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Design and optimization of a novel cryogenic Rankine power generation system employing binary and ternary mixtures as working fluids based on the cold exergy utilization of liquefied natural gas (LNG)

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ABSTRACT

A fundamental double-stage Rankine cycle system using the single-component working fluid in each stage for liquefied natural gas (LNG) cold exergy recovery is used as a base case in the present paper. An advanced scheme of three-stage Rankine cycle system with the cooling output part is then proposed and designed. A series of cases are simulated within the fundamental and the advanced system schemes by employing the single-component working fluid and binary or ternary mixture working fluids. To settle the optimization problem of the poly-stage system with the multi-component working fluids, the priority-oriented composition optimization is performed based on the Genetic Algorithm in the advanced three-stage system. The thermal efficiencies, the exergy efficiencies and the exergy analysis are conducted in all the cases. As a result, the performances of the thermal and exergy efficiencies rise from 3.5% and 7.16% in the initial case to 17.33% and 25.7% in the fully optimized case respectively. The heat transfer analysis and the parameter study of the pump outlet pressure of the working fluids in the advanced three-stage Rankine cycle system are presented. Furthermore, the economic analysis is conducted as well to evaluate the novel cryogenic Rankine power system for future engineering design.

1. Introduction

Liquefied natural gas (LNG) is the ultimate product of the natural gas after purification and liquefaction process with methane as its main component. Due to the absence of impurities such as sulfur after the purification, the emitted pollution gas after LNG burning is much less than that of the diesel oil, heavy oil and coal, which makes LNG a more environment-friendly and preferable choice among a variety of energy sources in the world.

The regasification process of LNG is generally demanded in the practical application, which will generate the cold energy at about 837 kJ/kg in terms of the LNG temperature at −162 °C.How to reasonably utilize the cold quantity becomes a significant problem both of environmental and economic benefits. The conventional ways of LNG cold energy recovery contain the air separation, cryogenic grinding, dry ice producing and electric power generation, etc. Considering the electric power characteristics of high quality and wide application in modern industry, establishing the cryogenic power generation cycles using LNG as its heat sink turns to be one of the considerable ways for the LNG cold exergy recovery. The main types of the LNG cryogenic power generation cycles include the direct expansion method, the Rankine cycle, the combined Rankine cycle, the Brayton cycle, the Kalina cycle and the multiple compound power generation cycles, etc. In the practical engineering, Japan has built several LNG power plant projects adopting the Rankine cycles. From the perspective of academic, the studies of LNG power generation cycles concentrate correspondingly upon the cryogenic organic Rankine cycles.

Working fluids employed in Rankine cycles vary from the widely used propane to ammonia-water, organic refrigerating mixtures and CO_2, etc. Heat sources are also extended from the seawater to industrial waste heat, flue gas, geothermic heat, and solar energy, etc.

Miyazaki et al. [1] built a Rankine cycle with direct expansion using the flue gas as the heat source and LNG as heat sink to separately analyze the performance of ammonia-water and water

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Nomenclature

W	power, kW
η	efficiency, %
Q	heat transfer rate, kW
e	unit mass exergy, kJ/kg
h	unit mass enthalpy, kJ/kg
s	unit mass entropy, kJ kg^{-1}°C^{-1}
T	temperature, °C
E	exergy flow rate, kW
$\dot{m}$	mass flow rate, kg/s
F	objective function
x	component mole fraction
ΔT	temperature difference, °C
I	equipment exergy loss flow, kW
P'_t	dynamic payback period, year
C_I	cash inflow, USD
C_O	cash outflow, USD
i_c	basic discount rate, %

Subscripts

i	stage number of the sub-cycle
net	net value
th	thermal
source	heat source
heat	heating process
0	reference state
ex	exergy
cold	cold fluid
in	input
out	output
C	cooling duty
max	maximum
j	component number
min	minimum
t	the given year t

