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Kanbur, Baris Burak; Dubey, Swapnil; Fei, Duan; Choo, Fook Hoong; Xiang, Liming

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Multiobjective Thermoeconomic Optimization of the LNG Cold Utilized Micro-cogeneration System

Baris Burak Kanbur

Energy Research Institute @NTU, Interdisciplinary
Graduate School,
School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore
e-mail: kanb0001@e.ntu.edu.sg

Xiang Liming

School of Physical and Mathematical Sciences,
Nanyang Technological University, Singapore
e-mail: LMXiang@ntu.edu.sg

Swapnil Dubey

Energy Research Institute @NTU, Interdisciplinary
Graduate School,
Nanyang Technological University, Singapore
e-mail: sdubey@ntu.edu.sg

Choo Fook Hoong

Energy Research Institute @NTU, Interdisciplinary
Graduate School,
Nanyang Technological University, Singapore
e-mail: EFHCHOO@ntu.edu.s

Fei Duan

School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore
e-mail: feiduan@ntu.edu.sg

Abstract—Liquefied natural gas (LNG) cold utilization systems are feasible options for the inland and stranded regions where the conventional pipeline technology is challenging. For the best operation conditions of the systems in the real engineering applications, the optimization is a significant step after the design and analysis steps. This study aims to optimize an LNG cold utilized micro-cogeneration system by using the multiobjective optimization strategy with the genetic algorithm. Thermodynamic and thermoeconomic investigations are performed, and then the multiobjective optimization study is carried out according to the net generated power rate, exergetic efficiency, and the levelized product cost as multiobjectives. The study is conducted between 288.15 K and 313.15 K, and the optimum operation conditions are detected between 301.0 K and 302.5 K with respect to the different relative humidities.

Keywords—multiobjective optimization; genetic algorithm; thermoeconomics; LNG cold utilization; LNG cold energy

I. INTRODUCTION

Liquefied natural gas (LNG) cold utilization systems allow to use of the LNG vaporizers in different combined systems as heat sinks, therefore many different engineering applications are able to be preferred in the LNG cold utilization processes [1,2]. The large-scale LNG cold utilization applications are widely used in today's industry, but the idea of the small-scale LNG cold utilization has been rising for many years thanks to the developed technologies in

the related areas [3]. Our group has been conducting several studies [4-10] to design, analyze and utilize the LNG cold energy in the small-scale applications in order to present a sustainable products for the real engineering applications. In addition to the design and analysis steps, the optimization is a strongly required step for detection of the best operation conditions of the proposed systems in the real engineering applications. The multiobjective optimization method is one of the well-known methods for the optimization of the energy conversion systems since the energy systems include multiple significant objectives for the assessments [11]. Although different objective functions are able to be selected as the multiobjectives, thermoeconomic and thermodynamic parameters have been generally using as the multiobjective functions in the optimization steps since they were firstly proposed by Toffolo and Lazzaretto [12]. Up to now, several studies considered the thermodynamic and thermoeconomic parameters as the multiobjectives in the optimization procedures [13-17]. This study aims to apply the multiobjective optimization procedure to an LNG cold utilized micro-cogeneration system by using the thermodynamic and thermoeconomic parameters as the multiobjectives. The net generated power rate, the exergetic efficiency, and the levelized product cost are taken into account in the study. The optimization study is applied for different ambient air temperature and relative humidity values which have ranges between 288.15 K-313.15 K and 50%-90%, respectively.

II. SYSTEM DESCRIPTION

The LNG cold utilized micro-cogeneration system is presented in Fig.1. The LNG is pumped to the LNG vaporizer by an LNG pump, then the vaporized natural gas, stream 3, enters to the combustion chamber of the microturbine that is selected as Capstone C30 model with the pressure ratio of 3.64. The electricity is generated as stream 15, and the exhausted product gas is sent to the heat exchanger for the hot water production that is pointed out as stream 13. The waste heat of the heat exchanger, stream 10, is used in the LNG vaporizer for the regasification of LNG, and the exhausted gas of the total system is shown with system 11.

