博士論文

Evaluation of Sewage Heat Utilization Potential Based on Urban Sewage State Prediction Model

（都市下水状態予測モデルに基づく
下水熱利用可能性の評価に関する研究）

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Chapter 1: Introduction

Chapter 1: Introduction

1.1 Research background

For the purpose of mitigating global warming, the strategies for both aspects of energy-saving, and the utilization of renewable energy are essential nowadays. In the field of building construction industry, the strategies for reducing CO_2 emission are indispensable not only in the field of the energy demand side of buildings but the application of energy supply in an area as well (Figure 1-1).

With regards to the regional energy application, there are several methods for estimating different kinds of renewable energy that have been proposed to comprehend the energy quantities retained in a certain area, such as geothermal energy, wind power[1], and biomass energy which are widely known[2,3]. Concerning to the long-term energy supply and demand strategy for Japan in 2015, it was announced that the renewable energy adoption ratio should be promoted from 5% to 24% until 2030[4]; therefore, there is a strong demand for effectively utilizing, widely spreading out and the enhancive integration of different kinds of renewable energy in order to achieve the goal[5–10].

Urban area, with a massive population and exuberant development of industry, brings about the huge energy consumption that the governments are eager to expand much more energy sources in order to apply to the urban area. At the meanwhile, making the upgraded energy utilization plan for the city is regarded as a priority policy. By 2030 it is predicted that almost 60% of the world's population will live in urban areas. In the European Union (EU) 74% of the total population lives in areas classified by national statistical offices as urban. With such growth in the urban centers, sustainability has become a key concept when planning for the future[2]. Therefore, it is essential to focus on the energy demand of the urban areas and the utilization of renewable energy instead of fossil fuels.

As an aspect of realizing the sustainable city and the low carbon society, renewable energy is highly expected to be applied and exploited to the greatest extent. In addition to the existed and well-known renewable energy which has been widely utilized, there are some kinds of obscure renewable energy that their utilizing method and using potential are still under reviewing and investigating; for instance, geothermal, waste heat from sludge, waste heat from sewage, etc[11,12]. These kinds of renewable energy were called unutilized renewable energy, and it is believed that the utilizing potential of these energy sources is prolific that cannot be ignored especially in urban area[13]. Thus, the exploitation of the unutilized renewable energy is now vigorously under development.

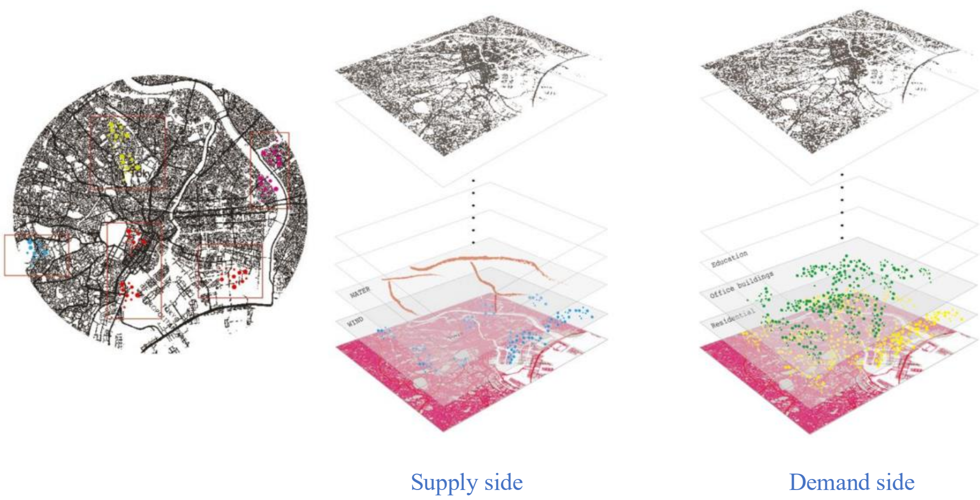

Figure 1- 1 Concept of mapping the energy demand and supply side in an area

1.1.1 Development of renewable energy and the current situation

As an aspect of reducing the CO_2 emission and replacing the utilization of fossil fuels, the expansion of renewable energy has grown significantly since 2004 (Figure 1- 2), and the increasing trend is still under progressing. In regards to the sources of renewable energy, the classification of renewable energy can be mainly classified into two types, one is the conventional renewable energy that has been widely utilized and well-known nowadays; for instance, solar PV, wind, bioenergy which are shown in Figure 1- 3. According to the figure, it is shown that the average annual growth rates of these renewable energies began increasing since 1990 and have been developed for a long period so far.

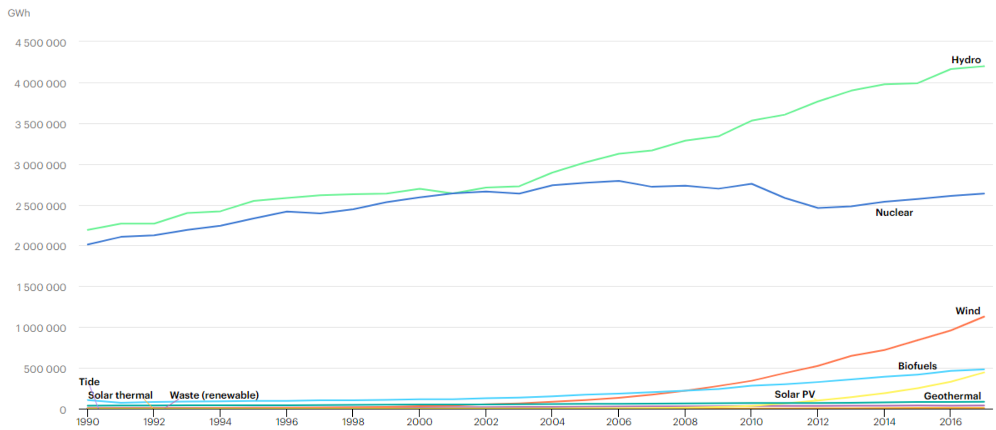

Figure 1- 2 Low-carbon electricity generation by source, World 1990-2017[14]

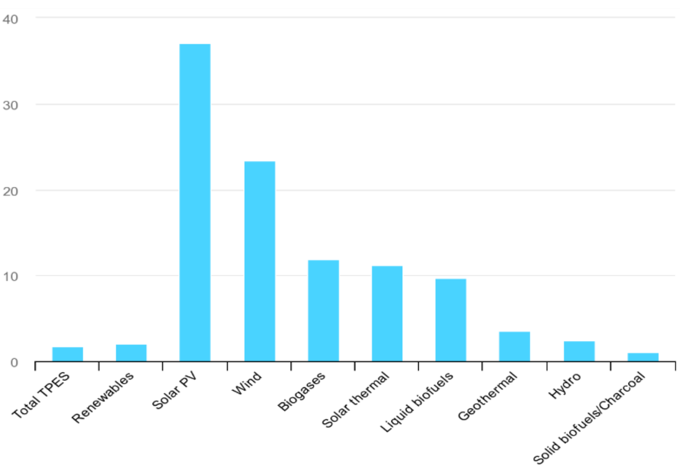

Figure 1- 3 Average annual growth rates of world renewables supply, 1990-2017[14]

In addition to conventional renewable energy, there are some novel types of renewable energy which are called unutilized renewable energy. The unutilized renewable energy is the energy that has not been completely explored, it means there is still some potential to make use of these kinds of renewable energy; for instance, the energy of temperature difference, energy from waste heat, energy from waste[15]. These kinds of unutilized renewable energy are expected to be exploited more widely in order to make maximum use of renewable energy.

The introduction of unutilized renewable energy is elaborated in the next section.

1.1.2 Unutilized renewable energy and using potential

Unutilized renewable energy is the energy source that existed with a great amount but still underutilized. The reasons that these kinds of renewable energy have not been widely used is because of the mismatch of time or space between demand side and supply side, dramatic time fluctuation of the energy source, etc. In order to take advantage of the unutilized renewable energy, it is important to grasp their features and temporal variation to evaluate the using potential in advance; furthermore, make suitable energy using strategy to efficiently utilize the energy[15].

The unutilized renewable energy can be classified into three main groups; the classification and utilizing pattern of the energy are listed in Table 1- 1. According to Table 1- 1, the exploitation of energy of temperature difference and energy from waste heat is now gradually developed for expanding the sources of renewable energy due to its massive heat occurrence; for instance, extracting sewage heat from the sewage pipelines, utilizing the temperature difference from stream, river or ocean[16], waste heat from factories, underground shopping centers, and subway stations. The exploit method of each energy source has its merits, demerits, features, and limitation; thus, it is important to draw up the appropriate utilization approaches and strategies in order to effectively make use of them.

Table 1- 1 The classification and utilizing pattern of unutilized renewable energy[15]

Energy source		Form	Range of temperature (℃)	Utilization pattern
Energy of temperature difference	Ocean	Water	5 ~ 25	Heat source of heat pump, cooling water
	River	Water	5 ~ 25	Heat source of heat pump, cooling water
	Groundwater	Water	10 ~ 20	Heat source of heat pump, cooling water
	Sewage	Raw wastewater	5 ~ 30	Heat source of heat pump, cooling water
		Treated water	5 ~ 30	Heat source of heat pump, cooling water
Energy from waste heat	Factory	High-temperature gas	200 ~	Heat source, power generation
		Warm water	~ 50	Heat source water
		LNG	~ 5	Power generation, cold and heat source
	Power station	Warm water	~ 50	Heat source water
	Electrical substation	Cooling water, coolant oil	20 ~ 40	Heat source of heat pump
	Subway and underground street	Air	10 ~ 30	Heat source of heat pump
	Waste heat from building	Air, water	20 ~ 40	Heat source of heat pump
Energy from waste	Garbage burning	High-temperature gas	200 ~	Heat source, power generation
		Warm water	~ 50	Heat source water
	Sludge burning	Burning heat	200 ~	Heat source, power generation
		High-temperature drainage	~ 50	Heat source water

1.1.3 Characteristics of sewage heat

Sewage heat, one of the unutilized renewable energy, is considered to be as a stable heat source for air conditioning and hot water supply through efficient heat pumps and heat exchangers due to its small temperature fluctuation affected by season[17]. For instance, when comparing the annual average air temperature and sewage temperature, the sewage temperature is about 6.2 °C higher than the air temperature.

According to Figure 1- 4, the monthly average sewage temperature during winter is significantly higher than the average air temperature, and the maximum temperature difference can reach up to 10 degrees; In contrast, there is just a little difference between the average air temperature and sewage temperature in summer. Specifically, the average sewage temperature is lower than the air temperature for about 2 °C to 3 °C in July and August. Besides, due to the sewage pipelines are buried underground and the great thermal insulation of soil, the sewage temperature is rarely affected by air temperature especially in winter[10]. Based on the reasons mentioned above, sewage heat is recently considered as an effective energy source to act as the heat source water that applied to air conditioning systems, hot water supply systems, and snow melting systems.

From the perspective of urban energy application, sewage heat is possible to be utilized in the urban area which the sewer system is highly penetrated; for instance, the penetration rate of sewage pipelines in Tokyo has recently become higher than 99.5%[18], owing to the wide construction of sewer system network, the extraction of sewage heat can be relatively approachable. Consequently, it is expected that the exploitation of sewage heat can achieve certain consequent in the urban area. Nevertheless, most of the utilization of sewage heat has been limited to sewage treatment plants and sewage facilities or regional heating and cooling system of large-scale buildings in nearby areas currently[19,20]. If the mechanism of sewage heat utilization can be widely exploited and spread out through not only sewage trunk pipelines but branch pipelines[21], the utilization of sewage heat can be expanded to numerous buildings that scattered in the urban area.

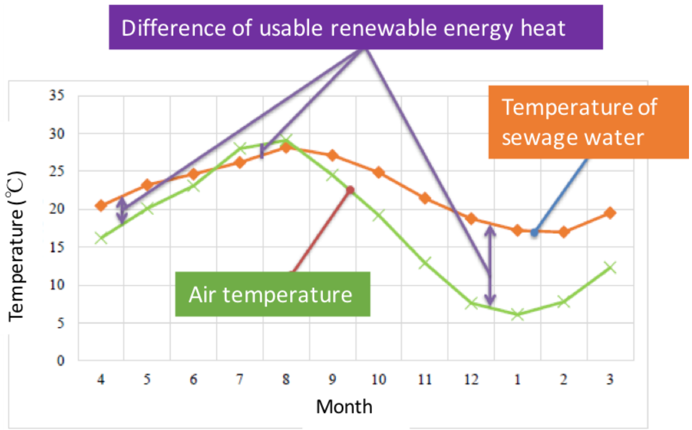

Figure 1- 4 Comparison between air temperature and sewage temperature[1]

1.1.4 Overview the sewer system

The sewer system is classified into two types: the combined sewer system and the separated sewer system. The combined sewer system (Figure 1- 5) is a sewage collection system composed of pipelines and tunnels designed to simultaneously collect surface runoff and sewage in a shared system[22], and all of the sewage water can travel towards treatment plants via piping and in a flow aided by gravity and pumps. Briefly speaking of the composition of surface runoff and sewage, the surface runoff is the flow that including rainwater, snow and ice melt (stormwater), or other sources flows over the earth's surface; as for the sewage, it is the wastewater generated by residential, institutional, commercial and industrial establishments.

The design of the combined sewer system was common when urban sewerage systems were first developed in the late 19th and early 20th centuries; therefore, many cities and towns which have been early developed continue to operate the previously constructed combined sewer systems[22]. In Tokyo, Japan, the proportion of the combined sewer systems is about 80% so far, though the separated sewerage systems are under upgrading. Owing to the reason that the combined sewer system currently takes account of the majority, the combined sewer system was determined to be the research object of sewage physical model in this study.

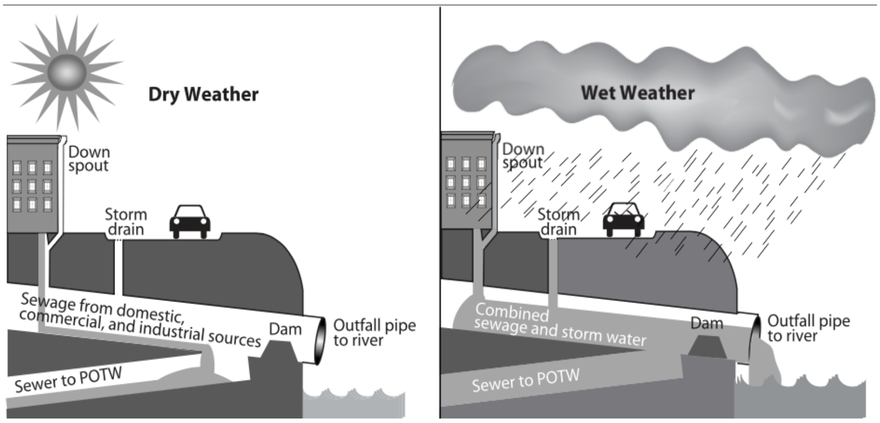

Figure 1- 5 Combined sewer system[22]

1.1.5 Overview the application of GIS data

The Geographic information system (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface. By relating seemingly unrelated data, GIS can help individuals and organizations better understand spatial patterns and relationships. GIS technology is a crucial part of spatial data infrastructure, it can use any information that includes location, and the location can be expressed in many different approaches, such as latitude and longitude, address, or ZIP code.

Many different types of information can be compared and contrasted through GIS. The information about different properties such as the location of streams and different kinds of soil are all included and can be shown in different layers respectively. Besides, it can illustrate the building types, land use, and infrastructure information that include their distribution, such as factories, farms, and schools, or storm drains, roads, and electric power lines (Figure 1- 6). With GIS technology, people can compare the locations of different things in order to discover how they relate to each other[23]. In order to construct the urban sewage state prediction model, it is essential to clarify the distribution and relationship between sewerage system network and buildings; thus, the GIS data of urban layout, building information, and sewerage system are used for constructing the regional spatial allocation of pipelines and buildings in the study.

In recent years, the application of GIS has been gradually used in the field of energy utilization for evaluating the relationship of spatial distribution between the energy demand side and supply side[2,8,24]. according to the function of visualization of GIS, the features and distribution of energy and buildings can be clearly realized by mapping the data, and can furthermore analyze the matching condition of energy supply and demand side.

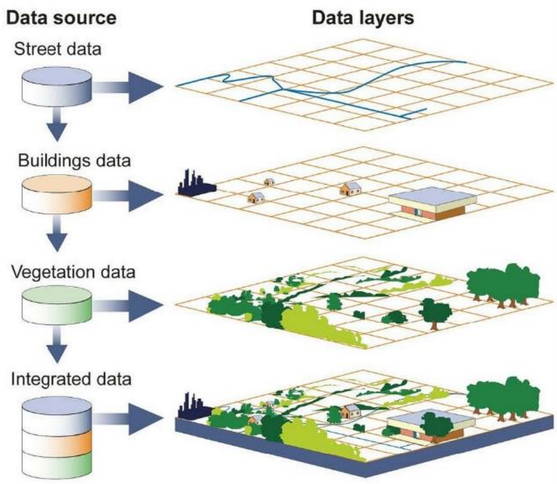

Figure 1- 6 Image of GIS data[23]

1.1.6 Current status and application of sewage heat

The utilization of sewage heat can be divided into two types by the place of sewage heat source is being extracted: sewage heat extracted at sewage treatment plants or pump stations, sewage heat extracted from pipelines directly[1]. The utilization type of recovering sewage heat at sewage treatment facilities is a common and well-known way in the field of regional heating and cooling system, and have been utilized for many years; on the other side, the way that extracts sewage heat in pipelines is regarded as a relatively newer method which has been gradually used recently. In order to popularize the utilization of sewage heat, extracting the heat from pipelines directly is believed to be an effective way that can be exploited by more buildings[25].

In addition, the optimal location for the installation of a heat exchanger in the sewer system depends on several criteria. First of all, it is important that the energy consumers are located close to the site where the heat is recovered. More heat can be reclaimed from the wastewater if the discharge is high, which is typically the case towards the end of the sewer system[26]. On the other hand, the wastewater temperature is usually highest in the initial part of the sewer system such as sewage pipelines. An additional aspect to be considered is that the efficiency of a nitrifying wastewater treatment plant is reduced if its influent wastewater temperature is lowered[24].

In order to clarify the sewage physical condition in the pipelines, David J. Du¨rrenmatt and Oskar Wanner proposed a new interactive simulation program for the estimation of the wastewater temperature in sewer, and it has been attempted to be applied. For instance, there is an undergoing project in Switzerland, about 30 facilities for heat recovery from wastewater already are in operation. A heat exchanger of 200 m in length which is installed in the sewer system of Zurich, Switzerland, produces heat and warm water for 800 apartments [27].

Regarding the application in Asia, for the purpose of maximum utilizing the sewage heat, the utilization type of recovering sewage heat through the pipelines has been widely conducted in Harbin, Shijiazhuang and Beijing, China, which are the cities located frigid zone [28–31]. For instance, there are several projects that the scale of these projects is very significant. Specifically speaking, there are three noticeable application projects in Harbin, the scale of the objective areas are respectively 18,000 m^2, 16,000 m^2, and 34,000 m^2; besides, the scale of one of the application projects in Beijing is about 50,000. Furthermore, one of the projects in Shijiazhuang is more markable that its application scale is even larger than Harbin and Beijing, the scale of the project in Shijiazhuang is about 550,000 m^2. According to the application examples in China, it is known that widely utilized the sewage heat in urban areas can achieve apparent energy conservation [30].

Based on the perspective of reclaiming more heat from the origin of heat source, in the past years, there are many cases of extracting sewage heat from pipelines in some countries, such as Germany Swiss, and China[25,32], and the application in Japan has been obviously increased nowadays. The application cases of both of the two sewage heat utilization types are introduced in the following article. In this study, we focus on the newer technique of extracting sewage heat from pipelines, its application cases will be mainly introduced in this study.

The application case of sewage heat extracted at sewage treatment facilities[25]:

- Sony City building (Sony's corporate headquarter in Tokyo.)

The Sony's corporate headquarter is adjacent to the Shibaura Water Reclamation Center of the Tokyo Metropolitan Sewerage Bureau, and the sewage heat is applied to the energy supply for air-conditioning of Sony City building, and the treated water used for air-conditioning is returned to the water reclamation center. Besides, this case is the first privately-owned building utilizing sewage heat, it was executed when the Japan government started to examine the possibility of using sewage heat as a new heat source for air-conditioning. Regarding to the utilization effect, the CO_2 emission can be reduced by about 22 tons per year (planned value), and the project information is outlined in Table 1- 2[25].

Table 1- 2 Sony City building project information

Begin time	October, 2006
Utilizing object	Sony City building
Utilizing type	Heat source for air-conditioning
Building floor area	162,888 m^2
Amount of supply heat source	60,000 m^3/day of treated water (maximum)

Figure 1- 7 Location of Shibaura Water Reclamation Center and Sony City [25]

Figure 1- 8 Sony city building [25]

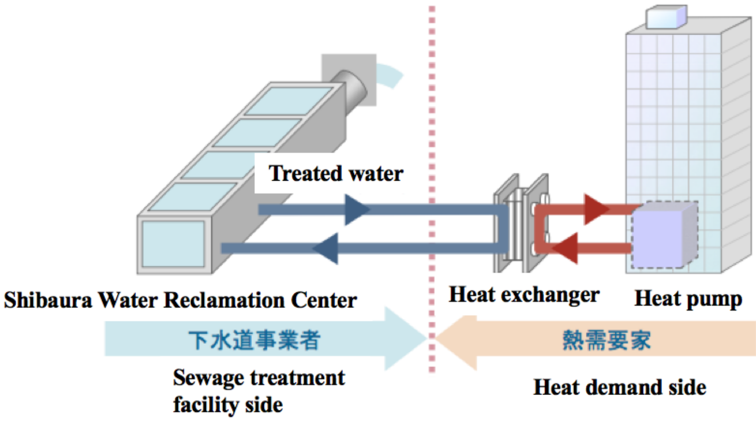

Figure 1- 9 System diagram of Sony City [25]

The application cases of sewage heat extracted from pipeline[25]:

- Asama Nanroku Komoro Medical Center

In Komoro City, Nagano, sewage heat is used as a heat source for hot water supply in Asama Minami Komoro Medical Center. It is the first case of installing heat exchanger directly in sewage pipeline; in addition, it was executed by a privately-owned corporation. Concerning to the utilization effect, the available heat amount extracted from pipeline is about 1,030 MJ/day, which is equal to 10% of the heat demand for hot water supply per day (10,000MJ/day). The project information is shown in Table 1- 3.

Table 1- 3 Asama Nanroku Komoro Medical Center project information

Begin time	December, 2017
Utilizing object	Asama Nanroku Komoro Medical Center
Utilizing type	Heat source for hot water supply
Execute company	Cenergy Co.
Load condition	1,030 MJ/day (available sewage heat amount)
Pipe condition	Pipe diameter: 250 mm Length of heat exchange pipe: 85m
Utilizing heat temperature (February)	Raw sewage water temperature:13~14°C Temperature difference for heat exchange: 5~6°C

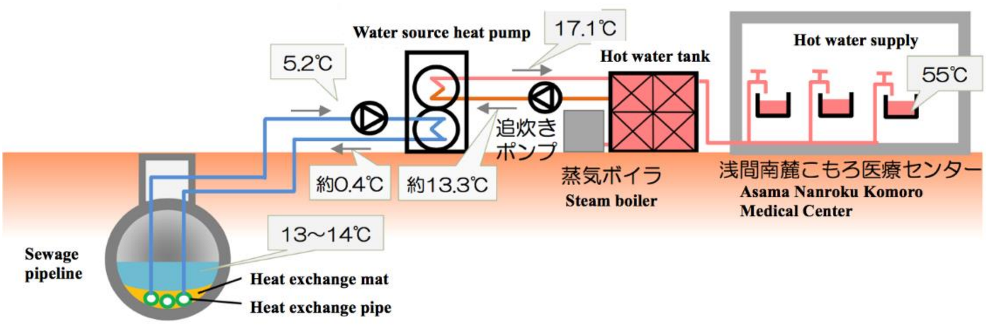

Figure 1- 10 System diagram of Asama Nanroku Komoro Medical Center [25]

- Suwa Red Cross Hospital

The sewage heat utilization is applied to the Suwa Red Cross Hospital in Suwa City, Nagano. The energy plan of the hospital follows the energy policy suggested by the Suwa city government, which includes sewage heat, geothermal and other waste heat. The effect of exploiting several kinds of unutilized renewable energy (sewage heat, geothermal, etc.) is expected to reduce the CO2 emission by 55%, which is compared to the existed system.

Table 1- 4 Suwa Red Cross Hospital project information

Begin time	April, 2018 (scheduled)
Utilizing object	Suwa Red Cross Hospital, new administration building
Utilizing type	Heat source for air-conditioning
Execute company	Cenergy Co.
Load condition	200 kW
Building floor area	21,272 m^2
Pipe condition	Pipe diameter: 2,000 mm Length of heat exchange pipe: 50 m
Heat exchange type	Heat exchange pipe installed under the pipelines
Hot water supply system	Gas boiler and water source heat pump
Utilizing heat temperature	Raw sewage water temperature:28℃ Heat exchange temperature: 15~25℃

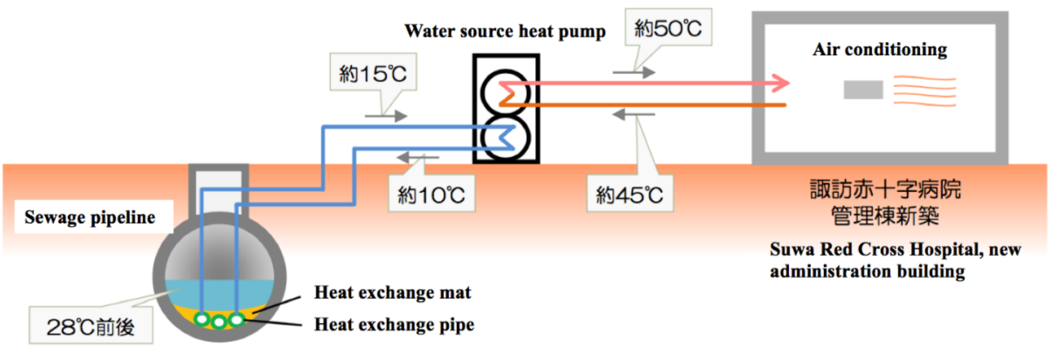

Figure 1- 11 System diagram of Suwa Red Cross Hospital, new administration building [25]

The application cases of sewage heat extracted from pipeline:

- York Benimaru supermarket

In Sendai City, a research project which related to sewage heat utilization is proposed by Sendai city government and Sekisui Chemical Co., Ltd. The York Benimaru supermarket located at Wakabayashi Ward, Sendai is one of the building that adopted the technique of exchanging sewage heat from pipeline through the spiral heat exchanger. In this case, the sewage heat is applied to provide the heat demand for hot water supply. Comparing the utility costs between former hot water supply system and the existed sewage heat utilization system, after installing the sewage heat utilization system, the utility costs can be cut down for about 360,000 yen per year (from 700,000 yen to 340,000 yen).

Table 1- 5 York Benimaru supermarket project information

Begin time	November, 2013
Utilizing object	York Benimaru supermarket
Utilizing type	Heat source for hot water supply
Execute company	Sekisui Chemical Co.
Load condition	Using temperature: 40℃ Using water volume: 4600 L/day
Pipe condition	Pipe diameter: 1,200 mm Length of heat exchange pipe: 45 m Sewage water level: 15%
Heat exchange type	Heat exchange pipe installed around the pipelines

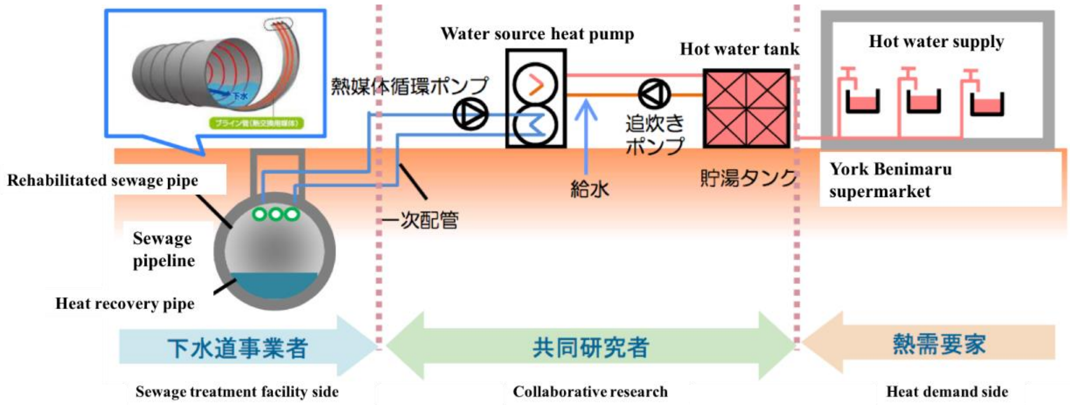

Figure 1- 12 System diagram of York Benimaru supermarket [25]

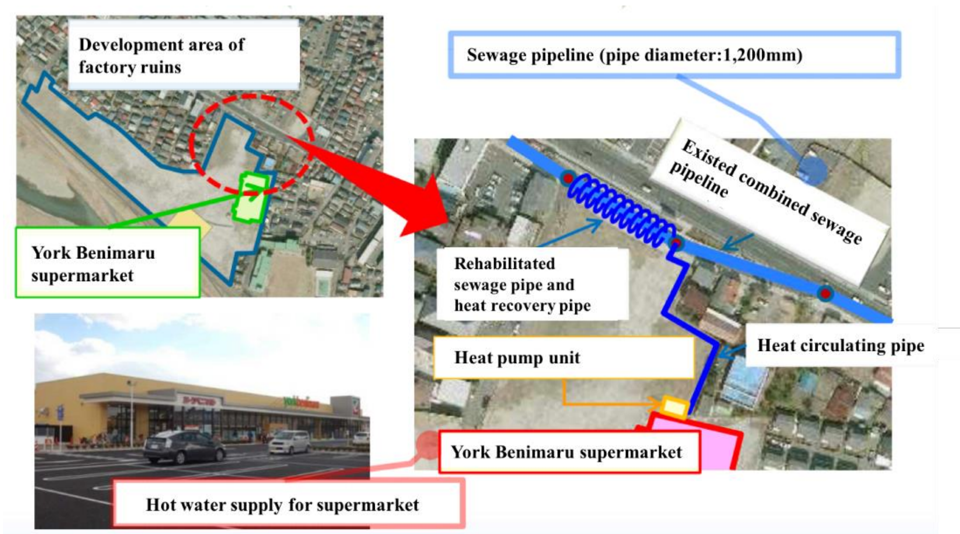

Figure 1- 13 Distribution of York Benimaru supermarket and pipelines [25]

The application cases of sewage heat utilization in Europe[25]:

The utilization of sewage heat was widely spread out in Europe; for instance, there are about 30 cases in Germany[32], and 80 cases in Swiss. Two cases in Germany is briefly introduced in the following article.

- IKEA (furniture mall)

The sewage heat utilization system is adopted to an IKEA's mall located in Berlin since 2010, and its utilization at IKEA is applied to the air-conditioning system. In this case, the sewage water is extracted to conduct heat exchange through double pipe heat exchanger. Comparing to the former gas boiler system, the CO_2 emission has been cut down for 1,270 ton per year by utilizing sewage heat.

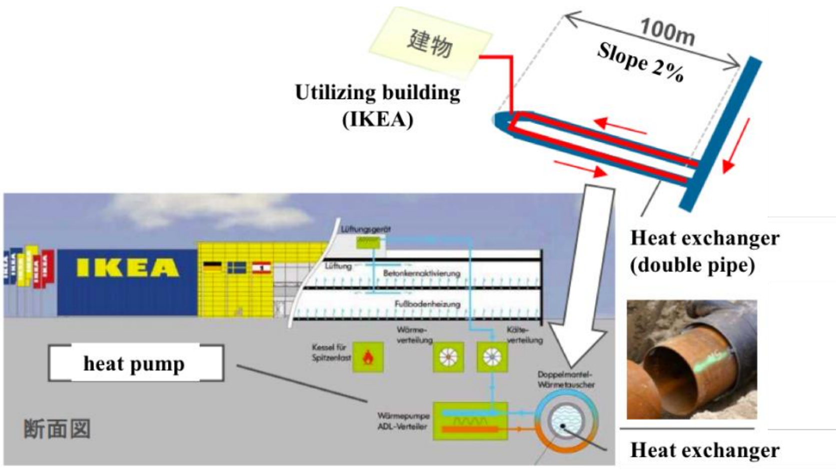

Figure 1- 14 System diagram of IKEA [25]

- Junior high school in Berlin

The case of utilizing sewage heat at a junior high school in Berlin was executed in 2006. Regarding to the heat exchange type, the heat exchanger pipes were installed under the existing sewage pipeline (Figure 1- 16) in front of the facility to conduct the heat exchange directly from sewage pipeline, and utilized the sewage heat through water source heat pump.

Figure 1- 15 Junior high school (Berlin) [25]

Figure 1- 16 Image of installation place of heat exchanger [25]

1.2 Literature review

The possibility of sewage heat utilization and its estimation methods have been discussed in some previous researches. Several review papers highlighted different perspectives to estimate the sewage flow rate, temperature, sewage heat and its utilization possibility. In this section, the previous studies related to sewage heat utilization are narrated by two parts, the evaluation of sewage physical state and the sewage heat utilization.

