Organic Rankine Cycle for Recovery of Liquefied Natural Gas (LNG) Cold Energy

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Abstract

Natural gas (NG) is an environment-friendly energy source. NG is of gas state in the environmental condition and it is liquefied to LNG at temperature of about −162°C for transportation and storage. Electric energy of 292–958 kWh is consumed when one ton of LNG is produced. Before being used, LNG must be regasified to NG again at the receiving site, and this process will release a great deal of energy, which is called cold energy. It's very important to recovery LNG cold energy, which is clean and of high quality. Power generation is a conventional and effective way to utilize LNG cold energy. 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 chapter has proposed a conception of multi-stage condensation Rankine cycle system. Furthermore, the performance of power generation systems will be enhanced with two aspects: improvement of system configuration and optimization of working fluids.

Keywords: organic Rankine cycle, LNG cold energy, two-stage condensation Rankine cycle, zeotropic mixture, system configuration

1. Introduction

Energy shortage and environmental pollution are two major themes in today's world [1]. More and more attentions are paid to Natural gas (NG) because it is clean and has high calorific value [2, 3], and it is widely consumed all over the world [4]. NG is of gas state in the environmental condition and it is liquefied to LNG at temperature of about −162°C for transportation and storage [5]. Electric energy of 292–958 kWh is consumed when one ton of LNG is produced [6]. Before being used, LNG must be regasified to NG again at the receiving site, and this process will release a great deal of energy, which is called cold energy [7]. It is very important to recovery LNG cold energy which is clean and of high quality. Usually LNG is heated by sea water or air, so that LNG cold energy is wasted and the sea near the regasification site also is affected [8]. Therefore, the recovery of the LNG cold energy a dual purpose [8].

One of effective ways to utilize LNG cold energy is power generation [9]. The traditional cycles include direct expansion cycle (DE), organic Rankine cycle (ORC) and combined cycle (CC) [10]. Although the simplicity for direct expansion cycle, it has limited applications with low efficiency and high operation pressure. Organic Rankine cycle and combined cycle are more popular and relatively mature. Osaka Gas Company in Japan built ORC and CC system using propane in 1979 and 1982, and the power output reached 1450 and 6000 kW, respectively [11]. Due to the importance of system parameters on the performance of power generation system, many researches are carried out. With seawater as heat source and LNG as heat sink, Kim et al. [12] found that there is an optimum condenser outlet temperature for ORC system. Heat source inlet temperature, evaporation pressure and condensation temperature are studied by Wang et al. [13] to achieve high exergy efficiency of ORC recovering LNG cold energy. With the heat integration of LNG at vaporization pressure of 70 bar, Koku et al. [14] obtained a thermal efficiency of 6% for the combined cycle with propane as working fluid.

Improvement of system structure and proper working fluid selection are two effective way to enhance the system performance. For system structure, the combinations of simple Rankine cycle in series or parallel is often considered by Zhang et al. [7] and García et al. [15] and they found that they were indeed more efficient. Cascaded Rankine cycles are also common improvement and are proved to be superior to simple Rankine cycles by Li et al. [16], Choi et al. [17], Cao et al. [18], and Wang et al. [19]. By combining the Rankine cycle and refrigeration cycle, the study of Zhang et al. [20] showed that both electricity and refrigeration can be produced simultaneously. Mosaffa et al. [21] compared four different cycles, and pointed out that different system structure is best when the objective function changes.

Selection of working fluids is also critical for the performance and economy of system except for cycle structure. By using eight kinds of working fluids, Zhang et al. [7] found n-pentane has the best system performance. A comparative study by Sung et al. [22] showed that R123 were the optimal working fluids for a dual-loop cycle with LNG cold energy as heat sink. Considering ethane, ethene, carbon dioxide, R134a, R143a and propene, Ferreira et al. [23] concluded that ethene and ethane had higher system efficiency. Zeotropic mixtures are also considered in power generation system for recovery of LNG cold energy. Ammonia-water mixture is used by Wang et al. [24], and they found there was an optimal mass fraction at which work output was largest. With R601-R23-R14 ternary mixture as the working fluid, Lee et al. [25] found that the exergy loss of ORC using mixture is lower than that of pure fluids. Kim et al. [26] selected R14-propane mixture as the working fluids for the first stage of a cascaded system and ethane-n-pentane mixture for the other two stages. Modi and Haglind [27] thought that zeotropic mixture is the development direction of working fluids with its higher thermodynamic performance.

In this chapter, the performance of power generation systems by LNG cold energy will be enhanced with two aspects: improvement of system configuration and optimization of working fluids. Firstly, the two-stage condensation Rankine cycle is introduced. Based on this, the effect of stage number of condensation process is discussed. Then, the influence of the arrangements for compression process and expansion process is studied. Regarding to the optimization of working fluids, pure working fluids are firstly compared, and then zeotropic mixtures are optimized. Finally, a simultaneous approach to optimize the component and composition of zeotropic mixture is put forward.

2. Improvement of system configuration

2.1. Two-stage condensation Rankine cycle (TCRC)

As shown in **Figure 1**, the TCRC system consists of an evaporator, two turbines, two condensers, a mixer, a splitter and two feed pumps. After heated in the evaporator by sea water, working fluid is evaporated to vapor and is divided into two streams in the splitter. The two streams flow into different turbines respectively and are expanded to two different condensation pressures. These two streams transferred heat energy to LNG in two different condensers and cooled to liquid. The two streams are pressurized by two different pumps and mixed in the mixer. The converged stream enters the evaporator again and the new cycle recommences. Except for absorbing the condensation heat from working fluids in two condensers, LNG is further heated to the scheduled temperature in the reheater with sea water. T-s diagram of the TCRC system is plotted in **Figure 2**, and the labeled state points in **Figure 2** is the same as that in **Figure 1**.

In order to determine whether the new proposed cycle has a better performance, the novel system is compared with the conventional methods under the same conditions.

