Advanced Heat Pump Systems Using Urban Waste Heat "Sewage Heat"

YOSHIE TOGANO*1 KENJI UEDA*2
YASUSHI HASEGAWA*3 JUN MIYAMOTO*1
TORU YAMAGUCHI*4 SEIJI SHIBUTANI*5

The application of heat pumps for hot water supply and heating systems is expected. Through this, the energy consumption of hot water supply and heating, which account for a substantial proportion of the total energy consumption in a building, will be reduced. The level of reduction can be dramatically increased by use of "sewage heat," which is part of waste heat in an urban area. So far, however, it has been difficult to determine whether sufficient technical or basic data available to widely use sewage heat exists. Therefore, demonstrations on the evaluation method for the potential of sewage heat in an urban area and the actual- equipment scale of verification using untreated sewage were conducted to understand the characteristics of sewage heat, and major technologies for use of sewage heat were developed. The technologies were applied to the system using sewage heat, and the system achieved a 29% reduction in the annual energy consumption and a 69% reduction in the running cost in the hot water system in lodging facilities compared to the conventional system using a boiler. The depreciation timespan of the difference in the initial cost between the conventional system and the heat pump system is about four years, and this system has an economically large advantage. In this report, the results obtained through the development and the demonstrations are systematically organized and the technical information needed for introduction of use of sewage heat is provided.

1. Introduction

In Japan, the energy consumption used for the supply of hot water and heating accounts for a significant portion of the final energy consumption, accounting for 34% in the business sector and 55% in the household sector.[1] In addition, for general heating and hot water supply systems, equipment using fossil fuel such as boilers are widely used, and therefore an energy saving effect can be expected through the introduction of a heat pump.

A heat pump draws heat from the outside air or waste heat and raises the temperature through the refrigerant cycle to supply hot water. Because the efficiency increases further when the heat source temperature is higher and differs less from the supply temperature, the selection of the heat source is important. In urban areas, 30% to 40% of the huge amount of waste heat from households generated by activities such as cooking, washing and bathing flows into the sewers[2], and therefore the temperature of sewage is constant at around 18°C even in winter, making it suitable as a heat source for a heat pump. There are, however, few past cases of the use of heat from untreated sewage in Japan, and it is difficult to say that the technology for the efficient use of heat from untreated sewage has been established.

*1 Chiller & Heat Pump Engineering Department, Air-Conditioning & Refrigeration Division, Machinery, Equipment & Infrastructure
*2 Deputy Director, Chiller & Heat Pump Engineering Department, Air-Conditioning & Refrigeration Division, Machinery, Equipment & Infrastructure
*3 Chiller & Heat Pump Engineering Department, Air-Conditioning & Refrigeration Division, Machinery, Equipment & Infrastructure
*4 Chief Staff Manager, Chiller & Heat Pump Engineering Department, Air-Conditioning & Refrigeration Division, Machinery, Equipment & Infrastructure
*5 Chief Staff Manager, Chiller & Heat Pump Engineering Department, Air-Conditioning & Refrigeration Division, Machinery, Equipment & Infrastructure

Figure 1 shows the technological flow required to begin to utilize sewage heat. The development and verification was conducted together with universities and companies that are familiar with each respective field, commencing with a commissioned project of the New Energy and Industrial Technology Development Organization (NEDO) that started in 2011 and ended in 2014. Furthermore, promotional activities are continuing today. The names of the universities and companies that played a central role in the development are introduced in the various chapters of this report.