1.2.1 Evaluation of sewage physical state

At the former step of utilizing the sewage heat, it is necessary to quantify the sewage heat amount retained in pipelines. Besides, in order to widely expand the utilization of sewage heat in urban area, it is important to clarify the variation of sewage flow rate and temperature in sewage pipelines[11,33]. However, such the databases are not completed, and still not clear, either. As for the current research related to the sewage flow simulation model for regional scale[34], there are still some possibility to improve the model to pursue the realistic situation. The previous studies and issues related to the estimation of sewage flow rate and temperature are listed in the following section.

(1) Estimation method of sewage flow rate and temperature in sewage trunk line[34]

In the study proposed by Takashi IKEGAMI, two models including sewage trunk line model and district heating and cooling plant model were proposed. In this model, sewage temperature variation after utilizing sewage heat and the minimum sewage flow rate which required for adoption of sewage heat utilization in area cooling and heating plant has been analyzed. According to the sewage trunk line model, the sewage flow rate and temperature were estimated at the target manhole which sewage water flow in at the setting area, and the sewage amount was calculated basing on the water consumption unit and building area. Besides, the distance between target manhole and the building which installed the sewage heat utilization system was also considered in order to simulate the usable sewage flow rate and temperature.

However, the model was limited to calculate the sewage flow rate in the main trunk sewer pipelines within the sewage treatment area without considering the possibility of sewage utilization in other tributary pipelines. In addition, regarding to other sewage flow physical conditions, the sewage flow velocity was assumed to be as a fixed value of 1 m/sec even the flow velocity is a crucial factor that affect the calculation of flow rate. As for the estimation method of sewage temperature in the study, the temperature was settled basing on the measurement data of Koraku1-Chome, and the timely sewage temperature variation trend was assumed to be as same in the whole study area, instead of considering the regional individual differences which may make influence on sewage temperature. According to the above, the accuracy of regional sewage flow rate and temperature estimation model can be improved.

(2) Estimation method of sewage flow rate and temperature based on measurement data

MIKE et al. [35] performed actual measurements of sewage flow rate and temperature at some areas in Osaka, Japan. Based on the measurement data, the research proposed an estimation model to obtain the sewage flow rate and temperature at the manholes in study area. Specifically, the hourly sewage flow rate was estimated by combining the daily integrated flow rate and the hourly variation rate basing on measurement data. As for the sewage temperature, the regression analysis between air temperature and sewage temperature are proposed in the study; however, the sewage temperature is not only affected by the weather condition, but also directly affected by the building drainage. Thus, when discussing the sewage temperature, it is essential to take the factor of building drainage into consideration.

In this study, the measurement points were far away from each other which means the study was conducted in a large scale that was difficult to accurately simulate the temperature and flow rate variation in pipelines. In addition, the simulation objective was set as manholes instead of pipelines; therefore, the variation of sewage water flow rate and temperature in pipeline between two manholes were not able to be clarified through this model though the variation existed between two manholes influenced by building wastewater, heat loss, etc. If the sewage physical features in pipelines are not exactly clarified, while adopting sewage heat utilization system, it is possible to be over or underestimated the utilizing potential.

(3) Estimation method of sewage flow rate in large scale by GIS data

ICHINOSE et al. [18] proposed an estimation model basing on GIS system to analyze the spatial consistency of heat demand and sewage heat in order to effectively reuse the unutilized heat extracted from sewage pipelines in urban area. In this study, the position of the sewage pipelines and sewage treatment facilities are located by 250 m mesh to clarify the distribution of sewage pipeline system based on the coordinates of the sewage trunk lines and their connection. In order to quantify the sewage heat retained in the area, the study conducted a simulation model to estimate the sewage flow rate only for sewage trunk line, and the flow rate of each trunk line was estimated at the end of the inflow area covered by each trunk line. The annual average of the hourly sewage flow can be estimated at each joint mesh of sewage trunk lines. Regarding to the generated amount of wastewater, it was calculated by the water consumption unit and building area, and all of the generated amount of building wastewater was accumulated at the end of the inflow area covered by same trunk line.

However, the sewage flow rate was only roughly estimated at the end of trunk line and the connected point of trunk line in this study, the sewage flow rate of tributary pipelines was not taken into consideration though the utilization possibility of sewage heat in tributary pipelines should not be ignored. In addition, when making a plan of installing the sewage heat utilization system, the timely variation of sewage flow rate is an important factor when simulating the equipment performance of sewage heat utilization system; however, the estimation method of timely flow was still not clear.

Although there were several studies related to the estimation method of sewage flow rate and temperature, most of them did not propose a sewage physical model which is closed to the realistic status in pipelines. For instance, the influence from velocity, wastewater from buildings or even the heat capacity of sewage water that may affect the retained heat in pipelines. Therefore, in order to clearly grasp the sewage status in pipeline, a simulation model which considered the fluid physical features and pipe features is essential to be constructed. According to the model, while making a sewage heat utilization plan in an area without measurement data of flow rate or temperature, it can provide the sewage physical status before conducting the simulation of sewage heat utilization system.

1.2.2 Sewage heat utilization

When concerning to the sewage heat utilization, the most important issue is to clarify the usable amount and extracted amount that can obtain from sewage. According to the previous studies, the simulation of the sewage heat utilization were discussed; however, most of the heat utilization temperature difference was supposed to be a fixed value as 5℃[1,20]to calculate the sewage heat utilization amount empirically, though the utilization temperature difference should be considered depending on the practical factors such as building heat demand, operating performance of heat source equipment, sewage physical state which are all unsteady.

In addition to the perspective of temperature difference of sewage heat utilization, there are numerous of previous research discussed the possibility of sewage heat utilization from the aspect of the heat source equipment and heat exchanger. For instance, the performance of the sewage source heat pump is discussed under different inlet temperature range by field testing; as for the heat exchanger, the application of different types of heat exchanger ware discussed to compare the heat amount recovered from sewage[5,7,40–43,7,9,19,32,36–39].

However, these previous studies were mainly focused on the application of a single building instead of evaluating the sewage heat utilization potential in an urban scale and did not concentrate on the perspective of district sewage heat utilization strategies. Owing to the sewage heat is a kind of waste heat that discharges from buildings all the time, it is regarded as a type of renewable energy with a great amount of utilization potential. In order to maximize the using amount of sewage heat, it is essential to extend the research objective from building scale to the area scale to evaluate the energy-saving potential.

The previous research related to the sewage heat utilization is elaborated as below.

(1) Sewage heat utilization system in field testing

There are several previous studies proposed field testing of sewage heat utilization through discussing the performance of the heat pump and the utilization effect of single to triple buildings. However, these studies were almost concentrated on discussing the sewage heat utilization from the aspect of the equipment, instead of the perspective of regional energy planning.

Specifically speaking, MIKE et al. [6,37]proposed a field testing of sewage heat utilization system in actual buildings to verify the availability of sewage heat and compared the simulation accuracy of heat exchange amount, equipment performance which affected by sewage physical status and the equipment operating capacity. In this study, the objective sewage heat utilization system was the type that conducting heat exchange through extracting sewage water, which is the conventional utilizing type usually adopted to the large-scale buildings. According to the study, the performance of the actual equipment operating was verified through the field testing which was based on the realistic building energy consumption, and the simulation accuracy of the hot water supply system was verified as well. In addition, the performance of different kinds of heat exchangers were compared and their merits and demerits are suggested in the study. The results of the experiment, field testing and simulation proposed by the study are useful for other researchers when conducting the related simulation, especially the setting conditions of the heat source equipment, heat exchangers, etc.

However, as mentioned above, the sewage heat utilization system settled in the study was the type it is essential to extract the sewage water to conduct heat exchange; therefore, the capacity of heat exchange is limited by the sewage flow rate. Thus, this kind of utilization system is applied to the district heating and cooling system or large-scale buildings which are located at the nearby area of sewage treatment plant or pump station. As an aspect of drawing up the strategies for regional sewage heat utilization, this conventional system may be difficult to widely exploited by more buildings in the urban areas.

(2) The sewage heat utilization temperature difference

While evaluating the utilization potential of sewage heat, the sewage heat utilization temperature difference is an important issue. The evaluation method of sewage heat utilization potential was proposed by “Sewage heat utilization manual” published by Ministry of Land, Infrastructure, Transport, Water management, Homeland preservation department. According to the manual, the utilization temperature difference was defined to be as 5 degree to calculate the sewage heat utilizing potential[1]. However, the utilization temperature difference is not proper to be determined as a fixed value due to the value is affected by the sewage temperature fluctuation, performance of equipment, and building heat demand. Furthermore, the heat utilization efficiency may change during different time period within a day due to the timely variation of heat demand and sewage status.

In order to promote greater use of sewage heat utilization system, MIKE et al.[44] proposed a study related to the estimation of available heat based on temperature of sewage water on treating process. The potential was calculated by the utilization temperature difference, and the temperature difference was assumed to be limited by the minimum inflow sewage temperature at sewage plant. In this study, several buildings located from upstream to downstream were appointed to install the sewage heat utilization system, after these buildings extracted sewage heat, the variation of the potential within the area is shown as the result. However, the simulation did not perform a model to clarify the variation of sewage temperature during the sewage flow process in pipelines which may make influence on the feasibility of sewage heat utilization. Therefore, it is essential to suggest a model based on grasping the temperature variation in pipelines for recognizing the sewage temperature is proper to extract or not, and furthermore make sure the usable amount of sewage heat.

Regarding to the sewage heat utilization, most of the simulation and field testing focused on the objective of single building; as for urban scale, however the general utilizing strategy and the estimation method has been suggested, there is still lack of regional simulation model which can reflect the actual variation after the sewage heat is extracted by different conditions of buildings or different utilization parameters.

Briefly speaking, the regional simulation model of sewage heat utilization potential is expected to simulate the case that sewage heat is not only utilized by a single building but several buildings located at the nearby area, and then eventually proposed the regional energy-saving potential.

1.3 Research objective

According to the research background and the unresolved issues mentioned in the previous studies, the research related to sewage heat utilization can still be improved. Especially, it is necessary to develop a regional simulation model for clarifying the sewage heat utilization potential in an urban scale.

In this study, we aim at suggesting an estimation methodology and judging criteria for evaluating the sewage heat utilization potential, recommended utilization objects, and suitable layout of building distribution in a regional scale (Figure 1- 17). Moreover, it is able to propose the optimal strategy for utilizing regional sewage heat based on the methodology.

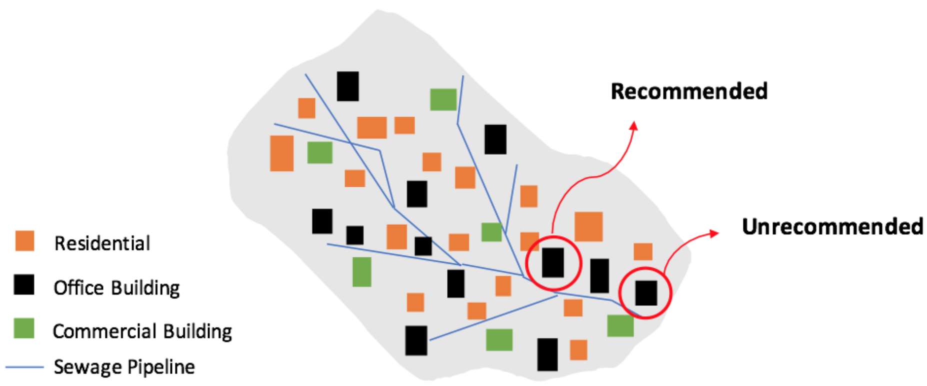

Figure 1- 17 Diagram of research purpose

An urban sewage state prediction model (Figure 1-18) is proposed in the study, which can predict the sewage state without measurement data, and conducting the regional simulation for evaluating the sewage heat utilization potential in order to make the regional optimal utilization of sewage heat. The urban sewage state prediction model is able to simulate the whole circulation from the energy supply side to the demand side, which including sewage physical model and sewage heat utilization system model. The two models are both established from the perspective of the urban energy utilization and were related to the features of heat rejection, energy demand, and heat utilization types of different building types.

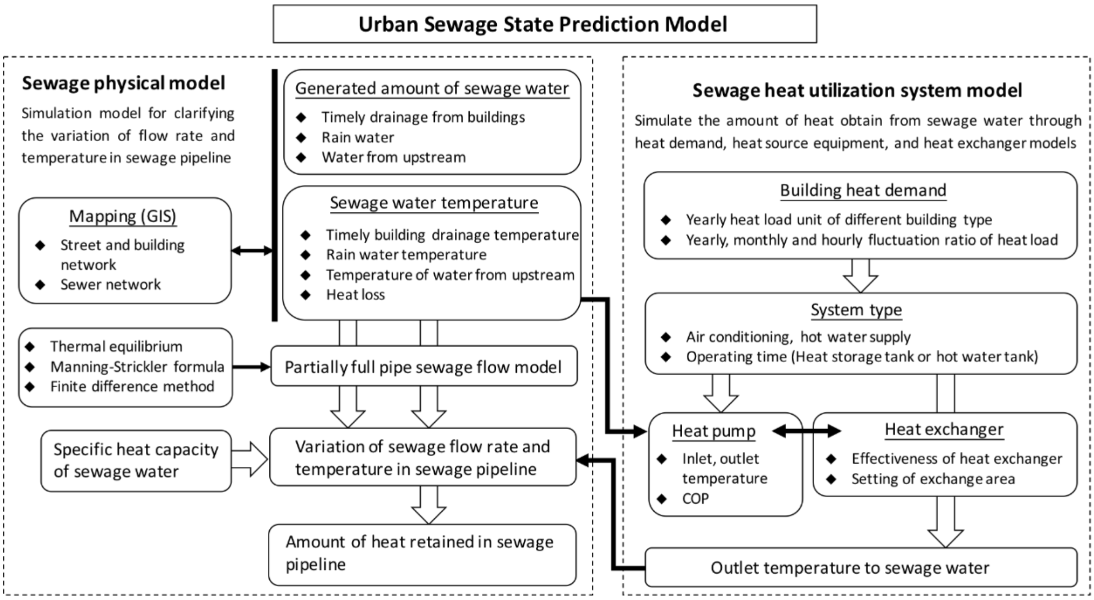

Figure 1- 18 Urban sewage state prediction model

With regards to the sewage physical model, the characteristics of the sewage pipeline, such as pipe materials, size, and the physical properties of the fluid were all taken into consideration. As for the sewage heat utilization system model, it was based on the heat demand of different building types, the performance of heat source equipment, and the heat exchanger model to calculate the outlet temperature which makes an influence on the sewage temperature after utilizing the sewage heat. Through the urban sewage state prediction model proposed in the study, the timely variation of sewage state in pipelines can be simulated at the step before and after utilizing sewage heat simultaneously. Furthermore, the model can be applied to the area as long as certain statistical databases are prepared, the measurement data of sewage flow rate and temperature are not essential in this model; therefore, the estimation method can be adapted to not only existed areas but new areas which are still under planning. In addition, through the urban sewage state prediction model, it is able to clarify the buildings which are recommended to utilize the sewage heat efficiently, and can thus draw up a suitable district energy utilization plan. The points that this research intends to clarify are listed as follows:

(1) To detailed clarify the amount of retained heat, the variation of sewage flow rate, and temperature in sewage pipelines, a theoretical sewage physical model is developed at the step

before extracting the sewage heat.

(2) To detailed simulate the sewage physical state, the discrete-time and space steps are applied to perform the simulation which is similar to the fluid features.

(3) To verify the properness of the theoretical sewage physical model, the model is verified by the measurement data in an actual area.

(4) To simulate the sewage heat utilization under different building conditions, a sewage heat utilization system model is constructed based on the heat demand side.

(5) To clarify the sewage temperature variation and the energy-saving potential after utilizing the sewage heat, the simulation is conducted under several different scenarios.

(6) To propose the strategy for the optimal utilization of sewage heat in urban areas, the simulation under different setting parameters and scenarios are conducted to compare the utilization potential.

1.4 Originality of this study

According to the current situation of sewage heat utilization for a regional scale, as mentioned in the research background, it is known that the sewage heat utilization method of directly recovering heat through the sewage pipelines has been widely applied to several large scale projects in Europe and China. For the purpose of drawing up an efficient regional energy plan for utilizing sewage heat, an evaluation method for clarifying the regional sewage heat utilization potential is necessary.

The study suggested an estimation method and criteria for evaluating the sewage heat utilization potential in order to make the regional optimal utilization plan for sewage heat; in addition, the evaluation methodology is able to determine the proper buildings which are the priority one to be recommended for utilizing the sewage heat based on building features such as building types and spatial distribution in the urban area.

According to the urban sewage state prediction model proposed in the study, the timely variation of sewage state in pipelines can be simulated at the step before and after utilizing sewage heat; furthermore, the model can be applied to the area as long as certain statistical data is prepared, the measurement data of sewage flow rate and temperature are not essential for the model; therefore, the estimation method can be adapted to not only existed areas but new areas which are still under planning. Specifically speaking, from the perspective of reducing the environmental load and energy saving in the urban area, the optimal strategies for sewage heat utilization proposed in this study can be applied to urban planning when drawing up the regional energy utilization plan for a new area which is still under developing.

1.5 Thesis structure

This study consists of seven chapters, and the configuration of the study is shown in Figure 1- 19.

In chapter 1, the research background, literature review, purpose, and the structure of this study were presented.

In order to clarify the sewage physical features and sewage heat utilization method, the sewage physical model and sewage heat utilization system model were respectively established in chapter 2 and chapter 4, which was called the urban sewage state prediction model (Figure 1- 18).

In chapter 2, the sewage physical model is constructed to simulate the sewage physical state. The sewage physical model can be mainly separated into two parts, the partially full pipe sewage flow model, and the generated amount of sewage water and its temperature. The variation of sewage flow rate and temperature in pipelines can be simulated through the theoretical model.

In chapter 3, the sewage physical model is verified by the measurement data in an actual area. In this chapter, the simulation results of sewage flow rate, sewage temperature, and velocity are compared to the measurement data and the designed value.

In chapter 4, the sewage heat utilization system model is constructed based on the aspect of the heat demand side, including building types, the performance of heat source equipment, and the heat exchanger model. The outlet temperature which affects the sewage water temperature after utilizing the sewage heat can be simulated by the model. In addition, the energy consumption including the sewage heat utilization system and the backup system is calculated.

In chapter 5, the application of the urban sewage state prediction model is applied to an actual urban area. According to the sewage physical model, the regional timely sewage state is simulated in order to clarify the sewage physical condition of each pipeline in the study area. Based on the simulated sewage condition, the sewage heat utilization system model is integrated to conduct the simulation of regional sewage heat utilization potential through several scenarios.

In chapter 6, in order to propose the strategy for the optimal utilization of sewage heat in urban areas, the simulation under different setting parameters and scenarios are conducted to discuss the utilization potential. Moreover, the recommended buildings and proper layout of building distribution for utilizing sewage heat can be clarified through analyzing the simulation results.

The conclusion and the brief findings obtained in this research are summarized in chapter 7, and the future works are described in the chapter as well.

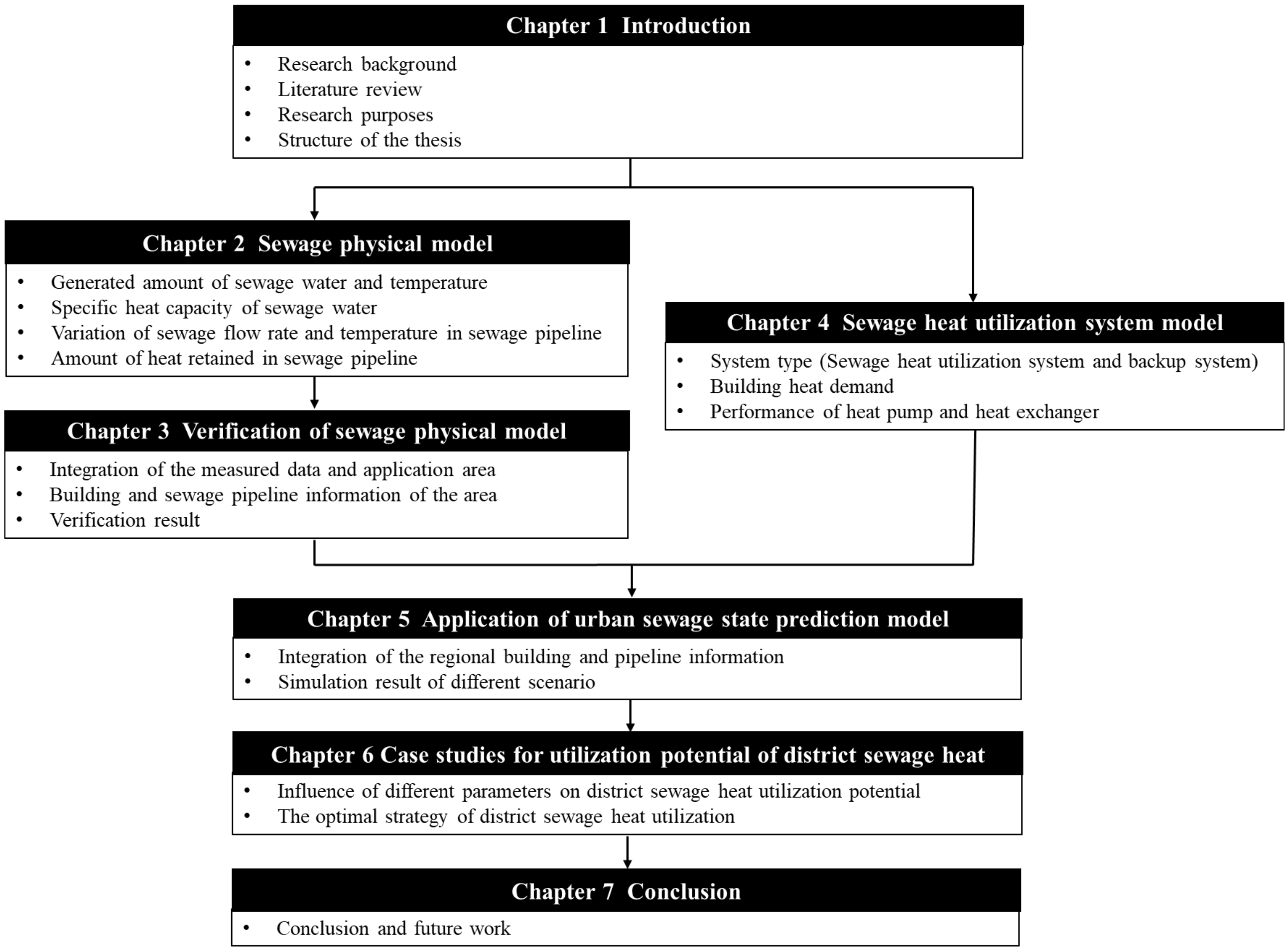

Figure 1- 19 Structure of the thesis

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Chapter 2: Sewage physical model

Chapter 2: Sewage physical model

2.1 Introduction and objective

The purpose of chapter 2 is to build up a theoretical physical model which is close to the realistic situation of sewage pipeline in order to clarify the sewage physical state in sewage pipelines at the step before exploiting the sewage heat utilization system.

The sewage physical model proposed in this study integrates the GIS data of polygon data for sewage network coordinates, the raster data for building types and areas in order to know in detail the spatial distribution of sewage pipeline networks and buildings. In addition, combining the statistical data[35,45,46] as input data for conducting the simulation of sewage flow rate, temperature, and the heat retained in pipelines. For instance, the essential data used for entering into the model including basic pipeline information (pipe length, size, material, GIS coordinate), building information (building type, floor area, GIS coordinate), the original unit of water consumption, etc. The main factors that affect the quantity of heat retained in sewage pipelines are the variation of flow rate and temperature; therefore, it is essential to clarify the variation of these two factors.

According to the sewage physical model, the generated amount of sewage water and its temperature which included the timely drainage from all types of buildings, rainwater and water from upstream pipelines can be calculated.

2.2 Overview the structure of sewage physical model

Regarding the composition of sewage physical model, it can be mainly separated into two main parts. As shown in Figure 2- 1, first of all, a prediction model for calculating the generated amount and temperature of the wastewater origins is proposed. The calculation result of wastewater generated amount and temperature act as input databases to conduct the simulation of sewage physical state variation in pipelines. Secondly, the variation of physical features such as sewage flow rate, temperature and velocity in pipelines are simulated depends on the theory formulas which are adopted to the partially full pipe model. At the final step, the variation of sewage flow rate, temperature, and the retained heat in pipelines can be clarified. Each of the simulation subsystem is elaborated in the following subsections.

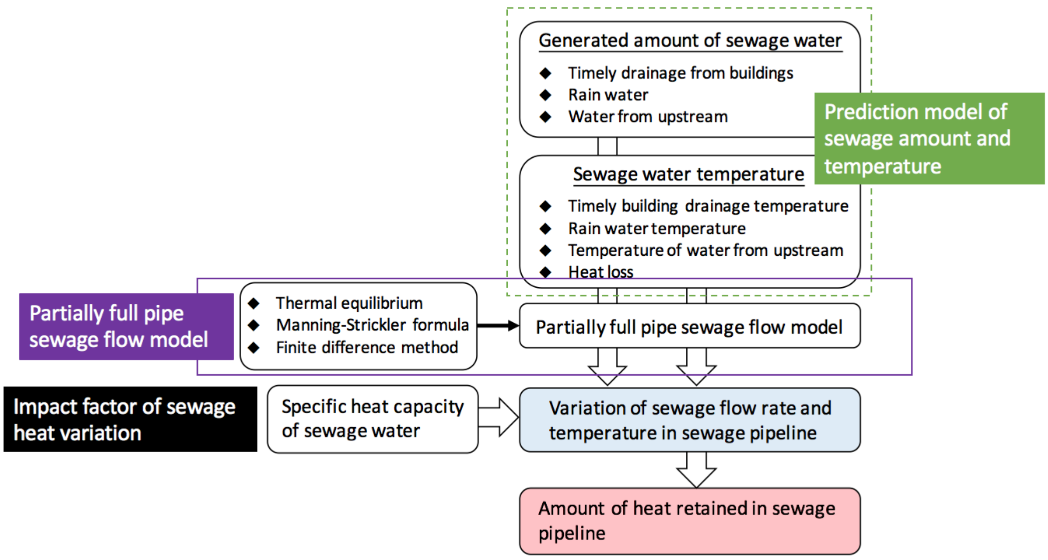

Figure 2- 1 Image of sewage physical model

2.3 Composition of sewer system

At the former step of depicting the sewage physical model, the composition of the sewer system and the main components related to the research are introduced briefly in this chapter to clarify their function and role in the sewer system.

2.3.1 Terms definition of sewer system

The sewer system is composed of many components (Figure 2- 2), the function of the main components and their definition are described to clarify their roles in the model[47].

- Regional trunk line

The regional trunk line is an underground sewer pipeline or tunnel system for transporting sewage to treatment facilities or disposal which collected the sewage from tributaries of the nearby area including residential area, commercial area, etc. Generally speaking, the diameter of trunk lines is above 1 meter due to its primary role is to transport the massive amount of sewage.

The recent studies of sewage heat utilization used to put focus on trunk lines as study objective due to their massive flow rate and steady sewage temperature; however, comparing to the tributaries, the trunk lines are usually far from the heat demand side.

- Local main sewer line

The local main sewer line is the tributary that mainly collects building drainage in the nearby area, and then subsequently aggregates sewage to the trunk line. The design of local main sewer line is determined by the drainage population and area; generally, the pipeline diameter is in the range of 0.1 meter to 1 meter, the sewage flow velocity is normally designed to be as 0.6 m/sec to 1.5 m/sec, and the maximum design velocity is acceptable to 3 m/sec.

- Manhole

A manhole is an opening to access the sewage pipelines; besides, it usually acts as a buffered space in case of a dramatic increase of sewage flow rate. According to the sewerage ledger, a sewage pipeline is divided by two manholes, and the features such as diameter, slope and material of the pipeline between the two manholes are the same. In this study, only pipelines are set to be the study objective, the impact of the manhole is ignored.

- Private service lateral

The building wastewater is draining to the public sewage pipelines through the private service laterals. According to the sewerage ledger, the allocation of private service laterals and the flow-in position to the sewage pipeline are not revealed in detail, only the rough area flow direction is shown. In this study, while constructing the estimated model of sewage origins related to building drainage, the flow-in position of building wastewater is set to be as the nearest section of the pipeline.

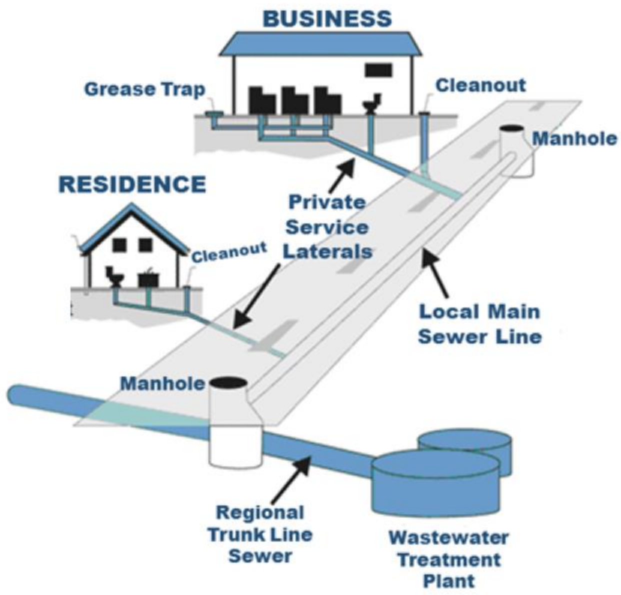

Figure 2- 2 Components of sewer system[48]

2.3.2 Components of sewage pipeline network and sewage ledger

The major components of public sewer system including trunk lines, tributaries, manholes, and the private part including private service laterals, grease traps. According to the sewage ledger released by the metropolitan sewage bureau[49], the basic information of public sewer system such as pipeline and manhole are shown in the online GIS map, which includes pipe and manhole number, pipe length, pipe diameter, shape, material, bed slope of pipeline, and the flow direction (Figure 2-3). Basing on the information, we can realize the critical conditions related to the simulation of sewage flow physical model; for instance, pipe diameter and pipe slope are the main impact factors of flow velocity and flow rate. Besides, the pipe slope can be positive or minus numbers which lead to the different calculation method of flow rate and sewage volume which will be described in the later section.

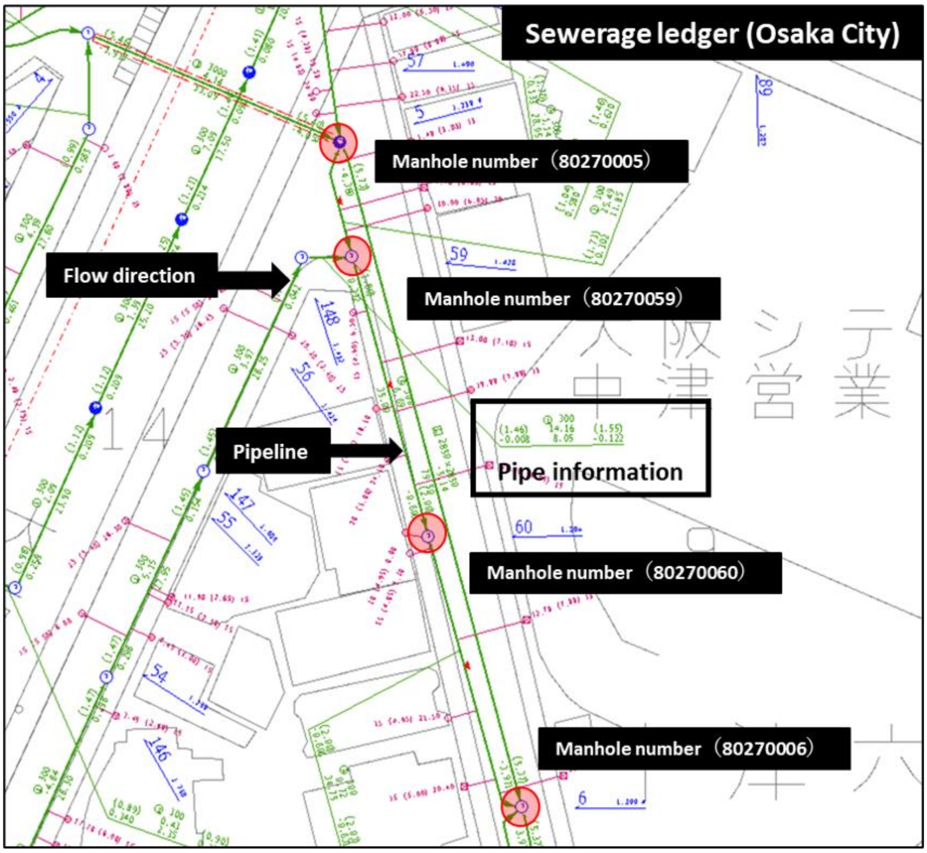

Figure 2- 3 Synopsis of sewage ledger [49]

2.3.3 GIS information of pipeline network and buildings

In this study, for clarifying the spatial relationship and distribution of pipelines and buildings, it is essential to build up the spatial distribution map of the study area basing on the GIS data of sewer system and building GIS data (Figure 2- 3). Specifically speaking, by inputting the coordinate information obtained from GIS data, the program proposed by the study is able to draw up the distribution graph and recognizing the connection of pipeline through upstream to downstream in advance; afterwards, the layout of pipelines and buildings can be connected to conduct the regional simulation. With regards to the building information, all of the essential data for conducting the simulation are provided in the building GIS file; for instance, building location, building type, floor area, and coordinate (Figure 2- 4)

Figure 2- 4 Distribution of sewer pipelines, manhole and building on GIS map [49]

2.4 Prediction model of generated amount of wastewater and temperature

At the former step of simulating the sewage physical conditions, it is essential to construct the prediction model to estimate the water amount and temperature of wastewater origins. The subsystem of the simulation model is elaborated in the following section.

