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VERIFICATION OF ENERGY EFFICIENCY OF DISTRICT HEATING AND COOLING SYSTEM USING REALISTIC PARAMETERS

Yoshiyuki Shimoda[1], Tomoji Nagota[1], Naoaki Isayama[1], and Minoru Mizuno[1]

Division of Sustainable Energy and Environmental Engineering,
Osaka University, Suita, Japan

ABSTRACT

This study aims to verify the advantages of district heating and cooling (DHC) systems in terms of energy efficiency. From the measurement data, the parameters that characterize the energy efficiency of a heating/cooling plant are identified for DHC and an individual building. A Simulation model that considers the difference in these parameters is developed. This model examines both the advantages and disadvantages of DHC systems and the effect of each parameter. The results show that the energy efficiency for cooling in DHC systems is superior to that in the case of individual cooling systems because of the "concentration effect" and "grade of operation".

INTRODUCTION

In Japan, district heating and cooling (DHC) has a 35-year history. DHC has many advantages such as high energy efficiency, prevention of air pollution, intensive use of chillers and machinery space, and improvement in landscape because they do not require cooling towers and chimneys at rooftops. In particular, energy efficiency has gained attention in recent years due to mitigation measures against global warming.

The energy efficiency characteristics of DHC are based on the following two factors:

Factor I: Economies of scale such as intensive operation of chillers and other equipments, introduction of highly efficient equipment and efficient operation and maintenance by well-trained operators.

Factor II: Use of an environmentally sound heat source available only for DHC, for example, waste heat from incinerators, combined heat and power, and river and sea water as heat sink/source of heat pump.

Since the advantage of the factor II is evident, we focus on the effect of the factor I in this paper.

Shimoda et al. have surveyed the energy efficiency of most of the Japanese DHC systems in a business district (Shimoda et al., 2003). Figure 1 shows a

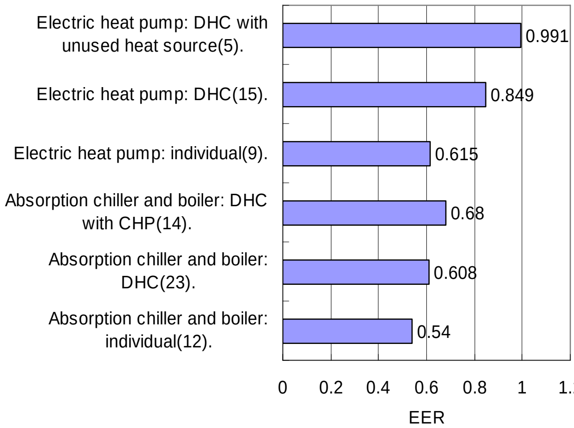


Figure 1. Average EER of DHC and individual system [()= number of sample]

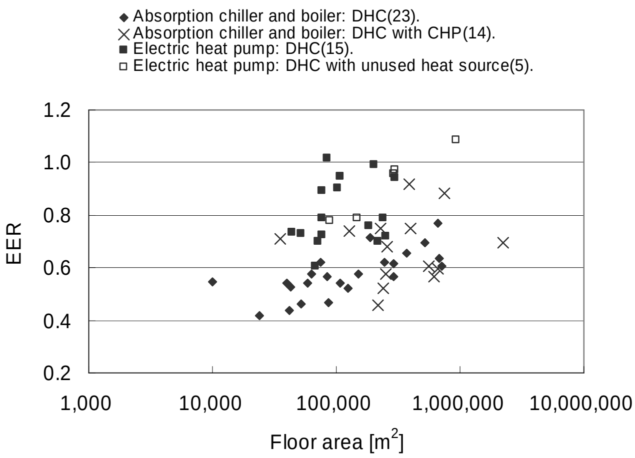


Figure 2. Distribution of EER in DHC

comparison of the measured energy efficiency ratio (EER) between DHC and a conventional heat source system in individual buildings. EER is defined as follows.

