Simulation and optimization of Rankine power generation cycle purposing the efficiency of liquefied natural gas cold exergy

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ABSTRACT

Liquefied natural gas (LNG) is obtained by cooling the natural gas to −162℃ at the atmospheric pressure. Methane is the major chemical component of LNG which varies between 87.0–99.8% for different sources. The cryogenic power generation cycle using LNG as its heat sink is known to be one of the considerable ways for the LNG exergy recovery. A double-stage Rankine power generation cycle using the single component working fluid in each stage for liquefied natural gas (LNG) cold exergy recovery is used as a base case in the present study. To improve the recovery of LNG cold exergy, a three-stage Rankine power generation cycle has been proposed using mixture working fluid. Optimization is done using the particle swarm algorithm. The performance of three-stage Rankine power generation cycle is studied regrading to the effects of thermal efficiencies, exergy efficiencies, overall heat transfer coefficient of condensers and natural gas distribution pressure. Specific power production of the cycle is 100.45 kJ/kg_{NG}, thermal efficiency is 12.76%, exergy efficiency is 27.92%. By decreasing the total coefficient of heat transfer, the condensers of different stages of the cycle reduce the maximum output power of the cycle with different trends. The results show that by decreasing the distribution pressure of natural gas, specific power production, thermal efficiency and exergy efficiency increases. So that their optimal values at 6 bar are 290.87 kJ/kg_{NG}, 25.63% and 39.12%, respectively.

KEYWORDS

Liquefied natural gas, Rankine cycle, Cold exergy, Regasification, Power generation

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1. Introduction

Liquefied natural gas (LNG) is 620 times denser than natural gas. Methane is the major chemical component of LNG which varies between 87.0–99.8% for different sources [1]. The cryogenic power generation cycles using LNG as its heat sink turns to be one of the considerable ways for the LNG cold exergy recovery. Rankine power generation cycle is one of the most used cycles of cold exergy recovery from LNG.

Sun et al. [2] Proposed a new Rankine power generation cycle that utilization mixtures of methane, ethane and propane, and methane, ethylene and propane as the working fluids, for the use of cold exergy LNG. They showed that the mixture of methane, ethylene and propane is more suitable for use as a mixture working fluid. Choi et al. [3] Reviewed five different power generation cycles including direct expansion of LNG, an organic Rankine cycle, a hybrid cycle (direct expansion and organic Rankine cycle), a two-stage Rankine cycle, and a three-stage Rankine cycle. In addition, three different pure organic fluids (methane, ethane and propane) were investigated. They found The three-stage cascade Rankine cycle with propane as the working fluid exhibited the highest net power output, thermal efficiency and exergy efficiency within the set.

The novelty of this paper is related to the previous studies of the use of mixture working fluid in the three-stage Rankine cycle and also the study of the effect overall heat transfer coefficient condensers on the power production cycle.

2. Methodology and purpose

A cycle that is considered as base is a two-stage Rankine cycle (first plan), Propane pure working fluid was used in both stages. In order to increase the efficiency, a three-stage Rankine cycle (second plan) is proposed that uses a mixture working fluid in each stage (Figure 1).

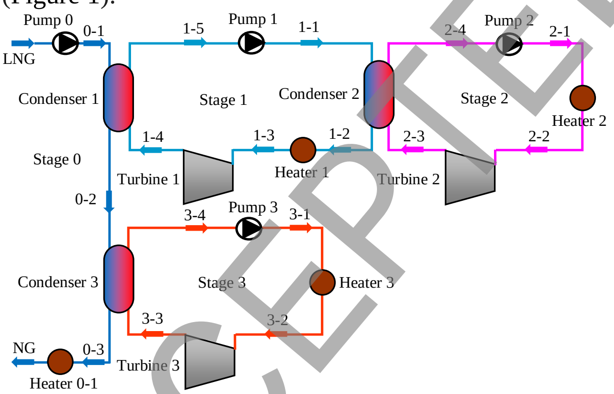

Figure 1. Process flow diagram for second plan utilizing LNG cold exergy

The mixture of methane, ethylene and propane is selected as the working fluid for first stage and second stage of the second plan [2] And since the third stage works at a higher temperature range, ethane, propane and i-butane are used for the third stage of the second plan.

Single stage Rankine cycle of Ferreira et al. [4] research is intended to validate the results.

To predict the thermodynamic properties mixture of hydrocarbons and nitrogen, the Peng-Robinson Equation is used in simulation [5]. Simulation of the cycle is done using the of Aspen HYSYS V10 software [2,5]. In this study, particle swarm optimization algorithm for maximizing net power output is used [6]. The optimization variables include the working fluid mass flow and composition, temperature and pressure of working fluid in the pump inlet, and the working fluid pressure in the pump outlet in each stage. Thermodynamic performance, exergy analysis, effect overall heat transfer coefficient of condensers on net power output and effect distribution pressure of natural gas on the performance of three-stage Rankine cycle investigated.

3. Results and Discussion

The specifications of the second plan after optimization by the particle swarm algorithm are shown in Table 1.

