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Integration of Low-level Waste Heat Recovery and Liquefied Nature Gas Cold Energy Utilization*

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Abstract Two novel thermal cycles based on Brayton cycle and Rankine cycle are proposed, respectively, which integrate the recovery of low-level waste heat and Liquefied Nature Gas (LNG) cold energy utilization for power generation. Cascade utilization of energy is realized in the two thermal cycles, where low-level waste heat, low-temperature exergy and pressure exergy of LNG are utilized efficiently through the system synthesis. The simulations are carried out using the commercial Aspen Plus 10.2, and the results are analyzed. Compared with the conventional Brayton cycle and Rankine cycle, the two novel cycles bring 60.94% and 60% in exergy efficiency, respectively and 53.08% and 52.31% in thermal efficiency, respectively.
Key words recovery of low-level waste heat, LNG cold energy utilization, power generation, cascade utilization

1 INTRODUCTION

Liquefied nature gas (LNG) is produced by cryogenic refrigeration of nature gas after the removal of the acid and water components. A significant amount of energy is consumed to produce low-temperature (about 113.15 K) LNG. However, LNG should be regasified for normal use at the receiving site. A great amount of cold energy is released from the regasification process and is usually discarded into the seawater or air which works as the heat source [1]. In addition, much low-level waste heat exists in the primary energy source consumption process, whose temperature is not high enough to transfer into power efficiently. Carnot efficiency based on the thermodynamic principles indicates that if the heat source temperature is lower than 673.15 K, the efficiency will be low for recovering the waste heat by vapor cycle. Therefore, it has been a hot topic on how to combine the low-level heat source with the LNG cold energy and transfer them efficiently into electrical energy [2–9]. Ammonia-water Rankine cycle is proposed for recovering waste heat and LNG cold energy in the Ref. [10, 11]. Ammonia and water make a non-azeotropic mixture, which boils with an increasing temperature. That means the mixture can maintain a temperature profile closer to that of a heat source with decreasing temperature than the profile of a single-component fluid. The same principle is valid for the condensing part of the cycle where the mixture can follow the temperature profile of the heat sink [12]. So, it is possible to recover the LNG cold energy of the higher temperature part efficiently using the ammonia-water Rankine cycle. In this article, LNG cold energy is divided into the lower temperature and higher temperature parts. The higher part is used in ammonia-water Rankine cycle. Cascade utilization of energy is realized in the two thermal cycles and the exergy efficiency and thermal efficiency of LNG cold energy utilization is enhanced.

2 CASCADE UTILIZATION OF LNG COLD ENERGY

Generally, there are three methods for the integration of low-level waste heat recovery and LNG cold energy utilization [13–15]. First, in direct expansion method, LNG is pumped to a high pressure and then is heated to normal atmospheric temperature by seawater or waste heat. Finally, it generates work through an expander [16]. Second, in indirect heating medium Rankine cycle method, LNG works as liquor condensate flowing through the condenser of Rankine cycle and the LNG cold energy transfers to indirect heating medium in this process. Temperature difference between ambient and LNG drives the indirect heating medium to generate power in Rankine cycle. Finally, in Brayton cycle method, LNG cools down the inlet gas of compressor [17]. High-pressure nitrogen is heated to a high temperature in the heater, and then it expands through an expander with work output. The lower the temperature of inlet gas of compressor, the less work required in the compression process, which means the utilization of LNG in nitrogen Brayton cycle can improve the cycle efficiency. However, these methods cannot use the cold energy of LNG completely. LNG cold energy of the higher temperature part is usually discarded into seawater or air, which causes a loss of energy.

Since Ammonia-water mixture can maintain a temperature profile close to LNG of the higher temperature part with increasing temperature (Fig. 1), it is possible to recover the cold energy of LNG of the higher part more completely by ammonia-water Rankine cycle.

