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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 is obtained by cooling the natural gas to −162℃ at the atmospheric pressure. Methane is the major chemical component of liquefied natural gas which varies between 87.0–99.8% for different sources. The cryogenic power generation cycle using liquefied natural gas as its heat sink is known to be one of the considerable ways for the liquefied natural gas exergy recovery. A double-stage Rankine power generation cycle using the single component working fluid in each stage for liquefied natural gas cold exergy recovery is used as a base case in the present study. To improve the recovery of liquefied natural gas 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 the three-stage Rankine power generation cycle is studied regarding 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%, and 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.

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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 the 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

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

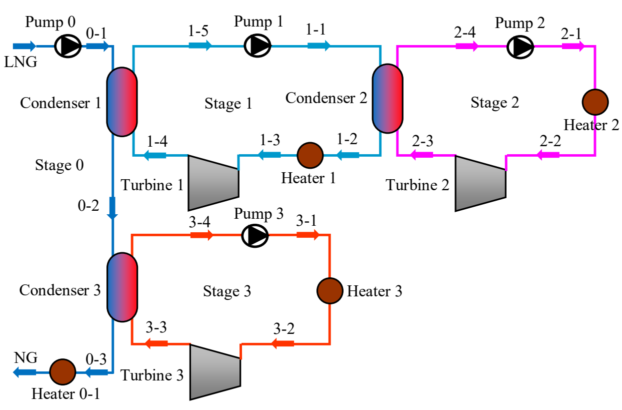

Fig. 1. Process flow diagram for the second plan utilizing LNG cold exergy

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The mixture of methane, ethylene, and propane is selected as the working fluid for the 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 Aspen HYSYS V10 software [2, 5]. In this study, the 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, affect overall heat transfer coefficient of condensers on net power output and effect distribution pressure of natural gas on the performance of the 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.

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

Distribution exergy losses of various equipment are shown in Fig. 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.

Fig. 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

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

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

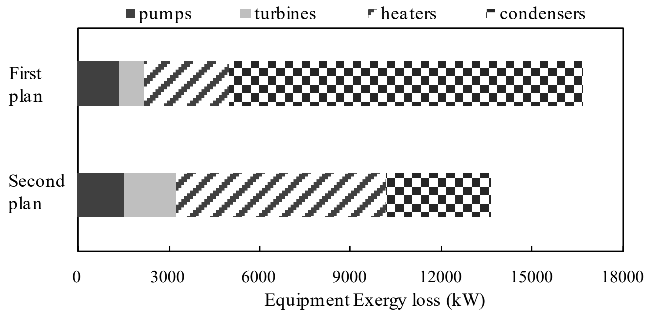

Fig. 2. Distribution exergy losses of various equipment

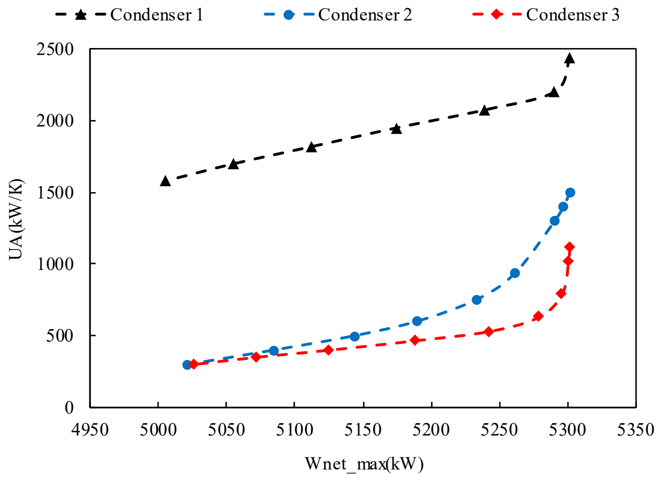

Fig. 3. Comparison between maximum power production and overall heat transfer coefficient for the second plan condensers

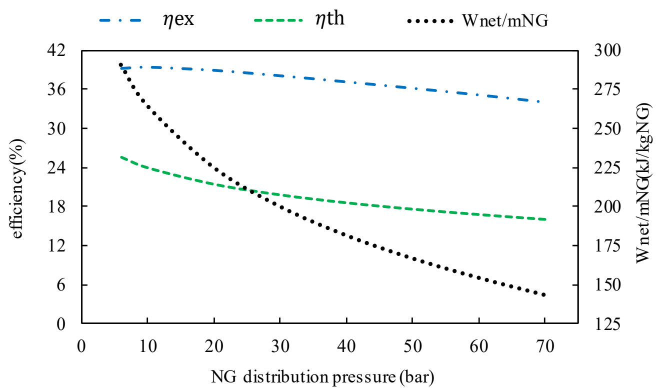

Fig. 4. Effect distribution pressure of natural gas on the performance cycle

power output.

Fig. 4 shows the effect of the 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.

4. CONCLUSIONS

In the first plan, the specific power production of the cycle is 42.69 kJ / kg_{NG}, thermal efficiency is 5.86%, and exergy efficiency is 11.88%. In the second plan, the specific power production of the cycle is 100.45 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 in 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 kJ / kg_{NG}, thermal efficiency reaches 25.63% and exergy efficiency reaches 39.12%, which is significantly higher than the second plan.

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