PREDICTION ABOUT PROGRESS IN PERFORMANCE OF DISTRICT HEATING AND COOLING SYSTEM USING COMBINED HEAT AND POWER

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ABSTRACT

This study aims to reveal the advantages of district heating and cooling system (DHC) in energy efficiency as an urban energy system in the future. In this study, an existing absorption-chiller-and-boiler-type DHC plant, which utilizes large-scale combined heat and power (CHP), is chosen for a case study. We evaluate the energy-saving potential of the plant in the future by a simulation model. The simulation model is developed based on actual equipment specifications and operating conditions of the plant, and the accuracy of this model is proved to be high based on comparisons with measurement data. The results show that the energy efficiency ratio will reach 2.13 by the introduction of various measures to conserve energy, including future advanced technologies. In particular, the utilization of CHP exhibits a great energy-saving effect. However, these results depend on future technical developments.

KEYWORDS

Actual condition analysis, Simulation, Performance progress, District heating and cooling system, Combined heat and power

INTRODUCTION

In Japan, district heating and cooling system (DHC) has a 35-year history, and now more than 150 plants are running. DHC has many social advantages, such as air-pollution abatement. Above all, energy-saving gains attention as one of the most important advantages of DHC in recent years with regard to the mitigation of global warming.

The Agency for Natural Resources and Energy in Japan showed the advantages of DHC in energy efficiency by comparing the measured energy efficiency of individual heat-source systems to that of DHC plants (2003). Shimoda et al. revealed the advantages of DHC in energy efficiency due to the concentration effect, the economy of scale in energy efficiency of chillers and the grade of operation (2005). However, nowadays the energy-saving effect of DHC is not clear as ever, because a variety of energy-saving technologies such as building energy management system and high-efficiency, small-capacity chillers are being introduced in individual heat-source systems. Even in this circumstance, DHC could retain its energy-saving effect in the future since DHC has unique advantages such as the utilization of natural and unused heat-source/sink or large-scale combined heat and power (CHP), which cannot be utilized in individual heat-source systems from an economic point of view. Thus, it is important to predict the energy-saving potential of DHC in the future. The results could contribute to not only the adoption of energy systems in the city planning phase but also the improvement of energy efficiency of existing DHC plants.

There are several studies reporting the energy-saving potential of DHC and heat-source systems. For example, Fujinami et al. showed the energy-saving potential of DHC through the utilization of exhaust heat from CHP (2004), and Liao Z. et al. showed the energy-saving potential of heating systems through improving boiler controls (2004). However, in these studies, the simulation models are developed with numerous assumptions. As a result, the calculated energy-saving potential seems to be an overestimation.

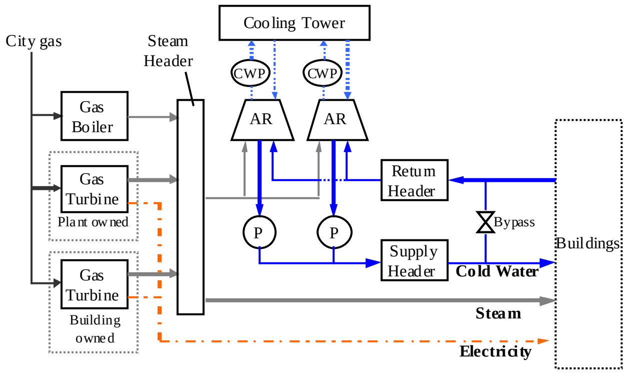
In this study, we target at the absorption-chiller-and-boiler-type DHC plant, which accounts for one-third of all DHC plants in Japan. This type of DHC is expected to save energy drastically by the technical innovation of CHP. We selected an actual DHC plant (A-Plant) that has the largest scale of CHP in Japan as a case study. A-Plant is modeled based on actual equipment specifications and operating conditions, and the accuracy of the model is proved to be high by comparisons with measurement data. With this simulation model, the energy-saving potential in the future is evaluated.

We use the energy efficiency ratio (EER) as the evaluation index of the energy efficiency. EER is defined as follows.

$$EER = \frac{Total\ amount\ of\ supplied\ heat\ [GJ/year]}{Total\ primary\ energy\ consumption\ [GJ/year]} \quad (1)$$

The primary energy conversion factor of electricity is set to 9.83 [GJ of primary energy / kWh of electricity] in accordance with the energy-saving law in Japan.