The exergy of LNG includes two parts: one is the low temperature exergy, which is defined as the thermal non-equilibrium exergy with the environment under the system pressure, and the other is the pressure exergy, which is defined as the system pressure non-equilibrium exergy with the environment under the ambient temperature [18].

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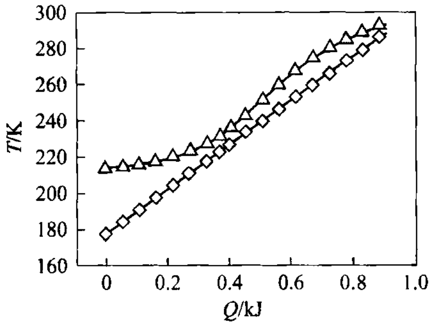


Figure 1 The temperature profile of ammonia water and low temperature NG
△ ammonia water; ◇ low temperature NG

Based on Brayton and Rankine cycles, two novel schemes (Figs. 2, 3) are proposed for recovering the cold exergy of LNG and the energy of low-level waste heat. Scheme 1 is the combination of nitrogen Brayton cycle, nature gas direct expansion and ammonia-water Rankine cycle. Scheme 2 is the combination of propane Rankine cycle, nature gas direct expansion and ammonia-water Rankine cycle.

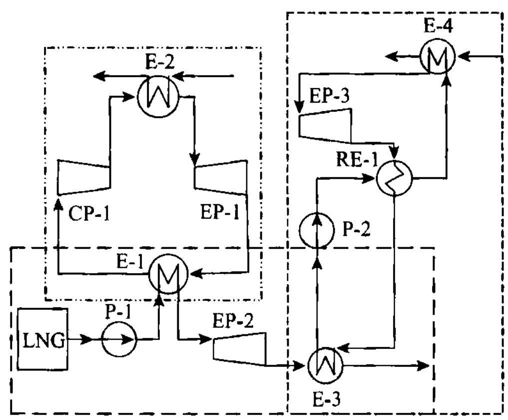


Figure 2 Flow process of scheme 1

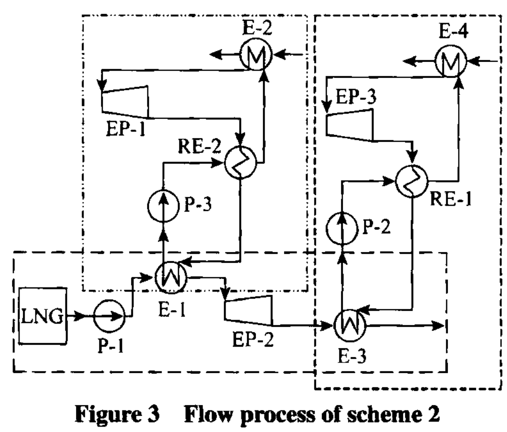


Figure 3 Flow process of scheme 2

The layout of scheme 1 is shown in Fig. 2, which can be decomposed into three parts.

(1) The first part (on the left block in Fig. 2) is nitrogen Brayton cycle derived by low-level waste heat and LNG cold energy. Low-level waste heat is the heat source and LNG cold energy is the heat sink in the cycle. Low-temperature nitrogen is compressed to a high pressure by compressor CP-1 and then flows into heater E-2. After heating, the nitrogen with high-temperature and pressure generates work through expander EP-1, and the temperature and pressure at the exit of the expander are decreased. Finally, low-pressure nitrogen is cooled by countercurrent LNG in cooler E-1.

(2) The second part (on the right block in Fig. 2) is ammonia-water Rankine cycle which is derived by low-level waste heat and low-temperature nature gas. Low-level waste heat serves as heat source and low-temperature nature gas acts as heat sink in the cycle. Liquid ammonia water is pumped to high pressure by pump P-2, and then flows into vaporizer E-4 through heat regenerator RE-1. After heating in the vaporizer, gaseous ammonia water generates mechanical work through expander EP-3. Low-pressure ammonia water flows into condenser E-3 by heat regenerator and is condensed by countercurrent low-temperature NG.

