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Conceptual design and system analysis of a poly-generation system for power and olefin production from natural gas

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ABSTRACT

In this paper, a novel poly-generation system for olefin and power production from natural gas is proposed, which integrates hydrocarbon production and the combined cycle power generation. Economic and technological evaluation based on the internal rate of return (IRR) and exergy efficiency is performed. The energy integration results in the proposed poly-generation system for simultaneous production of chemical products (ethylene and propylene) and electricity being more thermodynamically efficient and economically viable than single purpose power generation and chemical products production plants. IRR and exergy efficiency of the proposed poly-generation system are higher than that of natural gas methanol to olefin (NGMTO) system, 18.9% and 49.9%, respectively. The biggest exergy destruction segments, their causes, and possible measures for improvement are investigated simulation and thermodynamic analysis. To analyze the effect of unreacted syngas recycle on the exergy efficiency and economic gains from the proposed poly-generation system, its thermoeconomic optimization model is built by combining economic with thermodynamic analysis. Optimization analysis shows that when 78% of the unreacted syngas is recycled back to the reactor in the methanol synthesization process, the thermoeconomic performance of the poly-generation system is at its optimum.

1. Introduction

Industrial energy use is facing dual pressure from access to energy resources and environmental considerations. In some senses, energy shortages and environmental pollution have become critical bottlenecks to sustainable development of the world economy. The development and deployment of integrated energy conversion and chemical systems – poly-generation system – could be a promising approach to meeting increasingly stringent criteria and demand for reliable power supplies. There are many such integrated systems, particularly in chemical and energy industries where processes are flexible and output products could be cascaded and recycled to minimize environmental impacts [1]. Although the investment cost of poly-generation systems is higher, in the long run they are more economical than systems where power, heat and cooling are generated individually [2]. Poly-generation which can achieve the integrated production of energy, petrochemicals, and electricity, has captured the interest of many researchers. Gao investigated a coal-based poly-generation system for power and methanol production using graphical exergy analysis [3]. The results revealed that synthesis on the basis of thermal energy cascade utilization is the main contribution to the performance benefit of a poly-generation system. Kaggerud presented a superstructure block diagram of possible process trains for co-production of energy (electricity) and chemicals products (high purity H2, methanol, urea, and fertilizer). He stated that chemical and process integration gave economy of scale savings, better utilization of raw materials, improved energy efficiency and savings in investment costs [4]. Zhou proposed a co-feed and co-production system based on coal and natural gas for the production of electricity and Dimethyl ether (DME). The analysis results revealed that in terms of economy, energy utilization efficiency and environmental considerations, a Co–Co system is significantly better than single purpose production plant [5]. Wang integrated the traditional acetylene process with the use of fuel cells, and the results of exergy analysis showed that the systematic integration mechanism demonstrably improved the natural gas energy conversion efficiency [6], moreover, flowrate-exergy diagram (FED) was presented to describe the conversion rates of hydrogen and hydrogenous chemicals associating with the exergy loss [7].

Poly-generation, or co-production, has been highlighted in the literature as a promising alternative for the simultaneous production of electricity, hydrogen, synthetic liquid fuels, heat and/or chemicals, [8] and CO_2 capture and storage [9]. Using coal gasification, co-production of electricity and C1 chemicals, such as methanol and DME, is currently the focus of poly-generation research [10–14]. To our knowledge, however, using natural gas as

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Nomenclature

CCGT	combined cycle gas turbine
DME	dimethyl ether
GP	gasification process
NGMTO	natural gas methanol to olefin
HP	high pressure
IRR	internal rate of return
MP	medium pressure
MSP	methanol synthesis process
MTO	methanol to olefin
O&M	investment and operating & maintaining
OSP	olefin synthesis process
PP	power plant

feedstock, the combined production of power and olefin on integrated plant has still been lack of discussion. Natural gas, as a kind of fossil fuel resource, could play an important role in the future global energy system, particularly if security of supply considerations becomes more pressing. There are abundant natural gas resources in western China, but they are remote from markets or pipe lines. Thus it is a promising option to monetize such "stranded" gas by converting it into easily transported chemical products to bring it to market. With crude oil prices rising sharply and the public's increasing awareness of environmental issues unremitting efforts are being made to enhance the diversity of energy supply and efficient use of energy. Therefore, it is clearly necessary to develop and deploy integrated technologies to permit the conversion of natural gas into higher quality and more convenient energy carriers or chemical products in an efficient and clean manner with minimal environmental impacts.

