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Dynamic exergetic and environmental assessments of the small scale LNG cold utilized micro power generation systems

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Abstract

The present paper investigates the dynamic energetic, exergetic and environmental performances of two different small-scale LNG cold utilized micro-cogeneration systems under the different climate conditions. The hourly weather data are collected for Singapore, and the dynamic simulations are performed according to the hourly data for each month. Three sessions are determined for the investigations which are the morning, midday and evening sessions. Both designs have their lowest power generation rates at the midday session. The power generation and the exergetic efficiency of the Stirling engine have opposite trend against to the overall power rate of system. The maximum energetic efficiency values are at the midday session while the exergetic efficiencies reach their lowest values at the same session. The environmental analyses show that the emission reductions range between 6.8 and 7.7% when two designs are compared, and the highest emission reduction is obtained at the midday session.

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Keywords: Dynamic modeling; exergy analysis; LNG cold energy; environmental analysis; micro power generation.

1. Introduction

Small-scale LNG regasification processes have been gaining importance in the recent years since they are one of the alternative ideas for more feasible, efficient and sustainable LNG regasification method [1]. Especially for the

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inland and stranded areas in the LNG importer countries, small-scale systems can be good method to vaporize the LNG without complex pipeline grids or large-scale systems. During the small-scale LNG vaporization, the LNG cold energy can also be utilized in the systems like in the large-scale LNG cold utilization systems. There are few studies on the small-scale LNG cold utilization process in the literature although many different configurations were proposed for the large-scale systems which were summarized by Romero Gomez et al. [2]. Our group has been studying on the small-scale LNG cold utilization idea to improve the feasibility of these systems in the LNG importer countries, and we believe that the small-scale LNG cold utilization will be more popular in the near future by rising the LNG usage in the LNG importer countries with the technological developments. Up to now, steady-state analyses were conducted for the small-scale LNG cold utilized power generation systems in our group to investigate their energetic, exergetic, environmental, and thermoeconomic performance against to the conventional natural gas fuelled small-scale power generation systems [3,4]. This study aims to improve the investigation of the small-scale LNG cold utilization systems for real life engineering operations so that the dynamic modeling is applied to see the hourly performance trends of the systems in Singapore as an example of the LNG importer country. Dynamic modeling and analyses are efficient methods to see the peak and bottom points during the operation according to the real-life data so that the improvement studies can be performed for hourly, daily, weekly or monthly parameters as Yoru et al. [5] and Campos-Celador et al. [6] studied the dynamic modeling and analyses in their large-scale cogeneration system and micro-cogeneration integrated building energy simulation system, respectively.

2. System Description

Two different small-scale LNG cold utilized micro-cogeneration systems are studied as shown in Fig. 1. The first system that is shown in Fig. 1a vaporized the LNG in the LNG vaporizer by using the exhausted gas of the micro-cogeneration system (stream 10), hence the outlet temperature of the exhausted stream (stream 11) is decreased. A micro-turbine system and an integrated heat exchanger are the main parts of the micro-cogeneration system. The power is generated only from the micro-turbine system so that the system is called as the single system. More details on the system definition and assumptions can be found in Ref. [3]. The second system is called as combined cycle since the Stirling engine and micro-turbine are combined together as illustrated in Fig. 1b. The LNG vaporization occurs in the LNG vaporizer thanks to the thermal-fluid loop between the vaporizer and the cold end of the Stirling engine. Detailed descriptions for the combined cycle with the required assumptions can be found in Ref. [4].

