System Analysis on Absorption Chiller Utilizing Intermediate Wasted Heat from Micro Gas Turbine and Solid Oxide Fuel Cell Hybrid System

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Abstract

A system analysis has been performed for the multi-effect absorption chiller (MEAC) applied as a bottoming system of 30kW class hybrid system including micro gas turbine (MGT) and solid oxide fuel cell (SOFC) hybrid system. In this paper, an intermediate wasted heat utilization (IWHU) system is suggested for lifting up the energy efficiency of the whole system and coefficient of performance (COP) of MEAC. From the results, the suggested IWHU system was found to show the very high energy efficiency compared with a terminal wasted heat utilization (TWHU) system that uses only the heat exhausted from the terminal of MGT/SOFC system. When TWHU system is applied for MEAC, the utilized heat from the MGT/SOFC system is found to remain low because the temperature difference between the high temperature generator and the wasted heat becomes small. Then, the energy efficiency does not become high in spite of high COP of MEAC. On the other hand, the IWHU system could increase the utilized heat for MEAC as performs effectively. The exergy efficiency of IWHU system is also revealed to be higher than that of a direct gas burning system of MEAC, because the wasted heat is effectively utilized in the IWHU system.

Key words: Absorption Chiller, Intermediate Wasted Heat Utilization, System Analysis, Distributed Power Supply, Exergy Efficiency

Introduction

A distributed power supply system will become very important in the near future, because it has no energy loss in electricity transportation and it can make wasted heat utilized. In such a system, a fuel cell is paid attention to as a core system. In this paper, 30kW class hybrid system including micro gas turbine (MGT) and solid oxide fuel cell (SOFC) system is treated as such a distributed power supply system (Kimijima & Kasagi, 2003). This system has very high performance for electricity supply compared with a large-scale power supply system. However, its energy efficiency still remains around 0.5 to 0.6. For the improvement of its energy efficiency, a highly efficient system of wasted heat utilization is required.

In this paper, a system analysis has been performed for a multi-effect absorption chiller applied as a bottoming system of 30kW class MGT/SOFC hybrid system. A multi-effect absorption chiller (MEAC) can effectively provide cooling energy for building air-conditioning system or district cooling system from wasted heat. Then, it attracts many researchers working on energy saving systems with wasted heat utilization. MGT/SOFC hybrid system exhausts about 20kW heat from the bottom end of the system. However, its temperature is not high enough for a multi-effect absorption chiller in which a high-temperature generator requires a high-temperature heat source(Kojima, Akisawa & Kashiwagi, 1997; Kojima, Edera, Nakamura, Oka, Akisawa & Kashiwagi, 1997). Then, the cooling heat obtained from a MEAC utilizing the terminal wasted heat is not so large in spite of its high coefficient of performance (COP), compared with that obtained from a single-effect absorption chiller.

An intermediate wasted heat utilization (IWHU) system instead of a usual terminal wasted heat utilization (TWHU) system is suggested in this paper for lifting up the energy efficiency of the whole system. IWHU system utilizes the heat exhausted from SOFC, before given to MGT. There exits high temperature wasted heat with the temperature of about 1,000^{o}C. On the contrary, such high temperature heat gives serious damage to MGT located in the downstream of SOFC. Then, air-cooling supply is required normally. If such high quality heat source is supplied to a high-temperature generator of a MEAC, it cannot only make the energy efficiency of MGT/SOFC hybrid system high but also lead to prevent the heat damage to MGT. This is the concept of the present IWHU system.

A system analysis has been performed for MEAC applied as a bottoming system of 30kW class hybrid MGT/SOFC system in order to investigate the performance of the system. The exergy analysis has been also conducted for the system to compare the result with that in the case when a fuel gas burning system of an absorption chiller is applied to TWHU system.

Hybrid systems

In this study, a hybrid system of 30kW class MGT/SOFC with absorption chiller as bottoming system is treated. Figure 1 shows a TWHU system that utilizes terminal wasted heat exhausted from the MGT/SOFC hybrid system. Air compressed at compressor input to SOFC. Methane fuel gas also input to the SOFC through fuel reformer. SOFC cannot burn all fuel in it. Then, unburned fuel exhausted from SOFC is burned in a combustor. The gas exhausted from the combustor flows into a turbine. In order to maintain the turbine inlet temperature(TIT) high, additional fuel supplied to the combustor when the TIT is lower than the given condition. On the contrary, air is used for cooling the exhausted gas when the TIT becomes higher. Finally, gas from the turbine is exhausted from the outlet of the MGT/SOFC system through a heat exchanger.

Generally, the bottoming system as an absorption chiller is mounted to utilize this terminal wasted heat. This wasted heat is not so small as about 20kW, but it has no latent heat and its temperature becomes too low as 300ºC for the generator of a multi-effect absorption chiller as discussed below. Then, in this paper, intermediate wasted heat utilizing system(IWHU) system is suggested. Figure 2 shows the system. SOFC exhausted high temperature gas about 900ºC, and from here, high-level heat can be obtained. In the suggested system, a boiler is mounted between the SOFC and the combustor in order to obtain the intermediate heat. As increasing taken heat from the intermediate point, TIT decreases. When TIT becomes low, additional methane fuel gas is supplied into the combustor.

