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Design and optimization of cascade organic Rankine cycle for recovering cryogenic energy from liquefied natural gas using binary working fluid

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ABSTRACT

A cascade power generation system that utilized the cold exergy of liquefied natural gas (LNG) was proposed in this study. The proposed system adopts binary working fluids for each stage to minimize the exergy destroyed in the condensers of each stage of the cycle. The best combination of working fluids was selected through minimization of the amount of destroyed exergy by varying the flow rate, composition, and pressure of the working fluid. After selecting the working fluids, process optimization was performed through a parametric study. In addition, a sensitivity analysis was performed to observe the effect of temperature variation of the heat sources in the range of 25–85 °C on the net power generation.

As a result, the proposed cycle generated 151.78 kJ/h kgLNG under a 25 °C heat source and showed an efficiency of 18.64%. The performance of the proposed cycle was linearly increased according to the temperature of heat source. For instance, the proposed system generated 248.79 kJ/h kgLNG, with exergy efficiency of 27.11% under an 85 °C heat source.

1. Introduction

Natural gas is one of the most widely used form of fossil fuel with high levels of energy production and low greenhouse gas emissions. For transportation, it is liquefied, and transported to a regasification terminal carrying considerable amounts of energy. This energy is wasted during regasification if no retrieving process is applied. For this reason, various methods have been studied to recover this energy into some form of application at regasification terminals, and organic Rankine cycles (ORCs) have been known to be one of the most effective.

ORCs use organic working fluids for energy production, so heat sources and heat sinks of low temperature are often utilized. Many studies have been conducted on the use of LNG (liquefied natural gas) as the heat sink of an ORC, involving analyses of the key parameters and the development of new cycle configurations. Shi and Che [1] proposed a combined power system integrating an LNG power generation cycle with an ammonia-water mixture Rankine cycle. Their study analyzed key variables such as the ammonia turbine inlet pressure, ammonia mass fraction, LNG turbine inlet pressure, and heat source temperature. Liu and Guo [2] proposed a novel cryogenic cycle combined with a vapor absorption process to improve efficiency of the energy recovery rate. Optimization of the key variables resulted in increased efficiency compared to the conventional ORC by 66.3%. Zhang and Lior [3] presented a novel LNG-fueled power plant with a high efficiency and virtually zero CO_2 emissions. The proposed cycle was an integrated form of a supercritical CO_2 Rankine-like cycle and a CO_2 Brayton cycle, with a recuperation system to connect the two. Wang et al. [4] analyzed the thermodynamic aspects of an ammonia-water-based power system with an LNG heat sink. Optimization of the three main objective functions, the exergy efficiency, total heat transfer capability, and turbine size was performed to find the exergy efficiency. Gomez et al. [5] also performed a thermodynamic analysis of the combined cycle of a closed Brayton cycle and a steam Rankine cycle. Choi et al. [6] performed an optimization of a cascade ORC system utilizing the cold exergy of LNG. They concluded that a three-stage cascade ORC using a propane working fluid produced the most electricity. Lee et al. [7] introduced an ORC using LNG to a stream cycle with the CO_2 capture process. The amount of power generated

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was increased by 73% compared to the conventional case, and the energy requirement for CO_2 liquefaction in the CO_2 capture process was decreased by 9%. Sun et al. [8] proposed a novel ORC design for the recovery of LNG cold exergy using a ternary mixture working fluid. A working fluid composed of methane, ethane, and propane was selected as the optimum mixture. The proposed cycle produced 1.023 kWh of power without LNG expansion when LNG at 12 bar was used.

Meanwhile, various issues can be considered to maximize the efficiency of the ORC. Selecting the appropriate working fluids is one of the most relevant issues. Previous works have suggested various working fluids in order to elevate the cycle efficiency, including ternary organic mixtures [9], and zeotropic mixtures [10]. Also, many studies have been made to evaluate the performance of different working fluids by applying different modeling and optimization techniques [11–25]. They applied the selected working fluids to different ORC systems and reported cycle efficiency increase from 15 [10] to 56% [9], compared to the conventional working fluids.

Another important issue in ORC cycle research is the design of a novel Rankine cycle configuration. Xu et al. [26] created a regenerator-integrated ORC (RORC), using a vapor injector as the regenerator. Using R123 as the working fluid, a performance comparison was done between the RORC and conventional ORC, where RORC showed better thermal performance. Lemort et al. [27] modeled and tested a scroll expander-integrated ORC. Using HCFC-123 as the refrigerant, they sorted out the important variables, and the model showed a close match with the actual measurements. Zamfirescu et al. [28] studied the performance of an ORC using a positive displacement expander to flash the saturated liquid. Other various studies have been conducted on increasing the efficiency of different ORC configurations [29,30], and the use of various modeling techniques [31].