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

On an average basis, the effects of factor I and factor II are evident for "absorption chiller and boiler type" and "electric driven heat pump type" respectively. However, as shown in figure 2, the EER distribution of EER of each DHC system exhibits a wide dispersion even in the same category. This indicates that the energy efficiency of the DHC plant is affected by various kinds of factors such as the heat loss from pipeline, part-load operation of chillers, pumps and fans, as well as the efficiency of the equipment.

It should be noted that the actual operations of chillers and other equipment are usually different from the operation planned during the design stage. For example, in a multiple chiller plant, the number of operational chillers is usually greater than that required to meet the heat demand; consequently, since the load factor of the chillers decreases, the energy consumption of the chillers and that of pumps increases.

However, since the conventional simulation program of the DHC plant did not consider these discrepancies that occurred during actual operation, the simulated energy efficiency was usually higher than the measured values. Therefore, a simulation model that considers these discrepancies is necessary not only for verifying the advantages of DHC but also for improving the control system of chillers in the individual plants of the buildings (Chow et. al. 2002, Chang et. al. 2005, Spethmann 1985).

In this paper, we first identify the parameters that characterize the energy efficiency of the heating/cooling plant on the basis of the measurement data for DHC and individual buildings. These parameters are the efficiency of the equipment and the grade of operation and maintenance. A simulation model that considers the difference in these parameters is developed and the advantages and disadvantages of the DHC system are examined

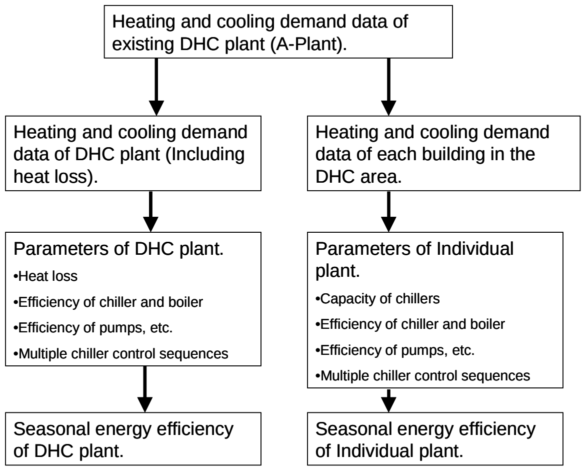


Figure 3. Flow of the study.

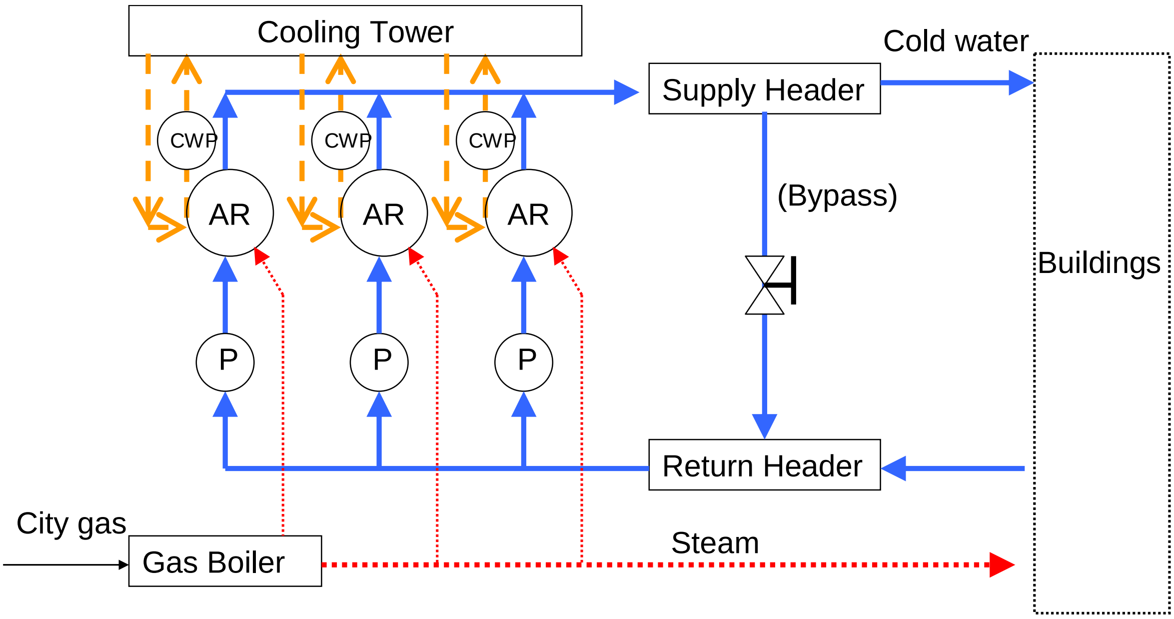
by using this model. Figure 3 shows the flow diagram of this study.