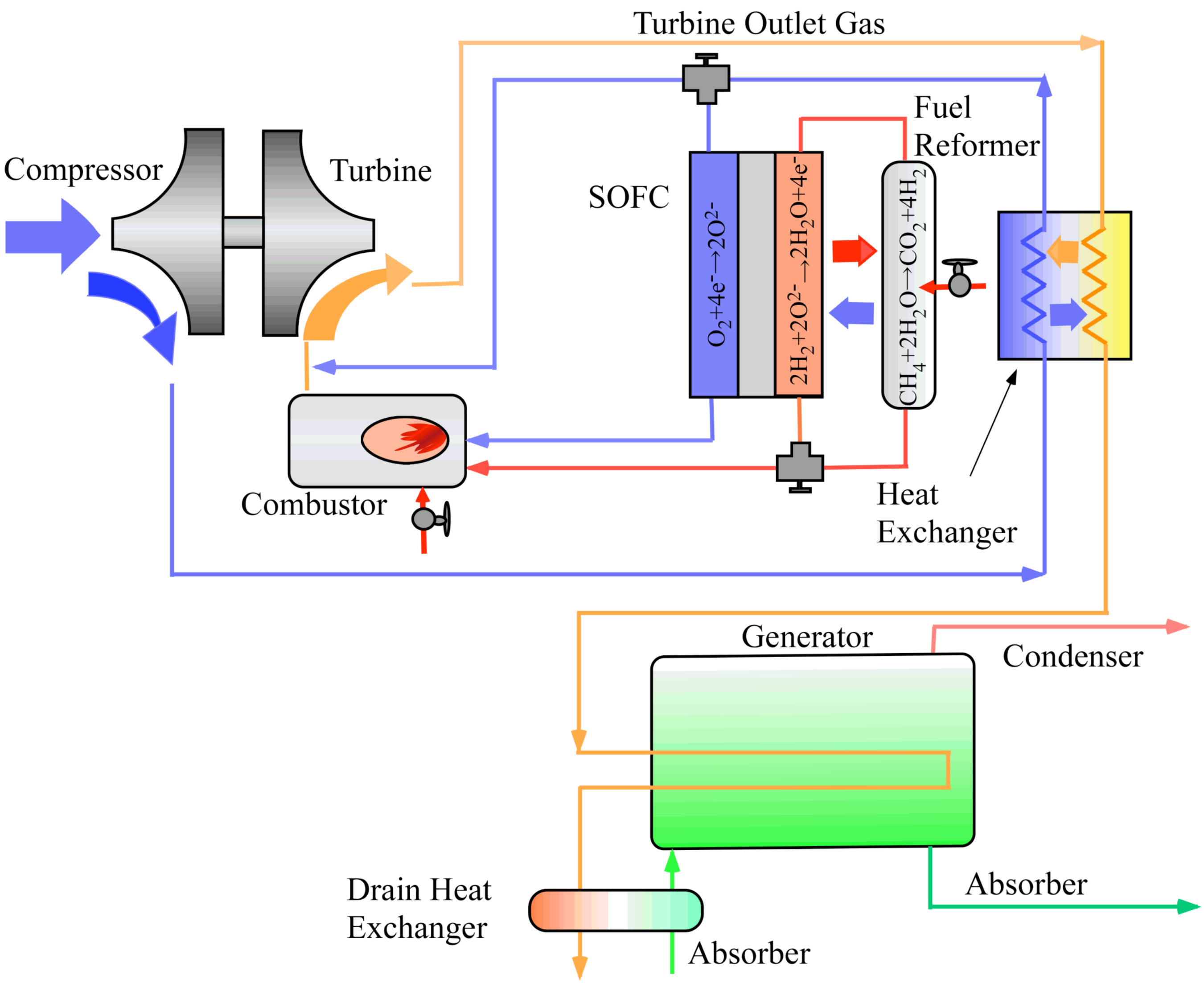

Fig.1 Terminal wasted heat utilization system

In this paper, single-, double- and triple-effect LiBr-water absorption chillers driven by such wasted heat are treated. Figure 3 shows a series-type triple-effect absorption chiller(Inoue, Irie, Saito & Kawai, 2003; Inoue, Saito & Kawai, 2003). Only series type of MEAC is treated in this study. All wasted heat is supplied into high-temperature generator and terminal wasted heat is exhausted through a drain heat exchanger, while the intermediate wasted heat is return back to the boiler.

In this paper, system analysis on the absorption chiller is mainly focused on, while the heat wasted from the MGT/SOFC system is analyzed by following the previous method(Yoshida, Iwamoto & Saito, 2003) and modifying for IWHU system.

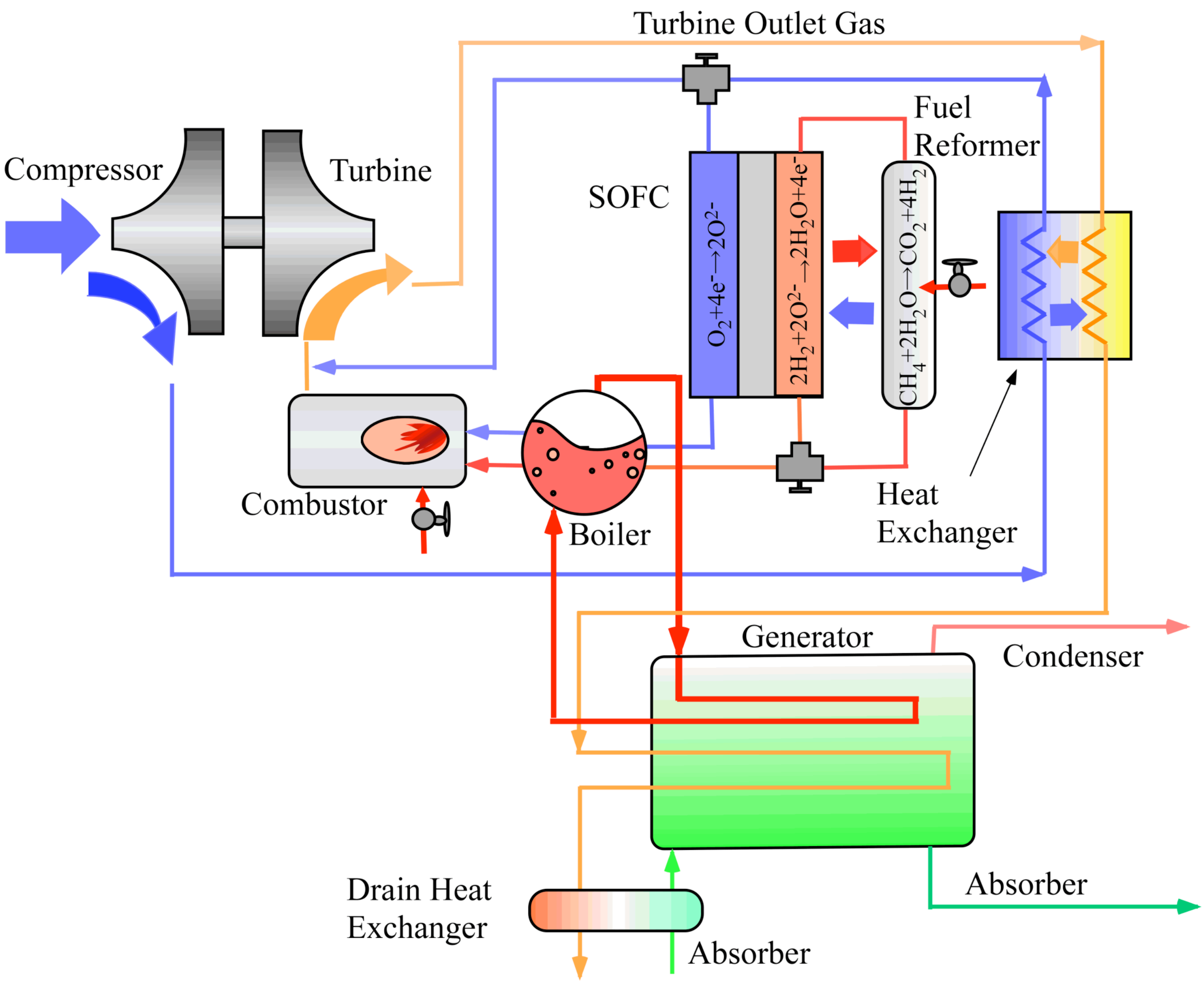

Fig.2 Intermediate wasted heat utilization system

System analysis methods

It is assumed that the system is steady and, that temperature, pressure and LiBr solution concentration are equiblium. Water re-generated in a condenser is supplied to a evaporator, In the evaporator, all water is evaporated and absorbed by high concentration LiBr solution in an absorber. No pressure difference between the evaporator and the absorber is assumed in this study.

