# A micro cogeneration system with LNG cold utilization-part 2 : exergy analyses

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

2017

Kanbur, B. B., Xiang, L., Dubey, S., Hoong, C. F., & Duan, F. (2017). A micro cogeneration system with LNG cold utilization-part 2 : exergy analyses. Energy Procedia, 105, 1910-1917. doi:10.1016/j.egypro.2017.03.559

https://hdl.handle.net/10356/89921

https://doi.org/10.1016/j.egypro.2017.03.559

---

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 1910 – 1917

Energy
Procedia

The 8th International Conference on Applied Energy – ICAE2016

# A micro cogeneration system with LNG cold utilization-part 2: exergy analyses

Baris Burak Kanbur[a,c], Liming Xiang[b], Swapnil Dubey[a], Choo Fook Hoong[a], Fei Duan[c] *

*[a]Energy Research Institute@NTU, Interdisciplinary Graduate School, Nanyang Technological University, Singapore, 637141*
*[b]School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore, 637371*
*[c]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798*

## Abstract

Exergy analyses provide to investigate the available work performance of thermal cycles. In this study, exergy analyses have been conducted for the conventional micro-cogeneration system and the Liquefied Natural Gas (LNG) cold utilized micro cogeneration system, respectively to detect exergy destruction and loss ratios which are related to second law analyses. In the LNG cold utilized micro-cogeneration system, the exhausted gas of micro turbine is supplied to the LNG vaporizer to change the phase of LNG from liquid to gas. Due to fact that exergy destruction and loss rates, exergetic efficiency decreases with the ambient air temperature increment by nearly 28%. Owing to the application of exhausted gas in the LNG vaporizer in the LNG cold utilized micro-cogeneration system, the exergy loss ratio decreases by approximately 81% when it is compared to the conventional micro-cogeneration system. At the same time, the exhausted gas temperature decreases nearly 2.93 K. Exergy destruction ratio is another evaluation criterion for exergy analyses and it is seen that the combustion chamber had a significant impact on the overall exergetic performance of both systems. The minimum exergy destruction rate belongs to the LNG pump and also the LNG vaporizer does not have a significant exergy destruction ratio.

*Keywords:* LNG cold energy, Cogeneration, Combined heat and power, Economic analysis, Environmental analysis, Exergy analysis.

## Nomenclature

| | |
|---|---|
| $\bar{e}$ | Specific exergy, (kJ/kg) |
| $\dot{E}$ | Exergy rate, (kJ/s) |
| $\bar{h}$ | Specific enthalpy, (kJ/kg) |

---

* Corresponding author. Tel.: +65 6790 5510; fax: +65 6792 4062.
*E-mail address:* feiduan@ntu.edu.sg

doi:10.1016/j.egypro.2017.03.559

| | |
|---|---|
| $\dot{n}$ | Molar flow rate, (kmol/s) |
| $P$ | Pressure, (bar) |
| $\bar{R}$ | Universal gas constant, (kJ/kmolK) |
| $\bar{s}$ | Entropy, (kJ/kmolK) |
| $T$ | Temperature, (K) |
| $x$ | Molar fraction, (- or %) |
| $y$ | Exergy ratio, (- or %) |
| *Greek letters* | |
| $\varepsilon$ | Exergetic efficiency, (%) |
| *Superscripts* | |
| $CH$ | Chemical |
| $M$ | Mechanical |
| $PH$ | Physical |
| $T$ | Thermal |
| *Subscripts* | |
| $0$ | Dead state |
| $comp$ | Component |
| $D$ | Destruction |
| $F$ | Fuel |
| $k$ | Chemical content |
| $L$ | Loss |
| $in$ | Input |
| $mt$ | Micro turbine |
| $net$ | Net generated |
| $p$ | Product |
| *Abbreviations* | |
| LNG | Liquefied natural gas |

## 1. Introduction

Exergy is a thermodynamic definition that includes entropy related terms so that it is possible to calculate the maximum available work by using exergy analyses instead of energy analyses [1,2]. Up to now, exergy analyses have been applied to some gas turbine based LNG cold utilization systems at different power generation capacities which were large scale power generation systems [3-5]. Exergy destruction and loss can be detected easily by using the exergy analysis that allows determining the key components to increase overall efficiency. In this paper, exergy analyses of the conventional micro-cogeneration system and the LNG cold utilized micro-cogeneration system are investigated.