This paper proposes, as one option to increase the overall efficiency, a novel natural gas-based poly-generation system for olefin and power production with the aim of coupling hydrocarbon production and combined cycle power generation. The main aim is to establish the technical and economic feasibility and thermodynamic performance of the poly-generation system as well as to determine the optimal process parameters.

The procedures and results that lead to the evaluation of the performance of the poly-generation system are discussed in detail. First, the concept and technology of the poly-generation system are illustrated in Section 2. Then it is explained how to set up modular flowsheet and simulate the whole system to get the simulation results for the following analysis. Section 4 presents a detailed analysis of the poly-generation system in terms of economic and exergy performance. In Section 5, a thermoeconomic optimization model for integrating the assessment of the economical and exergy performance is built. Based on the above analysis, an evaluation and conclusions are presented.

2. The system – a combined olefin with power generation

Using coal-based poly-generation as a model approach, methanol and olefin are synthesized simultaneously through different chemical conversions using natural gas as the feed stock. Steam produced from the synthesization processes and fuel gas released from the chemical conversion process is sent to a power plant to generate electricity. Combined olefin with power generation is schematically presented in Fig. 1, which includes several subsystems: the gasification process (GP), the methanol synthesis process (MSP), the olefin synthesis process (OSP), and the power plant (PP). In the gasification process, syngas is produced by steam reforming of natural gas in a multi-tubular fixed-bed reactor with a nickel catalyst at about 860–850 °C and 18–20 bar. Energy for the strongly endothermic reactor is provided by heating the reactor tubes in a furnace by combustion of natural gas or some fuel gas [15]. The main equilibrium reactions are:

$$CH_4 + H_2O = CO + 3H_2O \quad (1)$$

$$CO + H_2O = CO_2 + H_2 \quad (2)$$

The syngas produced from the gasification process is compressed and sent to the methanol process as the feed material. The methanol synthesis reactor uses a fixed-bed of copper-based catalyst at 200–280 °C and 80–100 bar [16]. The main (equilibrium) reactions are:

$$CO + 2H_2 = CH_3OH \quad (3)$$

$$CO_2 + 3H_2 = CH_3OH + H_2O \quad (4)$$

Both reactions are exothermic, so the temperature of the reactor needs to be kept at about 250 °C by controlling the evaporation pressure of the cooling water in order to maximize the equilibrium conversion. The reactor effluent is cooled to 40–45 °C to condense the crude methanol product and the unreacted gas is separated. The unreacted gas is divided into two streams in a separator: one is compressed and recycled by mixing with fresh gas as a recycle steam in order to increase the production of chemical products, the other is sent to the power side as a fuel feedstock.

UOP/HYDRO MTO technology [17], which produces a very high yield of ethylene (48%) and propylene (33%), is adopted in the olefin synthesis process. An attrition resistant SAPO-34 is employed as a catalyst. The UOP/HYDRO MTO unit employs a fluidized-bed reactor coupled to a fluidized-bed regenerator. The reaction heat is controlled by steam generation to keep the temperature of the reactor at around 400 °C. The main reaction is:

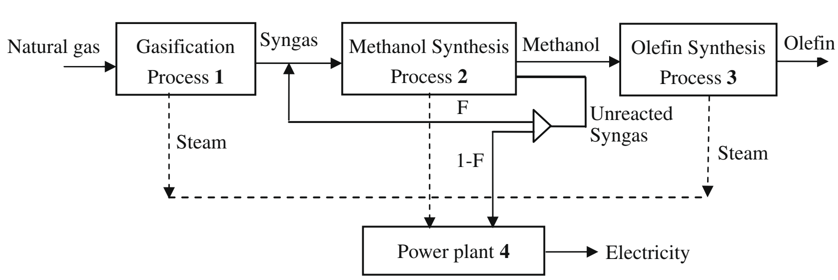

Fig. 1. Superstructure block diagram of co-production of chemicals and energy.