SIMULATION MODEL

Heating/cooling plant model

This study examines the plant consisting of an absorption chiller and boiler, which uses city gas as the main energy source. In a DHC plant of this type, a steam boiler and double-effect absorption chiller are employed. In the individual building plant, direct-fired double-effect absorption water chiller boiler is generally used. Figure 4 shows the system configuration of the DHC plant.

An existing DHC plant in Japan (A-Plant) is modeled in this study. This DHC area consists of 13 buildings.



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

Figure 4. District heating and cooling plant

In the “DHC” case, the energy consumption of the DHC plant is simulated by using total heating/cooling load data including heat loss from the pipeline and internal use (heat produced by the A-Plant) as input data. In the “individual heating/cooling” case, the energy consumption of the heating/cooling plant in each building is simulated respectively by using heat load data (measured heat supplied to each building from the DHC plant) as input data. The simulated energy consumption of the 13 buildings are summed and compared with energy consumption in the DHC case. In the simulation of cooling, cooling load data is provided as the measured flow rate and temperature difference.

Factors considered in the simulation.

In order to precisely simulate the difference between DHC plant and individual building plants, the difference in the following parameters is determined by means of the measured data of nine DHC plants and 19 individual buildings.

1. Heating and cooling load

In this simulation, cooling load data is supplied as the measured flow rate of chilled water and the measured temperature difference between the supply and return water in order to correctly simulate the chiller sequence control.

2. Efficiency of chiller and boiler

The efficiency of the steam boiler used in the DHC plant is set at 0.820 on the primary energy basis. This value includes the power consumption of accessories in the boiler system. Considering the economy of scale, the efficiency of water boiler used in each individual building plant is set as 0.791.

The COP of double effect absorption chiller used in the DHC plant is set as 1.2[= (cold heat)/ (steam)] at the rated condition. Change in the COP caused by part-load operation and the cooling water temperature are modeled as shown in figures 5 and 6, respectively. The cooling COP of the direct-fired double-effect absorption water chiller boiler is set as 1.0[= (cold heat)/(city gas)]. Changes in the COP are modeled in same manner as that adopted for the chiller in the DHC case.

3. Cooling capacity of the plant.

In the individual building case, there are three chillers in each building. The total capacity of the chillers is equal to the product of the peak load and “safety factor”. Therefore, the load factor of the chiller never reaches 1.0 even at the peak load. The capacities of the three chillers are set in the ratio of 1:2:2. In the DHC case, the capacities of all the chillers are set as 4220kW.