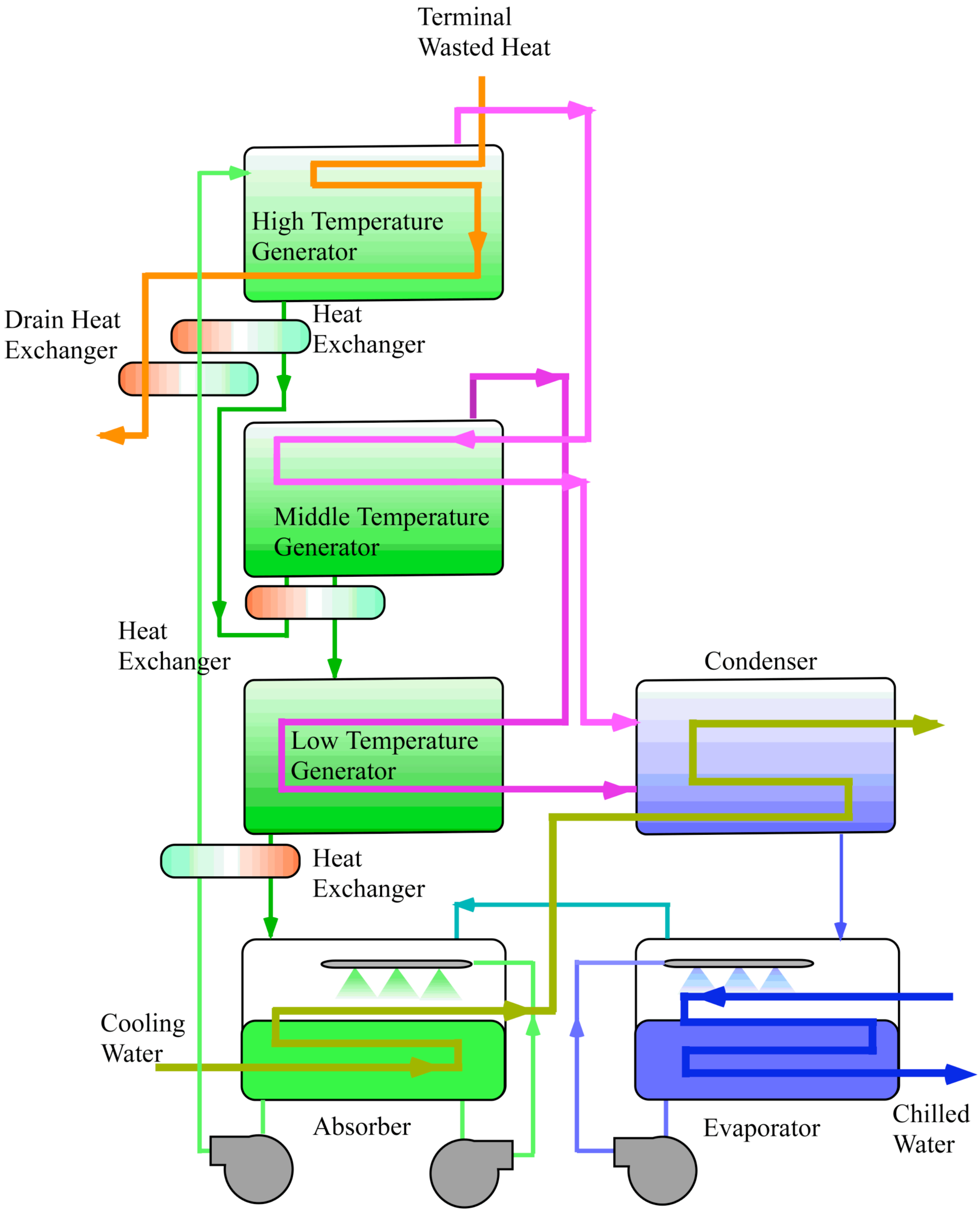

Fig.3 Triple effect absorption chiller

Low concentration LiBr solution in the absorber is pumped up to a high temperature generator. In the high temperature generator, wasted heat is utilized for re-generation of high concentration LiBr solution. The latent heat of vapor generated in the higher temperature generator is supplied to the lower temperature generators and is used for re-generation of high concentration LiBr solution. Finally, the vapor is condensed in the condenser by cooling water that is also used for cooling the absorber. The pressure in the condenser is kept at the same value as that of the lowest temperature generator.