Table 1. Specifications of the second plan after optimization

Parameter	Stage 1	Stage 2	Stage 3
Mass flow (kg/s)	35.47	19.45	18.86
Pump inlet temperature (°C)	-139.91	-125.30	-46.26
Pump inlet pressure (MPa)	0.242	0.391	0.219
Pump outlet pressure (MPa)	3.600	2.777	0.995
Percent molar methane (%)	45.87	34.48	0
Percent molar ethylene (%)	21.09	26.68	0
Percent molar propane (%)	33.04	38.84	56.73
Percent molar ethane (%)	0	0	27.84
Percent molar i-butane (%)	0	0	15.43

A summary of the first and second plan performance after optimization is shown in Table 2.

Table 2. Summary of cycles performance

Parameter	First plan	Second plan
specific power production (kJ/kg)	42.69	100.45
thermal efficiency (%)	5.86	12.76
exergy efficiency (%)	11.88	27.92

Distribution exergy losses of various equipment is shown in Figure 2. As it is known, most exergy losses of the first plan occur in cycle condensers. By optimizing the cycle in the second plan, losses in condensers are significantly reduced. Due to increased temperature differences between the inlet flows and outlet flows of the second plan heaters, the losses in the second plan heaters are higher than the first plan.

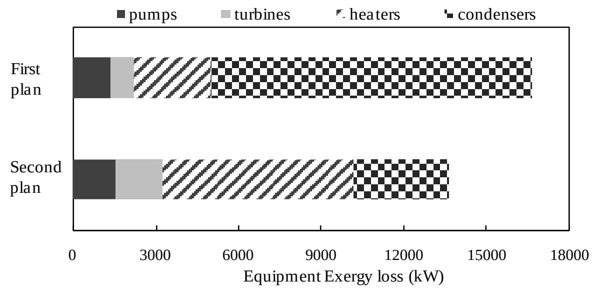

Figure 2. Distribution exergy losses of various equipment

Figure 3 shows the variations curve maximum power output cycle by changing the overall heat transfer coefficient of the condensers various stages of the second plan. For high values of the overall heat transfer coefficient, the overall heat transfer coefficient has a small effect on the power output and for small values of the overall heat transfer coefficient, the overall heat transfer coefficient has a higher effect on the power output.

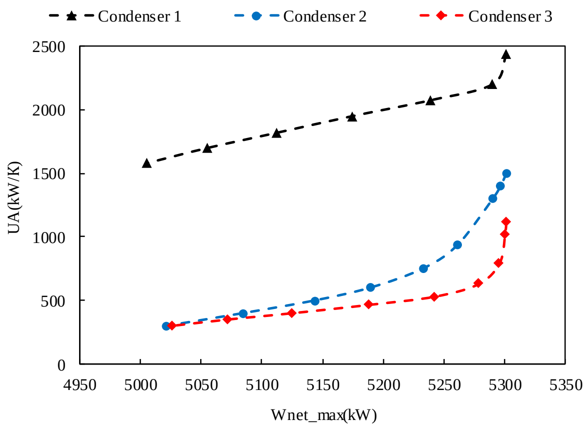

Figure 3. Comparison between maximum power production and overall heat transfer coefficient for the second plan condensers

Figure 4 shows the effect distribution pressure of natural gas on the performance cycle. As it is known, with the reduction distribution pressure of the natural gas, the specific power production cycle, thermal efficiency and exergy efficiency increase.

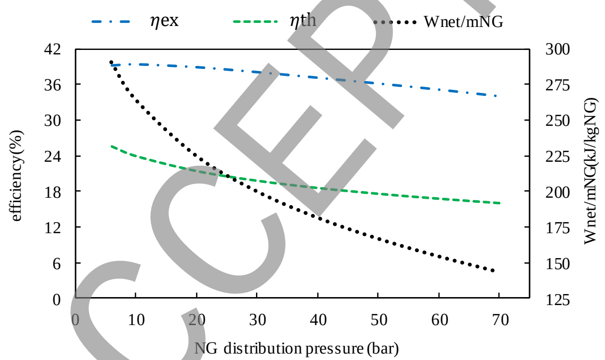

Figure 4. effect distribution pressure of natural gas on the performance cycle

4. Conclusions

In first plan, specific power production of the cycle is $42.69\,\mathrm{kJ/kg_{NG}}$, thermal efficiency is 5.86%, exergy efficiency is 11.88%. In second plan, specific power production of the cycle is $100.45\,\mathrm{kJ/kg_{NG}}$, thermal efficiency is 12.76%, exergy efficiency is 27.92%, Which shows a significant increase compared to the first plan. most exergy losses of the first plan occur in cycle condensers, By optimizing the cycle in the second plan, losses in condensers are significantly reduced. By reducing the overall heat transfer coefficient of condensers different stages, the maximum power output cycle decreases with different trends. The results of the first stage optimization affect the optimization results of the second stage and third stage. Therefore, the first stage condenser has the greatest effect on the power output cycle than of the second and third stages condensers. by decreasing the distribution pressure of natural gas to 6 bar, specific power production reaches $290.87\,\mathrm{kJ/kg_{NG}}$, thermal efficiency reaches 25.63% and exergy efficiency reaches 39.12%, Which is significantly higher than the second plan.

5. Refernces

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