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Efficient utilization of associated natural gas in a modular gas-to-liquids process: Technical and economic analysis

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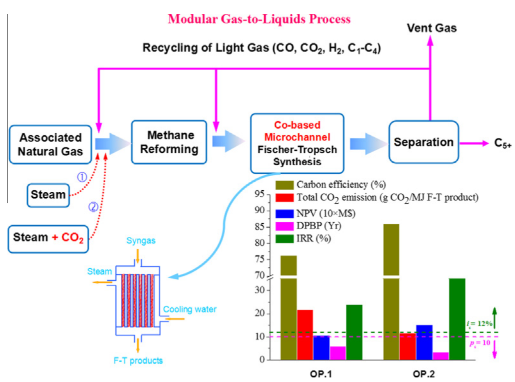
HIGHLIGHTS

- Two modular gas-to-liquids process options are proposed to convert associated gas to liquid fuels.
- Co-based microchannel F–T synthesis is applied to convert syngas to synthetic oils.
- Process modeling and conceptual design are implemented using Aspen Plus.
- Both technical and economic analyses are performed for the two modular GTL options.
- Both options are economically viable at the plant scale of 2500 BPD and more competitive in the event of high carbon tax.

GRAPHICAL ABSTRACT



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ABSTRACT

Two process models for modular gas-to-liquids (GTL) process mainly producing Fischer–Tropsch (F–T) synthetic oils were developed by Aspen Plus software. Both models mainly comprised a reforming unit, an F–T synthesis unit, and a recycle unit, with the syngas generation and syngas ratio conditioning methods as the main difference. In the reforming unit, either steam reforming or CO_2/Steam-mixed reforming was selected to generate the desired syngas. Co-based microchannel F–T synthesis was applied to convert the obtained syngas to synthetic oils. After F–T synthesis, a portion of the unreacted syngas was recycled to improve energy efficiency, and reduce CO_2 emissions. Technical and economic analyses were both employed to investigate the two modular GTL options. For the technical aspect, effects of recycling and splitting ratios on the performance of both options were investigated. Sensitivity analysis and break-even analysis were applied to the economic analysis. It was found that the increased energy efficiency and reduced CO_2 emissions could be achieved by recycling a portion of the unreacted syngas. Both options were economically viable at the plant scale of 2500 BPD, and were more competitive in the event of high carbon tax.

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1. Introduction

Associated natural gas, a byproduct of oil production, is generally flared or vented when it is technically or economically infeasible to establish infrastructure to deliver it to the market [1]. Because of the associated gas flaring and venting, huge amount of greenhouse gases are emitted into the atmosphere, resulting in dire global warming as well as energy waste [2]. In order to reduce the occurrence of gas flaring and venting, extensive efforts have been made since 2002 by the World Bank-led Global Gas Flaring Reduction Partnership (GGFR). Furthermore, an initiative known as "Zero Routine Flaring by 2030" was launched recently by GGFR as their future target [3]. Gas flaring can be reduced by adopting several technologies such as gas re-injection, liquefied natural gas (LNG), compressed natural gas (CNG), gas to wire (GTW) and gas to liquids (GTL) [4]. Among the above mentioned technologies, both LNG and CNG require high infrastructure costs. In addition, the large (>400 MMSCFD) and moderate gas reserves (>200 MMSCFD) are generally necessary for LNG and CNG, respectively. In contrast, gas re-injection, GTW and GTL are generally suitable for the small gas reserves (<200 MMSCFD). GTW, however, requires gas reserves with a nearby electricity market, and gas re-injection also requires high infrastructure costs for drilling deep re-injection wells without generating revenue [4,5]. Thus, the modular GTL based on the microchannel Fischer–Tropsch (F–T) technology is an ideal choice for efficient utilization of the associated natural gas, especially for the small gas reserves [5].

Within the past decade, modular GTL process based on the microchannel F–T synthesis has been gaining interest. Due to its greatly enhanced mass and heat transfer in the microchannel catalytic reactor and significantly reduced capital costs by numbering up, it is attractive compared to conventional reactors, especially at small plant capacity [6–9]. Similar to the conventional GTL process, the modular GTL process also consists of three main steps: (1) syngas generation by methane reforming technologies such as steam methane reforming (SMR) [10], autothermal reforming (ATR) [11], carbon dioxide reforming (CDR), [12] and partial oxidation of methane (POM) [13]; (2) syngas conversion to a broad range of hydrocarbons through microchannel F–T synthesis; (3) product upgrading to convert high molecular weight hydrocarbons to naphtha or diesel via catalytic hydrocracking [14–16]. Microchannel F–T synthesis is the key step in the modular GTL process, and Co-based F–T synthesis catalyst is typically used due to its high activity and selectivity toward long chain hydrocarbons [9,17,18]. Meanwhile, the H_2/CO ratio in syngas should be approximately 2 for Co-based F–T synthesis. Among the methane reforming technologies mentioned earlier, the ATR and POM can produce syngas with a H_2/CO ratio of 2. However, an expensive air separation unit (ASU) with a large footprint is necessary to generate pure oxygen, and the use of pure oxygen also poses challenging safety concerns [19]. While, for the SMR and CDR, the obtained H_2/CO ratio is deviated from 2, thus, an additional H_2/CO ratio adjustment unit is needed. However, if CO_2/Steam-mixed reforming is applied in the reforming unit, then, the H_2/CO ratio in syngas could be adjusted by controlling the two competitive reforming reactions SMR and CDR, to generate the syngas in flexible compositions [19,20].