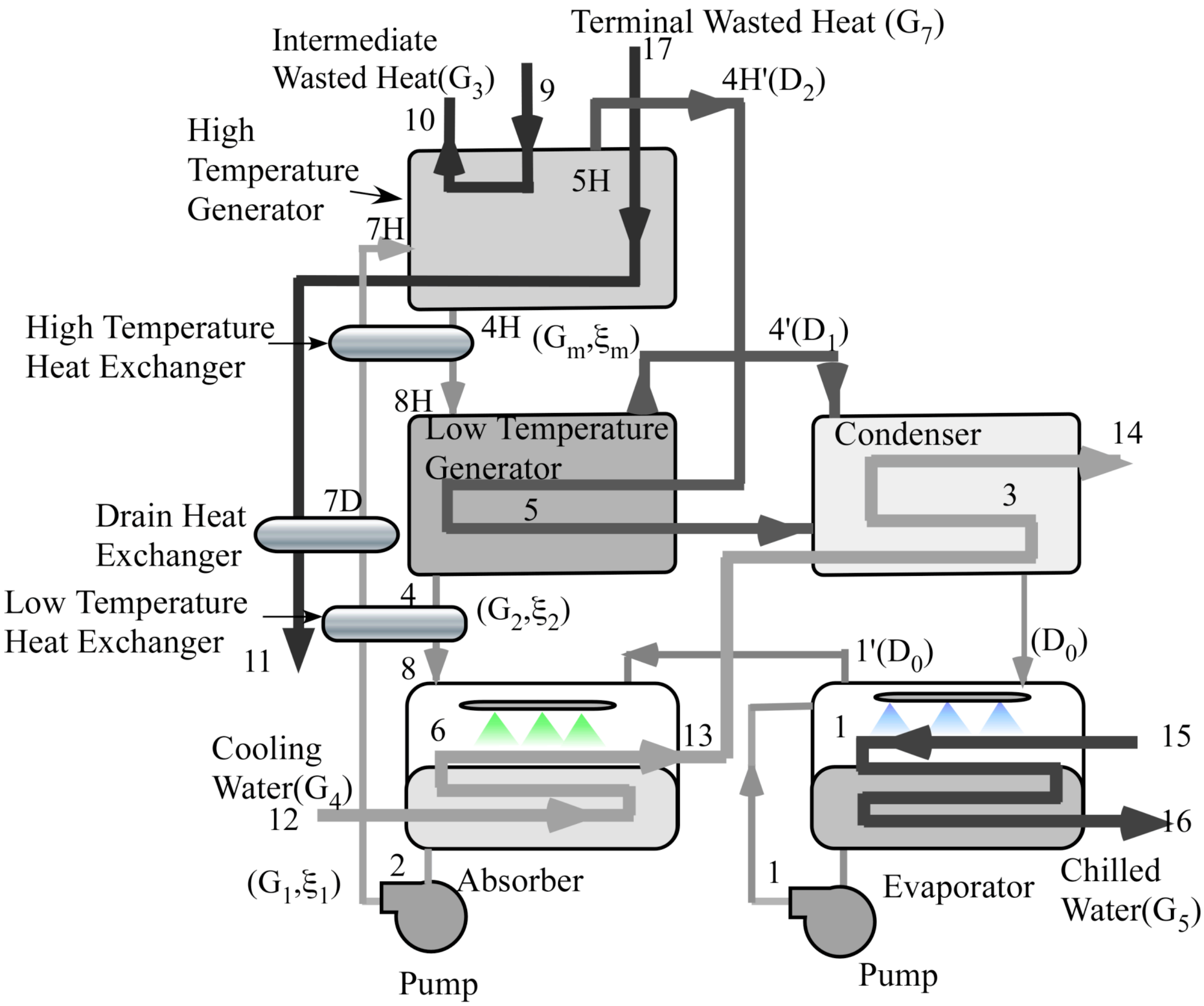

Fig.4 System schematic of series flow on double effect absorption chiller

By using a Duhring diagram, the pressure, temperature, enthalpy and concentration of LiBr at saturation condition is determined. The state variables of water-vapor are also determined with a vapor diagram. The terminal wasted heat from the SOFC/MGT hybrid system is supplied to the high-temperature generator and is also supplied to the drain heat exchanger. The intermediate wasted heat is supplied from the boiler mounted between SOFC and the combustor to the high-temperature generator, and there, its all latent heat drops.

In each heat exchanger, heat is exchanged with each heat exchange coefficient, η[-]. In this study, all of η are assumed to be unity.

A solution circulation ratio, a[-], is defined in the following.

$$a = \frac{\xi_2}{\xi_2 - \xi_1} \tag{1}$$

Here, ξ_1[-] and ξ_2[-] are concentrations of dilute and condense LiBr solutions, respectively. In this study, the solution circulation ratio is fixed at 12.

Xu, Dai, Tou & Tso(1996) suggested a simple system analysis method for series type absorption chiller. The present analysis follows their method. In the following, mass and energy balances equations are shown at each device.

Evaporator

$$Q_E = D_0\left(h_{1'} - h_3\right) = G_5\left(h_{15} - h_{16}\right) \tag{2}$$

Absorber

$$G_1 = D_0 + G_2 \tag{3}$$

$$G_1\xi_1 = G_2\xi_2 \tag{4}$$

$$Q_A = D_0 h_{1'} + G_2 h_8 - G_1 h_2 = G_4\left(h_{13} - h_{12}\right) \tag{5}$$

High-Temperature Generator

$$G_1 = D_1 + G_m \tag{6}$$

$$G_1\xi_1 = G_m\xi_m \tag{7}$$

$$\begin{aligned} Q_{HG} &= D_1 h_{4H'} + G_m h_{4H} - G_1 h_{7H} \\ &= G_3\left(h_9 - h_{10}\right) + G_7\left(T_{17} - T_5\right)C_P \end{aligned} \tag{8}$$

Low-Temperature Generator

$$G_m = D_2 + G_2 \tag{9}$$

$$G_m\xi_m = G_2\xi_2 \tag{10}$$

$$\begin{aligned} Q_{LG} &= D_2 h_{4'} + G_2 h_4 - G_m h_{8H} \\ &= D_1\left(h_{4H'} - h_{3H}\right) \end{aligned} \tag{11}$$

Condenser

$$D_0 = D_1 + D_2 \tag{12}$$

$$Q_C = D_2 h_{4'} - D_0 h_3 + D_1 h_{3H} = G_4\left(h_{14} - h_{13}\right) \tag{13}$$

High-Temperature Heat Exchanger

$$Q_{HEX} = G_m\left(h_{4H} - h_{8H}\right) = G_1\left(h_{7H} - h_{7D}\right) \tag{14}$$
$$\eta_{HEX} = \left(h_{7H} - h_{7D}\right)/\left(h_{5H} - h_{7D}\right) \tag{15}$$

Low-Temperature Heat Exchanger

$$Q_{LEX} = G_2\left(h_4 - h_8\right) = G_1\left(h_7 - h_2\right) \tag{16}$$
$$\eta_{LEX} = \left(h_4 - h_8\right)/\left(h_4 - h_6\right) \tag{17}$$

Drain Heat Exchanger

$$Q_{DEX} = G_1\left(h_{7D} - h_7\right) = G_7\left(T_{5H} - T_{11}\right)C_P \tag{18}$$

Here, h[kJ/kg] and T[K] are specific enthalpy and temperature, respectively, and their subscripts indicate values at the corresponding position of Fig. 4. G[kg/s] is mass flow rate of solution, chilled water and cooling water, and D[kg/s] is mass vapor flow rate, which subscript indicates the position in Fig.4. C_p[kJ/kgK] is specific heat of water. Q[kW] is also enthalpy per second through each element and the subscripts of E, HG, LG, C, HEX, LEX, DEX correspond evaporator, high-temperature generator, low-temperature generator, condenser, high temperature heat exchanger, low-temperature heat exchanger and drain heat exchanger in Fig.4. The subscript of m indicates the value at the intermediate position in Fig. 4.