2.4.1 Origins of sewage

The research objective of the sewer system is determined to be the combined sewer system which currently takes account for the majority. The origins of sewage in the combined sewer system are composed of building drainage and rainwater. With regards to the building drainage, it is generated by residential, institutional, commercial and industrial establishments which include household waste liquid from toilets, baths, showers, kitchens, and sinks draining into sewers[47].

In this study, the building types are classified into five types including residence, office, hospital, hotel, and retail. The building drainage from all types of buildings is taken into consideration.

2.4.2 Simulation subsystem of sewage origins

The sewage physical model proposed in this study focused on the scale from a single pipeline between two manholes to the whole area which includes several connected pipelines. Basing on a simple single pipeline, we analyzed the composition of sewage sources and the timely variation of sewage physical state through the finite difference method that a pipeline is segmented into tiny intervals. According to Figure 2- 5, the origins of sewage are defined to be composed of three sources, water from upstream pipelines, rainwater, and drainage from buildings, the generated amount of each part is calculated respectively.

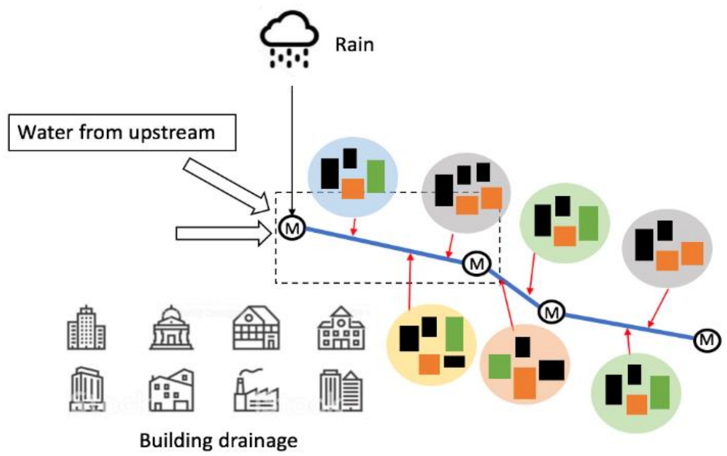

Figure 2- 5 Composition of sewage water

In regard to the part of building drainage, referring to the actual situation, the building drainage is designed to discharge into the nearest sewer branch; therefore, we set up a model which can recognize the location of buildings and pipelines by GIS data to determine which segmentation of pipeline is the inflow point for the drainage of each building supposed to flow in; besides, the setting condition related to building wastewater path is described in the simulation subsystem of building drainage in detail.

The generated amount of sewage water from the three sources is calculated by the following subsystems, and then combining into the simulation of sewage physical conditions through the partially full pipe sewage flow model at the meanwhile.

① Water from upstream pipelines

The flow rate and temperature of sewage water flow in from upstream is calculated by Eq. (1)~(2), which all the converging pipelines have been taken into consideration. In this study, all the wastewater from upstream pipelines is assumed to be assembled into a single source called "Gin", which is regarded as integrated inflow fluid before flowing into the downstream connected pipeline. In the following equations, the calculation time step is represented by superscript, and the spatial step is represented by subscript.

$$G_{in}{}_{n}^{t} = \sum_{j=1}^{k} G_{out}{}_{n-1,j}^{t} \qquad Eq.\ (1)$$

$$T_{in}{}_{n}^{t} = \frac{\sum_{j=1}^{K}\left(G_{out}{}_{n-1,j}^{t} \times T_{out}{}_{n-1,j}^{t}\right)}{\sum_{j=1}^{k} G_{out}{}_{n-1,j}^{t}} \qquad Eq.\ (2)$$

Where G_{in} is the flow rate of sewage water flow in from upstream pipe (m^3/sec), G_{out} is the outflow rate (m^3/sec), T_{in} is the temperature of sewage water flow in from upstream pipe (°C), T_{out} is the temperature of sewage water flow out from upstream pipe (°C), t is the time (sec), and n is the pipe number, *n-1* is the upstream pipelines adjacent to pipe n, k is the numbers of converging pipelines.

② Rainwater

The calculation of rainwater is affected by the following factors such as precipitation patterns, rainwater penetration rate of different kinds of ground materials, etc. To reasonably estimate the rainwater amount which is possible to make influences on sewage heat, the theory formula for rainwater estimation is adopted in this study (Eq. (3)~(4))[45]. The rainwater flow-in rate can be estimated by the rainwater flow-out coefficient, rain-fall intensity, and rainwater discharge area[10)]. According to the model, the rainwater flow-in rate was assumed to be calculated at only each manhole, and the rainwater temperature is assumed to be same as tap water temperature, which is related to the air temperature.

$$G_{rain}{}_m^t = \frac{1}{360} \times C \times I \times A_{discharge} \qquad \text{Eq. (3)}$$

$$T_{rain}{}_m^t = T_{cold} \qquad \text{Eq. (4)}$$

Where C is the rainwater flow-out coefficient (Table 2- 1), I is the rain-fall intensity (mm/hr), $A_{discharge}$ is the rain water discharge area (ha), m is the manhole number (The rain water is only happened at the initial manhole adjacent to pipe n), T_{rain} is the rain water temperature (°C), T_{cold} is the supply water temperature (°C).

Table 2- 1 Standard of rainwater flow-out coefficient[45]

Area type	Runoff coefficients	Area type	Runoff coefficients
Road	0.8~0.9	Residential and Commercial premises	0.80
Roof	0.85~0.95	Residence with gardens, industrial district	0.65
Water surface	1	Detached house	0.5
Ground	0.10~0.30	Suburb district	0.35
Park	0.05~0.25		

③ Drainage from buildings

The estimation of building drainage amount and temperature is calculated by timely building drainage flow rate and temperature model proposed by the study which is based on the statistical data including original unit of water consumption, using ratio of hot and cold water. In this study, the building type is classified into five types, residence, office, retail, hotel, and hospital, which the classification criteria is congruence with the statistical data of original unit of water consumption[35].

Regarding to the original unit of water consumption, the existed statistical data is the value of each hour; however, in order to conduct the simulation that meets the fluid characteristics with proper calculation time interval, the hourly data is interpolated into second.

Referring to the sewage ledger released by the metropolitan sewerage bureau, the specific inflow position of building drainage is not shown in the sewage ledger. Therefore, at the former step of simulating the building drainage, it is essential to clarify the position of where the building wastewater flows in; in the other words, the connection node from the private service laterals to local sewer line should be set as a reasonable condition to conduct the simulation.

According to the previous research[35], the flow-in point of building drainage was assumed to be as flowing into the nearest manhole instead of the pipeline; however, the setting is not similar to reality. In this study, the building drainage is assumed to flow into the nearest pipeline. Owing to a pipeline is segmented into several sections in the model proposed by the study, the drainage amount and temperature that flows into the same section of sewage pipeline is aggregated from all types of building drainage that connected to the same pipeline section. Therefore, the simulation of sewage flow rate and temperature may be closer to the actual situation that affected by building drainage.

As shown in the simulation process of building drainage flow rate and temperature (Figure 2- 6), according to this model, the using water volume and temperature of buildings are first calculated, and the using and drainage time is assumed to be simultaneous.

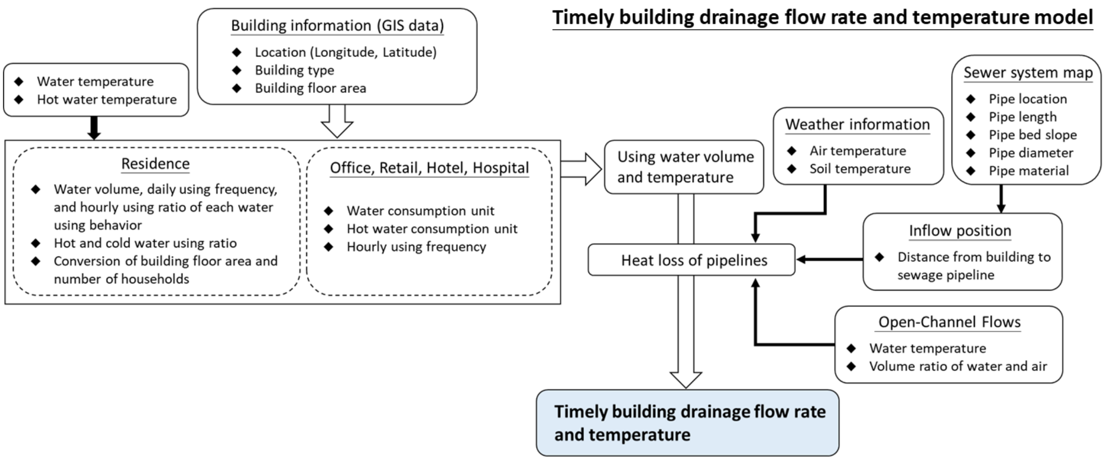

Figure 2- 6 Timely building drainage flow rate and temperature model

Based on the using temperature and the heat loss in the pipeline connected from building to sewage pipeline, the drainage temperature can be calculated (Eq. (5)~(9)). Specifically, the heat loss is calculated through the distance between the building and the sewage pipeline, in which the distance is estimated through the coordinate of building and pipeline.

$$G_{waste,total}{}_n^t = G_{use,Residence}{}_n^t + G_{use,Office}{}_n^t + G_{use,Retail}{}_n^t + G_{use,Hospital}{}_n^t + G_{use,Hotel}{}_n^t \qquad Eq.\ (5)$$

$$T_{use,total}{}_n^t = (G_{use,Residence}{}_n^t \times T_{use,Residence}{}_n^t + G_{use,Office}{}_n^t \times T_{use,Office}{}_n^t + G_{use,Retail}{}_n^t \times T_{use,Retail}{}_n^t + G_{use,Hospital}{}_n^t \times T_{use,Hospital}{}_n^t + G_{use,Hotel}{}_n^t \times T_{use,Hotel}{}_n^t)/G_{waste,total}{}_n^t \qquad Eq.\ (6)$$

$$Q_{loss,1}{}_n^t = \left[K_{sewage} \times \left(T_{use,total}{}_n^t - T_{soil}\right) \times l_{water} + K_{air} \times \left(T_{use,total}{}_n^t - T_{air}\right) \times l_{air}\right] \times L_B \qquad Eq.\ (7)$$

$$Q_{loss,1}{}_n^t = C_{waste} \times \rho_{waste} \times \left(T_{use,total}{}_n^t - T_{waste,total}{}_n^t\right) \times G_{waste,total}{}_n^t \qquad Eq.\ (8)$$

$$T_{waste,total}{}_n^t = T_{use,total}{}_n^t - \frac{Q_{loss,1}{}_n^t}{C_{waste} \times \rho_{waste} \times G_{waste,total}{}_n^t} \qquad Eq.\ (9)$$

The calculation of building using water volume and temperature are separated into two main types in the study, residence and the building types except residence (Figure 2- 6). The drainage amount and using temperature of residence is calculated by the using water volume, daily using frequency, hourly using ratio of each water using behavior, and hot and cold water using ratio [46] (Eq. (10)~(17)).

$$G_{use,Residence}{}_{n}^{t} = \sum_{i=1}^{9} G_{use,i}(t) \times A_{Residence,n} \quad Eq. (10)$$

$$G_{use,i}(t) = G_{day,i} \times N_i \times f_i(t) \quad Eq. (11)$$

$$G_{use,i}(t) = G_{cold,i}(t) + G_{hot,i}(t) \quad Eq. (12)$$

$$G_{cold,i}(t) = G_{use,i}(t) \times r_{cold,i} \quad Eq. (13)$$

$$G_{hot,i}(t) = G_{use,i}(t) \times r_{hot,i} \quad Eq. (14)$$

$$r_{cold,i} + r_{hot,i} = 1 \quad Eq. (15)$$

$$T_{use,i}(t) = \frac{G_{cold,i}(t) \times T_{cold} + G_{hot,i}(t) \times T_{hot}}{G_{cold,i}(t) + G_{hot,i}(t)} \quad Eq. (16)$$

$$T_{use,Residence}(t) = \frac{\sum_{i=1}^{9} G_{cold,i}(t) \times T_{cold} + \sum_{i=1}^{9} G_{hot,i}(t) \times T_{hot}}{\sum_{i=1}^{9} G_{cold,i}(t) + \sum_{i=1}^{9} G_{hot,i}(t)} \quad Eq. (17)$$

Where $G_{use,Residence}$ is the total using water volume of residence ($m^3/hr.m^2$), $G_{use,i}$ is the using water volume of different behavior (m^3/hr), $A_{Residence}$ is the floor area of residence (m^2), G_{day} is the daily using water volume of different behavior (m^3/day), N_i is the daily using number of times ($number\ of\ times/day$), f is the hourly using frequency (%), G_{cold} is the supply water volume (m^3/hr), r_{cold} is the supply water ratio(%), G_{hot} is the hot water volume (m^3/hr), r_{hot} is the hot water ratio (%),$T_{use,i}$ is the using water temperature of different behavior (°C), T_{cold} is the supply water temperature (°C), T_{hot} is the hot water temperature (°C), $T_{use,Residence}$ is the using water temperature of residence (°C), i is the water using behavior(i = 1~9).

Regarding other building types (office, retail, hotel, and hospital), the drainage amount and temperature is calculated by the original unit of water consumption, hot water consumption unit, and hourly using frequency [45]. Owing to the calculation of the drainage amount and temperature from these four types of building are the same, it was presented as the same equation as below (Eq. (18)~(21)).

$$G_{use,B}{}_{n}^{t} = \left(G_{cold,B}(t) + G_{hot,B}(t)\right) \times A_{B,n} \qquad \text{Eq. (18)}$$

$$G_{cold,B}(t) = G_{cold,day,B} \times r_{cold,B}(t) \qquad \text{Eq. (19)}$$

$$G_{hot,B}(t) = G_{hot,day,B} \times r_{hot,B}(t) \qquad \text{Eq. (20)}$$

$$T_{use,B}(t) = \frac{G_{cold,B}(t) \times T_{cold} + G_{hot,B}(t) \times T_{hot}}{G_{cold,B}(t) + G_{hot,B}(t)} \qquad \text{Eq. (21)}$$

Where $G_{use,B}$ is the total using water volume of building (m^3/hr), A_B is the building area (m^2), $G_{cold,day}$ is the unit of daily water consumption ($m^3/daym^2$), G_{hot} is the unit of daily hot water consumption ($m^3/daym^2$), $T_{use,B}$ is the using water temperature of building, B is the building type (office, retail, hotel, hospital)

Based on the original unit of water consumption, the calculation result of the drainage amount from different building types is shown in Figure 2-7; as for the using water temperature of all the building types are shown in Figure 2-8. (Calculation condition of water temperature was based on supply water: 15°C, hot water: 60°C)

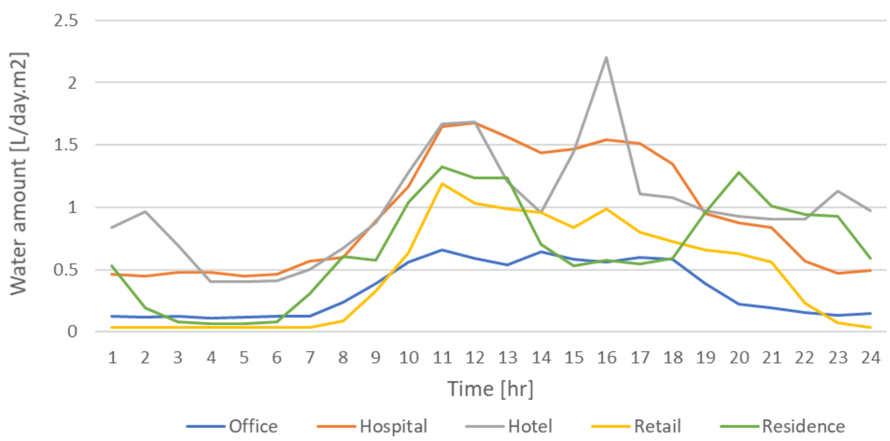

Figure 2- 7 Drainage amount from different building types

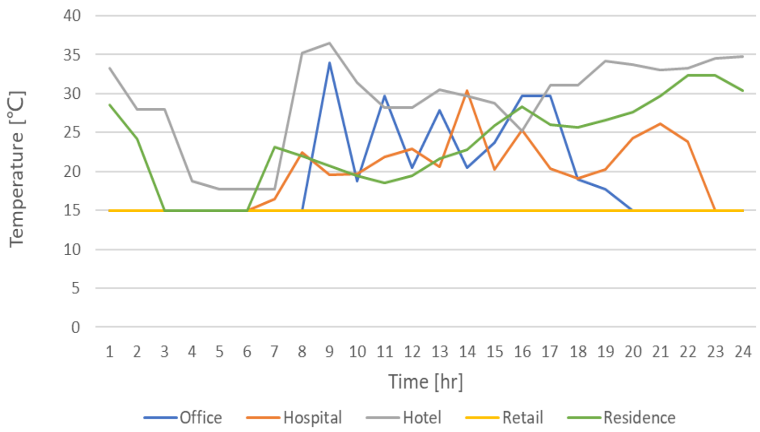

Figure 2- 8 Using water temperature from different building types

2.5 Construction of sewage physical model

While constructing the sewage physical model, it is indispensable to discuss different sewage situations in pipelines basing on its features; for instance, pipe slope, flowing and transportation type.

Regarding the features of sewage, the sewage flow rate is constantly changing and is difficult to be accurately measured due to many uncertainties, such as the timely drainage from buildings is different from different building types or scales, rainfall intensity, and the water infiltrating from unknown sources. Therefore, it is necessary to leave some reserved space in the pipeline section as a partially full pipe status for the intervention of unforeseen water volume, to prevent the overflow of sewage from obstructing environmental sanitation, and to allow the leakage of wastewater to drain smoothly [50] . In this section, we will briefly introduce the transportation type of sewer system and focusing on the partially full pipe model which is the majority of sewage pipelines.

2.5.1 Configuration of pipeline transportation system

There are two types of sewage transportation way within the sewage pipeline transportation system, gravity sewer system and vacuum sewer system. A gravity sewer system is a conduit utilizing the energy resulting from a difference in elevation to remove sewage water, and most of the sewage pipelines are the type of gravity sewer system[50]. Besides, during the path that transporting the wastewater to the water treatment plant or pump station, owing to some limitations caused by topography or techniques, the vacuum sewer system is constructed in some cases. In this study, we focus on the gravity sewer system which is the main type of sewage pipelines distributed in the urban area[22].

With regards to the gravity flow, the slope of the pipeline can be a positive number and minus, which are all included in the flow type of gravity (Figure 2- 9). The calculation methods adopted to the different types of bed slope are suggested in the study.

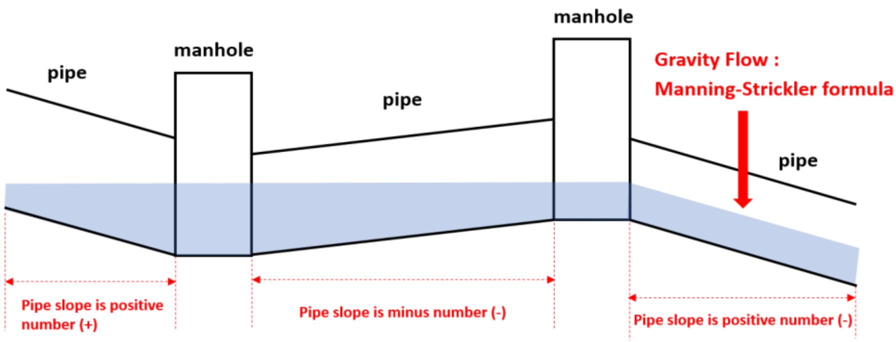

Figure 2- 9 Synopsis of pipe slope

Specifically speaking, two methods that mainly used for calculating the flow rate and flow velocity of gravity flow are Manning–Strickler formula [51] and Ganguillet-Kutter formula [47], both of these two mathematic methods are generally used to calculate the design value of velocity in the sewage system. In this study, Manning–Strickler formula is selected to solve the flow velocity of sewage water.

The Manning–Strickler formula is an empirical formula estimating the average velocity of a liquid flowing in a conduit that does not completely enclose the liquid, i.e., open channel flow. However, this equation is also used for calculation of flow variables in case of flow in partially full conduits, as they also possess a free surface like that of open channel flow. All flow in so-called open channels is driven by gravity. It was first presented by the French engineer Philippe Gauckler in 1867, and later re-developed by the Irish engineer Robert Manning in 1890 [51].

According to the Manning–Strickler formula, the hydraulic radius, Gauckler–Manning coefficient, and slope of the hydraulic grade line are related to the calculation of flow velocity. Specifically, the hydraulic radius is one of the properties of a channel that controls water discharge which related to the flow rate; in addition, in the case of sewage pipeline, the slope of the hydraulic grade line means the slope of pipeline and the Gauckler–Manning coefficient is determined by the material of pipeline. In brief, once the features of the pipeline such as material, pipe length, diameter and slope are known, the flow rate and flow velocity can be calculated by the Manning–Strickler formula.

2.5.2 Partially full pipe model

Under the normal circumstances of the sewage network system, the water flow in pipelines is the status of open channel flow, and the designed fullness limitation of water level is determined by the pipe diameter. The fullness of the pipeline is represented by the ratio between water depth (h) and pipe diameter (D). It is called full pipe flow while the ratio of water depth and pipe diameter equal to 1 (h/D=1); while the ratio is smaller than 1 (h/D<1), it is called partially full pipe flow [50]. Based on the designed theories of sewage system mentioned above, in order to capture the unsteady timely wastewater flow rate variation in pipelines, we set up a partially full pipe sewage flow model to simulate the timely inflow and outflow rate between the connected pipelines.

- Calculation of outflow rate

Under the situation of gravity flow, when the slope of the pipeline is the positive number, the outflow rate of sewage water is calculated by Manning–Strickler formula which is adopted to the unsteady flow that related to the timely flow velocity. The velocity is a variable value depends on the features of the sewage pipeline and timely sewage status.

Based on the Manning-Strickler formula, the flow velocity is determined by the cross-sectional area, wetted perimeter and hydraulic radius which are related to timely sewage amount, bed slope of the pipeline, and the Gauckler–Manning coefficient which depends on the material of conduit (Figure 2- 10). The calculation of the outflow rate and flow velocity are listed in the equation below (Eq. (22)~(24)) [51].

With regards to the situation that the slope of the pipeline is a minus number, the outflow rate of sewage water is assumed to be the same as the inflow rate in this study.

$$G_{out}{}_n^t = A_n^t \times v_n^t \qquad Eq. (22)$$

$$A_n^t = \frac{V_n^t}{pl_n} \qquad Eq. (23)$$

$$v = \frac{1}{m} R^{2/3} S^{1/2} = \frac{1}{m}\left(\frac{A}{l_{water}}\right)^{2/3} S^{1/2} \qquad Eq. (24)$$

Where A is the Cross-sectional area of sewage water (m^2), v is the flow velocity (m/sec), pl is the pipe length (m), m is the Gauckler–Manning coefficient (m=0.013 s/[$m^{1/3}$]), R is the hydraulic radius (m), S is the bed slope of pipeline (%), and l_{water} is the wetted perimeter (m)

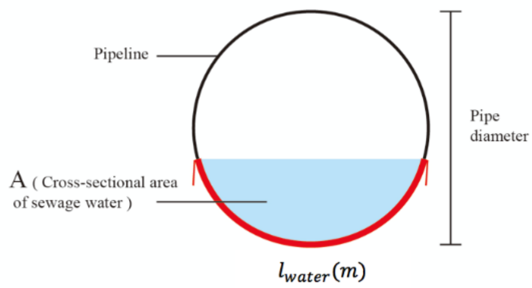

Figure 2- 10 Symbolic mark in equation (22) ~ (24)

- Setting of the initial condition

The calculation of the initial condition in pipelines is separated into two parts through the slope of the pipeline as well. When the pipe slope is a positive number, the initial water volume retained in pipelines is set as the water depth of 10% (Eq. (25)). While the pipe slope is a minus number (Figure 2- 11), the initial water volume retained in pipelines is calculated half of the cone volume (Eq. (26), Figure 2- 12).

$$V_0 = \frac{D^2}{8} \times (\theta - \sin\theta) \times \Delta x, \qquad \theta = 2arc\sin(0.6) \qquad Eq. (25)$$

$$V_0 = \frac{\left(\sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - h\right)^2} \times h \times \pi\right) \times {}^{pl}/_{3}}{2} \qquad Eq. (26)$$

Where V_0 is the initial water volume retained in pipeline (m^3), D is the diameter of pipeline (m), Δx is the distance interval (m), h is the water depth, pl is the pipe length.

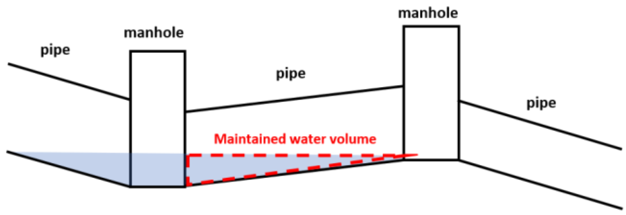

Figure 2- 11 Diagram of the initial water in pipeline with slope of minus number

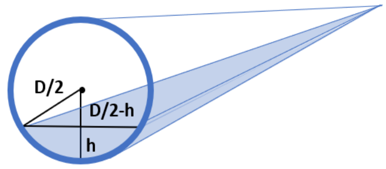

Figure 2- 12 Half of the cone volume

2.5.3 Thermal equilibrium in pipeline

The sewage heat retained in pipelines and the timely sewage temperature variation can be calculated by the series of equations (Eq.(27)~Eq.(33)), which was based on the thermal equilibrium and finite difference method. In the following equations, the calculation time step is represented by superscript, and the spatial step is represented by subscript, t is the time (sec), and n is the pipe number.

In this study, the sewage composition is divided into three parts, including the wastewater from the upstream pipelines, building drainage, and rainwater. According to Eq.(27), while calculating the timely heat variation, heat quantity from three parts of wastewater are taken into consideration separately, and the heat loss in pipeline is taken into account as well. In addition, the outflow rate of sewage is calculated by the Manning–Strickler formula mentioned in the former section.

$$(C\rho)_{pipe} \times V_n^t \times \frac{dT_n^t}{dt} = \Big\{\Big[(C\rho)_{in} \times {G_{in}}_n^t \times {T_{in}}_n^t + (C\rho)_{waste,total} \times {G_{waste,total}}_n^t \times {T_{waste,total}}_n^t + (C\rho)_{rain} \times {G_{rain}}_m^t \times {T_{rain}}_m^t\Big] - (C\rho)_{pipe} \times {G_{out}}_n^t \times T_n^t - {Q_{loss,2}}_n^t\Big\} \qquad Eq.(27)$$

$$T_n^t = \Big\{V_n^t \times T_n^{t-1} + \Big[(C\rho)_{in} \times {G_{in}}_n^t \times {T_{in}}_n^t + (C\rho)_{waste,total} \times {G_{waste,total}}_n^t \times {T_{waste,total}}_n^t + (C\rho)_{rain} \times {G_{rain}}_m^t \times {T_{rain}}_m^t\Big] \times \Delta t + \Big[\big({l_{water}}_n^t K_{sewage} T_{soil}\big) \times \Delta t \times \Delta x\Big] + \Big[\big({l_{air}}_n^t K_{air} T_{air}\big) \times \Delta t \times \Delta x\Big]\Big\} / \Big\{(C\rho)_{pipe} \times V_n^t + (C\rho)_{pipe} \times {G_{out}}_n^t \times \Delta t + \big({l_{water}}_n^t K_{sewage} + {l_{air}}_n^t K_{air}\big) \times \Delta t \times \Delta x\Big\} \qquad Eq.(28)$$

$$V_n^t = V_n^{t-1} + \Big({G_{in}}_n^t + {G_{waste,total}}_n^t + {G_{rain}}_m^t - {G_{out}}_n^t\Big) \times \Delta t \qquad Eq.(29)$$

Where $(C\rho)_{pipe}$ is the volumetric specific heat of sewage water in pipe (MJ/m^3K), V is the sewage water volume (m^3), $(C\rho)_{in}$ is the volumetric specific heat of sewage water flow in from upstream pipe (MJ/m^3K), G_{in} is the flow rate of sewage water flow in from upstream pipeline (m^3/sec), T_{in} is the temperature of sewage water flow in from upstream pipeline (℃), $(C\rho)_{waste,total}$ is the volumetric specific heat of building drainage (MJ/m^3K), $G_{waste,total}$ is the total water drainage of buildings connected to the same pipeline (m^3/sec), $T_{waste,total}$ is the wastewater temperature from all the buildings (°C), $(C\rho)_{rain}$ is the volumetric specific heat of rain (MJ/m^3K), G_{rain} is the rainwater flow-in rate (m^3/sec), T_{rain} is the Rainwater temperature (°C), G_{out} is the outflow rate (m^3/sec), T is the sewage temperature (°C), $Q_{loss,2}$ is the heat loss in sewage pipeline (MJ), Δx is the distance interval (m), Δt is the time interval (m).

Regarding the volumetric specific heat of raw wastewater, due to the volumetric specific heat is one of the factors that make influence on heat retained in pipelines, the volumetric specific heat of raw wastewater is also considered in the study. The volumetric specific heat of raw wastewater is calculated by the proportion of sludge and water (Table 2- 2) [52]. According to the design instructions of sewage pipeline, the design of sewage pipeline should be prevented from the accumulation of sediment [50], and the sewage basin is installed before the drainage installed before drainage flows into the sewage pipeline; therefore, the proportion of sediment in sewage pipelines is only about 5%~8% [53]. According to the previous study [54], the specific heat of sludge is estimated as 1.7 [MJ/kgK], and the density of sludge is 1.26 [kg/m^3]. Based on the design value, the raw wastewater in this study is composed of sludge of 8% and water of 92%; therefore, the setting condition of volumetric specific heat of raw wastewater is set as 4.01 [MJ/m^{3}K].

Table 2- 2 Setting condition of volumetric specific heat of raw wastewater

	Specific heat [MJ/kgK]	Density [kg/m^3]		100% water	95% water	92% water
Water	4.18	1	Proportion of water and sludge	1	0.95	0.92
Sludge	1.7	1.26		0	0.05	0.08
Volumetric specific heat				4.18	4.0781	4.01696

In regard to the heat loss, the timely heat loss in pipelines is determined by the timely wastewater amount, wastewater temperature and the air temperature in the pipeline. In this study, heat loss is considered to be related to two parts, from sewage water to soil, and from sewage water to the air in pipelines. The wastewater and air temperature, the heat transmission coefficient of wastewater and air in pipelines are all different, and these factors are all taken into consideration in Eq.(30). According to the previous research [37], the heat transmission coefficient of sewage is set as 53.4 [W/(m^2 K)] and the heat transmission coefficient of air in pipe is set as 25.6 [W/(m^2 K)].

$$Q_{loss,2}{}_n^t = \left[K_{sewage} \times (T_n^t - T_{soil}) \times l_{water}{}_n^t + K_{air} \times (T_n^t - T_{air}) \times l_{air}{}_n^t\right] \times \Delta x \qquad Eq.(30)$$

Where K_{sewage} is the heat transmission coefficient of sewage water(W/m^2K), T_{soil} is the soil temperature (°C), l_{water} is the wetted perimeter (m), K_{air} is the heat transmission coefficient of air in pipe (W/m^2K), T_{air} is the air temperature in pipe (°C), l_{air} is the air perimeter in pipe (m), Δx is the distance interval (m).

The wetted and air perimeter are related to the proportion between sewage and air in the pipeline, and the wetted perimeter and air perimeter is respectively calculated through the cross-sectional area of sewage by Eq.(31) to Eq.(33) [55]. The Symbolic marks in the series of equations are shown in Figure 2- 13.

$$A_n^t = \frac{\theta}{2\pi} \times \frac{\pi D^2}{4} + \frac{1}{2} \times \frac{D^2}{4} sin(2\pi - \theta) = \frac{D^2}{8}(\theta - sin\,\theta) \qquad Eq.(31)$$

$$l_{water}{}_n^t = D \times \frac{\theta}{2} \qquad Eq.(32)$$

$$l_{air}{}_n^t = D \times \sin\frac{\theta}{2} \qquad Eq.(33)$$

The sewage physical model is composed of the prediction model of the sewage origins and the partially full pipe model. By integrating the two models, the variation of sewage physical state can be calculated by the series of theoretical formulas proposed in this chapter.

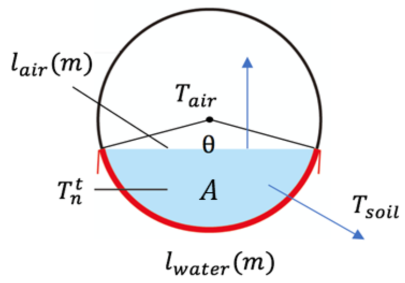

Figure 2- 13 Symbolic mark in equation (30) ~ (33)

2.6 Summary

In chapter 2, the sewage physical model is constructed to simulate the sewage physical condition including sewage temperature, flow rate, and flow velocity. The sewage physical model is proposed basing on the partially full pipe model which is close to the realistic sewage state that respectively discusses the different situations of the slope of the pipeline which may be a positive or minus number. Moreover, the factors that make the influence on retained heat amount in pipelines are all taken into consideration such as heat loss in the pipeline, the volumetric specific heat of raw wastewater.