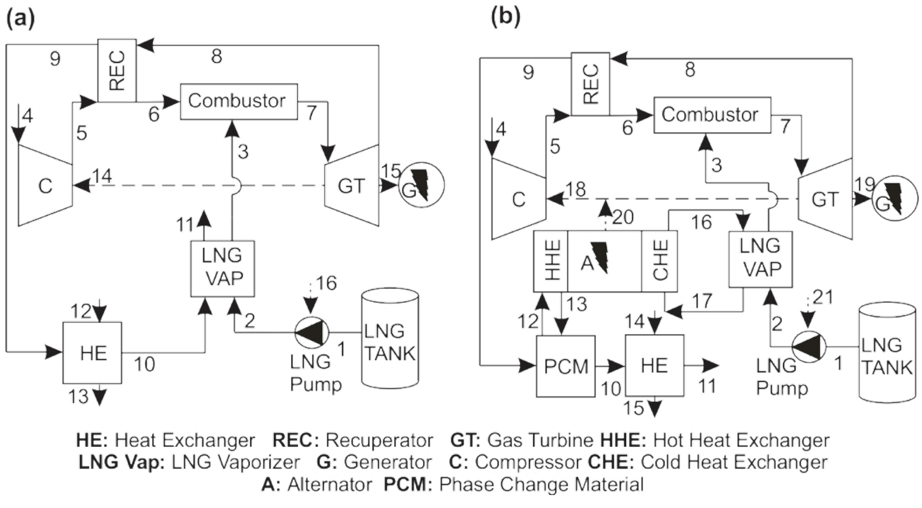

Fig. 1. The simplified schematics of the (a) single system; (b) combined system.

The required data for the dynamic simulations are the ambient air temperature and the relative humidity so that the climate data for Singapore are collected according to the average of last five years (2012-2016) [7]. The data are collected between 8:00 am and 8:00 pm of the 15th day of each month. Therefore, it is possible to see the dynamic simulations of the systems according to hourly data for all the months in one year. Table 1 presents the climate data for Singapore as mean temperature and relative humidity in the last five years.

Table 1. The mean ambient air temperature and relative humidity data for Singapore.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)	T (C)- RH (%)
08:00	25.6- 86.6	25.6- 87.4	26.2- 86.8	27.4- 88.0	28.2- 86.0	28.4- 86.0	27.4- 85.0	28.0- 82.0	27.2- 83.0	27.0- 89.2	26.8- 85.8	26.8- 86.0
09:00	26.6- 82.6	26.6- 84.8	27.2- 82.8	28.0- 81.0	29.2- 82.0	29.2- 77.2	28.4- 81.0	28.6- 78.0	28.0- 78.2	28.0- 80.4	28.2- 81.0	28.0- 79.4
10:00	28.0- 77.0	28.0- 78.0	28.4- 78.0	29.2- 75.4	30.2- 77.2	30.0- 74.4	29.0- 79.0	28.6- 78.0	29.2- 74.6	29.6- 72.8	29.2- 74.4	28.8- 78.6
11:00	29.0- 72.6	29.0- 72.6	29.6- 70.4	31.2- 67.0	30.8- 73.4	29.8- 75.8	29.4- 76.2	29.8- 73.6	30.0- 72.6	29.8- 71.0	29.8- 71.0	30.0- 71.8
12:00	29.8- 69.6	29.8- 67.6	30.4- 67.8	31.8- 65.0	30.2- 76.0	30.0- 72.8	30.0- 73.6	29.8- 71.6	28.2- 74.8	31.2- 65.2	30.6- 69.6	30.6- 67.8
13:00	31.0- 63.8	31.2- 63.0	31.2- 62.4	31.6- 65.8	30.0- 74.6	30.2- 72.0	30.0- 71.6	30.8- 66.2	28.2- 72.6	32.0- 60.0	29.8- 73.2	31.2- 65.4
14:00	30.6- 66.0	32.0- 61.0	32.0- 59.6	31.6- 67.0	30.6- 74.2	31.2- 67.0	30.6- 69.2	31.0- 65.6	29.6- 69.8	32.4- 56.6	30.0- 70.4	31.8- 63.4
15:00	30.8- 64.0	31.6- 61.6	31.8- 60.6	32.0- 66.4	31.0- 71.6	31.6- 62.6	30.4- 67.6	31.0- 65.2	29.6- 71.4	32.2- 57.2	30.2- 71.4	31.6- 65.4
16:00	30.4- 64.8	30.9- 66.0	32.2- 59.6	32.0- 64.2	31.0- 70.6	32.2- 61.2	30.0- 70.0	31.0- 67.0	29.4- 72.8	32.2- 57.8	30.4- 69.6	31.0- 67.8
17:00	29.8- 66.4	29.8- 69.8	32.0- 58.6	32.0- 62.4	30.6- 72.6	32.0- 60.0	30.0- 71.0	30.6- 66.0	29.4- 71.8	32.0- 57.8	30.0- 69.4	29.2- 72.8
18:00	30.0- 65.8	29.0- 73.4	31.2- 62.4	31.8- 62.6	30.4- 73.8	31.6- 62.4	30.0- 70.0	29.6- 69.6	28.8- 77.0	31.4- 61.0	28.8- 77.2	28.6- 77.0
19:00	29.4- 67.4	28.2- 76.2	30.2- 66.8	30.6- 70.4	30.0- 74.6	30.8- 66.4	29.4- 73.8	29.6- 71.4	28.0- 81.4	30.6- 67.2	28.0- 80.8	28.4- 78.6
20:00	28.4- 72.0	27.6- 79.2	29.0- 71.6	30.0- 74.4	29.4- 79.6	30.2- 68.8	28.8- 75.4	29.0- 76.4	27.4- 84.2	30.2- 68.6	27.8- 82.0	27.8- 79.4