In this paper, exergy efficiency is also discussed(Asano, Fujii, Wang, Origane, Katayama & Inoue, 2002). Specific exergy, e[kJ/kgK] is defined as follows.

$$e = h - h_0 - T_0\left(s - s_0\right) \tag{19}$$

Here, s[kJ/kgK] is specific entropy and h_0[kJ/kg] and s_0[kJ/kgK] are specific enthalpy and specific entropy of cooling water at the inlet temperature of 32°C, respectively.

The other computational conditions are tabulated in Table 1.

Results and Discussions

Terminal wasted heat utilization system

At first, the results of the terminal wasted heat utilization (TWHU) system are discussed. Figure 5 shows the wasted heat given to the generator and cooling capacity of each effect absorption chiller. As shown in the figure, it is found that the cooling capacity increases as the effect number increases. However, the increase rate decreases unexpectedly. This is caused by the decrease of utilized wasted heat as the effect number, because the temperature difference between the wasted heat and the high temperature generator decreases as the effect number increases. Thus, it is found that a MEAC is not effective in TWHU system. This is a reason that IWHU system is suggested in this paper.

Table 1 Model Condition

Chilled Water	
Inlet Temperature	12℃
Output Temperature	7℃
Evaporator Temperature	5℃
Cooling Water Temperature	32℃
Flow Rate	5000kg/h
Wasted Heat Outlet Temperature	100℃
Solution Circulation Ratio	12
Concentration of Strong LiBr Solution	63wt%
High Temperature Heat Exchanger	
Heat Exchanger Coefficient	1.0
Low Temperature Heat Exchanger	
Heat Exchanger Coefficient	1.0
Drain Heat Exchanger	
Heat Exchanger Coefficient	1.0
Pressure in High Pressure Generator	1.0×10^{5}Pa
<Single Effect Absorption Chiller>	
Pressure in Generator	1.0×10^{5}Pa
<Double Effect Absorption Chiller>	
Pressure in Low Pressure Generator	1.0×10^{4}Pa
Pressure in High Pressure Generator	1.0×10^{5}Pa
<Triple Effect Absorption Chiller>	
Pressure in Low Pressure Generator	1.0×10^{4}Pa
Pressure in Middle Pressure Generator	1.0×10^{5}Pa
Pressure in High Pressure Generator	4.0×10^{5}Pa

Intermediate wasted heat utilization system

In this paper, the following conditions are taken into consideration for the analysis of IWHU system. Figure 6 shows the additional fuel to the combustor in order to increase TIT to the given condition when the wasted heat from the intermediate position of SOFC/MGT system is intercepted. From this, it is found that the additional fuel is not required until intercepted heat becomes 7.7kW because TIT becomes higher than the given condition. When intercepted heat becomes higher than 7.7kW, the additional fuel is required as shown in Fig.6. Increase of intercepted heat causes the decrease of terminal wasted heat because the flow rate of cooling air input to the upstream of turbine to keep TIT. Figure 7 shows the terminal wasted heat when heat is intercepted from the position between SOFC and the combustor. Until intercepted heat becomes 7.7kW, the terminal wasted heat decreases because flow rate of cooling air decreases.

In the range when the additional fuel is required, the terminal wasted heat gradually increases as fuel increases. However, the value does not recover sufficiently and becomes low compared with TWHU system. In this paper, this terminal wasted heat is taken into analysis of IWHU system. Related to this, the power generated from the turbine also decreases due to the decrease of flow rate. In order to keep the given value of 30kW power supply of this system, the additional fuel is required to SOFC in the case when IWHU system is adopted. Figure 8 shows the additional fuel energy to SOFC in IWHU system.

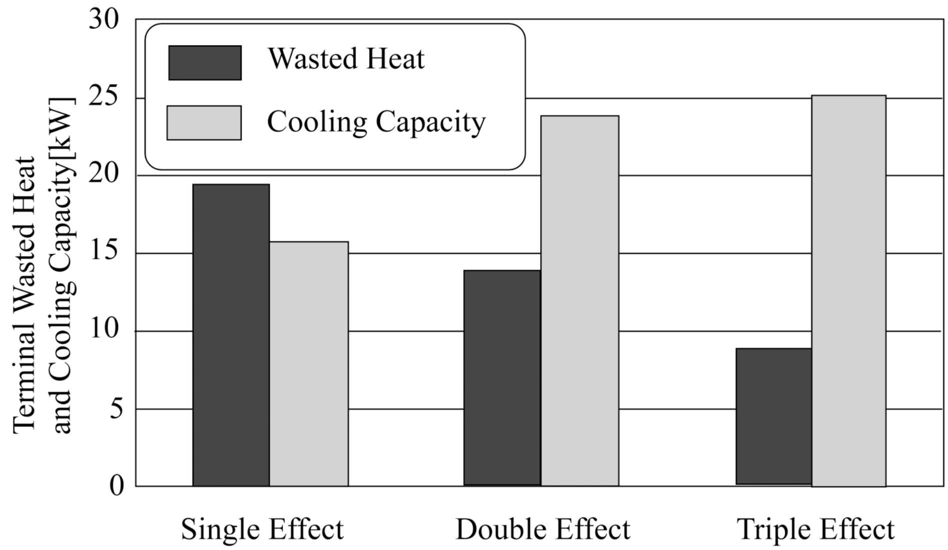

Fig.5 Terminal wasted heat utilization system

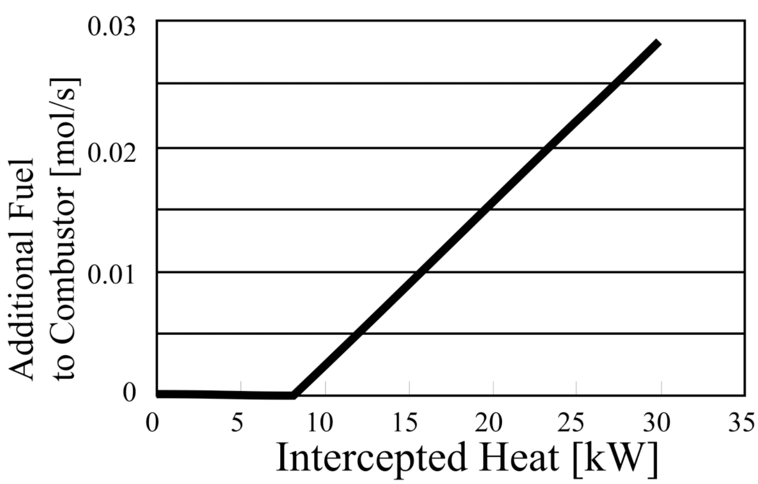

Fig.6 Additional fuel to combustor

Figure 9 shows the coefficient of performance (COP) of each effect absorption chiller. Here, COP is defined as the ratio of cooling capacity to the total value of the heat supplied to the high temperature generator and supplied to the drain heat exchanger. In this figure, the case of no intercepted heat corresponds to that of TWHU system.