For making an overall view of the sewage physical model, we can clearly realize the model through the calculation flow (Figure 2- 14). First of all, the basic information of pipeline and building needs to be prepared through the GIS data, such as pipe length, diameter, material and pipe slope; as for the building information, floor area, location and building type are the essential information.

Afterwards, the timely generated amount of sewage origins can be calculated through the statistical data of the original water consumption unit; furthermore, combining to the location of pipelines and building, the inflow position of building drainage is determined. Before conducting the simulation of sewage flow rate and temperature variation in pipelines through the partially full pipe model, the initial condition of retained water volume is calculated respectively basing on the condition of pipe slope which considered the situation of positive and minus pipe slope.

Eventually, the timely variation of sewage physical state including flow rate, temperature, and flow velocity can be simulated through the partially full pipe model which is based on the thermal equilibrium, Manning-Strickler formula, and finite difference method.

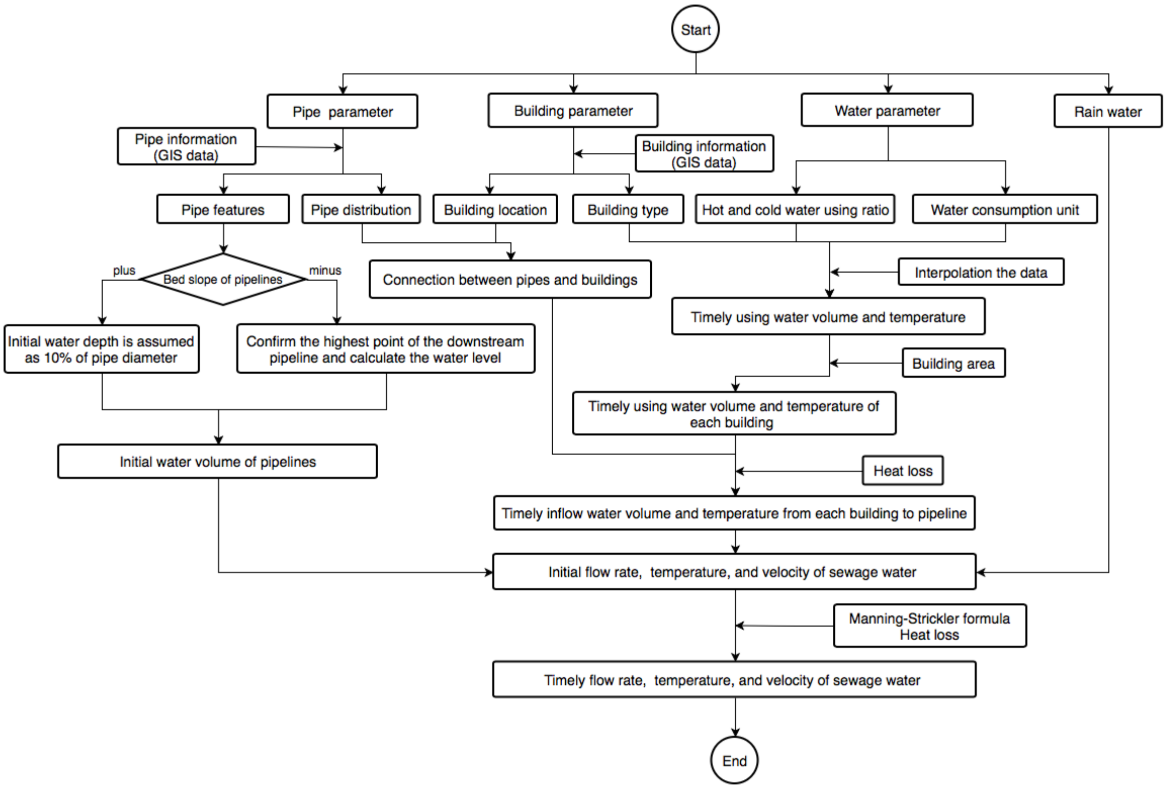

Figure 2- 14 Calculation flow of sewage physical model

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Chapter 3: Verification of sewage physical model

Chapter 3: Verification of sewage physical model

3.1 Introduction and objective

The purpose of chapter 3 is to verify the adequacy of the sewage physical model proposed in chapter 2. Owing to the sewage physical model is a theoretical model constructed based on mathematical formulas, it is necessary to confirm the appropriateness of the physical model.

The sewage physical model is verified by the measurement data of sewage flow rate and sewage temperature in an actual area to confirm the daily variation trend. In this chapter, input data is verified as well, and the simulation results of sewage flow rate and sewage temperature are compared to the measurement data, as for the sewage flow velocity, it is confirmed by the design value.

3.2 Overview of the verification area

The simulation results are verified by the measurement data in an actual area in Osaka city. The provided measurement data was conducted by Professor Masaki Nakao and his research team of Osaka City University [10], and the sewer system GIS map was provided by the Osaka City Sewer Bureau [49].

The measurement data is within the range of the red block in Kita-Ku, Osaka, which the area is in northern Osaka city (Figure 3- 1 and Figure 3- 2). In this study area, the sewer system is the type of combined sewer system which is the same type with the objective system set in this study.

There are two measurement points in the study area(Figure 3- 3), which are respectively of measurement point 10 (manhole number NO. 80100005), and measurement point 7 (manhole number NO. 80270060), the distance between the two measurement point is about 2 kilometers; in addition, the two measurement points are both set at the manholes on the main trunk line that connected the tributaries which aggregated the building drainage from the nearby areas. With regards to the flow direction, the measurement point 10 is located at the upstream side, and the measurement point 7 is located at the downstream of the area.

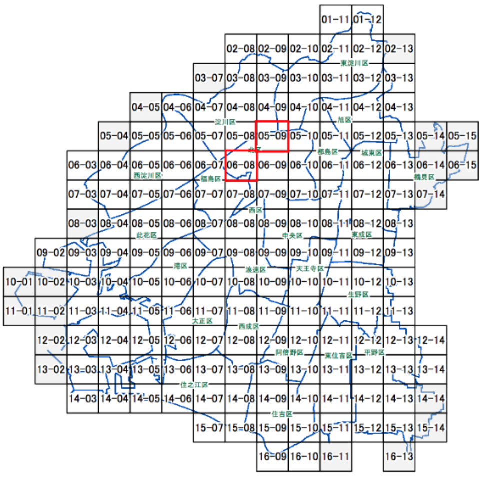

Figure 3- 1 Osaka city map[49]

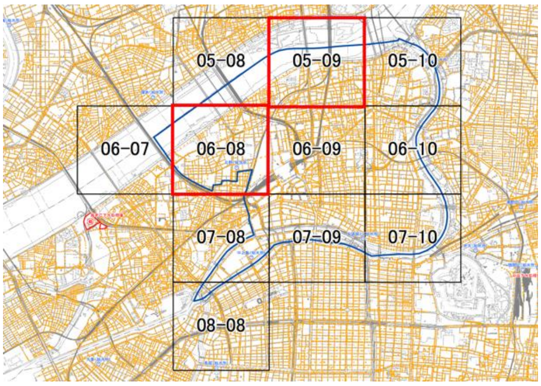

Figure 3- 2 Partially Osaka city map[49]

Figure 3- 3 Distribution of measurement point 10 and measurement point 7

3.2.1 Integration and overview of the GIS data of regional building and pipeline

In order to utilize the GIS data of the building and sewer system efficiently, it is necessary to arrange the GIS data at the initial step. The intelligence of buildings and pipelines are integrated to clarify the composition in the study area. Besides, the spatial distribution and the relationship between buildings and pipelines can be revealed.

The allocation of sewage pipelines and buildings scattered in the study area is as shown in Figure 3- 4. In Figure 3- 4, the sewage pipelines are presented by gray lines, the manholes are presented by gray points, and the color points are represented as buildings. The numbers of buildings that existed in the study area are 460. Regarding the building types, there are 315 residential buildings, which take the majority in the area, and the remaining buildings are 130 office buildings, 1 hotel and 14 retail stores. As for the sewer system, the numbers of pipelines are 396, and 397 manholes. The distribution of pipelines and manholes are shown respectively in Figure 3- 5 and Figure 3- 6.

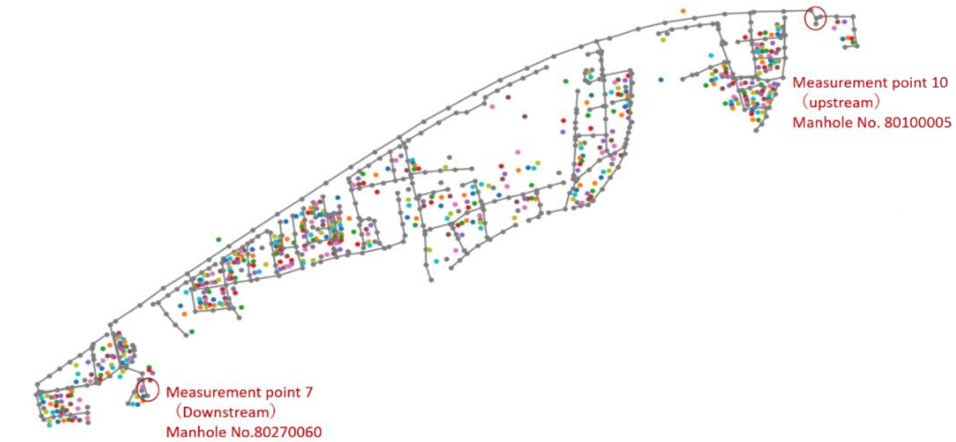

Figure 3- 4 Distribution of sewage pipelines and buildings in study area

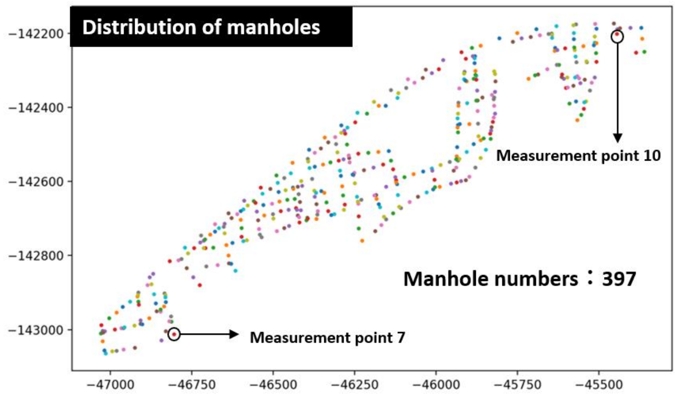

Figure 3- 5 Distribution of manholes in study area

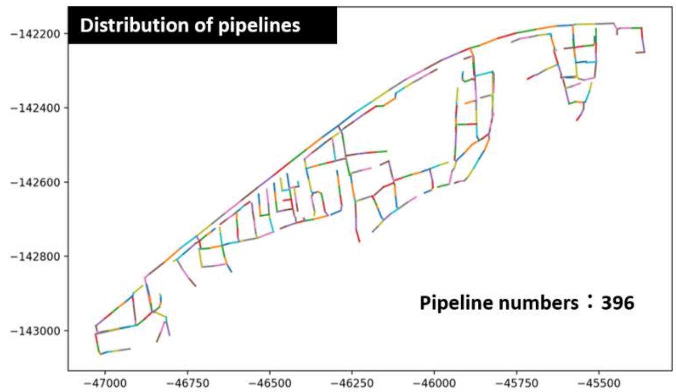

Figure 3- 6 Distribution of sewage pipelines in study area

According to the measurement data, the two measurement points are both set at the manholes on the main trunk line that connected the tributaries which aggregated the building drainage from the nearby areas.

For the purpose of clarifying the amount of wastewater, not only the trunk line is discussed in this study, other connected tributaries and the amount of wastewater in these pipelines are considered as well. Basing on the GIS data of the sewer system and the program proposed by this study, the relationship of pipe connection and their elevation can be illustrated; in addition, we can efficiently grasp the spatial distribution through the graph. The information of trunk lines is shown inFigure 3-8; as shown inFigure 3- 8, the features of the trunk lines such as pipe diameter, pipe length and pipe slope are listed in detail. The distribution of the tributaries is shown in Figure 3- 7, in this figure, the trunk lines are presented by the color lines, and the tributaries are presented by the gray lines.

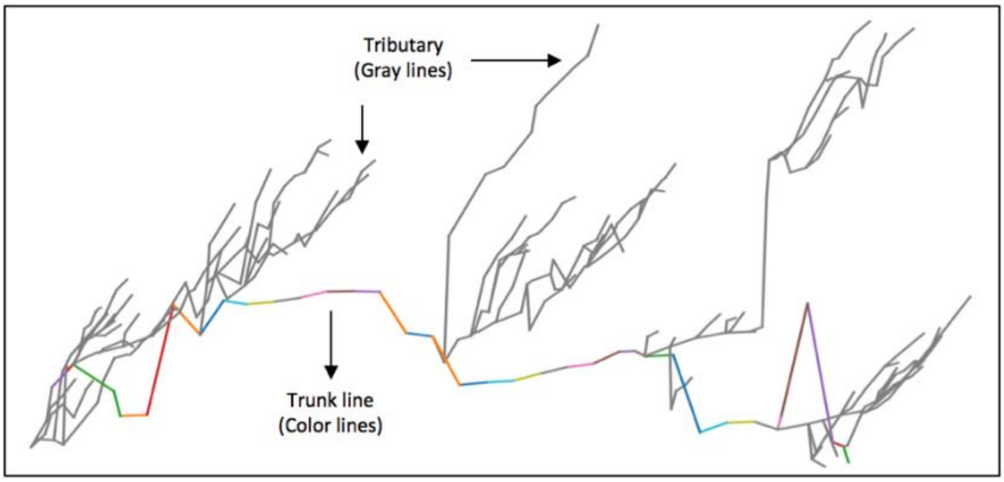

Figure 3- 7 Distribution of trunk lines and tributaries

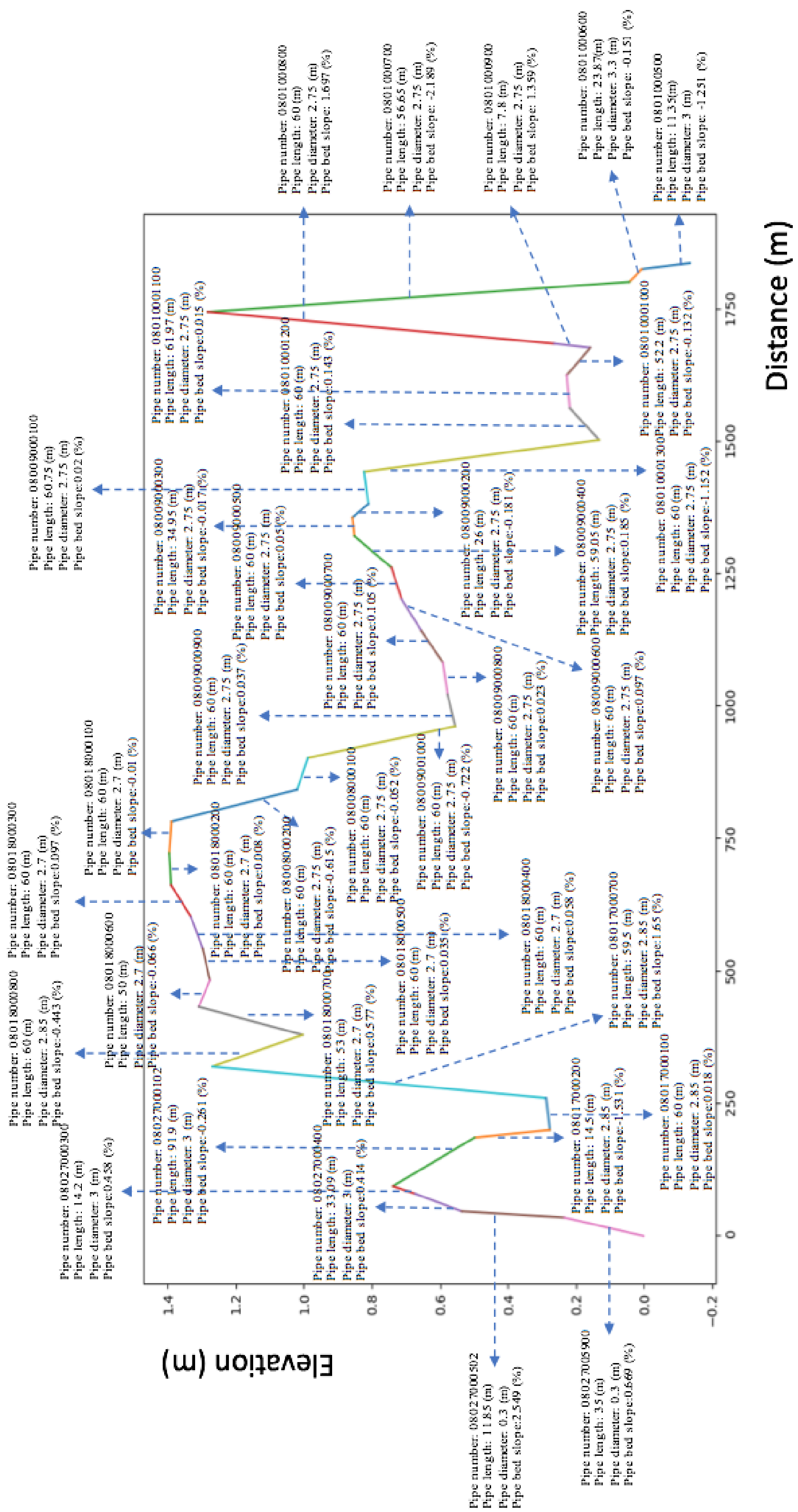

Figure 3- 8 Information of trunk lines in study area

3.2.2 Overview of the measurement data

The annual measurement results of sewage flow rate and sewage temperature are included in the measurement data provided by Professor Masaki Nakao and his research team. The measurement was conducted from March, 2011 to February, 2012 in Osaka city [10].

According to the previous research, sewage heat is considered to be as renewable energy which is proper to utilized especially in winter due to its temperature is higher than the air temperature. Owing to the reason, this study focuses on the simulation results in winter [1]. Therefore, the measurement data in winter will be mainly discussed in this section.

- Measurement data of sewage flow rate

Annual sewage flow rate data at measurement point 10 (upstream) and measurement point 7 (downstream) are shown in Figure 3- 9 and Figure 3- 10. According to the measurement data of two measurement points, the sewage flow rate is increasing from the upstream measure point to downstream, which means that there is building drainage aggregated into the main trunk line and then flow through the sewage flow path to downstream.

As shown in Figure 3- 9, the maximum value of sewage flow rate at measurement point 10 which is located at upstream is about 8 o'clock in the morning, and the increasing trend began from 5 o'clock; from 0 o'clock to 5 o'clock, the flow rate shows a decreasing trend. The result is thought to be caused by the pattern of water consumption that closed to the behavior of general household, due to the building composition in the study area is mainly composed of residential buildings. Specifically speaking, the water consumption after midnight decreased during the period of sleeping time, and then increased after people waking up in the morning.

With regards to the result of measurement point 7 shown in Figure 3- 10, as mentioned above, the flow rate at downstream is higher than upstream. Besides, the variation trend of the sewage flow rate is similar to the result of measurement point 10. Concerning to the maximum value of sewage flow rate, it occurred at 9 o'clock, which was an hour later than upstream; in addition, the sewage flow rate at downstream began increasing from 6 o'clock in the morning, which is an hour later than upstream as well. According to the result, it can be speculated that the increasing flow rate is caused by the building drainage that aggregated through the sewage flow path from upstream to downstream; moreover, the aggregated and flowing time of wastewater within the path lead to an hour time lag which results in the peak time occurred at downstream is later than upstream.

With regards to the measurement data of sewage flow rate in different season, it was shown that the sewage flow rate is relatively higher in summer and winter. It was speculated that the frequency of people taking shower in summer is higher than other seasons; as for winter, the behavior of bathing may increase. Both of the reasons lead to the result of increasing flow rate.

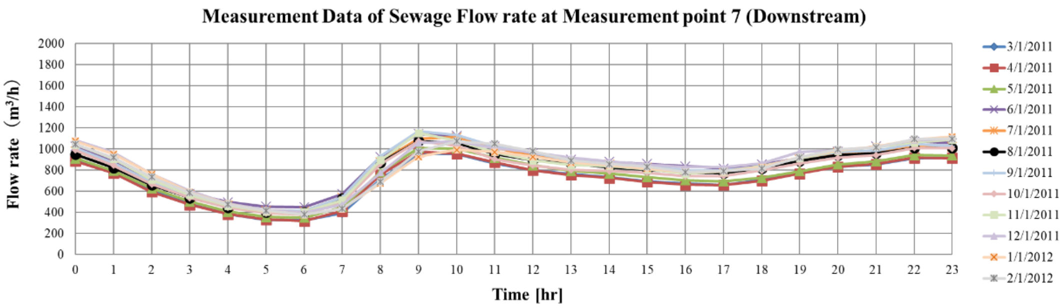

Figure 3- 9 Sewage flow rate at measurement point 7[35]

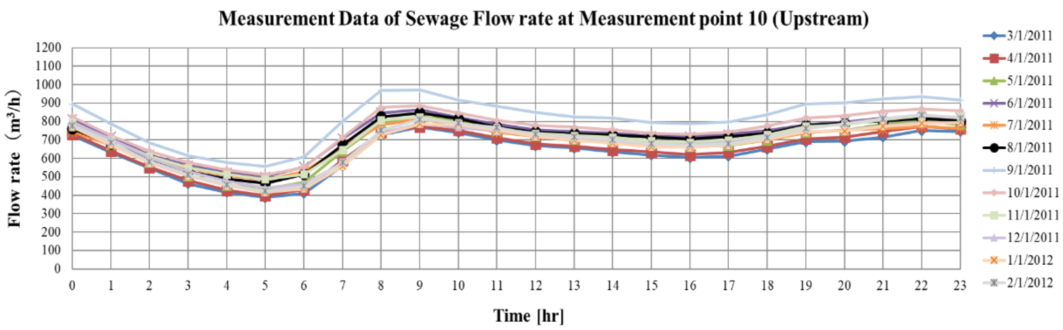

Figure 3- 10 Sewage flow rate at measurement point 10[35]

- Measurement data of sewage temperature

The annual sewage temperature at measurement point 10 (upstream) and measurement point 7 (downstream) are measured by an interval of 15 minutes. There is a massive amount of existed measurement data, we focused on the results of February and the represented day in February. In addition, the simulation conducted in this thesis is supposed to be in winter, and certain calculations selected the statistical data of February as input data; therefore, the measurement data of sewage temperature in February was selected to be mainly discussed.

The measurement results of sewage temperature in February at measurement point 10 (upstream) and measurement point 7 (downstream) are shown in Figure 3- 11. According to the measurement result, it was shown that the sewage temperature of the upstream measurement point is higher than the sewage temperature at downstream at most of the time. Besides, the temperature variation in the whole month is not obvious except for four to five days that occurred at a relatively low temperature.

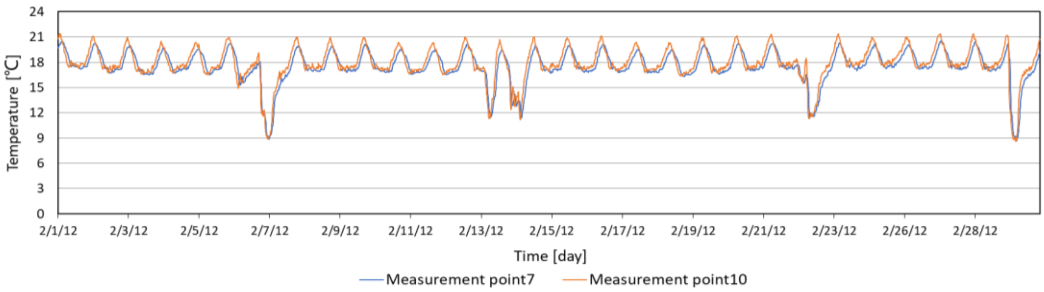

Figure 3- 11 Sewage temperature of February at measurement point 10 and measurement point 7[35]

In addition, the measurement data of represented days in February is selected to discuss the daily variation of sewage temperature. As it was shown in Figure 3-11, the variation trend of sewage temperature at two measurement points is similar; besides, the sewage temperature of the upstream measurement point is higher than the measurement point at downstream except the time period from 3 o'clock to 7 o'clock in the morning. It was speculated that the sewage temperature is directly affected by building drainage while the building types that located nearby the measurement points are different. According to the wastewater discharged from different building types, it may lead to the result of different sewage water temperature at different location.

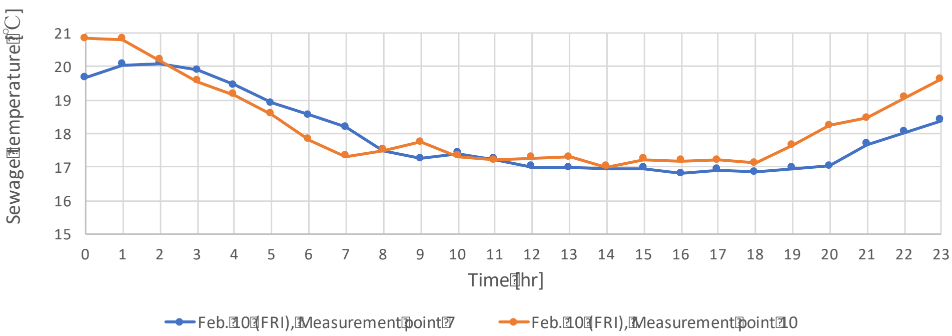

Figure 3- 12 Daily measurement data of sewage temperature [35]

3.3 Verification of the model

According to the features of sewage heat that it is a kind of renewable energy that is recommended to be utilized effectively in winter, the setting conditions of the simulation in this thesis are set to discuss the cases in winter. In this section, the simulation results of sewage temperature and flow rate are verified by the measurement data in February. In this study, the verification of the model was separated into two parts, the verification of input data and the verification of the sewage physical state.

3.3.1 Verification of input data

At the former step of conducting the simulation of the regional sewage physical state, it is essential to verify the adequacy of the input data at the first step.

According to the sewage physical model proposed in chapter 2, the generated amount of building drainage is calculated by the original unit of water consumption[45], which is classified into five building types, including residence, office, retail, hospital, and hotel [35]. Basing on the original unit of water consumption, the timely building drainage is assumed to be the same with the value. In this section, the increasing amount of daily sewage accumulated flow rate from measurement point 10 (upstream) to measurement point 7 (downstream) is compared to the simulation result.

First of all, we input the measurement data of daily accumulated flow rate at measurement point 10 (upstream); afterwards, referring to the simulation model proposed in chapter 2, the daily accumulated amount of building drainage discharged from all the buildings in the study area is calculated through the original unit of water consumption based on the building type and floor area. The calculation result of building drainage from each building in the study area is shown in Figure 3- 13. In Figure 3- 13, each building is represented by each color point. In addition, the relationship between building floor area and drainage amount in the study area is shown in Figure 3- 14.

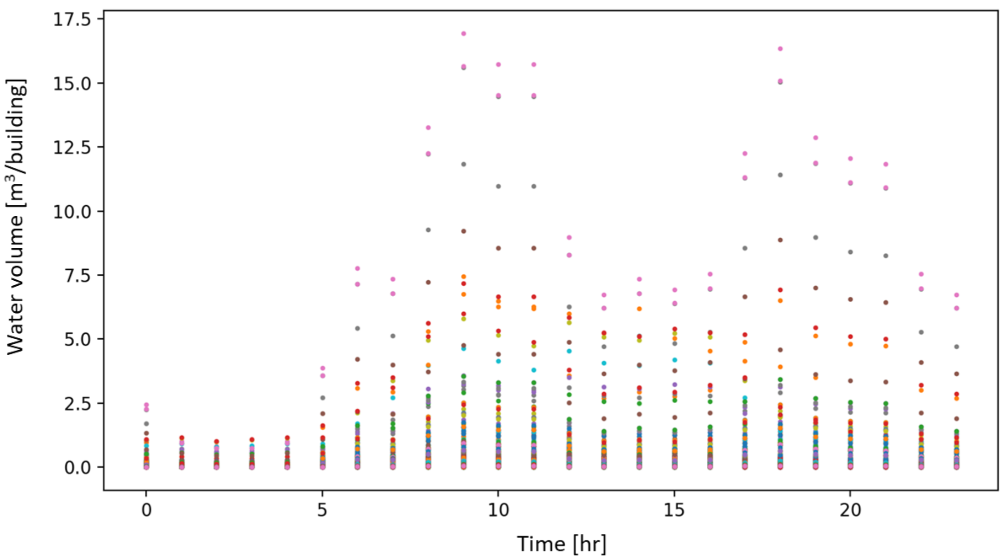

Figure 3- 13 Drainage amount of each building in the study area

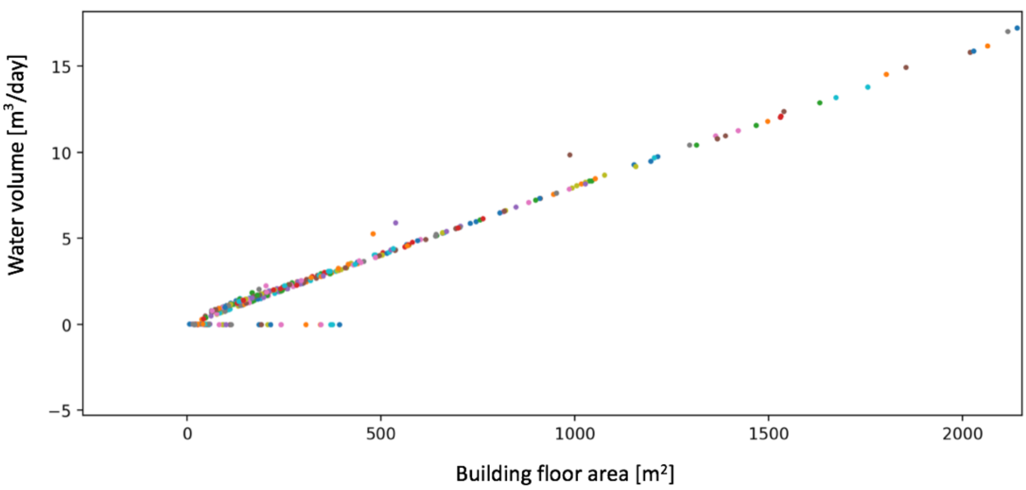

Figure 3- 14 Relationship between building floor area and drainage amount in the study area

At the final step, the sum of the daily accumulated amount of building drainage and daily accumulated flow rate at measurement point 10 (upstream) is compared to the daily accumulated flow rate at the measurement point 7 (downstream). According to the increasing sewage water amount between two measurement points, the accuracy of building drainage amount calculated by the statistical data can be confirmed.

The increasing amount of daily accumulated sewage flow rate between two measurement points of each month is shown inFigure 3- 15. With regards to the result of February, the calculation value of the daily increasing amount of sewage water is very closed to the measurement data. It was speculated that the daily accumulated sewage flow rate was an average value calculated by the average flow rate in February, and the simulation result is a statistical data of February and therefore lead to the approximate result.

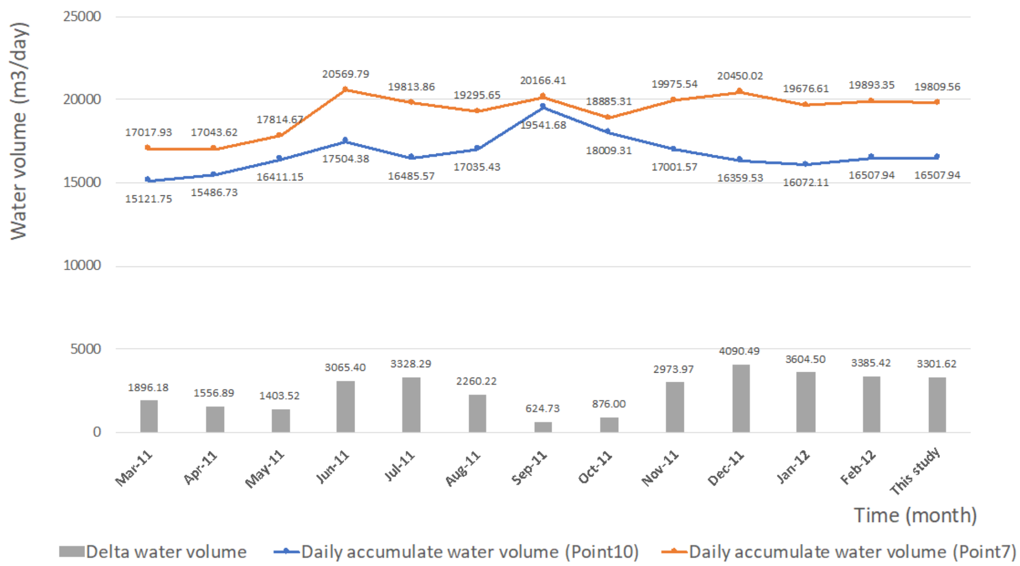

Figure 3- 15 Daily average increasing sewage amount from upstream to downstream

The increasing amount of daily accumulated sewage flow rate between two measurement points in February is shown in Figure 3- 16 . As shown in the figure, the daily accumulated sewage increasing amount of measurement data is 3301.62 [m^3/day], and the result of the simulation is 3385.42 [m^3/day]. The difference in sewage increasing amount between input data for simulation and measurement data is about 2.4%, and the relative error is thought to be acceptable.

