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Modeling and techno-economic analysis of shale-to-liquid and coal-to-liquid fuels processes

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ABSTRACT

To alleviate the conflict between oil supply and demand, Chinese government has accelerated exploration and exploitation of alternative oil productions. STL (Shale-to-liquid) processes and CTL (coal-to-liquid) processes are promising choices to supply oil. However, few analyses have been made on their energy efficiency and economic performance. This paper conducts a detailed analysis of a STL process and a CTL process based on mathematical modeling and simulation.

Analysis shows that low efficiency of the STL process is due to low oil yield of the Fushun-type retorting technology. For the CTL process, the utility system provides near to 34% energy consumption of the total. This is because that CTL technologies are in early development and no heat integration between units is implemented. Economic analysis reveals that the total capital investment of the CTL process is higher than that of the STL process. The production cost of the CTL process is right on the same level as that of the STL process.

For better techno-economic performance, it is suggested to develop a new retorting technology of high oil yield for the STL process. The remaining retorting gas should be converted to hydrogen and then used for shale oil hydrogenation. For the CTL process, developing an appropriate heat network is an efficient way to apply heat integration. In addition, the CTL process is intended to be integrated with hydrogen rich gas to adjust H_2/CO for better resource utilization.

1. Introduction

Consumptions of gasoline and diesel in China kept increasing, as shown in Fig. 1 [15]. The average increasing rate for gasoline was 8.8% and that for diesel was 8.3% in the years from 2004 to 2014. Liquid fuels production depends to a great extent on petroleum consumption. According to the energy reserve in China, more than half of oil consumption is imported from abroad. For example, oil production was 210 Mt, while the apparent consumption was 518 Mt in 2014. It is clear that 60% oil was imported [20] and this number will increase to 75% till 2030 [2]. The continuous growth of oil consumption requires development of alternative energy resources.

The energy reserve in China is marked by richness in coal, while scarcity in oil and gas. National Bureau of Statistics [22] investigated the energy production from coal, oil, and natural gas and found their percentages of total national energy production at 75.1%, 15.2%, and 2.8%, respectively. Chinese government enforced the policy to promote exploration and exploitation of unconventional oil productions [23]. Depending on statistics, extractable amount of shale oil is 47.6 $\times$ 10^9 t, double of China's oil reserve [12,14]. By 2014, the total oil production capacity of STL (shale-to-liquid) plants was 1.0 Mt/y. These plants are mainly built in Liaoning, Jilin, and Shandong provinces. The largest STL plant was built by Fushun Mineral Co., Ltd. with the capacity of 0.37 Mt/y (0.06 Mt/y gasoline and 0.31 Mt/y diesel) [24]. It is predicted that the capacity will increase to 3.0 Mt/y by 2018 [8].

Depending on the report by Ref. [3], the proven reserves of coal in China were 114.5 $\times$ 10^9 t, accounting for 13.3% of the world total. In a long time, coal will be the dominant energy resource in the country. CTL (Coal-to-liquid) technologies are important to relieve the shortage of oil [13]. In 2014, capacity of the biggest CTL plant reached 1.0 Mt/y oil, including 0.25 Mt/y gasoline and 0.75 Mt/y diesel. The capacity will grow continuously and quickly to a capacity of 20 Mt/y by 2020 [33].

Development of STL technologies and CTL technologies gives a feasible way to mitigate the shortage of oil supply. However, there

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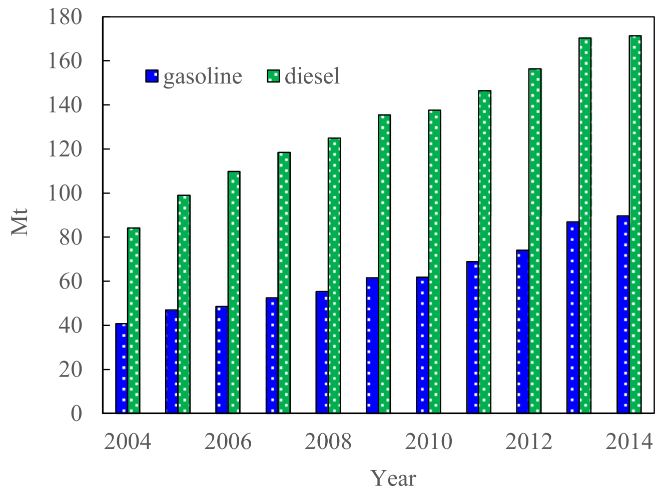

Fig. 1. Consumptions of gasoline and diesel in China.

are limited studies on their techno-economic performance. This paper models and simulates a STL process and a CTL process. Based on simulation, techno-economic analysis is made to explain their performance and give suggestions for future development of these technologies.

2. Process modeling and simulation

A STL process and a CTL process are utilized to analyze with the capacities of 0.37 Mt/y oil and 1.0 Mt/y oil. These two processes are modeled based on practical industrial processes. Aspen Plus software (version 7.2) is used for modeling and simulation. For analysis of the two processes, we use an OTL (oil-to-liquid) process as the base case. It is built by PetroChina Yunnan Petrochemical with the scale of 10 Mt/y oil [5].