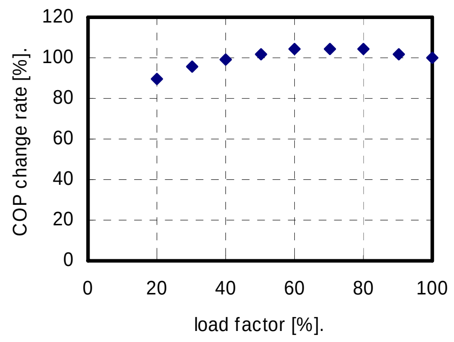


Figure 5. COP change by load factor

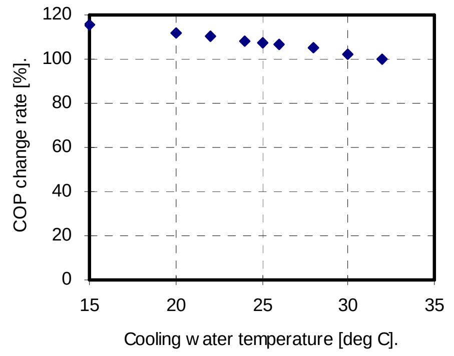


Figure 6. COP change by cooling water temperature

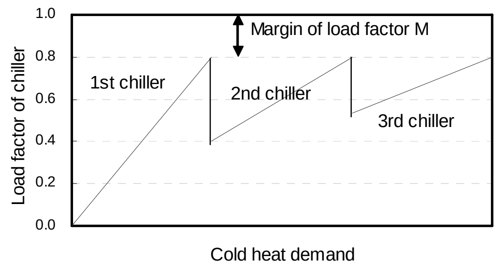


Figure 7. Margin of load factor

4. Power consumption of pumps, accessories and cooling tower.

By comparing the actual data obtained from DHC systems and individual buildings, the power consumption of the cooling water pump, chilled water pump, accessories of absorption chillers and cooling tower are set as follows:

The power consumption of the cooling water pump per unit capacity of the chiller is set to the same value for DHC and the individual buildings.

The power consumption of the cold water pump per unit capacity of the chiller in DHC is set to be larger than that in the individual buildings since there is a pressure loss in the pipeline.

The power consumption of accessories of the absorption chiller P_a is modeled as a function of the cooling capacity of the chiller, R[kW], as follows:

Table 1. Parameters used in the base case.

	DHC	Individual plant in the building
Safety factor of the chiller capacity	-	120%
Cooling water pump [kW/RT]	0.134	0.134
Cold water pump [kW/RT]	0.075	0.053
Cooling tower[kW/kW of waste heat]	0.0058	0.0078
Margin of load factor *M*	10%	30%
Minimum flow rate of bypass pipe [% of the flow rate of smallest chiller]	20%	50%
Energy efficiency of the Boiler	0.820	0.791

$$P_a[kW] = -1.05\times10^{-2}R + 0.0276 \qquad (2)$$

The power consumption of the abovementioned machines is set to a constant value during the operation of the chiller that they are connected.

The power consumption of the cooling tower per unit waste heat from the chiller in DHC is set to be smaller than that in the individual building due to the economy of scale.

5. Multiple chiller control sequence

The chiller control sequence which determines the number of operational chillers is determined on the basis of the total heat load and flow rate of cold water as follows:

In order to respond to the sudden increase in the cooling load and avoid short-cycling of the chiller operation, chillers are operated in a manner such that they have a margin of load factor as shown in figure 7. Johnson termed this margin as "dead band" (Johnson, 1985). Owing to the difference in the operator's skill, the measured value of the margin *M* (1.0: maximum load factor of chiller) in DHC is lower than that in an individual plant, as shown in figures 8 and 9. The results of this survey also indicate that the chiller sequence was not controlled in two-thirds of the individual cooling plants.

In addition, in order to respond to a sudden increase in the flow rate of cold water, the flow rate in the bypass pipe shown in figure 4 should be larger than a certain value. Therefore, the total flow rate of chillers must be larger than the sum of the supplied flow rate and the minimum bypass flow rate (figure 10). If valuable water volume (VWV) control in the building always functions properly, a restriction in the cooling water volume has the same effect as the restriction in the cooling load. However, since the temperature difference between the supply and return water becomes smaller with decreasing cooling load, as shown in the figure 11, an increased flow rate and more chillers are necessary to meet the heat demand.