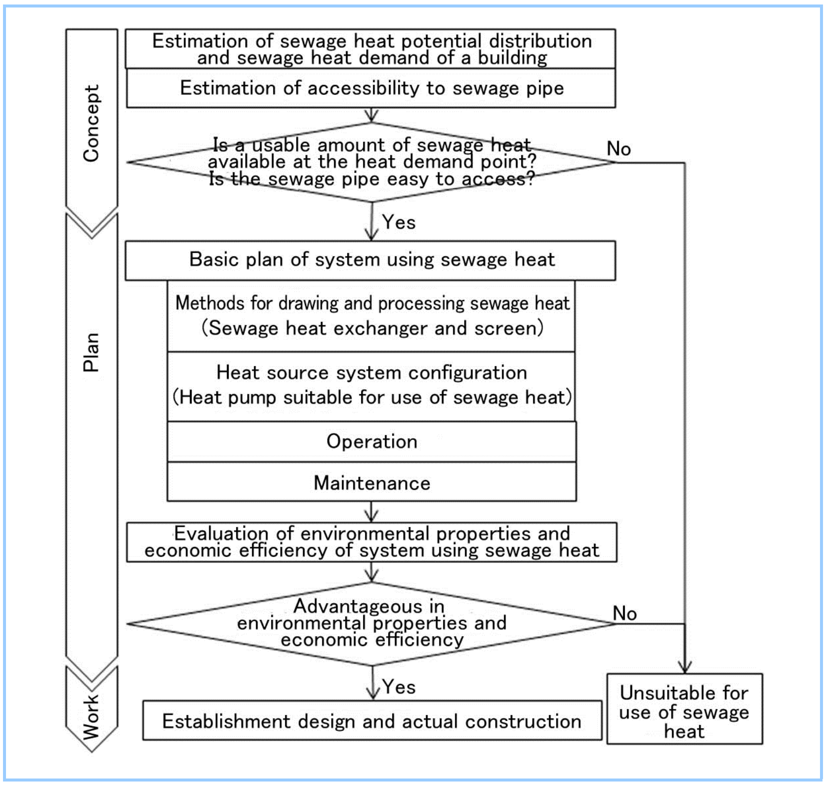


Figure 1 Flow to beginning use of sewage heat

2. Characteristics of urban waste heat "sewage heat”

Figure 2 shows the actual measurement results of sewage flow in a business area and a residential area in Osaka City.[3] This represents the sewage flow ratio for each hour compared to the total sewage flow for one day. The sewage flow hits its peak at midnight and decreases significantly in the early morning to half of the peak in both, the residential area where residential properties account for 72% of the entire area, and the business area where residential properties account for 24% of the entire area.

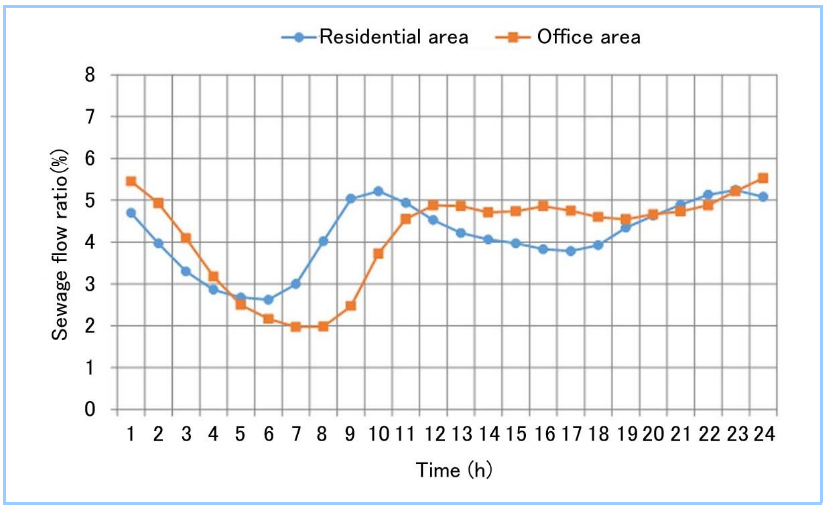


Figure 2 Measurement results of sewage flow (Osaka City)

Figure 3 shows the actual measurement results of the sewage temperature in Osaka City.[3] Both the sewage temperature and the outside air temperature are average values throughout the month. The sewage temperature ranges from 18°C (winter) to 30°C (summer) and is stable in comparison with the outside air temperature, which ranges from 0°C (winter) to 30°C (summer). Particularly in winter, the sewage temperature is on average 18°C, which is 10°C higher than the outside temperature, and therefore sewage heat is useful as a heat source for a heat pump.