SIMULATION MODEL



AR: absorption chiller , P: cold water pump , CWP: cooling water pump

Note: The number of absorption chillers and gas turbines is different from the actual plant.

Figure 1. System configuration of A-Plant

Table 1. Heat source equipment (A-Plant)

	Heat source equipment	Performance	Number of equipment
Cooling heat source system	Absorption chiller	7032kW	4
	Absorption chiller	3516kW	3
Heating heat source system	Steam boiler	15.0t/h	3
	Steam boiler	4.8t/h	2
Other facilities	Gus turbine (Power)	1500kW	4
	(Steam)	4.45t/h	4

Figure 1 shows the system configuration and Table 1 shows the heat-source equipment. The EER of A-Plant is 0.77, and this EER is higher than average of Japanese absorption-chiller-and-boiler-type DHC plants. A-Plant has four gas turbines. Three gas turbines are building-owned, and one gas turbine is plant-owned. However, all CHP are installed at the plant, and all electricity from CHP is transmitted to one building in the region. The electricity demand of the building is nearly constant throughout the year, and the maximum demand is about 5600 [kW]. DHC plant utilizes only exhaust heat from CHP.

In order to precisely simulate the actual condition, following parameters are basically determined by the measured data of A-Plant. However, missing parameters are determined by the measured data of other DHC plants.

Factors considered in the simulation model

1. Heating and cooling load

In order to correctly simulate the chiller sequence control, the cooling load is supplied as the measured flow rate of chiller water and the measured temperature difference between the supply and return water. The cooling load data includes the heat loss from the pipeline and internal use, and the heating load data includes only the heat loss from the pipeline.

2. Efficiency of chiller and boiler

The coefficient of performance (COP) of the double-effect absorption chiller is set as 1.2 at the rated condition from the measured data of A-Plant. A change in the COP caused by part-load performance and the cooling water temperature is modeled from characteristics provided by a manufacturer.

The efficiency of the steam boiler is set at 0.82 under any load factor. This value includes the power consumption of accessories in the boiler system.

3. Power consumption of pumps, accessories of chillers and cooling tower

A-Plant has variable-speed control in the cooling water pump and the cold water pump. Hence, the power consumption of pumps is calculated using the equation that is derived from the relationship between the flow rate and the power consumption of the pump.

The power consumption of accessories of absorption chillers and cooling tower is set by the measured data of other DHC plants. The power consumption of accessories of chillers Pa is modeled as a function of the cooling capacity of the chiller $R[kW]$, as follows:

$$Pa[kW] = -2.43\times10^{-7}\times R^2 + 0.00785\times R \qquad (2)$$

The power consumption of the cooling tower per unit of waste heat from the chiller is calculated, and the average value of two DHC plants is used.

4. Multiple chiller control sequence

The number of operation chillers is determined according to the amount of heat demand and flow rate. The multiple chiller control sequence of A-Plant is set optimally depending on the heat load, and it is different each month. This operation is simulated in the model. In a general way, in order to respond to the sudden increase in the cooling load, chillers are operated in a manner such that they have a margin of load factor. This margin is 10% at A-Plant.

5. CHP

CHP is equipment that generates electricity and heat at the same time. In Japan, 50 DHC plants introduce CHP, and electricity from CHP is not used in a DHC plant in almost all cases. There are various methods to evaluate the exhaust heat from CHP (COGEN Europe Briefing 2001, Fujinami et al. 2004). In this study, we calculate the theoretical energy consumption for exhaust heat. In this approach, the input energy increment caused by utilizing CHP instead of using commercial power is considered as the input energy for obtaining the exhaust heat. We use "CHP exhaust heat coefficient" to show the efficiency of steam production with CHP. With this value, we can compare the efficiency with the steam boiler. Figure 2 shows this evaluating method. With this method, in the case where the generating efficiency of CHP is higher than that of commercial power, the input energy for exhaust heat becomes a negative number. However, it is set to zero in this simulation model.