Figure 1. The simplified schematic of the system.

The detailed thermodynamic and thermoeconomic analyses were studied [7], hence the current study focuses on the optimization case to obtain the optimum operation conditions in the real engineering applications. More details on the design and analysis steps can be found in our former study [7]. In the study, the LNG price and the interest rate are selected as 7.39133×10^{-5} \$/kJ [18] and 0.43% [19], respectively.

III. MODELING

A. Thermodynamic Modeling

Thermodynamic modeling is based on the energetic and exergetic terms. The energetic part includes the first law analyses whereas the exergetic part focuses on the second law terms. In the optimization case, the net generated power rate and the exergetic efficiency are selected as the objective functions of the energetic and exergetic parts, and they are shown as Eqs. (1) and (2), respectively,

$$\dot{W}_{net} = \dot{W}_{Gas\ Turbine} - \dot{W}_{Compressor} - \dot{W}_{LNG\ Pump} \quad (1)$$

$$\varepsilon = \dot{E}_P / \dot{E}_F \quad (2)$$

The details of the energetic and exergetic calculations of the presented system are able to be found in Kanbur et al. [7].

B. Thermoeconomic Modeling

Thermoeconomics simply mean the combination of both thermodynamic and economic parameters for more reliable assessments of the energy conversion systems in the real applications. The levelized product cost is one of the significant assessment criteria in the thermoeconomic studies, thus it is selected as the objective function of the thermoeconomic part in this study. The general definition of the levelized product cost is presented in Eq. (3),

$$\dot{C}_p = \dot{C}_F + \dot{Z}_{TOT} \quad (3)$$

where $\dot{C}_F$ and $\dot{Z}_{TOT}$ are the levelized fuel cost and the levelized total component cost for the overall system, respectively. The levelized fuel cost is obtained by the multiplication of the fuel cost and the fuel exergy rate. The levelized total component cost is related to the unit cost of the components, and it is obtained as shown in Eq. (4).

$$\dot{Z}_{TOT} = [(CRF + C_{OM}) \cdot PEC] / \tau \quad (4)$$

where CRF and C_{OM} are the capital recovery factor and the cost of operation and maintenance, respectively, PEC is the purchased equipment cost of the overall system, and τ is the annual operation time of the system. PEC of the microturbine, and LNG pump are assumed as 1130 \$/kW and 700 \$/kW, respectively [7]. The annual operation time is 8000h. More details on the thermoeconomic modeling can be found in [7]. Thanks to the presented thermoeconomic equations, the exergy-cost matrix of the proposed system can be generated with the general and auxiliary equations, and the unit cost and the relevant levelized costs are able to be calculated.

C. Optimization Modeling

The multiobjective optimization concept is built for the proposed LNG cold utilized micro-cogeneration system. The net generated power rate, exergetic efficiency and the levelized product cost are three main objectives of the multiobjective optimization study. The maximization is aimed for the net generated power rate, and the exergetic efficiency while the minimization is purposed for the levelized product cost. Thus, the multiobjective optimization study is aimed to find the optimum points for these maximization and minimization functions which are shown in Eqs. (5)-(7), respectively,

$$\max[\dot{W}_{net}] \text{ subject to } \begin{cases} 288.15K \leq T_{amb} \leq 313.15K \\ 50\% \leq RH \leq 90\% \end{cases} \quad (5)$$

$$\max[\varepsilon] \text{ subject to } \begin{cases} 288.15K \leq T_{amb} \leq 313.15K \\ 50\% \leq RH \leq 90\% \end{cases} \quad (6)$$

$$\min[\dot{C}_p] \text{ subject to } \begin{cases} 288.15K \leq T_{amb} \leq 313.15K \\ 50\% \leq RH \leq 90\% \end{cases} \quad (7)$$

