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A novel cascade refrigeration process using waste heat and its application to coal-to-SNG

Sheng Yang, Jianeng Liang, Siyu Yang, Yu Qian*

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

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ABSTRACT

To efficiently develop coal-based chemical processes in China faces many challenges. A large amount of waste heat in the process is not efficiently employed. The proportion of energy that is fully utilized is extremely low. This paper proposes cascade refrigeration technology (CRT) that combines a LiBr absorption refrigeration with a NH_3 absorption refrigeration. The CRT is driven by low-grade waste heat below 150 °C and produces high-grade cold energy. The CRT is applied to a coal-to-SNG project as a case study. In a 4 billion Nm^3/a coal-to-SNG plant, the CRT is integrated to use low-grade heat taken from the methanation unit. Produced cold energy is used in the Rectitsol unit to remove CO_2. Results show that it reduces the compression refrigeration by 16%. The absolute gain is 3.4×10^7 million CNY per year.

1. Introduction

There is abundant coal reservation in China. As reported, 70% of total energy consumption comes from coal in China [1]. Coal is mainly used for chemical products, liquid fuels, and electricity powers. According to the statistics, there are 117 large-scale coal based chemical plants in China, of which 37% are for chemical products, 36% for oil synthesis, and the rest for power generation. In addition, the development of coal based chemical plants is in full swing and the growth rate is as high as 5% [1]. Five new coal based chemical technologies are coal-to-olefins, coal-to-SNG, coal-to-glycol, coal-to-oil, and coal-to-aromatics. By July 2014, 7 coal-to-olefins plants had been in operation. The production capacity was estimated to be 3.26 million tons/a olefins. National Development and Reform Commission in China has approved 17 coal-to-SNG projects since 2013, resulting in more than 70 Nm^3/a SNG production. These projects are manly located at Xinjiang, Inner Mongolia, Shanxi and Anhui provinces. By June 2014, 7 coal-to-glycol plants with total capacity of 1.1 million tons/a had been in operation. Coal-to-oil technologies include direct liquefaction and indirect liquefaction. These technologies have been successfully commercialized and were predicted to increase to 16 million tons in 2016. The coal-to-aromatics projects are now still in demonstration stage [2].

Development of coal based chemical industries are limited by its low energy efficiency and high environmental waste emission. It was found that high energy consumption in coal based chemical industries is mainly due to the loss of waste heat [3]. According to the work of Li et al. [4], the waste heat of coal based chemical plant accounts for 17–67% of total fuel consumption and about 60% of total the waste heat is recyclable to use.

There are three types waste heat: high-temperature waste heat upper 600 °C, middle-temperature waste heat between 300 °C and 600 °C, and low-temperature waste heat below 300 °C [5]. In general, waste heat utilization technologies include heat exchange, thermal power conversion, and waste heat refrigeration [6]. This paper focuses on using low temperature waste heat below 150 °C to produce high grade cold energy. NH_3 absorption and LiBr absorption refrigeration are two classical absorption refrigeration technologies [7]. Neither a single-stage LiBr absorption refrigeration process nor a NH_3 absorption refrigeration process can produce high grade cold energy by using low temperature waste heat. In this paper, a new cascade refrigeration technology is proposed by combining a LiBr absorption refrigeration and a NH_3 absorption refrigeration process. This technology can produce cold energy between −40 °C and −30 °C. Compared with a LiBr absorption refrigeration, the NH_3 absorption refrigeration requires higher grade heat as driving force. The concept of the energy cascade utilization is that the waste heat is used by a NH_3 absorption

* Corresponding author.
E-mail address: ceyuqian@scut.edu.cn (Y. Qian).
URL: http://www2.scut.edu.cn/ce/pse/qianyuen.htm

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refrigeration process and a LiBr absorption refrigeration process in sequence. Cold water generated by the LiBr absorption refrigeration process is used to reinforce the NH_3 absorption refrigeration process. The cascade absorption refrigeration process is designed and modeled using Aspen Plus. Its thermodynamic properties are revised by DECHEMA 2014 for simulation.

The remaining part of the paper is organized as follows: section 2 is a detailed description of cascade absorption refrigeration technology, section 3 is designing and simulating the cascade absorption refrigeration technology, and in the last section, a 4 billion Nm^3/a coal-to-SNG process is examined as a case study. The cascade absorption refrigeration process uses waste heat from the methanation unit and produces the cold energy for the Rectisol unit. The cold energy replaces part of the compression refrigeration in the Rectisol. An economic analysis is conducted. Results show that it can reduce the compression refrigeration by 16%. The absolute gain is estimated to be 3.4×10^7 million CNY per year.

2. The cascade absorption refrigeration system

The cascade absorption refrigeration technology (CRT) consists of a NH_3 refrigeration process and a LiBr absorption refrigeration process. The new process has applied for a Chinese patent, as shown in Fig. 1[8].