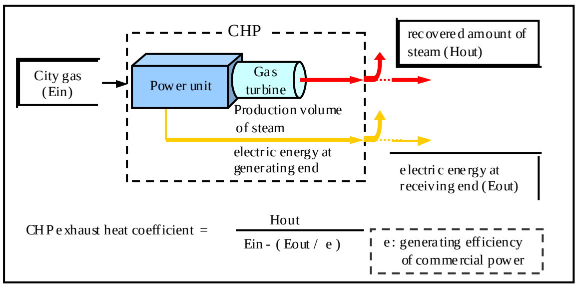


Figure 2. Evaluating method of CHP

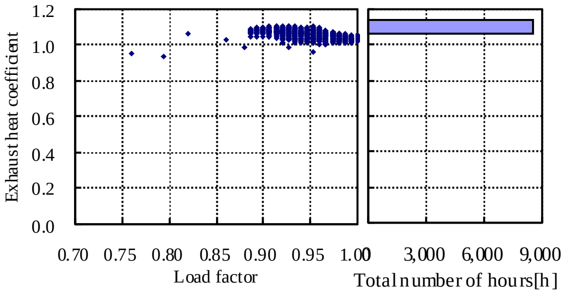


Figure 3. CHP exhaust heat coefficient (Plant-owned CHP)

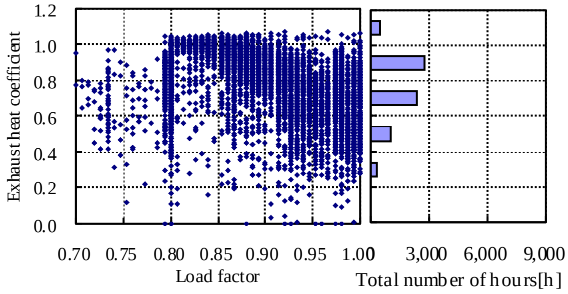


Figure 4. CHP exhaust heat coefficient (Building-owned CHP)

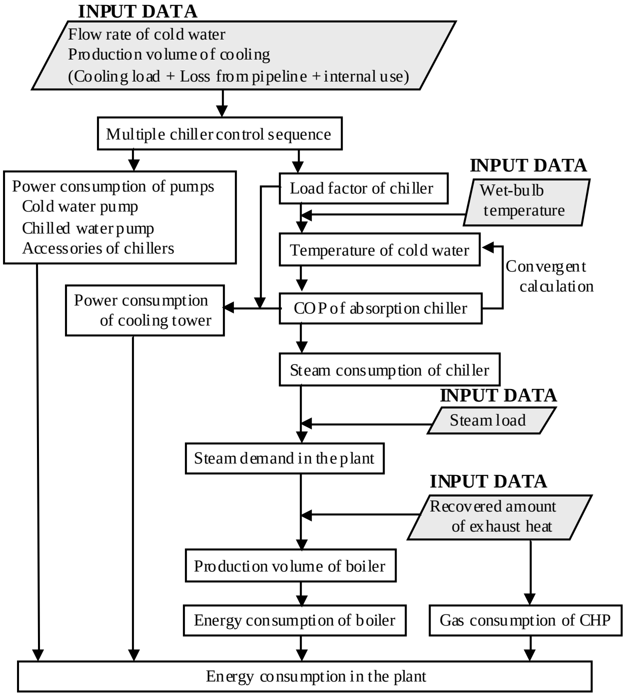


Figure 5. Calculation algorithm of energy consumption

In A-Plant, the operation of plant-owned CHP is determined by the steam demand in the plant. On the other hand, the operation of building-owned CHP is determined by the electricity demand at one building. Then all exhaust heat from building-owned CHP is not utilized because it exceeds the required amount of steam. This difference in the manner of operation leads to a differential of CHP exhaust heat coefficient (Figures 3-4). Moreover, there are many hours that the boiler is operating, although there is enough exhaust heat from CHP due to lack of information exchange between the building and DHC plant. In the simulation model, the generated electricity and the amount of exhaust heat recovery of each CHP are used as input data to reflect the actual operating condition.

Calculation algorithm of the simulation model

The primary energy consumption in A-Plant is calculated as shown in Figure 5.

SIMULATION RESULTS

Base case result

Table 2 lists the annual primary energy consumption of the actual condition and the simulation result. The difference between the actual condition and simulation result is small according to the energy source, and the difference of EER is 1.7%. Also with the monthly comparison (Figure 6) and hourly comparison of the representative day, the primary energy consumption between the actual condition and simulation result is close. Therefore, the accuracy of this simulation model is verified. Hereafter, this result is used as the base case result.

