A scenario-based clean gasoline production strategy for China National Petroleum Corporation

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Abstract: Facing increasingly strict environmental regulations on transportation fuels, China National Petroleum Corp. (CNPC), the second largest supplier of petroleum products in China, needs to upgrade its transportation fuels. Using the scenario-based analysis method, this paper analyzes how the emission related properties, including antiknock index, and sulfur, olefin, benzene and aromatics contents of gasoline produced by CNPC, vary with the change in the configuration of gasoline production units in the future 5-15 years. The results showed that for CNPC to upgrade its gasoline, the share of fluid catalytic cracking (FCC) naphtha must be reduced, but just increasing reformate or alkylate and isomerate will result in excessive increase in benzene and aromatics contents or a great loss of gasoline octane number. Therefore, CNPC should suitably control the capacity of its FCC units and increase the capacity of reformer, alkylation and isomerization units. Most importantly, CNPC should dramatically expand the capacity of its hydrotreating or non-hydrotreating gasoline upgrading units to decrease the olefin and sulfur contents in FCC gasoline that takes a dominant share of about 80% in the gasoline pool of China.

Key words: China National Petroleum Corporation, scenario analysis, clean gasoline production

1 Introduction

With a crude oil processing capacity of 304 million tons per annum, China's petroleum refining industry now ranks second in the world. China's petroleum refining industry has also become fairly sophisticated in terms of the variety of products and the volume of processing units such as catalytic cracking, hydrocracking, hydrotreating, and coking units for upgrading heavier feedstocks to more valuable lighter fractions.

As the largest producer and supplier of crude oil and natural gas, and the second largest producer and supplier of refined petroleum products and petrochemicals in China, China National Petroleum Corporation (CNPC) is playing a critical role in meeting the social and economic demands for petroleum products. In 2005, CNPC processed 110.6 million tons of crude oil, accounting for about 38.6% of the total production in China, and the output of the main petroleum products was 71.2 million tons, including 22.0 million tons of gasoline and 44.9 million tons of diesel, accounting for more than 40% of the total output in China.

With the fast growth of Chinese automobile industry and the increasingly stricter environmental regulations on transportation fuels, China's petroleum refining industry confronts many uncertainties and thus must be well prepared

to address many important challenges. The fast-updating regulations require Chinese refiners to speed up their technology upgrading to produce cleaner transportation fuels, such as gasoline and diesel as well as to increase their outputs to meet the ever-increasing demands. Supplying more and cleaner gasoline and diesel is one of the most important tasks for CNPC's petroleum refining sector in the future 5-15 years. This paper is aimed at discussing CNPC's clean gasoline production.

In China's commercial gasoline pool, FCC gasoline, in which the contents of olefins and sulfur can be as high as 60% and 2000 ppm, respectively, takes a share of about 80% (Liu and Tian, 2004), while other high octane-number gasoline blending components, such as reformate, alkylate and ethers that have lower sulfur and olefin contents take only about 20%, significantly different from the situation in the United States and Europe (Theodore, 2007; David, 2007) wherein FCC gasoline and reformate account for about 30% and 28%, respectively.

When the national standard GB 17930-1999 on reformulated gasoline came into effect in China in 2003, China's refineries found that reformulating their gasoline pool is the most effective measure to upgrade their gasoline (Zheng, 2004; Lü, 2004). For this purpose, Chinese refiners need to reconfigure their gasoline production units. In order to research the optimum configuration of gasoline production units for CNPC to produce clean gasoline in the future 5-15 years, twelve scenarios were developed to show how change in the configuration of CNPC's gasoline production units

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would influence the quality of the commercial gasoline pool. Part of the results presented in this paper has been adopted in the “Eleventh Five-Year Research & Technology Development Strategy of CNPC”.

2 Methodology

Because of the relative uniqueness in its configuration of petroleum processing units, CNPC faces many choices to upgrade its gasoline. However, the insufficient supply of low-sulfur domestic crude oil, the immaturity of related clean fuel production technologies, and the unknown future regulations on vehicle fuels give rise to uncertainties in CNPC's options for revamping its refining units to produce and supply cleaner fuels.

