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Simulation and optimization of a novel Rankine power cycle for recovering cold energy from liquefied natural gas using a mixed working fluid

Heng Sun [a,*], Hongmei Zhu [b], Feng Liu [a], He Ding [a]

[a] National Engineering Laboratory for Pipeline Safety/Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, No. 18 Fuxue Road, Changping District, Beijing 102249, China
[b] Department of Civil Engineering, North China Institute of Science and Technology, Beijing 101601, China

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ABSTRACT

A novel Rankine power cycle which uses a mixture of three hydrocarbons as working fluid is proposed to utilize the cold energy in LNG (liquefied natural gas). Process simulations and composition optimization of four schemes for the cycle are carried out. The results show that while the cycle is relatively simple, a high efficiency can be achieved. Ethylene is most appropriate for application in the mixed working fluid. The cycle, without LNG expansion, can output 1.023 kWh of work for 1 kmol of LNG after composition optimization. The cycle with LNG expansion can output 1.346 kWh of work for 1 kmol of LNG. An exergy analysis is also conducted. The results indicate that the normal heat exchanger and expander produce most of the exergy loss. A parameter analysis of the inlet and outlet pressures of the expander is carried out and the most appropriate values of the pressures are deduced.

1. Introduction

Natural gas is a widely used fossil energy resource with high caloric value and low emission problems. Liquefaction to produce LNG (liquefied natural gas) is the only practical way for mass transportation of natural gas across oceans. LNG is also the appropriate form to use for natural gas resources obtained from remote gas fields, coalbed methane, offshore gas, and other unconventional gas resources. Therefore, LNG technology has developed rapidly in recent years.

However, considerable energy is consumed in LNG plants to liquefy natural gas. Therefore, when the LNG is subsequently regasified in the appropriate terminals, a large amount of energy referred to as 'cold' or 'cryogenic' energy is released. Therefore, recovery of this cold energy from LNG is both valuable and necessary. Electrical power generation is regarded as an important, and efficient, method of using such cold energy. The method is also rather flexible as electrical power can be used anywhere. The power generation capabilities of gas turbines could be improved by cooling the inlet air. To generate more power from LNG, it is necessary to use an individual power cycle: this is a topic of current research and engineering interest and various different power cycles have recently been considered. Most of these power cycles involve the use of waste heat from other sources.

The Rankine power cycle is the one most widely applied in cold energy recovery from LNG. Different kinds of working fluid can be used in the cycle. Szargut and Szczygiel [1] studied the use of ethane in the Rankine power cycle for cold energy recovery from LNG. Three different schemes were presented. One is a single Rankine cycle with two-stage expansion and the others are cascading Rankine cycles. La Rocca and Dispenza et al. [2–4] proposed a modular LNG re-gasification unit which employs a simple Rankine cycle using C_2 hydrocarbons as working fluid. A modular design was suggested as this feature can deal with the cold recovery problem in remote locations.

A mixture of ammonia and water is another material which is commonly used as a working fluid. Wang et al. conducted a thermodynamic analysis of an ammonia–water Rankine power cycle and optimized the process parameters by multi-objective optimization [5]. The optimized exergy efficiency varied from 19% to 28%. Miyazaki et al. [6] studied a combined power cycle using refuse incineration and LNG cold energy. The combined cycle includes an ammonia–water Rankine power cycle and an LNG direct expansion unit. Meratizaman et al. [7] studied a similar power cycle but with

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* Corresponding author. Tel.: +86 15810738439; fax: +86 1089733959.
E-mail addresses: bddukesh@163.com, LNGCUP@126.com (H. Sun).

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Nomenclature

C	cooling obtained (kW)
H	enthalpy flow (kW)
E	exergy flow (kW)
P	power output or input of the cycle (kW)
co_i	composition of the ith component of the MF
Subscripts	
t	total
Ex	expander
p	pump
NG	natural gas
MF	mixed fluid
Abbreviations	
NG	natural gas
LNG	liquefied natural gas
MSCHE	multi-stream cryogenic heat exchanger
MF	mixed fluid
Mt/a	millions ton annual
Min	minimum approach in the MSCHE
LMTD	logarithmic mean temperature difference.

the important modification that a part of the gas is fed to the incinerator to increase power generation. Shi and Che [8] proposed a different combined power system with an ammonia-water Rankine cycle and an LNG direct expansion cycle. In these cycles, a mixer and a separator are used in an adsorption-desorption process during the combined cycle. Simulations of the cycle show that their proposal was efficient. An available power generation cycle which uses the pure NH_3 Rankine cycle for cold recovery in a Spanish LNG terminal is reported elsewhere [9]. Shi et al. [10] studied a combined power cycle which uses a steam Rankine power cycle and an LNG direct expansion unit. Both inlet air-cooling and inter-cooling are used to maintain the power output of the gas turbine.