After verifying the input data of the simulation model, the boundary condition and initial condition for simulating the sewage physical state are elaborated in the following article; afterwards, the sewage flow rate, sewage temperature and velocity will be verified.

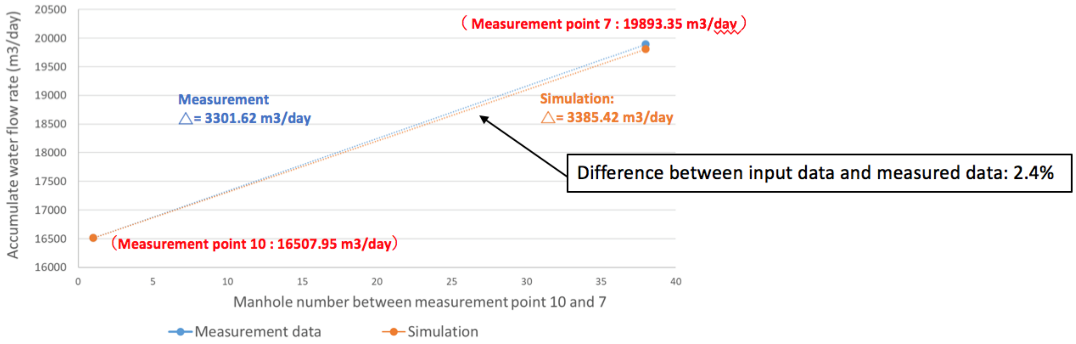

Figure 3- 16 Daily average increasing sewage amount from upstream to downstream in February

3.3.2 Boundary condition and initial condition

The setting of boundary conditions and initial conditions for simulating the sewage physical state are described in this section.

- Boundary conditions at upstream manhole (Starting point):

In this simulation model, the starting point is set at the same point with the measurement point 10 (manhole NO. 80100005) located at upstream. Basing on the measurement data, the existed flow rate measurement data is the average value of an hour; therefore, the measurement data is interpolated by time in 2-second intervals. The sewage flow rate which is interpolated into 2 seconds is set to be the inflowing sewage flow rate at the beginning point. Regarding the inflow sewage temperature, the measurement data of sewage temperature at measurement point 10 (manhole NO. 80100005) is set to be as the inflow temperature.

- Initial condition of sewage water temperature in pipelines

The initial sewage water temperature in all the pipelines including trunk line and tributaries is set to be 18 degrees, which is the average sewage temperature of February [10].

- Initial condition of sewage water volume retained in pipelines

According to the sewage physical model proposed in chapter 2, the calculation of the initial condition in pipelines is separated into two parts based on the slope of pipelines. When the pipe slope is a positive number, the initial water volume retained in pipelines is set as the water depth of

10% (Eq. (25)). While the pipe slope is minus number, the initial water volume retained in pipelines is calculated half of the cone volume (Eq. (26)).

$$V_0 = \frac{D^2}{8} \times (\theta - sin\,\theta) \times \Delta x, \qquad \theta = 2arc\,sin(0.6) \qquad \text{Eq. (25)}$$

$$V_0 = \frac{\left(\sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - h\right)^2} \times h \times \pi\right) \times {}^{pl}/_3}{2} \qquad \text{Eq. (26)}$$

Where V_0 is the initial water volume retained in pipeline (m^3), D is the diameter of pipeline (m), Δx is the distance interval (m), h is the water depth, pl is the pipe length.

3.3.3 Verification of the time variation of sewage temperature and flow rate

Basing on the setting of the initial condition and boundary condition mentioned above, the sewage physical state is verified by the measurement data. The results of sewage flow rate and sewage temperature simulated by the sewage physical model proposed in chapter 2 are compared to the measurement data of measurement point 7 which is located at downstream. In addition, after verifying the simulation result of sewage flow rate and sewage temperature by the measurement data of downstream measurement point 7 (manhole NO. 80100005), the simulation results of other branch pipelines are shown in this chapter as well. In addition, the simulation of the sewage flow rate and temperature are conducted by the time interval of 2 seconds and the spatial interval of 6 meters; the results are shown by hour.

- Verification result of sewage flow rate

The verification result of sewage flow rate is shown in Figure 3- 17, in order to mitigate the influence of initial condition, the results of the second day are shown; besides, the result shown in the figure is the instantaneous result by hour. According to Figure 3- 17, the simulation result occurred higher sewage flow rate than measurement data during certain time periods, and during certain time periods, the simulated value is lower than the measurement data; however, the variation trend of simulation results and measurement data is similar.

Specifically, regarding the simulation result, the maximum sewage flow rate value occurred at 10:30 in the morning, which the sewage flow rate is 0.36 [m3/hr]; as for the measurement data, the maximum sewage flow rate value is about 0.31 [m3/hr] at 22:30. Concerning to the increasing trend of sewage flow rate, the simulation result shows that the sewage flow rate increased from 5 o'clock in the morning, and reached the first peak value at 10:30; as for the measurement data, the sewage flow rate increased from 6:30, and reached the first peak value at 10 o'clock in the morning. Afterwards, both the result of measurement data and simulation value of sewage flow rate decreased and remained moderate trend until 17:00 in the evening.

Besides, the sediment or sludge in pipelines that may make an influence on the simulation result of flow rate are ignored in the sewage physical model, it was speculated to be as the reason that the simulated flow rate is higher than measurement data.

In general, there is a certain difference between the measurement data and simulation result of the sewage flow rate; however, as a scale of regional simulation, the relative error is thought to be acceptable.

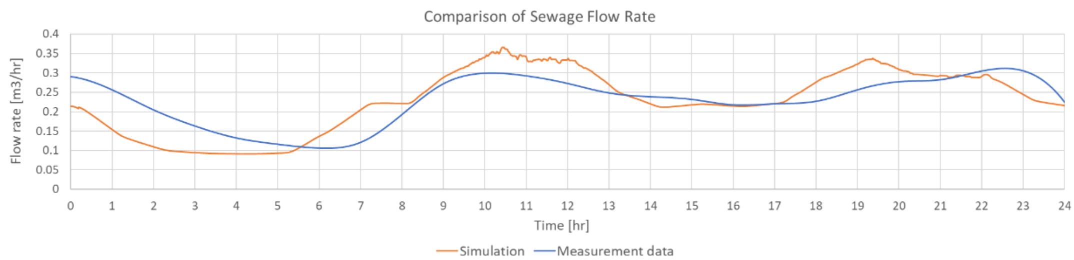

Figure 3- 17 Verification result of sewage flow rate

- Verification result of sewage temperature

The verification result of sewage temperature is shown in Figure 3-17, in order to mitigate the influence of initial condition, the results of the second day are shown; besides, the result shown in the figure is the instantaneous result by hour. According to the result shown in Figure 3-17, the measurement data of sewage temperature performed an extremely stable result that the variation is not obvious. However, unlike the measurement data, since the simulation model estimates the sewage flow rate and temperature based on the origin unit of water consumption and the using ratio of cold and hot water, it was thought that temporal fluctuation of sewage temperature is directly affected by the fluctuation of building drainage.

While discussing the simulation result from the perspective of domestic water using behavior, it was shown that the sewage temperature decreases after midnight and increase in the morning which was affected by the living behaviors. Furthermore, during the time period from 18:00 to 24:00, the sewage temperature remaining at a relatively high temperature. The reason resulted in the phenomenon was thought that it is the time period for people to take a shower and continued to midnight.

Generally speaking, the comparison result of sewage temperature between measurement data and simulation value existed certain errors; however, as a simulation conducted in a regional scale, the simulation result of sewage temperature can be regarded as a reasonable result that the temperature is in the normal range.

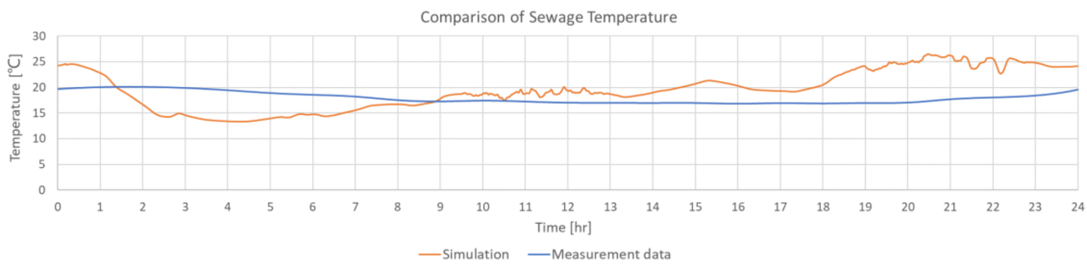

Figure 3- 18 Verification result of sewage temperature

- Verification result of sewage flow velocity

The verification result of sewage flow velocity is shown in Figure 3- 19, in order to mitigate the influence of initial condition, the results of the second day are shown; besides, the result shown in the figure is the instantaneous result by hour. Owing to the measurement data of timely sewage flow velocity does not exist, the simulation result is compared to the standard design value of sewage flow velocity.

The standard design value of sewage flow velocity is considered to be in the range between 0.6 [m/sec] to 3 [m/sec]. According to the result shown in Figure 3- 19, the simulation value of sewage flow velocity is confirmed to be in the standard range; therefore, it can be regarded as a reasonable result.

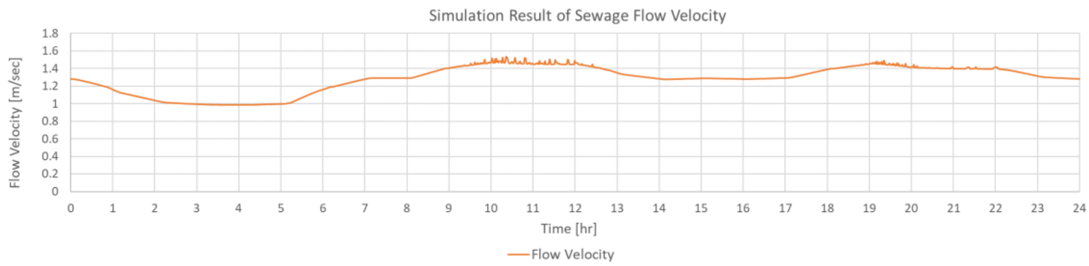

Figure 3- 19 Verification result of sewage flow velocity

- Simulation result of sewage flow rate and temperature in tributaries

Not only the results of the pipeline which measurement data is provided have been confirmed, but all the simulation results of each pipeline in the study area have been checked as well. The simulation result of sewage temperature and sewage flow rate in every branch pipeline are shown in the following contents. In addition, certain special cases occurred in the simulation are described in this section, for instance, the situation of full pipe and the result of the pipeline with small amount of water.

The simulation results of sewage temperature in all the pipelines in the study area are shown by an hour from Figure 3- 20 to Figure 3- 23. According to the results, the general variation trend of sewage temperature is similar to the simulation result of the pipeline which the measurement data is provided. Specifically speaking, the sewage temperature from 1:00 to 5:00 remaining at relatively low temperature; afterwards, the sewage temperature increased from 5:00 in the morning. Take the result of 5:00 for example, sewage temperature in several pipelines remaining at low temperature, but the temperature in certain pipelines begin increasing.

While confirming the composition of the buildings that connected to these pipelines with higher sewage temperature, it can be found that one of the reasons is the floor area of the buildings connected to these pipelines are larger than others; another reason is that the connected numbers of buildings are more than other pipelines. It means, there is a relatively larger amount of building drainage discharged into these pipelines at that time. Once a large amount of wastewater with higher temperature discharged into these pipelines, the sewage temperature in these pipelines increased in a short time.

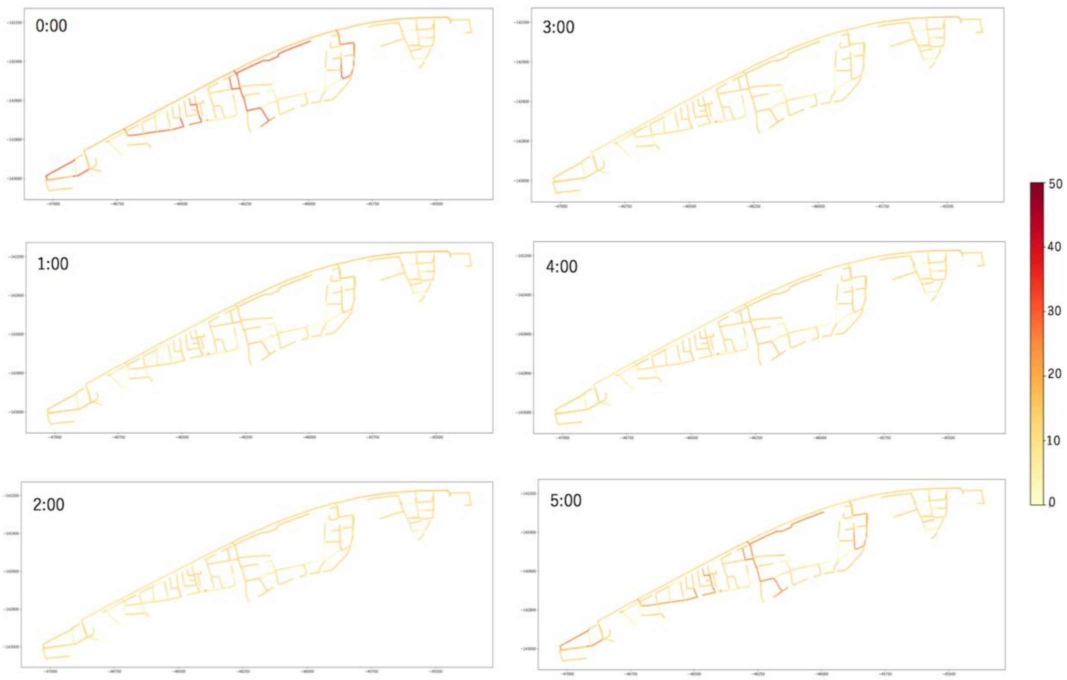

Figure 3- 20 Simulation result of sewage temperature in tributaries (0:00~5:00)

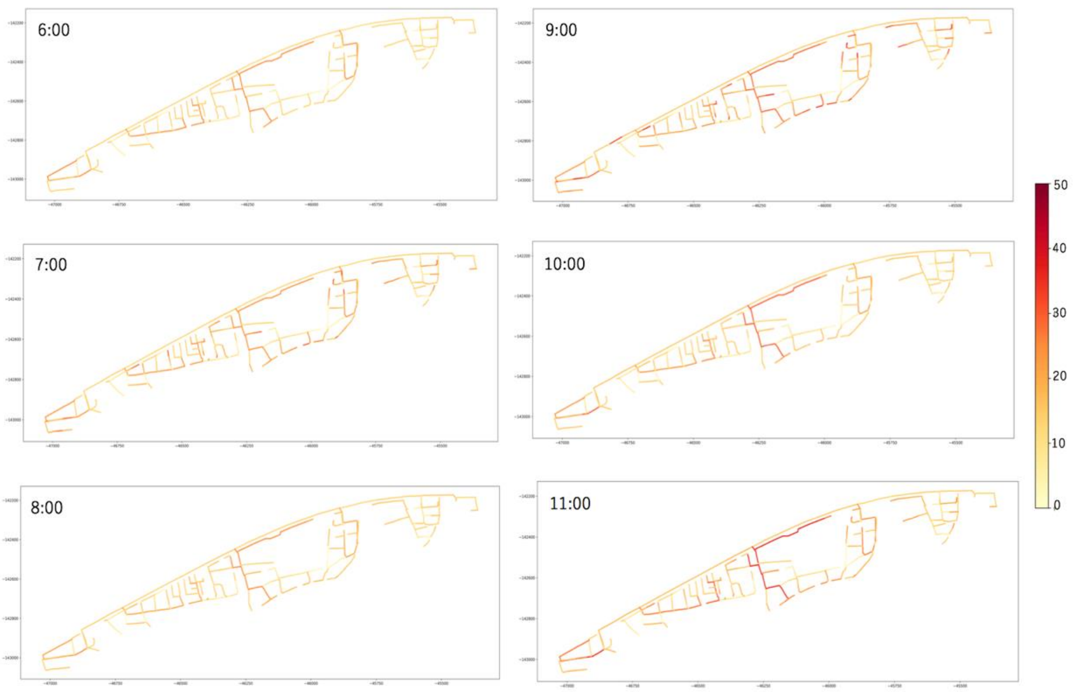

Figure 3- 21 Simulation result of sewage temperature in tributaries (6:00~11:00)

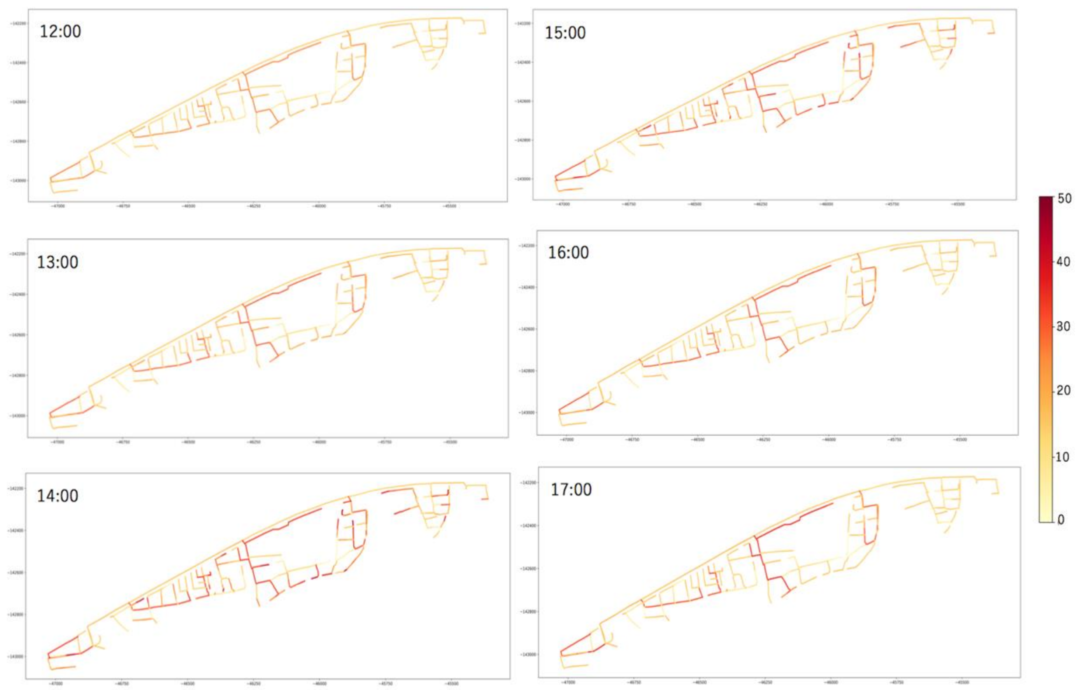

Figure 3- 22 Simulation result of sewage temperature in tributaries (12:00~17:00)

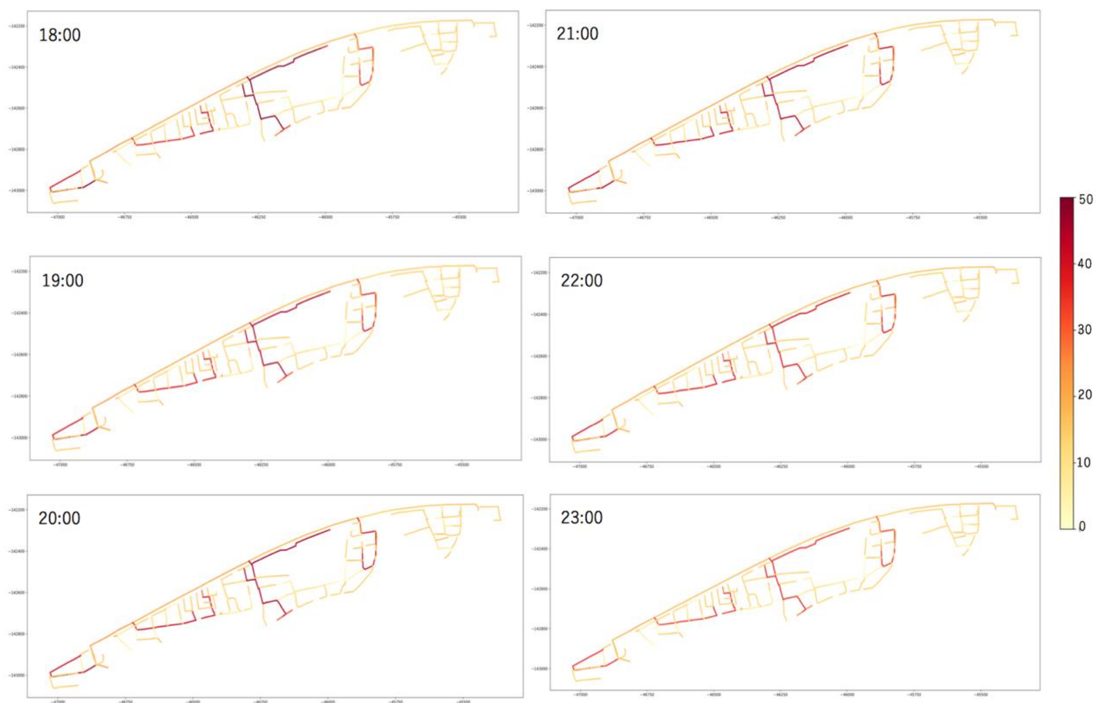

Figure 3- 23 Simulation result of sewage temperature in tributaries (18:00~23:00)

- Simulation results of special cases in the study area

Within the simulation results of the pipelines in the whole study area, there are some special cases that occurred in the simulation; for instance, the situation of full pipe and the pipelines with a small amount of sewage water. In this section, the speculated reasons for these situations are briefly discussed.

Referring to Figure 3- 24, take one of the simulation results of the full pipe as an example, the situation of a full pipe occurred at pipe NO. 80080003 to pipe NO. 80080004 which is the tributaries before the confluent point at the trunk line (pipe NO. 80080001). It was speculated that these pipelines are the connection that connected between tributaries and trunk lines; therefore, the sewage amount is larger than other pipelines.

The occurrence rate of full pipe in the study area is about 1.8%; in the other words, within the total 396 pipelines in the study area, the situation of a full pipe occurred to 7 pipelines. This situation only occurred at tributaries which are the pipeline before the confluent pipeline.

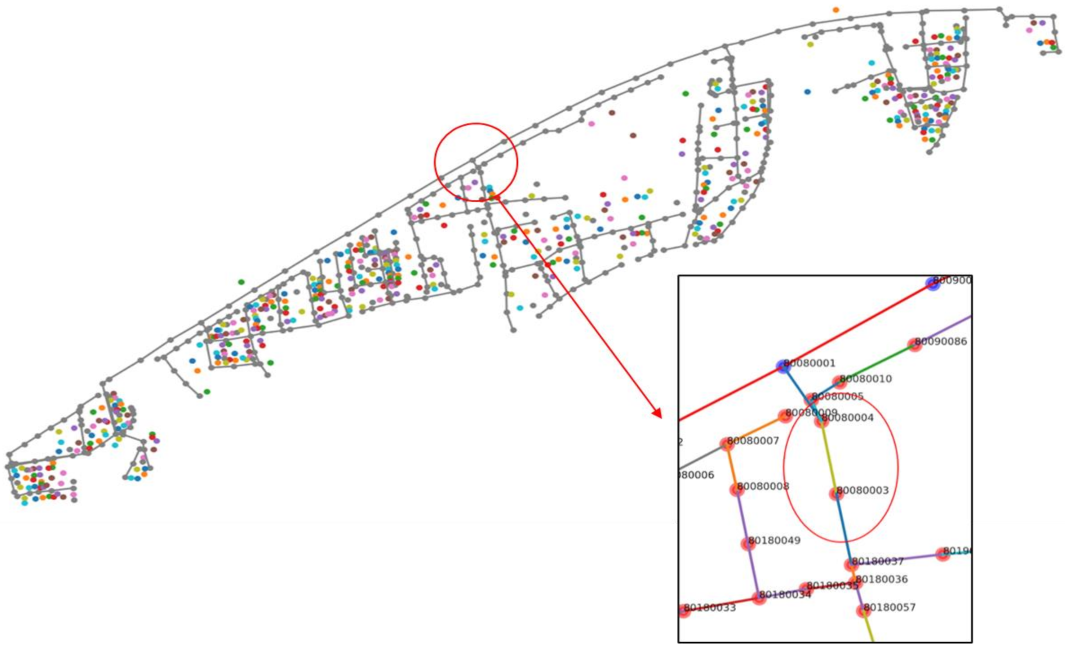

Figure 3- 24 Diagram of pipelines in study area

Regarding the situation of full pipe, the simulation results of sewage flow rate and temperature under the full pipe situation is shown in Figure 3- 25 and Figure 3- 26.

According to the simulation result of the sewage temperature in the full pipe situation, it is speculated that there is a great amount of high-temperature sewage keeps flowing into the pipelines; therefore, the sewage temperature in this kind of sewage pipelines is higher than other pipelines.

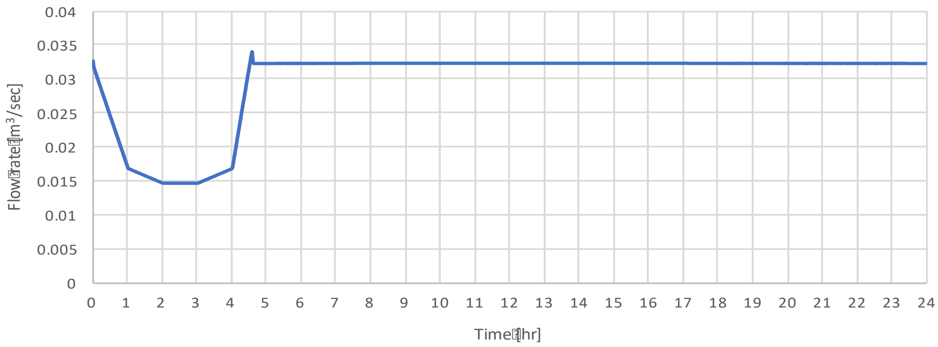

Figure 3- 25 Simulation result of sewage flow rate under the situation of full pipe

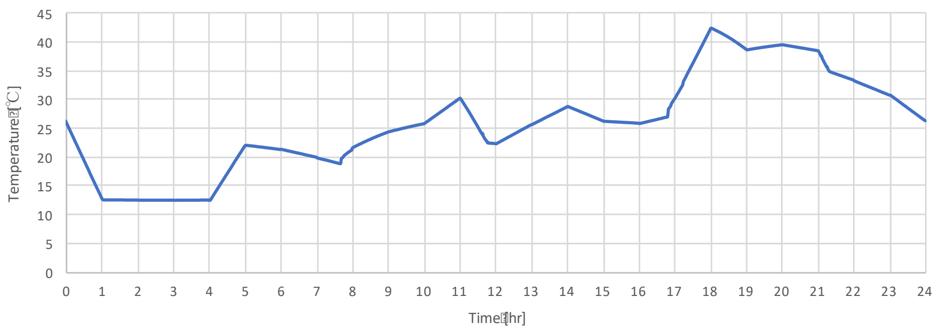

Figure 3- 26 Simulation result of sewage temperature under the situation of full pipe

Regarding the results of the pipelines with a small amount of sewage water, as shown in Figure 3-27, the pipelines with a small amount of sewage water occurred at the pipelines located at the most upper stream or the pipelines connected with a few numbers of buildings. The occurrence rate of the pipelines with a small amount of sewage water in the study area is about 10%; the situation occurred to 40 pipelines within 396 pipelines in the study area.

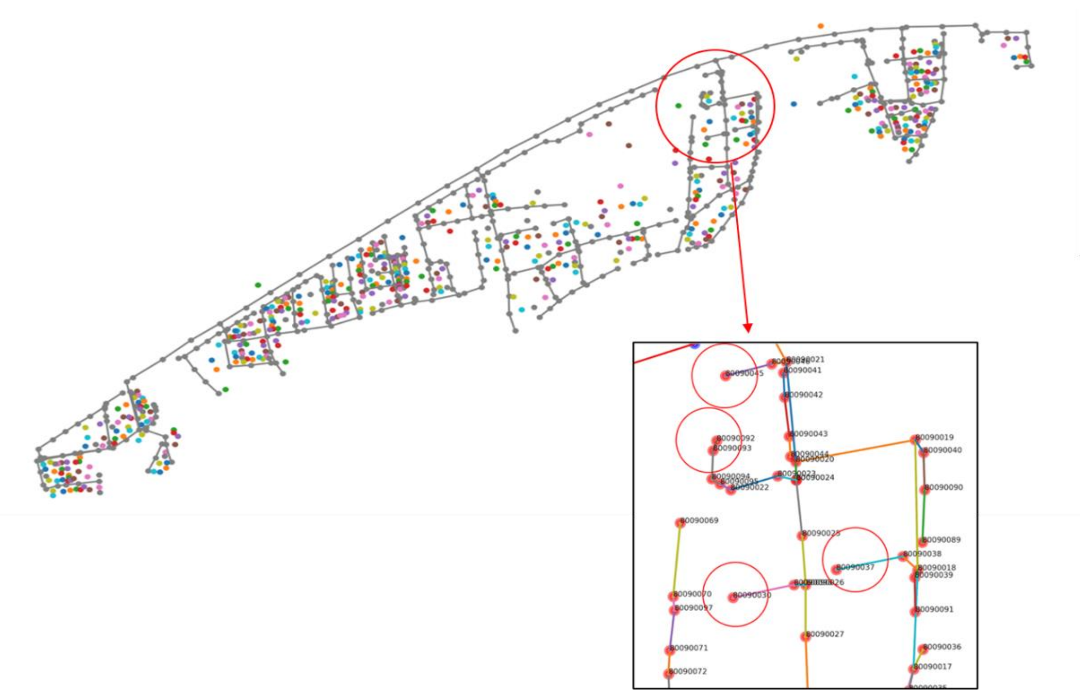

Figure 3- 27 Diagram of pipelines in study area

With regards to the situation of the pipelines with a small amount of sewage water, the simulation results of the sewage flow rate and temperature under this situation is shown in Figure 3- 28 and Figure 3- 29. According to the results, the sewage flow rate and sewage temperature in these pipelines are relatively unstable. In addition, the sewage temperature in this kind of pipelines is lower than other pipelines. One of the reasons is that the building connected to these pipelines is the building types with smaller drainage such as office building and retail store which the drainage amount is smaller than other building types, and the sewage temperature is relatively lower. Another reason is speculated that these pipelines are connected to fewer buildings or the floor area of the buildings connected to the pipelines is small. Besides, the sewage flow rate is calculated by the finite difference method in this study; therefore, it is a possible reason lead to unstable results.

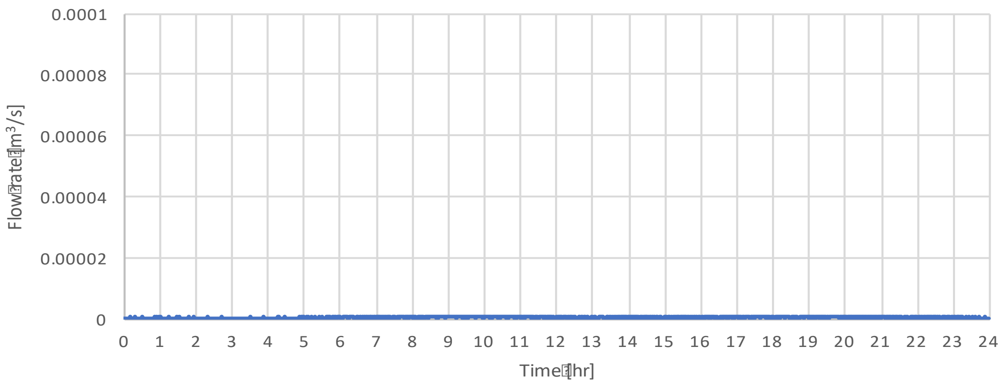

Figure 3- 28 Simulation result of sewage flow rate under the situation of full pipe

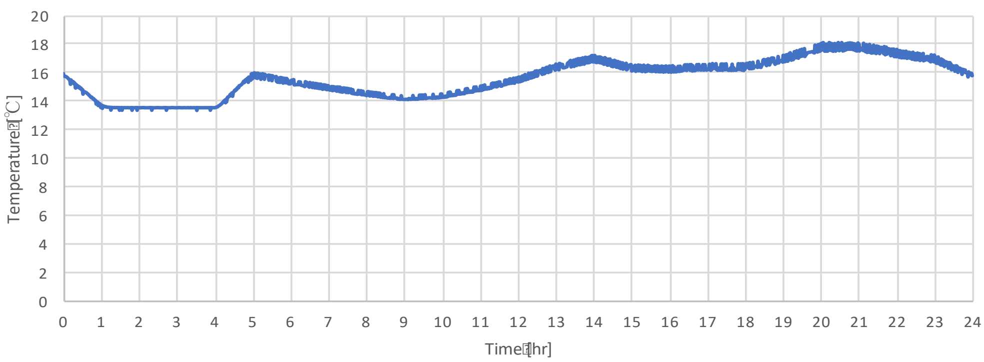

Figure 3- 29 Simulation result of sewage temperature under the situation of full pipe

3.4 Summary

In chapter 3, the sewage physical model is verified by the measurement data in an actual area in Osaka city to confirm the adequacy of the model; besides, the synopsis of verification area and the provided measurement data have been overviewed to make an overall understanding for readers to comprehend the data which was utilized in the study.