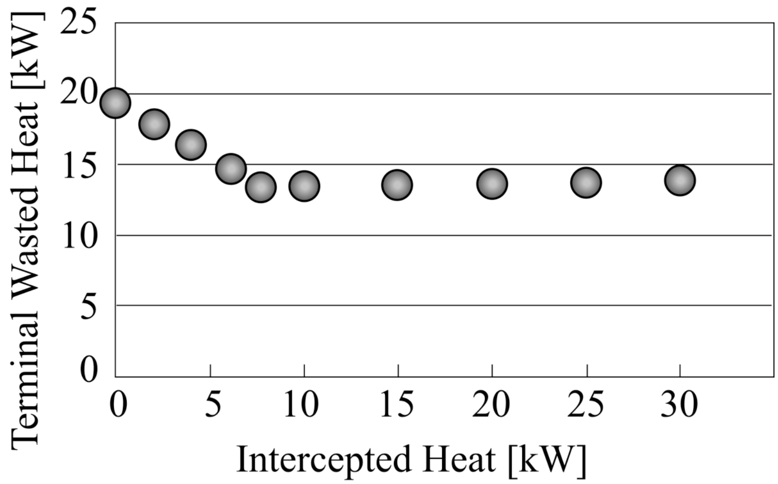

Fig.7 Terminal wasted heat

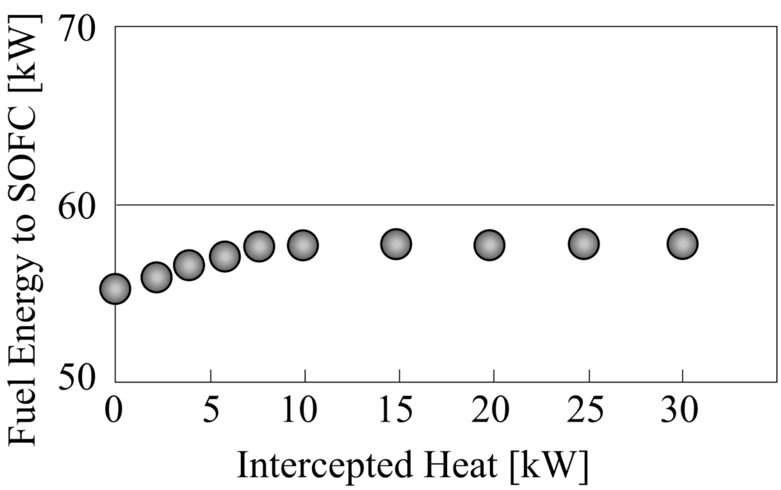

Fig.8 Fuel energy inputted to SOFC

From this figure, it is found that the effect of intercepted heat is small in the cases of single- and double- effect systems. This is because low effect absorption chiller can effectively recover the terminal wasted heat. In the case of triple-effect system, the terminal wasted heat is mainly added to the drain heat exchanger, because the temperature difference between the terminal wasted heat and the high temperature generator. The cooling capacity against the heat given to the generator increases in proportion to the effect number as shown in Fig. 5, but COP based on the total energy including the heat added to the drain heat exchanger becomes small in the case of TWHU system. On the other hand, COP increases as intercepted heat increases in the case of IWHU system due to the increase of utilized heat in the high temperature generator. From this, it is found that IWHU system make the MEAC effective.