(3) The third part (at the bottom block in Fig. 2) is a LNG direct expansion open cycle, which utilizes the pressure exergy of LNG. Non-pressurized LNG is pumped to high pressure by pump P-1, and then flows into the cooler of nitrogen Brayton cycle where it is heated to high temperature by nitrogen. Then the nature gas with high-temperature and pressure expands through expander EP-2 to the required supply pressure and generates work through the expander. Low-temperature nature gas which flows into the condenser of ammonia-water Rankine cycle is heated to 288.15 K and then goes into the supply system.

In conventional Brayton cycle, the bottom temperature rises with the increment in the peak temperature when LNG supply temperature is given, but scheme 1 has a constant bottom temperature; Moreover, LNG is heated to rather higher temperature in heat exchanger E-1 in scheme 1 than that of the conventional Brayton cycle.

The layout of scheme 2 is shown in Fig.3, which also consists of three parts. The first part (on the left) is propane Rankine cycle derived by low-level waste heat and LNG cold energy. Liquid propane is pumped by pump P-3 to a high pressure and then flows into vaporizer E-2 through heat regenerator RE-2. After heating in the vaporizer, gaseous propane generates work through expander EP-1 and the temperature and pressure of the gas at the outlet of expander are reduced. Low-pressure propane flows into condenser E-1 through heat regenerator and is condensed by countercurrent LNG.

The second and the third parts of scheme 2 work the same way as in the parts of scheme 1, respectively.

Compared with the conventional Rankine cycle, LNG is pumped to supercritical pressure in scheme 2, rather than pumped to subcritical pressure in the conventional Rankine cycle, which means that LNG is in supercritical pressure when it exchanges heat with propane in heat exchanger E-1 in scheme 1. Besides, LNG is heated to rather higher temperature in heat exchanger E-1 of scheme 2 than that of the conventional Rankine cycle.

3 SYSTEM ANALYSIS AND SIMULATION RESULTS

Thermal efficiency (work output of the cycle divides by heat input of the cycle) is the conventional index for thermodynamic cycle efficiency analysis, but it is not perfect enough at the point of thermodynamic principles [19, 20]. In this article, both the thermal efficiency and the second law of the thermodynamic efficiency (exergy efficiency) are selected to value the system performance, which is defined as:

$$\eta_{\mathrm{E}}=\frac{EX_{\mathrm{out}}}{EX_{\mathrm{in}}}=\frac{W_{\mathrm{net}}}{m_{\mathrm{L}}e_{\mathrm{L}}+m_{\mathrm{f}}e_{\mathrm{f}}}100\% \quad (1)$$

$$\eta_{\mathrm{T}}=\frac{W_{\mathrm{net}}}{Q}100\% \quad (2)$$

The EX_{out} and EX_{in} for the schemes in this article can be expressed as:

$$EX_{\mathrm{out}}=W=\left(W_{\mathrm{EP-1}}+W_{\mathrm{EP-2}}+W_{\mathrm{EP-3}}\right)-\left(W_{\mathrm{CP-1}}+W_{\mathrm{P-1}}+W_{\mathrm{P-2}}\right) \quad (3a)$$

$$EX_{\mathrm{out}}=W=\left(W_{\mathrm{EP-1}}+W_{\mathrm{EP-2}}+W_{\mathrm{EP-3}}\right)-\left(W_{\mathrm{P-1}}+W_{\mathrm{P-2}}+W_{\mathrm{P-3}}\right) \quad (3b)$$

$$EX_{\mathrm{in}}=m_{\mathrm{L}}e_{\mathrm{L}}+m_{\mathrm{f(E-2)}}e_{\mathrm{f(E-2)}}+m_{\mathrm{f(E-4)}}e_{\mathrm{f(E-4)}} \quad (4)$$

