A STUDY ABOUT IMPROVEMENT OF EFFICIENCY OF A SEWAGE HEAT UTILIZATION SYSTEM

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Abstract: We investigate an optimum design and operation of a sewage heat utilization system by extracting and analyzing operational data on the Makuhari High-Tech Business Area District Heating and Cooling System (hereafter referred to as “Makuhari DHC System”). The analysis revealed that a constant high effect can be obtained in terms of different cold/hot heat ratios required by consumers, and that the effectiveness of using sewage as a heat source would be increased.
Furthermore, compared with "the conventional concentrated heating system", "a distributed heat pump systems with separate heat sources water" uses sewage more effectively.

Key Words: ***sewage heat, district heating and cooling, unused-energy, heat pumps, centrifugal refrigerating machine***

1 BACKGROUND AND PURPOSE OF STUDY

The properties of treated sewage are such that the temperature level is lower than the atmospheric temperature in summer and higher in winter, and an enormous, stable amount of sewage heat is generated in the vicinity of cities. Taking advantage of these characteristics, treated sewage water can be used as cooling water (heat sink) in summer and as the heat source in winter for heat pumps, whose performance has been improved and functions have been increased by technological development in recent years.
The application of sewage heat shows high potential in urban area both as an energy conservation system, and as an effective countermeasure against the heat island phenomenon. Therefore, it is necessary to analyze and evaluate an existing sewage heat utilization system, and then we study the possibility of developing a more advanced system. For this study, we selected “Makuhari DHC System”, which is a conventional sewage heat utilization system of a concentrated heat source type.

2 OUTLINE OF THE MAKUHARI DHC SYSTEM

The Makuhari DHC System is a heat supply plant using treated sewage from the Chiba-ken Inbanuma Basin Hanamigawa Sewage Treatment Plant. The service area to which heat is supplied is about 490,000 m^2 with a total floor area of about 900,000 m^2.
The Hanamigawa Sewage Treatment Plant handles a maximum of 410,000 m^3 wastewater per day (310,000 m^3 on average per day). The Makuhari DHC System uses a maximum of 200,000 m^3 treated sewage per day as heat source water or cooling water. An outline of the system is shown in Figure 1.

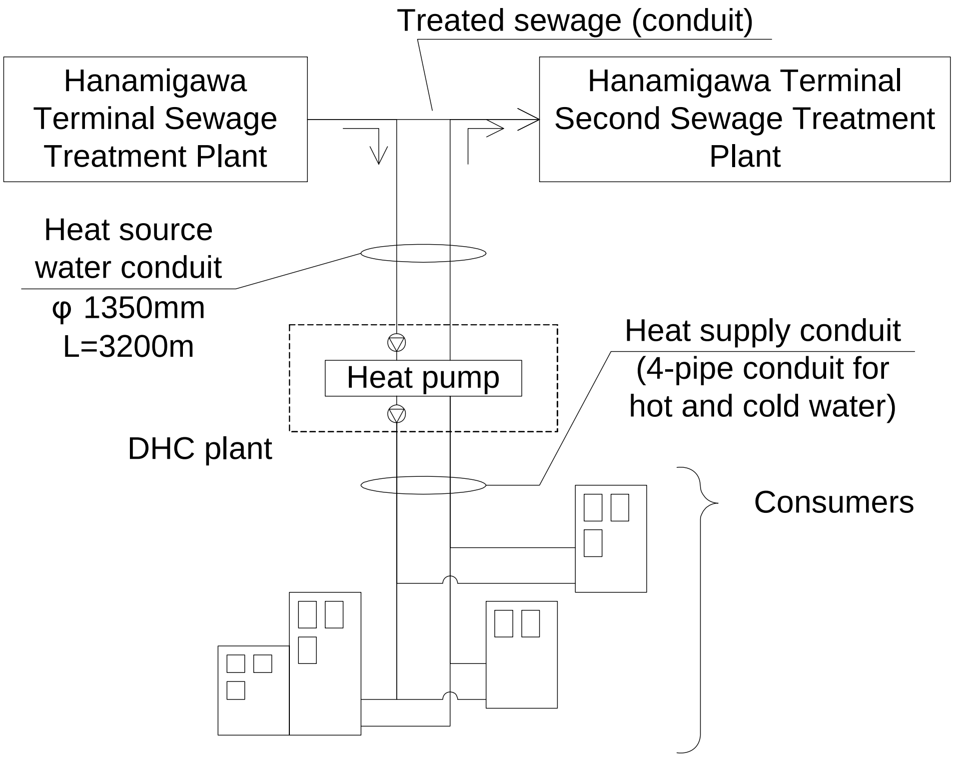

Figure 1: Basic concept of Makuhari DHC

As shown in Table 1, the heat source equipment of the Makuhari DHC System is composed of centrifugal refrigerate machines and water source heat pumps, capable of producing 251 GJ/h total cold/hot heat.