Firstly, because of the ever-increasing consumption of petroleum products and the slowly increasing production of domestic crude oil with low sulfur content in recent years, China's refiners have to process more and more imported crude oils of high sulfur content. Actually, China's net imports of crude oil reached 138.8 million tons in 2006, and about 33% of the imported crude oils are heavy ones with high sulfur content (Tian, 2007). This will aggravate the difficulty for Chinese refiners in producing clean transportation fuels. Secondly, most of the Chinese refiners have limited capacities of hydrotreatment units. In 2006, the total hydrotreating capacity of China was only 23.37 million tons per annum (Mt/a), much smaller than that of the United States (that is 715.9 Mt/a) (David, 2006). Thirdly, the future regulations on vehicle fuels will be stricter to reduce the pollutant emission from gasoline- and diesel-powered automobiles and thus require

Chinese refiners to supply clean gasoline with higher octane number and lower contents of olefins, benzene, aromatics, and sulfur.

According to the above-mentioned uncertainties, CNPC has more than one choice for upgrading its gasoline: reformulating its gasoline pool, or increasing the capacities of hydrotreating or non-hydrotreating units to upgrade FCC gasoline and other poor blendstocks. Even in reformulating the gasoline pool, CNPC can either increase its reformate production gradually or increase its alkylate and isomate production dramatically. So, the future development of CNPC's clean gasoline production is far from predetermined.

As pointed by Hugues (2000), the future is always not already predetermined; on the contrary, it is open to many possibilities. So, embodying a wide variety of ideas about the future and integrating them in a communicable and useful way can form a set of carefully crafted stories, or scenarios. Generally, a scenario-based analysis aims at separating and understanding the predictable future from the uncertain alternatives (Kees, 2000). Serving as a popular, long-range, and qualitative forecasting technique, scenario-based planning is able to take complex elements and weave them into a story which is coherent, systematic, comprehensive and plausible (Joseph, 2000).

The first main principle of scenario-based planning is system thinking. When building scenarios, enterprises must perceive their environment as a complex network of influenceable and noninfluenceable factors connected to each other. The second main principle is multiple futures. Enterprises must not reduce their strategic thinking to only

Table 1 Scenarios of gasoline configuration of CNPC in 2005-2020 –“business as usual”

Gasoline blending components	2005 Scenario 1	2010		2015		2020	
		Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
FCC gasoline	75.0%	70.0%	60.0%	60.0%	60.0%	60.0%	50.0%
Reformate	15.0%	20.0%	25.0%	25.0%	20.0%	25.0%	30.0%
Alkylate	0.5%	1.0%	2.0%	3.0%	5.0%	5.0%	5.0%
MTBE ^a	2.0%	3.0%	5.0%	5.0%	5.0%	5.0%	10.0%
Others ^b	7.5%	5.5%	8.0%	7.0%	10.0%	5.0%	5.0%
Quality of gasoline							
(RON+MON)/2	88.0	88.2	88.6	89.6	89.3	89.7	91.2
Olefin, v%	36.0	33.2	29.5	29.2	30.0	28.7	24.2
Sulfur, µg/g	375-1500	350-1400	300-1200	300-1200	300-1200	300-1200	250-1000
Benzene, v%	1.87	2.05	2.15	2.15	1.90	2.15	2.25
Aromatics, v%	35.1	36.3	37.5	37.2	34.7	36.5	36.9

Notes: ^a MTBE: methyltertiarybutyl ether. ^bOthers include butanes, straight-run naphtha, thermal naphtha (such as coker naphtha), etc.

one exact prognosticable future; instead, they should ensure that alternative futures are created and used in strategic management (Juergen et al, 1998).

According to the above two principles, a scenario creation runs through the following three stages: (1) Scenario field analysis: Based on an assessment of the decision-field in its current situation, key factors, which either are characteristic for the development or play a great role in the determination of the scenario-field, are identified; (2) Scenario prognostic: Based on defining a future horizon, no more than three possible developments, or so-called projections, for each key factor are searched for; (3) Scenario development: By combining the consistent projections to so-called projection bundles and by eliminating those bundles that show total inconsistencies towards their projections, a suitable amount of scenarios are finally figured out.

Following the above three stages, the following two types of scenarios are developed:

(1) The first type of scenarios is developed by gradually modulating the proportions of various gasoline blending components using the gasoline configuration of CNPC in 2005 as the base scenario (Scenario 1 in Table 1). The scenarios built in such a way are usually named as “business as usual” (Shell, 2001), which represents evolutionary change (see Scenarios 2-7 in Table 1).