In the NH_3 refrigeration process, the concentrated NH_3 solution is fed into the lower portion of the NH_3 producer. Dilute NH_3 solution leaves the bottom of the column, and NH_3 leaves from the top. The column is heated by the waste heat from the methanation unit. The condenser is cooled by the chilled water generated from the LiBr absorption refrigeration unit. NH_3 from the top of the column is condensed into liquid NH_3. The liquid NH_3 is fed into the Rectisol via the NH_3 solution valve and then evaporated into NH_3 gas in the Rectisol unit to produce cold energy. NH_3 gas enters the subcooler to condense the liquid NH_3 and is then fed into the NH_3 absorber. The dilute NH_3 solution is fed into the NH_3 absorber from the NH_3 storage. The NH_3 gas is absorbed by dilute NH_3 solution in the NH_3 absorber. At the same time, the absorber is cooled by the chilled water from the NH_3 condenser. Concentrated NH_3 solution from the NH_3 absorber is fed into NH_3 producer.

In the LiBr absorption refrigeration process, the dilute LiBr solution is fed into the LiBr producer. The concentrated LiBr leaves the bottom of the producer, while water steam leaves from the top. The LiBr producer is heated by the waste heat from the NH_3 producer. Steam water from the top of the LiBr producer is cooled in the water condenser. Liquid water enters the NH_3 absorption refrigeration process via the water valve. The chill water is evaporated into steam water to produce cold energy, while the steam water is fed back into the LiBr absorber. The concentrated LiBr solution from the bottom of the LiBr producer is fed into the LiBr absorber from the LiBr storage. The steam water is absorbed by the concentrated LiBr in the LiBr absorber. The dilute LiBr from the LiBr absorber is fed into the LiBr producer.

3. Design and simulation of the CRT

Design and modeling of the NH_3 absorption refrigeration process are similar to those of the LiBr absorption refrigeration process. Thus, we explain the NH_3 absorption refrigeration process in details here and explain the LiBr absorption refrigeration process briefly. The NH_3 absorption refrigeration process is introduced by Herald et al. [9]. The schematic diagram of the NH_3 absorption refrigeration is shown in Fig. 2.

The following assumptions are made to simplify the simulation [6]:

1. Pressure drop and heat loss in connecting pipes and heat exchangers are neglected;
2. The refrigerant leaving the evaporator is saturated vapor;
3. The refrigerant leaving the condenser is saturated liquid;
4. The throttling process of refrigerant and solution is isenthalpic;
5. The refrigerant and the solution leaving the generator are in thermal equilibrium.

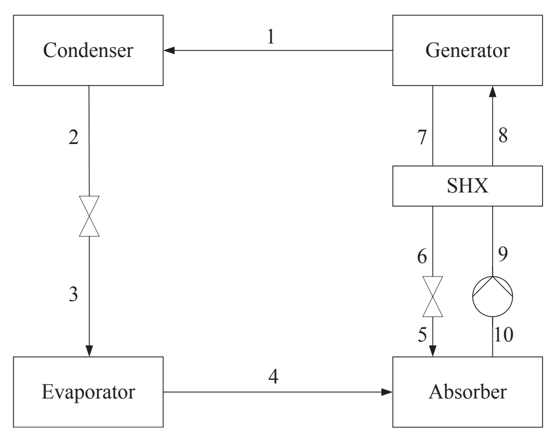

Fig. 2. Schematic of NH_3 absorption refrigeration.

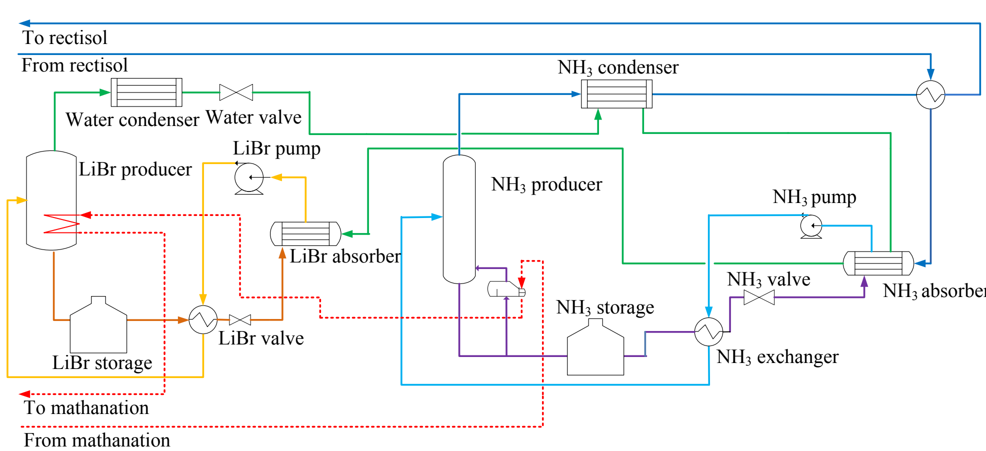

Fig. 1. Flow diagram of the CRT.