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Using cryogenic exergy of liquefied natural gas for electricity production with the Stirling cycle

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ABSTRACT

Cryogenic generation is one of the most important ways to utilize cold energy during LNG (liquefied natural gas) regasification. This paper fundamentally investigates LNG cryogenic generation with the Stirling cycle method based on previous studies. A basic process of LNG cryogenic generation with the Stirling cycle was presented initially with seawater and LNG as heat source and heat sink. And its thermodynamic analysis was performed to verify the theoretical feasibility of the Stirling cycle method. The generating capacity, the exergy efficiency and the cold energy utilization efficiency of the basic process were also calculated. Subsequently, the influences of evaporation pressure on net work, equipment performance and comprehensive efficiency of cold energy utilization were discussed and the effect of LNG mass flow as well as the ambient temperature was also studied. Finally an improved process of LNG cryogenic generation with Stirling cycle method combined with an air liquefaction process is proposed as feasibility in improvements of the basic process.

1. Introduction

LNG (Liquefied natural gas) has a large temperature difference (about 182 K) between ambient air and water, and thus contains considerable cold energy which can be recovered for electricity generation, air separation, food freezing etc. Using cold energy to generate electricity is more efficient than using waste heat with the same temperature difference [1]. Thus, cryogenic generation is the most effective way to recover the cold energy of LNG. What's more, many previous studies about more effective way to use LNG cold energy for power generation have been conducted. Wang et al. [2] proposed an ammonia–water power system with LNG as its heat sink to utilize the low grade waste heat, and optimized the key thermodynamic design parameters. Szargut et al. [3] investigated three variants of cryogenic power plant and studied the influence of the changing ambient temperature on the efficiency of the cryogenic power plant. Dispenza et al. [4,5] proposed an innovative process which uses LNG as the cold source in an improved CHP (combined heat and power) plant, and analyzed the performance based on thermodynamics and economics. Meanwhile, to improve the cold energy recovery efficiency of an LNG cryogenic power plant, some studies have been carried out. Tsatsaronis and Morosuk [6,7] presented a detailed advanced exergetic analysis of a novel co-generation concept that combines LNG regasification with the generation of electricity. In recent years, researches for the production of electricity form LNG by utilizing its cryogenic energy have developed in China. Liu and Guo [8] proposed a novel cryogenic cycle by using a binary mixture as working fluids and combined with a vapor absorption process for LNG cold energy recovery. Lu et al. [9] proposed a cascading power cycle with LNG directly expanding consisting of a Rankine cycle with ammonia–water as working fluid and a power cycle of combustion gas to recover cold energy of LNG.

Japan is the most successful country in the cryogenic generation application field. It has built around 15 cryogenic power plants from 1979 to 2000 [10]. These plants operate by using the Rankine cycle method or NG (natural gas) directly expanding method or combination type of these two methods. However, the recovery efficiency of LNG cold energy in Japan is usually about 14% [11]. No matter in academic research field or in engineering application field, ORC (organic Rankine cycle) is the most commonly used to generate electricity for LNG cold energy recovery. Compared with ORC, ideal Stirling cycle has several advantages in theory, such as higher thermal efficiency, larger cycle net work etc. [12]. Moreover, the device works with Stirling cycle – Stirling engine, has many merits like operation with low noise, operation with constant power output, consist of fewer parts, etc. These advantages give Stirling cycle engine vast application potential.

In 1978, a Japanese researcher named Oshima [13] proposed a scheme using LNG or LH_2 (liquid hydrogen) cold energy for power generation by a cryogenic type Stirling engine. Many years later, Servis

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[14] innovatively proposed the NSCE (New Stirling Engine Concept) to develop a large cryogenic type Stirling engine by adding a isobaric heat addition process in the cycle, which has already authorized in several patents [15,16]. The application possibilities of using the NSCE for generating power coupled with LNG regasification process were also investigated by Servis [17]. Meanwhile, Tan [18] made a preliminary discussion that Stirling engine is evidently more favorable to recover LNG cold energy. Li [19] put forward a complex system comprising a gas turbine along with a Stirling engine to utilize LNG cold energy and thermodynamically analyzed the system. However, these preliminary researches do not explain the principle of LNG cryogenic generation with Stirling cycle method in depth.

Based on the existing researches, we propose a basic Stirling cycle cryogenic generation process for LNG cold energy recovery in this paper. The energy and exergy changes in thermodynamic process, both of LNG regasification process and Stirling cycle operation process are calculated. The effects of some key parameters on performance of the basic process, such as LNG vaporization pressure and ambient temperature, are also investigated. Additionally, we put forward an improved process of LNG cryogenic generation with Stirling cycle combined with air liquefaction to study the feasibility for optimizing the basic process.

