Applied Energy 113 (2014) 639–647

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Techno-economic analysis of the coal-to-olefins process in comparison with the oil-to-olefins process

Dong Xiang, Yu Qian, Yi Man, Siyu Yang *

School of Chemical Engineering, South China University of Technology, Guangzhou 510640, China

HIGHLIGHTS

- Present the opportunities and challenges of coal-to-olefins (CTO) development.
- Conduct a techno-economic analysis on CTO compared with oil-to-olefins (OTO).
- Suggest approaches for improving energy efficiency and economic performance of CTO.
- Analyze effects of plant scale, feedstock price, CO_2 tax on CTO and OTO.

ARTICLE INFO

Article history:
Received 12 May 2013
Received in revised form 1 August 2013
Accepted 4 August 2013
Available online 29 August 2013

Keywords:
Olefins
Coal-to-olefins process
Oil-to-olefins process
Techno-economic analysis

ABSTRACT

Olefins are one of the most important oil derivatives widely used in industry. To reduce the dependence of olefins industry on oil, China is increasing the production of olefins from alternative energy resources, especially from coal. This study is concerned with the opportunities and obstacles of coal-to-olefins development, and focuses on making an overall techno-economic analysis of a coal-to-olefins plant with the capacity of 0.7 Mt/a olefins. Comparison is made with a 1.5 Mt/a oil-to-olefins plant based on three criteria including energy efficiency, capital investment, and product cost. It was found that the coal-based olefins process show prominent advantage in product cost because of the low price of its feedstock. However, it suffers from the limitations of higher capital investment, lower energy efficiency, and higher emissions. The effects of production scale, raw material price, and carbon tax were varied for the two production routes, and thus the operational regions were found for the coal-to-olefins process to be competitive.

1. Introduction

Ethylene, propylene, butadiene, and butylenes (olefins for short) are among the most important petrochemicals and the primary building blocks for various chemical intermediates, polymers, and rubbers. Their production capacities are critical to petrochemical industry as well as the sustained economic development of a country. The world's total capacity of olefins was about 220 Mt in 2012. It was predicted that the demand growth rate would be 4.1% on average in the period from 2012 to 2017 [1]. The driving force of the quick growth is the booming economy associated with large-scale investment in manufacturing industries. This is more evident in developing countries, such as China, the Middle East, and India. In China, the yields and equivalent demands of olefins increased by 15.6% and 11.2% from 2005 to 2011, as shown in Fig. 1. It is seen that the self-sufficiency rates of ethylene and propylene were only around 50% and 70%, respectively. The situation can only be improved by the quick development of olefins industry.

The soaring demand for olefins is conflicted with the increasing depletion of oil. In world energy reserve, coal accounted for 59.9%, oil for 23.4%, and natural gas for 16.7% at the end of 2012. The corresponding reserves-to-production ratios were 109, 52.9, and 55.7, respectively [3]. Oil remains the world's leading energy resource accounting for about 33.1% of total energy consumption, as shown in Fig. 2. In order to reduce oil consumption, coal is considered as a natural alternative feedstock for olefins production. For coal-rich countries, especially China, developing coal-based olefins industry is regarded as of great important to sustainable development of chemical processing industry as well as national economy. In addition, due to inefficient planning, China's methanol industry has suffered from serious overcapacity in the last few years. The designed plant capacity for methanol production of China was only 6.2 Mt in 2003, but increased nearly eight times to 51.5 Mt in 2011. However, the real production was only 22.3 Mt in 2011 [4]. This problem can also be solved by using the surplus methanol to produce

* Corresponding author. Tel.: +86 20 87112056, +86 18588887467; fax: +86 20 87112046.
E-mail address: cesyyang@scut.edu.cn (S. Yang).

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http://dx.doi.org/10.1016/j.apenergy.2013.08.013

Nomenclature

CCS	carbon capture and storage	Mt/a	million metric tons per annum
CTO	coal-to-olefins	OTO	oil-to-olefins
DMTO	dimethyl ether/methanol-to-olefins	RMB/t	Renmingbi per metric ton
FMTP	fluid-bed methanol-to-propylene	$/bbl	US dollar per barrel
MTO	methanol-to-olefins	SMTO	Sinopec methanol-to-olefins
MTP	methanol-to-propylene		

about 10 Mt olefins since producing 1 t olefins needs to consume around 3 t methanol.

A number of coal-to-olefins (CTO) processes have been developed. The representatives of them are UOP/Hydro MTO, DMTO developed by Dalian Institute of Chemical Physics of Chinese Academy of Science, SMTO by Sinopec, Lurgi MTP, and FMTP by Tsinghua University [5–7]. Of these, the DMTO technology is considered as world leading. A CTO plant based on the technology was built by Shenhua Group and successfully put into commercial production on January 2011. It is the first and still the largest commercial CTO process till now, with the capacity of 0.7 Mt/a olefins (0.3 Mt/a ethylene, 0.3 Mt/a propylene, and 0.1 Mt/a $C_4^=$). The methanol conversion rate is close to 100% and the olefins selectivity is over 80% [8].

