of FTS syncrudes determines the hydroprocessing strategy. Normally, hydrogenation and hydrocracking technologies used in refineries can be applied for this task. However, it is noticed here that operation conditions must be re-optimized in FTS product working up purposes in order to meet the demands in CTL plants. It is also important to think about the point that the existing oil refining technologies work under sulfur, involving conditions that definitely increase the sulfur content of the final CTL products from zero to a few ppm (< 5 ppm). Typical hydrocracking data by using conventional refinery technology are listed in Tab. 1. This can be a deficiency when the CTL products are used with higher values for lower sulfur content. Under this consideration, Synfuels China has successfully developed the sulfur-free hydrogenation and hydrocracking catalysts and process concepts at laboratory level. These technologies produce fractions with definitely zero sulfur content (< 0.5 ppm). Some of the catalysts have been tested in pilot plants. The direct diesel fraction obtained from sulfur-free technology has been analyzed (see Tab. 1). The sulfur-free technology of CTL product working up eventually produces very pure products with an extremely faint smell and a water-like appearance. The continuous optimization of the final products is arranged together with cooperation partners from both fuel specific organizations and car/engine industries.

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3.3 Poly-Generation: Direction for CTL in China

When single CTL processes are considered, the benefit from the energy recovery discussed in Section 2.2 (see Fig. 2) of this article has to be evaluated carefully. However, for long-term consideration of efficiently using limited resources, energy should be pushed to maximize the desired products by using new technologies, and energy losses in a process should be minimized as much as possible. In view of the overall demanding products from coal, producing both liquid fuels and electricity from coal in the poly-generation processes becomes very attractive. Adding power generation units in the CTL process as shown in Fig. 2 becomes demanded, naturally, also for improving the process efficiency. Although there may exist different options for electricity poly-production in a CTL plant, a principal scheme is described in Fig. 8.

The efficiency of the poly-production process with maximized liquid fuel productivity becomes:

$$\text{Eff (oil + electricity)} = \text{Tce}((8)+(12))/\text{Tce}((1)+(2)+(3)+(4)+(5)) = 53.62\,\% \qquad (5)$$

Observe a significant efficiency improvement of the CTL process.

Our study has shown that with the increase in the IGCC capacity by reducing the portion of the syngas for FTS, the energy efficiency to products does not significantly change, reflecting the flexibility of such co-production processes in varying the capacities of the two major products.

Further consideration has been put on the coal treatment by pyrolysis before gasification (of coke). This concept is oriented to get tar that can be upgraded by hydrogenation and blending with CTL liquids. The efficiency to products for the CTL-IGCC process with combination of the pyrolysis process may reach 60 %. However, the technology for large-scale pyrolysis of coal has not been validated in industrial fields. Breakthrough in this process technology is very important not only for coal processing but also for biomass processing before gasification, leaving a valuable topic for technology development.

In addition to the production of high quality fuels and electricity, chemicals can be produced making use of the process features and the special properties of FTS products. This aspect has been noticed and research is also planned to increase the market opportunity of CTL plants in the future. The economics of establishing the CTL field in China using the current technology has continuously been analyzed by the case study team in Synfuels China. Establishing large-scale CTL plants on the pitheads of several main coalfields, where long distance (> 800 km) transportation from the end users of primary energy (coal) is needed, is feasible and competitive when oil price is well above 25 $/barrel. Setting the critical oil price at 23 $/barrel, the coal cost should be below 10 $/ton (raw coal with 5500–6000 kcal/kg, at the gasification feed) for a CTL plant with a lowest capacity of about a half a million tons of liquid fuel products. From the critical capacity of a half a million - tons liquid fuel products defined for CTL plants, capacity expanding will further reduce the cost of the final products. Coal properties are essential for successful CTL projects since any problem in the gasification section will significantly increase the cost. The most suitable sites currently in China are the coal fields distributed over the area covering Inner Mongolia, Shaanxi, and Shanxi, where the cost of coal is normally low and coal properties are good for gasification. Co-production processes are very attractive in improving CTL efficiency but need much high construction investment, and balance between the construction cost and the efficiency improvement is the key factor for optimizing these processes.

3.4 CTL Projects/Pre-projects in China

Demonstration of Synfuels China: On the basis of the laboratory and pilot plant development of CTL technology, conceptual design of a demonstration plant has been accomplished, and the detailed basic design of the plant was accomplished in 2004. This demonstration plant is thus designed to validate the process integration concepts and to demonstrate the key technologies. Some profits are expected for the plant owner by policy supports. For all the purposes above, the minimum capacity of this demonstration plant will be 2500–3500 barrels/day. For meeting all targets, Synfuels China is cooperating with industrial partners to design and construct the demonstration plants. Technically, gasification technology has been evaluated for this demonstration plant. The favorable choice is the entrained flow gasification technology with high syngas output from specific coal fed into the gasification reactor and at the same time with high syngas quality. In order to increase the efficiency of the single train process, the process has been severely evaluated and optimized. This plant is estimated to be well profitable at the current oil price, although at the planned demo-scale.

Commercial scale CTL plants: Planned under government schedule, three commercial-size CTL processes are now in the design and construction phase. The core technologies for these three CTL plants seem to be selected from the available FTS technologies proved in large-scale production. The major industrial companies involved in these planned projects are coal mining and conventional power companies. Although the interests in establishing CTL complexes are growing, it should be made clear that the huge capital input for constructing CTL complexes makes both great opportunities and investment risk.

4 Conclusion

Oil supply in China has reached the stage, at which a comprehensive strategy must be considered to limit the rapid increase in oil consumption with the background of rapid economic growth. Among all the possible oil replacement options, production of liquid fuels from coal is practically the most feasible route to cope with the dilemma in oil supply. The CTL solution using FTS technology can provide high quality diesel fuels, meeting the stringent environmental requirements with competitive economics and overall energy efficiency. These high quality products can seamlessly be combined with modern diesel engine technologies, forming a well-structured and highly efficient power train system for the transportation sector.

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The development of CTL technologies using FTS from the ICC has entered the stage for pursuing commercialization considerations. This includes intensive research and development at both laboratory and pilot plant scales. Further systematic scale-up of this technology will strongly promote the CTL applications at large scales, forming a completely new energy field in China.

CTL processes operated under co-production modes are very attractive in system efficiency compared to conventional power generation systems, indicating a direction for CTL development to follow. Large-scale CTL projects are in pre-project stages. These projects are, on the one hand, strongly pushed by the market demands, and on the other hand are suppressed by the requirement for huge capital investment and the uncertainty of the oil price in the world market.

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Erratum

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In the title and the first sentence of the abstract phosphonic acid has to be read as phosphinic acid.
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