## 2. Modeling

The simplified schematic is presented in Fig 1(a, b) for the conventional micro-cogeneration system and the LNG cold utilized micro-cogeneration system, respectively. Streams 1 and 2 denote the LNG in the atmospheric condition and the LNG pump outlet, respectively. Stream 3 is the vaporized natural gas. Stream 4 is the ambient air and the stream 5 is the compressed air after the compression process. The compressed air is also heated by the exhausted gas (stream 8) and it enters to the combustion chamber as stream 6. Streams 7 and 9 are the combustor and recuperator outlets, respectively. Stream 10 is the exhausted gas from the cogeneration system to the environment. The water enters to the heat exchanger as stream 11 and leaves as hot water, stream 12.

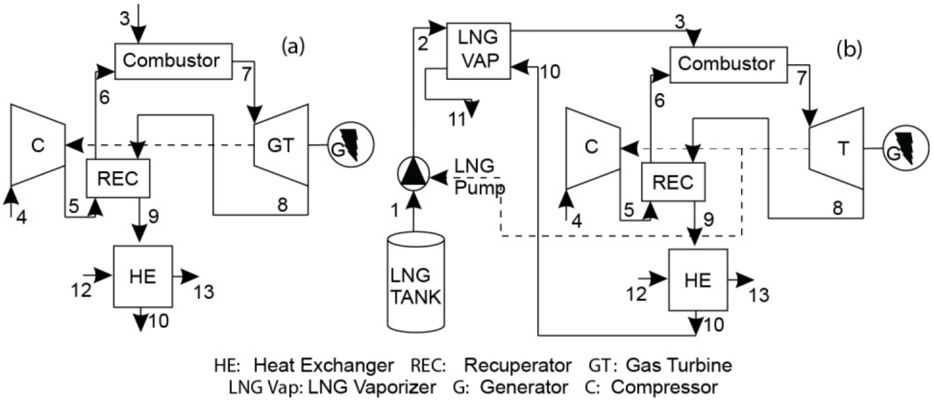

Fig.1: Simplified schematic of (a) conventional micro-cogeneration system and (b) LNG cold utilized micro-cogeneration system.

The conventional micro-cogeneration system includes a compressor, a recuperator, a combustion chamber, coupled gas turbine/generator and a heat exchanger. The micro-cogeneration system has 30 kW capacity and its design is based on Capstone C30 model. For the conventional system, natural gas is supplied to the combustion chamber and it is burnt with the air which comes from the recuperator. The supplied air first compressed in the compressor and its pressure is increased and then it is heated by the exhausted gas of micro turbine in the recuperator. Gas turbine and generator couple produced electricity by using high pressure gas mixture. The heat exchanger is used to producing hot water. In Fig 1b, LNG cold utilization components are integrated to the conventional micro cogeneration system. LNG is at atmospheric conditions in the LNG tank and it is pressurized by the LNG pump before sent to the LNG vaporizer. LNG is vaporized by using the exhausted heat of gas mixtures from the micro-cogeneration system.