IV. RESULTS AND DISCUSSIONS

The energetic, exergetic, and thermoeconomic trends of the system are illustrated in Figs. 2a, b, and c, respectively. As seen from Figs. 2a and b, the net generated power rate and exergetic efficiency have similar trends that mean their performances decrease by rising of the ambient air temperature. The relative humidity has also similar impact

on these two thermodynamic assessment parameters, namely, the performances of the net generated power rate and exergetic efficiency rise by increasing of the relative humidity. The detailed analyses are performed for all the parameters in the study. For the net generated power rate in Fig. 2a, the mean decrement is calculated as 14.78% by rising of the ambient air temperature from 288.15 K to 313.15 K. It is also seen that the decrement of the net generated power rate from 90% to 50% increases significantly from 288.15 K to 313.15 K. That is, the decrement from maximum relative humidity to the minimum reaches the maximum value at the highest ambient air temperature. The ambient air temperature and the relative humidity have more significant impacts on the exergetic efficiency than the net generated power rate when Fig. 2b compared to Fig. 2a. The mean decrement from 288.15 K to 313.15 K is 27.61% and the decrement decreases by rising of the relative humidity. Similarly, the difference between the maximum and minimum relative humidity values rises by rising of the ambient air temperature while the average decrement 2.38% in the range between 288.15 K to 313.15 K. The leveled product cost is presented Fig. 2c, and it is seen that the leveled product cost trends decreases by rising of the ambient air temperature and relative humidity like the net generated power rate and exergetic efficiency trends. The decrement of the leveled product cost from 90% RH to 50% RH is smaller than the thermodynamic parameters whereas the mean decrement is calculated as 0.38%.

Figure 2. The results of energetic analysis (a), exergetic analysis (b), and thermoeconomic analysis (c).

The thermodynamic and thermoeconomic analyses infer that the highest ambient air temperature is the desired point for the lower leveled product cost while it is the undesired for the net generated power rate and the exergetic efficiency since their values find the minimum. Both three assessment criteria are important for the thermodynamic and thermoeconomic investigations, thus the optimization study is performed for these parameters as the multiobjective optimization case. The multiobjective optimization is performed with the genetic algorithm, and the Pareto frontier plot gives the optimal points after the solution of the multiobjective functions with genetic algorithms. The optimization procedure presents multiple optimal points, and the decision maker can select the single optimum point or the detected best trade-off region according to the priorities. In the current study, the single point detection is aimed in the multiobjective optimization study.

The first multiobjective optimization study is performed with the net generated power rate and the leveled product cost. The minimization of the leveled product cost and the maximization of the net generated power rate are studied, and the Pareto frontier plot deduces the optimal points for these two objectives in Fig. 3.

Figure 3. The Pareto frontier plot of the leveled product cost and the net generated power rate.

When Fig. 3 is evaluated in detail, it is seen that the relative humidity does not have an impact on the optimal points at the higher levelized product cost and the net generated power rate, but the difference is observed at the low levelized product cost and net generated power rate values. Moreover, the optimal points are closer to one another at the relative humidity of 90% when compared to the relative humidity of 50%. The desired single point is defined as the closest point to the minimum and maximum values of the levelized product cost and the net generated power rate, respectively. To find the desired single optimum point for each relative humidity, the diagonals of the square figure are used, and the optimal points, which coincide to the both diagonals, are determined as the single optimum points for the corresponding relative humidity values. The similar approach is applied for the multiobjective optimization study of the exergetic efficiency and the levelized product cost, and the Pareto frontier is presented in Fig. 4.