2. Basic process description

We propose a basic Stirling cycle cryogenic generation process. The scheme of the basic Stirling cycle cryogenic generation process for LNG cold energy recovery and the corresponding *T–s* diagram are shown in Figs. 1 and 2, respectively. The basic process includes two branches: a LNG regasification process and a nitrogen Stirling cycle process. ①The LNG regasification process is shown as 1L–2L–3L–4L–5L. From the beginning of the basic process, LNG is stored at −162 °C under 0.14 MPa. And then, LNG is pumped into the pipeline from a storage tank and pressurized to vaporization pressure (from state 1L to 2L). It is then heated to saturated temperature in heat exchanger HX3 (heat exchanger 3) (2L–3L). Afterwards, it flows through the nitrogen compressor to cool down the nitrogen and is partly gasified (3L–4L). Finally, LNG is totally gasified through the heat exchanger HX2 and heated to the supply temperature (4L–5L). ②The nitrogen Stirling cycle process is depicted as 1–2–3–4–1. Nitrogen goes into the seawater-heating turbine, and isothermally expands from state 1 to state 2. Then it flows into heat regenerator (HX1) and gives off heat isochorically (state 2 to state 3). Subsequently, nitrogen is isothermally compressed by a LNG-cooling compressor (state 3 to state 4). Eventually, it goes through the

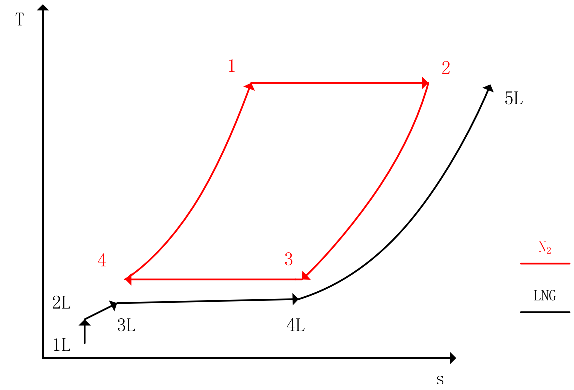

Fig. 2. *T–s* diagram of the basic cycle.

heat regenerator (HX1) again and takes heat back (to state 1). Thus, nitrogen completes an ideal Stirling cycle.

LNG is a mixture (consists of methane, ethane, propane, etc.) without a fixed phase-transition temperature at a constant pressure. However, it may exist in a relatively stable phase-transition period with little temperature change. We call this relatively stable phase-transition period the gasification level section. The Stirling cycle requires constant-temperature heat source and heat sink for minimizing irreversible loss. Therefore, when LNG is regarded as the heat sink of the Stirling cycle for power generation, the isothermal compression process (state 3–4), should be in the gasification level section.

In this article, the isothermal compression process and the isothermal expansion process of Stirling cycle are respectively implemented by a constant temperature compressor and a constant temperature turbine. The compressor is cooled by LNG and isothermally compresses nitrogen. The turbine is heated by seawater and drives a generator to produce electricity. On the other hand, nitrogen is chosen as the working fluid in the ideal Stirling cycle in this paper instead of hydrogen and helium, for it is substantial and easy to produce.

3. Basic process performance

3.1. Parameters calculation

Assumptions:

(1) LNG is a mixture that consists of methane, ethane, propane and nitrogen, which is listed in Table 1.

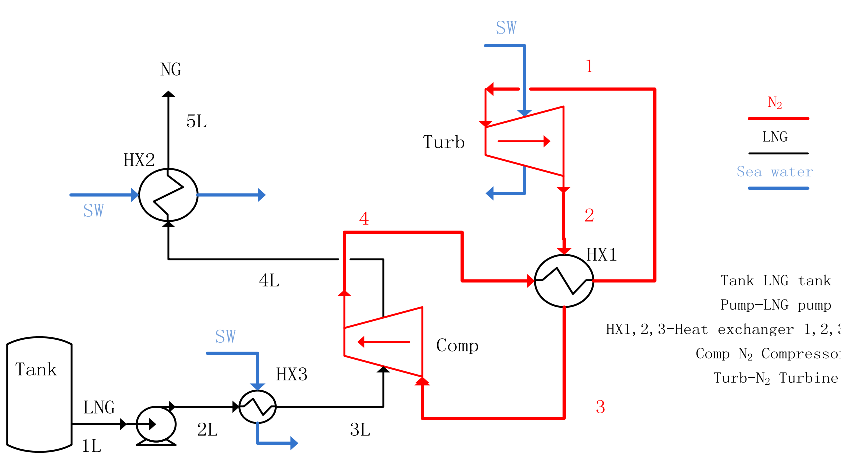

Fig. 1. The detailed process of the basic cycle.