Given the potential importance of CTO industry to sustainable development, a systematic techno-economic study is imperative. However, very few literatures can be found on this subject. Hang [9] and Yang and Dong [10] carried out a simple cost analysis of a CTO plant. Ren et al. [11,12] made comparative analysis of olefins production from oil, coal, natural gas, and biomass. They paid more attention on energy utilization and CO_2 emissions of these processes. However, the economic analysis of the CTO process has not been involved in their study.

The purpose of this article is to make a technical and economic analysis of a CTO process and meanwhile explores the opportunities as well as challenges of CTO industry. In the study, an oil-to-olefins (OTO) process is used as the base case for comparison with the CTO process. The main indicators for assessment are energy efficiency, capital investment, and product cost. In addition, the study also attempts to identify the techno-economic bottleneck for the CTO process.

2. Methodology

2.1. Process modeling

At present, olefins are mainly produced from oil by steam cracking technology, although there are a number of other oil-based

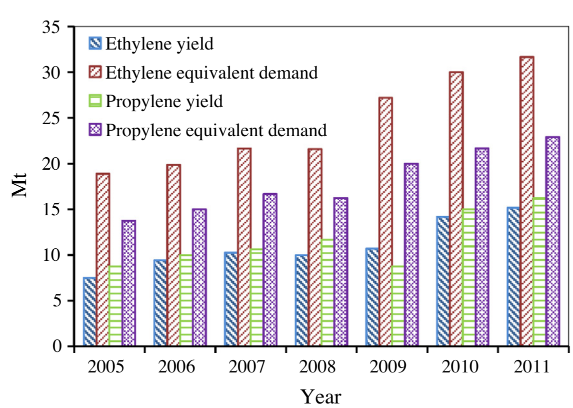

Fig. 1. The yields and equivalent demands of olefins in China [2].

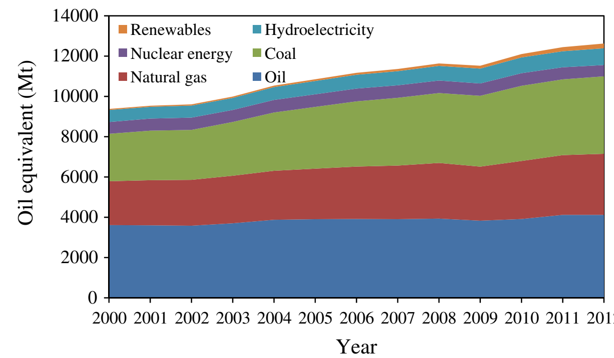

Fig. 2. Profile of major energy consumption in world [3].

technologies [12,13]. For steam cracking technology, the main feedstocks are naphtha and natural gas. North America and the Middle East use natural gas as the major raw materials of olefins production because of their big reserves of this resource. Naphtha and light diesel oil are usually the raw materials in most Asian countries [14]. It was reported that naphtha accounted for about 66% of the raw materials in cracking processes in China [15]. Thus, this paper uses the naphtha steam cracking technology as the benchmark.

The diagram of a naphtha steam cracking process is shown in Fig. 3. In this process, naphtha is first cracked into gas in the tubular furnace heated by the combustion of fuel gas. The heat of the cracking gas is recovered through quench boilers to produce high pressure steam. The cooled gas is then fed into gasoline splitter to separate gasoline and fuel oil. After quenching, alkaline washing, drying, and compression, the light gas is separated into pure ethylene and propylene via front-end depropanization separation [14]. The OTO process was modeled in Aspen plus simulation software. In the simulation, detailed components of naphtha are necessary and they are shown in Table 1. RYield model was used to simulate naphtha steam cracking reaction at 1113 K and 0.27 MPa. The composition of cracking gas was calculated according to the work of Sadrameli and Green [16]. PetroFrac model was used for simulating the gasoline splitter and RadFrac model was used for other distillation columns. The process compressors were modeled by assuming common isentropic and-mechanical efficiency [17,18].

A CTO process mainly contains three sub-processes, including coal gasification, methanol synthesis, and olefins synthesis. The flow sheet of CTO process is illustrated in Fig. 4. At the top left corner, there are the coal gasification unit, the air separation unit, and the water gas shift unit. After crushing and screening, solid coal is ground with water to produce the coal slurry with mass fraction 65%. The coal slurry is fed together with 95% pure oxygen into the gasifier to produce syngas, which is cooled in a radiant cooler and a convection condenser. The oxygen is derived from the air separation unit, in which air is first compressed, cleaned and then sent to cryogenic distillation column that separates air into O_2 and