Abbreviations

LNG	liquefied natural gas
NG	natural gas
C1	methane
C2	ethane
C2X	ethylene
C3	propane
GA	genetic algorithm
PEC	purchased equipment costs
USD	United States dollar
DC	total direct costs
CNY	China Yuan

vapor. Wang et al. [2] adopted Heat Recovery Vapor Generator (HRGV) to replace the conventional vaporizer in Rankine cycle using ammonia-water as the working medium and an optimal components ratio of ammonia and water was discovered via NSGA-II (Non-dominated Sorting Genetic Algorithm-II) for the peak of the network output. Kim et al. [3] carried out a modified combined cycle with regeneration part, using a low grade heat of 200 °C and ammonia-water as working fluid with ammonia mass fraction of 60%. Wang et al. [4] proposed an isentropic fluid, which was a mixture of propane and isobutane at a mole fraction ratio of 0.7: 0.3, in LNG-waste flue gas single-stage Rankine cycle. The isentropic mixture was able to maintain the turbine exhaust at a lower pressure and temperature, and consequently improved the efficiency of the turbine. Andreasen et al. [5] provided a systematic methodology using a genetic algorithm optimizer to find promising pure fluids and binary mixtures for the maximization of the net power output of the single organic Rankine cycle and ethane was found as a fluid which obtained a large net power increase when used in mixtures. Sun et al. [6] performed a single stage Rankine power cycle which used the MSCHE (multi-stream cryogenic heat exchanger) and a mixture of three hydrocarbons as the working fluid to utilize the LNG cold energy and the so-called BOX optimization method was used. Wang et al. [7] investigated a *trans*-critical CO_2 cycle using geothermal resources as heat source and LNG as the heat sink to drop the CO_2 turbine back pressure sharply and NSGA-II method was carried out to determine the optimal CO_2 turbine inlet pressure that yields the maximum exergy efficiency. Angelino et al. [8] presented a CO_2 regenerative Rankine cycle which offered a moderately good efficiency (for example, 46.3% at 600 °C of the top temperature, 15 MPa steam parameters) combined with a very simple layout.

The poly-stage inclination is another important method of Rankine cycle to make structures enhanced, which mainly bases on the theory of cascade utilization of LNG cold energy according to LNG regasification curve. Kim et al. [9] reported a cascade Rankine cycle adopting binary working fluids for each stage of the system to minimize the exergy destroyed in the condensers and it was proved that the R14-propane combination was found to be the most suitable working fluid for the first stage, and an ethane-*n*-pentane combination was selected for the second and third stages. Yang [10] established the LNG-seawater two-stage Rankine cycle of horizontal focusing on 7 MPa LNG in the condition of supercritical regasification employing ethane and propylene as the working fluid for the first and the second stage and working fluids in two stages obtained LNG cold energy successively and individually drove their own Rankine sub-cycle. Yang [10] also set up a three-stage vertical cycle to cut down the systematic exergetic loss, using propylene, ethylene and ethylene as the working fluids for the different stages, respectively. Oliveti et al. [11] promoted two-stage Rankine cycle with the exergy efficiency at 39.48%, using ammonia for the first stage and steam for the second stage. Bisio et al. [12] considered a cascading three-stage Rankine cycle regarding LNG as its heat sink and flue gas as its heat source with direct expansion part, in which steam, propane and methane were used as the working fluids for the different three stages. Xue et al. [13] proposed a two-stage organic Rankine cycle, utilizing low-grade heat of exhaust flue gas and the cryogenic energy of LNG and R227ea and R116 were selected as working fluids for the system with the exergy efficiency at 31.02%.

Besides Rankine cycles, the Brayton cycle uses LNG cold energy to reduce the compressor inlet temperature, which significantly reduces the power consumption of the compressor at a definite compression ratio and improves the net power output of the cycle. Agazzani et al. [14] suggested an enhanced Brayton cycle, where the helium was used as its working fluid and the combustion heat was used as its heat source. In this cycle, a regenerator was arranged between the working fluid compressor and the heat exchanger for the purpose of increasing the helium turbine inlet temperature. Dispenza et al. [15] established a novel Brayton cycle. After the double-stage expansion, the combustion natural gas was used as the heat source. The expansion of helium and the natural gas jointly made contribution to the total power output of the system and the