Bejan et al. [6] proposed exergy analysis model for gas turbine cogeneration system. For the conventional micro cogeneration case, the proposed method is applied. In this method, chemical and physical exergies are considered while kinetic, potential and radiation exergy terms are neglected. The specific physical and chemical exergy definitions are presented in Eqs.(1) and (2), respectively.

$$\bar{e}^{PH} = \bar{h}(T,p) - \bar{h}(T_0,p_0) - T_0[\bar{s}(T,p) - \bar{s}(T_0,p_0)] \tag{1}$$

$$\bar{e}^{CH} = \sum x_k \bar{e}_k^{CH} + \bar{R}T_0 \sum x_k \ln x_k \tag{2}$$

where $\bar{e}^{PH}$ and $\bar{e}^{CH}$ are the specific physical and chemical exergy definitions, respectively, $\bar{h}(T,p)$ and $\bar{s}(T,p)$ denote the specific enthalpy and the specific entropy of the stream at corresponding temperature and pressure, $\bar{h}(T_0,p_0)$ and $\bar{s}(T_0,p_0)$ are the specific enthalpy and the specific entropy of the dead state, $T_0$ is the dead state temperature that is also equal to ambient air temperature. In Eq.(2), $x_k$ and $\bar{e}_k^{CH}$ are the molar fraction and the standard molar chemical exergy of chemical contents of the air and product gas, $\bar{R}$ is the universal gas constant. Due to fact that both systems include combustion in the combustion chamber, enthalpy of formation and absolute entropy are also considered in the calculations of specific enthalpy and specific entropy of. For the exergy analyses of LNG cold utilization components, Morosuk and Tsatsaronis' proposed method [7] are performed in the LNG pump and the LNG vaporizer. They proposed to divide the specific physical exergy into two components as thermal and mechanical to see the accurate exergetic performances of the LNG pump and the LNG vaporizer. It is known that LNG enters to the vaporizer as cryogenic liquid and exits as vaporized natural gas which means inlet side of the LNG vaporizer is below 0°C while the outlet side is above 0°C. Thus, thermal and mechanical components show different behaviors. By calculating these two components separately, exergetic investigations become more accurate. The specific thermal and the specific mechanical components of the physical exergy are shown in Eqs.(3) and (4).

$$\bar{e}^T = \bar{h}(T,p) - \bar{h}(T_0,p) - T_0[\bar{s}(T,p) - \bar{s}(T_0,p)] \tag{3}$$

$$\bar{e}^M = \bar{e}^{PH} - \bar{e}^T \tag{4}$$

where $\bar{e}^T$ and $\bar{e}^M$ denote the thermal component and the mechanical component of the specific physical exergy. Total exergy rate of the stream is found by multiplying the molar flow rate of the stream with its summarized specific exergy values in Eq.(5).

$$\dot{E} = \dot{n}[(\bar{e}^T + \bar{e}^M) + \bar{e}^{CH}] = [(\dot{E}^T + \dot{E}^M) + \dot{E}^{CH}] \tag{5}$$

After the exergy rate calculation of the stream, exergetic performances of the system components are performed. According to the second law of thermodynamics, each thermal process produced entropy which means some amount of the exergy is destructed during the energy transfer. Moreover, if the thermal system has any heat loss, exergy loss is also occurred. Thus, it is known that the produced exergy is always smaller than the supplied exergy. The produced and the supplied energy are known as the product exergy and the fuel exergy, respectively. The exergy balance equation for the thermal system is written as Eq.(6).

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{6}$$

where $\dot{E}_F$, $\dot{E}_P$, $\dot{E}_D$ and $\dot{E}_L$ are exergy of the fuel, exergy of the product, the exergy destruction, and the exergy loss, respectively. By using these terms, exergy analyses of mentioned these two systems are conducted according to three parameters as exergetic efficiency, exergy loss and exergy destruction ratio. Exergetic efficiency and exergy destruction ratio terms are defined in Eq. (7) and (8), respectively.

$$\varepsilon = 1 - [(\dot{E}_D + \dot{E}_L)/\dot{E}_F] = \dot{E}_P/\dot{E}_F \tag{7}$$

$$y_{D,comp} = \dot{E}_{D,comp}/\dot{E}_F \tag{8}$$

where $y_{D,comp}$ is exergy destruction ratio of the system component, $\dot{E}_{D,comp}$ is exergy destruction rate of the system component, and $\dot{E}_F$ is the total fuel exergy rate of overall cycle. The exergetic efficiency and the exergy destruction ratio can also be calculated for the overall cycle.