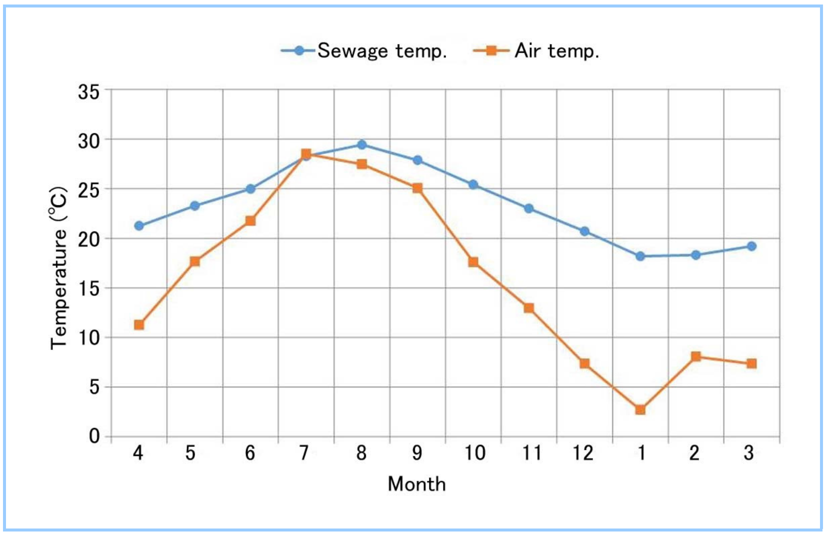


Figure 3 Measurement results of sewage temperature (Osaka City)

[Osaka City University and Sogo Setsubi Consulting Co., Ltd.]

3. Major technologies for the effective use of sewage heat

For the effective use of sewage heat, it is necessary to understand the distribution of sewage heat. It is also important to be able to draw the heat in an efficient and stable manner, and use it to supply hot water efficiently. In this chapter major technologies for this purpose, that were verified in Osaka City, are presented.

3.1 Estimation technology of distribution and presence amount of sewage heat (Sewage Heat Potential Maps)

The use of sewage heat can be established, provided that the heat supply-demand balance between the sewage heat supply potential, that changes from moment to moment, and the sewage heat demand of the building can be favorably ensured. In the present situation, however, a technology to arrange and provide information required by the project organizer for the consideration of these conditions has yet to be established. For this reason, we developed a technique that can quantify the applicability of sewage heat by calculating the sewage heat potential based on estimating the sewage flow and temperature and comparing the calculated sewage potential with the geographic information of the sewage heat demand in a building (**Figure 4**, **Figure 5**).

