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The effect of the arrangements for compression process and expansion process on the performance of the two-stage condensation Rankine cycle

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ABSTRACT

Aiming at the problem that the irreversible loss of the condensation process for the traditional LNG power generation system is too large, this paper presents four different two-stage condensation Rankine cycles based on different arrangements of pumps and turbines. The effects of the operating conditions (the first-stage and second-stage condensation temperatures) and various working fluids on the performance of the four cycles with different structures are investigated. The results show that when the arrangement of the turbines is the same, the arrangement of the pumps (series or parallel) has little effect on the net output power. However, when the arrangement for the pumps is the same, the arrangement for the turbines has a significant effect on the net output power. When the working fluid is n-pentane and the turbines are of series arrangement, the maximum net output power is increased by about 17% compared with the condition that the turbines are of parallel arrangement. In addition, for the same cycle, whether the isentropic efficiency of turbine is a constant value or not has a significant effect on the maximum net output power, the optimal operating conditions, and the optimal working fluid.

1. Introduction

Sustainable development is among the major issues in the world, where economic and environmental topics are two of the most important issues [1]. For its high combustion efficiency and less carbon dioxide emission, natural gas (NG) becomes one of the most demanding energy sources after the oil is developed [2]. Because of the uneven distribution for natural gas, it usually need to be cooled to liquefied natural gas (LNG) that is $-162\,^{\circ}C$ to facilitate long-distance transport and then is re-gasified to the gaseous before being used by residents. It should be noted that the re-gasification process will produce a lot of cold energy, about 830 kJ/kg [3]. Effective use of the cold energy will play an important role in saving energy.

Power generation is a common means of utilizing LNG cold energy. Traditionally, there are three main ways to utilize the LNG cold energy for power generation: LNG direct expansion, Rankine cycle and combined cycle. Although the structure of the LNG direct expansion system is simple, this method can only use the pressure exergy of LNG and can't use the thermal exergy (all yield to the heat source) so that its efficiency is low [4]. Organic Rankine cycle has received extensive attention as a mature technology [5,6], and LNG can be used as a cold source in the condenser. In order to increase the power generation capacity, it is often combined with the direct expansion method, which is combined cycle [7,8]. However, most of the studies on combined cycle are mainly to improve the Rankine cycle, so enhancing the efficiency of the Rankine cycle is the key to utilize the LNG cold energy effectively.

The studies on enhancing the efficiency of power generation with Rankine cycle mainly focus on the improvement of the cycle structure and the choice of working fluids. On the aspect of the cycle structure, Zhang et al. [9] and García et al. [10] combined three single-level Rankine cycles in series or parallel to utilize the LNG cold energy and pointed out that they were more efficient in power generation compared with the condition when they were separated. Li et al. [11], Choi et al. [12], Cao et al. [13], and Wang et al. [14] proposed four different types of cascaded Rankine cycles recovering LNG cold energy and they were proved to be superior to the conventional cycles. Zhang et al. [15] combined the Rankine cycle with a CO_2 compression–refrigeration subsystem to utilize LNG cold energy for turbine inlet air cooling and not only the cold output but also the power generation is higher than conventional systems. In addition, Mosaffa et al. [16] compared four different cycles that combined with LNG direct expansion and found that the regenerative system and the system with internal heat exchanger had the highest energy efficiency and exergy efficiency respectively, while the cascade system has the maximum output power.

Besides the cycle structure, the working fluid used also has a significant effect on the cycle performance. In the new cycle proposed by

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Nomenclature

W	power output (kW)
h	specific enthalpy (J/kg)
η_{is}	isentropic efficiency (%)
η_{th}	thermal efficiency (%)
m	mass flow rate (kg/s)
V_r	volume ratio
SP	turbine size parameter (m)
T	temperature (K)
s	specific entropy (kJ/kg/K)

Subscripts

turb	turbine
eva	evaporator
con1	Condenser 1
con2	Condenser 2
re	Reheater
tot	Total

Abbreviations

ORC	Organic Rankine cycle
NG	Natural gas
LNG	Liquefied natural gas
SW	Sea water
WF	Working fluid
C	Constant
NC	Non-constant