The main assumptions can be briefly mentioned. The compressor pressure ratio is 3.64 for both systems. The LNG is assumed 100% methane, and the related chemical features are used according to methane properties. The heat losses in the heat exchangers are negligible so that the heat loss is only considered for the combustion chamber. More details and assumptions on the system operations can be found in Refs. [3] and [4] for the single and combined systems, respectively.

3. Modeling

Thermal and environmental aspects are considered during the dynamic modeling of the presented systems. The energetic and exergetic approaches are the parts of thermal modeling while the environmental modeling is based on the exhausted carbon dioxide rate. The energetic modeling includes the net generated power rates and energetic efficiencies of the single and combined cycles, respectively. Exergetic efficiencies of the single and combined systems are the main parts of the exergetic modeling. Also, the power generation rate and the exergetic efficiency of the Stirling engine are calculated under the energetic and exergetic modeling parts, respectively. The net power generation rates of the single and combined systems are given in Eqs. (1) and (2), respectively. The power generation rate of Stirling engine ($\dot{W}_{20}$) depends on the engine characteristics such as reversibility factor, polytropic states, etc., and the detailed calculations can be found in Ref. [4]. The energetic efficiencies of the single and combined systems are presented in Eqs. (3) and (4), respectively,

$$\dot{W}_{net,single} = \dot{W}_{15} - \dot{W}_{14} - \dot{W}_{16} \tag{1}$$

$$\dot{W}_{net,combined} = \dot{W}_{19} + \dot{W}_{20} - \dot{W}_{18} - \dot{W}_{21} \tag{2}$$

$$\eta_{single} = \left(\dot{W}_{net,single} + \dot{Q}_{HE,single}\right)/\dot{Q}_{in,single} \tag{3}$$

$$\eta_{combined} = \left(\dot{W}_{net,combined} + \dot{Q}_{HE,combined}\right)/\dot{Q}_{in,combined} \tag{4}$$

where $\dot{W}_{net}$ and η denote the net power generation rate and the thermal efficiency, respectively; $\dot{Q}_{HE}$ and $\dot{Q}_{in}$ are the thermal energy production from the heat exchanger, and the inlet energy rate of the overall systems, respectively. Details on the $\dot{Q}_{HE}$ and $\dot{Q}_{in}$ can be found in Ref. [3] and [4] for the single and combined systems, respectively. The exergetic efficiencies of the single system, combined system, and Stirling engine are shown in Eqs. (5)-(7), respectively,

$$\varepsilon_{single} = \dot{E}_{P,single}/\dot{E}_{F,single} \tag{5}$$

$$\varepsilon_{combined} = \dot{E}_{P,combined}/\dot{E}_{F,combined} \tag{6}$$

$$\varepsilon_{Stirling} = \dot{E}_{P,Stirling}/\dot{E}_{F,Stirling} \tag{7}$$

where ε denotes the exergetic efficiency; $\dot{E}_P$ and $\dot{E}_F$ are the product and fuel exergy rates, respectively. The details of the exergy analyses of the single and combined systems can also be found in Refs. [3] and [4], respectively. The carbon dioxide emission rate of the presented systems are calculated by using the carbon dioxide component in the exhausted gas, and the emission rate is defined the emitted carbon dioxide per generated energy as shown in Eqs. (8) and (9) for the single and combined systems, respectively,

$$\varsigma_{single} = \left(x_{CO_2}^{P} \cdot \dot{n}_p \cdot M_{CO_2}\right)/\dot{W}_{net,single} \tag{8}$$