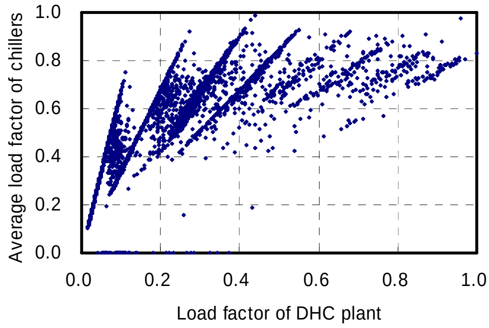


Figure 8. Multiple chiller sequence in DHC plant

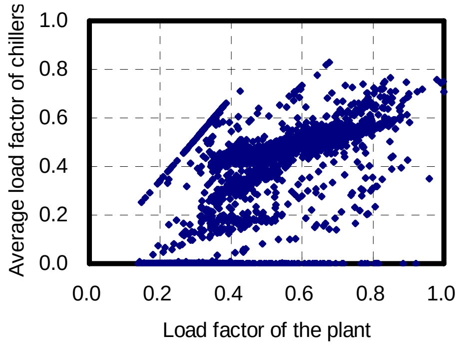


Figure 9. Multiple chiller sequence in individual plant

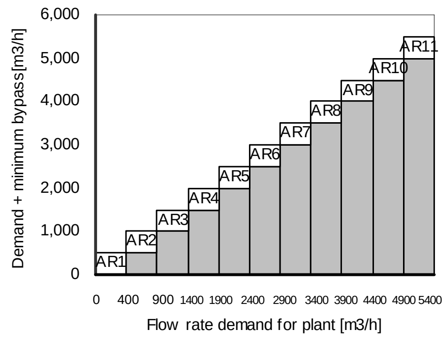


Figure 10. Chiller control sequence by flow rate

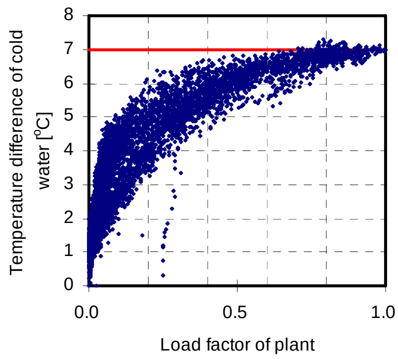


Figure 11. Relationships between cooling load and temperature difference in cold water in the A-Plant.

Therefore, both types of restrictions are necessary (Shimoda et. al., 1999).

Table 1 lists the parameters used in the simulation.

SIMULATION RESULTS

Base case result

Table 2 lists the simulation result of the annual primary energy consumption in the DHC case and the individual heating/cooling case. The simulated EER of the DHC case is 0.69, which is close to the simulated EER of 0.64 measured at the A-Plant.

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

		DHC case [GJ]	Individual case [GJ]	Energy conservation
Cooling	Chiller	216,476	203,940	−0.06
	Accessories	7,516	12,824	0.41
	Cooling tower	6,472	8,899	0.27
	Cooling water pump	41,881	68,212	0.39
	Cold water pump	23,459	26,979	0.13
	Sub-total	295,803	320,853	0.08
Heating	Boiler	117,173	89,790	−0.30
	Accessories	1,431	1,057	−0.35
	Sub-total	118,604	90,847	−0.31
Total	Total	414,407	411,700	−0.01
	EER	0.69	0.69	-

This result indicates that the energy efficiency in the DHC case is almost the same as that in the individual case. A summary of this result follows.

- The COP of the chiller at the rated condition (load factor = 100%, cooling water temperature = 32°C) of the DHC case is slightly smaller than that of the individual case. In this rated condition, the conversion efficiency of gas to cold heat in the individual case is 1.0, while it is equal to 0.82 (Boiler)×1.2 (Absorption chiller) = 0.984 in the DHC case.
- Additionally, since the COP of the absorption chiller is not affected by the part-load ratio to a significant extent, as shown in figure 5, the energy consumption of the chiller itself is not affected by parameters related to the operation.
- However, since the energy consumption of accessories and pumps is in proportion with the operational hours of the chiller, their energy consumption becomes smaller in the DHC case. In total, the energy consumption for cooling in the DHC case is lower than that in the individual cooling case by 8%.
- On the basis of the survey of the DHC and individual plants, the energy efficiencies of the boiler and its accessories does not vary with part load and further, these efficiencies are almost constant. Therefore, the difference in operation between the DHC and individual plants does not affect the amount of energy consumption.
- On the other hand, there is a large amount of heat loss in the DHC plant. Since there is a small heating demand in the A-Plant, i.e., the heating demand is one-third of the cooling demand, the ratio of the heat loss to heating demand reaches 35%. Therefore, the total energy consumption of the DHC case does not show the advantage over that in the individual case.