Table 1; Heat source equipment

	Operation mode	Cold heat		Hot heat	
		Capacity (GJ/h)	**Production temperature**	**Capacity (GJ/h)**	**Production temperature**
R- 1	Exclusively for cooling	15.8	5 °C		
R- 2	Exclusively for cooling	10.7	-3 °C		
R- 3	For heat recovery	8.7	6 °C	11.3	47 °C
R- 4	For heat recovery	8.7	6 °C	11.3	47 °C
R- 5	For heat recovery	17.1	6 °C	20.9	47 °C
R- 6	For Switching of cooling/heating	38.0	5 °C	39.8	50 °C
R- 7	Exclusively for cooling	38.0	5 °C		
R- 8	For Switching of cooling/heating	38.0	5 °C	39.8	50 °C
R- 9	For Switching of cooling/heating	38.0	5 °C	39.8	50 °C
R-10	Exclusively for cooling	38.0	5 °C		
	Total capacity	251.0		162.9	

The configuration of this heat-production system is classified into thermal storage systems (R-1, R-2), heat recovery systems (R-3 to R-5) and usual closed systems (R-6 to R-10). The heat storage system and the closed system use treated sewage as heat-source water or cooling water, and the heat recovery system is a double-bundle heat pump that simultaneously produces hot water and cold water. So that sewage heat is not used. Buildings in the supply target area are mainly office buildings, and about 80% of the total amount of heat produced from the Makuhari DHC System throughout the year is used to meet the cooling demand in this area. The primary energy conversion overall coefficient of performance (hereafter referred to as “total COP (*Rt*)”) has been about 1.35 in recent years. The total COP (*Rt*): *Rt* is defined by:

$Rt = Q_D / Et$ Equation (1)

Q_D : Amount of heat sold
E_t : Amount of primary energy input

3 PERFORMANCE EVALUATION OF SEWAGE HEAT UTILIZATION SYSTEM

3.1 Evaluation method

The Makuhari DHC System is composed of various heat-production systems including those for thermal storage and heat recovery. In evaluating a system that uses only sewage heat, it is essential to analyze and clarify the factors contributing to the total COP (Rt). The analysis methodology is described below.
First, a schematic flow diagram from energy input to production and supply (demand end) of heat is created, as shown in Figure 2.

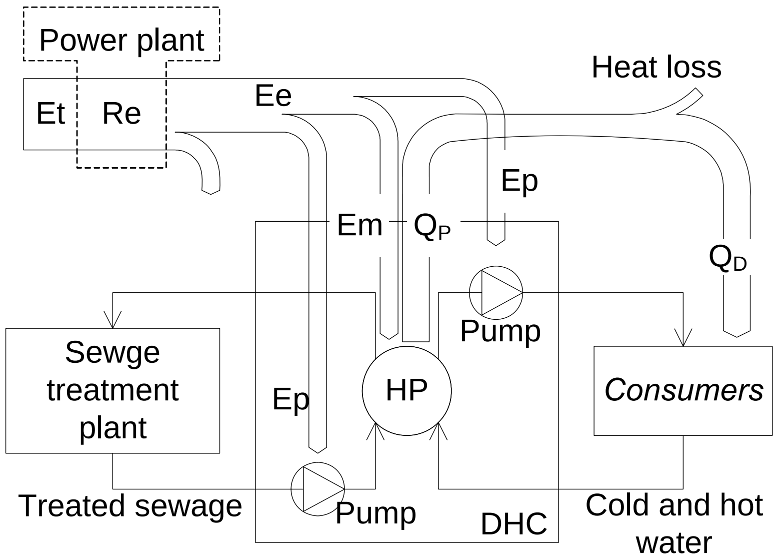

Figure 2: Basic concept of heat pump system

The symbols shown in Figure 2 are defined as follows:

Ee : Input electric energy
Re : Power generating efficiency (estimated to be 0.37)
Et : Amount of primary energy input
Em : Electric energy input to HP (main machine)
Ep : Electric energy input to auxiliary equipment power
Qp : Amount of heat produced
Q_D : Amount of heat supplied (demand end)
Ms : Heat conveyance efficiency of a heat supply facility (Q_D / *Qp*)
COP : Co-efficient of performance of heat pump in itself (*Qp* / *Em*)
(hereafter referred to as “COP of equipment”)

Equation (1) can be converted into equation (2), because of following 3 reasons.
1) "Re" into "Ee" gives "Et".
2) "Ee" is the sum of "Em" and "Ep".