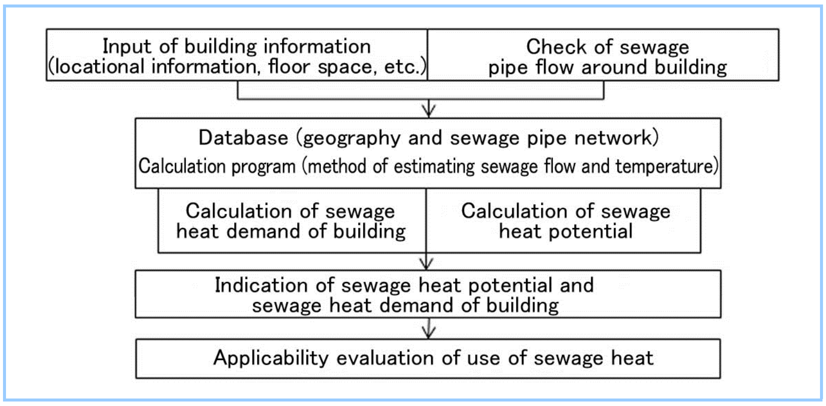


Figure 4 Applicability evaluation flow of use of sewage heat

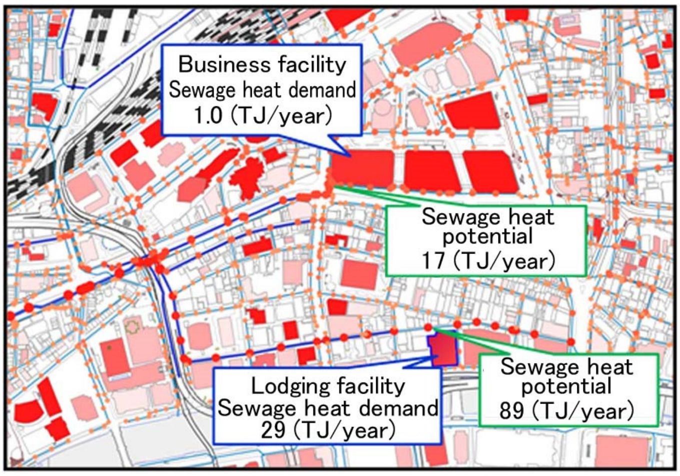


Figure 5 Comparison and consideration example of heat supply-demand balance Business facility

Through the use of part of this technique, the Ministry of Land, Infrastructure, Transport and Tourism and Ministry for the Environment has created sewage heat potential maps for six cities (Sendai, Urayasu, Toyota, Ibaraki, Kobe, and Fukuoka) and published the "Guide to Creation of Sewage Heat Potential Maps[4]" since fiscal 2013.

[Osaka City University and Sogo Setsubi Consulting Co., Ltd.]

3.2 Technology for drawing sewage heat (sewage heat exchanger and screen)

There are two types of heat exchangers for drawing sewage heat: the in-pipe installation type that is installed in a sewage pipe and the off-pipe installation type that is installed outside a sewage pipe and uses sewage collected from the sewage pipe through a screen. The selection is based on the sewage flow, the manhole structure, and the pipe section size (**Figure 6**).

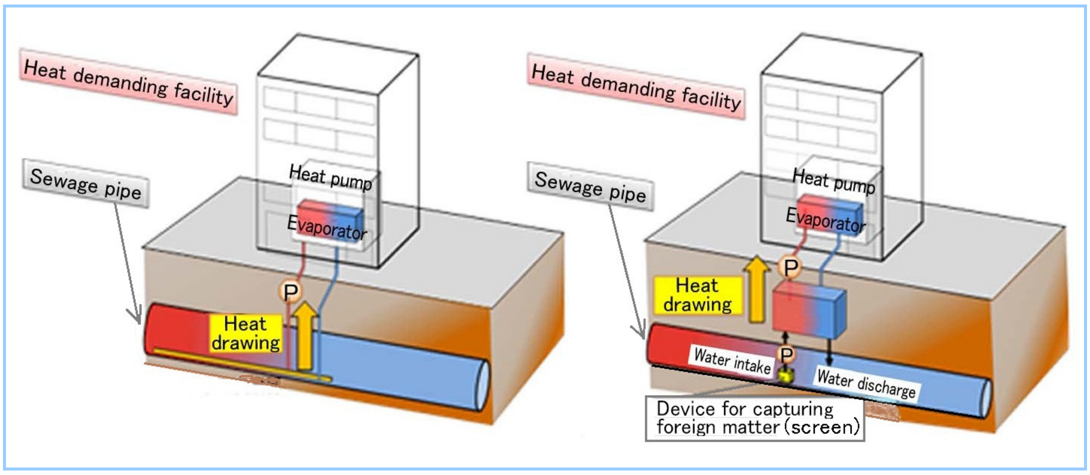


Figure 6 Method of drawing sewage heat

(1) Sewage heat exchanger

How efficiently can the sewage heat exchanger draw heat from sewage containing foreign matter and biofilm was measured and verified on an actual-equipment scale with the adherence of biofilm to check the effect of the heat exchanger (**Table 1**).