Effect of operation on cooling energy efficiency

As mentioned previously, the energy consumption for cooling in the DHC case is lower than that in the individual case by 8%. Figure 12 shows the hourly change in the total capacity of operational chillers and their average part-load factor on 15th June. This figure shows that the part-load factor of chillers in the DHC plant is maintained higher than that in the individual plant by 60 − 100 % all throughout the

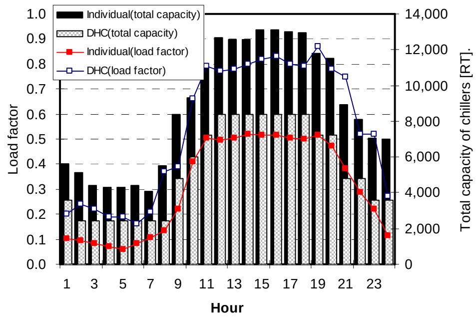


Figure 12 Hourly change of chiller sequence on 15th June.

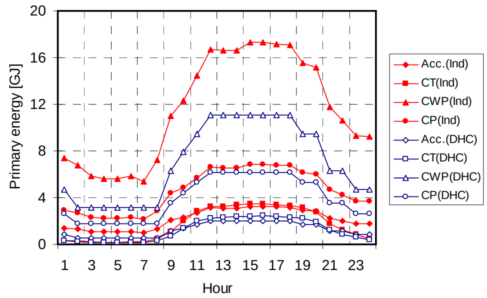


Figure 13 Hourly change of energy consumption of pumps and other machines.

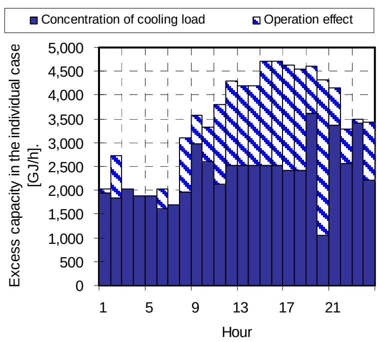


Figure 14 Breakdown of the operation effect.

day. This fact brings about the difference in the energy consumption of the pumps and that of accessories, as shown in figure 13.

By comparing this result with the optional simulation result of the individual case in which the parameters "margin of load factor" and "minimum flow rate of bypass pipe" are set to the same values as in the DHC case, the effect of operation on the total energy efficiency can be evaluated as shown in the figure 14. This result demonstrates that 32% of the reduction in the total operating chiller capacity is due to the difference in operation. The reminder is due to the concentration of the cooling load in one DHC plant. In particular, at midnight, at least one chiller must be operated at a very small cooling load in each building in the individual cooling case, whereas in the DHC case, cooling loads are concentrated into the DHC plant and handled by one or a few chillers.

Factorial experiment

In order to clarify the effect of each factor on the total energy efficiency, optional simulations as shown in the table 3 are performed.

a) The difference between RUN-0 and RUN-1 indicates the "concentration effect", which refers to the correction of the heat load of one plant in each building. This effect is peculiar to district heating and cooling systems.

b) The difference between RUN-1 and RUN-2 indicates the "heat transportation loss", which includes the heat loss from the pipeline and the additional power consumption of the cold water pump.

c) The difference between RUN-2 and RUN-3 indicates the "economy of scale" of the DHC systems plant. This includes the difference in the efficiency of machine.

d) The difference between RUN-3 and RUN4 indicates the difference in the "grade of operation".

Figure 15, 16 and 17 exhibit the effects of these differences on cooling, heating and total energy consumption, respectively. The results indicate that the concentration effect is the most prominent advantage of the DHC system. In the case of cooling, the grade of operation also has a large effect.