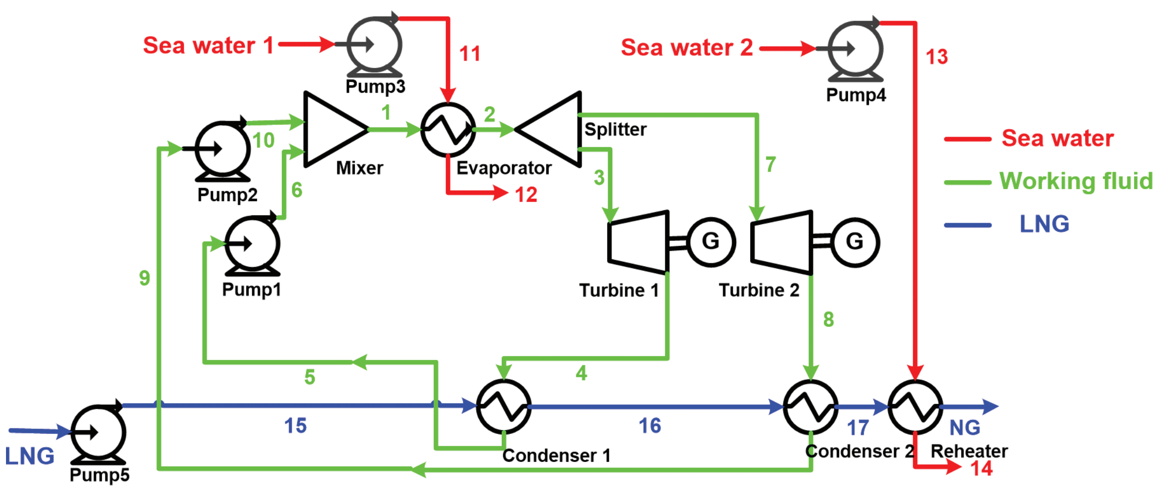

Figure 1. Schematic diagram of the TCRC system.

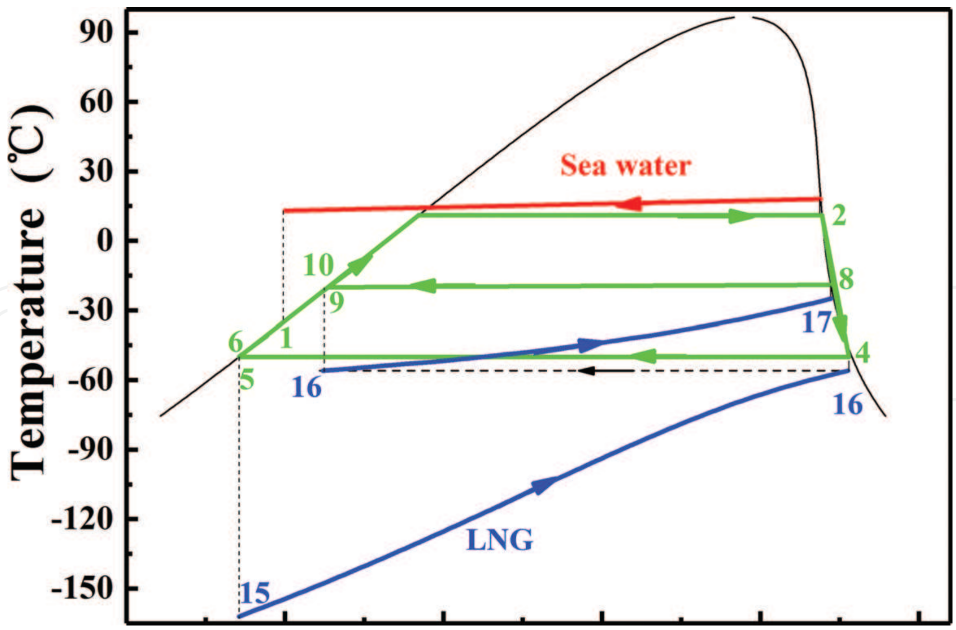

Figure 2. T-s diagram of the TCRC system.

Net power output, thermal efficiency and exergy efficiency of TCRC system is compared with the traditional cycles (DEC, ORC and CC), as shown in **Figure 3**. It should be pointed out that four systems all used propane as working fluid. From **Figure 3**, it can be found that the performance of proposed system is remarkably superior to the traditional power generation cycles. Combined cycle has the highest net power output, thermal efficiency and exergy efficiency among the traditional systems. However, compared with CC system, TCRC system has a 45.27%, 42.91% and 52.31% increase respectively, in term of net power output, thermal efficiency and exergy efficiency.

In order to explain the reason why TCRC system could have a better performance than the traditional cycle, the heat transfer curves between working fluid and LNG of ORC and TCRC systems are plotted in **Figure 4**. It can be seen from **Figure 4** that heat transfer irreversibility of ORC system is larger than that of TCRC system. The main reason is that compared with ORC system, the condensation process of TCRC system is two-stage, which could lower the heat transfer irreversibility of the condenser.

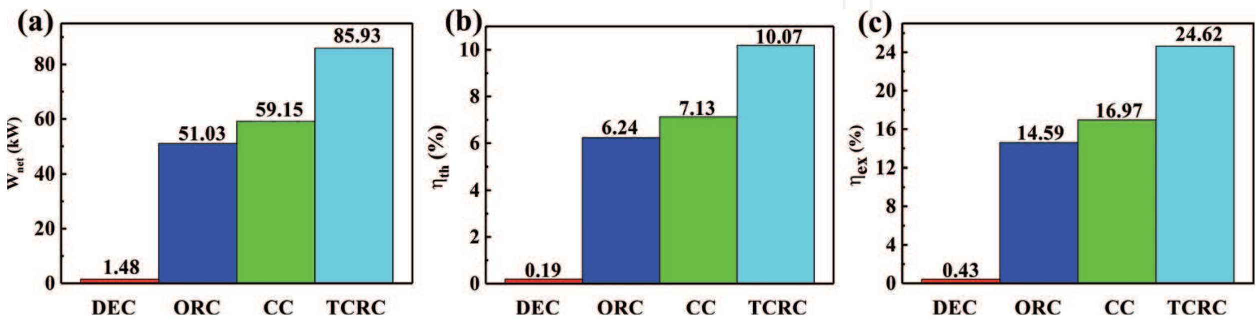

Figure 3. System performance of the four power generation methods: (a) net power output, (b) thermal efficiency, and (c) exergy efficiency.