3) Ratio of "QD" to "Qp" is "Ms"
So that the total COP(Rt) can be expressed as shown in Equation (2).

$$Rt = Q_D / Et = Q_D / (Ee / Re) = Re\, Q_D / (Em + Ep) = Re\, Ms\, Qp / (Em + Qp)$$
$$= Re\, Ms / (1 / COP + Ep / Qp) \qquad \text{Equation (2)}$$

The heat production and supply system can be divided into three operational modes: (1) Chilled water production and supply purposes mode (c); (2) Hot water production and supply purposes mode (h) and (3) The other purpose mode (r). When divided into each operational mode as shown in Eq. (2), and the ratio of the amount of heat supplied in each operational mode is given as α, β, γ ($\alpha + \beta + \gamma = 1$), Equation (3) can be obtained by expanding Equation (2).

$$1 / Rt = \alpha / Rc + \beta / Rh + \gamma / Rr \qquad \text{Equation (3)}$$

Here,
Rc : Total COP (Rc) of a system for chilled water production and supply purposes
Rh : Total COP (Rh) of a system for hot water production and supply purposes
Rr : Total COP (Rr) of the other system

According to Equation (3), even a composite system such as the Makuhari DHC System, the total COP(Rt) can be expressed in easy additions simply as the sum of a linear expression by using reciprocals ($1/Rc$, $1/Rh$, $1/Rr$) of the total COP of each system and the ratio of heat supplied (α, β, γ).
Equation (3) is used for the analysis and evaluation of performance data in the next and subsequent sections.

3.2 Analysis of COP of heat source equipment

In this section, we analyze the COP of each equipment which is using sewage heat. We choose the existing data of R-6, R-7, R-8 and R-9 for producing cold heat, and also R-8 and R-9 for producing hot heat. Because these equipment was operated stably. Figure 3 shows the COP of cold/hot heat production by month. The COP fluctuated in the range of 4.0 to 6.0.

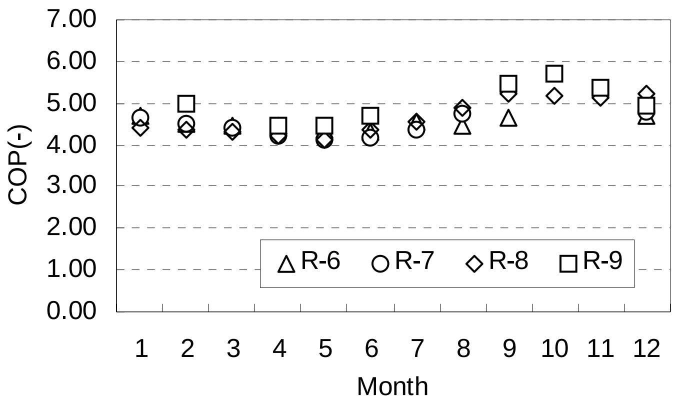

Figure 3: COP of heat source equipment (FY2002)

3.3 Performance of auxiliary equipment power

When using sewage, pumps for cooling water used for conveyance of sewage, is added to the ordinary system configuration. Since the amount of power required for the auxiliary equipment varies depending upon the distance from the auxiliary equipment to the generating source of sewage heat, the difference of temperatures between going to and coming from consumers, and the efficiency of the pump, these factors affect the evaluation of total COP (*Rt*). Consequently, auxiliary equipment power per amount of heat produced is determined as follows.

We arrange the existing data of " *Ep / Qp* " shown in Equation(2), and the arrangement of data targeted the range where the load factor becomes 50% or more. Because operation time at a load factor below 50% is short, and the amount of heat produced is about 10%of the total. The results of analysis are shown in Table 2.

Table 2; Auxiliary Equipment Power per Amount of Heat Produced

	Cold heat	**Hot heat**
Unit energy consumption of auxiliaries (-)	0.035	0.034

3.4 Performance of heat conveyance efficiency

In concentrated heat-source systems including the Makuhari DHC System, the hot and cold water produced is supplied through local conduits, and thus heat loss must be taken into consideration. The Makuhari DHC System uses a local conduit of about 1.5 km in length. The heat conveyance efficiency (*ηs)* is determined as follows.