The simulations were carried out using the commercial Aspen Plus 10.2. To simplify the computation, it was assumed that the natural gas is pure methane, ambient temperature and pressure are 298.15 K and 0.1 MPa, respectively. Operational parameters of the two schemes are: peak temperature is 663.15 K; peak pressure of the left part is 0.9 MPa in scheme 1 and 7 MPa in scheme 2; bottom pressure of the left part is 0.1 MPa; supercritical pressure of LNG is 10 MPa in scheme 1 and 7 MPa in scheme 2; peak pressure of the right part is 5 MPa in scheme 1 and 7 MPa in scheme 2; bottom pressure of the right part is 0.015 MPa in scheme 1 and 0.032 MPa in scheme 2; isentropic efficiency of the pump and compressor is 0.75; isentropic efficiency of the expander is 0.85; minimum temperature difference in the heat exchanger is 3 K; initial LNG pressure is 0.1 MPa and temperature is 111.5 K; natural gas supply pressure is 0.15 MPa and its temperature is 288.15 K.

In selecting the property equations, Peng-Robinson equation is selected for the nitrogen Brayton cycle, Non-Random-Two-Liquid (NRTL) equation is selected for the ammonia-water Rankine cycle, and Redlich-Kwong-Soave (RKS) equation is selected for LNG and propane.

Simulation results indicate that the exergy efficiency and thermal efficiency of scheme 1 are 60.94% and 53.08%, respectively, and those of scheme 2 are 60% and 52.31%, respectively. Exergy flow charts of schemes 1 and 2 are shown in Figs.4 and 5, respectively.

The layout of the conventional nitrogen Brayton cycle with the utilization of LNG cold energy is shown in Fig. 6 (a) and the layout of the conventional propane Rankine cycle with the utilization of LNG cold energy is shown in Fig. 6 (b). Their exergy efficiencies are 27.59% and 25.67%, respectively, and their thermal efficiencies are 31.35% and 30.07%, respectively. Operational parameters of the two cycles are: peak pressure is 0.9 MPa for Brayton cycle and 7 MPa for Rankine cycle; bottom pressure of the two cycles is 0.1 MPa; peak pressure of LNG is 0.15 MPa; other operational parameters and the assumptions are the same as in the two novel schemes.

Compared with the conventional' Brayton and Rankine cycles, the two novel schemes have the following advantages:

(1) LNG is heated in heat exchanger E-1 to a rather high temperature than ambient temperature and LNG is pumped to supercritical pressure exchanging heat in heat exchanger E-1. Thus the LNG maintains a temperature profile closer to that of the heat flow in heat exchanger E-1 in the two novel schemes than that of the conventional Brayton cycle and Rankine cycle, respectively. Exergy efficiency is enhanced because of the reduction of temperature difference in the heat exchangers. The simulation shows that the exergy efficiencies of heat exchanger E-1 in the conventional