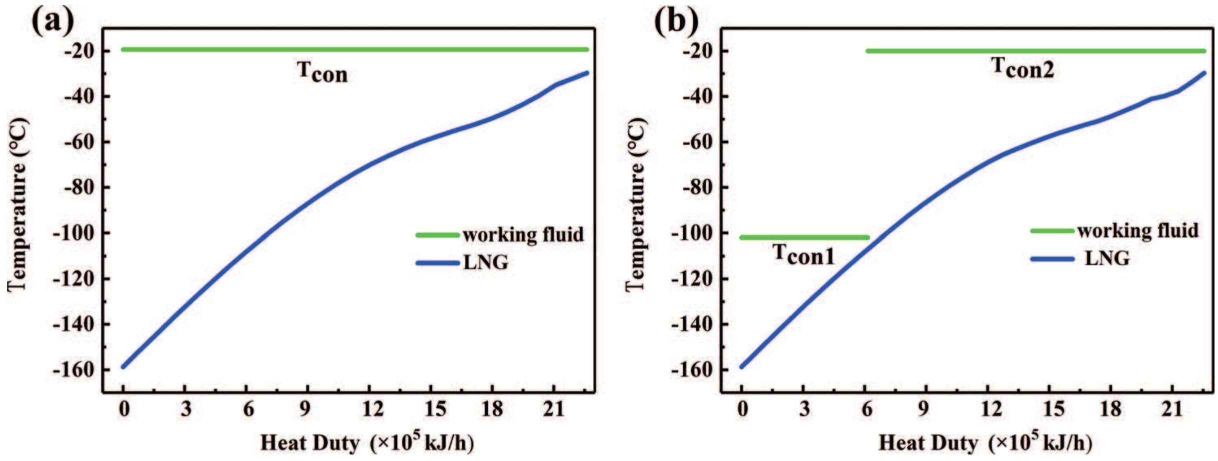

Figure 4. Heat transfer characteristics between working fluid and LNG: (a) ORC and (b) TCRC.

2.2. Effects of stage number of condensation process

In the previous section, it has been proved that two-stage condensation process has the potential to improve the performance of power generation systems by LNG cold energy. If the number of condensation stage is increased, the performance of power generation systems should be better at the cost of greater initial investment with more equipment. How many stages of condensation process should be chosen?

Figure 5 shows the schematic of six different cycles from single-stage to three-stage condensation Rankine cycle with or without direction expansion. To take a comparison object, direction expansion cycle (DC) is also considered.

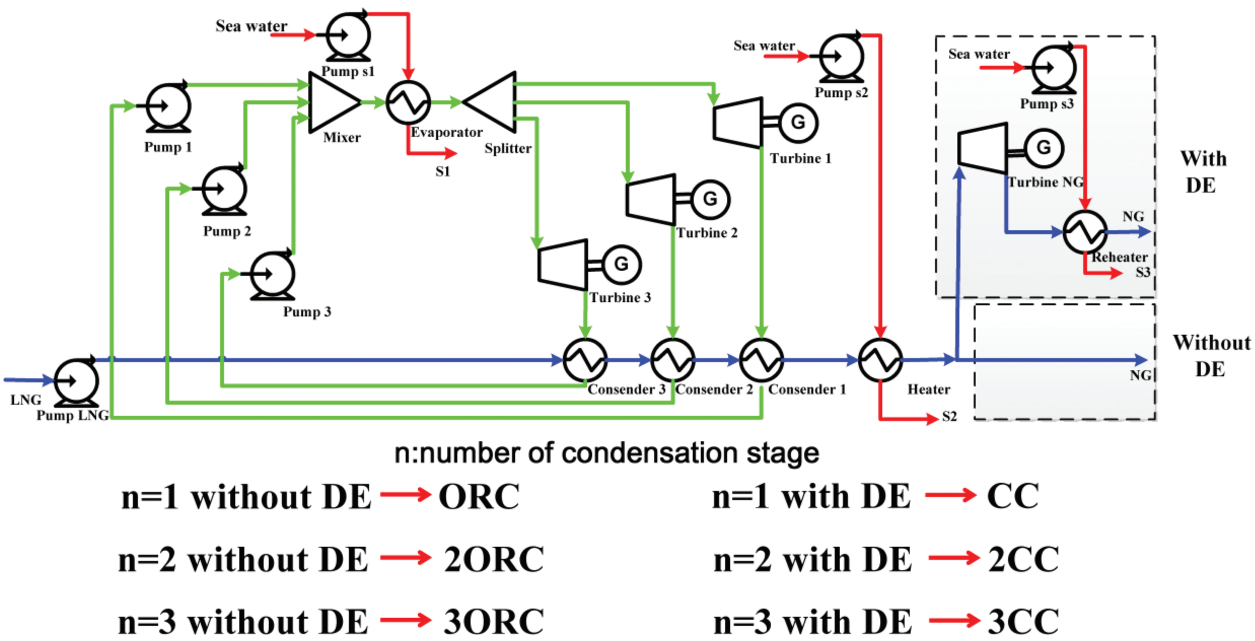

Figure 5. Schematic of single-stage, two-stage and three-stage condensation Rankine cycles with or without direction expansion.

Net power output of system:

$$W_{net} = \sum W_{tur,j} - \sum W_{p,l} \tag{1}$$

The electricity production cost (EPC) can be expressed as:

$$EPC = \frac{3600\, C_{total}}{W_{net}} \tag{2}$$

The annual total net income (ATNI) of the system can be defined as:

$$ATNI = 7300(EP - EPC)\, W_{net} \tag{3}$$

where EP is electricity price.

From **Figure 6** it can be seen that the net power output of the 3CC is the largest and the DE is the least at any LNG vaporization pressure. When stage number of condensation process increases, the net power output of Rankine cycles and combined cycles both increases. The performance of combined cycles is better than that of Rankine cycles at the same stage number of condensation process.

Figure 7 shows the minimum EPC of seven different cycles at different LNG vaporization pressures. The EPC of the Rankine cycle is larger than that of the combined system at the same stage number of condensation process. The EPC of combined cycle is the least at the LNG vaporization pressure less than 30 bar. With the increase of the stage number of condensation process, EPC of combined cycles and Rankine cycles augments, but its increase rate decreases. When the LNG vaporization pressure increases, the difference of EPC between combined cycles and Rankine cycles at the same stage number of condensation process tends to zero.