(2) The second type of scenarios is developed on the following assumption: After 2010, the volumes of alkylation and isomerization units for producing high octane-number gasoline blending components will be dramatically increased in CNPC and thereby the blending proportions of these components will be significantly increased; correspondingly, the proportions of FCC gasoline, reformate, and other poor-quality blendstocks from thermal-processing units will be

decreased. The resulting scenarios are usually referred to as “spirit of coming age” (Shell International, 2001), which represents revolutionary change (see Scenarios 8-10 in Table 2). Table 1 Scenarios of gasoline configuration of CNPC in 2005-2020 –“business as usual”

3 Results and discussion

3.1 Gasoline quality

To understand how CNPC’s gasoline quality changes in the various scenarios, the main types of blendstocks are defined and their blending proportions in commercial gasoline pool are related to some key quality specifications of clean gasoline, such as antiknock index in terms of the average of research octane number (RON) and motor octane number (MON), Reid vapor pressure (RVP), contents of olefins, benzene, aromatics and sulfur, and boiling point range. Among the various gasoline blending components, alkylate is the only one that simultaneously meets all the quality specifications of Categories III and IV unleaded gasoline as regulated by the World-Wide Fuel Charter (WWFC) (JAMA, 2002), but it is prohibitively expensive to be used as a primary blending component, whereas FCC naphtha and reformate are far more prevalent in China, so in all the ten scenarios they are considered as the primary blending components, with FCC naphtha ranking first and reformate taking the next place. According to the shares and properties of the various gasoline components listed in Table 3, the main properties of finished gasoline, including antiknock index expressed by $(RON+MON)/2$ and the contents of sulfur, olefins, benzene and aromatics, are estimated and the results are shown in Tables 1 and 2, respectively. The related formulas are as

Table 2 Scenarios of gasoline configuration of CNPC in 2010, 2015 and 2020 –“spirit of coming age”

Gasoline blending components	2010-Scenario 8	2015-Scenario 9	2020-Scenario 10
FCC gasoline	60.0%	55.0%	50.0%
Reformate	20.0%	15.0%	15.0%
Alkylate	6.0%	10.0%	14.0%
MTBE	5.0%	5.0%	5.0%
Isomerase	5.0%	10.0%	10.0%
Others ^a	4.0%	5.0%	6.0%
Quality of gasoline			
$(RON+MON)/2$	89.4	89.1	89.4
Olefin, v%	28.4	26.4	24.5
Sulfur, $\mu\text{g/g}$	300-1200	275-1100	250-1000
Benzene, v%	1.90	1.57	1.50
Aromatics, v%	32.8	28.4	27.2

Notes: ^a Others include butanes, straight-run naphtha, thermal naphtha (such as coker naphtha), etc.

follows:

$$\text{RON} = \sum (\text{RON}_i \times R_i) \quad (1)$$

$$\text{MON} = \sum (\text{MON}_i \times R_i) \quad (2)$$

$$\text{Sulfur}(\mu\text{g/g}) = S_{\text{FCC}} \times R_{\text{FCC}} \quad (3)$$

$$\text{Olefin}(\text{v}\%) = O_{\text{FCC}} \times R_{\text{FCC}} + O_{\text{thermal}} \times R_{\text{others}} \quad (4)$$

$$\text{Benzen}(\text{v}\%) = B_{\text{FCC}} \times R_{\text{FCC}} + B_{\text{reformat}} \times R_{\text{reformat}} \quad (5)$$

$$\text{Aromatics}(\text{v}\%) = A_{\text{FCC}} \times R_{\text{FCC}} + A_{\text{reformat}} \times R_{\text{reformat}} + A_{\text{thermal}} \times R_{\text{others}} \quad (6)$$

In Eqs. (1)-(6), RON_i and MON_i stand for the RON and MON of component i , respectively; R_i the share of component i in finished gasoline; S_{FCC} the sulfur content of FCC gasoline; O_{FCC} and O_{thermal} the olefin contents of FCC gasoline and thermal gasoline, respectively; B_{FCC} and B_{reformat} the benzene contents of FCC gasoline and reformat, respectively; A_{FCC} , A_{reformat} and A_{thermal} the aromatics contents of FCC gasoline, reformat and thermal naphtha, respectively.