## 3. Results and Discussions

As mentioned in Section 2, the heat transfer in the LNG vaporizer affects the thermal component and the mechanical component of the specific physical exergy. Fig. 2(a,b) presents the behaviors of these components at streams 2 and 3, respectively. The presented data is calculated at compressor pressure ratio

3.64 that is the actual pressure ratio of the micro gas turbine system in the real life applications. Moreover, the vaporized gas calculations are done according to 298.15K temperature.

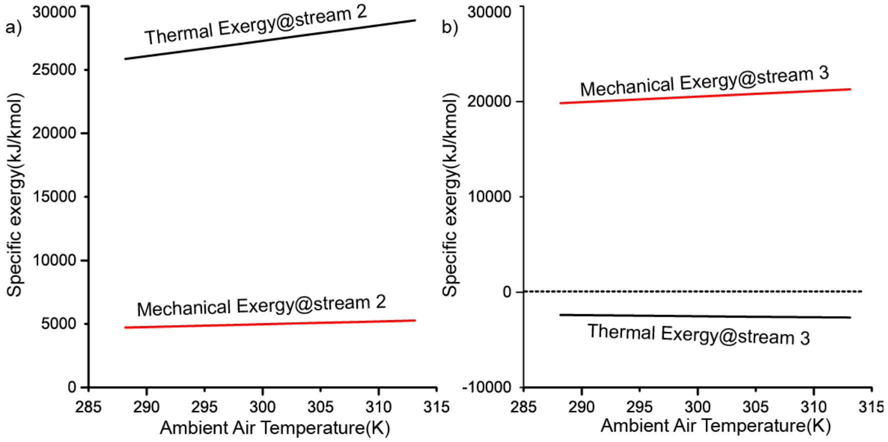

Fig.2: Thermal and mechanical components of specific physical exergy (a) stream 2 and (b) stream 3.

It is seen that the thermal component of the physical exergy increases in stream 2 while it decreases in stream 3 by the rising of ambient air temperature. Also, the thermal component of the specific physical exergy drops dramatically during the phase change in LNG vaporizer. These results prove that LNG vaporizer provides to thermal component usage of the physical exergy of the LNG while expansion systems such as a turbine, etc. provide only the mechanical component usage of the specific physical exergy. Overall exergetic performance can be seen in Fig. 3 with the related energetic efficiency.

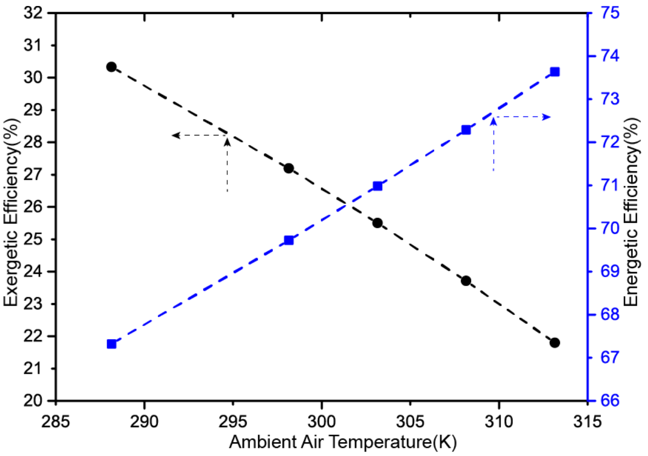

Fig.3: Exergetic and energetic efficiency of LNG cold utilized micro-cogeneration system.