At the former step of conducting the simulation of regional sewage physical state, it is essential to verify the adequacy of the input data at the first step; therefore, the appropriateness of input data is confirmed in this chapter as well. According to the comparison results, the sewage flow rate and temperature variation simulated by the model have a similar trend with the measurement data though the value existed certain differences. However, owing to the simulation conducted in this study is the regional scale, so the error is thought to be acceptable. Besides, the main purpose of this thesis is to propose the methodology of the comprehensive evaluation instead of constructing a high precision model. Therefore, at this stage, it is thought that once the more accurate input data can be provided in the future, the precision of this physical model can be improved.

Regarding the verification results proposed in this chapter, the sewage physical model is considered as a reasonable model for simulating the sewage physical state including sewage flow rate, temperature and flow velocity. Consequently, the sewage physical conditions are able to be simulated through the sewage physical model proposed in chapter 2 which provides the databases of sewage flow rate and sewage temperature before conducting the simulation of sewage heat utilization.

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Chapter 4: Sewage heat utilization system model

Chapter 4: Sewage heat utilization system model

4.1 Introduction and objective

The sewage heat utilization system model is constructed in chapter 4. The main purpose of the model is to simulate the outlet temperature which makes an influence on the sewage water temperature after utilizing the sewage heat due to the outlet temperature is a pivotal factor of evaluating the regional sewage heat utilization potential.

Regarding the issue of the regional sewage heat utilization potential, owing to the heat exchanger outlet temperature of the buildings located at relatively upstream which utilized the sewage heat make an influence on the heat exchanger inlet temperature of the downstream buildings which intend to extract sewage heat; therefore, it is essential to clarify the variation of sewage temperature while utilizing the sewage heat [20]. In addition, it is necessary to build up a simulation model to reflect the heat utilizing temperature difference which is close to the practical situation. In this study, the heat utilizing temperature difference is simulated based on the reasonable sewage heat utilization system which is similar to practical circumstances.

When concerning the sewage heat utilization, the most important issue is to clarify the usable amount and extracted amount that can be obtained from sewage. The critical part of how much sewage heat needs to be extracted or can be extracted from sewage heat are determined by the heat utilization types and the techniques and method of extracting heat. Therefore, it is vital to grasp the timely variation of sewage state in order to confirm the retained amount and usable amount of sewage heat which depends on different conditions of pipelines and buildings.

According to the previous research, the simulation of the sewage heat utilization was discussed; however, most of the heat utilizing temperature difference was supposed to be a fixed value as 5℃ to calculate the sewage heat utilization amount empirically [1], though the utilization temperature difference should be considered depending on the heat demand, the operating performance of equipment, sewage status, etc. In addition, certain novel techniques for extracting sewage heat was developed in the recent year [38,56], the discussion of sewage heat utilization potential can therefore be updated through the certain setting conditions of the novel system.

With regards to the sewage heat utilization system, the diagram of the sewage heat utilization system applied in this study is shown in Figure 4 - 1 [21]. Based on this system, the outlet temperature is calculated according to the heat demand of different building types, the performance of heat source equipment and heat exchanger, which are all included in the sewage heat utilization simulation model. The setting condition of each part of the sewage heat utilization system will be introduced in the following section.

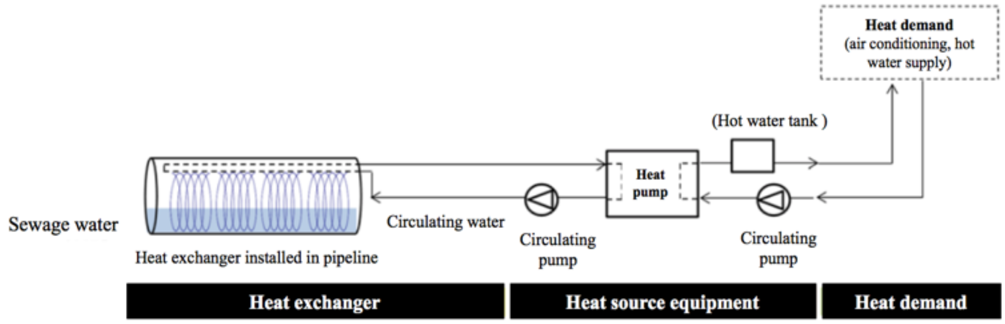


Figure 4 - 1 Diagram of sewage heat utilization system [21]

4.2 Overview of the sewage heat utilization system

The sewage heat utilization system can be mainly divided into two types by the place of sewage heat source is being extracted: sewage heat extracted at sewage treatment plants or pump stations; sewage heat extracted from pipelines directly [25].

The utilization type of recovering sewage heat at sewage treatment facilities is a common and well-known way in the field of regional heating and cooling system, and have been utilized for many years; on the other side, the way that extracts sewage heat in pipelines is regarded as a relatively novel method which has been gradually utilized recently. In order to popularize the utilization of sewage heat, extracting the sewage heat from pipelines directly is expected to be as an effective way that can be exploited by more buildings [21]. In addition, the wastewater temperature usually is highest in the initial part such as pipelines, and more heat can be reclaimed from the wastewater if the discharge is high; therefore, the sewage heat utilization type is focused on the method of extracting heat inside the pipelines in the recent years. Based on the perspective mentioned above, the sewage heat utilization type of recovering sewage heat from pipelines is mainly elaborated in this section.

Regarding to the utilization type of recovering sewage heat directly from sewage pipelines, as shown in Figure 4 - 2, there are two system types to conduct the heat reclaiming: recovering sewage heat outside the pipeline through extracting sewage water and recovering sewage heat inside the pipeline without extracting sewage water.

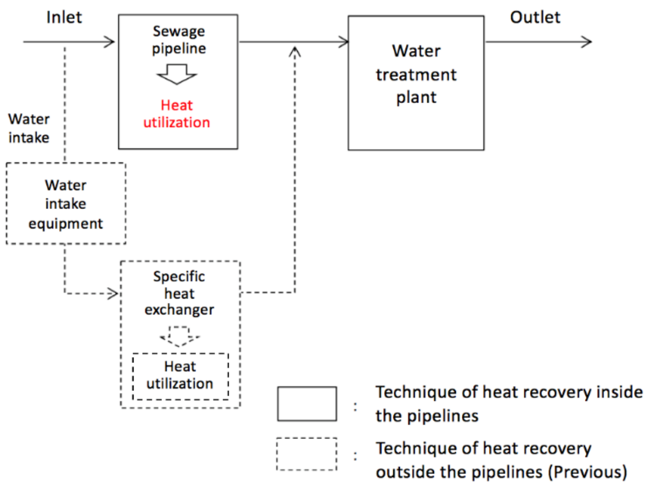


Figure 4 - 2 Diagram of sewage heat utilization system [21]

The comparison and features of two different techniques for recovering sewage heat from sewage pipelines are respectively listed in Figure 4 - 3 below [21]. The technique of conducting heat exchange outside the pipeline through extracting sewage water is the conventional utilizing type usually adopted to the large-scale buildings or regional heating and cooling system due to there is a requirement of minimum sewage flow rate; therefore, this type of sewage heat utilization system is usually applied to the sewer trunk line which an abundant of sewage amount exists.

Owing to the limitation, the technique of recovering heat outside the pipeline is thought to be relatively difficult to be installed and utilized widely. Besides, due to the technique of conducting heat exchange outside the pipeline reclaiming sewage heat through sewage water, the specific water intake equipment is needed. Moreover, the sewage water flows into the heat exchanger that leads to the maintenance and inspection costs of the system increased [25]. Briefly speaking, the technique of heat recovery outside the pipeline is harder to be extended widely due to its limitation caused by water intake equipment and sewage flow rate.

Another technique of recovering sewage heat is the type of conducting heat exchange inside the pipeline which the heat exchanger is installed at the bottom or around the pipeline. Recently, the technique of heat recovery inside the pipeline has been promoted by the government and some related companies in order to popularize and expand the utilization of sewage heat.

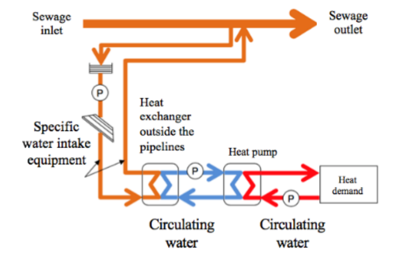
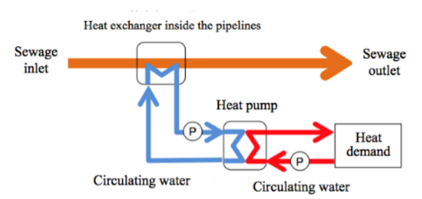
	Technique of heat recovery outside the pipelines	Technique of heat recovery inside the pipelines
Installed area and Characteristic	● The application is limited to the surroundings buildings of sewage treatment facilities ● Difficult to be installed widely	● Utilization area can be expanded. ● Energy consumers are located close to the heat recovery site ● The system can be applied to tributary pipelines
Specific water intake equipment	Required	Unrequired
Sewage treatment	The raw wastewater flows into the heat exchanger, the maintenance and inspection costs is increasing	It is possible to conduct heat exchange directly with the raw wastewater flowing in the sewage pipeline.
System diagram		

Figure 4 - 3 Comparison of different sewage heat recovery techniques [21]

Concerning to the heat exchanger which is installed inside the sewage pipeline, it is a novel technique for reclaiming sewage heat without extracting sewage water. The principle of the technique is to install the heat recovery conduits under the sewage pipeline or around the pipeline to reclaim the sewage heat through the circulating water inside the heat recovery conduits [25]. The installation pattern is determined by the size of the pipeline [56]. Specifically speaking, as shown in Figure 4 - 4, the pattern of heat recovery conduits installed under the sewage pipeline is able to install at the tributary; moreover, it is suitable for even the diameter of the pipeline is under 800 mm. As for the pattern of installing the heat recovery conduits around the pipeline is applied to the larger pipeline.

Generally speaking, basing on the perspective of reclaiming more heat from the origin of heat source, the sewage heat can be extracted directly through the technique of heat recovery inside the pipeline. Furthermore, the energy consumers (heat demand side) are located close to the site where the heat is recovered, and the heat can therefore be efficiently utilized without extra profligacy [26].

In brief, through applying the technique of recovering heat inside the pipeline, the utilization objects of sewage heat are expected to be expanded owing to the possibility of conducting heat exchange straightly with the raw wastewater flowing in the sewage pipeline.

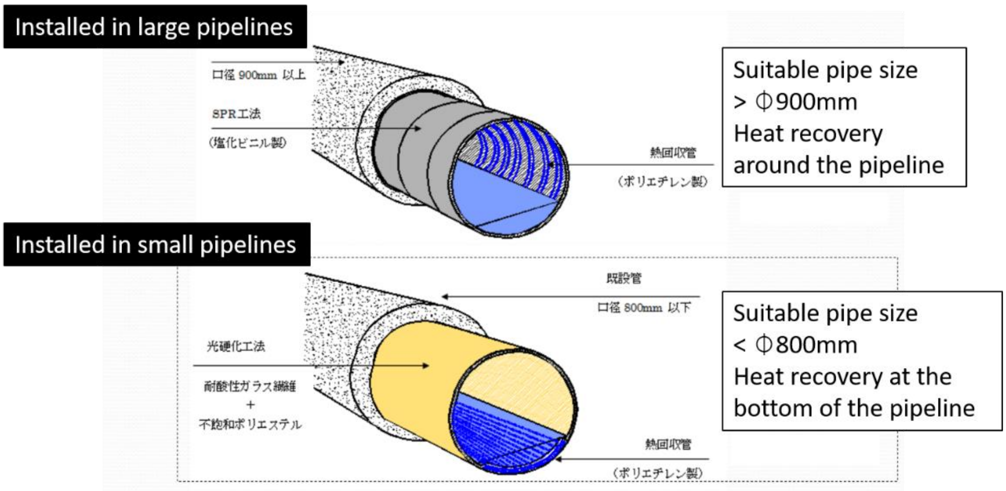


Figure 4 - 4 Demonstration of sewage heat utilization system installed in pipeline [56]

4.3 Construction of sewage heat utilization system model

In order to clarify the variation of sewage temperature while recovering the sewage heat, it is essential to build up the simulation model of sewage heat utilization system. The following factors are all taken into consideration in the sewage heat utilization system model proposed in this study such as the heat demand of different building types, the performance of heat source equipment and heat exchanger.

With the objective of simulating the sewage heat utilization potential which is similar to the actual situation as much as possible, the simulation conditions are set up under certain reasonable assumptions and are all elaborated in the following section. In addition, the construction of the sewage heat utilization system is introduced to begin from the heat demand side to the heat supply side (Figure 4 - 5).

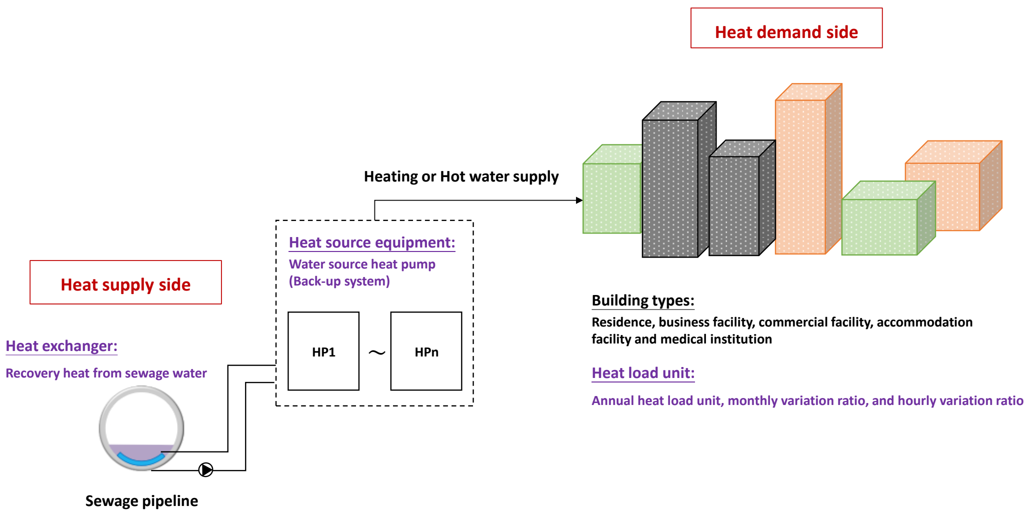


Figure 4 - 5 Diagram of sewage heat utilization system model

4.3.1 Introduction of building heat demand

When concerning the discussion of regional sewage heat utilization, the sewage heat is regarded as the energy supply side, and the buildings are regarded as the energy demand side. In order to clarify the heat demand for buildings, it is necessary to calculate the heat demand amount.

In this thesis, the building heat demand and heat load are defined as the same. However, the heat demand of different building types is not the same, it is essential to clarify the heat demand of different building type which is classified in the study. After clarifying the building heat demand, the conditions of sewage heat utilization types are assumed based on the heat demand characteristics of different building types. The classification of building type is classified into five types, including residence, office, retail, hotel, and hospital. The classification of building types and the building examples are listed in Table 4-1; in addition, the building types included in the classification are listed as well.

Table 4- 1 Classification of building type

Building type	**Building examples**
Residence	Mansion, apartment, (single-family) house, etc.
Office	Office, civic center, administrative center, etc.
Retail	Department store, convenience store, etc.
Hotel	Accommodation facility, dormitory, nursing home, etc.
Hospital	Medical institute, clinic, etc.

According to the *"District heating and cooling handbook"* [57] published by the Japan district heating and cooling association, the heat load unit of heating and hot water supply are sorted by different building types. Referring to the annual heat load unit, monthly variation ratio, and hourly variation ratio revealed in the district heating and cooling handbook, the heat load unit can be calculated by hour (Eq. (34)).

$$Q_{load,hr}(b) = Q_{load,y}(b) \times r_{month}(b) \times r_{hour}(b) \qquad \text{Eq. (34)}$$

Where $Q_{load,hr}$ is the hourly heat load unit (kWh/m^2), $Q_{load,y}$ is the annual heat load unit (kWh/m^2), r_{month} is the monthly variation ratio (%), r_{hour} is the hourly variation ratio (%), b is the building type.

The essential databases for calculating the building heat demand of different building types including annual heat load unit, monthly variation ratio, and hourly variation ratio are list from Table 4- 2 to Table 4- 4.

In this study, due to the sewage heat is supposed to be recommended to utilized in winter, the utilization type is assumed to be heating and hot water supply. Specifically speaking, according to Table 4- 2, the annual heat load unit for the hot water supply of residence and hospital are higher than the annual heat load unit for heating; as for the hotel, the annual heat load unit for hot water supply and the annual heat load unit of heating is the same. With regards to the office and retail, the annual heat load unit for heating is higher than the annual heat load unit of hot water supply. According to the annual heat load unit, the sewage heat utilization type of residence, hospital, and hotel are assumed to be as hot water supply; as for the sewage heat utilization type of office and retail are assumed to be as heating in this study (Table 4- 2).

Table 4- 2 Annual heat load unit of heating and hot water supply [57]

Building type	Residence		Office		Retail		Hotel		Hospital	
Utilization type	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply
Annual heat load unit (Mcal/m^2 year)	20	30	31	2.2	35	23	80	80	74	80
Utilization type assumed in this study	Hot water supply		Heating		Heating		Hot water supply		Hot water supply	

Table 4- 3 Seasonal variation ratio of the heat load unit [57]

Building type		Residence		Office		Retail		Hotel		Hospital	
		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)	
Utilization type		Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating
Season	1	12.08	24.03	13.79	25.93	7.66	32.8	10.14	20.54	9.51	27.94
	2	12.55	20.03	17.24	22.79	8.02	19.64	10.07	17.87	9.98	21.2
	3	12.32	20.08	13.79	17.66	9.17	15.87	9.51	14.41	10.05	19.92
	4	10.32	8.11	10.34	4.27	9.07	0	8.65	3.07	9.85	2.67
	5	9.04	0	6.9	0	7.83	0	7.78	0	8.09	0
	6	6.76	0	3.45	0	7.26	0	7.33	0	7.88	0
	7	5.41	0	3.45	0	7.99	0	7.33	0	7.13	0
	8	3.76	0	3.45	0	7.84	0	6.23	0	5.54	0
	9	3.87	0	3.45	0	8.12	0	7.02	0	5.76	0
	10	6.22	0	6.9	0	7.62	0	7.58	0	7.88	0
	11	7.1	8.95	6.9	7.98	9.07	0	8.72	12.77	8.19	8.65
	12	10.57	18.77	13.34	21.37	10.35	21.69	9.64	18.83	10.14	20.07

Table 4- 4 Variation ratio of heat load unit by hour (Winter) [57]

Building type		Residence		Office		Retail		Hotel		Hospital	
		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)		Variation ratio (%)	
Utilization type		Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating	Hot water supply	Heating
Time (hr)	1:00	2.7	4	0	0	0	0	2.37	3.05	0.58	0.2
	2:00	0.3	2.6	0	0	0	0	1.43	3.43	0.45	0.3
	3:00	0.2	1.8	0	0	0	0	0.64	3.81	0.35	0.3
	4:00	0	1.8	0	0	0	0	0.38	3.43	0.29	0.3
	5:00	0	1.8	0	0	0	0	0.73	3.05	0.48	0.3
	6:00	0.3	2.3	0	0	0	0	2.35	3.05	1.45	5.1
	7:00	2	3.1	1.97	0.3	0	0	4.64	3.24	0.97	4.7
	8:00	3.5	5.6	0.33	16.99	0	0	4.53	4.19	0.39	4.7
	9:00	2.9	4.4	1.64	12.29	1.25	16.9	3.97	5.71	7.58	10.3
	10:00	3.5	4.5	6.57	8.09	9.17	12.8	3.8	4.95	9.39	8.3
	11:00	2.9	2.7	5.75	10.29	10.1	10.3	4.51	5.14	10.06	7.5
	12:00	2.6	4	14.78	10.49	2.5	9.4	3.25	4.95	8.1	6.9
	13:00	2.1	3.9	12.48	10.29	8.41	7.5	3.59	4.95	8.9	6.4
	14:00	2.1	3.9	27.09	8.39	17.15	6.9	4.08	5.14	9.52	5.2
	15:00	1.8	3.9	8.7	8.19	17.12	5.6	3.8	4.95	8.71	5
	16:00	1.8	4.1	4.43	9.09	5.36	5.4	3.95	6.1	6.87	4.8
	17:00	3.6	4.1	4.27	5.59	3.67	7.3	4.23	7.24	5.65	4.9
	18:00	7.2	5.7	4.27	0	10.54	8.8	4.68	6.86	5.77	5
	19:00	8.5	6.1	3.78	0	13.54	9.1	5.36	6.1	4.97	5
	20:00	11.8	6.1	3.94	0	1.19	0	7.48	5.33	3.9	3.5
	21:00	13.3	6.2	0	0	0	0	8.57	1.52	2.24	3.5
	22:00	11.3	6	0	0	0	0	8.97	1.14	1.29	3.6
	23:00	9	5.8	0	0	0	0	7.73	0	1.03	4
	24:00	6.6	5.6	0	0	0	0	4.96	2.67	1.06	0.2

The calculation results of hourly heat load for heating and hot water supply in February of different building types are shown in Figure 4 - 6 and Figure 4 - 7. According to the annual heat load unit, it is known that the heat load for heating and hot water supply of hotel and hospital are extremely larger than other building types, and are thought to be as the high heat demanded building types; the heat demand of residence and business facility is regarded to be as relatively small.

When conducting the simulation of sewage heat utilization potential, the setting conditions of the heat demand of different building types can be set up based on the heat load unit of heating and hot water supply.

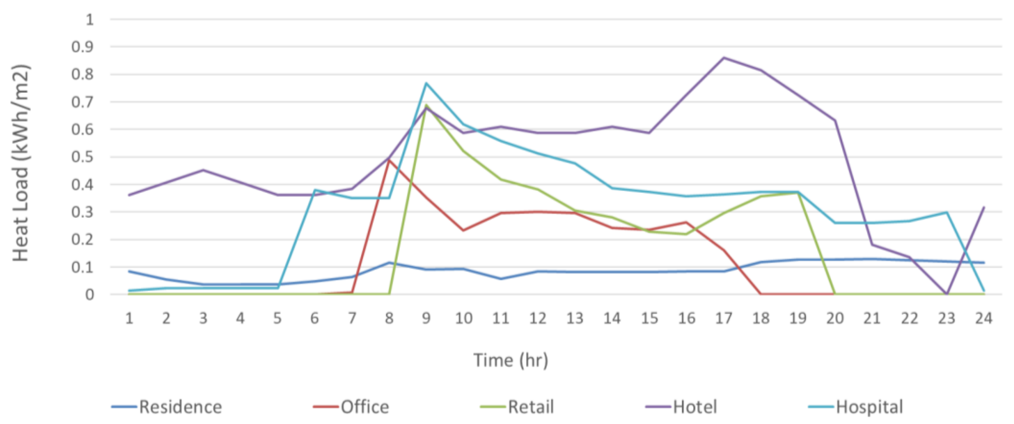


Figure 4 - 6 Heat load for heating of different building types

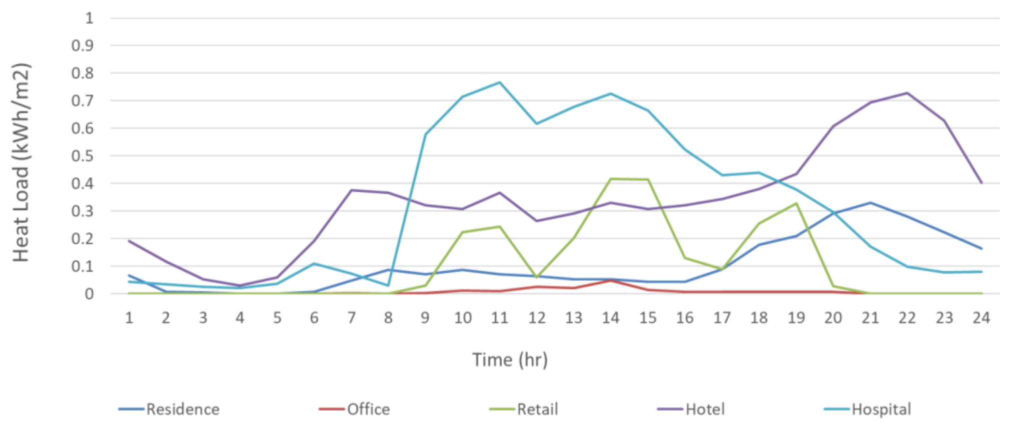


Figure 4 - 7 Heat load for hot water supply of different building types

4.3.2 Heat source equipment model

The simulation setting conditions of heat source equipment are elaborated in this section including operating type, operating schedule, and the performance of the heat pump. In this study, the heat source equipment is set to be the water source heat pump which is able to recover heat from sewage water.

- Operating type of heat source equipment

Referring to the heat pump operating design guidebook and previous research [35], it is recommended to operate the heat pump by the type of thermal storage operation for basically 20 hours a day. Thermal storage operation is an operating type that averaged the daily heat load into operating hours and the influences from peak load are lessened. There are several merits of the thermal storage operation. For instance, by thermal storage operating, the daily heat load is averaged into the time period of operating hours; therefore, the peak load of heat demand is mitigated and the required heat capacity of a heat pump can be diminished; furthermore, the initial cost of the heat pump can be decreased. According to the reasons, thermal storage operation is gradually spread out nowadays. Basing on the reasons mentioned above, the setting condition of the heat pump operating type is assumed to be as thermal storage operation in this study.

- Operating schedule of heat source equipment

The operation time of the heat pump is set to be operating from 6 o'clock in the morning to 1 o’clock of the next day. Regarding the setting condition of operating schedule, it is determined by the sewage physical state simulated by the sewage physical model proposed in chapter 2.

Take the simulation results of sewage temperature and sewage flow rate at manhole NO.80270060 for example, according to Figure 4 - 8 and Figure 4 - 9, it is shown that the sewage flow rate during 2 o’clock to 5 o’clock is relatively smaller than other time periods; as for the sewage temperature, the temperature between 2 o’clock to 5 o’clock is lower than other time periods as well.

Referring to the result, it can be considered that during 2 o'clock to 5 o'clock, the retained heat in sewage pipelines is fewer than other time periods. Consequently, because it is inefficient to recover sewage heat during 2 o’clock to 5 o’clock, the operation of the heat pump is assumed to stop operating during the time period.

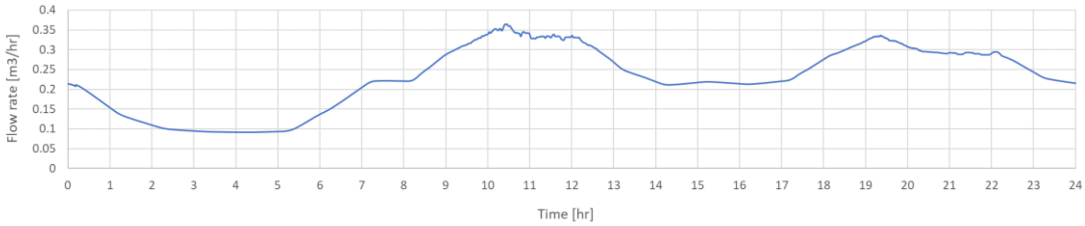


Figure 4 - 8 Simulation result of sewage flow rate

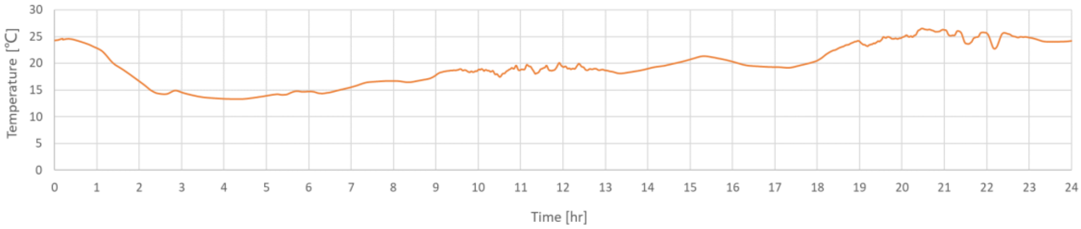


Figure 4 - 9 Simulation result of sewage temperature

In this study, the sewage heat utilization type of residence, hospital, and hotel are assumed to be as hot water supply; as for the sewage heat utilization type of office and retail are assumed to be as heating. Regarding different building types and their setting conditions of heat utilization, the results of heat demand for heating and hot water supply are shown in Figure 4 - 10.

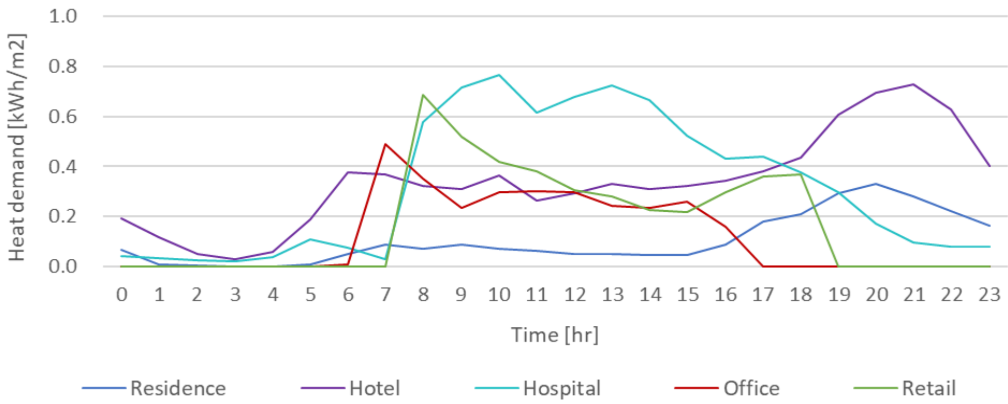


Figure 4 - 10 Building heat demand by utilization type setting in the study

The hourly heat demand for heat pump operating is calculated based on the daily heat demand, and then averaged into the operating time of 20 hours (Eq. (35)) [35]. The heat needed for the heat pump that provided by sewage water is calculated based on the heat pump performance (Eq. (36)); however, the actual heat amount need to be compared to the heat amount that sewage heat can provide according to the sewage physical state.

$$Q_{Hp\_hr} = \frac{\sum_{hr=1}^{24} Q_{load,hr}}{T_{HP\_day}} \qquad \textit{Eq. (35)}$$

$$Q_{HP\_sewage} = Q_{Hp\_hr} \times \frac{(COP-1)}{COP} \qquad \textit{Eq. (36)}$$

Where Q_{Hp_hr} is the Required heat output of heat pump (MJ), Q_{load} is the heat load of building (MJ), T_{HP_day} is the operating time of heat hump per day, *COP* is the coefficient of performance, Q_{HP_sewage} is the heat needed for heat pump provided by sewage water (MJ).

The results of daily heat load and the daily heat output of the heat pump which is averaged into 20 hours are shown in the figures from Figure 4 - 11 to Figure 4 - 15 by different building types.