Table 2. Simulated and actual annual primary energy consumption in the base case

		Actual condition	Simulation model	Differential
Consumption of city gas [GJ]	CHP	304,025	299,602	-1.5%
	Boiler	59,570	61,063	2.5%
Consumption of electricity [GJ]		45,712	41,827	-8.5%
sum total [GJ]		409,307	402,493	-1.7%
EER		0.77	0.78	1.7%

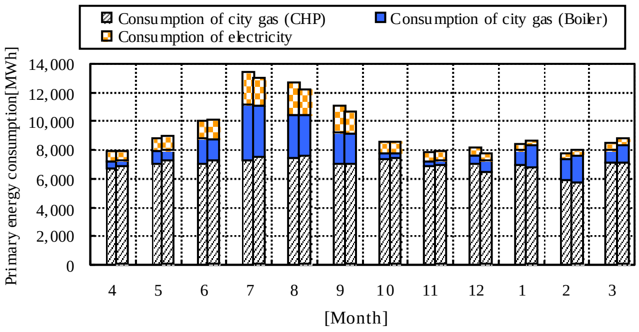


Figure 6. Monthly comparison of primary energy consumption (Left: Actual condition, Right: Simulation result)

Quantification of energy-saving effect of A-Plant

In this part, we quantify the energy-saving effect of elements that contribute to high EER of A-Plant with the simulation model. Following three elements are verified.

1. CHP

In order to measure the energy-saving effect of CHP, we verify the case where all steam is provided with the boiler and compare the energy consumption to the base case result. In A-Plant, large-scare CHP is introduced, and CHP exhaust heat coefficient is 0.87. This value is higher than the efficiency of the steam boiler (0.82). Hence, the introduction of CHP leads to the high-efficiency production of steam.

2. Variable-speed pump

In order to measure the energy-saving effect of the variable-speed pump, we verify the case where the pump has a constant flow, and compare the energy consumption to the base case result. With the variable-speed control, the power consumption of the pump is reduced, especially when the heat demand is small.

3. Temperature difference

In order to measure the energy-saving effect of the temperature difference between the supply and return water, we verify the case where the temperature difference is changed and compare the energy consumption to the base case result. In this study, we focus attention on the load factor of the cooling load, where the temperature difference starts to descend. We call this load factor “border value”. Three patterns of temperature differences are set based on temperature differences of other DHC plants (Figure 7). A-Plant corresponds to the border value 0.1.

The amount of energy consumption reduction with each case is shown in Figure 8.

The introduction of CHP contributes to 4% of energy saving in A-Plant. It is contemplated that CHP has the largest effect on the energy saving of absorption-chiller-and-boiler-type DHC plants. However, under existing conditions, the energy-saving effect is far from large since exhaust heat from the building-owned CHP is not used effectively (Figure 4). The case where this operation is improved is verified later in this paper.

The effect of the introduction of the variable-speed pump contributes to 4% of energy saving. In absorption-chiller-and-boiler-type, the difference of the COP of chillers is small. Hence, the energy consumption of transfer pumps and fans has a big energy-saving effect, and reduction of the power consumption of pumps is effective.