Figure 4 shows the heat conveyance efficiency of hot/cold heat by month. The efficiency fluctuates, but the annual mean value of hot heat conveyance efficiency is 90.5%, whereas that of cold heat conveyance efficiency is 92.4%.

3.5 Analysis and evaluation of total COP (*Rt*)

We compare the total COP(Rt) using the result of Section 3.2 to 3.4, with the total COP(Rt') which is calculated by supposing that all equipment of the Makuhari DHC is a sewage heat utilization system. Figure 5 shows the total COP (*Rt*, *Rt'*) by hour and the cold/hot heat ratio. Meanwhile, *Rt* actually attained was 1.39 and *Rt'* of the sewage heat utilization system was 1.33. The cold/hot heat ratio indicates the value in which the total cold heat is divided in the total amount of hot / cold heal load.

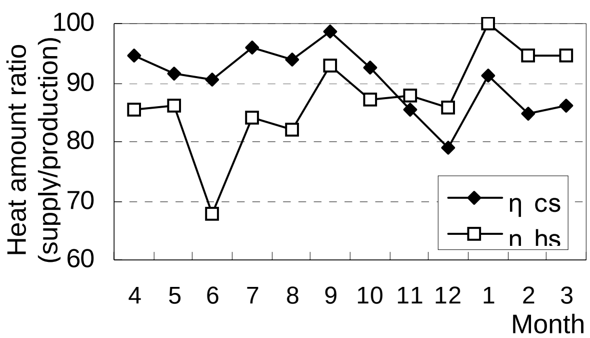

Figure 4: Ratio of supplied heat at demand side to production heat (FY2002)

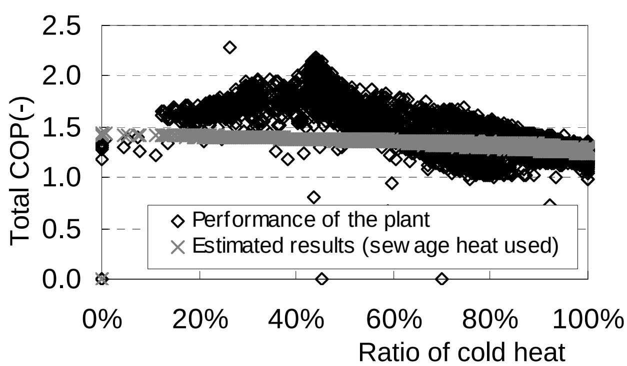

Figure 5: Total COP(Rt,Rt') by hour and the cold / hot heat ratio

According to Figure 5, the total COP (*Rt*) based on the performance of the Makuhari DHC System indicates that the highest value is in the vicinity of a cold/hot heat ratio of 45% and then it goes down toward both ends (0% or 100%) of the cold/hot heat ratio. This is because the heat recovery system works most efficiently around the 45% ratio, which can be seen in the Figure 5. In other words, in a plant where cold heat and hot heat are simultaneously generated as is the case with the Makuhari DHC System, optimum operation would be achieved by using mainly a heat recovery system.

On the other hand, since the total COP (*Rt'*) of a sewage heat utilization system is stable irrespective of the cold/hot heat ratio, a high rate of efficiency can be maintained even if cold heat and hot heat are generated at any balance.

That is, the sewage heat utilization system can be operated at a high COP with various kinds of urban heat load, and its applicable field is various, so it may be possible to design a highly flexible system.

4 STUDIES ON IMPROVED EFFICIENCY OF SEWAGE HEAT UTILIZATION SYSTEM

To improve the usage of sewage heat based on the conclusions obtained by the above discussion, we study an improved sewage heat utilization system by effectively using sewage heat and optimizing the plant configuration.

4.1 Study on the effectiveness of sewage heat

To confirm the effectiveness of sewage heat, we analyze the correlation between outside air temperature, cooling water temperature of a cooling tower and sewage temperature, and the relationship between these temperatures and the generation frequency by cold/hot heat.

The following data was used in the analysis: "Outside Air Temperature" (Tokyo area) reported by the Meteorological Agency; "Cooling Water Temperature of a Cooling Tower," which is the calculated value at a rated load obtained from the cooling tower performance curve of Corporation A based on meteorological data; "Sewage Temperature" and "Heat Demand" obtained from actually measured values of the Makuhari DHC System (all the above data is based on values obtained by actual measurement in 2002(FY)).