When it is compared to the energetic efficiency, exergetic efficiency shows a contrary trend. It decreases nearly by 28% while the energetic efficiency increases more than 8.5%. Exergy destruction and loss rates are the main reason for this contrary situation. Due to fact that the energy efficiency does not include destruction and loss terms, the effect of these two terms are only seen in exergy efficiency terms. The exergy loss shows the useful exergy that could not be evaluated in the system. Fig. 4 presents the exergy loss and exhausted gas mixture temperature from the system together according to various ambient air temperatures.

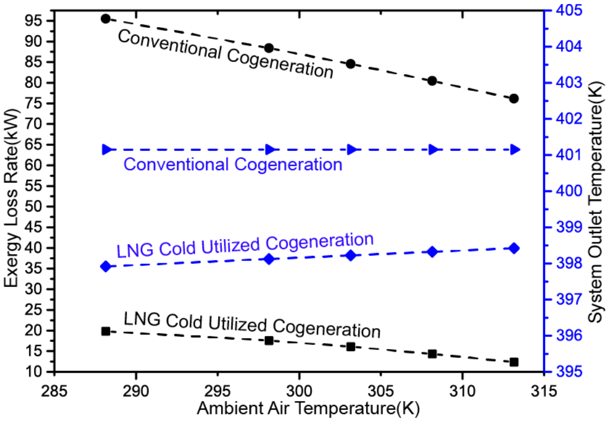

Fig.4: Exergy loss and outlet temperature values of both micro-cogeneration systems.

As it can be obtained from Fig. 4, exergy loss rate decreases by the rising of ambient air temperature in both cases. However, it is also significant to know that the exergy loss rate drops dramatically when exhausted gas is applied to the LNG vaporizer for LNG cold utilization. The decrement is nearly 81% with the ambient air temperature range between 288.15 K and 313.15 K. Beside exergy loss rate, the outlet temperature of the exhausted gas also changes. Due to fact that the exhausted gas is applied to the LNG vaporizer, the outlet temperature is approximately decreased 2.93 K when it is compared to the exhausted gas temperature of the conventional micro-cogeneration system. Lastly, exergy destruction ratios of system components are investigated and the results are shown in Fig 5.

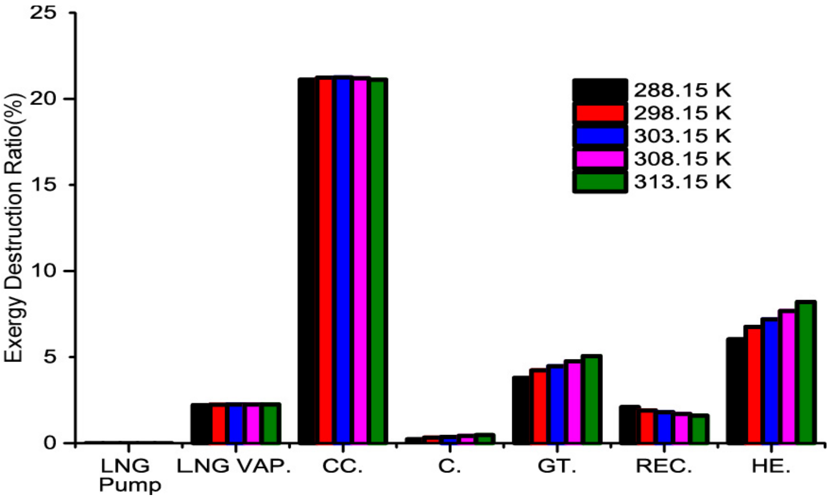

Fig.5: Exergy destruction ratio values (%) of LNG cold utilized micro-cogeneration system.

