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System development of integrated high temperature and low temperature Fischer–Tropsch synthesis for high value chemicals

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ABSTRACT

The conventional indirect coal-to-liquid process suffers from improperly utilization of Fischer–Tropsch (FT) syncrude and poor economic performance. In consideration of the potential synergies in the process and product integration from the high temperature Fischer–Tropsch (HTFT) and the low temperature Fischer–Tropsch technology (LTFT), the novel HTFT–LTFT system integrated HTFT and LTFT synthesis is proposed based on the advanced coal gasification and FT techniques to improve efficiency and add products value. The HTFT–LTFT system is firstly modelled in Aspen Plus platform and then evaluated by the energy, exergy, and detailed economic analysis. The synergies of the integrated system are discussed by comparing with the separate HTFT or LTFT system. Results show that the integrated HTFT–LTFT system is efficiently and economically superior to the separate HTFT or LTFT system, which reduces the capital investment by 18.2% and increases the annual income by more than 10%. The integrated HTFT–LTFT system with the coproduction of olefins and base oil simultaneously presents the IRR of 15.2% and has high ability against product prices fluctuation.

1. Introduction

Fischer–Tropsch (FT) synthesis converts syngas to hydrocarbons and has a great importance for countries with depletable resource of oil to meet the increasing energy demand. Indirect coal-to-liquid (CTL) process via FT synthesis in China has attracted an increasing attention because of the oil and gas resources. Significant technical progresses in FT synthesis have been made recently. The successful commercialization of the indirect CTL plant with the capacity of millions ton per year is a key technical breakthrough (Hao et al., 2017). The current focus on the CTL process deals with the production of liquid transportation fuels such as gasoline and diesel, which are in the carbon range of C5–C20. To increase the selectivity of transportation fuel, the conventional effort necessitates a further extensive refining to convert lighter and higher hydrocarbons to transportation fuel based on the carbon number distribution of FT syncrude, in addition to the catalyst improvement and the process condition optimization. Due to the lack of selectivity towards gasoline and diesel, the capital-intensive CTL process faces the poor economic performance. However, the poor economic performance is also because the FT syncrude are improperly used. FT syncrude can be further refined not only to transportation fuels, but also to high value chemicals (de Klerk, 2008). The lack of selectivity of FT towards gasoline and diesel provides an opportunity for the chemicals manufacture. High value chemicals production represents a valuable solution to increase the economic profitability at an industrial scale.

With the production of high value products, integrated high temperature and low temperature Fischer–Tropsch (HTFT–LTFT) system represents a competitive advantage to the conventional system with

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Nomenclature

ASF	Anderson-Schulz-Flory
Aspen	Advanced system for process engineering
ASU	Air separation unit
ARGE	Arbeits-Gemeinschaft Lurgi and Ruhrchemie
CC	Catalytic cracking
CEPCI	Chemical engineering plant cost index
CTL	Coal-to-liquid
DC	Direct cost
FCI	Fixed capital investment
FT	Fischer–Tropsch
FORTRAN	Formula translator
HC	Hydrocracking
HI	Hydroisomerization
HTFT	High temperature Fischer–Tropsch synthesis
ICTL	Indirect coal-to-liquid
IRR	Internal rate of return
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LHV	Low heating value
LTFT	Low temperature Fischer–Tropsch synthesis
M	Million
NPV	Net present value
PSA	Pressure swing adsorption
ROI	Return on investment
RYield	The reactor based on product yield
Sep1	Multi-outlet component separator
TBP	True boiling point
TCI	Total capital investment
TDC	Total direct cost
TPC	Total product cost
TPD	Ton per day
WGS	Water gas shift reaction

Capital letters

C_0	The cost of reference equipment
C_t	The net cash flows
E_{fuels}	The output energy of fuels
$E_{chemicals}$	The output energy of chemicals
E_{coal}	The low heating value of coal
$E_{ex,fuels}$	The exergy of liquid fuel product
$E_{ex,chemicals}$	The exergy of chemicals product
$E_{ex,coal}$	The exergy of coal feed
S_r	The capacity of the new equipment
S_0	The capacity of the reference equipment