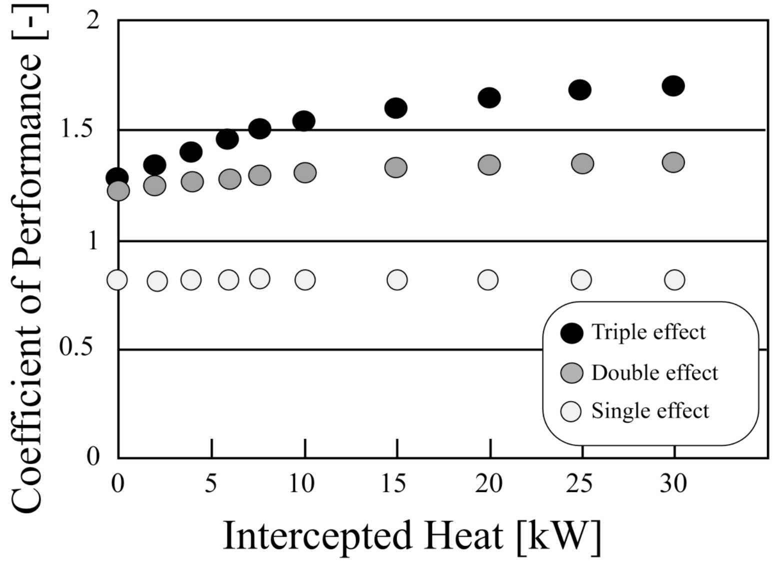

Fig.9 Coefficient of performance

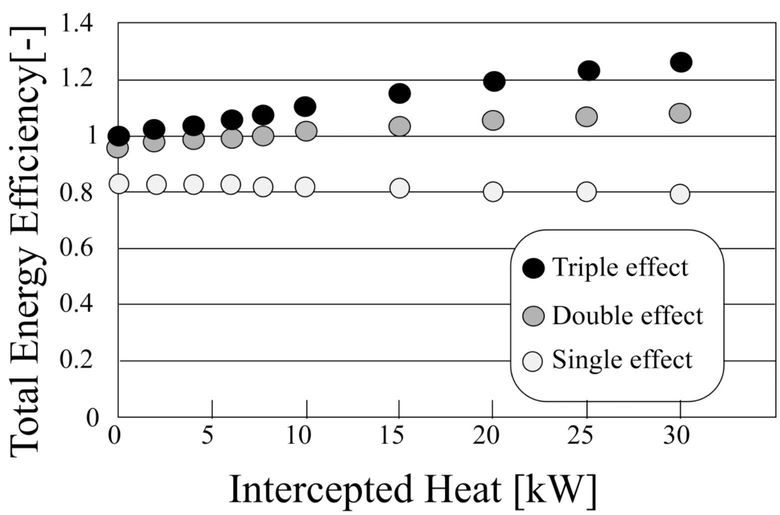

Fig.10 Total energy efficiency

Figure 10 shows the total energy efficiency on SOFC/MGT with each effect system. Here, the total energy efficiency is defined as the electric power generated by SOFC and MGT and cooling heat by each effect absorption chiller against the fuel energy added to the SOFC and the combustor. The energy efficiency is 0.60 in the case without absorption chiller system. From this figure, it is found that the total energy efficiency remains low in the case of TWHU system due to its low cooling capacity. On the other hand, the total energy efficiency in the case of triple-effect system becomes very high by the utilization of intermediate heat in spite of the requirement of additional fuel to the SOFC and combustor for keeping TIT. In the present condition, it reaches a very high value of 1.25. From this, it is found the combination of MEAC and IWHU system is very effective for heat recovery.

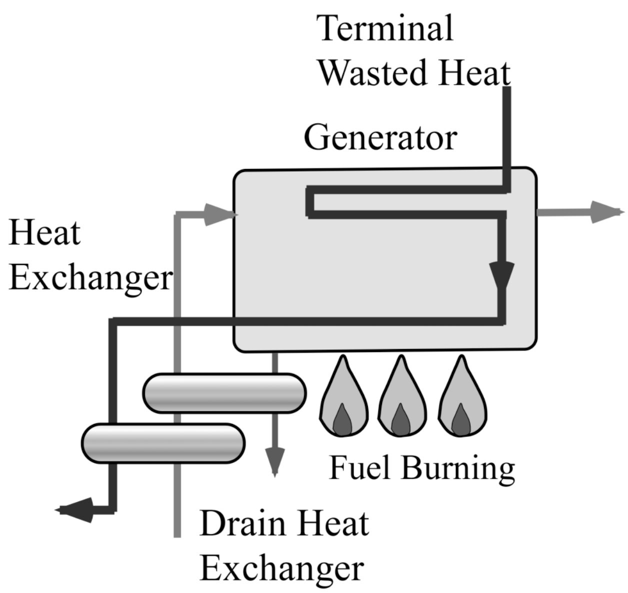

Fig.11 Fuel burning absorption chiller

Comparison with fuel-burning absorption chiller system

In this paper, the effectiveness of IWHU system for heat recovery with MEAC is discussed. As mentioned above, there exists the case requiring additional fuel to keep TIT in the present conditions. Generally, a system using fuel burning directly in high-temperature generator as high temperature heat source has been discussed for MEAC utilization. In this section, the comparison of the present system to such a fuel burning absorption chiller will be discussed. In the following, the energy and the exergy efficiency only of triple-effect absorption chiller will be treated.

Figure 11 shows the energy flow of fuel burning absorption chiller. In this system, the terminal wasted heat adds to the high temperature generator and the drain heat exchanger as shown in the figure. The terminal wasted heat takes a value in the case when the intercepted heat is zero in Fig. 7 and the fuel added to SOFC also takes the value in the case without intercepted heat in Fig. 8. When fuel is directly burned in the generator, more fuel than that of the additional fuel required for IWHU system is required due to heating air. When the air-fuel ratio is 19, 8.14% of fuel is used for heating air.

Figure 12 and 13 show COP and total energy efficiency of each absorption chiller.

The abscissa is the total energy input to the high-temperature generator in the figures. That means the total of the terminal wasted heat and fuel energy in the case of fuel burning system and the total of the terminal wasted heat and intercepted heat in the case of IWHU system.

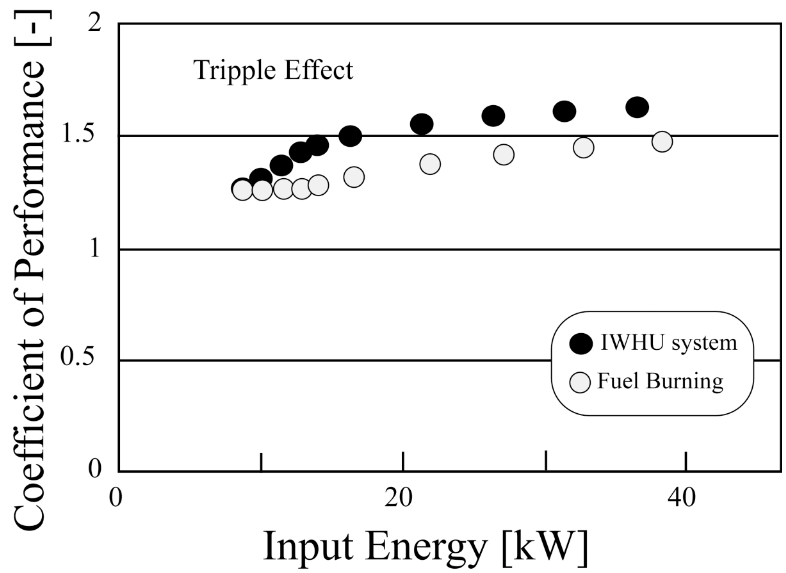

Fig.12 Comparison of COP

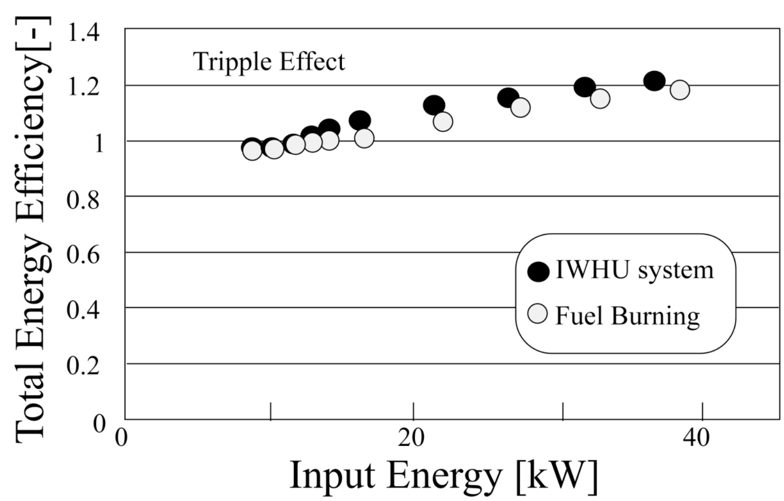

Fig.13 Comparison of total energy efficiency

From Fig. 12, it is found that IWHU system shows higher COP than that of fuel burning system. This is caused because 8.14% energy is lost for heating air in the fuel burning system. On the other hand, enough high temperature vapor is supplied to the generator with IWHU system. From this effect, the total energy efficiency takes higher values with IWHU system than that in the case of fuel burning system as shown in Fig. 13.