As seen in Fig. 5, the LNG pump has the lowest exergy destruction ratio and it is followed by the compressor. In both components, exergy destruction ratio increase with the ambient air temperature increment but values are not significant for the evaluation of overall system. The exergy destruction ratio of the LNG vaporizer is nearly the same in various ambient air temperatures and the mean value is nearly 2.24%. The heat exchanger and the gas turbine have positive trends while the exergy destruction ratio of the recuperator decreases by the rising of ambient air temperature. Mean values are less than 5% in the gas turbine and the recuperator. However, the heat exchanger has the second highest exergy destruction ratio. Beside all these component analyses, the combustion chamber is the most significant component due to its dramatically high exergy destruction ratio. For various ambient air temperatures, it is seen that the exergy destruction ratio has its maximum points at 303.15 K. The mean exergy destruction ratio is 21.18% and it is showed that combustion chamber is the most important component to increase exergetic efficiency of the LNG cold utilized micro cogeneration system. By the exergy analyses of this system, it is learned that the LNG vaporizer and the LNG pump do not significantly affect the overall gas turbine system and the combustion chamber is still the most crucial component from the point of the exergy destruction and the exergetic efficiency like in other conventional gas turbine systems.

## 4. Conclusions

Two micro cogeneration cycles were defined as a conventional micro-cogeneration system and a LNG cold utilized micro-cogeneration system respectively. The LNG pump and the LNG vaporizer were the components of the LNG cold utilization system that was embedded into the conventional micro-cogeneration system. Exergy analyses were applied to these two cycles and they were investigated according to three parameters as exergetic efficiency, exergy loss rate, and exergy destruction ratio, respectively. It is seen that exergetic efficiency of both cycles were nearly the same and they decreased by 28% with ambient air temperature increment. These trends were contrary to the energy efficiency trends according to ambient air temperature parameters. The conventional micro-cogeneration system had higher exergy loss rate than the LNG cold utilized micro-cogeneration system due to fact that exhausted gas from the micro turbine was used in LNG vaporizer in the LNG cold utilized system. Therefore, the exergy loss ratio was decreased by 81%. Besides, the outlet temperature of exhausted gas was dropped nearly 2.93 K. Combustion chamber had the highest exergy destruction ratio with meanly 20% rate. It is suggested that improvement studies must be mainly based on combustion chamber to decrease exergy destruction and increase exergetic efficiency. Moreover, it is seen that LNG vaporizer and LNG pump did not have a significant impact on exergy destruction ratio.

## Acknowledgement

The work was funded under the Energy Innovation Research Programme (EIRP, Award No. NRF2013EWT-EIRP001-017), administrated by the Energy Market Authority (EMA). The EIRP is a competitive grant call initiative driven by the Energy Innovation Programme Office and funded by the National Research Foundation (NRF).

## References

[1] Dincer I, Rosen MA. *Exergy: energy, environment and sustainable development*. Oxford(UK):Elsevier Science; 2013.

[2] Cengel YA, Boles MA. *Thermodynamics: an engineering approach.* 5th ed. Boston:McGraw-Hill; 2006.

[3] Arsalis A, Alexandrou A. Thermoeconomic modeling and exergy analysis of a decentralized liquefied natural gas fueled combined cooling-heating and power plant. *J Nat Gas Sci Eng* 2014;**21**:209-20.

[4] Tsatsaronis G, Morosuk T. Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas. *Energy* 2010;**35**:820-9.

[5] Kaneko K, Ohtani K, Tsujikawa Y, Fujii S. Utilization of cryogenic exergy of LNG by a mirror gas turbine. *Appl Energ* 2004;**79**:355-69.

[6] Bejan A, Tsatsaronis G, Moran MJ. *Thermal design and optimization*. NY:Wiley;1996.

[7] Morosuk T, Tsatsaornis G, Comparative evaluation of LNG-based cogeneration systems using advanced exergetic analysis. *Energy* 2011;**36**:3771-8.

## Biography

Mr. Kanbur, M.Sc., is currently Ph.D. Candidate at Energy Research Institute, NTU, Singapore. He received his B.Sc. and M.Sc. from Yildiz Technical University, Turkey. Thermoeconomic analysis and optimization are his current research topics. Dr. Duan is Associate Professor at NTU, Singapore. Thermal management of systems is one of his interest areas.