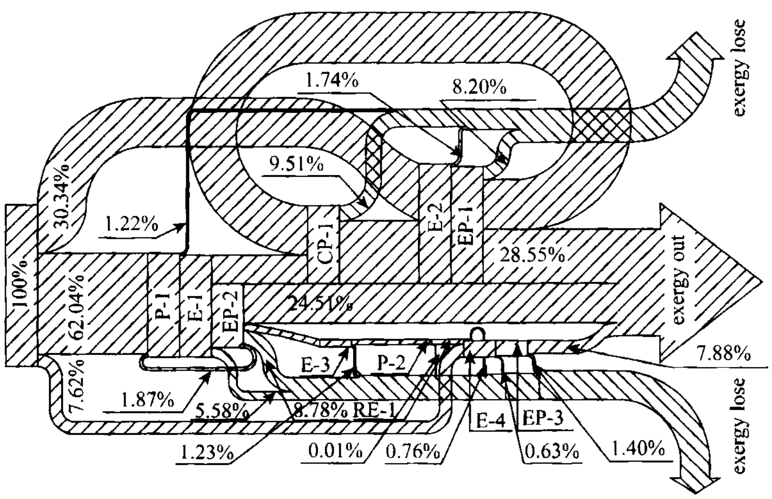


Figure 4 Exergy flow chart of scheme 1

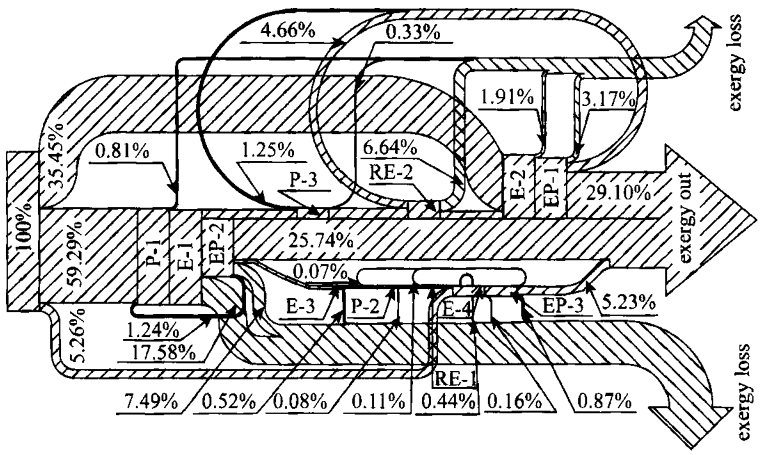
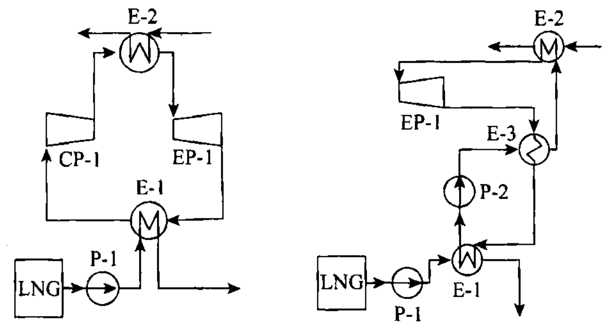


Figure 5 Exergy flow chart of scheme 2



(a) Nitrogen Brayton cycle (b) Conventional Rankine cycle

Figure 6 The utilization of LNG cold energy with conventional cycles

Brayton cycle and Rankine cycle are 25.67% and 7.35%, respectively, but they are 75.8% and 24.56% in schemes 1 and 2, respectively.

(2) High-temperature and pressure nature gas generates work through the expander, which utilizes the pressure exergy of LNG.

(3) When expanded in the expander, the high temperature of nature gas becomes low, which acts as the heat sink of ammonia-water Rankine cycle. In addition, ammonia-water Rankine cycle utilizes the cold energy of low-temperature NG more fully and heats NG to the required temperature of 288.15 K.

4 CONCLUSIONS

Cascade utilization of energy is realized in the two systems. The simulation results indicate that the novel schemes can utilize the LNG cold energy and low-level waste heat efficiently.

(1) Conventional Brayton cycle and Rankine cycle cannot utilize the LNG cold energy fully and there is some room for the improvement in the exergy efficiency.

(2) On the basis of cascade utilization of the energy, the two novel schemes can utilize the low-level waste heat and LNG cold energy more fully than the conventional Brayton cycle and Rankine cycle. At the same time, the two novel schemes also utilize the pressure exergy of LNG.

NOMENCLATURE

EX_{in}	exergy into the system, kJ
EX_{out}	exergy out of the system, kJ
e_f	heat exergy of flue gas for unit mass, $kJ\cdot kg^{-1}$
e_L	cold exergy of LNG for unit mass, $kJ\cdot kg^{-1}$
m_f	mass flow of flue gas, kg
m_L	mass flow of LNG, kg
Q	heat flow, kJ
Q_T	total heat input to system, kJ
T	temperature, K
W_{net}	net work output of the system, kJ
η_E	exergy efficiency
η_T	thermal efficiency

Subscripts

E	exergy
f	flue
L	LNG
T	thermal

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