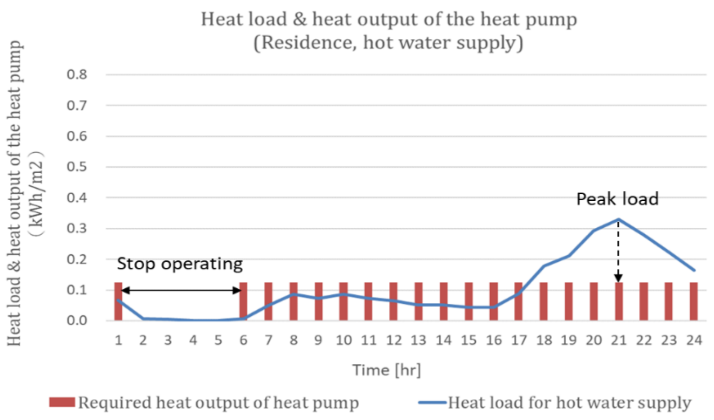


Figure 4 - 11 Heat load and heat output of the heat pump (Residence)

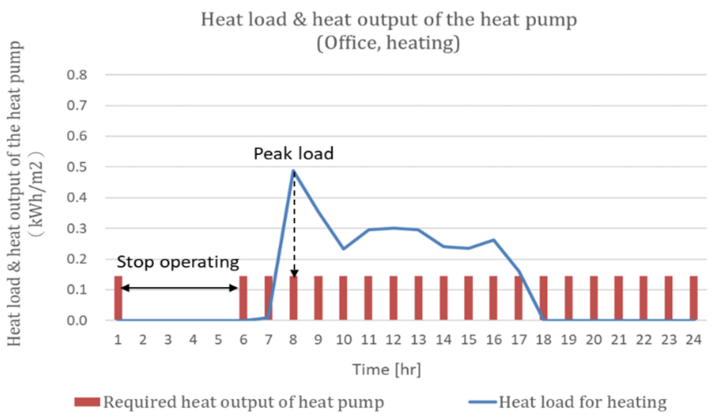


Figure 4 - 12 Heat load and heat output of the heat pump (Office)

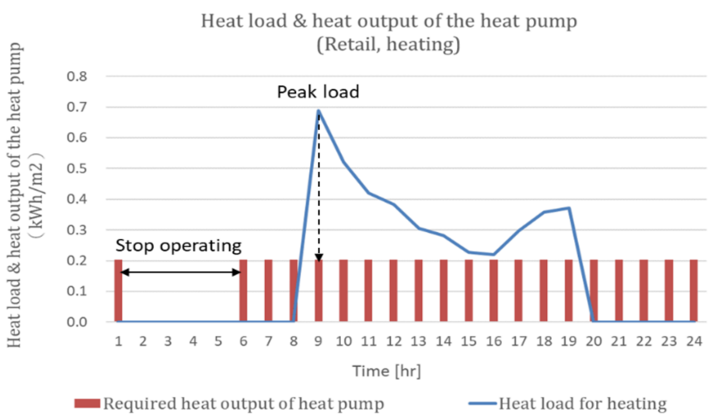


Figure 4 - 13 Heat load and heat output of the heat pump (Retail)

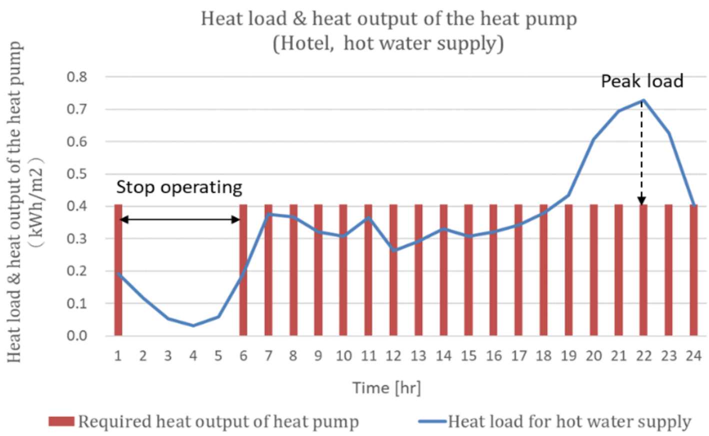


Figure 4 - 14 Heat load and heat output of the heat pump (Hotel)

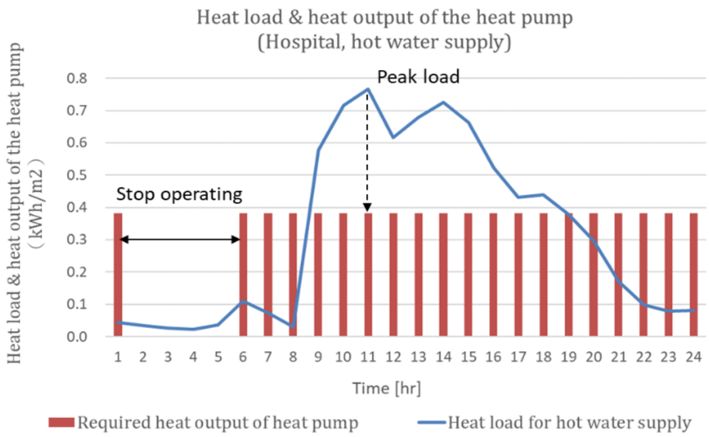


Figure 4 - 15 Heat load and heat output of the heat pump (Hospital)

- Performance of the heat pump

While conducting a simulation of sewage heat utilization potential, it is essential to set up the heat pump numbers and heat capacity that suitable for each building in which the sewage heat utilization system is installed. According to the building area and building types, the building heat demand can be clarified; afterwards, it is able to determine the proper heat pump with an adequate heating capacity based on the daily operation time of the heat pump (Eq. (35)).

The water source heat pump (CRHV-P650A) [58] with three different heating capacities are adopted to the study for simulation. According to the specification of the heat pump provided by the maker, the relationship between the inlet temperature of heat source water and COP is shown in Figure 4 -

16 to Figure 4 - 18; in addition, the hot water supply temperature is set to be 55 degrees.

When recovering the sewage heat through the circulating water, the circulating water connected to the heat pump and heat exchanger installed in the pipeline act as the inlet temperature of heat source water for the heat pump. Therefore, the performance of the heat pump is affected by the sewage temperature and the performance of the heat exchanger installed in the sewage pipeline.

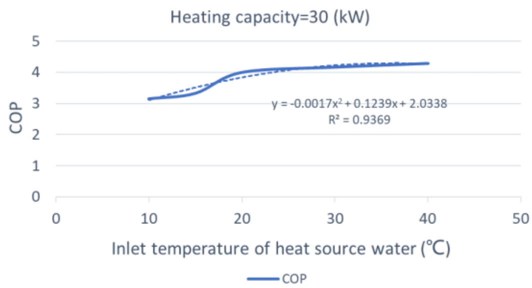


Figure 4 - 16 The relationship between COP and inlet temperature of heat source water

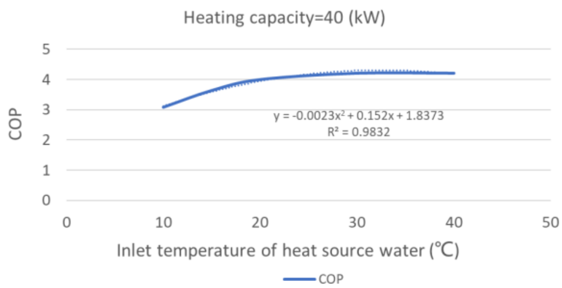


Figure 4 - 17 The relationship between COP and inlet temperature of heat source water

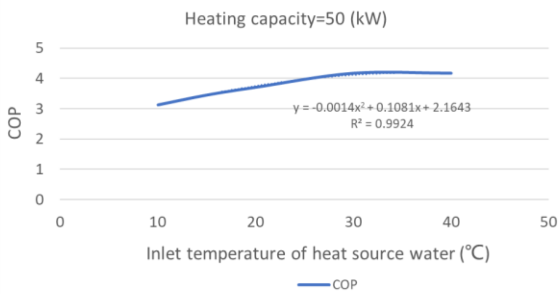


Figure 4 - 18 The relationship between COP and inlet temperature of heat source water

4.3.3 Heat exchanger model

The heat exchanger module set up in the study is the form that installed inside the sewage pipeline (Figure 4 - 19), which is no need to executing heat exchange through sewage water. Besides, it is a novel heat exchange type to utilize the sewage heat in the recent. There are many merits to adopt the heat exchanger that installed in pipelines, such as it is slightly affected by the sewage flow because of the heat exchanger does not need to set up a particular water intake equipment and can therefore decrease the maintenance fees; moreover, the sewage heat utilization area can be expanded due to the equipment can be installed in the small size of branch pipelines [25]. According to the reasons mention above, with the objective of widely utilizing the sewage heat, the heat exchanger installed at the bottom of the pipeline is determined to be set up as the heat exchanger type in this study.

At the former step of elaborating the heat exchange model, the setting conditions related to the heat exchanger are first introduced in this section, including the heat exchange area and heat transfer coefficient. Afterwards, the heat exchange model including the calculation method of heat amount that can be reclaimed from sewage water and the variation of sewage temperature after heat exchange is clarified in the following contents.

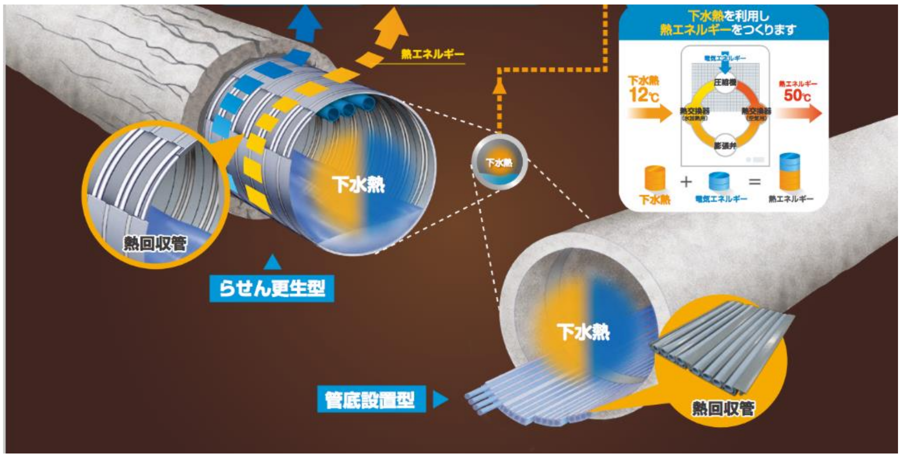


Figure 4 - 19 Diagram of the heat exchanger installed inside the pipeline [59]

- Condition setting of heat exchange area and heat transfer coefficient

The heat exchanger adopted to the study is the type which composed of several heat recovery conduits installed at the bottom of sewage pipelines (Figure 4 - 20), these conduits are abreast arranged, and then form a shape like a mat.

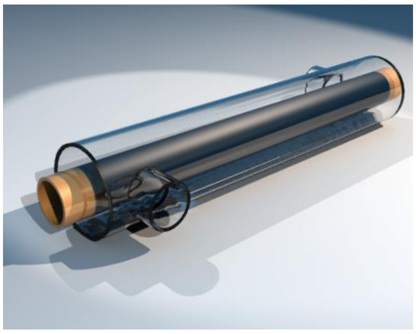


Figure 4 - 20 Diagram of the heat recovery conduit [60]

For the purpose of simulating the heat amount that can be recovered from sewage water, a reasonable assumption of heat exchange area and a suitable transfer coefficient related to the material of the conduit are essential to be assumed in advance. According to the heat exchange area and heat transfer coefficient, the heat exchange amount is able to be calculated through a method called NTU method which will be introduced in detail in the next section.

The setting condition of the heat exchange area is determined by the features of the pipeline, including pipe diameter and water depth, which can be calculated by Eq.(37) and Eq.(38). Referring to the previous research [1], when discussing the setting condition of sewage water depth, the water depth is usually empirically set as 10% ~ 15%; therefore, the width of the heat exchanger is assumed to be 10% of the water depth in this thesis.

$$A_{exchange} = pl \times b \times \pi \qquad \textit{Eq. (37)}$$

$$b = D \times \frac{\theta}{2} \times \pi,\ \theta = 2arc\,sin(0.6) \qquad \textit{Eq. (38)}$$

Where $A_{exchange}$ is the heat exchange area (m^2), pl is the pipe length (m), b is the width of the heat exchange area, D is the diameter of pipeline (m).

According to Figure 4 - 21, the width of heat exchange area is set to be as the range which is equivalent to 10% of water depth ($\theta = 2arc\ sin(0.6)$), and the length is equivalent to the length of the pipeline; in this study, the length of heat exchange area is assumed to be as the same with the spatial calculation interval.

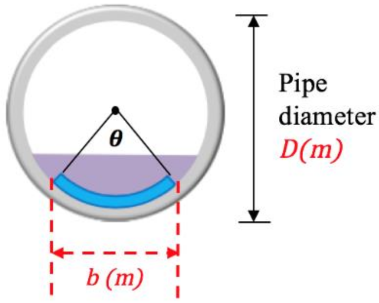


Figure 4 - 21 Symbolic mark in equation (37)~(38)

With regards to the setting condition of heat recovery conduit, according to the previous research, stainless steel pipe and polyethylene tube are the materials that generally used to be as the heat recovery conduit. In this study, when conducting the simulation, the material of the heat recovery conduit is assumed to be stainless steel (Table 4- 5).

Table 4- 5 Setting condition of heat recovery conduit [61]

Material	Tube thickness (mm)	Thermal conductivity (W/mK)	Heat transfer coefficient (W/m^2K)
Stainless steel pipe (SUS304-TP)	3.4	16	4706
Polyethylene tube (PE)	3.4	0.42	123.5

Reference:
Annual report on technical research & development, Vol.40, 2016. Bureau of Sewerage, Tokyo Metropolitan Government.

- Number of Transfer Units (Effectiveness-NTU) Method [62]

When concerning the heat exchange model, The Effectiveness-NTU and Log Mean Temperature Difference (LMTD) are two solution methods that approach heat exchanger analysis from different angles. Both methods share common parameters and concepts and will arrive at the same solution to heat exchanger thermal capacity [63].

The Effectiveness-NTU method is a method generally used to calculate the rate of heat transfer in heat exchangers (especially counter current exchangers) when the information for calculating the Log-Mean Temperature Difference (LMTD) is insufficient. Specifically speaking, regarding the heat exchanger analysis, if the inlet and outlet temperature of fluid are specified or can be determined by simple energy balance, it can be analyzed by the LMTD method. In the contrast, if more than one of the inlet and outlet temperature of the heat exchanger is unknown or not available, The Effectiveness-NTU method which related to the effectiveness of a heat exchanger is used [60]. In this study, owing to the inlet and outlet temperature of the heat exchanger is insufficient; therefore, the Number of Transfer Units (Effectiveness-NTU) method is suitable for applying to the heat exchange model proposed in the study to calculate the outlet temperature of heat exchanger which return to the sewage water. In addition, the exchanger type of counter-current flow is assumed in this study.

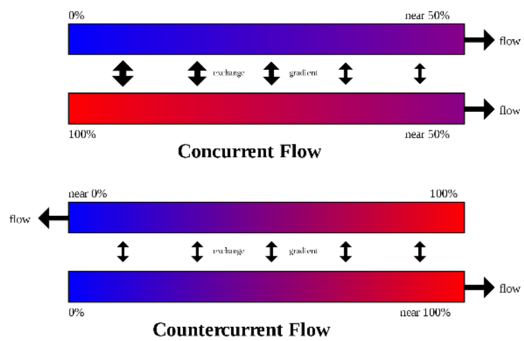


Figure 4 - 22 Diagram of concurrent and counter-current flow of heat exchanger[60]

The application of The Effectiveness-NTU method is elaborated in the below contents. The Effectiveness-NTU method solves the heat exchange analysis by using three dimensionless parameters: Heat Capacity Rate Ratio (W_S/W_l), Effectiveness (ε), and Number of Transfer Units (NTU). The relationship between these three parameters depends on the type of heat exchanger and the internal flow pattern.

To define the effectiveness of a heat exchanger we need to find the maximum possible heat transfer (Q_{max}) that can be hypothetically achieved in a counter-current flow heat exchanger of infinite length. Therefore, one fluid will experience the maximum possible temperature difference; in this study, which is the difference of $T_{sewage1} - T_{c1}$ (The temperature difference between the inlet sewage temperature of the hot stream and the inlet circulating water temperature of the cold stream). The method proceeds by calculating the heat capacity rates (i.e. mass flow rate multiplied by specific heat) $c_h G_h$ (heat capacity rates of hot stream fluid) $and\ c_c G_c$ (heat capacity rates of cold stream fluid) for the hot and cold fluids respectively, and denoting the smaller one as $(cG)_s$ (Eq.(39), Eq.(40)) [62]. In this study, the sewage water means the hot stream fluid, and the circulating water means the cold stream fluid.

$$Q_{max} = (cG)_s \times (T_{sewage1} - T_{c1}) \qquad \textit{Eq. (39)}$$

$$(cG)_s = min(c_h G_h, c_c G_c) \qquad \textit{Eq. (40)}$$

Where Q_{max} is the maximum heat that can be transferred between the fluids per unit time (MJ), $(cG)_s$ is the smaller one of the heat capacity rates of hot and cold fluids, $T_{sewage1}$ is the inlet sewage temperature (°C), T_{c1} is the inlet temperature of circulating water (°C), $c_h G_h, c_c G_c$ is respectively the heat capacity rates of hot and cold fluids.

Based on the quantity of the maximum possible heat transfer and Effectiveness (ε), the heat that recovers from sewage water can be calculated [60]. In addition, the relationship between the inlet sewage temperature of the heat exchanger and outlet sewage temperature of heat exchanger which return to the sewage water can be clarified. The Effectiveness (ε), the quantity of the heat that recover from sewage water, and the outlet sewage temperature of the heat exchanger are calculated by the series of equations from Eq.(41) to Eq.(47).

$$T_{sewage2} = T_{sewage1} - \frac{Q_{sewage}}{c_h G_h} \quad \textit{Eq. (41)}$$

$$Q_{sewage} = \varepsilon (cG)_s \times \left(T_{sewage1} - T_{c1}\right) = c_h G_h \left(T_{sewage1} - T_{sewage2}\right) \quad \textit{Eq. (42)}$$

Where $T_{sewage2}$ is the outlet sewage temperature (℃), Q_{sewage} is the heat recovered from sewage (MJ), ε is the effectiveness of heat exchanger.

The effectiveness (ϵ : epsilon) is the ratio between the actual heat transfer rate and the maximum possible heat transfer rate, which is a dimensionless with ranging between 0 to 1. For any heat exchanger, the effectiveness is the function of Heat Capacity Rate Ratio (W_S/W_l) and Number of Transfer Units (Eq.(43)) [62].

$$\varepsilon = \frac{Q_{sewage}}{Q_{max}} = f(\mathrm{NTU}, W_S/W_l) \quad \textit{Eq. (43)}$$

$$\varepsilon = \begin{cases} (1 - e^{-B}) \Big/ \left(1 - \frac{W_s}{W_l} e^{-B}\right), W_s \neq W_l \\ NTU/(1 + NTU), W_s = W_l, \end{cases} \quad \textit{Eq. (44)}$$

$$B = (1 - W_s/W_l) NTU \quad \textit{Eq. (45)}$$

$$NTU = K A_{exchange}/W_s \quad \textit{Eq. (46)}$$

$$W_s = \min(c_h G_h, c_c G_c), W_l = \max(c_h G_h, c_c G_c) \quad \textit{Eq. (47)}$$

Where NTU is the number of transfer units, K is the heat transfer coefficient (W/m^2K), the Heat capacity rates of hot and cold fluids respectively, denoting the smaller one as $min(c_h G_h, c_c G_c) = W_s$, and the bigger one as $max(c_h G_h, c_c G_c) = W_l$,

According to the heat exchanger model based on Effectiveness-NTU method, the variation of sewage temperature after utilizing the sewage heat and the quantity of heat that can be recovered from sewage water is clarified in this section.

4.3.4 Combination of heat source equipment and heat exchanger

Based on the heat source equipment model and heat exchanger model proposed in section 4.3.2 and section 4.3.3, the required heat output of the heat pump at the building side and the actual heat amount that sewage can provide is clarified. However, the heat amount that can be reclaimed from sewage is determined by the sewage physical state and the effectiveness of heat exchanger, it cannot be guaranteed to be as a sufficient heat source that always fulfilled the heat demand of the building side. Consequently, the backup system needs to be taken into consideration.

In this section, the required heat for heat pump operation provided by sewage water is compared to the quantity of heat that can be exactly recovered from sewage. Specifically, the required heat amount that expected to be recovered from sewage water is calculated through the COP of the heat pump (Eq.(36)), and the maximum heat amount provided by the heat exchanger which is installed in the pipeline is calculated by the Effectiveness-NTU method; at the meanwhile, according to the relationship between the required heat for heat pump operation provided by sewage and the recovery heat amount from sewage, the outlet temperature of the heat pump is calculated. Besides, whether the backup system is needed or not can be determined.

The output temperature of the heat pump is calculated depends on different situations of the required heat for heat pump operation provided by sewage and the recovery heat amount from sewage. The equations for calculating the outlet temperature of the heat pump under different circumstances are separately listed below (Eq.(48) ~Eq.(53)); in addition, the quantity of heat need to be provided by the backup system is calculated as well (Eq.(53)).

Under the circumstance that the heat amount can be reclaimed from sewage is larger than the required heat amount for heat pump operation, instead of recovering all the sewage heat, it is determined to barely recover the heat amount for heat pump operation from sewage; in this case, the outlet temperature of the heat pump is calculated by Eq.(48) ~Eq.(50).

$Q_{sewage} > Q_{HP\_sewage}$:

$$Q_{HP\_sewage} = c_c G_c (T_{hp\_in} - T_{hp\_out}) \qquad Eq.\ (48)$$

$$T_{hp\_out} = T_{hp\_in} - \frac{Q_{HP\_sewage}}{c_c G_c} \qquad Eq.\ (49)$$

$$T_{hp\_out}(t) = T_{c1}(t+1) \qquad Eq.\ (50)$$

Where Q_{HP_sewage} is the heat needed for heat pump provided by sewage (MJ), T_{hp_in} is the inlet temperature of the heat pump (°C), T_{hp_out} is the outlet temperature of the heat pump (°C), t is the time step (sec)

While the circumstance that the heat amount can be reclaimed from sewage is less than the required heat amount for heat pump operation, it is determined to recover all the sewage heat that can obtain from sewage, and the outlet temperature of the heat pump is calculated by Eq.(51) ~Eq.(52). In addition, due to the sewage heat is insufficient to fulfill the required heat amount for heat pump operation, the backup system is essential in this case; the heat amount provided by the backup system is calculated by Eq.(53).

$Q_{sewage} < Q_{HP\_sewage}$

$$Q_{sewage} = c_c G_c (T_{hp\_in} - T_{hp\_out}) \qquad Eq.\ (51)$$

$$T_{hp\_out} = T_{hp\_in} - \frac{Q_{sewage}}{c_c G_c} = T_{c1}(t+1) \qquad Eq.\ (52)$$

$$Q_{backup} = Q_{Hp\_hr} - \frac{Q_{sewage} \times COP}{COP - 1} \qquad Eq.\ (53)$$

After confirming the heat amount respectively obtained from sewage heat utilization system and backup system, the total energy consumption is calculated at the final step through Eq.(54).

$$Energy\ consumption_{total} = Energy\ consumption_{HP} + Energy\ consumption_{backup} \qquad Eq.\ (54)$$

Where $Energy\ consumption_{total}$ is the total energy consumption including sewage heat utilization system and backup system (MJ), $Energy\ consumption_{HP}$ is the energy consumption of sewage heat utilization system (MJ), $Energy\ consumption_{backup}$ is the energy consumption of backup system (MJ).

4.3.5 Setting condition of backup system

Owing to the sewage heat may not be always sufficient for the required heat of heat pump in the sewage heat utilization system, it is essential to set up a backup system in case the heat demand cannot be fulfilled by sewage heat.

The backup system assumed in this study is set up as the water source heat pump which the water source is tap water. When the sewage physical condition is unable to provide sufficient heat for the sewage heat utilization system; for instance, the sewage temperature is low or lack of sewage flow rate, the backup system is set to operate under this circumstance.

4.4 Summary

In chapter 4, the sewage heat utilization system model is constructed. From the aspect of building heat demand which is the energy demand side to the sewage water of the energy supply side, the connection between energy demand and supply side is all taken into consideration in the sewage heat utilization system model.

According to the sewage heat utilization system model, the pivotal factors of evaluating the regional sewage heat utilization potential can be simulated. For instance, the outlet temperature which makes an influence on the sewage water temperature after utilizing the sewage heat, the sewage heat can be recovered from sewage, and the required heat amount of building side. Moreover, the building energy consumption is calculated at the final step of the simulation based on the required heat amount for heat pump operation which is provided by sewage heat utilization system and backup system if needed.

Referring to the calculation flow of the sewage heat utilization system (Figure 4 - 23), the setting parameters are divided into three parts at the initial stage, the sewage physical condition, building features, and heat demand of heat pump operation. The parameters of building features such as building type, location, and floor area act as a connection to link up the parameters of pipeline and heat source equipment. Specifically speaking, according to the location of buildings and pipelines, the connection between pipeline and building is assumed that the building is making a pair to the nearest pipeline; besides, this setting condition is the same as the connection of building drainage and flow-in pipeline proposed in chapter 2. Regarding the setting of this study, when utilizing the sewage heat in a specific pipeline, the sewage heat is recovered by the building which is connected to this pipeline.

Through the parameters of sewage physical condition simulated by the sewage physical model proposed in chapter 2, and the heat exchanger model based on Effectiveness-NTU method, the quantity of heat retained in sewage pipeline and the heat amount can be reclaimed are able to be known; at the meanwhile, according to the parameters of the building, heat demand, and the performance of heat source equipment, the required heat amount that expected to reclaim from sewage can be clarified by each building.

After clarifying the heat amount that can be extracted from sewage water and the heat demand of the building, the exact heat amount that needs to be recovered from sewage water can be confirmed. Based on the logic mentioned above, the outlet temperature after utilizing sewage heat and the energy consumption which includes sewage heat utilization system and the backup system can be calculated.

The Urban Sewage State Prediction Model proposed in this study is composed of the sewage physical model proposed in chapter 2 and the sewage heat utilization system model proposed in chapter 4, through integrating this two model, the simulation of regional sewage heat utilization potential can be conducted, and the application of the urban sewage state prediction model is elaborated in chapter 5.

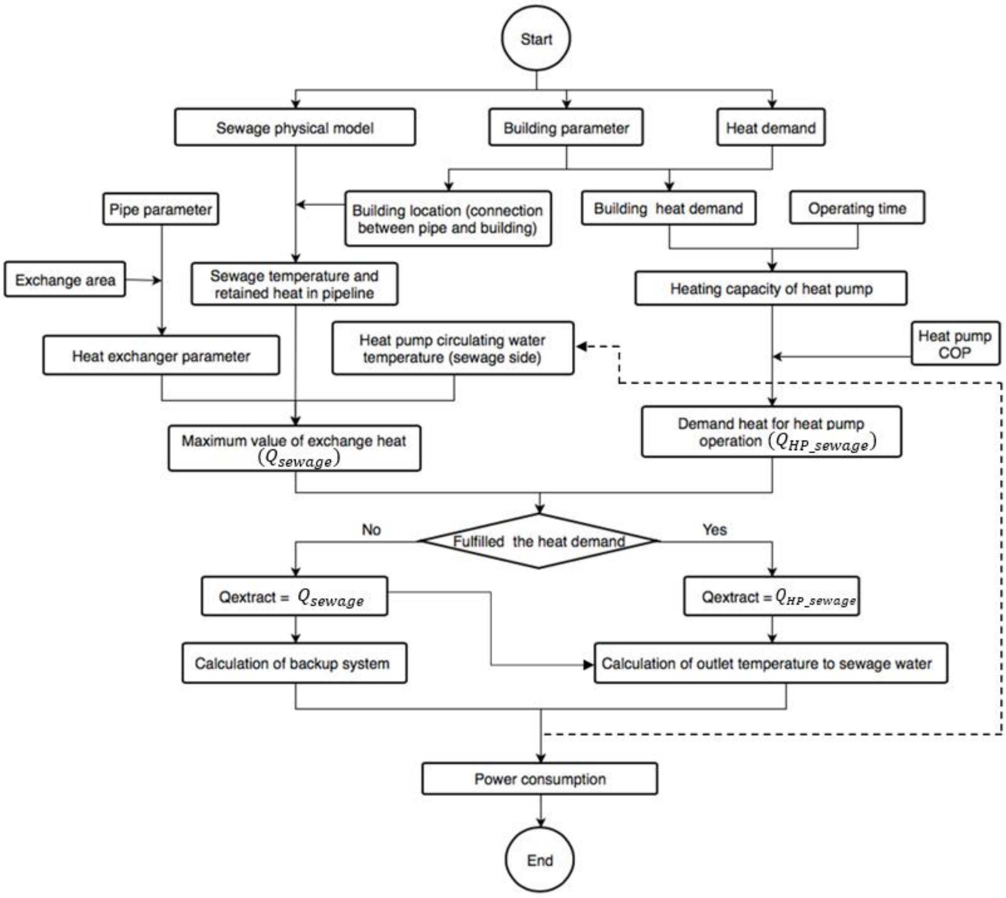


Figure 4 - 23 Calculation flow of the sewage heat utilization system model

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Chapter 5: Application of urban sewage state prediction model

Chapter 5: Application of urban sewage state prediction model

5.1 Introduction and objective

In chapter 5, the application of the urban sewage state prediction model is applied to an actual urban area in order to discuss the variation of sewage temperature and the regional energy saving potential after utilizing the sewage heat. According to the sewage physical model proposed in chapter 2, the regional timely sewage state is simulated in order to clarify the sewage physical condition of each pipeline in the study area; based on the simulated sewage condition, the sewage heat utilization system model is integrated to conduct the simulation of regional sewage heat utilization potential through several scenarios from different perspectives.

In this section, the application of the model is discussed by two different scales of the study areas. First of all, in order to simply clarify the factors that may make influences on sewage heat utilization; for instance, building scale and location, the model is initially applied to a part of the study area, which was defined as a small-scale area. Based on the simulation in the small-scale area, the simulation results are discussed in detail; for example, the relationship between building scale, location, the utilization efficiency of sewage heat utilization system, and energy consumption. The simulation results of different building scales and their location in the study area can be clarified in detail.

After attempting the application of the model in a small-scale area, the study area is expanded to the whole area. The main purpose of this section is to clarify the comprehensive sewage heat utilization potential from a general aspect. Therefore, the scenarios are set from two perspectives, such as the influence on the sewage utilization potential at the downstream area which is related to sewage temperature, and the relationship between sewage heat utilization potential and penetration rate. According to the two scenarios, the relationship between sewage heat utilization patterns in the upstream area, the penetration rate, and the sewage heat utilization potential can be clarified.

- Definition of sewage heat utilization potential and the setting condition of standard system

In this study, the sewage heat utilization potential is defined as the reduction of building energy consumption between the cases that sewage heat utilization system is utilized by the building and the case that sewage heat is not utilized. In other words, the building energy consumption is compared by a standard system and sewage heat utilization system, and then clarify the sewage heat utilization potential (Figure 5- 1).

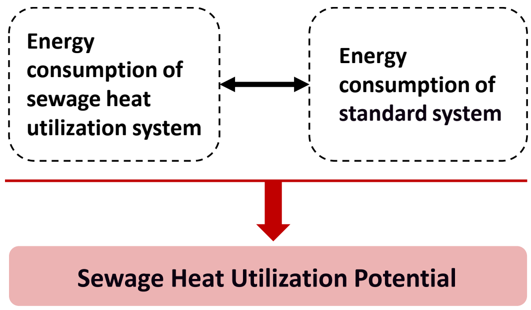

Figure 5- 1 Definition of sewage heat utilization potential

Regarding the sewage heat utilization system which is introduced in chapter 4 in detail, part of the building heat demand is provided by the sewage heat through the heat exchanger installed in the sewage pipeline. As shown in Figure 5- 2, part of the heat required by the water source heat pump is supplied by the sewage heat. In addition, when the recovery quantity of sewage heat is insufficient for the required heat output of the heat pump, the remaining heat will be provided by the backup system which is set to be as the tap water source heat pump.

Concerning the standard system, it is set for comparing the energy consumption with other cases that sewage heat is utilized in order to clarify the energy saving potential, and the setting condition of the standard case is that the building heat demand is fulfilled by the heat pump of tap water source without utilizing sewage heat (Figure 5- 3).

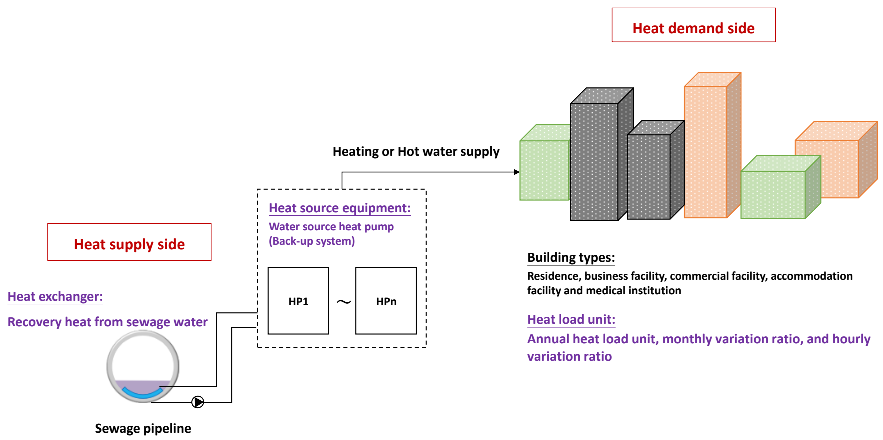

Figure 5- 2 Diagram of sewage heat utilization system

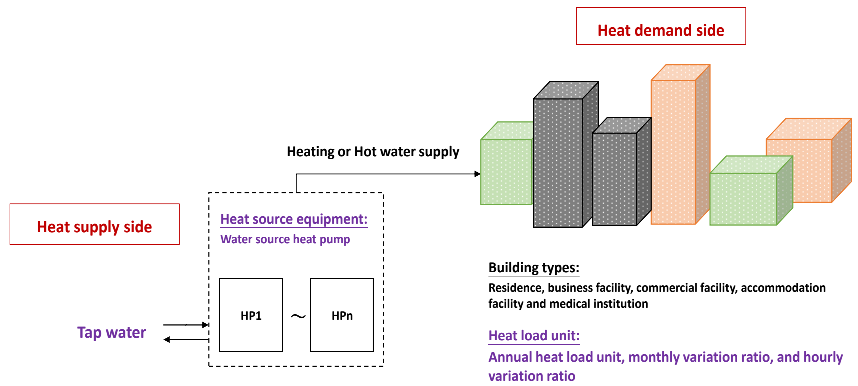

Figure 5- 3 Diagram of standard system

- Setting condition of the simulation

In the following simulation, the simulation time period is set in winter, the general input data and the setting condition introduced here are applied to the following simulation in chapter 5 and chapter 6. According to the introduction of input data, it can be divided into two parts which including sewage side and building heat demand side.

Regarding the calculation setting of sewage side, the average tap water temperature of February (9.4℃) and the hot water temperature (55℃) are adopted to the input data of sewage physical model to set as the cold water temperature and the supply hot water temperature. Based on the water temperature, timely water consumption unit, and the sewage physical model introduced in chapter 2, the sewage physical condition in pipelines can be calculated.

