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Strengthening power generation efficiency utilizing liquefied natural gas cold energy by a novel two-stage condensation Rankine cycle (TCRC) system

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ABSTRACT

For the low efficiency of the traditional power generation system with liquefied natural gas (LNG) cold energy utilization, by improving the heat transfer characteristic between the working fluid and LNG, this paper has proposed a two-stage condensation Rankine cycle (TCRC) system. Using propane as working fluid, compared with the combined cycle in the conventional LNG cold energy power generation method, the net power output, thermal efficiency and exergy efficiency of the TCRC system are respectively increased by 45.27%, 42.91% and 52.31%. Meanwhile, the effects of the first-stage and second-stage condensation temperature and LNG vaporization pressure on the performance and cost index of the TCRC system (net power output, thermal efficiency, exergy efficiency and UA) are analyzed. Finally, using the net power output as the objective function, with 14 organic fluids (such as propane, butane etc.) as working fluids, the first-stage and second-stage condensation temperature at different LNG vaporization pressures are optimized. The results show that there exists a first-stage and second-stage condensation temperature making the performance of the TCRC system optimal. When LNG vaporization pressure is supercritical pressure, R116 has the best economy among all the investigated working fluids, and while R150 and R23 are better when the vaporization pressure of LNG is subcritical.

1. Introduction

With the development of economy, the contradiction between energy supply and demand is increasingly prominent, and environmental pollution is becoming more and more serious [1]. Natural gas (NG) has been receiving much more attentions in recent years as an environment-friendly energy source because of its high calorific value and less pollution [2,3], and it is widely used in various fields [4]. Under ambient temperature and pressure, NG is gaseous. For the purposes of transport and storage, it must be liquefied to LNG at the atmospheric pressure and temperature of about −162 °C and the volume of LNG is reduced as approximately 600 times than NG, which improves transport efficiency [5].The production of one ton of LNG by liquefying NG requires approximately 292–958 kW h of electric energy [6]. However, LNG must be regasified at the receiving site before it is utilized, and a great amount of cold energy in the LNG regasification process will be released, which is about 830–860 kJ/kg [7]. LNG cold energy is a kind of high quality clean energy. If the efficiency of the LNG cold energy converted to electricity is 100%, one ton of LNG will produce about 240 kWh of electrical energy [2]. In the traditional LNG vaporization process, the LNG cold energy is usually transferred to sea water or air, which results in the extreme waste of energy, and has a great environmental impact on the sea near the regasification site [8]. The effective recovery of the LNG cold energy can not only achieve reasonable utilization of energy, but also reduce environmental pollution.

Power generation is a conventional and effective way to utilize LNG cold energy [9]. At present, the traditional methods to generate electricity are the direct expansion (DE), organic Rankine cycle (ORC) and combined cycle (CC), which is the combination of previous two technologies [10]. The direct expansion cycle is simple, but its applications are limited, which is the result of the low LNG cold energy utilization efficiency and the high-pressure application background for NG users. However, organic Rankine cycle and combined cycle have been come into use, which are relatively mature. In early 1979 and 1982, Osaka Gas company in Japan respectively used propane as working fluid for organic Rankine cycle and combined cycle to generate electricity with LNG cold

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Nomenclature

Q	heat transfer rate (kJ/h)
M	mass flow rate (kg/h)
h	mass enthalpy (kJ/kg)
W	power (kW)
η	efficiency (%)
Ex	mass exergy (kW/kg)
Ex	exergy (kW)
I	irreversibility loss (kW)
T	temperature (°C)

Abbreviations

TCRC	two-stage condensation Rankine cycle
LNG	liquefied natural gas
NG	natural gas
DE	direct expansion
ORC	organic Rankine cycle
CC	combined cycle

Subscripts

eva	evaporator
tur1	turbine 1
tur2	turbine 2
con1	condenser 1
con2	condenser 2
con	condensation
sp	splitter
mix	mixer
re	reheater
p1	feed pump 1
p2	feed pump 2
p3	sea water pump 3
p4	sea water pump 4
p5	LNG pump 5
wf	working fluid flow into evaporator
wf1	working fluid flow into condenser 1
wf2	working fluid flow into condenser 2
sw1	sea water 1
sw2	sea water 2
tot	total
th	thermal
in	inlet
out	outlet
1–17	The position of the number corresponding with in Fig. 1

energy, and their power output were 1450 kW and 6000 kW respectively [11].