Therefore, on the basis of the above consideration as well as our previous work on CO_2 utilized GTL process using Co or Fe-based F–T synthesis, [20–22] we now suggest two modular GTL processes, mainly applied in the small gas reserves, converting the wasted associated gas and CO_2 to valuable synthetic oils. Both technical and economic analyses have been conducted to evaluate the energy efficiency, CO_2 emissions and economic feasibility. In the economic analysis, several indicators, such as net present value (NPV), discounted payback period (DPBP) and internal rate of return (IRR) were calculated for the base cases of both options. Meanwhile, the effects of several factors, such as synthetic oil price, natural gas (NG) price, carbon tax and plant scale were investigated in detail. It was found that the improved energy efficiency and significantly reduced CO_2 emissions were realized by recycling a portion of the unconverted syngas. Moreover, the two modular GTL processes were economically viable at the plant scale of 2500 BPD, as per the economic assessment indicators NPV, DPBP and IRR, and were more competitive in the event of high carbon tax.

2. Material and methods

2.1. Process modeling

Generally, a modular GTL process usually consists of several units: units for feeding, gas pretreatment, reforming, microchannel F–T synthesis, product upgrading, and separation. However, the gas pretreatment, product upgrading and separation units were not investigated in detail in the present work, given that they are already well established in current petrochemical industry and their effects on the whole process performance is relatively small, as described in our previous work [20–22]. Hence, two simplified but meaningful modular GTL process options are instead proposed, mainly considering the feeding, reforming, microchannel F–T synthesis, and recycling units along with several separation units as a whole, which are illustrated in Fig. 1. Here, the main differences between the proposed options 1 and 2 are as follows: (1) In option 1, steam reforming is applied in the reforming unit, and before the microchannel F–T synthesis unit, a membrane separator is selected to adjust the H_2/CO ratio in syngas to about 2, by separating the excess H_2 from the produced syngas in the reforming unit. (2) Instead of steam reforming, option 2 uses CO_2/Steam-mixed reforming to generate the syngas in flexible compositions, and the produced syngas directly enters into the microchannel F–T synthesis unit without using a membrane separator for syngas ratio conditioning.

The reforming unit in both options consists of two parts, a prereformer and a reformer. The prereformer is operated under 550 °C and 5 bar (gauge). Under these conditions, the prereformer converts almost all the C_{2+} hydrocarbons contained in the fresh NG feedstock and in the recycled light gas from the microchannel F–T synthesis unit into methane, over a Ni catalyst [20]. Meanwhile, the equilibrium type reactor model RGibbs is selected to simulate the prereformer, as per the Gibbs free energy minimization. Moreover, the RGibbs reactor model is also applied in the reformer and two typical reactions SMR and CDR are as follows:

$$\text{SMR}: \quad H_2O + CH_4 \rightarrow CO + 3H_2 \quad \Delta H_{298K} = 206\ \text{kJ/mol} \tag{1}$$

$$\text{CDR}: \quad CO_2 + CH_4 \rightarrow 2CO + 2H_2 \quad \Delta H_{298K} = 247\ \text{kJ/mol} \tag{2}$$

Meanwhile, the reformer is operated under 850 °C and 5 bar (gauge). Under these circumstances, the aforementioned two reforming reactions could be supposed to reach chemical equilibrium at an elevated temperature, given that the reaction rates are very fast [22]. Meanwhile, the "Restricted chemical equilibrium" option was chosen in the RGibbs model to simulate the reformer well.

After reforming, in option 1, the produced syngas first enters into the membrane separator, and then into the F–T synthesis unit. While, in option 2, the produced syngas directly enters into the F–T synthesis unit without using membrane separator, since the H_2/CO ratio could be adjusted by the CO_2/Steam-mixed reforming itself, as mentioned before. The microchannel F–T synthesis reactor is operated under 235 °C and 20 bar (gauge), respectively. The main