The effect of the other potential parameters

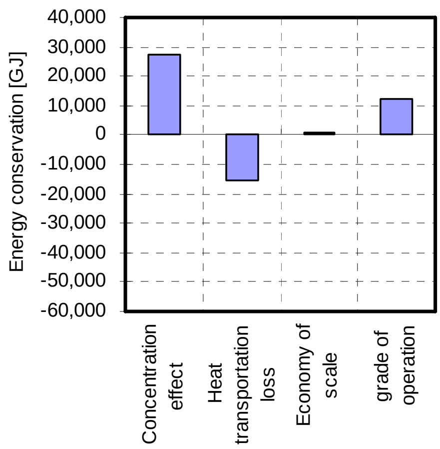


Figure 15. Effects of the factors on cooling.

Table 3. Details of the optional simulation for the factorial experiment

	RUN-0 (Base case of Individual plant)	RUN-1	RUN-2	RUN-3	RUN-4 (Base case of DHC)
Model*	Individual	DHC	DHC	DHC	DHC
Chiller and Boiler	Direct-fired double effect absorption water chiller boiler	Direct-fired double effect absorption water chiller boiler	Direct-fired double effect absorption water chiller boiler	Double effect absorption chiller & Steam boiler	Double effect absorption chiller & Steam boiler
Heat loss	Not Included	Not included	Included	Included	Included
Cold water pump [kW/RT]	0.053	0.053	0.075	0.075	0.075
Cooling tower[kW/kW of waste heat]	0.0078	0.0078	0.078	0.058	0.058
Margin of load factor *M*	20%	20%	20%	20%	10%
Minimum flow rate of bypass pipe [% of the flow rate of smallest chiller]	50%	50%	50%	50%	20%

*DHC model: Simulation of the one plant that handles total heating/cooling load for all of the building.
Individual model: Simulation of 13 plants that handle each building's load individually.

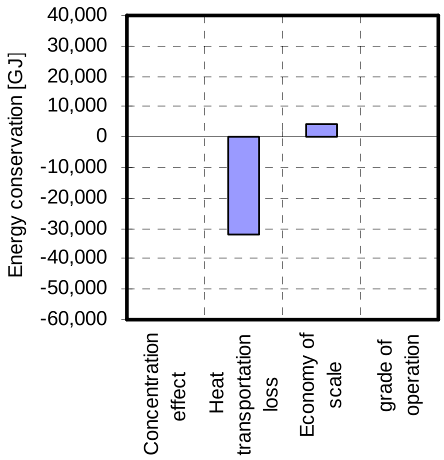


Figure 16. Effects of the factors on heating

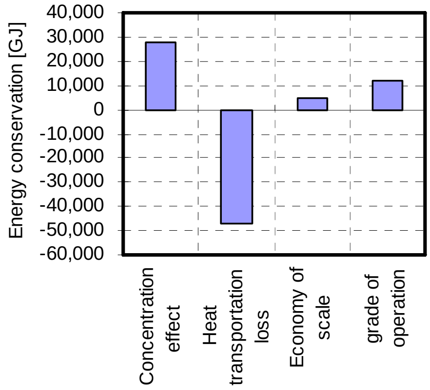


Figure 17. Effects of the factors on total heat supply.

From the base case result, it can be seen that the energy efficiency of the DHC system is almost the same as that in the case of the individual heating and cooling. However, the average EER measured in the DHC system is higher than that measured in the individual heating and cooling plant, as shown in figure 1. One of the reasons for this is the existence of other factors which affect the difference in the energy efficiency. In addition, there is a possibility of reducing the heat loss, which is the main reason that the energy efficiency of the DHC plant is inferior to that of the individual heating and cooling plant.

In this part, the effects of the other factors, which were not observed in our analysis of measurement data, are discussed.

A. Allocation of cooling capacity to chillers in the individual cooling plant.

In the well-designed cooling plant employed in the individual building, cooling capacities of chillers are allocated unevenly to ensure efficient operation at a small load as base case of this study. However, this differentiation in cooling capacity is not common in most of the individual buildings. The case wherein the cooling capacity is allocated as 1:1:1 is simulated (RUN-A).