$$\varsigma_{combined} = \left(x_{CO_2}^{P} \cdot \dot{n}_p \cdot M_{CO_2}\right)/\dot{W}_{net,combined} \tag{9}$$

where ς denotes the carbon dioxide emission rate; $x_{CO_2}^{P}$ is the molar fraction of the carbon dioxide in the exhausted gas; $\dot{n}_p$ and M_{CO_2} are the molar flow rate of the exhausted gas, and the molar mass of the carbon dioxide, respectively. The dynamic analyses are performed by calculating these thermal and environmental parameters for each hour of the day in the determined period for all the months in a year. The hourly data are divided in three parts as the morning, midday, and evening sessions in a day to be evaluated efficiently.

4. Results and Discussion

The energetic and exergetic analyses of the single and combined systems are presented in Fig.2. Figs.2a and b illustrate the dynamic results of the power generation rates for the single and combined systems. Both systems have similar trends according to the hourly data in all the months. The peak values are observed in the morning session for both systems while the midday session has the lowest power generation rates. Although the power generation rates increase during the evening session, they are not as high as the power generation rates in the morning session. When the dynamic analyses are investigated for the monthly results, the lowest power generation rates are obtained in February, May and October so that it is possible to say that the power generation rate does not depend on the seasons in Singapore since the country is in the tropical region, and the climate data are roundly steady in all the periods in a year. For the peak power generation rates, January has the highest power generation performance, and it is followed by October, November, and December. That is, the middle of the year is less feasible than the beginning and end of the year. The power generation differences between the single and combined systems are related to the Stirling engine performance that ranges between 1.94 and 2.08 kW during the whole year. The energetic efficiencies for the single and combined systems are shown in Figs. 2c and d, respectively. It is realized that the energetic efficiency has completely opposite trends with the power generation rates. The middle of the year is the best monthly period, and the midday session is the peak session for the energetic efficiency. However, there is no big differences are observed between the single and combined systems from the point of energetic efficiency in the peak regions while the combined system provides better energetic efficiency than the single system in the regions where the lowest values are observed. When the exergetic efficiencies are investigated, it is seen that the exergetic efficiency trends are nearly the same and opposite with the power generation rates and the thermal efficiency trends as shown in Figs. 2e and f, respectively. The opposite trends between two efficiency definitions show the importance of the exergy destruction and loss terms. It is also seen that the integration of Stirling engine increased the exergetic efficiency. The highest exergetic efficiency increment is observed at the evening session of December with meanly 6.5% while the smallest increment is at the midday session of June with 1.4%.