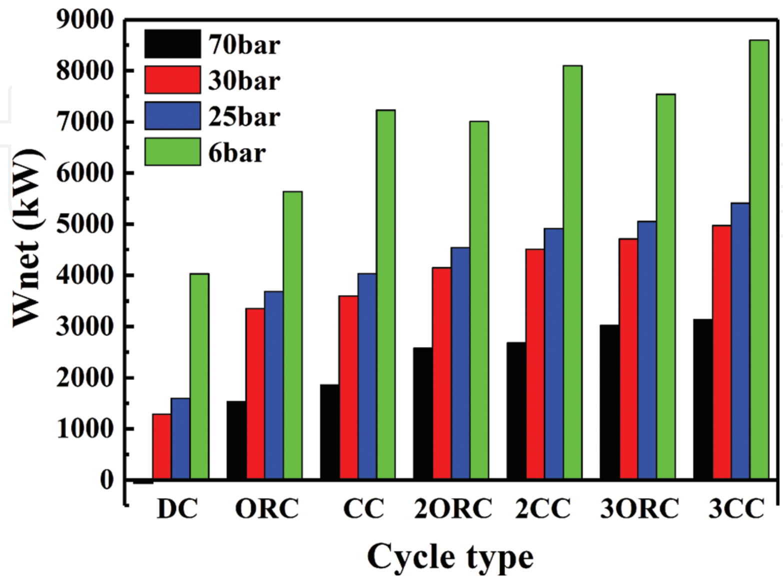

Figure 6. The maximum net power output at different LNG vaporization pressures.

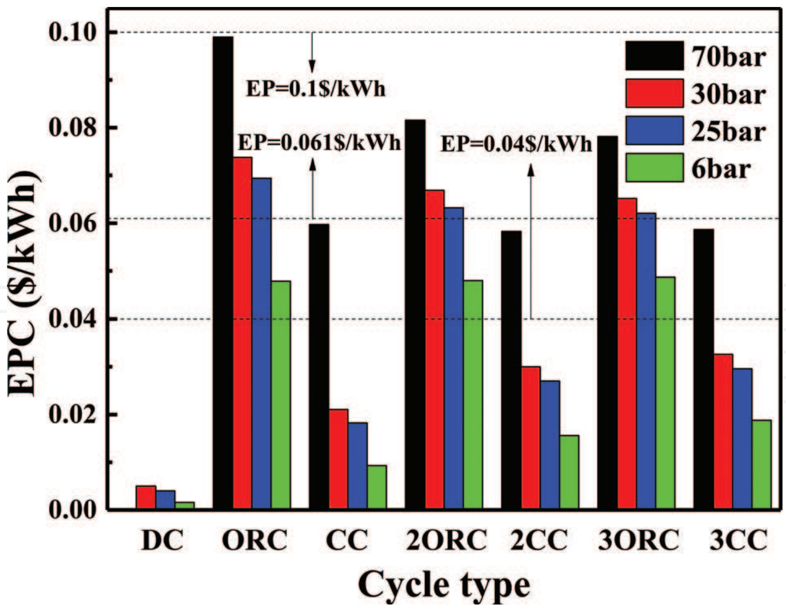

Figure 7. The minimum EPC of seven systems at different LNG vapor pressures.

The electricity prices of literatures are different, such as 0.04, 0.061, 0.1, 0.123 and 0.18$/kWh [28]. DC and CC systems should be selected at the LNG vaporization pressure less than 30 bar if the electricity price is 0.04$/kWh. No system is profitable at the LNG vaporization pressure of 70 bar. The CC systems are suitable at all the LNG vaporization pressure when the electricity price is 0.061$/kWh. At the LNG vaporization pressure less than 30 bar, it should be considered DE system. Seven cycles could be profitable if electricity price is larger than 0.1$/kWh.

The capacity of power generation can be weight by net power output, and whether cycle is profitable could evaluated by EPC. But the maximum profitability of the system is determined by both the net power output and EPC, which be reflected by annual net income. The electricity price of 0.123 $/kWh is taken as the referenced electricity price. It can be seen from **Figure 8** that the annual net income of the 3CC system is largest, while the least is the DC cycle. The annual net income of the Rankine cycles is lower than that of the combined cycles at the same stage number of the condensation process. When the stage number of the condensation process increases, both the annual net income of the Rankine cycle and the combined cycle systems goes up, but their increase rates decrease.

2.3. Influence of the arrangements for compression process and expansion process

In the field of utilizing LNG cold energy by ORC (organic Rankine cycle), most studies focus on how to reduce the irreversible loss of the heat exchange process but pay little attention to the arrangements for compression and expansion process. The compression and expansion process, as the parts of the cycle that consumes and products energy, affect the cycle performance as well due to that their different arrangements make the efficiency of the component different.

The structures of four different two-stage condensation Rankine cycles are shown in **Figure 9**. There are two types of arrangements for the pumps in the compression process.

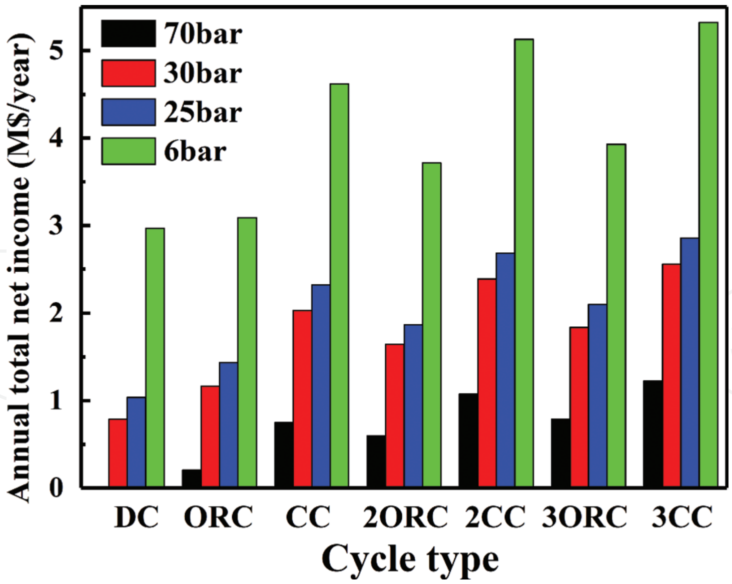

Figure 8. The maximized annual net income of seven cycles at different LNG vapor pressures.