Lowercase letters

i_0	The acceptable discount rate
sf	The scaling factor

Greek letters

η_1	The energy efficiency
η_2	The exergy efficiency

the potential to a high average product price and a high yield of total hydrocarbon products (Steynberg and Dry, 2004). The integrated HTFT–LTFT plant (Sasol I) was firstly developed in history in Sasolburg, South Africa. This HTFT–LTFT plant integrated American Kellogg circulating fluidized-bed Fe-HTFT and Arbeits-Gemeinschaft Lurgi and Ruhrchemie (ARGE, LTFT) fixed-bed Fe-LTFT unit. However, the above mentioned HTFT–LTFT integrated plant suffers from the following three major problems: (i) the FT syncrude is only used for conventional products, such as gasoline, diesel and wax. The advantages of higher olefin content characteristic in the both Fe-based FT products and higher wax yield in LTFT for various high value chemicals production have been neglected; (ii) the Lurgi fixed-bed coal gasification technique is inefficient with large amount of waste water and waste gas emission; (iii) heat removal is an obvious problem for the fixed-bed LTFT reactor, and the circulating fluidized-bed HTFT reactor is confronted with many operational disadvantages. Recently, advanced coal gasification technique and FT reactors have been well developed. The entrained flow bed coal gasification technique is well developed, which is characterized with high carbon conversion and much less waste water and waste gas emission (Higman and Tam, 2013; Wen et al., 2016). With nearly isothermal operation of the catalytic bed, the slurry LTFT reactors have been developed and commercialized with a number of advantages over the fixed-bed reactor (Saeidi et al., 2015; Wang et al., 2007). And the operational disadvantages of circulating fluidized-bed HTFT reactor have been overcome by the development of the fixed- and fluidized-bed reactor, which is relatively easy to operate and more economic with other advantages, such as excellent isothermal characteristics, higher pass per conversion, and lower catalyst consumption (Duvenhage and Shingles, 2002; Steynberg et al., 2004). Based on the advanced coal gasification and FT techniques, indirect coal-to-liquids (ICTL) projects have been established and operated since 2015 in China, such as the Shenhua ICTL project and Yankuang ICTL project. The Yankuang group has developed both the advanced HTFT and LTFT techniques, and plans to integrate the HTFT and LTFT process together. The feasibility study of one integrated project of 4 million tons per year has been completed and is under construction now. However, in an academic research only a few studies proposed the use of stand-alone FT syncrude for chemicals production (Onel et al., 2015; Xiang et al., 2016). And there is still no investigation on high value chemicals production as regards to the integrated HTFT–LTFT system.

To solve the problem mentioned above, the novel integrated HTFT–LTFT system is proposed based on the advanced coal gasification and FT techniques. The key feature of the proposed system is the high value chemical production. Light olefins and α-olefins are produced to take advantage of the high olefin content characteristic in the HTFT and LTFT syncrude fractions (<C10). In this paper, due to the saturated market for wax, we investigate three integrated HTFT–LTFT systems with different FT wax upgrading approaches. The systems are modelled in Aspen Plus software. Thermodynamic analysis and a detailed economic analysis are performed to guide technology selection and research efforts towards more efficient HTFT-LTFT systems. The synergies of the integrated system is also discussed with a comparison of the separate HTFT or LTFT system. Sensitivity analysis is implemented to investigate the effects of chain growth probability and post FT processing options on the efficiency of the systems. Sensitivity analysis for the profitability of the systems is further executed by the variation of key parameters, such as the feedstock price, capital cost and product price.

2. Integrated HTFT–LTFT system and plant modeling

2.1. Integrated HTFT–LTFT system description

Fig. 1(a) illustrates the HTFT–LTFT integrated system including coal gasification and syngas treatment unit, FT synthesis unit, and FT syncrude integrated upgrading unit. Texaco entrained flow coal gasification technology is considered for syngas production in this paper because of the high effective gas components and cold gas efficiency, low emission and economic benefits as well as the mature application in China (Wen et al., 2016). The H_2/CO ratio of 0.7–0.8 in the raw syngas from coal gasification unit is then increased by the water gas shift (WGS) unit. The pollutants including sulphur and nitrogen compounds, as well as carbon dioxide, are removed by Rectisol process, which has advantages over other processes