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Cold energy utilization of liquefied natural gas for capturing carbon dioxide in the flue gas from the magnesite processing industry

Liang Zhao [a], Hui Dong [a,*], Jiajun Tang [b], Jiuju Cai [a]

[a] SEP Key Laboratory of Eco-Industry of Northeastern University, Shenyang 110819, China
[b] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

In the present paper, a novel system based on LNG (liquefied natural gas) cold energy utilization was proposed to capture CO_2 in the exhaust gas discharged from the magnesite processing industry located in Liaoning Province (China). The system also combined with a twin-stage ORC (organic Rankine cycle) power generation sub-system using LNG as heat sink and exhaust gas as heat source. Based on the exergy analysis method, the LNG regasification pressure and the CO_2 capture pressure were investigated as the key operation parameters to find the suitable working conditions of the system. The results show that, in Liaoning Province, the amount of LNG cold energy received at Xianrendao Port can theoretically afford to capture CO_2 in the exhaust gas from the magnesite processing industry at Dashiqiao Area. In addition, when the LNG regasification pressure and the CO_2 capture pressure is respectively set as 1.0 MPa and 0.15 MPa, the system can reach exergy efficiency of 0.57 and provide 119.42 kW electric power and 0.75 t liquid CO_2 per ton LNG. For downstream utilization of CO_2, a CO_2 utilization sub-system was proposed. It integrates Rankine cycle, water electrolysis and carbon dioxide hydrogenation for methanol production by solar energy and liquefied CO_2 cold energy utilization.

1. Introduction

As the world continuously develops, the conflict between environment problems and energy sector has become more and more obvious. NG (natural gas) is a kind of environment friendly resource with high conversion within the combustion process [1]. Thus, using NG instead of other traditional fossil fuels for energy supply is considered as a suitable way to ease this contradiction.

LNG (liquefied natural gas) is the main transportation form of long-range transport by water transportation and short-range ground transportation. In addition, during the liquefied process, LNG contains enormous cold energy (or cryogenic energy) which consists of low temperature (about 110 K) sensible heat and latent heat of vaporization. The cold energy can be released during the regasification process of LNG. That means, LNG can be used as a chemical energy resource and also as a cold energy resource. However, the conventional regasification systems squander the cold energy but require significant energy supply [2]. Therefore, many researchers focus on developing some methods to recover the cold energy during the LNG regasification process.

Among the methods for recovering cold energy, electricity power generation is one of the most efficient way. About 15 cryogenic power plants using cold energy of LNG have been built in Japan since 1979 to 2000 [3]. In the past three decades, the performances of those cryogenic power plants have been constantly improved. Dispenza [4,5] proposed an innovative process which used a cryogenic stream of LNG during regasification as cold source in an improved CHP (combined heat and power) modular plant. Szargut [6] investigated the efficiency differences between three variant types of cryogenic power plant by some key parameters including ambient temperature, heat transfer temperature difference etc. Consequently, the production of electricity power recovering the available cold energy during LNG regasification process, should be a very suitable option for an improved power plant or in a cryogenic power plant. Therefore, lots of researches put emphasis to increase the efficiency of LNG cold energy utilization for power generation by combining traditional power cycles or with further optimization of some key parameters of these cycles. Choi [7] proposed a cascade Rankine cycle with propane as the working fluid for recovering LNG cold energy for power generation. The process simulation indicated that the parameters such as net power output, energetic efficiency,

* Corresponding author. Fax: +86 024 83672218.
E-mail addresses: zhliang8341@163.com, Dongh@smm.neu.edu.cn (H. Dong).

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and exergy efficiency generally increased as the number of stages increases (≤3 stages). Gómez [8] presented a novel power plant consisting of a combination of a CBC (closed Brayton cycle) with a SRC (steam Rankine cycle) while exploiting the cold exergy available in the regasification process of LNG. An energy and exergy analysis was also carried out to evaluate the effect of some key parameters on the efficiency. Still Gómez [2], carried out a review of the current state of thermodynamic cycles for improving power generation efficiency by using cold energy during LNG regasification process, and also established a selection criteria of the working fluids. Dong [9] fundamentally investigated a method which utilized LNG cold energy for power generation with Stirling cycle based on previous studies, and made some improvements of the method.

The power generation performance is, however, significantly affected by the thermodynamic properties of the working fluids. As a consequence, some researches focus on investigating the working fluid properties to find the more suitable one [10] (or a group [11–13]) for recovering cold energy of LNG. Indeed, carbon dioxide (CO_2) is also a feasible choice for power generation cycle with utilization of LNG cold energy [14,15]. It indicates that LNG with low temperature can be regarded as a heat sink to condense the CO_2 under the specific conditions. It could be a good solution to some environmental problems such as global warming and rising sea levels, that utilizing LNG cold energy to capture CO_2. Therefore, some researchers have studied about capturing CO_2 though cold energy recovery in LNG fueled power plant. Liu [16] presented a thermo-economic analysis aimed at the optimization of a novel zero-CO_2 and other emissions and high-efficiency power and refrigeration cogeneration system. Zhang [17] presented a novel scheme of LNG fueled power plant, which could liquefy CO_2 after combustion process and capture it from the cycle without consuming additional power. Alabdulkarem [18] integrated a LNG plant with a CCS (CO_2 capture and sequestration) plant for recovering waste heat to reduce energy consumption during CO_2 liquefaction process. These researches about CO_2 capture of power generation system were focused on 'self-capture' system which belongs to post capture system. However, some industries also can produce large amounts of carbon dioxide without combustion, for instance, the magnesite processing industry.