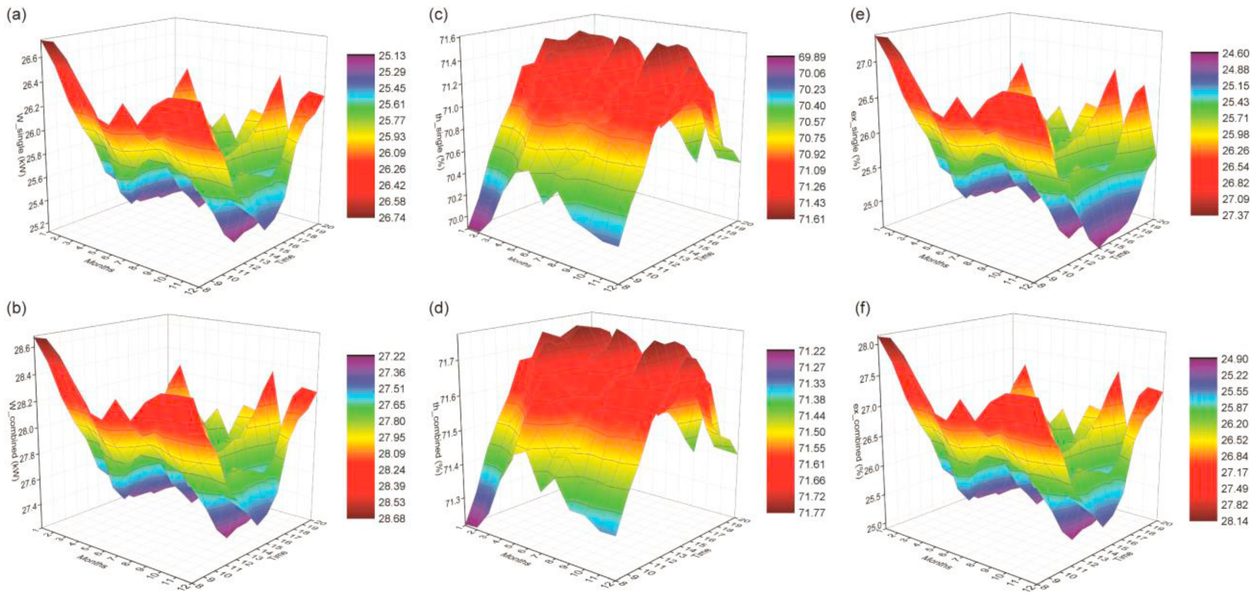

Fig. 2. Thermal analyses of the systems: (a) single-power generation; (b) combined-power generation, (c) single-energetic efficiency; (d) combined-energetic efficiency, (e) single-exergetic efficiency; (f) combined- exergetic efficiency.

The Stirling engine increases the power generation rate and the exergetic efficiency in the combined system. Fig. 3a illustrates the dynamic performance trends of the exergetic efficiency of Stirling engine. It is inferred that the Stirling engine trends are similar with the overall energetic efficiency trends, and the peak exergetic efficiency is observed at the midday session for all the months. Also, the maximum Stirling engine data are obtained at the middle of the year. The exergetic efficiency ranges between 34 and 35.6%, and the lowest values are at the morning session of January. The emission results are presented in Figs. 3b and c for the single and combined systems, respectively. It can be said that the performance trend of the Stirling engine significantly affects the carbon dioxide emission trend of the combined system when the emission trends of the single and combined systems are compared. In general, it is realized that the midday session has the highest emission rate, but there are no significant differences observed between the monthly performances for the single and combined systems. The combined cycle decreases the emissions which range between 6.8 and 7% during the yearly period.

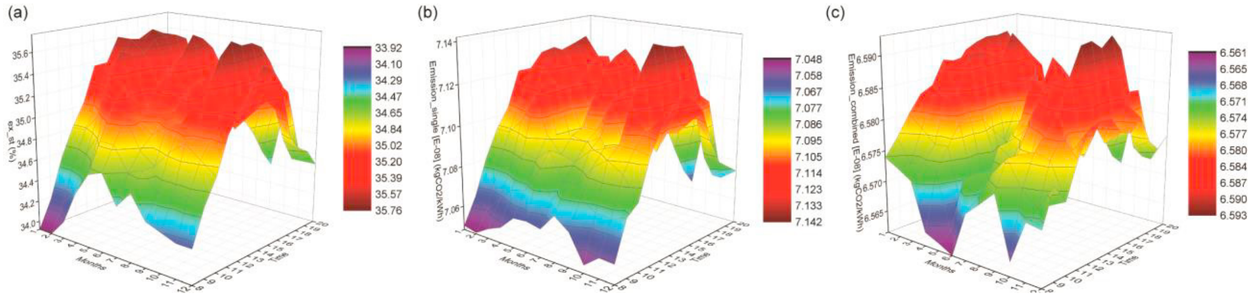

Fig. 3. Results for the (a) exergetic efficiency of the Stirling engine; (b) single system emission rates; (c) combined system emission rates.

5. Conclusions

The dynamic simulations of the single and combined small-scale LNG cold utilized systems were performed according to the thermal and environmental parameters for Singapore by using the average climate data of the last five years. The results showed that the power generation rate and exergetic efficiency of the systems had similar trends while they had opposite trends with the energetic efficiencies and emission rates of the overall systems, and the exergetic efficiency of the Stirling engine. The midday session was the worst session in the hourly simulation for the power generation rates, exergetic efficiencies, and emission rates while it was the most convenient session for the energetic efficiencies of overall systems, power generation rate and exergetic efficiency of Stirling engine. It was also seen that the Stirling engine performance affected the emission reductions between the single and combined systems. The emission reduction ranged between 6.8 and 7% during the yearly period. Although the dynamic simulation presented the useful data for the application of the small-scale LNG cold utilization systems, it also showed that the gaps which are still not filled. The opposite trends between the assessment criteria make difficult to determine the best operation points of the presented system so that the future studies will focus on the optimization strategies which will try to determine the most convenient operation values.

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