The coupled exergetic efficiency and the levelized product cost functions present slightly different optimal trends than the optimal points of the coupled net generated power rate and the levelized product cost functions. Since the levelized product cost are one of the objective functions in both multiobjective optimization study, it can be said that the different trends are occurred due to the difference between the exergetic efficiency and net generated power rate trends. Similar to Fig. 3, the optimal points of the different relative humidity values are closer to one another at the high values of the objective functions which are the exergetic efficiency and the levelized product cost. However, the differences between the optimal points at the different relative humidities increase by decreasing of the objective function values. Therefore, it must be highlighted that if the decision maker wants to select the optimum points at the high objective functions values, the relative humidity changes do not affect its selection while the relative humidity would be an important factor for the selection at the low objective function values. The single optimum point of Fig. 4 is detected with the same method in Fig. 3, and the diagonals of the square figure are used for the determination of the single optimum point for each different relative humidity value.

Figure 4. The Pareto frontier plot of the levelized product cost and the net generated power rate.

The detected single optimum points for different relative humidity values are illustrated in Fig. 5 with respect to the coupled multiobjective functions. For the coupled net generated power rate and the levelized product cost functions, the optimum temperature points are found as 301.62, 301.45, 301.25, 301.33, and 301.44 K at the relative humidity values of 50, 60, 70, 80, and 90 %, respectively. For the coupled exergetic efficiency and the levelized product cost functions, the optimal temperature points are obtained as 301.43, 301.84, 301.83, 302.09, and 302.52 K at the relative humidity values of 50, 60, 70, 80, and 90 %, respectively.

Fig. 5 deduces that the both coupled functions present the optimum points between 301.0 K and 302.5 K for the different relative humidity values. That is to say, this ambient air temperature range is the best operation range of the investigated system from the viewpoints of thermodynamics and thermoeconomics. Fig. 5 also illustrates that there is no relation between the detected optimum points, and the increment in the relative humidity or the ambient air temperature in both coupled multiobjective functions.

Figure 5. The optimum operation points at different relative humidity values for two coupled multiobjective functions.

The present multiobjective optimization study is conducted according to the thermodynamic and thermoeconomic parameters, but there are still some gaps in the optimization step for application in the real engineering studies. For instance, the environmental, enviroeconomic and sustainability parameters may be performed in the multiobjective optimization concept in the further studies in order to have a wider multiobjective optimization concept for the real engineering applications. However, it must be noted that the detection of the best trade-off region would be better choice than the single optimum point detection in the multiobjective optimization step since the different concepts like the environmental, enviroeconomic and sustainability may have different performance trends. Furthermore, the external economic parameters like the fuel price and the interest rate are able to be carried out as the variables in the further multiobjective optimization studies since these two economic parameters may vary according to the applied region of the system like the ambient air temperature and the relative humidity. Also, the system is designed and analyzed for the real operation so that the dynamic parameters like the

momentary changes may be considered in the future multiobjective optimization concepts. Lastly, the multiobjective optimization study can be extended with the lower and higher ambient air temperatures and the relative humidities. The current study presents the optimum values accurately according to the determined ranges and assumed parameters, but the mentioned gaps can make the multiobjective optimization study more feasible for the real operations.

V. CONCLUSIONS

The multiobjective thermoeconomic optimization study was carried out for the LNG cold utilized micro-cogeneration system according to two different coupled functions. The study was conducted in the ranges of 288.15 K-313.15 K and 50%-90% for the ambient air temperature and the relative humidity, respectively. The multiobjective optimization problem was solved with the genetic algorithm, and the optimal points were plotted in the Pareto frontiers. The optimal points of different relative humidity values were found close to one another at the high objective values while the difference could be realized at the low objective values in both coupled multiobjective functions. The single optimum points were selected by using the diagonals of the square figures, and the results showed that the optimum points vary between 301.0 K and 302.5 K for the relative humidity range of 50-90% according to the determined multiobjective functions which were the coupled net generated power rate-levelized product cost, and the exergetic efficiency-levelized product cost, respectively. In order to expand the concept of the multiobjective optimization study, some research gaps were mentioned and suggested for the further studies.

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