A duration curve was plotted for outside air temperature (one-hour mean value), with a horizontal axis of 8,760 hours per year, and the sewage temperature, cooling water temperature, amount of cold heat supplied and amount of hot heat supplied corresponding to specific hours of the duration curve are indicated in the graph shown in Figure 6. Concerning the sewage temperature and cooling water temperature, a first-order approximation of each data set was used.

4.1.1 Relationship between sewage temperature and outside air temperature

Generally, sewage temperature is stable throughout the year compared with outside air temperature. According to Figure 6, since the maximum sewage temperature is about 27°C when outside air temperature is highest (about 35°C), using sewage heat during an extremely hot summer period is more advantageous than using an air-cooled heat pump chiller, and the effect of alleviating the heat island phenomenon is also considered to be high.

On the other hand, since sewage temperature is about 18°C when outside air temperature is lowest (about 0°C), the difference between sewage temperature and outside air temperature is larger in an extremely cold winter period than in an extremely hot summer period.

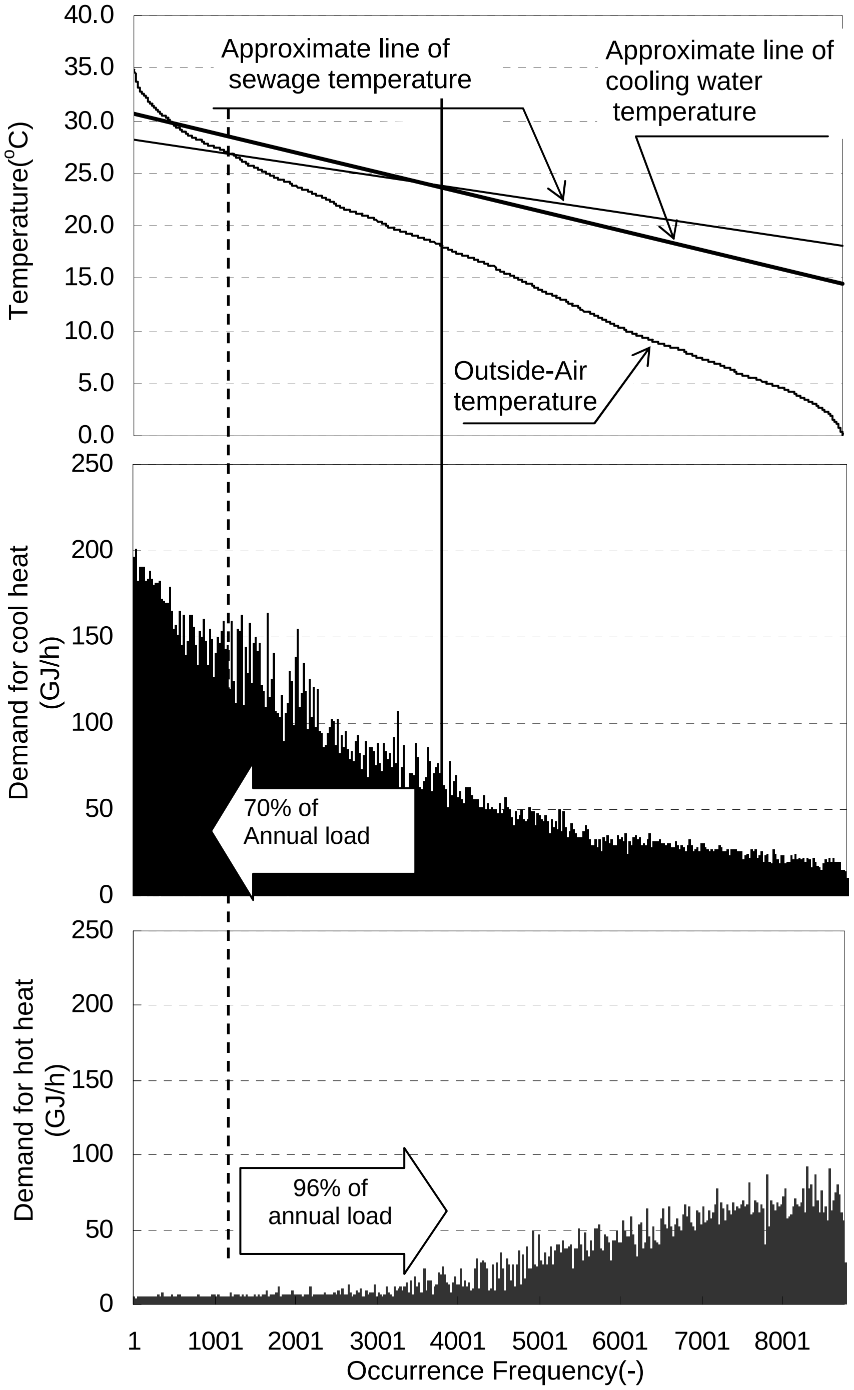

Figure 6: Relationship between temperature and cold/hot heat load (FY2002)