Because about 90% of olefins and more than 98% of sulfur in finished gasoline come from FCC gasoline, the sulfur and olefin contents decrease with the decreasing share of FCC gasoline from Scenario 1 to Scenario 7, as shown in Table 1. Nevertheless, only increasing the share of reformat in the gasoline pool will increase the contents of benzene and aromatics in finished gasoline. In Scenarios 3, 4, 6 and 7,

when reformat takes a share of 25% or 30%, the contents of benzene and aromatics in finished gasoline may reach as high as 2.25 v% and 37.5 v%, respectively. Actually, the excessive contents of benzene and aromatics due to a higher share of reformat in finished gasoline are the same challenge U.S. refiners are facing in upgrading their gasoline.

In the future, much stricter constraints will be imposed on the contents of benzene and aromatics in addition to those on olefins and sulfur. For examples, WWFC requires that the maximum contents of aromatics and benzene in unleaded gasoline of Category III or IV should be below 35 v% and 1.0 v%, respectively; the new benzene limit regulated by the U.S. EPA (Environmental Protection Agency) that came into operation on February 9, 2007 is 0.62 v%, and this benzene limit will likely be taken by Canada, Europe and Japan (David, 2007). As shown in Table 3, reformat and FCC naphtha are responsible for high contents of benzene and aromatics in finished gasoline, and FCC naphtha and thermal naphtha (for example, coker naphtha) give rise to a high content of olefins. Intuitively, it is conceived that the best way for CNPC to produce gasoline that meets the constraints for olefin, benzene and aromatics contents as well as low content of sulfur is to decrease the volumes of FCC naphtha, thermal naphtha, and reformat and to increase other high-octane number components such as alkylate and isomerate, as Scenarios 8, 9 and 10 shown in Table 2.

The contents of olefins, benzene and aromatics in Scenario 8, which are based on Scenario 3 for year 2010 in Table 1 but with alkylate content being increased from 2.0 v% to 6.0 v% and isomerate from 0 to 5.0 v%, and reformat being decreased from 25 v% to 20 v% and others from 8.0 v% to 4.0 v%, decrease by 1.1, 0.25 and 4.7 units, respectively, in comparison with the corresponding items of Scenario 3 in Table 1, while the antiknock index increases by 0.8 units. This result shows that increasing alkylate and isomerate plays an important role in upgrading gasoline. In Scenario 9 for year 2015 when the proportions of alkylate and isomerate

Table 3 Emission related chemical and physical properties of various gasoline blendstocks

Gasoline blendstocks	Sulfur $\mu\text{g/g}$	Aromatics v%	Benzene v%	Olefin v%	RON	MON	RVP kPa
Butane ^a	0	0	0		95	92	
Straight-run naphtha	100-200	2-4	1-2	<1	65~80	60~75	70-80
Reformat	0	60-75	3-5	<1	100	89	30-35
FCC gasoline	500-2000	25-35	0.7-1.5	40-50	93	80	40-50
Thermal naphtha	2-4000	5-60	2-35 ^b	20-35	82-96	74-85	70-80
Isomerate	0	<0.5	<0.5	<0.5	85-88	82-85	70-80
Alkylate	0	<0.5	<0.5	<1	94	92	40-45
MTBE	0	0	0		113-117	95-101	55

Notes: ^a1v% $n\text{C}_4$ can increase RVP by 50 kPa; ^bBenzene content is lower in coker and visbroken naphtha than that in steam cracking fraction

further increase up to 10%, compared with those in Scenarios 4 and 5, the contents of olefins, benzene and aromatics further decrease, and the antiknock index decreases by 0.2-0.5 units. In Scenario 10 for year 2020 when the shares of FCC naphtha and reformate decrease to 50% and 15%, respectively, compared to those of Scenario 6, the olefin, benzene and aromatics contents decrease by 4.2, 0.65 and 9.3 units, respectively, and the antiknock index decreases by 0.3 units; while compared with Scenario 7, the olefin content in finished gasoline in Scenario 10 almost remains at the same level, and the benzene and aromatics contents decreases by 0.75 and 9.7 units, respectively, and the antiknock index decreases by 1.8 units due to the simultaneous decreases in the shares of FCC naphtha, reformate and MTBE, which are all octane contributors.

