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Analysis and optimization of cascade Rankine cycle for liquefied natural gas cold energy recovery

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ABSTRACT

This study proposes a new concept called the cascade Rankine cycle, which recovers LNG (liquefied natural gas) cold energy for power generation, optimizes the cycle by investigating the effects of key parameters on its performance, and compares its thermal efficiency, exergy efficiency and economic evaluation to those of the conventional alternatives. The cascade Rankine cycle consists of multiple stages of the organic Rankine cycle in a layered structure in which the first stage encompasses the second one that, in turn, encompasses the next. Due to its layered configuration, optimization of the cycle is straightforward and involves sequentially optimizing the individual stages. Optimization of the subsequent stages, however, required process simulation considering the equipment efficiency and the thermodynamic properties of the working fluid. Process simulation indicated that the indicators such as net power output, thermal efficiency, and exergy efficiency generally increase as the number of stages increases. These indicators were, however, significantly affected by the thermodynamic properties of the working fluids. The proposed cycles demonstrated significantly better performance in these indicators than the conventional cycles. The three-stage cascade Rankine cycle with propane as the working fluid exhibited the highest net power output, thermal efficiency and exergy efficiency within the set.

1. Introduction

The supply chain of liquefied natural gas (LNG) generally consists of four segments: natural gas production, LNG production, LNG transport, and LNG regasification. Within this supply chain, the LNG production segment consumes a significant amount of exergy due to the required liquefaction processes. Numerous liquefaction processes have been developed to reduce the energy required for liquefaction. Of the commercialized processes, the C3 mixed refrigerant cycle is known to exhibit the highest efficiency, consuming approximately 300 kWh of electrical energy to produce one ton of LNG, or 1080 kJ/kg-LNG [1].

In the LNG regasification segment, LNG is converted into natural gas and releases its cold energy into the heating medium, usually seawater, without any useful byproduct. In other words, the large amount of energy absorbed during the LNG production segment is discharged into the seawater. The cold energy contained in LNG is approximately 864 kJ/kg at the ambient temperature (20 °C), which is equivalent to 240 kWh/t of LNG [2].

The effective recovery of LNG cold energy has drawn significant research attention. LNG cold energy can be directly utilized in the air separation, ethylene separation, liquefied CO_2 production, freezing of food, hydrogen liquefaction, low-temperature crushing, freeze drying, high purity ozone production, and many other applications.

In addition to direct utilization, the LNG cold energy can be recovered through power generation. While the direct expansion cycle (DEC) directly utilizes LNG as a working fluid, the organic Rankine cycle (ORC) uses seawater as the primary heat source and LNG as the heat sink with other hydrocarbons as working fluids. Since both the DEC and the ORC have relatively low first law efficiency due to the utilization of the ambient heat sources, the modified ORC and the Combined Cycle (CC) have been developed to improve their thermal efficiency and performance using various heat sources and working fluids.

Many studies have been dedicated to developing power cycles from different temperature heat sources and working fluids and improving the efficiency of their cycles. Table 1 presents a review of previous studies on power generation cycles using cold energy sources. They are classified into three groups according to the heat source temperature: high-temperature heat sources, medium-temperature heat sources and low-temperature heat sources.

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Nomenclature

DEC	direct expansion cycle
ORC	organic Rankine cycle
CC	combined cycle
CRC	cascade Rankine cycle
C1	methane as a working fluid
C2	ethane as a working fluid
C3	propane as a working fluid
LNG	liquefied natural gas
MSVEP	maximum saturated vapor enthalpy pressure, bar
NG	natural gas
LCC	life cycle cost
CAPEX	capital expenditure
OPEX	operational expenditure
HFC	hydrofluorocarbons
Pump_LNG	boosting pump of LNG
Pump_WF,*i*	boosting pump of working fluid in *i*-th stage
Pump_SW,*i*	boosting *i*-th pump of seawater in *i*-th stage
Turbine, *i*	turbine in *i*-th stage
Vaporizer,*i*	vaporizer in *i*-th stage
Condenser–Evaporator,*i*	condenser–evaporator in *i*-th stage
$P_{V,\ i}$	pressure of working fluid at the *i*-th vaporizer, bar
$P_{C,\ i}$	pressure of working fluid at the *i*-th condenser –evaporator, bar
w	work per unit mass, kJ/kg
$\dot{W}$	power, kW or kJ/s
$\dot{Q}$	heat transfer rate, kW or kJ/s
$\dot{m}$	mass flow rate, kg/s
m	mass, kg
k	ratio of C_p and C_v
C_p	constant pressure heat capacity, kJ/kg K
C_v	constant volume heat capacity, kJ/kg K
n	polytropic coefficient
ρ	liquid density, kg/m^3
η	efficiency, %
P	pressure, Pa
$\dot{V}$	volume flow rate, m^3/s
T	temperature, K
$\dot{E}x$	exergy transfer rate, kW or kJ/s
Δex	exergy change per unit mass, kJ/kg
ΔH	enthalpy change, kJ
h	specific enthalpy, kJ/kg
s	specific entropy, kJ/kg K