2.1. Shale-to-liquid process

The flow diagram of the STL process is illustrated in Fig. 2. After grinding and screening, oil shale particles with the diameter from 10 to 75 mm are fed into the retort and converted into semi-coke and oil-gas mixture at 0.1 MPa and 525 °C. The oil-gas mixture is subsequently separated into retorting gas and shale oil by the washing tower, the indirect cooling tower, and the electrostatic tower. Most of the retorting gas is heated by burning a part of it and recycled back to the retort. Shale oil is mixed with hydrogen. The mixing stream is heated by the furnace and then sent to the hydrogenation reactor. The products from the hydrogenation reactor are sent into the HP (high-pressure) separator to separate gaseous and liquid phases. Most of the gas is recycled back, while the liquid is refined in the fractionation tower to gasoline and diesel. Residual oil from the bottom of the fractionation tower is mixed with hydrogen and fed into the hydrocracking reactor, in which high molecular hydrocarbons are cracked into small molecular hydrocarbons.

A STL process mainly includes an OSR (oil shale retorting) unit and a SOH (shale oil hydrogenation) unit. The key operational parameters for the simulation are given in Table A in Appendix. Details of the modeling and simulation of the OSR unit will be undertook in the following section.

Oil shale retorting technologies comprise of gas-heat-carrier technologies and solid-heat-carrier technologies. A number of retorting technologies of gas-heat-carrier have been commercialized in China. The representative is Fushun-type retorting technology. Its production capacity occupies 85% of all oil production [24]. Thus, this paper uses Fushun-type retorting technology as the study case. For the simulation, the oil shale with 7% oil content in Fushun, Liaoning, China is selected with its proximate and elementary analyses in Table 1, where M, FC, V, and A respectively denote the moisture, fixed carbon, volatiles, and ash; ar denotes as-received basis of shale.

Composition of the oil shale is complex. In order to facilitate the simulation, oil shale is defined as the mixture of water, minerals, and kerogen. These components can be modeled as MIXED, SOLID, and NC in Aspen Plus. RK-SOAVE is chosen as the property method. The Fushun-type retort includes a drying, a retorting, and a gasification stages from top to bottom. In the drying stage, oil shale particles are preheated to 180 °C for drying. In the retorting stage, the kerogen is retorted to shale oil, retorting gas, and semi-coke at the temperature ranging from 180 °C to 525 °C. In the gasification stage, the reactions are combustion and gasification of semi-coke, aiming to produce hot gas at 850 °C to supply heat for the decomposition.

Modeling of the Fushun-type retort is illustrated as Fig. 3a. The corresponding program in Aspen Plus is shown as Fig. 3b. The

Table 1
Proximate and elementary analyses of oil shale in Fushun, China.

	Proximate analysis (wt.%, ar)				Elementary analysis (wt.%, ar)				
	M	FC	V	A	C	H	O	N	S
Oil shale	5.00	3.69	18.56	72.79	79.07	9.93	7.02	2.12	1.86

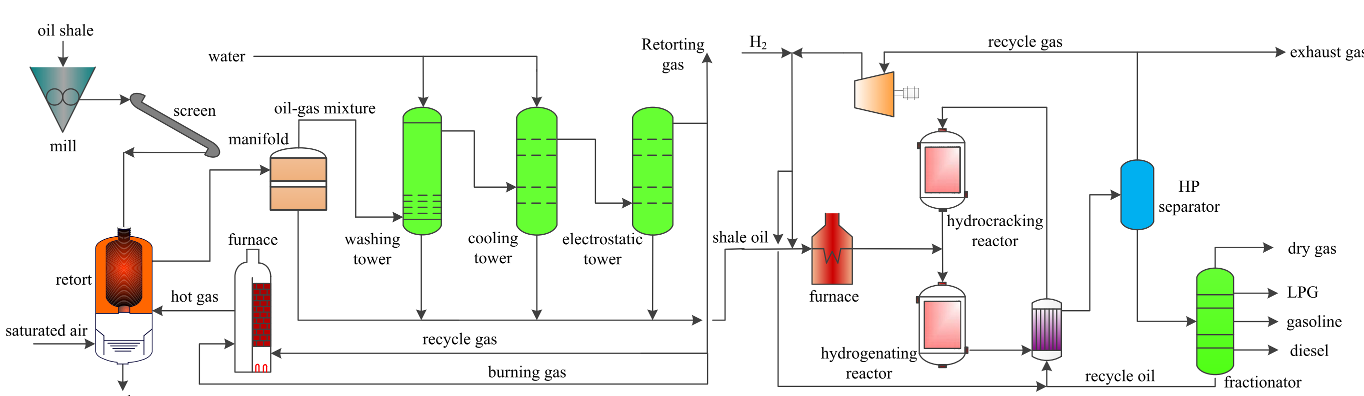

Fig. 2. Flow diagram of the STL process.