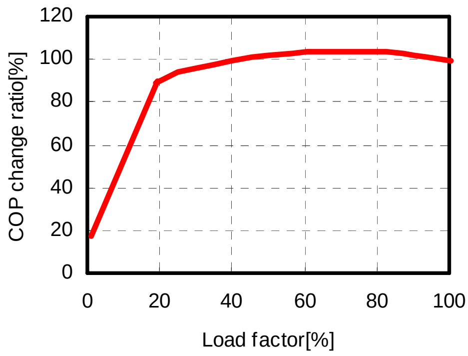


Figure 18. Relationships between the COP and load factor (Takahashi, et. al. 1999)

Table 4 Results of simulation with the additional parameters

RUN	Energy Consumption [GJ]			EER
	Cooling	Heating	Total	
Individual (Base case)	320,853	90,847	411,700	0.69
Individual (RUN-A)	324,449	90,847	415,295	0.69
Individual (RUN-B)	329,861	90,847	420,708	0.68
Individual (RUN-C)	366,419	102,617	469,036	0.61
DHC (Base case)	295,803	118,604	414,407	0.69
DHC (RUN-D)	296,959	90,795	387,754	0.74
Individual (RUN-E)	320,853	272,541	593,394	0.72
DHC (RUN-E)	295,803	293,806	589,609	0.73

Since heat load of RUN-E is different from other case, energy consumption in RUN-E is not comparable with other case.

B. Decrease in COP of absorption chiller at low load factor

In the base case, the COP of the chiller when the load factor is less than 20% is considered to be the same as the COP at a load factor of 20%. However, Takahashi et al. pointed out that the COP, when the load factor is less than 20% is lower, as shown in figure 18, since a large energy loss occurs due to the repeated on and off operations of the chiller. Therefore, the case wherein the relationship between the load factor and COP is modeled as shown in figure 18 is also simulated (RUN-B).

C. Difference in the degree of maintenance

In this study, the degradation in the energy efficiencies of the chiller and boiler is not considered. However, in general, the degree of maintenance in the DHC plant is higher than that in the individual buildings. Therefore, the case wherein the chiller's COP of the individual plant decreases by 20% and the efficiency of the water boiler in the individual plant also decreases by 10% as a result of aged deterioration is simulated (RUN-C).

D. Improvement in the heat loss ratio of the DHC plant

In the A-Plant, the heat loss in heating reaches 35% of the heating demand. In addition to the low heat demand (denominator of heat loss ratio) in the A-Plant, the total heat loss in heating is 23,555 GJ/yr, which is considerably greater than the ideal value of 2,619 GJ/yr; this ideal value is calculated from the standard size of the pipe and insulation in the A-Plant. Therefore, the case wherein the heat loss reduces to this ideal value is simulated (RUN-D).

Furthermore, the case wherein the total heat demand is increases to 300% of the present amount and accordingly the heat loss ratio decreases to 12% is also simulated (RUN-E).

The results of these simulations are presented in table 4. These results show that the advantage of DHC becomes evident when one of the parameters is considered, especially the difference in the degree of maintenance or the improvement in the heat loss. If the heating demand becomes almost the same as the cooling load, the EER of the DHC plant exceeds that of the individual plant.

CONCLUSION

In this study, the energy efficiency of the district heating and cooling plant is examined. The results of this study are as follows:

The advantage of district cooling is verified quantitatively by simulation using realistic parameters obtained from the measurement data. The reasons for advantages are categorized as the concentration effect, grade of the chillers and pumps, and grade of operation. The effects of these factors are quantified by simulations.

Furthermore, the result also indicates the importance of improving the operation of the individual cooling plant, such as the chiller sequence by Building Energy Management Systems (BEMS). The introduction of the valuable speed pump can alleviate the disadvantages caused by the concentration effect.

The magnitude of the effect of each factor depends on the cooling and heating load profile of the DHC plant. Therefore, it is necessary to conduct sensitivity analysis on the load profile by this simulation model in order to determine the ideal load profile for obtaining the maximum energy efficiency.

Due to insufficient data, it is very difficult to define “standard” parameters for individual heating and cooling plants. Therefore, further field survey is required.

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