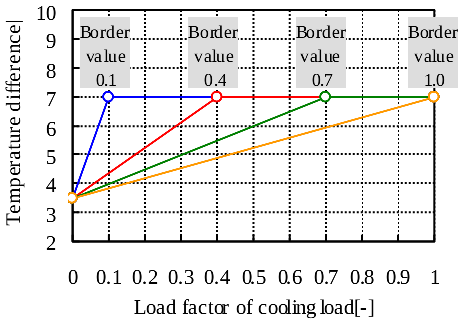


Figure 7. Temperature difference

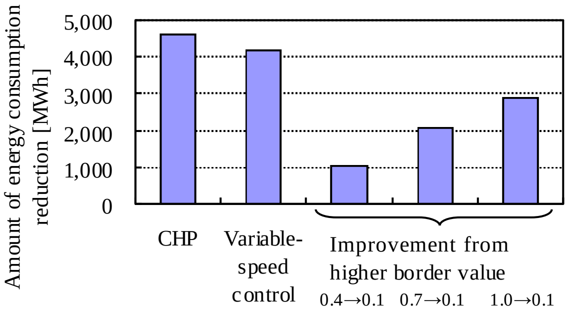


Figure 8. Amount of reduction of energy

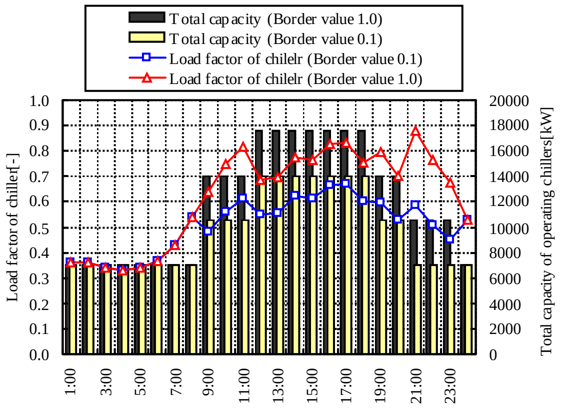


Figure 9. Comparison capacity of operating chiller and load factor of chiller

The energy consumption of accessories of chillers and the cooling water pump and cold water pump increase with descending temperature difference. Since increase of the flow rate with low temperature difference leads to the increase of operating chillers and the decrease of load factor of chillers (Figure 9).

Progress in Performance of DHC

In this part, we predict about progress in the performance of A-plant by the improvement of operation or introduction of future energy-saving technologies. The cases shown in Table 3 are verified.

Table 3. Measures to conserve energy

Case A	Change of manner of the operation of CHP
Case B	Introduction of the latest model of absorption chiller
Case C	Introduction of other types of CHP (1. Gas engine, 2. Solid oxide fuel cell)
Case D	Introduction of the turbo refrigerator

Case A: Change of manner of the operation of CHP

In the actual operating condition, exhaust heat from building-owned CHP is not used efficiently almost all the time (Figure 4), and there are many hours that the boiler is operating even though there is enough exhaust heat from CHP. In Case A, exhaust heat from CHP is used at a maximum and the production of steam from the steam boiler is reduced.

Case B: Introduction of the latest model of absorption chiller

Recently, the COP of the double-effect absorption chiller has been advanced. The COP of the latest model of absorption chiller is 1.35, and in Case B, the latest model of absorption chiller is introduced. The change in the COP caused by part-load performance and the cooling water temperature is the same as in the base case.

Case C: Introduction of other types of CHP

In Case C, a gas engine or solid oxide fuel cell (SOFC) is introduced instead of the gas turbine. Gas engine and SOFC have high generating efficiencies. Gas engine has already been put into practical use and SOFC is still being investigated. The generating efficiency and efficiency of exhaust heat at the rated condition are shown in Table 4. Figure 10 shows the efficiency change of gas engine by the load factor. SOFC is not influenced by the load factor, and efficiencies are constant under any condition. In the case of gas engine, recovered hot water is put in the single-effect absorption chiller.

Case D: Introduction of the turbo refrigerator

In Case D, a turbo refrigerator is introduced for increasing the operation hours of CHP. The electric demand of one building in the region and the power consumption of a turbo refrigerator are always covered with electricity from CHP. If CHP can generate more electricity, the power consumption for accessories can be provided by CHP. This operation allows CHP to be operated at high load factor.

Figure 11 shows the advancement of EER with a gradual introduction of above settings.

In Case A, the production of steam from the boiler is reduced and CHP exhaust heat coefficient is improved, as shown in Table 5. This result shows that not only the introduction of CHP but also the utilization of exhaust heat is important.

The result of Case B shows that the capability of the heat-source equipment is one element toward the realization of a high-efficiency system. Hence, the introduction of high-efficiency heat-source equipment is required in the planning stages, and maintenance and renewal of the equipment at an appropriate time

Table 4. Efficiency of CHP

	Generating efficiency	Efficiency of steam recovery	Efficiency of hot water recovery
Gas turbine	21.0%	48.6%	-
Gas engine	41.2%	19.4%	8.7%
SOFC	50.0%	30.0%	-