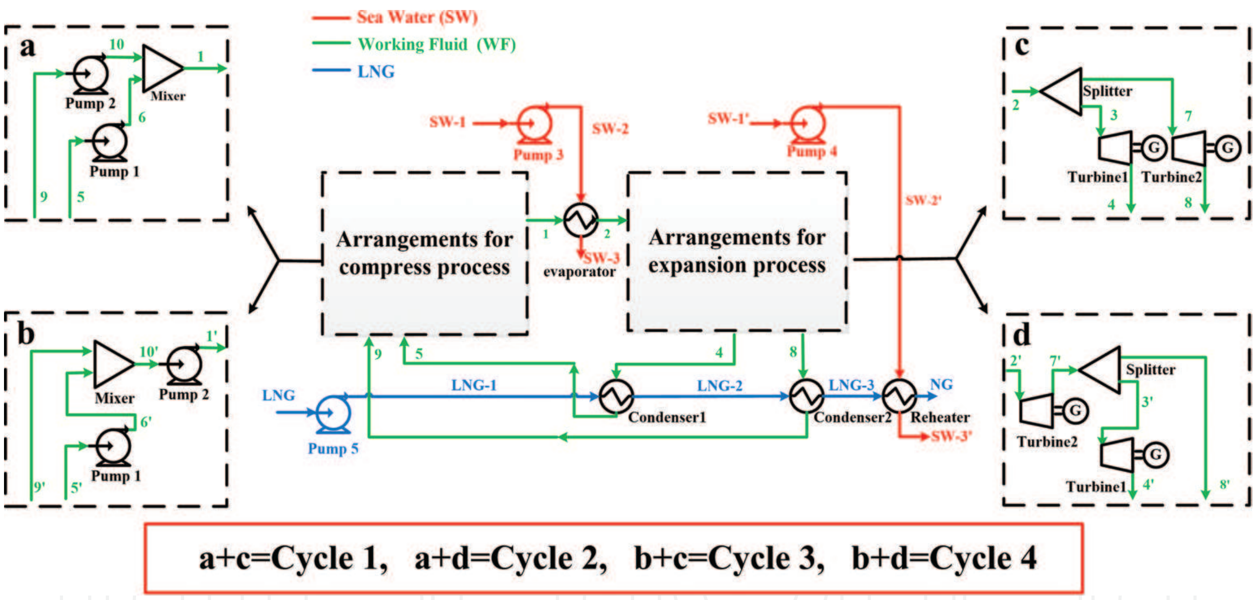

Figure 9. The configurations of four different two-stage condensation Rankine cycles.

The arrangement a shown in **Figure 9** is called parallel compression arrangement. The other arrangement b shown in **Figure 9** is called series compression arrangement. Similarly, there are also two types of arrangements for the turbines in the expansion process. The arrangement c shown in **Figure 9** is called parallel expansion arrangement. The arrangement d shown in **Figure 9** is called series expansion arrangement.

This paper takes 80% as the reference efficiency when the turbine efficiency is constant. When the turbine efficiency is non-constant, this paper adopted the turbine efficiency prediction model with the turbine size parameter (SP) and the specific volume (Vr) as the input parameters, as is shown in Eq. (4).

$$\eta_{turb,is} = \sum_{n=0}^{15} F_n A_n \tag{4}$$

where F_n is input parameter SP and Vr, and A_n is the regression coefficients, which could be found in Ref. [29].

In order to study the arrangements of the pumps, cycle 1 is compared with cycle 3 with constant turbine efficiency and same arrangements of the turbines, as shown in **Figure 10a**. Although the condensation temperatures vary within a range, cycle 1 performs almost the same as Cycle 3, which indicating that the impact of the arrangements of the pumps on the system performance is little. The reason is that the consumed power of WF-pump 1 and WF-pump 2 is small (< 0.05 kW), which has a very little effect on the net power output.

To investigate the arrangements of the turbines, Cycle 1 is compared with Cycle 2, as shown in in **Figure 10b**. It can be seen that the net output power of Cycle 2 is always a little higher than that of Cycle 1 at different condensation temperatures, which suggests that the series compress arrangement performs better than the parallel.

Net power output of cycle 1 is compared with cycle 2 and cycle 3 with non-constant turbine efficiency, as shown in **Figure 11**. It could be found that the impact of the arrangements for

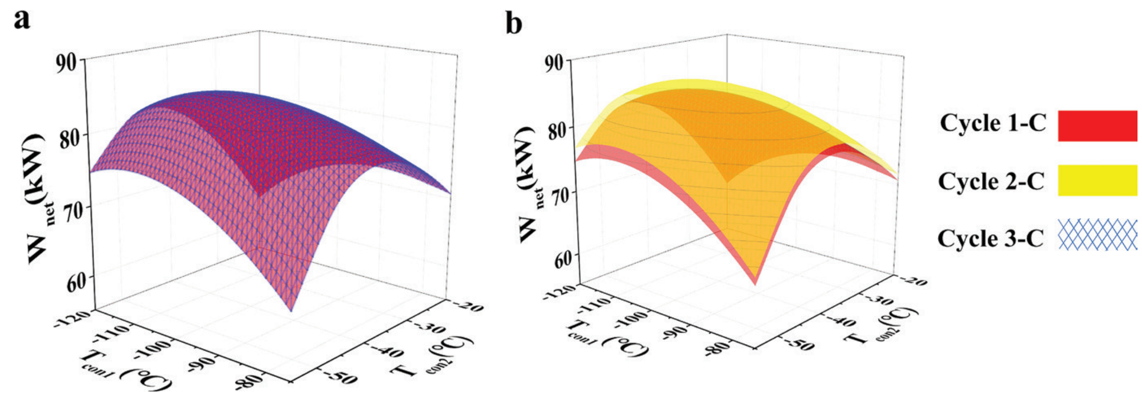

Figure 10. The comparison of the net power output between (a) cycle 1 and cycle 3, (b) cycle 1 and cycle 2 under the constant turbine efficiency.

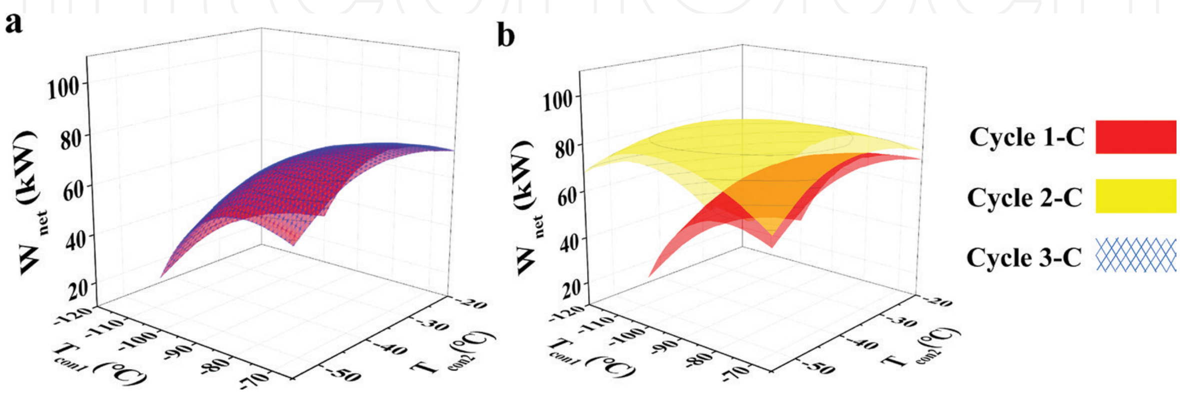

Figure 11. The comparison of the net power output between (a) cycle 1 and cycle 3, (b) cycle 1 and cycle 2 under non-constant efficiency.

pumps on the system performance is little but the influence of the arrangements for turbine is great. The series arrangement for turbines has a greater impact on the system performance than the parallel arrangement. Meanwhile, this impact for non-constant turbine efficiency is much more pronounced than that for constant turbine efficiency, with comparing **Figures 10** and **11**.