4.1.2 Characteristics of sewage heat as a cooling source

Looking at the generation frequency of demand for cold heat (middle graph of Figure . 6), it is clear that a cold heat load in which cooling water temperature is higher than sewage temperature accounts for about 70% of the annual cold heat load.
Thus, in cases where sewage is used as a cooling source, improved COP can be expected in this specific range.

4.1.3 Characteristics of sewage heat as a heating source

Compared with outside air temperature, sewage temperature is high for most of the year. Judging from the generation frequency of demand for hot heat in the Makuhari DHC System (bottom graph of Figure . 6), a hot heat load in which sewage temperature is higher than outside air temperature accounts for about 96% of the annual hot heat load. The higher the demand for hot heat in accordance with the decline in outside air temperature increase, the larger the difference between sewage temperature and outside air temperature becomes. So, sewage heat is more effective than an air heat source. Furthermore, fluctuations in sewage temperature throughout the year (18°C to 27°C), if the most up-to-date inverter type heat pump is used, are in a temperature range in which hot water can be produced without difficulty. Sewage thus has a stable heat source water temperature level.

In summary, we conclude that when sewage is used as a heat source to produce hot heat, it greatly improves the COP in a heat pump system.

4.2 Studies on Optimization of Plant Configuration

"The distributed heat source system", considered as an advanced system for effective use of sewage heat, is studied in comparison with "the concentrated heat source system" represented by the Makuhari DHC System.

When entire area was developed like Makuhari area redevelopment, "the concentrated heat source system" was used to be adopted. Because "the concentrated heat source system" brought some advantages as follows.
The advantages of "the concentrated heat source system" as deemed at the time are as follows:
(1) Unification of sewage treatment management is possible.
(2) Compared with a general-purpose machine, a custom-built machine can be made larger and more efficient.
(3) A heat recovery system providing higher efficiency can be introduced.

On the other hand, its disadvantages include a lack of flexibility since the cold and hot water produced is supplied through a local conduit and heat conveyance efficiency drops (about 10% loss in the case of the Makuhari DHC System), and the supply temperature of cold and hot water must be kept constant throughout the year.

"The distributed heat source system "avoids these problems and is also effective due to (1) the introduction of a compact and high-efficiency water-cooled heat pump system and (2) the increased efficiency by inverter equipment to meet the demand of various variable temperatures required by consumers, because of recent technological developments in the heat pump.

The next section compares " the concentrated heat source system " (Case 1) of a simple configuration having only a heat pump using sewage heat, where large equipment is installed in a concentrated plant, from which cold and hot water is supplied to each building through conduits, and two " distributed heat source systems " (Case 2-1, Case 2-2) where treated sewage is supplied to individual consumers' buildings, and each individual heat source system is installed in each building.

4.2.1 The study cases

Figure 7 shows the system outline of "the concentrated heat source system " and " the distributed heat source system ". Table 3 shows the setting of the study cases. Figure 8 shows the COP of the heat pump used for this study.

Unlike in "the concentrated heat source system "(Case 1), in "the distributed heat source systems" (Case 2-1, 2-2), heat loss due to the conveyance of cold and hot water is excluded, as shown in Table 3. Also, in Case 2-1, the supply temperature is kept constant (cold water: 7°C, hot water: 47°C) as in Case 1, whereas in Case 2-2, the supply temperature is reduced greatly (cold water: 7–9°C, hot water: 35°C) on the premise that the air-conditioning system of consumers side in each building are optimized.