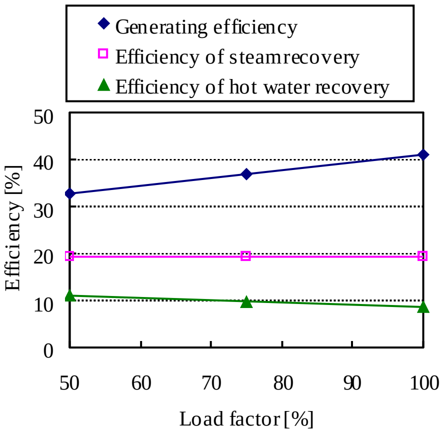


Figure 10. Efficiency change by load factor

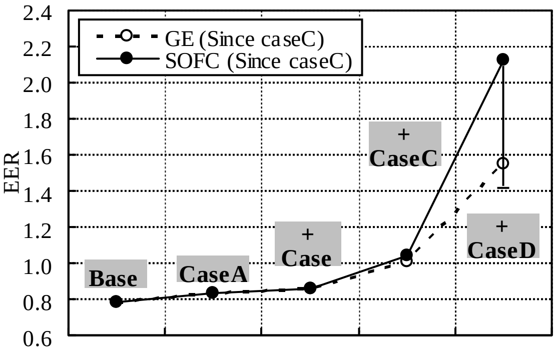


Figure 11. Advancement of EER

Table 5. Generated steam of CHP and boiler

[GJ]	Production of steam		CHP exhaust heat coefficient
	CHP	Boiler	
Base case	261,334 84%	50,682 16%	0.87
Case A	282,496 91%	29,521 9%	0.94
Case C (Gas engine)	64,660 23%	218,915 77%	-
Case C (SOFC)	79,533 27%	213,634 73%	-
Case D (Gas engine)	84,130 57%	63,982 43%	-
Case D (SOFC)	103,167 68%	49,544 32%	-

Table 6. Set capacity and production amount of heat from each refrigerator

	Capacity of CHP	Capacity of turbo refrigerator	Produced amount of heat [GJ]		
			Absorption chiller	Single effect absorption chiller	Turbo refrigerator
Gas engine + Turbo refrigerator	3700kW × 4	28,480kW	4,988 2%	22,645 10%	194,432 88%
SOFC + Turbo refrigerator	4000kW × 6	31,292kW	10,197 5%	0 0%	211,868 95%

are necessary at existing DHC. However, the effect is small compared to other elements.

Introduction of gas engine and SOFC has a high energy-saving effect. The result of Case C shows that absorption-chiller-and-boiler-type DHC plants have the potential for further improvement in energy efficiency with the progress of CHP.

In Case D, increasing the operation of CHP (Table 5) and utilization of the turbo refrigerator (Table 6) lead to the largest efficiency gain (COP of absorption chiller is 1.35. COP of turbo refrigerator is 6.0). This result shows that securing the electric demand is important in the case where CHP of high generating efficiency is used.

It becomes clear that EER can stand at 2.13 with all the above-mentioned measures. This result shows high energy-saving potential with absorption-chiller-and-boiler-type DHC plants in the future. However, this EER is greatly influenced by the introduction of SOFC. Hence, future technical developments of SOFC will make a difference in this result. We also verified the case that the efficiency of steam recovery of SOFC is 10% and 20% incrementally. Incidentally, the feasibility of the pre-set generating efficiency (50%) is high (Anon.). As a result, EER is 1.41 when the efficiency of steam recovery is 10% and EER is 1.75 when the efficiency of steam recovery is 20%. Thus, the efficiency gain of steam recovery of SOFC is important.

CONCLUSION

In this study, progress in the performance of district heating and cooling system is examined. The results of this study are as follows,

Energy efficiency of an actual DHC plant with CHP is verified using a numerical simulation model. The energy-saving effect of gas turbine is small in actual operation. However, if exhaust heat is directed to practical use, gas turbine will have a large effect on the energy saving.

It becomes clear that absorption-chiller-and-boiler-type DHC plants have high energy-saving potential. In order to establish a high-efficiency heat-source system, following elements are essential:

- Introduction of high-efficiency CHP and utilization of exhaust heat
- Energy efficiency of transfer pumps
- Conservation of high performance of heat-source equipment

Above all, CHP is a key factor. In the case of gas turbine, which is applied in existing DHC plants, utilization of exhaust heat is important for energy saving. Meanwhile, in the case of gas engine or SOFC, this has high generating efficiency and will be adopted in the future, and securing electric demand will lead to a high-efficiency system. In order to secure electric demand, the introduction of the turbo refrigerator is effective.

Under existing conditions, EER of electric-driven-heat-pump-type DHC is higher than that of absorption-chiller-and-boiler-type DHC with CHP. The average EER of absorption-chiller-and-boiler-type DHC with CHP is 0.68, and the average EER of electric-driven-heat-pump-type DHC with unused heat-source is 0.99 (Shimoda et al. 2005). Therefore, with the existing system of A-Plant, absorption-chiller-and-boiler-type DHC cannot establish higher-efficiency heat-source system than electric-driven-heat-pump-type DHC. In order to accomplish this, introduction of CHP with high generating efficiency (gas engine or SOFC) is essential.

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