3. Optimization of working fluids

3.1. Pure working fluids

For power generation systems using LNG cold energy, the choice of working fluid has a great influence on the performance of the system. Due to the low temperature of the LNG, it is necessary to consider several aspects when selecting working fluid. Based on the previous study, this paper selects 11 kinds of working fluids, including hydrocarbons (HCs) and hydrofluorocarbons (HFCs), and the physical properties of them are shown in **Table 1**.

The evaporation temperature, the condensation temperatures and the inlet pressure of NG turbine of the two-stage condensation combined cycle are optimized with the net power output as objective function. T The maximum net power output and the critical temperatures of the 11 different pure working fluids are shown in **Figure 12**.

It can be seen from **Figure 12** that the net power output of the two-stage condensation combined cycle is the largest when n-C_5H_{12} is chosen as working fluid, and the net power output of C_2F_6 is the least. From the trend lines of the net power output and the critical temperature for 11 kinds of working fluids, it can be found that the variation trend of the net power

Working fluids	Chemical formula	Critical temperature (°C)	Critical pressure (bar)	Normal boiling point (°C)
R170	C_2H_6	32.17	48.72	−88.82
R1270	C_3H_6	91.06	45.55	−47.62
R290	C_3H_8	96.74	42.51	−42.11
—	i-C_4H_8	144.94	40.09	−7.00
R600	n-C_4H_{10}	151.98	37.96	−0.49
R601	n-C_5H_{12}	196.55	33.70	36.06
R23	CHF_3	26.14	48.32	−82.09
R134a	$C_2H_2F_4$	101.06	40.59	−26.07
R125	C_2HF_5	66.02	36.18	−48.09
R116	C_2F_6	19.88	30.48	−78.09
R218	C_3F_8	71.87	26.40	−36.79

Table 1. Physical properties of selected pure working fluids.

output is approximately the same as that of the critical temperature of working fluids. With the increase of the critical temperature, the net power output of the system increases roughly.

3.2. Mixed working fluids

In this section, 11 pure working fluids are combined to binary mixtures. With the net power output as the objective function, evaporation temperature, condensation temperatures, the inlet pressure of the NG turbine and the molar fraction of binary working fluids are optimized. When the net power output of the system is maximum, the optimized results of different binary mixtures are shown in **Figure 13**.

The gray dotted line in **Figure 13b** represents the trend line of net power output of 11 pure working fluids, and the black dotted line represents the trend line of maximum net power output in each column. From Figure b, it can be found that the optimal net power output for pure fluids changes from 2158.49 to 2712.41 kW. While the optimal net power output for mixtures distributes between 2894.47 and 3107.91 kW, which has an obvious increase than that for pure fluids and the variation range for mixtures is much smaller than that of pure fluids.

Figure 14 shows the maximum net power output of the two-stage condensation combined cycle when the component numbers of working fluids change from one to five. When the component number of mixed working fluid is five, it is actually quaternary mixture due to the results of optimization. As shown in **Figure 14**, with the increase of the component number of mixed working fluid, the net power output of the two-stage condensation combined cycle is increased, but the increase rate is gradually reduced. When the component numbers of the mixed working fluid are three and four, the net power output of the system is almost the

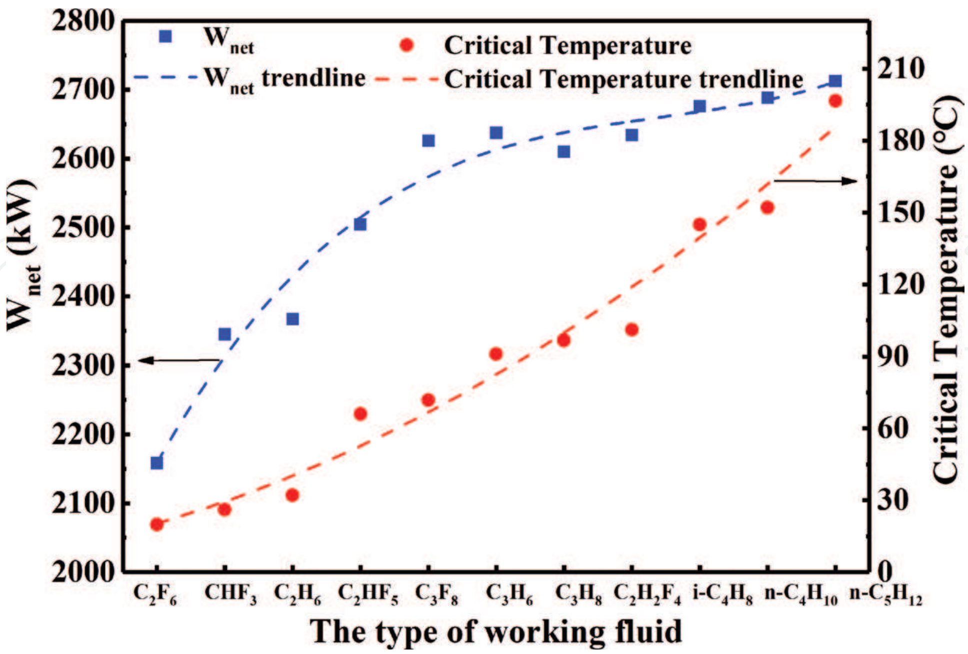

Figure 12. The maximum net power output and the critical temperature for different working fluids.

same. With the increase of the component number of mixture, the difficulty of charging working fluids into system becomes significant. Therefore, considering the increase rate of the net power output and the difficulty of charging working fluids, the optimum component number of hydrocarbon mixtures is three for the two-stage condensation combined cycle.