In view of the extensive application of organic Rankine cycle and combined cycle, the research on the influence factors of LNG power generation efficiency have attracted much attention. Kim et al. [12] analyzed the performance of organic Rankine cycle with seawater as heat source and LNG as cold source, and pointed out that it exists an optimal outlet temperature of the LNG condenser, which makes the system net power output maximized. Wang et al. [13] discussed the impact of condensation temperature, heat source temperature and evaporation pressure on exergy efficiency of organic Rankine cycle using LNG cold energy. When LNG vaporization pressure was 70 bar, Koku et al. [14] found that the thermal efficiency of the combined cycle was 6%, when used propane as working fluid and seawater and LNG cold energy as energy sources.

In order to improve the power generation efficiency of LNG cold energy, many researchers have made some improvements in the perspective of the structure of thermodynamic cycle. Angelino et al. [15] and Rao et al. [16] respectively added a regenerator to the organic Rankine cycle and combined cycle to improve the system performance. In addition to this, Szargut and Szczygiel [17] discussed the utilization of LNG cold energy by the regenerative organic Rankine cycle with ethane as working fluid and seawater as the heat source. Two Rankine cycles in series is another method to improve the power generation efficiency of LNG cold energy. Two of these examples are Liu et al. [18] and Li et al. [19].The difference between them is the type of the top cycle. Liu et al. discussed the steam Rankine cycle as the top cycle while Li et al. researched organic Rankine cycle as the top cycle.

Because of the large temperature range of LNG vaporization process, LNG cold energy utilization rate of the single-stage condensation process for ORC system is relatively low. In order to make full use of LNG cold energy, Meng et al. [20] proposed two Rankine cycles in parallel. The two parallel Rankine cycles have the same highest temperature but the different condensation temperatures. Shi and Che [21] proposed a combined power system, in which low-temperature waste heat can be efficiently recovered and cold energy of LNG can be fully utilized as well. By changing the condensation temperature and working fluid, the system performance achieves the best. Choi et al. [22] analyzed and optimized the cascade Rankine cycle for recovering LNG cold energy, and they found that the three-stage cascade Rankine cycle with propane had the highest net power output. When the LNG vaporization pressure is 60 bar, the thermal efficiency can reach 12.5%. Ramón Ferreiro García et al. [23] proposed and analyzed an efficient power plant composed of series Rankine cycles combined with a direct expansion cycle, where the rejected heat from each cascade power unit is used to heat the liquefied natural gas in a regasification plant. Zhang et al. [7] also proposed that the combined series and parallel Rankine cycle. They concluded that the performance of this cycle system was better than simple Rankine cycle system, and n-pentane emerged the best performance among eight working fluids.

From the review of previous literature, for the simple organic Rankine cycle, the condensation process of working fluid is not well matched with the LNG vaporization process, which makes the thermal efficiency low. The combined series and parallel Rankine cycle could improve the heat transfer characteristic between working fluid and LNG, however, which is at the cost of increasing the system independent loop, the complexity of the system and control difficulty remarkably. Therefore, in order to reduce the irreversible loss in the condenser and improve the power generation system with liquefied natural gas (LNG) cold energy, without increasing the system independent loop and control difficulty greatly, this paper propose a novel two-stage condensation Rankine cycle (TCRC) system. Firstly, the TCRC system is simulated by Aspen Hysys software, and is compared with the conventional methods of generating electricity by LNG cold energy. Then the effects of the first-stage condensation temperature, second-stage condensation temperature and LNG vaporization pressure on the performance (net power output, thermal efficiency and exergy efficiency) and cost index UA of the TCRC system are analyzed. Finally, the net power output is used as the objective function, with 14 kinds of organic fluids (such as propane, butane etc.) as the