(2) Screen

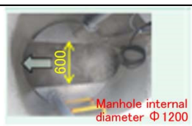
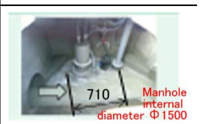
When an off-pipe installation type heat exchanger is used, it is necessary for sewage collection to capture foreign matter with a screen. Each automatic cleaning function was evaluated and it was confirmed that the moving spray method is more effective than the raking method (**Table 2**).

[Osaka City University and Chuo Fukken Consultants Co., Ltd]

Table 1 Sewage heat exchanger

<table>
<tr><td colspan="2">Classification</td><td colspan="3">Outside installed type of sewer line</td><td colspan="3">Inside installed type of sewer line</td></tr>
<tr><td colspan="2" rowspan="2">Heat exchange system</td><td rowspan="2">Resin + aluminum</td><td rowspan="2">Falling film type</td><td rowspan="2">Double pipe</td><td colspan="2">Pipe bottom installation type</td><td rowspan="2">Integrated pipe type (Resin)</td></tr>
<tr><td>Parallel type</td><td>Series type</td></tr>
<tr><td colspan="2">Appearance</td><td></td><td></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td rowspan="2">Flow velocity (m/s)</td><td>Heat source water</td><td>0.25</td><td>2.70</td><td>0.75</td><td colspan="2">0.30</td><td>0.24</td></tr>
<tr><td>Sewage</td><td>0.10</td><td>0.52kg/ (m・s)</td><td>1.00</td><td>2.80</td><td>1.40</td><td>0.13</td></tr>
<tr><td rowspan="3">Heat transfer coefficient (W/m²・K)</td><td>Initial</td><td>180</td><td>2000</td><td>800</td><td>850</td><td>800</td><td>120</td></tr>
<tr><td>After biofilm adhesion</td><td>120</td><td>1300 (When 120 hours have passed)</td><td>350 (When 120 hours have passed)</td><td>350</td><td>280</td><td>100</td></tr>
<tr><td>After cleaning</td><td>180</td><td>1700</td><td>650</td><td>600</td><td>400</td><td>—</td></tr>
<tr><td rowspan="3">Cleaning</td><td>Water used</td><td>Industrial water</td><td>Sewage</td><td>Industrial water</td><td colspan="2">Sewage</td><td rowspan="3">No cleaning</td></tr>
<tr><td>Method</td><td>Watering at 0.52 L/min per pipe unit length</td><td>Watering at 1.0 kg/m-s</td><td>Water flowing at 1.5 m/s</td><td colspan="2">Water flowing at 0.9 m/s</td></tr>
<tr><td>Duration</td><td>120 minutes</td><td>3 minutes</td><td>5 minutes</td><td colspan="2">1 minute</td></tr>
<tr><td colspan="2">Definition of heat transfer area for heat transfer coefficient</td><td>Using the external diameter of the heat transfer coil as a reference (sewage contact surface)</td><td>Using the external diameter of the heat source water heat transfer pipe as a reference (sewage contact surface)</td><td>Using the internal diameter of the sewage pipe as a reference (sewage contact surface)</td><td colspan="2">Sewage contact surface of heat exchanger (upper half of external diameter)</td><td>Sewage contact surface of ribbed part where heat source water flows</td></tr>
<tr><td colspan="2">Suitability for sewage heat collection</td><td>Acceptable</td><td>Superior</td><td>Good</td><td colspan="2">Superior</td><td>Acceptable</td></tr>
</table>