Figure 14 shows the exergy efficiency of each abosorption chiller. The exergy efficiency is defined by the total exergy of terminal wasted heat, and intermediate wasted heat or fuel burning to the cooling heat exergy obtained by each absorption chiller. Here, the exergy exhausted from the system is taken away from the added exergy. In the figure, the abscissa is the total energy added to the high-temperature generator.

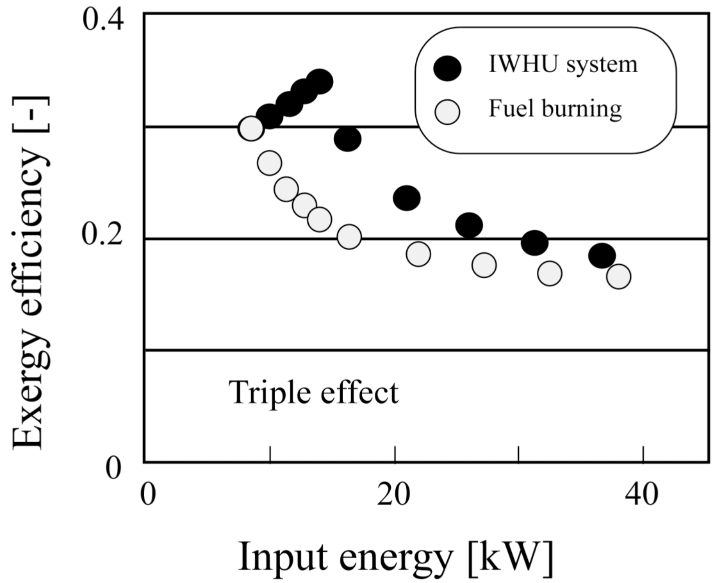

Fig.14 Exergy efficiency of absoption chiller

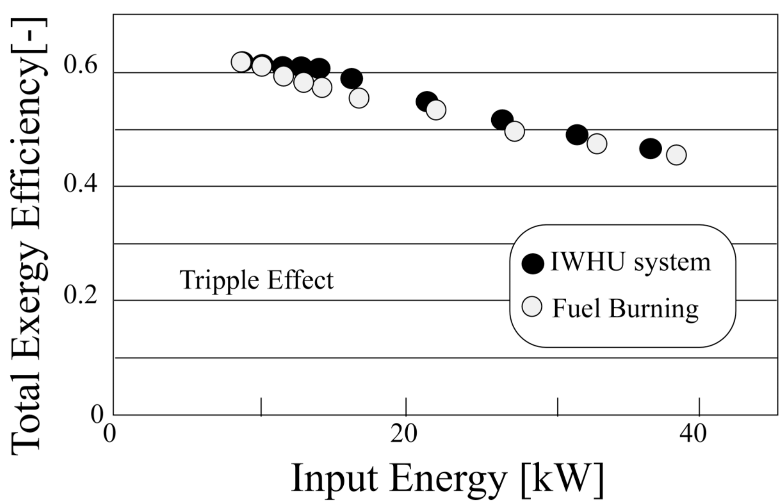

Fig.15 Total Exergy Efficiency

From the figure, the exergy efficiency is found monotonically to decrease with the amount of fuel in the case of fuel burning system. This is caused by the fact that the cooling exergy obtained by the fuel burning absorption chill does not increase so much against increase of exergy loss by fuel burning. On the other hand, the exergy efficiency for the IWHU system sharply increases in the lower range than 7.7kW (13.9kW in supplied energy) where the fuel added to the combustor is not required. After that, however, the exergy efficiency decreases. This is because the cooling heat obtained by the system sharply increases until 13.9kW of supplied energy but the exergy loss increases due to the excess addition of fuel after that.

However, it is found that the exergy efficiency in the case of IWHU system takes much higher values that those in the case of fuel burning abosorption chiller. This indicates the IWHU system for the absorption chiller is effective compared with the normal fuel burning system.

Figure 15 shows the total exergy efficiency of SOFC/MGT hybrid system with each absorption chiller. Here, the total exergy efficiency is defined as the electric power and cooling heat obtained by each system against the total energy added to the whole system.

Unfortunately, the exergy efficiency is found from the figure to decrease with added energy. This is caused by the decrease of the ratio of cooling heat obtained by each system to the fuel exergy loss. As the results, the total efficiency takes the highest value in the case of TWHU system. The decreasing ratio becomes small in the lower range than 13.9kW when the additional fuel is not required in the case of IWHU system. From this, the present system has advantage to the fuel burning system. When much cooling heat is required, MEAC is indispensable. For such a system, the present system has advantage.

5. Conclusion

In this paper, the system of 30kW class MGT/SOFC with absorption chiller used as the bottoming system has been discussed. From the results, it is found that the MEAC is not effective for TWHU system generally used for the bottoming system in such a distributed power supply system. Then, in the present study, IWHU system is suggested in order to utilize high-level wasted heat. From the system analysis, the energy efficiency with multi-effect absorption chiller is found to become very high. This is found that the cooling capacity obtained by MEAC effectively increases and leads a high value of energy efficiency in spite of the requirement of addition fuel. On the other hand, the exergy efficiency is found to decrease due to increase of fuel exergy loss. However, its decrease ratio becomes small in the region where additional fuel is not required compared with that in the case of using a fuel burning system. Additionally, the present IWHU system has advantage in exergy efficiency when multi-effect absorption chiller is used.

In this study, the optimization of absorption chillers on the working condition is not discussed. On the decrease of exergy efficiency, more discussion will be required.

Acknowledgement

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Nomenclature

a	= circulation ratio	
C_P	= specific heat	$kJ \cdot kg^{-1}K^{-1}$
D	= flow rate of vapor	$kg \cdot s^{-1}$
e	= specific exergy	$kJ \cdot kg^{-1}$
G	= flow rate of solution, cooling and chilled water and heat source	$kg \cdot s^{-1}$
h	= specific enthalpy	$kJ \cdot kg^{-1}$
Q	= energy added to each device	kW
s	= specific entropy	$kJ \cdot kg^{-1}K^{-1}$
T	= temperature	K
η	= heat exchanger efficiency	
ξ	= concentration of LiBr solution	

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