Gasoline blending is a complex operation, because a number of specifications must be met simultaneously. From the aforementioned analyses, it can be seen that as the specifications for olefins, benzene and aromatics become tighter and tighter, the volumes of FCC naphtha and reformate in finished gasoline should be continually reduced. As is well known, butanes are highly volatile components, nevertheless, they tend to be used in gasoline blending because they are inexpensive, have very high octane number, and are free of such hydrocarbons as benzene, aromatics and olefins. With the more stringent constraint on RVP, blending butanes into gasoline will be further limited. As a gasoline additive, MTBE is good for reducing harmful air emissions, but can also cause serious contamination of drinking water supplies, so some countries especially the United States have enacted legislation to ban MTBE, indicating a gloomy future for MTBE being used as gasoline additive.

The above analysis shows that to upgrade commercial gasoline, or more exactly, to decrease the olefin and sulfur contents and to control the benzene and aromatics contents while maintaining the octane number of the finished gasoline, CNPC could reduce the share of FCC naphtha. Nevertheless, the reduced share of FCC naphtha cannot be offset only by increasing the share of reformate or only by increasing the shares of alkylate and isomerate, because they will result in excessive increases in the contents of benzene and aromatics or a great loss of gasoline octane number. So, when reformulating its gasoline pool, CNPC should carefully balance the shares of various gasoline blending components according to their specific properties.

Furthermore, just reformulating its gasoline pool is not sufficient for CNPC to upgrade its gasoline. For example, in Scenarios 7 and 10, even if the share of FCC naphtha is limited to 50% in finished gasoline, olefin and sulfur contents are still as high as 24.0 v% and 250 ppm, respectively, much higher than the corresponding specifications of Categories III and IV unleaded gasoline of WWFC. Therefore, CNPC needs to develop various hydro- or nonhydro-treating processes to improve the quality of FCC gasoline while increasing its production capacities of other clean gasoline blending components. On one hand, if CNPC increases the share of reformate to the same level of the United States or Europe, the problem of higher benzene and aromatics

contents that American and European refiners are facing will be inevitable; on the other hand, given the quite low heavy oil hydrotreating and hydrocracking capacities, residue FCC (RFCC) will remain to be the predominant secondary process for Chinese refiners to convert heavy feedstocks to valuable light fractions. Consequently, the situation that FCC naphtha is the predominant blending component in the gasoline pool of China will not be changed in the foreseeable future. Actually, CNPC is now resorting to various hydro- or nonhydro-treating processes for upgrading its FCC gasoline as well as new techniques for increasing the production of high octane number components. These techniques include novel olefin reduction FCC catalysts, novel FCC process configurations for olefin reduction, ionic liquid catalyzed alkylation technology, FCC gasoline hydro-upgrading catalysts and processes, and low temperature C4 and FCC naphtha aromatization technology (Xu et al, 2006).

3.2 Gasoline blending component production capacities

Because of the rapid development of Chinese automobile industry, China's demand for gasoline has remained at a high level in recent years. From 1997 to 2006, China's gasoline consumption went up at an annual rate of 5.4% (Shi and Bai, 2007). During the time from 1998 to 2006, about 44.0% of the total gasoline consumption was supplied by CNPC. Given the fact that China's total consumption of gasoline in 2005 was 48.28 million tons (Shi and Bai, 2007), and assuming that it will increase at an annual rate of 5.4% and CNPC's share will remain at its current level (44.0%) in the future 5-15 years, it is predicted that by 2010, 2015 and 2020, CNPC's gasoline outputs will reach 26.98, 34.27, and 43.52 Mt/a, respectively.

Based on the above predictions, the output (Mt/a product), production capacity (Mt/a feed) and capacity expansion (Mt/a feed) for each of the gasoline blending components required by CNPC in 2020 in the different scenarios are listed in Table 4. The capacity and the capacity expansion of each production unit were calculated on the basis of CNPC's actual average gasoline yield in 2003 (see Table 5).