Table 2 Screen for capturing foreign matter in sewage collection

<table>
<tr><td colspan="2">Screen</td><td>Bottom Φ3 mm Punched metal</td><td>Bottom 2.5 vertical Slit parallel to water flow</td><td>Side 2.5 mm horizontal Slit parallel to water flow</td><td>Side 2.5 mm horizontal Slit parallel to water flow</td></tr>
<tr><td colspan="2">Appearance</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Water intake</td><td>Capacity (L/s)</td><td>14</td><td>50</td><td>14</td><td>10</td></tr>
<tr><td colspan="2">Number of households to which a heat pump system can supply heat (converted to hot water supply load)</td><td>500 households</td><td>1300 households</td><td>500 households</td><td>350 households</td></tr>
<tr><td rowspan="2">Cleaning system</td><td>Method</td><td>Hydraulic drive
Moving spray</td><td>Electric motor
Rotating rake</td><td>Electric motor
Rotating rake</td><td>Electric motor
Rotating rake</td></tr>
<tr><td>Details</td><td>Foreign matter on the mesh is blown away by cleaning water sprayed from the nozzle moving in the pipe axial direction and discharged with sewage.</td><td>Nothing</td><td>Nothing</td><td>Nothing</td></tr>
<tr><td rowspan="2">Construction work</td><td>Method</td><td>Drying construction</td><td>Drying construction</td><td>Drying construction (one-side water flowing construction is possible depending on the manhole structure and the flow)</td><td>Drying construction (one-side water flowing construction is possible depending on the manhole structure and the flow)</td></tr>
<tr><td>Construction period</td><td>1 day</td><td>1 day</td><td>1 day</td><td>1 day</td></tr>
<tr><td colspan="2">Maintenance</td><td>- There is a risk of corrosion and a shortened lifetime of the hydraulic cylinder, which is always submerged.
- When inspection is performed in the manhole, the cleaning spray needs to be stopped.</td><td>- There is a major risk of damage to the teeth and the slit caused by fluid passing above the rake.</td><td>- If the captured foreign matter dries out, damage to the rotating rake results.</td><td>- Accumulation of the raked foreign matter hinders the moving teeth and causes their deformation.</td></tr>
<tr><td colspan="2">Suitability for sewage heat collection</td><td>Good</td><td>Acceptable</td><td>Acceptable</td><td>Inferior</td></tr>
</table>

3.3 Technology for using sewage heat to supply heat (water cooling heat pump)

The performance of a heat pump becomes more efficient when the temperature difference between the hot water and the heat source water is smaller. If sewage (18°C (winter) to 30°C (summer)) can be used as a heat source, significant improvement in efficiency can be expected in comparison with a conventional heat pump using the outside air (0°C (winter) to 30°C or higher (summer)), particularly in winter when the temperature is low. As described above, the efficiency increases when the temperature difference between the hot water and the heat source water is smaller, and therefore the 35°C hot water specification is set assuming that the hot water temperature is changed by heating load in the heating application.

Table 3 lists the specifications of the heat pump and **Figure 7** shows its external view. On the assumption that the heat pump is used for lodging facilities and housing complexes, the capability is set to 30 kW per module, and both hot water supply and heating operation can be performed using a single heat pump. The top-class COP of 6.91 for hot water supply and 4.01 for heating was thus attained.

Table 3 Heat pump specifications

Item	Specifications	
	Air conditioning Heating	Hot water supply
Capacity	30kW	30kW
Hot water temp.	Inlet 30°C, outlet 35°C	Inlet 9°C, outlet 65°C
Heat source water temp.	Inlet 15°C	Inlet 15°C
Sewage temp. (Estimated)	18°C	
COP note 1)	6.91	4.01
Refrigerant	R410A	
Dimensions (L×W×H)	0.784m×1.05m×1.55m	
Weight	450kg	

Note 1: Coefficient of Performance. The higher value means better energy efficiency.

Figure 7 Outline of the heat pump

[Mitsubishi Heavy Industries, Ltd.]

4. Environmental properties and economic efficiency of heat pump system using sewage heat

4.1 Design and operation philosophy of heat pump system using sewage heat

For the effective use of sewage heat, the system needs to be designed and operated in an enhanced manner in comparison with the boiler system for hot water supply and the air cooling system for heating.