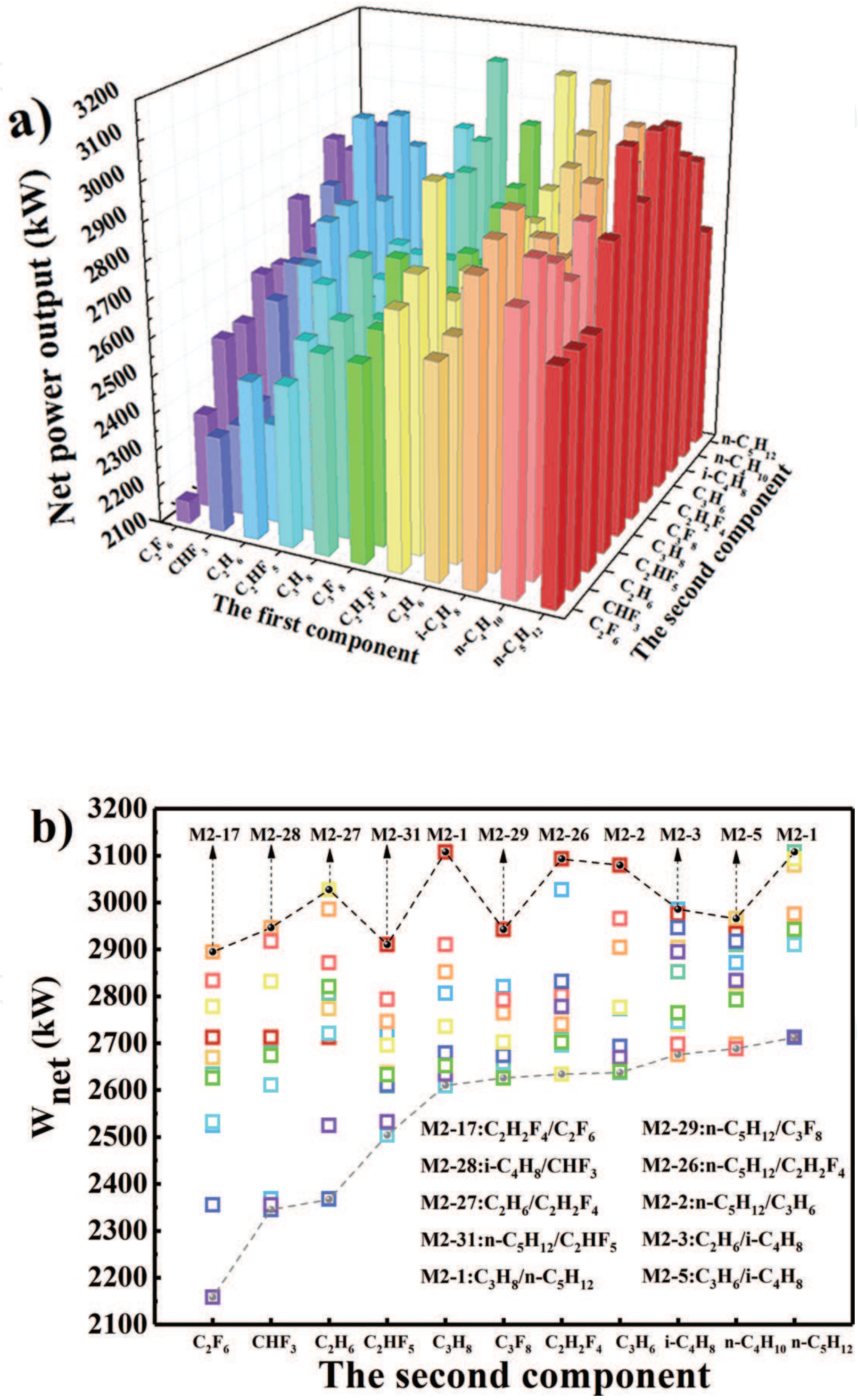

Figure 13. The maximum net power output of different pure working fluids and binary mixtures: (a) 3-D histogram and (b) 2-D diagram.

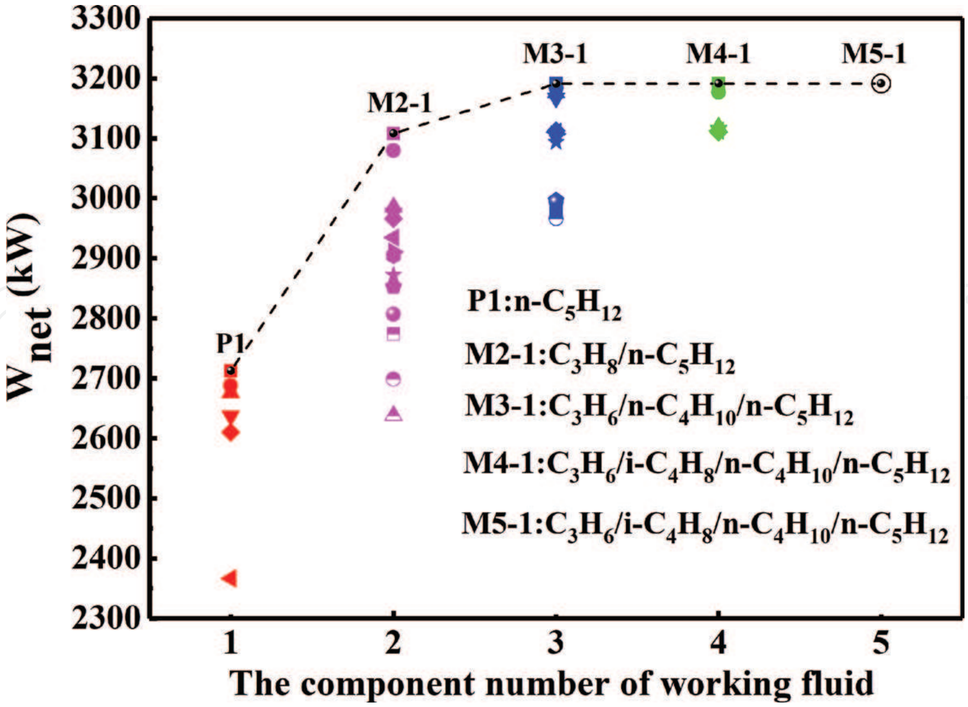

Figure 14. The net power output of the system corresponding to the mixtures with different component numbers.

