Utilizing carbon dioxide from refinery for methanol and electricity co-production: system design and economic assessment

Qian Ma 1, *, Yuxi Wang 1, Xu Zhang 1, Xiaodan Yu 1, Anqi Liu1, Bo Yuan 1, Xiaojun Chen3

1 Research Institute of Safety & Environment Technology, China National Petroleum Corporation, Beijing 102206, China
2 Daqing Oilfield water supply Company, Daqing 163000, China
3 Chinese Academy of Environmental Planning, Beijing 100012, China

Abstract. Mitigating greenhouse gas (GHG) emissions to curb climate change has become a consensus among international community. Refining is one of the major industries with high energy consumption and high emissions, which is responsible for 4–10% of global carbon dioxide (CO2) emissions and approximately 25% is generated by fluid catalytic cracking (FCC) units. The flue gas discharged from FCC units has a high CO2 content, presenting potential for methanol and electricity co-production production when the methane in the dry gas is considered. To unlock this green chance for enterprises, we designed a methanol production system that uses the CO2 recovered from the flue gas of fluid catalytic cracking (FCC) unit in a refinery and the CH4 separated from dry gas as feedstock (hydrogen to be added from an internal hydrogen production unit of the refinery). We analyzed economic feasibility of the process, the results show that the developed system is economically feasible for annual methanol yields of 1.0–2.5 Mt and the internal rate of return increases by 8.3%.

1. Introduction

As the world's largest emitter of CO2, China has made a commitment to become carbon neutral by 2060 and to begin cutting its CO2 emissions within the coming decades. China's ambitious plan to meet the goal of carbon neutrality requires a set of diversified emission reduction strategy, which has become a long-term strategy to ensure the achievement of China's carbon neutral goal[1]. With the rapid urbanization and economic development of national economy, environmental problems caused by carbon emissions have attracted more and more attention. Refining and chemical industry is one of the main industries, represents a significant source of China's GHG emissions[2]. In the face of increasingly severe environmental protection requirements, bear the corresponding responsibility for emission reduction and develop strategies to work toward the deep decarbonization of the refineries are critical to meet the goal of carbon neutrality.

Studies on low-carbon refinery development are not rare. Johansson et al. [3] concluded that fuel substitution helps to reduce short-term CO2 emissions in a refinery. Zhang improved refinery energy efficiency by recovering low temperature waste heat through Organic Rankine Cycle power generation[4]. Thus, previous studies primarily focused on improving the energy efficiency of refineries, whereas endeavors to direct GHG emission reduction via CO2 capture and utilization are usually lacking.

In addition to improve refinery energy efficiency, CO2 is a valuable C1 raw material. It offers a good opportunity for refineries to improve decarbonization while to improve CO2's economic value through chemical conversion[5]. Fernández-Dacosta C used Aspen to simulate CO2 capture from a hydrogen production unit to co-produce dimethyl-ether (DME) and polyols, providing refineries with an approach to mitigate CO2 emissions [6]. Through carbon capture technology to recover CO2 from flue gas, and then realizing its utilization by chemical reaction promises an optimistic outlook for low-carbon refineries. In addition to environmental benefits, converting CO2 into high added value chemicals can also bring considerable economic benefits[7]. At present, Chinese petrochemical enterprises are facing the dual pressure of increasing oil-gas supply and the reduction of CO2 emissions. How to balance this dilemma, this is the significance of this study.

We developed a novel CO2 utilization process in refinery using Aspen Plus. Specifically, we designed a process turning "waste" into wealth in refinery that uses the CO2 recovered from the flue gas of an FCC unit and the CH4 separated from dry gas as feedstock for producing methanol, Fig. 1 displays the conceptual design of this study.
2. Methodology of economic evaluation

