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Research Paper

Study on integrating a gas turbine in steam methane reforming process

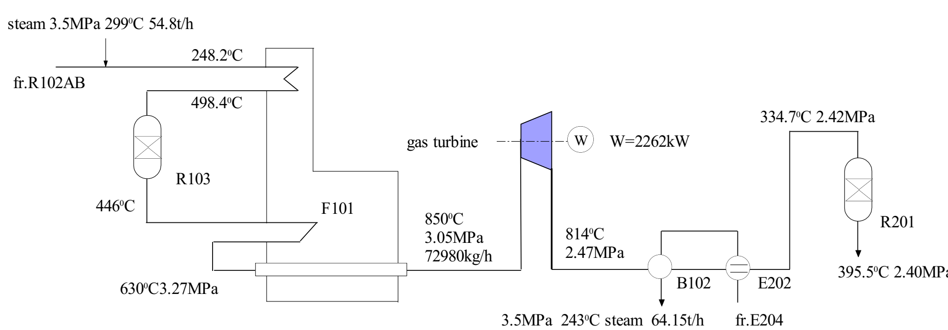
Guoqing Li [a], Guotian Zhong [a,*], Qing Wu [b]

[a] School of Chemistry & Chemical Engineering, South China University of Technology, Guangzhou 510640, China
[b] CNOOC OIL & Petrochemical Co. Ltd. (COPL), Huizhou 516000, China

HIGHLIGHTS

- A new route is proposed to improve the steam methane reforming process.
- Combined pinch and exergy is used to optimize the energy consumption.
- Global optimization is used to produce more turbine power.

GRAPHICAL ABSTRACT



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ABSTRACT

Since only heat energy of synthesis gas is recovered in existing steam methane reforming process, locating a gas turbine at the outlet of reforming furnace is proposed as a new route to have the heat and pressure energy recovered simultaneously. A case with hydrogen yield of 7×10^4 Nm^3h^{-1} shows the new gas turbine harvests power of 2262 kW. Questing for more power generation, the integration area is enlarged from the reforming furnace into the total route taking the transfer pressure (P_t) and operating pressure of H_2 purifying PSA device (P_p) as variables. The study demonstrates the new gas turbine harvests the power of 5462 kW when P_t and P_p are stipulated as 3.63 MPa and 1.70 MPa, respectively. Consequently, the total energy consumption and CO_2 emission are reduced by 2.5% and 735 gCO_2/kgH_2, respectively, and the process exergy loss of the synthesis gas is reduced by 5.15% as well.

1. Introduction

The gas turbine and heat recover steam generator (HRSG) are generally applied in the thermodynamics integration to recover the energy of high-temperature and high-pressure fluid [1], which is a prevalent method in the academic research and engineering application [2–5]. Perold et al. improved a phthalic anhydride process by letting the reaction gas (320 °C, 1.6 MPa) into the turbine first to expand, which achieved the 2651 MJ/ton phthalic anhydride export and 4.5% exergy loss reduction [6]. Greeff et al. made the methanol synthesis through the turbine expander and the new route consumed overall 24% less energy than the original one [7]. Sahafzadeh et al. integrated a gas turbine in the process associated with ammonia synthesis loop. It was shown that 4 MW of electricity can be produced and the total amount of exergy loss is reduced by 3323 kW [8]. Janssen et al. described the reaction for the synthesis of ethane from methane, which occurred in a gas turbine combustion chamber. The expansion work from the combustion products in the turbine is used to drive the methane and combustion air compressor [9]. Marechal and Favrat used a mixed integer linear programming formulation to optimize the utility system by heat pump and Pinch technology [10]. Kralj et al. utilized nonlinear programming (NLP) to optimize the methanol process with turbine and regarded the maximum annual profit as target

* Corresponding author. Tel.: +86 15899956892.
E-mail address: 619014224@qq.com (G. Zhong).

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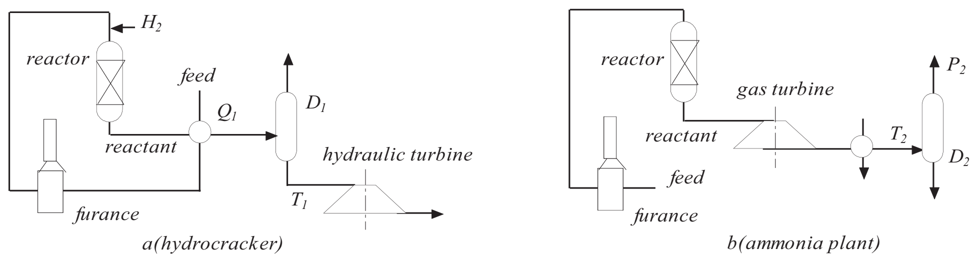

Fig. 1. Two typical processes.

function. As a result, the optimal outlet pressure of turbine is 3.5 MPa and the electricity produced from the turbine is 12.7 MW [11].