Zhang et al. [9] mentioned above, eight kinds of working fluids were studied and it was found that the system perform best when using n-pentane as the working fluid. Sung et al. [17] proposed a dual-loop cycle recovering the waste heat of engine and the cold energy of LNG and a comparative study of some pure working fluids showed that n-pentane and R123 were the optimal working fluids. Ferreira et al. [18] used ethane, ethene, carbon dioxide, R134a, R143a and propene as the working fluids in the study of the conventional Rankine cycle utilizing LNG cold energy and found that ethene and ethane performed better than the other working fluids. There are some studies using zeotropic mixture as the working fluid as well. Wang et al. [19] found that when the mass fraction of ammonia was about 80%, the thermal efficiency and output power of the cycle reached the maximum. Lee et al. [20] used R601-R23-R14 ternary mixture as the working fluid of the ORC integrated with a steam cycle as a bottoming cycle and found that the power generated by the ORC was significantly enhanced because of the lower exergy loss than pure working fluid. Kim et al. [21] proposed a novel cascaded power generation system and indicated that R14-propane mixture was the most suitable working fluid for the first stage while the optimal working fluid for the other two stages was ethane-n-pentane mixture. Furthermore, Modi and Haglind [22] gave a review of zeotropic mixtures used in recent studies and pointed out that the use of these mixtures generally improved the thermodynamic performance of the power cycle.

In addition, as the main component generating energy in the cycle, turbine plays an important role in the cycle performance [23]. The efficiency of the turbine is constant in most literatures, but it actually varies with the working fluids and operating conditions. Jubori et al. [24] gave a model to predict turbine efficiency and compared the effects of axial and radial-outflow turbines on the efficiency of Rankine cycle. It was found that the maximum cycle thermal efficiency was 11.74% and 10.25% for axial and radial-outflow turbines respectively. Song et al. [25] also proposed a one-dimensional model to give a prediction of the radial-outflow turbine efficiency. They found that the calculated turbine efficiency was significantly different from the constant one under the same conditions, which made the output powers are very different as well. Therefore, turbine efficiency is also a key factor to be considered when LNG cold energy generation systems are studied.

According to the literature review, it can be seen that reducing the irreversible loss of the heat transfer in condenser can effectively improve the efficiency of the LNG power generation system. Meanwhile, choosing suitable working fluids is the other effective way. And the isentropic efficiency of turbine also needs to be considered in the analysis of cycles and comparisons of working fluid. In our previous work [26], in order to reduce the irreversible loss of the heat transfer between working fluid and LNG in the condenser and improve the system efficiency, a novel two-stage condensation Rankine cycle was proposed, which significantly improved the performance of LNG power generation system. On the basis of that, this paper presents four different types of two-stage condensation Rankine cycles according to the

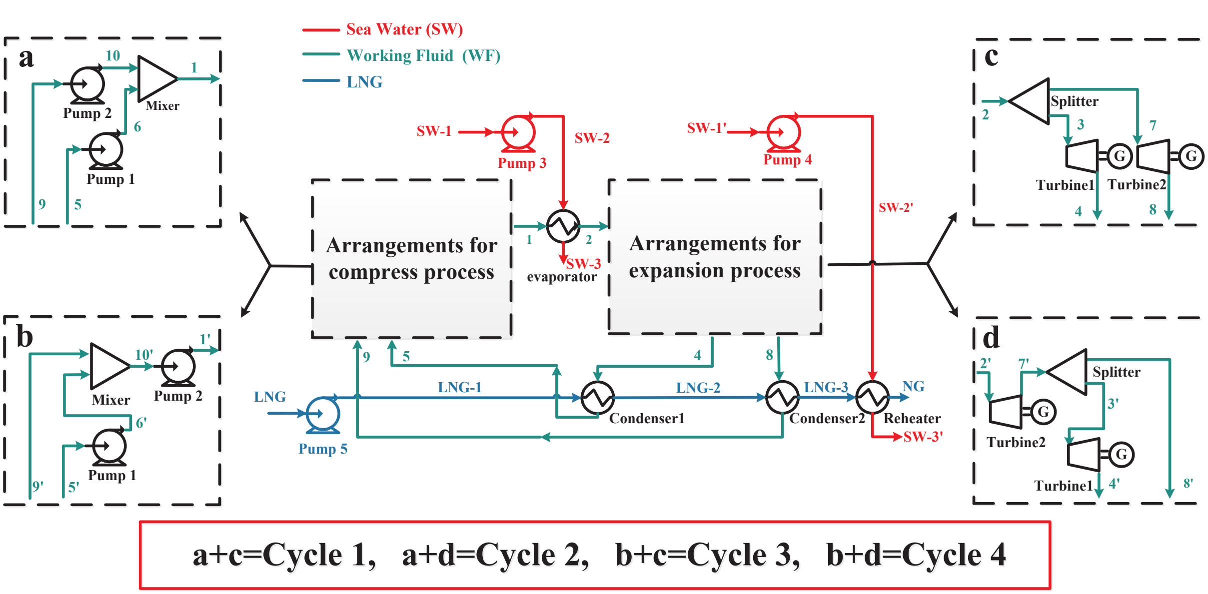

Fig. 1. The configurations of four different two-stage condensation Rankine cycles.