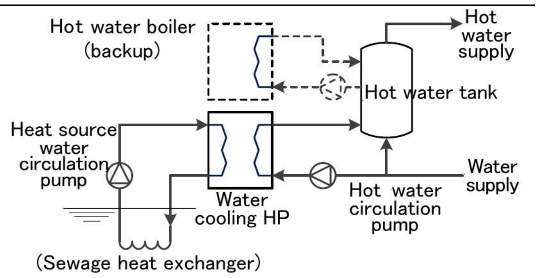
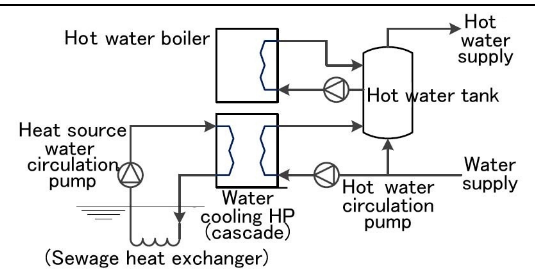
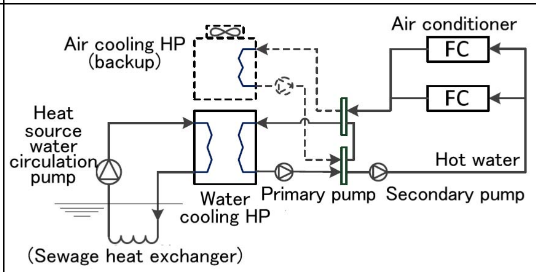
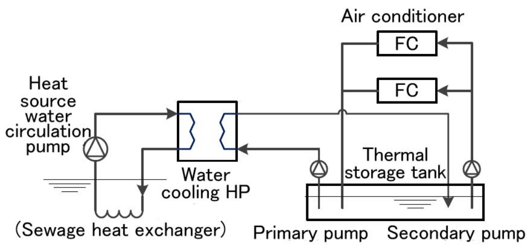
[1] Enabling stable heat utilization consistent with demand in consideration of seasonal and time variations of sewage temperature and flow. A plan to store heat and hot water and to provide a backup in anticipation of such variations is necessary.

[2] Selecting a method for which the hot water supply temperature can be set lower such as equipment body thermal storage, radiant heating, etc., in order to ensure efficient use including the secondary side of the heat pump. The sewage temperature in winter is at least 10°C higher than the air temperature, and therefore the heat pump can be used efficiently if the hot water temperature of the heat pump can be lowered suitably.

4.2 Effective heat pump system using sewage for hot water supply and heating

For lodging facilities (90 rooms) and housing complexes (60 residential units) that have significant demand for hot water supply and heating, hot water supply and heating using sewage heat was planned (**Table 4**) based on enhanced design and the operation of the heat pump described above. An effective configuration was selected in a relatively warm area (equivalent to Osaka) while comparing the environmental properties and economic efficiency with typical hot water supply and heating on a seasonal bases. As a result, the utilization of sewage heat can facilitate a significant improvement of the environmental properties and economic efficiency (running cost) in comparison with the boiler system for hot water supply and the air cooling system for heating.

Table 4 Overview of hot water supply and heating system using sewage heat

<table>
<tr><td rowspan="3">Hot water supply</td><td>Conventional</td><td>Boiler</td><td>—</td></tr>
<tr><td rowspan="2">Sewage heat</td><td>(1) Water cooling HP
+ Boiler (backup)
When the sewage heat decreases such as at the time of low sewage flow, the backup boiler is activated.</td><td>
</td></tr>
<tr><td>(2) Water cooling HP
+ Boiler (cascade)
The temperature of supply water is raised by the water cooling HP to 40°C and then by the boiler from 40°C to 65°C.
This method aims at high efficiency by decreasing the hot water outlet temperature of the water cooling HP.</td><td>
</td></tr>
<tr><td rowspan="4">Heating</td><td>Conventional</td><td>Air cooling HP</td><td>—</td></tr>
<tr><td rowspan="3">Sewage heat</td><td>(3) Water cooling HP
+ Air cooling HP (backup)
When the sewage heat decreases such as at the time of low sewage flow, the backup air cooling HP is activated.</td><td>
</td></tr>
<tr><td>(4) Water cooling HP (thermal storage)
Change in sewage heat is absorbed by the thermal storage tank.</td><td rowspan="2">
</td></tr>
<tr><td>(5) Water cooling HP (thermal storage/alternating temperature)
This method aims at high efficiency by decreasing the hot water outlet temperature when the heating load is small in addition to the use of the thermal storage tank.</td></tr>
</table>