From Table 4, it is seen that except for Scenarios 6, 7 and 10 in 2020, in which the FCC capacities need to be increased by 17.0 Mt/a at maximum (Scenario 6) and 6.37 Mt/a at minimum (Scenarios 7 and 10), respectively, for the other 7 scenarios CNPC does not have to expand its FCC capacity dramatically. For all the scenarios, however, CNPC needs to expand its reformate production capacity despite reformate remaining at a relatively low proportion (15%) in finished gasoline in Scenarios 9 and 10. By 2015, the minimum and maximum reformer capacities required to provide enough reformate will be 5.82 Mt/a for Scenario 9 and 9.70 Mt/a for Scenario 4, respectively; for Scenario 7 in 2020, the total reformer capacity will reach 14.8 Mt/a, viz., CNPC needs to increase its reformer capacity by 12.1 Mt/a.

In contrast to other countries especially the United States, the petrochemical industry reformers in China are mainly used for producing benzene, toluene and xylenes (BTX), only about 30% of the reformers are used to produce gasoline blendstock. For CNPC, the volume of reformers used to

Table 4 Output, capacity and capacity expansion for each gasoline component required by CNPC in the different scenarios

Scenarios		FCC gasoline	Reformat	Alkylate	MTBE	Isomerase	Others
1	Output, Mt/a	15.9	3.19	0.11	0.42	0.00	1.59
	Capacity, Mt/a	38.8	3.61	–	–	–	–
	Capacity expansion, Mt/a	–	0.95	–	–	–	–
2	Output, Mt/a	18.9	5.40	0.27	0.81	0.00	1.48
	Capacity, Mt/a	46.0	6.11	–	–	–	–
	Capacity expansion, Mt/a	–	3.45	0.10	0.27	–	–
3	Output, Mt/a	16.2	6.75	0.54	1.35	0.00	2.16
	Capacity, Mt/a	39.4	7.64	–	–	–	–
	Capacity expansion, Mt/a	–	4.98	0.37	0.81	–	–
4	Output, Mt/a	20.6	8.57	1.03	1.71	0.00	2.40
	Capacity, Mt/a	50.0	9.70	–	–	–	–
	Capacity expansion, Mt/a	3.46	7.04	0.86	1.17	–	–
5	Output, Mt/a	20.6	6.85	1.71	1.71	0.00	3.43
	Capacity, Mt/a	50.0	7.76	–	–	–	–
	Capacity expansion, Mt/a	3.46	5.10	1.54	1.17	–	–
6	Output, Mt/a	26.1	10.9	2.18	2.18	0.00	2.18
	Capacity, Mt/a	63.5	12.3	–	–	–	–
	Capacity expansion, Mt/a	17.0	9.66	2.00	1.64	–	–
7	Output, Mt/a	21.8	13.1	2.18	4.35	0.00	2.18
	Capacity, Mt/a	52.9	14.8	–	–	–	–
	Capacity expansion, Mt/a	6.37	12.1	2.00	3.81		
8	Output, Mt/a	16.2	5.40	1.62	1.35	1.35	1.08
	Capacity, Mt/a	39.4	6.11	–	–	1.71	–
	Capacity expansion, Mt/a	–	3.45	1.45	0.81	1.54	–
9	Output, Mt/a	18.8	5.14	3.43	1.71	3.43	1.71
	Capacity, Mt/a	45.8	5.82	–	–	4.34	–
	Capacity expansion, Mt/a	–	3.16	3.26	1.17	4.17	–
10	Output, Mt/a	21.8	6.53	6.09	2.17	4.35	2.61
	Capacity, Mt/a	52.9	7.39	–	–	5.51	–
	Capacity expansion, Mt/a	6.37	4.73	5.92	1.64	5.35	–

produce gasoline blendstock is only 2.66 Mt/a in 2003. Obviously, if CNPC can substantially expand its alkylation and isomerization production capacities after 2010, the pressure for dramatically increasing its reformer volume can be mitigated.

Unlike the reforming process, FCC has been the predominant process for increasing the yields of light fractions such as gasoline and diesel since its advent in the 1940s. Specifically, in China about 80% gasoline and 30% diesel are from FCC or RFCC units. This had led to continuous investment in FCC, especially RFCC processes during the 1990s and made China the country with the second largest FCC and RFCC capacities in the world.