However, all of these researches regarded the parameters of high-temperature and high-pressure stream and downstream route after turbine as constants, resulting in the limitation in improvement when placing a turbine in the original route, which, of course, is not a global optimization. On one hand, the parameters of high-temperature and high-pressure stream can change, for example, the temperature (T_1) of oil from the separation drum (D_1) in the Hydro-Cracking plant will increase with the lower heat transfer in the feed heat exchanger (Q_1) leading to more power export work by hydraulic turbine (Fig. 1a). On the other hand, the parameters of downstream route after turbine cannot be kept constant as well; for instance, the pressure (P_2) of the product separation drum (D_2) in the ammonia synthesis loop can be reduced with the lower temperature (T_2) thus leading to more energy recovered by gas turbine (Fig. 1b). Actually, the change of parameters can create a new chance for system integration and optimization. For example, in the ammonia synthesis loop (Fig. 1b), an effective method to reduce the temperature (T_2) of synthesis gas is to heat 25 °C water to 98 °C by using the waste heat of synthesis gas. And then the 98 °C hot water drives the Br-Li absorption chiller to produce the 7 °C water so that it can decrease the feed's temperature of D_2. Consequently, a lower pressure of D_2 is achieved for producing more work by gas turbine. In addition, the waste heat could be digested and therefore reduce the cooling load. Moreover, in the Hydro-Cracking unit (Fig. 1a), the feed could be preheated by the diesel product which could reduce the heat transfer Q_1 and increase T_1, and as a result, lead to more work produced by the hydraulic turbine.

Hence, the energy recovery is not just to place a turbine but also to consider the global improvement of stream parameters and system integration. The wider the range heat and power integration are, the more turbine work and waste heat can be recovered. As mentioned above, the global system optimization with the turbine integration in the steam methane reforming route is investigated. With the increase of reaction pressure and decrease of PSA pressure, it can increase the inlet temperature (T_{in}) and pressure difference (ΔP) of turbine. So with the increase of T_{in} and ΔP, the power produced by the turbine is largely increased. The case shows that the global system optimization with turbine integration route increases the power by 141% and decreases by 5.15% process exergy loss than the original route.

2. Thermodynamic analysis

Thermodynamic analysis is an effective way applied in chemical process. For example, oxygen-enriched combustion [12] and natural gas reforming used in the gasifier [13] are investigated in the steam methane reforming process to demonstrate the utility of exergy analysis [14]. Besides, Pinch analysis is one of the methods for energy optimization [15]. All the hot streams composite a virtual hot stream as well as all the cold streams composite a virtual cold stream combining them into composite curves (CC) and grand composite curves (GCC) (Fig. 2). Based on the minimum temperature difference (Δt_{min}), CC and GCC can show the minimum cold and heat utilities and optimize the energy consumption [16]. For example, Lara et al. optimized the carbon capture route by Pinch technology and increased the total energy efficiency by 0.91% [17]. Foenell et al. applied the Pinch analysis in an ethanol production plant for heat integration, which decreased the energy consumption by 35–40%. In addition, more and more researches are related to the Pinch technology applied in the petrochemical yield [18]. With the consideration of heat recovery, total cost and heat exchange areas, Bakhtiari et al. decreased the utilities cost by 39.4% with the Pinch technology in the catalytic cracking unit [19]. Joe et al. showed that 34% drop of energy consumption was achieved by optimizing the heat exchange network of the crude oil distillation by the Pinch technology [20]. However, more and more practices indicate that though Pinch analysis can effectively deal with the heat exchange problems, it is unable to solve the pressure change problems during the process [21]. Conventional pinch analysis determines the most economical energy consumption about heat loads and provides practical design guidelines. However, in analyzing systems involving heat and power, for example, steam and gas turbines, etc., pure heat load analysis is insufficient [22]. Hence, the technology combined Pinch and exergy analysis is developed to solve above problems. Exergy is the

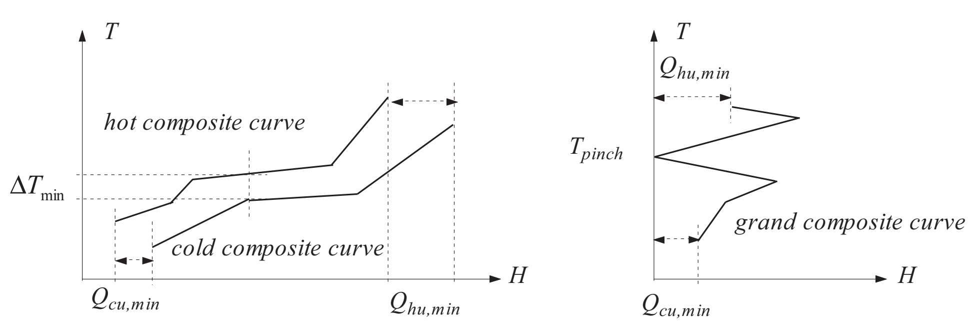

Fig. 2. CC and GCC.