Freon can also be used as the working fluid in LNG cold recovery and there are still many reports being produced about this kind of power cycle. Hisazumi et al. [11] utilized a mixture of refrigerant gases (R23 and R134a) in a simple Rankine power cycle for LNG cold recovery, which was combined with an LNG direct expansion unit. The results showed that about 400 kWh of power could be generated per ton of vaporized LNG. Freon mixtures are made up of HFCs (hydrofluorocarbons). Liu and Guo [12] proposed another novel cold power cycle for LNG cold energy recovery using a mixture of propane and CF_4 as the working fluid (the propane was employed as an absorbent for the CF_4). This fluid gave improved power generation compared to the use of pure CH_4.

The Brayton cycle is another power cycle which is widely used in LNG cold energy recovery. Kaneko et al. [13] presented two kinds of inverted Brayton cycle which could attain an exergy efficiency of more than 60% when the working temperature was 1500 °C. However, its high temperature requirement limits its actual application. To recover low-level waste heat, a sophisticated system consisting of an LNG direct expansion section, an ammonia–water Rankine power cycle, a nitrogen Brayton cycle, and a propane Rankine cycle was proposed by Bai and Zhang [14]. Although high efficiency could be obtained by this cascade utilization of cold energy, the system is too complicated for engineering usage. Lu and Wang [15] conducted an optimization procedure for the cascading power cycle involved in LNG cold recovery. Their system consisted of an LNG direct expansion cycle, a simple ammonia–water Rankine cycle, and a Brayton cycle, which used fumes as the working fluid. Their results show that the increase in work generated by an expander in an open LNG cycle contributed most to the cycle performance. As a refrigerant, pure helium is an expensive substance. The use of helium as a working fluid in the Brayton cycle has been studied in the literature [16,17] and the results show that good performance can be achieved. Morosuk and Tsatsaronis [18] have presented two cold recovery systems which consist of LNG direct expansion and nitrogen Brayton cycles. An exergy analysis for the alternative case system provided a detailed, reliable understanding of the system leading to potential improvements therein.

Dong et al. [19] proposed a system which applied the Stirling cycle for the cold recovery of LNG. In their system, the LNG is used to cool the nitrogen in the nitrogen compressor. Their results showed that the cycle has the potential for further investigation, development, and application. Meng et al. [20] presented an extremely complex system comprising five different parts: an ammonia–water Rankine system, an ethane Rankine cycle, a propane Rankine cycle, an LNG direct expansion part, and a metal hydride heat pump. It is, however, deemed by the authors as too complex for cold energy recovery from LNG. A zero-emission power system for cold energy recovery from LNG is another interesting proposition. Such a system commonly employs a Rankine cycle using CO_2 as the working fluid. The CO_2 gas can be condensed using the cold energy from the LNG and stored. Thus, CO_2 emission into the environment can be avoided. Literature reports involving such systems are quite promising [21–24].

It can be concluded from the literature that it should be easy to improve the energy efficiency of the power cycle for cold recovery of LNG by developing a sophisticated enough system. However, the complexity of the system itself may be the main obstacle in actual engineering applications. Therefore, it is important to achieve a balance between energy efficiency and system complexity. From this viewpoint, a novel power cycle using a mixture of hydrocarbons is proposed and optimized in this paper.

2. Description of the mixed working fluid cycle for LNG cold energy recovery

The proposed Rankine power cycle uses a mixture of hydrocarbons as its working fluid. The mixed fluid includes: methane, ethane (or ethylene), and propane. The process which uses the proposed cycle to recover the cold energy of LNG to generate power is shown in Fig. 1. In the scheme, the cold energy at a temperature of below −40 °C is used to generate electric power. The cold energy of LNG existing above −40 °C and the cold energy released by the mixed working fluid in HE1 could be supplied for air conditioning or cold storage purposes. Here, the "cooling medium" is used to transfer energy from HE1 to air conditioning and cold storage units.

The LNG is first pumped to the high pressure required for output and then enters the first channel of a MSCHE (multi-stream cryogenic heat exchanger), wherein the LNG is heated to about −40 °C. The LNG evaporates here and releases a massive amount of cold energy. The NG (natural gas) leaves the MSCHE and passes into heat exchanger 3 (HE 3), where the NG is heated up to the ambient temperature. Part of the cooling effect released in HE 3 could be delivered to an air conditioner using a cooling medium, such as ethanediol. In the power cycle, the MF (mixed fluid) from the expander enters the third channel of the MSCHE and absorbs the cold energy released by the LNG. The MF is cooled down and condenses to liquid. The liquid MF leaves the MSCHE and is pressurized to a certain pressure using an MF pump. The high-pressure liquid MF is at an extra low temperature. Therefore, the MF is

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