3.3. A simultaneous approach to optimize the component and composition of zeotropic mixture

The traditional method of determining the components and compositions of mixtures is firstly to predefine some fluids, and then, according to the number of components, these fluids are chosen and combined as the component of mixed working fluids one by one. At last, the compositions of the formed mixtures and the corresponding system parameters are optimized at the specified system structure respectively. It is difficult to optimize the components of a

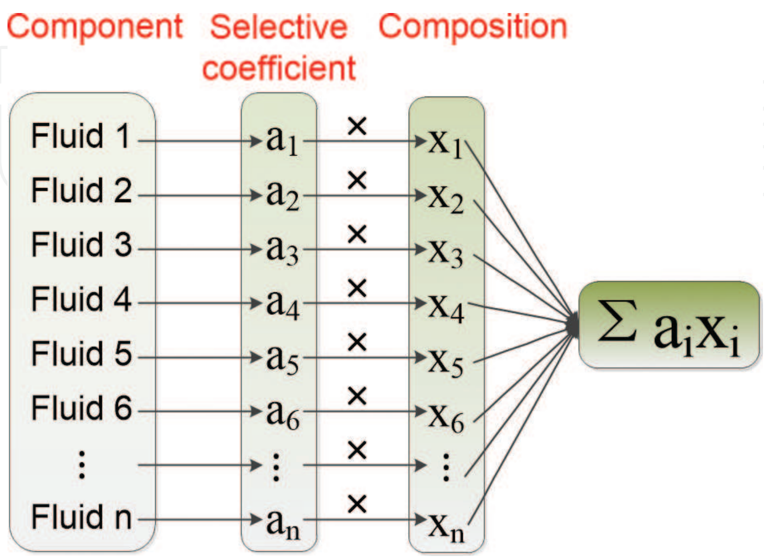

Figure 15. Basic idea for simultaneous approach to optimize component and composition of zeotropic mixture.

mixture, because the components of the mixed working fluids are independent of each other and discrete, and meanwhile it is difficult to describe them with mathematical variables. In order to reduce the intensity of calculation for components and compositions of zeotropic mixtures and achieve the simultaneous optimization of components and compositions for zeotropic mixtures, a selective coefficient a_i is introduced, as shown in **Figure 15**. Because the components of mixture are discrete, only discrete variables can be used to describe them. Each component of mixture is expressed by a selective coefficient. The selective coefficient a_i is a binary variable, and it has two values 0 or 1. When the value of selective coefficient a_i is 1, the component expressed by this selective coefficient is selected. While the value of selective

Control variables	Range	Results of pure fluid	Optimal results of binary mixture	Optimal results of ternary mixture
Ethane selective coefficient a_1	{0,1}	0	0	0
Ethylene selective coefficient a_2	{0,1}	0	0	0
Propylene selective coefficient a_3	{0,1}	0	0	1
Propane selective coefficient a_4	{0,1}	0	0	0
Butane selective coefficient a_5	{0,1}	0	0	0
Isobutane selective coefficient a_6	{0,1}	0	1	1
Pentane selective coefficient a_7	{0,1}	1	1	1
R23 selective coefficient a_8	{0,1}	0	0	0
R32 selective coefficient a_9	{0,1}	0	0	0
R41 selective coefficient a_{10}	{0,1}	0	0	0
R116 selective coefficient a_{11}	{0,1}	0	0	0
Ethane mole fraction x_1	[0,1]	0.441	0.485	0.598
Ethylene mole fraction x_2	[0,1]	0.162	0.488	0.254
Propylene mole fraction x_3	[0,1]	0.399	0.527	0.492
Propane mole fraction x_4	[0,1]	0.211	0.410	0.852
Butane mole fraction x_5	[0,1]	0.752	0.539	0.570
Isobutane mole fraction x_6	[0,1]	0.825	0.836	0.319
Pentane mole fraction x_7	[0,1]	1	0.164	0.189
R23 mole fraction x_8	[0,1]	0.622	0.734	0.494
R32 mole fraction x_9	[0,1]	0.300	0.390	0.351
R41 mole fraction x_{10}	[0,1]	0.705	0.503	0.188
R116 mole fraction x_{11}	[0,1]	0.583	0.304	0.452
Evaporation temperature x_{12} (°C)	[5,10]	6.3	10.0	10.0
First-stage condensation temperature x_{13} (°C)	[−140, −90]	−100.0	−113.9	−129.7
Second-stage condensation temperature x_{14} (°C)	[−80, −40]	−42.9	−56.2	−71.2

Table 2. The range of control variables and their optimal results in case 2.

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coefficient a_i is 0, it means this component is not selected. The sum of the selective coefficient a_i is used to control the number of component for mixture. For example, binary mixture can be optimized by $\Sigma a_i = 2$. While the composition x_i of each component is the continuous variable and its value is between 0 and 1. There are no constraint conditions for composition x_i, but the total sum of compositions for all the selected components should be 1, i.e., $\Sigma a_i x_i = 1$.

Net power output is selected as the objective function, and the optimization variables include the selective coefficients of components, operation parameters of system and compositions of components. For the two-stage condensation Rankine cycle shown in **Figure 1**, the main operation parameters are evaporation temperature, the first-stage condensation temperature and the second-stage condensation temperature. The range of control variables and their optimal results are shown in **Table 2**.

Table 2 shows that the best ternary mixture is propylene/isobutane/pentane (0.492/0.319/0.189, by mole fraction), and the optimum binary mixture isobutane/pentane (0.836/0.164, by mole fraction). Pure fluid pentane is best among pure fluids.

4. Conclusions

This chapter has proposed a conception of multi-stage condensation Rankine cycle (TCRC) system. The performance of the power generation systems is enhanced by two aspects: improvement of system configuration and optimization of working fluids. Compared with the combined cycle, the net work output, thermal efficiency and exergy efficiency of the TCRC system are respectively increased by 45.27, 42.91 and 52.31%. The two-stage condensation Rankine cycle is more suitable from the viewpoint of economy. For the arrangements for compression process and expansion process of TCRC, the arrangements for pumps have little impact on the net output power and the series arrangement for turbines performs better than the parallel arrangement. With the increase of the critical temperature for pure fluids, the net power output of the system increases roughly. Zeotropic mixture can improve the performance, and the optimum component number of hydrocarbon mixtures is three for the two-stage condensation combined cycle. A simultaneous approach to optimize the component and composition of zeotropic mixture is put forward which can reduce the consumed calculation time greatly.

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Conflict of interest

The author declared that there is no conflict of interest.

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