[1] Hot water supply

(a) The method consisting of a water cooling heat pump and a boiler (backup) shown as [1] in Table 4 was most promising. This method operates the water cooling heat pump preferentially and uses the boiler when the capacity of the water cooling heat pump is insufficient. This method achieved a 69% reduction in the running cost and a decrease of 29% in the energy consumption for lodging facilities, as well as a 69% drop in the running cost and a 28% decline in the energy consumption for housing complexes.

(b) The annual operating rate of a water cooling heat pump is high because the hot water supply load exists year-round. Accordingly, the depreciation timespan of a water cooling heat pump is about four years. This is an economically significant advantage.

[2] Heating

(a) The method consisting of a water cooling heat pump (thermal storage + variable temperature) shown as [5] in Table 4 was most promising. This method has a thermal storage tank and changes the hot water supply temperature according to the monthly load. This method attained a 41% reduction in the running cost and a decrease of 33% in the energy consumption for lodging facilities, and a 23% drop in the running cost for housing complexes.

(b) For heating, the running cost can be reduced by around 40%. Because the period when heating is necessary is limited, however, the annual operating rate of a water cooling heat pump is lower than that of hot water supply (estimated to be 150 days per year) and the depreciation timespan is longer, at more than ten years for lodging facilities and more than thirty years for housing complexes.

[Kansai Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd.]

5. Conclusion

It is expected that sewage in urban areas can be used as a heat source for a heat pump system to drastically save energy, but this use of sewage has yet to be established. In this research, the developed equipment required for the use of sewage heat was verified in a sewage treatment plant in Osaka City. It was a significant achievement that we were able to understand the equipment properties such as the performance changes caused by adhesion/cleaning of foreign matter or biofilm, and were also able to acquire various data required for designing the establishment of a heat pump system. The details have been reported in technical reports[5,6] for the collaborative research partners and academic conference presentations.[7] We have also provided various data for the "Sewage Heat Utilization Manual (tentative title)[8]" drafted by the Ministry of Land, Infrastructure, Transport and Tourism.

It is very important for the future diffusion of this technology to accumulate examples of its advanced application, regardless of the scale, in areas where effective sewage heat potential exists and matches the demand, while cooperating with and mutually supporting administrative agencies in charge of sewerage works.

In closing this report, we would like to express our gratitude to Osaka City University, Kansai Electric Power Co., Inc., Chuo Fukken Consultants Co., Ltd. and Sogo Setsubi Consulting Co., Ltd. for their considerable support.

References

1. Japan's Energy White Paper 2014, Agency for Natural Resources and Energy
2. Ukaji, M. et al., Development of a System for Hot Water Supply by a Heat Pump that Recovers Heat from Daily Waste Water, Transactions of The Society of Heating, Air-Conditioning and Sanitary Engineering of Japan No. 51 (1993-2) p. 79
3. Mike, M. et al., An Evaluation of Sewage Temperature and Flow Rate for Estimating Sewage Temperature and Flow Rate in Sewer Line, Transactions of The Society of Heating, Air-Conditioning and Sanitary Engineering of Japan No. 202 (2014-1) p. 11
4. Guide to Creation of Sewage Heat Potential Maps, Ministry of Land, Infrastructure, Transport and Tourism http://www.mlit.go.jp/common/001029464.pdf
5. Journal of Sogo Setsubi Consulting Co., Ltd. Vol.39 (2014-10)
6. Journal of Chuo Fukken Consultants Co., Ltd. No. 45 (2015-1)
7. Nakao, M. et al., Development of Sewage Heat Utilization Technology in Sewage Pipes Proceedings of The 51th Research Workshop by Japan Sewage Works Association (2014) pp. 526-552
8. Guide for Using Sewage Heat, Ministry of Land, Infrastructure, Transport and Tourism http://www.mlit.go.jp/common/001088742.pdf