Subscripts

0	ambient condition (1 atm, 298 K)
net	net output from a cycle
net,*i*	net output from *i*-th-stage of cycle
input	input into a cycle
output	output from a cycle
in	inlet
out	outlet
p	polytropic efficiency
p_turbine	polytropic efficiency of turbine
is	isentropic efficiency
is_pump	isentropic efficiency of pump
is_turbine	isentropic efficiency of turbine
pump	pump
pump_LNG	boosting pump of LNG
pump_WF,*i*	boosting pump of working fluid in *i*-th stage
pump_SW,*i*	boosting pump of seawater in *i*-th stage
turbine	turbine
turbine, *i*	turbine in *i*-th stage
th	thermal
ex	exergy
loss	loss
i	integer number (1,2,3,...)
j	integer number (1,2,3,...)

Superscript

s	isentropic process
n	polytropic coefficient

Table 1
Summary of previous investigations on power generations combined with cold energy recovery.

Reference	Cycles	Cycle description	Working fluids	Heat source	Heat source temperature
Liu et al. [3]	ORC	Conventional ORC	10 Working fluids	High	300 °C
Wei et al. [4]	ORC	Conventional ORC	HFC-245fa	High	370 °C
Desai and Bandyopadhyay [5]	Modified ORC	ORC with regeneration and turbine bleeding	16 Organic	High	370 °C
Tsatsaronis and Morosuk [6]	CC	ORC with gas–turbine	N_2	High	1290 °C
Hisazumi et al. [7]	CC	ORC with gas/steam turbines	HFC	High	1000–1300 °C
Kim and Ro [8]	CC	ORC with gas turbine	–	High	1350 °C
Miyazaki et al. [9]	CC	ORC with refuse incinerator	Ammonia–water	High	950 °C
Lu and Wang [10]	CC	ORC with combustion process	Ammonia–water	High	990 °C
Deng et al. [12]	CC	Combined cycle	CO_2	High	1250 °C
Zhang and Lior [13]	CC	ORC with Brayton cycle	CO_2	High	1300 °C
Zhang [14]	CC	ORC with Brayton cycle	CO_2	High	720 °C
Vélez et al. [15]	ORC	Transcritical ORC	CO_2	Medium	60–150 °C
Qiang et al. [16]	CC	ORC with DEC	Propane	Medium	60–90 °C
Shi and Che [17]	CC	ORC with DEC	Ammonia–water	Medium	157–197 °C
Roy et al. [18]	ORC	Conventional ORC	R-12, R-123, R-134a	Medium	140 °C
Chen et al. [19]	ORC	Supercritical Rankine cycle	Zeotropic mixture	Medium	120–200 °C
Wang et al. [20]	ORC	Conventional ORC	Various working fluids	Medium	70–230 °C
Baik et al. [21]	ORC	Subcritical ORC/Transcritical ORC	Four R125-based HFC	Medium	100 °C
Wang et al. [22]	ORC	Conventional ORC	Ammonia–water	Medium	200 °C
Liu and Guo [23]	Modified ORC	Organic Rankine cycle with a vapor absorption process	Binary mixture (CF_4 and C_3H_8)	Low	20 °C
Szargut and Szczygiel [24]	CRC	Cascade Rankine cycle	8 Organic compounds	Low	15 °C