In this study, several key indicators, such as the total capital cost (TCI), the total product cost of methanol (TPC), the accumulative net present value (NPV) and internal rate of return (IRR) were calculated for economic evaluation due to their wide application in economics [8,9,10]. TCI mainly includes fixed asset investments and fluid capital. Peters proposed that the fixed asset investments of general chemical plants account for approximately 85% of the total project investment. He also proposed that there is an exponential relationship between the cost of similar chemical process equipment and scale rather than a simple linear relationship. In this paper, the scaling factor method is used to estimate the purchased equipment investment and fixed investment (instrument and control, pipeline, installation costs, etc.), and its calculation equation is expressed as

\[ C_p = C_A \times \left( \frac{S_B}{S_A} \right)^n \] (1)

where \( C_A \) and \( C_p \) are the equipment cost of the reference scale and the required scale to be estimated, respectively; \( S_A \) and \( S_B \) denote the scale of A and B, respectively; and \( n \) is the equipment scale factor. The TCI is the sum of all purchased equipment investment and fixed investment (instrument and control, pipeline, installation costs, etc.), and its calculation equation is expressed as

\[ TCI = 1 \times (1 + \sum F_i) \] (2)

where \( F_i \) is the ratio of the other purchased equipment cost to the total equipment investment, and \( i \) is the components of investment.

TPC is all the costs generated in the process of producing products, which is divided into two parts: operation cost and general expense. It is determined by Eq. (3).

\[ TPC = C_{RM} + C_U + C_{O&M} + C_{PR&R} + C_D + C_{TI&I} + C_P + C_{GE} \] (3)

where \( C_{RM} \), \( C_U \), \( C_{O&M} \), \( C_{PR&R} \), \( C_D \), \( C_{TI&I} \), \( C_P \) and \( C_{GE} \) denote raw materials, utilities, operation and maintenance costs, patents and royalties, depreciation, taxes and insurance, plant overhead and general expenses, respectively. Among these, the depreciation cost adopts the average life method with an assumption of a 20-year plant life and 5% salvage value.

NPV and IRR are also significant criteria used to assess the feasibility of a system. The specific method for NPV is given by

\[ NPV = f(t, n) = \sum_{t=0}^{n} \frac{CI - CO}{(1 + I)^t} \] (4)

\[ \sum_{t=0}^{n} \frac{NPV}{(1 + IRR)^t} = 0 \] (5)

where \( CI \) and \( CO \) denotes the inflow cash and outflow of cash, \( t \) is the cash flow year, \( i \) is the discount rate and \( n \) is the total number of years.

3. Results and discussion

Fig. 3 displays the IRR, TCI and constitution of costs with methanol production ranging from 0.35 Mt/yr to 3.5 Mt/yr. From the point of view of IRR, it is economically infeasible when the capacity is less than 0.7Mt/yr, which is lower than the value specified in the industry standard of China (12%). As can be seen, the value of IRR increases with increasing methanol capacity, which is similar to the effect of plant scale on capital investment. Compared with the traditional process, the IRR increases by 8.25 at the production of 1.8 Mt/yr [12]. With production changes in the scope of 3.5–2.45 Mt/yr, the TCI and constituent costs increase exponentially with increasing production. It is obvious that production of 2.45Mt/yr is a threshold, and increasing production beyond this point leads to significant increases in TCI. This bottleneck implies that there is a requirement for more processing units and power consumption to meet the higher capacities of methanol. The unit investment (TCI divided by production) decreases dramatically when the production is no more than 1.5 million tons. In general, the TCI for fixed asset investments is dominant, followed by working capital and equipment investment.
of the red circle, the longest payback period is 7 years, while the capacity is 0.35 Mt/yr. When the capacity is in the range 1.05–3.15 Mt/yr, the payback period is 4 years.

4. Conclusion

In this study, we proposed a promising way to reduce greenhouse gas emissions in the petrochemical field by recovering the CO₂ in the flue gas of the FCC unit and the methane in dry gas to unlock a solution for green refinery development. Specifically, a CO₂–dry gas to methanol production process was modeled based on Aspen Plus. The techno-economic and environmental performance of the system was analyzed. The results show that the proposed process could not only demonstrate excellent performance in mitigating carbon emissions in refineries but also make it possible to make good use of the methane in dry gas compared to the traditional methods. With the aid of economic analysis, the economic performance of the CTM process is better considering the annual production capacity within 100–300 million and compared with the conventional technique of methanol production, IRR increases by 8.3%. In addition, sensitivity analysis shows that the raw materials, O&M and utilities costs are the three main factors that affect the unit of methanol cost.

Acknowledgments

This work was supported by National Key R&D Program of China No. 2022YFC3702900. Thanks are also due the China National Petroleum Corporation (CNPC) Research Institute of Safety & Environment Technology for access to the database.

References