Currently, CNPC has only two H_2SO_4 catalyzed alkylation units and the sum of their capacities is about 170 kilotons per annum (see Table 5). As shown in Table 4, by 2010, the capacity of alkylation units is expected to increase by 0.10 Mt/a (Scenario 2) at minimum and by 1.45 Mt/a (Scenario 8) at maximum, while the corresponding increases by 2020 are 2.00 Mt/a (Scenarios 6 and 7) and 5.92 Mt/a (Scenario 10), respectively.

In China, alkylate and MTBE production units are usually considered as the downstream units of FCC and RFCC as they use liquefied petroleum gas (LPG) from FCC units as feedstocks. The isobutene (which accounts for about 30% in LPG) in LPG is used to produce MTBE and the other C_3 and C_4 fractions are partially used to produce alkylate (Hou, 2001). Because the average LPG yield of FCC units is usually 12%-14%, here we assume that the yield of LPG is 13% and that the capacity of CNPC's FCC units will remain at 46.56 Mt/a (equivalent to that of 2003), the annual LPG yield of CNPC will be 6.05 million tons, in which about 4.24 million tons (after the separation of isobutenes) can be used to produce more than 3.82 million tons of alkylate. If the capacity of alkylation units needs to be further increased (for example, it can reach more than 6.0 Mt/a in Scenario 10 for 2020), the refiners can expand their FCC capacities, or use new FCC-based techniques to increase the yield of LPG, or purchase LPG from the overseas market.

3.3 Configuration of CNPC's clean gasoline production units

To reformulate its gasoline pool, CNPC could reconfigure its gasoline production units. The predicted configurations of CNPC's clean gasoline production units in 2010 and 2020 are shown in Figs. 1 and 2, respectively. The units include FCC, reforming, alkylation, MTBE, isomerization and coking. For compliance with the stricter and stricter constraints on sulfur and olefins in future specifications, FCC naphtha and thermal naphtha could be hydrotreated to control sulfur and olefin contents before being blended into finished products.

Yuan (2005) predicted that by 2010 and 2020, the crude oil processing capacity of China would be 350 and 470 million tons per annum, respectively. Correspondingly, the crude oil processing capacity of CNPC by 2010 and 2020 will be 140 and 188 million tons per annum, respectively, if CNPC maintains its current share (40%) of crude oil processing capacity in China.

As shown in Figs. 1 and 2, assuming that CNPC's FCC capacity in 2010 remains at 46.56 Mt/a and that in 2020 will be 52.93 Mt/a (increased by 6.37 Mt/a at minimum in Scenarios 7 and 10 from that in 2003), the proportion of straight-run naphtha will be 7.33%, in which the lighter (about 25%) and heavier (75%) fractions can be used to produce isomerate and reformate, respectively. Here, it is assumed that all reformers in these configurations are used to produce gasoline blendstock. According to the analysis in section 3.2, the minimum demands for reformate to be blended into gasoline in 2010 and 2020 are 5.40 (Scenarios 2 and 8) and 6.53 (Scenario 10) million tons, respectively. The feedstock of MTBE and alkylation units is LPG from FCC units and the feedstock of cokers is vacuum residue (VR) which accounts for 30% of the total VR from vacuum distillation units (the VR yield of CNPC is about 43.0%), and the thermal naphtha yield is 13.7%. Theoretically, the outputs of various gasoline components and their proportions in the finished gasoline pool in 2010 and 2020, namely, Scenario 11 and Scenario 12, respectively, can be estimated and the results are shown in Table 6. The output of each gasoline component is estimated according to its average yield in each gasoline production unit of CNPC in 2003, as listed in Table 5.

Table 5 Capacities and average yields of main gasoline components of CNPC in 2003

Production units	Capacities Mt/a	Yields wt %
FCC	46.56	41.11
Reformer ^a	2.66	88.30
Alkylation	0.17	>90 ^b
Isomerization	0.17	78.88
MTBE	0.54	

Source: Basic Data Collection of Petroleum Refining Units, PetroChina, in 2003

^a Over 70% reformers of petrochemical industry in China are now used for producing benzene, toluene and xylenes (BTX), and only about 30% reformate can be used to blend in gasoline. In 2003, the total volumes of reformer of CNPC is 8.85 Mt/a;