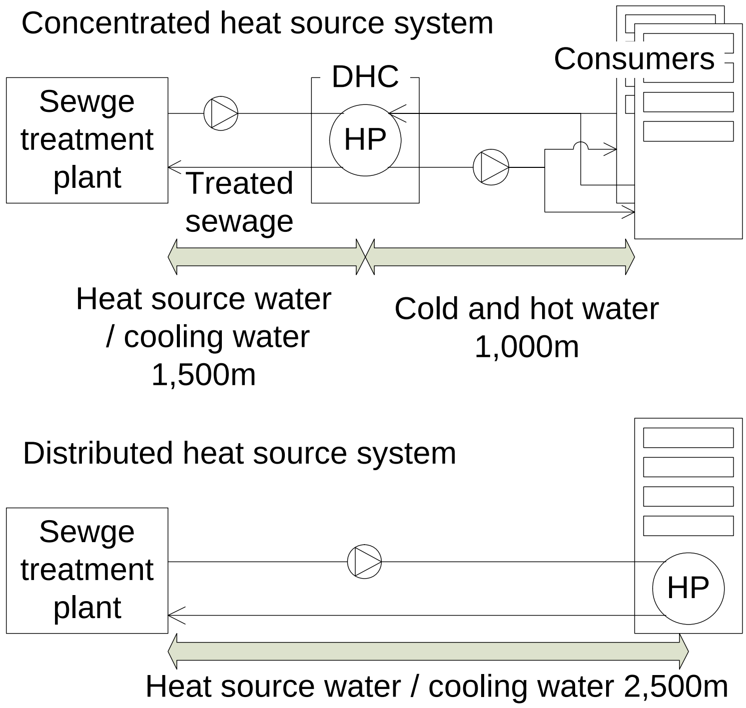

Figure 7: Basic concepts

Table 3; Condition setting of simulation

			Case 1		Case 2-1		Case 2-2	
			Cold heat	Hot heat	Cold heat	Hot heat	Cold heat	Hot heat
Heat source water / cooling water	Conveyance distance	m	3,000	3,000	5,000	5,000	5,000	5,000
	Lift	kPa	392	392	588	588	588	588
	Temperature difference	°C	5.0	5.0	5.0	5.0	5.0	5.0
Supply	Conveyance distance	m	2,000	2,000	0	0	0	0
	Lift	kPa	392	392	98	98	98	98
	Temperature difference	°C	7.0	7.0	7.0	7.0	7.0	7.0
	Supply temperature	°C	6	47	6	47	7,9	35
Heat conveyance efficiency		%	92	91	100	100	100	100
Pump efficiency		%	70	70	70	70	70	70

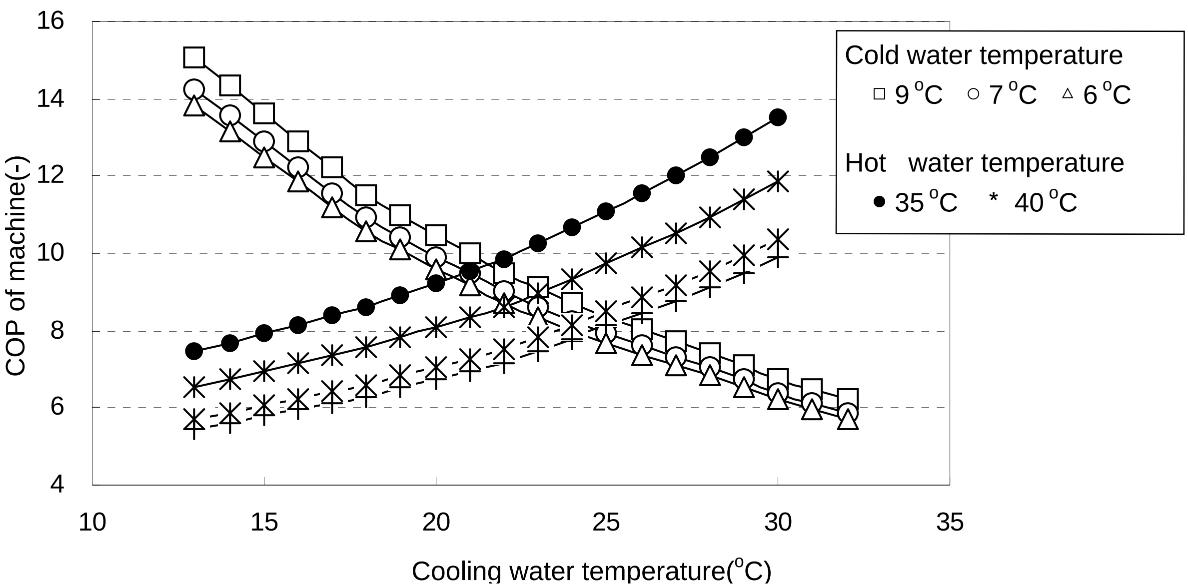

Figure 8: COP of heat pump at different cooling water temperature

4.2.2 Study results

The study results are shown in Table 4 and Figure 9.
According to Table 4, the COP of the machine is remarkably improved in Case 2-2 due to the effect of reducing the temperature of supply water.

