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Thermodynamic analysis of a novel hybrid solar-LNG cold energy recovery system

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Abstract. Due to the low temperature of LNG (liquefied natural gas), there is abundant cold energy can be utilized during the regasification process. Therefore a novel hybrid solar-LNG cold energy recovery system was proposed. In this system, LNG cold energy is used as a heat sink for a propane Rankine power cycle and a cascaded ethylene glycol refrigeration cycle. Then through a direct expanding combined with the preheating of solar thermal energy, more power is generated by the regasified LNG. A thermodynamic analysis was carried out to investigate the best system design. Meanwhile, the influences of some key operating parameters on net output power and exergy efficiency were investigated. The results show that higher inlet temperature and pressure of NTB (natural gas turbine) are beneficial to system performance.

1. Introduction

As the consumption of natural gas is sharply increased in China, more LNG has been imported during recent years. Generally, LNG is stored at atmospheric pressure with a low temperature of −162 ℃, which contains a large amount of cold energy. However, LNG needs to be regasified before fed into the urban distribution system. Since most LNG receiving terminals are constructed on the coast, sea water is typically employed as the heat source to complete the regasification process. As a result, plenty of cold energy is wasted and the marine ecosystem is also damaged [1]. Therefore, a growing number of researchers are attracted to study the cold energy recovery system.

Different technologies have been developed to provide an efficient and economic method to utilize the cold energy, among which the combined power cycle is considered most promising. Zhang [1] proposed a combined system utilizing both the cold exergy of LNG and the low temperature waste heat. A thermodynamic and thermal-economic analysis has been conducted with eight organic working fluids. García [2-3] presented an analysis of a LNG power plant composed of cascaded Rankine cycles and a direct expansion power unit, in which argon and methane have been used as working fluid. An objective function was optimized and the highest possible exergy efficiency was obtained. Franco [4] conducted a detailed analysis of two particular direct expansion solutions. The multistage turbine and internal heat recovery system were developed and the specific power production for LNG was improved. Zhao [5] proposed a novel LNG cold energy utilization system containing a two stages ORC power generation sub-system and a CO2 capturing sub-system. The LNG regasification pressure and the CO_2 capture pressure were investigated to find the optimal working conditions of the system. Shi [6] developed an integrated advanced thermal power system to improve the performance of the conventional combined cycle power plant with the cold energy of LNG. The latent heat of spent steam and the compression heat were used to heat LNG and generate electrical energy. Furthermore, to improve the system performance, a combined cycle of LNG cold energy recovery and solar energy utilization was proposed by Rao [7].

In this paper, a novel hybrid solar-LNG cold energy recovery system was proposed to obtain power, hot water and cold water simultaneously. LNG cold energy is used as a heat sink for a propane Rankine power cycle and a cascaded ethylene glycol refrigeration cycle. Besides, the stored solar thermal energy is used to heat the regasified LNG to generate more power. A thermodynamic analysis was carried out to investigate the optimal system performance.

2. System description

Figure 1 shows the schematic diagram of the cold energy recovery system. During the gasification process, the LNG is firstly pressurized by the LNG pump (LP) and gasifies in HX1. Then the high pressure nature gas is heated in HX3 by ethylene glycol and HX5 by thermal oil successively to achieve a high temperature. Finally, it expands in natural gas turbine (NTB) to generate power and the waste heat is used to produce hot water in HX6. Meanwhile, the propane is condensed in HX1 and then pumped by refrigerant pump (RP). The high pressure liquid propane is evaporated in HX2 by ethylene glycol and then expands in refrigerant turbine (RTB). The ethylene glycol is cooled in HX3 and HX2 successively and then the cold energy is used to produce industrial cold water in HX4. Before the gasification process, low temperature thermal oil from cold oil tank (COT) is heated by the solar thermal collector (STC) to get a high temperature and then stored in the hot oil tank (HOT). Therefore, the LNG cold energy is successfully utilized to produce power, hot water and cold water.