^b based on the feedstock

In 2010, CNPC's crude oil processing capacity would be 140 Mt/a and FCC capacity would be 46.56 Mt/a, the theoretical output of finished gasoline for Scenario 11 would be about 37.54 million tons. Then, the gasoline pool consists of 50.9% FCC gasoline, 18.2% reformate, 10.2% alkylate, 5.41% isomerates, 8.76% MTBE, and 6.61% thermal naphtha. Compared with those for Scenario 8, the olefin, sulfur, benzene and aromatics contents for Scenario 11 are all decreased due to the reduced proportion of FCC naphtha and reformate in finished gasoline; while the antiknock index is improved because of the increased volumes of alkylate and

Fig. 1 Configuration of clean gasoline production units of CNPC in 2010

Fig. 2 Configuration of clean gasoline production units of CNPC in 2020

MTBE, showing a more desirable perspective for gasoline quality upgrading. From these results, it could be seen that for decreasing olefin and sulfur contents, FCC gasoline must be reduced; and for decreasing benzene and aromatics contents, reformate must be reduced.

In 2020 when CNPC's crude oil processing capacity and FCC capacity reach 188 Mt/a and 52.93 Mt/a, respectively, and the predicted output of finished gasoline for Scenario 12 is 45.08 million tons. Then, the gasoline pool consists of 48.4% FCC gasoline, 20.4% reformate, 9.63% alkylate,

6.03% isomerate, 8.25% MTBE, and 7.36% thermal naphtha. Compared with Scenarios 7 and 10, the olefin and sulfur contents for Scenario 12 decrease with the decreasing FCC naphtha volume in finished gasoline; while compared with Scenario 7, the antiknock index also decline with the decreasing volumes of MTBE and reformate. Compared with Scenario 10, the antiknock index increase with the increasing volume of reformate, implying that reformate as well as alkylate and MTBE are the main contributors to antiknock property.

From the above analysis, it is seen that for CNPC to produce gasoline with higher octane such as RON 97 or RON 98 gasoline, the proportion of high octane components such as reformate, alkylate and MTBE must be increased in finished gasoline. The volume of reformate could be increased as high as possible so that the quality specifications on benzene and aromatics limits can be met, and the volume of alkylate could also be increased as much as possible, while the volume of MTBE could be increased by a limited amount, because MTBE has already been prohibited to be blended

into finished gasoline in California, United States.

From Table 6, it is seen again that by reformulating the gasoline pool, the antiknock index and aromatics content can meet the corresponding specifications of the Category III gasoline of WWFC, except for the gasoline with 95 RON. However, the contents of olefins and sulfur that come mainly from FCC naphtha are much higher than the corresponding specifications. Therefore, CNPC needs to take various measures to upgrade its FCC naphtha and other poor-quality gasoline blendstocks.

Table 6 Predicted outputs of various gasoline components required by CNPC in 2010 and 2020 and their properties

	2010 Scenario 11	2020 Scenario 12
Total output, Mt	37.54	45.08
Shares of various components, v%		
FCC gasoline	50.9	48.4
Reformate	18.2	20.4
Alkylate	10.2	9.63
MTBE	8.76	8.25
Isomerase	5.41	6.03
Thermal naphtha	6.61	7.36
Others	–	–
Quality of gasoline		
(RON+MON)/2	90.2	90.2
Olefin, v%	24.7	23.8
Sulfur, µg/g	255-1018	242-968
Benzene, v%	1.29	1.35
Aromatics, v%	29.7	30.4

4 Conclusions

Using the scenario-based analysis method, this paper analyzes how emission related properties including antiknock index and sulfur, olefin, benzene, and aromatics contents of gasoline produced by CNPC vary with the change in the configuration of gasoline production units in the future 5-15 years. The results showed that for CNPC to upgrade its gasoline, the share of FCC naphtha must be reduced, but only increasing reformate will result in the excessive increase in the contents of benzene and aromatics; only increasing alkylate and isomerase will result in a great loss of gasoline octane number. Therefore, CNPC needs to reconfigure its gasoline production units by suitably controlling its capacities of FCC units and by dramatically increasing

those of reforming, alkylation and isomerization units while moderately expanding those of MTBE units. Furthermore, just reformulating the gasoline pool is not sufficient for CNPC to upgrade its gasoline, because the situation that FCC naphtha having higher olefin and sulfur contents will continue to be the main gasoline blending component will not be changed in the foreseeable future. So, CNPC also needs to expand its hydrotreating or non-hydrotreating units to upgrade FCC naphtha.

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