Next, the value of total sum of auxiliary equipment power increased in both cold heat and hot heat to a greater extent in Case 2-1 and Case 2-2 (distributed type) than in Case 1 (concentrated type). This is because there was no cold/hot water supply conduit (△t = 7°C), and the conveyance distance of treated sewage (△t = 5°C) was accordingly made longer.

In addition, compared with "the concentrated heat source system", "the distributed heat source system" is efficient because there is no heat loss inthe process of the heat conveyance.

As a result, the total COP (*Rt*) was 1.97 in Case 1, whereas it was 1.98 in Case 2-1 and 2.13 in Case 2-2, so that the total COP (*Rt*) of " the distributed heat source system " was better than that of " the concentrated heat source system ".
Figure 9 shows the relationship between the cold/hot heat ratio and total COP of each case. Compared with Case 1, in Case 2-1 and the total COP was improved irrespective of the cold/hot heat ratio, but in Case 2-2, the total COP tended to be improved remarkably when the cold/hot heat ratio was low. In other words, the effect of alleviating supply temperature conditions was in accordance with the characteristics of heat demand.

Table 4; Result of calculation

		Case 1		Case 2-1		Case 2-2	
		Cold heat	Hot heat	Cold heat	Hot heat	Cold heat	Hot heat
COP of machine(-)		7.64	6.88	7.64	6.88	8.03	9.42
Unit of auxiliary equipment consumption energy source (-)	**Heat pump**	0.13	0.15	0.13	0.15	0.12	0.11
	Heat source water / cooling water pump	0.030	0.023	0.045	0.035	0.045	0.036
	Supply pump	0.019	0.019	0.010	0.010	0.010	0.010
	Total sum of auxiliary equipment power	0.049	0.042	0.055	0.044	0.054	0.046
	Total	0.180	0.188	0.185	0.190	0.179	0.152
Heat conveyance efficiency (%)		92	91	100	100	100	100
Annual load(GJ)		309,166	80,757	309,166	80,757	309,166	80,757
Total COP(-)		1.90	1.79	1.99	1.96	2.06	2.44
		1.87		1.98		2.13	

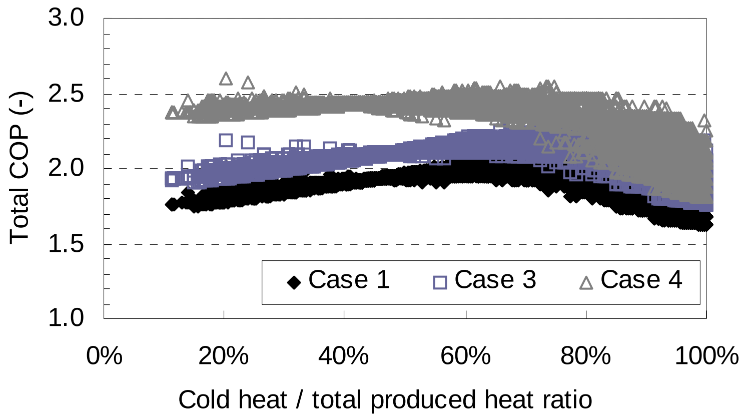

Figure 9: Relationship between cold heat / total produced heat Ratio and total COP of each case

5 CONCLUSIONS

Using the results obtained by analyzing the performance data of the existing Makuhari DHC System, this study evaluated the features of "the distributed heat source plant" and analyzed the possibility of improving the efficiency of using sewage heat in the future.

The followings are clarified:

(1) The effect of improving the COP of heat source equipment due to using sewage is outstanding when producing hot water. Thanks to this characteristic, a constantly stable and high COP can be obtained even under a variety of cold/hot heat demand balances.

(2) "The distributed heat source system" has the potential to further increase the efficiency of using sewage heat.
(a) Compared with "the concentrated heat source system", in "the distributed heat source system", power for auxiliary equipment such as pumps increases, but heat loss due to the conveyance of cold and hot water can be avoided, and relatively high efficiency is likely to be achieved.
(b) The cold/hot water production temperature can be properly controlled in accordance with the temperature level required by the air-conditioning system of consumers, so that the efficiency of using sewage heat can be increased.

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