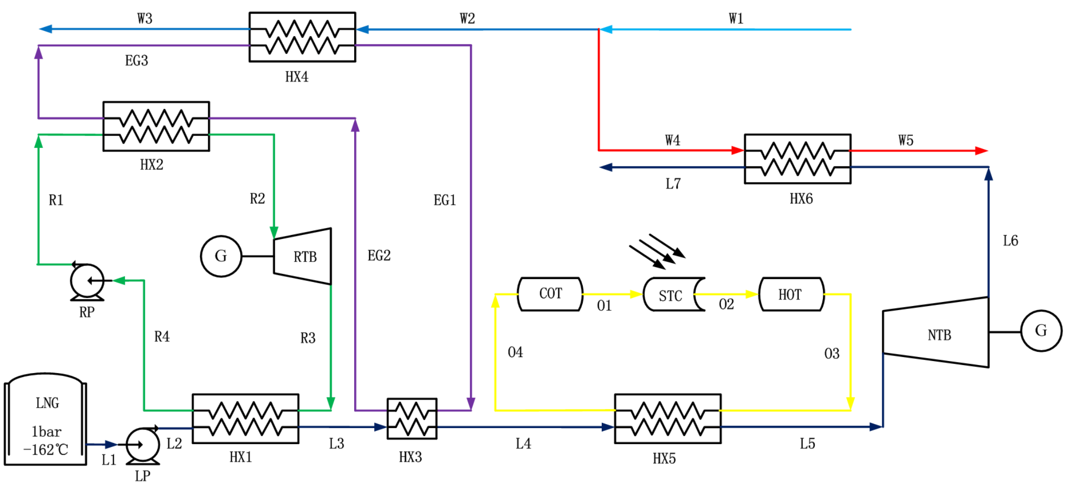

Figure 1. Schematic diagram of the solar-LNG cold energy recovery system.

3. Thermodynamic analysis model

3.1. Energy and exergy analysis model

For the LP and RP, the power consumption can be calculated as:

$$W_P = W_{LP} + W_{RP} = m_{L1}(h_{L2} - h_{L1}) + m_{R4}(h_{R1} - h_{R4}) \tag{1}$$

where m is the mass flow, h is the specific enthalpy, the subscripts L and R represent LNG and propane.

For the NTB and RTB, the output power is:

$$W_{TB} = W_{NTB} + W_{RTB} = m_{L5}(h_{L5} - h_{L6}) + m_{R2}(h_{R2} - h_{R3}) \tag{2}$$

Therefore, the net output power during the regasification process can be expressed as:

$$W_{net} = W_{TB} - W_P \tag{3}$$

For HX1to HX6, the unified energy balance equation is:

$$m_H \left(h_{H,in} - h_{H,out}\right) = m_C \left(h_{C,out} - h_{C,in}\right) \tag{4}$$

where the subscript H, C, in and out represent hot fluid, cold fluid, inlet and outlet, respectively.

For the STC, the effectively absorbed solar heat is:

$$Q_{STC} = m_{O1} \left(h_{O2} - h_{O1}\right) \tag{5}$$

where the subscript O represents thermal oil.

In order to quantify the qualities of different types of energy, the exergy analysis is also conducted here to tell the exergy destruction and irreversibility of each component. Generally, the enthalpy exergy of each state point can be written as:

$$Ex_j = m\left[\left(h_j - h_0\right) - T_0\left(s_j - s_0\right)\right] \tag{6}$$

where s is the specific entropy, the subscripts j and 0 represent stream number and ambient condition, respectively.

Especially for the STC, the effectively exergy input for the system can be given as:

$$Ex_{STC} = m_{O1}[(h_{O2} - h_{O1}) - T_0(s_{O2} - s_{O1})] \tag{7}$$

3.2. Performance assessment indexes

In the solar-LNG cold energy recovery system, there are different types of energy input and output, i.e. the electric power, the LNG cold energy and the solar thermal energy. In order to obtain a comprehensive evaluation criterion, the exergy efficiency is calculated as:

$$\eta_{ex} = \frac{Ex_{output}}{Ex_{input}} \tag{8}$$

4. Results and discussions

Based on the calculation methodology listed above, a thermodynamic simulation was carried out to validate the proposed solar-LNG cold energy recovery system.

4.1. Thermodynamic simulation results

Table 1 shows the simulation results of the proposed solar-LNG cold energy recovery system. All the parameters in this simulation are set based on current industrial level. For example, the isentropic efficiency of turbines and pumps were set as 85% and 75%, respectively. According to reference [8], the therminol 66 was chosen for solar thermal collector for its high boiling point. Considering the temperature zone of cold energy, propane and ethylene glycol were selected as the cold energy transfer medium. Also, the temperature of hot water is 60℃ which is the recommended value for hot water supply in China and the cold water is 4℃ for its wide application in industry. Besides, the environmental temperature is 25℃ and the inlet and outlet oil temperatures of STC are 25℃ and 250℃, respectively. The outlet pressure of the natural gas after expansion is 4 bar.

Table 1. Simulation results of the proposed solar-LNG cold energy recovery system.

Term	Unit	Value
Power of LP	kW	25
Power of RP	kW	3
Power of NTB	kW	1054
Power of RTB	kW	228
Net output power	kW	1253
Mass flow of LNG	t/h	10
Mass flow of hot water (60℃)	t/h	11
Mass flow of cold water (4℃)	t/h	102
η_{ex}	%	39.6

4.2. Parametric sensitivity analysis

Figure 2 shows that the mass flow of hot water has a sharp increase while the mass flow of thermal oil has a slow decrease with the increasing inlet temperature of NTB. As no parameters change for the HX4, the mass flow of cold water remains a constant value of 102 t/h.