Magnesite ($MgCO_3$) processing industry in China, particularly in Liaoning Province, is another bulky CO_2 emission source which could avoid separating process to reducing energy consumption. According to the U.S. Geological Survey [19], there is a large amount of magnesite mine reserves in China (20.9% of total world). Most magnesite mine resources in China (85.5% of total China) are discovered at west and south of Liaoning Province, especially at Yingkou City (over 30%) [20]. For long time, magnesite processing industry has been widely pullulated in Liaoning Province. Over hundreds of enterprises are specialized in magnesite processing, and the total production of these companies can reach to 7.87 million tons per year [21]. Approximately, almost 4 million tons of CO_2, which accounts for 1% of total carbon emission in Liaoning Province will be discharged to the environment [22]. The mechanism of CO_2 generation process in a magnesite processing plant is inherently different in a power generation plant. The magnesite is heated by electric arc in a pillar furnace and decomposed to MgO and CO_2. There are two types of electric arc furnace used by magnesite processing plant: open-type and closed-type. The closed-type furnace puts a moving petticoat pipe structure on the mouth of furnace when the magnesite is heating in the furnace. Thus, the flue gas can be effectually centralized for subsequent treatment, such as dust removal [23]. As a consequence, the concentration of CO_2 in the centralized flue gas from a closed-type furnace is higher than it in the uptight flue gas from an open-type furnace. Some test results shows that the CO_2 volume fraction in the flue gas of the open-type furnace is 0.31 on average [21]. Recently, three closed-type furnaces of different magnesite processing plants at Yingkou City were chosen for testing the CO_2 concentration of flue gas. The results show that the CO_2 volume fraction in the flue gas of the closed-type furnace reaches 0.40–0.49. Because of the negative pressure environment needed by the dust control system, a large quantity of air that can be inhaled though unsealed places, such as the joints of pipe. For this reason, it is difficult to get CO_2 volume fraction over 0.50 in the flue gas of the closed-type furnace.

In China, CO_2 capture is concentrated in power generation system because of 73% of the total carbon emissions come from this sector [24]. Post-combustion CO_2 capture and oxy-fuel combustion are two basic technologies for capturing CO_2 from power systems [25]. Until now, the major obstacle deterring the development of CO_2 capture technology is high-energy penalty for separating CO_2 from flue gas [26]. Therefore, concentrating CO_2 in flue gas is the first and main energy consumption process of CO_2 capture. LNG cold energy can be utilized as energy supplement for CO_2 capture process. Nevertheless, the research is still blank that utilize LNG cold energy for capture CO_2 from magnesite processing industry in Liaoning Province.

In this paper, a novel system of LNG cold energy utilization for generating power and capturing CO_2 is proposed. The system combines a power generation sub-system which consists of two organic Rankine cycles both considered LNG as heat sink and the flue gas as heat source. The mathematical model of the system is established to calculate the thermodynamic parameters of the system. And then, the model is applied to evaluate a real case in Liaoning Province, China. In this case, CO_2 in flue gas from magnesite processing industry located at Dashiqiao Area will be captured by LNG cold energy located at Xianrendao Port. In addition, the sensitive analysis of some key operation parameters is conducted to examine the system performance for finding the suitable working conditions. Furthermore, the feasibility analysis is made for a CO_2 utilization sub-system for methanol production.

2. System description

The specific system design of LNG cold energy utilization for power generation and CO_2 capture is shown in Fig. 1. CO_2 is liquefied within this system using LNG cold energy recovery. The system employs the flue gas from the magnesite processing industry as heat source to supply heat energy to a parallel twin-stage Rankine cycle, which considering LNG as heat sink to generating power. This overall system consists of a CO_2 capture sub-system, a twin-stage organic Rankine cycle power generation sub-system and a LNG regasification sub-system.

The CO_2 capture sub-system consists of a CO_2 compressor, two heat exchangers and a liquid–vapor separator. The flue gas, firstly, is compressed by the compressor for overcoming the pressure drops within heat exchangers. Then, the flue gas is cooled down in two heat exchangers respectively. Finally, CO_2 is liquefied though releasing heat to Rankine cycle and separated from air in the liquid–vapor separator. The waste heat of the flue gas is the only heat source for heat energy supply to the power generation sub-system. The process is shown as C1 to C6. C5 and C6 denotes air and liquefied CO_2, respectively.

For using LNG cold energy efficiently and simplifying the overall system, a parallel twin-stage organic Rankine cycle is selected for power generation sub-system. Though organic Rankine cycle is a widely option for generating power associated with LNG regasification process, a working fluid with appropriate physical properties should be used [8]. According to the working conditions of the