Different heat sources result in different power outputs, and many studies have been conducted on the use of available heat sources. These include geothermal energy [17,24] and solar energy [14,21].

Recently, some studies were published on the recovery of LNG cold exergy using multi-component working fluids to extract cold exergy more effectively from LNG [2,8]. However, the efficiency needs to be further improved. In this study, a novel cascade Rankine cycle design using binary mixture working fluids to utilize LNG cryogenic energy was proposed for enhancing the efficiency of LNG regasification terminals. Both the configuration and the binary working fluid selection contributes to the objective of maximizing the power output. LNG cold exergy is thoroughly utilized by a two-stage sequential contact with different binary mixture working fluids. An additional stage is synthesized to recover cold exergy that was transferred from LNG to the working fluids of the first two stages, conducting a three-stage configuration. A total of three stages were optimized in a sequential manner, considering the relevant variables selected by a parametric study.

2. Description of the proposed cascade organic Rankine cycle

To reduce some confusions, the cycle indicates the whole power generation system and the stage indicates each stage which composes the whole cycle. A new concept for a cascade ORC was proposed in this study. Three stages were used, and each stage used a binary mixture as the working fluid. The basic concept of the proposed system can be summarized as Fig. 1. The first stage and the second stage are in a series arrangement to recover the cold exergy of LNG more efficiently. The working fluids of the first stage and the second stage receive the cold exergy from LNG directly. Thus, the first and second stages are considered as a process block called LNG cold exergy recovery part. The first stage can recover only a part of LNG cold exergy in lower temperature level so some amount of LNG cold exergy remains to be utilized at relatively higher temperature level. Then, the second stage recovers the remaining cold exergy of LNG. Each stage adopts a binary working fluid in order to reduce the irreversibility. Recovering the cold exergy throughout two stages in series and adopting binary working fluids make it possible to reduce the irreversibility significantly because it makes the temperature profile of working fluid condensation process fitted to that of LNG regasification process.

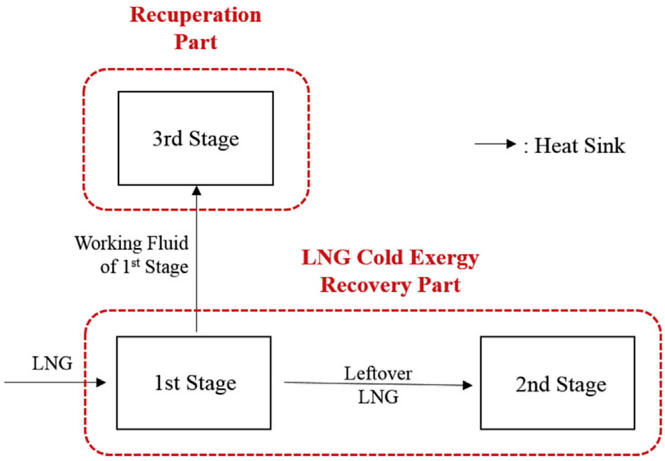

Fig. 1. Concept for proposed cycle.

Meanwhile, the third stage is parallel with the first stage. The third stage can be considered as a separate process block because it recovers the cold exergy not from the LNG but from the first-stage working fluid. The third stage recuperates the cold exergy from the first stage so this process block is called the recuperation part. There have been studies on ORCs with an LNG heat sink that used a multi-heat exchanger for recovering the cold exergy of the working fluid [6,8]. However, since the working fluid is designed to fit the temperature gliding of the LNG rather than the working fluid itself, the introduction of a multi-heat exchanger to the cycle can increase the exergy destruction. By introducing a third stage, an appropriate working fluid can be selected to minimize the amount of exergy destroyed when the cold exergy of the first stage is recuperated in the third stage. The third stage also utilizes a binary working fluid to fit the temperature gliding of the first-stage working fluid condensation.

A schematic diagram is presented in Fig. 2. To enhance the readability, each component in the schematic diagram is named according to a specific naming system. The name of component is in order of the type of unit, the number of the stage, and a specific number of the component. For instance, the name S1-1 represents that this unit is a stream in the first stage.

First, the LNG, which has components as summarized in Table 1, is pressurized up to 30 bar at the LNG pump and vaporized once at

Table 1
LNG composition.

Component	Mole fraction
N2	0.0007
Methane	0.8877
Ethane	0.0754
Propane	0.0259
n-butane	0.0056
i-butane	0.0045
n-pentane	0.0001
i-pentane	0.0001