Figure 3 shows that both the W_{net} and η_{ex} increase with the increasing inlet temperature of NTB. This is because the power of NTB is dominant and it can generate more power with a higher inlet temperature. A higher inlet temperature of NTB is preferable, but it is constrained by the properties of thermal oil.

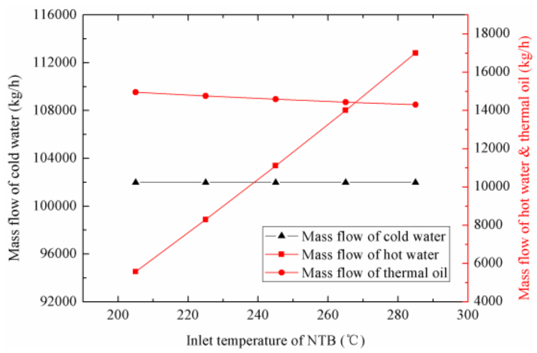

Figure 2. Effect of inlet temperature of NTB on mass flow of hot water, cold water and thermal oil.

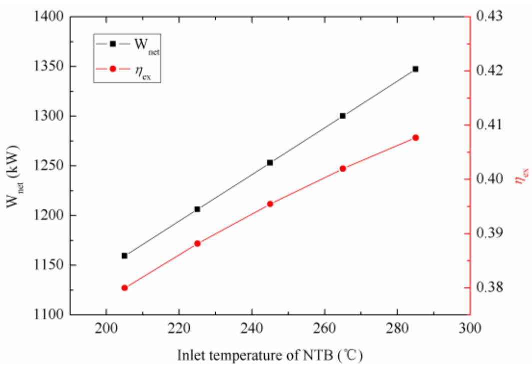

Figure 3. Effect of inlet temperature of NTB on W_{net} and η_{ex}.

Figure 4 presents that the mass flow of hot and cold water both decrease with the increasing inlet pressure of NTB attributed to a lower outlet temperature of NTB and heat duty in HX3, respectively. However, the mass flow of thermal oil has a small increase as the heat capacity of nature gas increases.

Figure 5 shows that both the W_{net} and η_{ex} increase with the increasing inlet pressure of NTB. As that in Figure 3, it is also because the power of NTB is dominant and more power can be generated with a higher inlet pressure. But the growth rate of both the W_{net} and η_{ex} tends to be slower. As the costs of high pressure equipment are larger, the inlet pressure of NTB should not be too high.

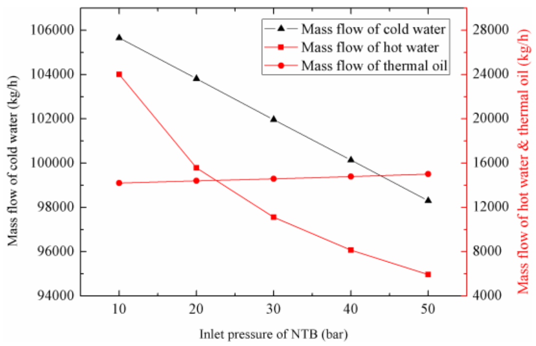

Figure 4. Effect of inlet pressure of NTB on mass flow of hot water, cold water and thermal oil.

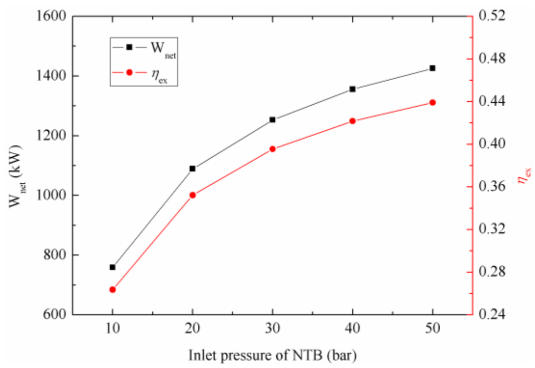

Figure 5. Effect of inlet pressure of NTB on W_{net} and η_{ex}.

5. Conclusions

For the purpose of increasing the net output power and exergy efficiency, a novel hybrid solar-LNG cold energy recovery system was proposed and analyzed. The system can transform LNG cold energy into electric energy, while yielding hot and cold water simultaneously. Besides, the thermodynamic analysis and parametric sensitivity analysis were both conducted to investigate the best system performance. The results show that the net output power is 1253 kW and the η_{ex} is 39.6%. Moreover, higher inlet temperature and pressure of NTB are beneficial to system performance.

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