As for the calculation setting of the building heat demand side, the average heat demand of hot water supply and heating in February are set to conduct the simulation (Table 4- 2~Table 4- 4). Based on the annual heat load unit of hot water supply and heating, the building heat demand of residence, hospital and retail are set to be utilizing the objective system for hot water supply, and the office and retail are set as heating. Specifically speaking, the annual heat load unit for hot water supply accounts for a large proportion in residence hotel, and hospital, on the contrary, the annual heat load units for heating of office and retail are larger; therefore, the objective systems in residence, hotel, and hospital are set to be supplying the building heat demand for hot water supply, and the setting for office and retail are assumed as heating.

According to the sewage physical model proposed in chapter 2, and the sewage heat utilization model constructed in chapter 4, these two models are integrated as the urban sewage state prediction model to conduct the simulation of regional sewage heat utilization potential in chapter 5 and chapter 6.

5.2 Overview of the application area

The application area of urban sewage state prediction model is the same area with the verification area in chapter 3, which is a part of Osaka city. According to the GIS map of the sewer system, there are six confluent points in the study area; based on the confluent points, the whole study area is divided into 6 small areas. Referring to Figure 5- 4, Area 1 to Area 6 is distributed from upstream to downstream.

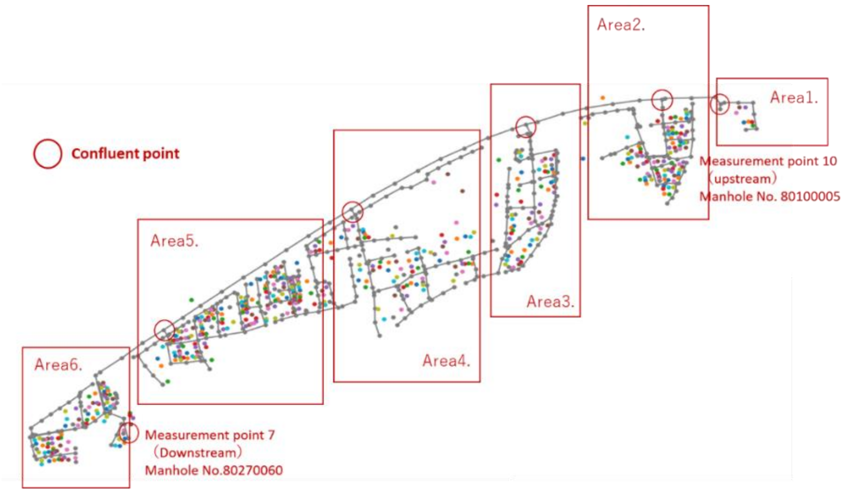

Figure 5- 4 Spatial distribution of Area 1 to Area 6 in the study area

At the former step of conducting the simulation of sewage heat utilization potential, it is essential to determine which pipelines are possible to install the sewage heat utilization system. In this study, based on the heat exchange area is set up as 10% of water depth, we filtered out the pipelines that the average retained water volume is less than 10%, and the buildings that connected to these pipelines are assumed to be incapable to utilize sewage heat.

According to the result, the pipelines in Area 1 and Area 2 are regarded as unsuitable to install the sewage heat utilization system owing to the buildings in Area 1 and Area 2 are mostly small scale; therefore, the average sewage flow rate in these two area is too small to utilized. As a result, the sewage heat utilization system is assumed not to be installed in Area 1 and Area 2. Specifically speaking, after filtering out the buildings that connected to the pipelines which the average retained water volume is less than 10%, within the total building amount of 460 in the study area, there are 146 buildings connected to the pipelines that the sewage physical conditions in these pipelines are regarded as a proper condition to install the sewage heat utilization system. Therefore, the simulation objectives of sewage heat utilization focusing on the 146 buildings located in Area 3 to Area 6. The building amount, building type, and composition ratio of the objective buildings in each area which are intended to utilize sewage heat are listed in Table 5- 1. According to Table 5- 1, the total numbers of buildings that intend to install the sewage heat utilization system are 146; within the 146 buildings, there are 105 residences, 32 office buildings, 8 retail stores, 1 hotel, and there is no hospital in the study area.

Table 5- 1 Composition of building type and building area in Area 3 to Area 6

	Area 3			Area 4		Area 5			Area 6			
Building type	Residence	Office	Retail	Residence	Office	Residence	Office	Retail	Residence	Office	Retail	Hotel
Building numbers	17	7	5	39	4	29	3	2	20	18	1	1
Total building area(m^2)	7257.66	2886.474	2601.62	41027.99	3869.41	16055.92	2943.41	649.63	5746.48	7778.29	134.0002	986
Ratio	57%	23%	20%	91%	9%	82%	15%	3%	39%	53%	1%	7%

In the following simulation cases in this chapter, based on the sewage heat utilization system model proposed in chapter 4, the operation schedule of the heat pump is set as 20 hours operation. Besides, the setting of the heat utilization type for different building types follows the setting in chapter 4 as well. Specifically, the residence, hotel, and hospital are assumed as hot water supply; office and retail are assumed as heating. In addition, when conducting the simulation of sewage heat utilization, under the circumstance that inlet sewage temperature for heat exchanger is lower than 10 degrees, the sewage heat utilization system is assumed to stop operating and the required heat will be provided by backup system. When the sewage temperature is less than 10 degrees, the efficiency of the sewage source heat pump will be reduced significantly. In this situation, the heat pump system using tap water will be more energy-saving. Therefore, when the temperature of the sewage is less than 10 degrees, the standby system is used instead.

Regarding the proportion of total building area in Area 3 to Area 6, as shown in Figure 5- 5, Area 4 is the largest area within Area 3 to Area 6, which the total building area is the largest one, followed by Area 5, Area 6 and Area 3. As for the proportion of building types in Area 3 to Area 6, according to Figure 5- 6 this area is mainly composed of residence, the residence takes a majority of the proportion for 76 %, office for 19 %, retail for 4 %, and hotel for 1%.

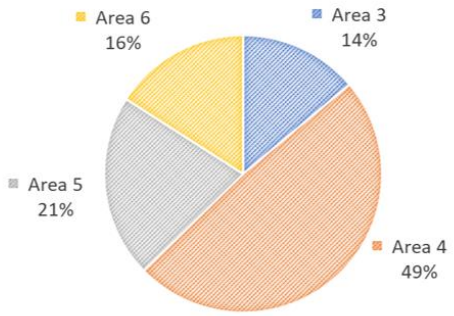

Figure 5- 5 Proportion of building area from Area 3 to Area 6

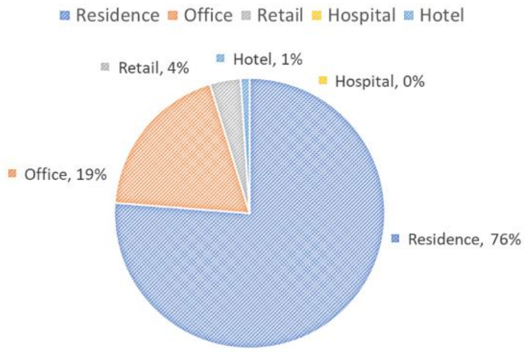

Figure 5- 6 Proportion of building types from Area 3 to Area 6

Concerning the proportion of building areas of different building types in each area are shown in Figure 5- 7 to Figure 5- 10 in detail. According to the figures, the residence takes a majority of the proportion in Area 3 to Area 5 except Area 6. Different from other areas, office is the main building type in Area 6 for 53%, in addition, there is one hotel located in Area 6.

After clarifying the composition of building type and building area in Area 3 to Area 6, the simulation of sewage heat utilization potential is discussed from the following section.

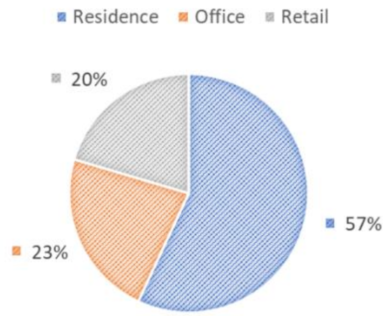

Figure 5- 7 Proportion of building types in Area 3

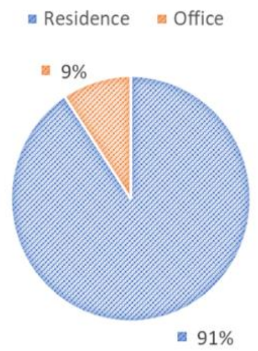

Figure 5- 8 Proportion of building types in Area 4

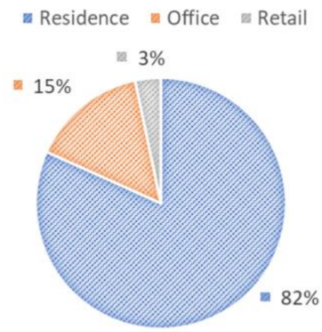

Figure 5- 9 Proportion of building types in Area 5

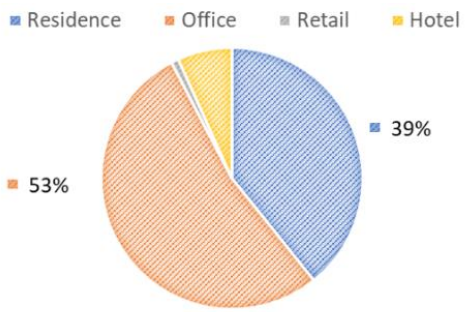

Figure 5- 10 Proportion of building types in Area 6

5.3 Application in small-scale area

In this section, we firstly discuss the sewage heat utilization potential in a small area in several cases. To clarify the relationship between total energy consumption and the ratio of energy provided by the sewage source heat pump, which means the ratio of heat amount that can be recovered by sewage, the simulation scenarios are set on a small scale to discuss and analyze the simulation results simply. In this section, Area 3 is set as an example of an objective area.

5.3.1 Scenario 1: Utilization strategy decided by building scale

The sewage heat utilization rate of large-scale buildings and small-scale buildings located in Area 3 is set in five cases of different utilization rates, the setting condition and the simulation result of energy saving potential of the cases are listed in Table 5- 2. Regarding the definition of large-scale building, it is determined by the heat pump numbers installed in the building. Specifically, according to the setting condition of heat source equipment proposed in chapter 4, the maximum specification of heat pump capacity is selected as the equipment of 50 kW; therefore, the heat output of the heat pump per hour should be 50 kWh, and the heat pump number required for each building can be calculated by Eq.(55). Under the circumstance that the required heat pump numbers of the building are above 5, then the building is defined as the large-scale building in this scenario.

$$N_{HP} = \frac{Q_{Hp\_hr}}{50} \qquad \text{Eq. (55)}$$

Where N_{HP} is the required number of heat pump, Q_{Hp_hr} is the required heat output of heat pump (kWh).

The proportion of large-scale buildings and small-scale buildings located in Area 3 is shown in Figure 5- 11, the percentage is calculated by the total floor area of large-scale buildings and small-scale buildings. As shown in the figure, the large -scale buildings take the majority in Area 3 of 66%, and the proportion of small-scale is 34%.

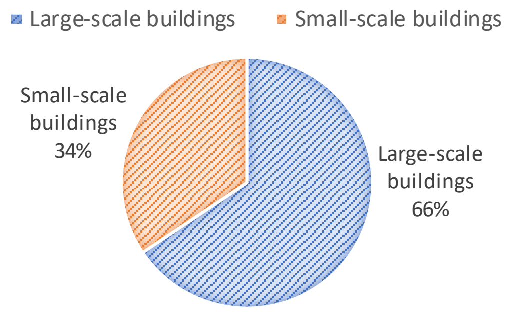

Figure 5- 11 Building composition of different scale in Area 3

As for the definition of the sewage heat utilization rate (Table 5- 2), for instance, when the utilization rate of large-scale building is 100 %, it means the heat pump numbers installed in these large-scale buildings meet the required numbers (N_{HP}); similarly, the utilization rate of 50 % means the installed numbers of the heat pump is half of the numbers it required.

Concerning the standard case, it is set for comparing the energy consumption with other scenarios in order to clarify the energy saving potential, and the setting condition of the standard case is that the building heat demand is fulfilled by the heat pump of tap water source.

In addition, when the recovery quantity of sewage heat is insufficient for the required heat output of the heat pump, the remaining heat will be provided by the backup system which is set as the tap water heat pump.

The simulation result of each case is elaborated respectively, and the sewage heat utilization potential of different cases is compared in the following article.

Table 5- 2 Case setting

Case	Area 3-A-HP	Area 3-L-HP	Area 3-M-HP	Area 3-N-HP	Area 3-O-HP	Area 3-P-HP
Utilization rate of large-scale buildings	0%	100%	50%	100%	0%	100%
Utilization rate of small-scale buildings	0%	0%	100%	50%	100%	100%
Sewage heat utilization potential	Standard case	9.91%	10.54%	11.87%	4.16%	10.29%

- Simulation result of case. Area 3-L-HP

The simulation result of case. Area 3-L-HP is shown in Figure 5- 12. The result shown in Figure 5- 12 is the energy consumption of all the buildings in Area 3, which includes the energy consumption of sewage source heat pump and backup system. As shown in Figure 5- 12, the orange bar, gray bar, and blue fold line represent the energy consumption of the sewage source heat pump, backup system, and the proportion of energy consumption of sewage heat pump in the total energy consumption. The simulation results show that at 1:00 in the morning, the percentage of sewage source heat pumps in the overall energy consumption decreases. It is speculated that the reduction of the drainage amount and temperature from all buildings at 1:00 led to a shortage of heat that can be recovered from the sewage. Therefore, when it is insufficient to meet the heat demand of the building, the backup system is activated. The increase in the proportion of backup systems at this time just proves this statement. Besides, we can find that there are two peaks of the proportion of sewage source heat pump usage in a day, respectively occurred at 10:00 and 19:00. Considering the heat demand of the building, due to these two time periods are the peak period of building heat utilization, this also means a considerable degree of high-temperature drainage from buildings. Therefore, during this period, the sewage in the sewer has a relatively higher flow rate and temperature, which means that there is a lot of heat that can be recovered from the sewage. Therefore, the utilization rate of the sewage source heat pump becomes higher, and lead to the proportion in the total energy consumption increases.

Reflecting the demand of the building, there is the highest heat demand at 19:00, and the sewage flow rate is high in the meanwhile; therefore, the energy consumption ratio of the sewage heat pump in total energy consumption at 19:00 became higher than 10:00 owing to the sufficient heat in sewage water can be recovered by the heat pump.

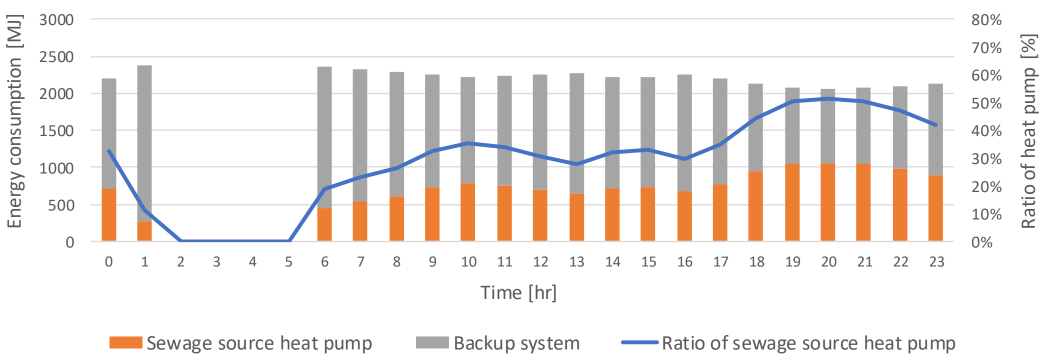

Figure 5- 12 Simulation result of case. Area 3-L-HP (February)

- Simulation result of case. Area 3-M-HP

Figure 5- 13 shows the simulation results of case3-M-HP. In case3-M-HP, the sewage heat pump utilization rate for large-scale buildings is 50%, while the sewage heat pump utilization rate for small-scale buildings is set as 100%. Compared with the previous case 3-L-HP, it is known that the trend of the energy consumption of the sewage heat pump in the total energy consumption during the whole day is almost the same as the previous case.

Compared with the previous case, it can be found that the trend of the energy consumption of the sewage heat pump in the total energy consumption during the day is almost the same as the previous case 3-L-HP. Different from the last case, in case 3-M-HP, during the two peak periods in the morning and evening (10:00 and 18: 00 ~ 23: 00), the utilization rate of sewage heat pumps exceeded 50%. Therefore, it is speculated that there is a sufficient amount of sewage heat that can be utilized. Due to the sewage heat is also utilized in the small-scale buildings in this case, compared to the case 3-L-HP without utilizing sewage heat in small-scale buildings, the results show that the sewage heat utilization potential is greater than the case 3-L-HP. It can be speculated that there is a great amount of sewage heat that can be recovered in the area, through broadly utilized the sewage heat, the sewage heat utilization potential of this case is 10.54%.

However, compared to the result of case 3-P-HP, if the utilization rate of the large-scale building reduces to 50%, the sewage heat utilization potential increase. It means that if excessively utilize the sewage heat, it may lead to the worse result. In other words, there is still a limitation of the utilization rate of sewage heat.

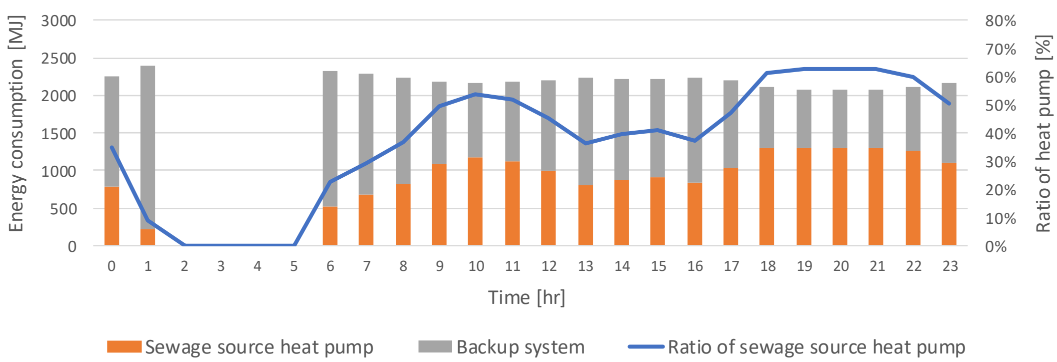

Figure 5- 13 Simulation result of case. Area 3-M-HP (February)

- Simulation result of case. Area 3-N-HP

Figure 5- 14 shows the simulation results of case 3-N-HP. Contrary to case 3-M-HP, in this case, the utilization rate of sewage heat pumps for large-scale buildings is 100%, and the utilization rate of sewage heat pumps for small-scale buildings is 50%. By comparing the results of case 3-L-HP and 3-M-HP, it can be confirmed that there is sufficient heat in sewage in this area, and the utilization of large-scale buildings can obtain better sewage heat utilization potential. Compared with the standard case, the final result shows that the sewage heat utilization potential of this case is 11.87%, which is higher than the results of case 3-L-HP and 3-M-HP.

Compared with case 3-M-HP, the utilization ratio of sewage heat pumps reached 70% during the peak period in the evening period. Therefore, it is known that the total energy consumption in the same time period is the lowest in a day. In addition, by comparing to case 3-M-HP, it can be known that when there is a limitation for the utilization building numbers, priority to meet the needs of large-scale buildings will get better sewage heat utilization potential than meet the needs of small-scale buildings. In fact, the sewage heat utilization potential will be affected by building types as well; the relationship between sewage heat utilization potential and building type will be discussed in the next chapter.

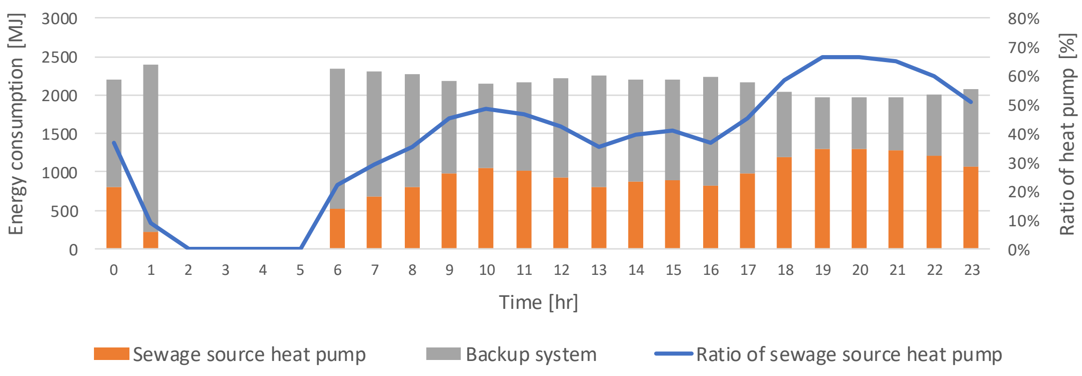

Figure 5- 14 Simulation result of case. Area 3-N-HP (February)

- Simulation result of case. Area 3-O-HP

Figure 5- 15 shows the simulation results of case 3-O-HP. Contrary to case 3-L-HP, in this case, the utilization rate of sewage heat pumps for large-scale buildings is 0%, and the utilization rate of sewage heat pumps for small-scale buildings is 100%. By comparing to the results of case 3-L-HP

and 3-M-HP, it is speculated that there is sufficient heat in sewage, broadly utilized the sewage heat utilization system in the whole area will achieve the better sewage heat utilization potential. However, due to the large-scale buildings do not utilize the sewage heat in this case, it can be expected that the total sewage heat utilization potential will be insufficient. As shown in Table 5- 2, by comparing to the standard case, the final result shows that the sewage heat utilization potential of this case is 4.16%, which is the lowest value of all cases.

Regarding the reason, first of all, the sewage heat is not fully utilized in this case (the utilization rate of large-scale buildings is 0%), which means the operation mode of merely using the backup system results in a lower sewage heat utilization potential.

On the other hand, as shown in Figure 5- 11, large-scale buildings account for 66% of the total area of the buildings in Area 3, while small-scale buildings stand for 34%. Obviously, the use of efficient and high-efficiency sewage heat pump systems for massive areas will lead to lower energy consumption. Therefore, the result of case 3-O-HP is lower than that of case 3-L-HP, which is 100% utilized by large-scale buildings.

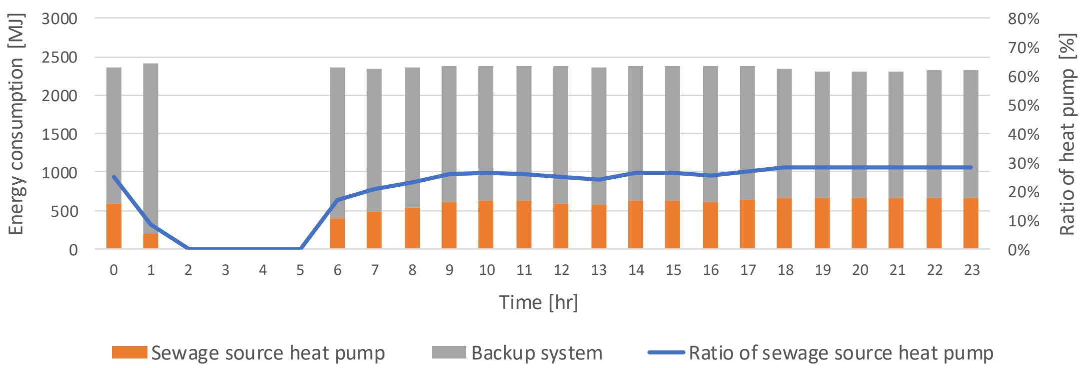

Figure 5- 15 Simulation result of case. Area 3- O-HP (February)

- Simulation result of case. Area 3-P-HP

Figure 5- 16 shows the simulation results of case 3-P-HP. In this case, the utilization rate of the sewage heat utilization system of large-scale buildings is set as 100%, and the utilization rate of the sewage heat utilization system of the small-scale buildings is 100% as well to maximize the utilization of sewage heat. According to the final result, it is known that the utilization rate of the

sewage heat pump reached almost 80% during the peak period at night, which is the highest value in all cases.

By comparing the results of case 3-L-HP and 3-M-HP, it is speculated that due to there is sufficient heat in sewage, broadly utilize the sewage heat in the whole area will obtain better sewage heat utilization potential. Therefore, Case 3-M-HP and Case 3-N-HP, which have a large amount of utilization of sewage heat utilization system, achieved excellent sewage heat utilization potential. Comparing to the standard case, although the utilization rate of the sewage heat pump system is the highest of all cases, the final result shows that the sewage heat utilization potential of case 3-P-HP is 10.29%, which is slightly lower than the results of Case 3-M-HP and Case 3-N- HP. We argue that the primary reason for this result is the inefficient use of sewage heat rather than the insufficient use of sewage heat. As shown in the results, the energy consumption of Case3-P-HP is slightly higher than Case 3-N-HP from 17:00 to 23:00. This result may be caused by the excessive utilization of sewage heat. In this calculation, the set value of the tap water, which is the heat source of the backup system is 9.4 degrees. The lower limit of the operation of the sewage source heat pump is 10 degrees. To ensure sufficient efficiency, when the sewage temperature is less than 10 degrees, the sewage heat pump is assumed to stop operating, and the backup system will be used. Assuming that the temperature difference between the sewage and the circulating water is 1 degree, the sewage heat pump will keep operating when the inlet sewage temperature is between 10 degrees and 10.4 degrees. However, the efficiency of the sewage source heat pump will be lower than the backup system under this situation, which may result in relatively high energy consumption.

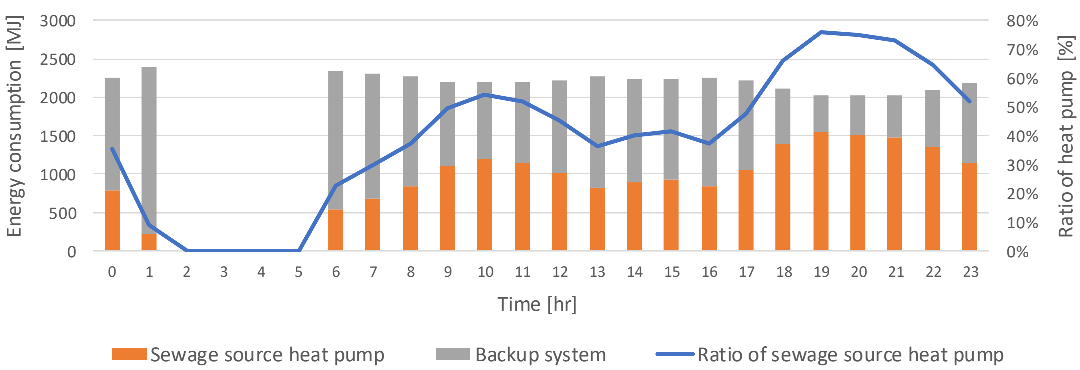

Figure 5- 16 Simulation result of case. Area 3-P-HP (February)

Figure 5- 17 shows the comparison results of each case. As shown in the figure, the results of case 3-M-HP, 3-N-HP, 3-P-HP show the outstanding sewage heat utilization potential. It is speculated that owing to there is a great amount of sewage heat retained in Area 3, and the utilization rates of these three cases are higher than other cases. In other words, the sewage heat utilization system is broadly utilized in these three cases. In contrast, the sewage heat utilization potential of case 3-L-HP and case 3-O-HP are low; both of the results are below 10%. The reason is that in both cases, there are buildings of different scales that do not utilize the sewage heat. Due to the utilization of relatively low-efficiency backup systems, energy consumption can not be reduced.

At the same time, the sewage heat utilization potential of case 3-M-HP is higher than the potential of case 3-N-HP because the large-scale buildings account for a large proportion in Area 3. Case 3-M-HP uses a high-efficiency sewage source heat pump to provide heat to a relatively large number of buildings, thus achieving higher energy savings. However, it is worth noting that through the comparison of case 3-P-HP with case 3-M-HP and case 3-N-HP, it can be known that excessive use of sewage heat may cause the opposite effect. Therefore, it is necessary to discuss the utilization strategy of sewage heat in detail.

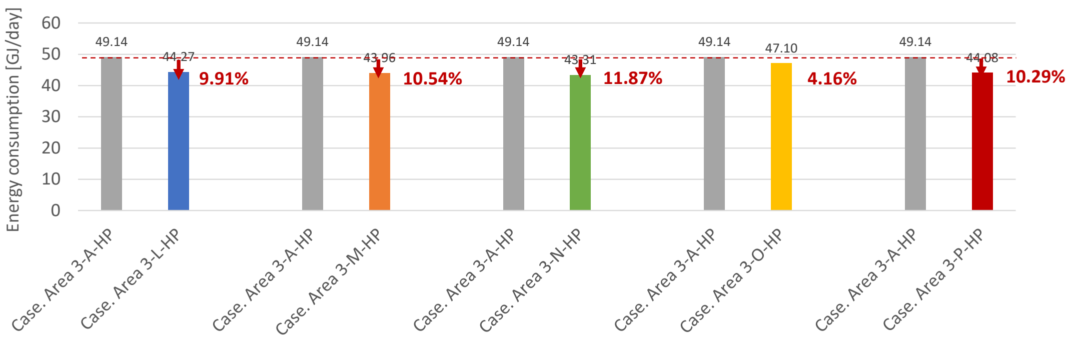

Figure 5- 17 Comparison of sewage heat utilization potential of different cases (February)

5.3.2 Scenario 2: Utilization strategy decided by area location

In this section, the regional sewage heat utilization potential is discussed by the scenario of different area locations to clarify the impact of heat recovery location in a regional scale.

Different installation rates of sewage heat utilization system in three locations including upstream area, middle, and downstream in Area 3 are respectively set up in order to clarify the energy saving potential. Based on the building location in Area 3, all the buildings are classified into three parts that located at relatively upstream, middle and downstream, the proportion of total building area at the upstream, middle, and downstream is shown in Figure 5- 18. As for the aspect of regional energy saving potential, due to the heat recovery at upstream buildings may make an influence on the recoverable heat amount at the downstream building, it is essential to clarify the relationship between sewage heat utilization potential and the heat recovery place.

The setting condition of each case is listed in Table 5- 3, and the simulation result of sewage heat utilization potential of each case is listed in the table as well. The setting condition of the standard case is that the building heat demand is fulfilled by the heat pump of the tap water source, which is the same as the former section (5.3.1).

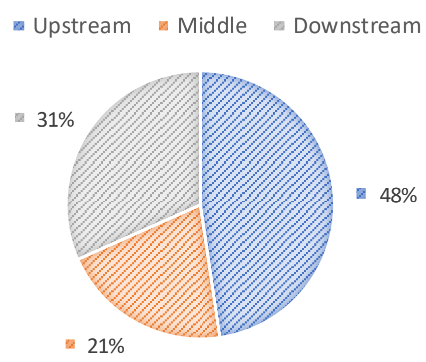

Figure 5- 18 Proportion of building area at different location in Area 3 (February)

According to the definition of the sewage heat utilization rate, for instance, when the utilization rate of upstream is 100 %, it means all the buildings located at the upstream area installed the sewage heat utilization system and the heat pump numbers installed in the buildings meet the required numbers. Regarding the backup system, when the recovery quantity of sewage heat is insufficient for the expected heat output of the heat pump, the remaining heat will be provided by the backup system, which is set as the tap water heat pump.

Table 5- 3 Case setting

Case	Area 3-A-HP	Area 3-Q-HP	Area 3-R-HP	Area 3-S-HP	Area 3-P-HP
Utilization rate of upstream	0%	100%	0%	0%	100%
Utilization rate of middle	0%	0%	0%	100%	100%
Utilization rate of downstream	0%	100%	100%	100%	100%
Sewage heat utilization potential	Standard case	9.49%	4.43%	7.35%	10.29%

The simulation results of the cases under different installation rates of sewage heat utilization system in three locations, including upstream area, middle, and downstream are shown in Figure 5- 19. In the previous section, we can know from the comparison results of the sewage heat utilization potential of different building scales, because there is a considerable amount of available heat in the sewage pipelines in Area 3. Broadly utilize the sewage heat can obtain better energy conservation. Therefore, in this scenario, it can be known from the results that case 3-R-HP has the lowest sewage heat utilization potential due to its low utilization rate, though the utilization area of sewage heat is mainly concentrated in the downstream area, which can receive a great amount of high-temperature sewage. Because of the lowest utilization rate of the sewage heat utilization rate, case 3-R-HP has the lowest sewage heat utilization potential in all cases. For the same reason, the case 3-P-HP, which the sewage heat utilization system is introduced into the upstream, middle, and downstream area, has the highest sewage heat utilization potential within all cases.

The results also indicate that, compared to the standard case, case 3-Q-HP and case 3-S-HP respectively obtain 9.49% and 7.35% of the sewage heat utilization potential. Comparing to the standard case, case 3-Q-HP and case 3-S-HP respectively get 9.49% and 7.35% of the sewage heat utilization potential. Regarding the result of case 3-Q-HP is higher than that of case 3-S-HP, it is speculated that the different utilization rates at different locations of sewage heat utilization lead to the difference of sewage heat utilization potential. The sewage heat utilization location of Case 3-Q-HP is set as upstream and downstream, and there is no sewage heat utilization in the midstream. After the sewage heat recovered by the buildings located in the upstream area, the sewage obtains extra heat from the drainage of the buildings in the midstream. Hence, the sewage temperature return to a relatively higher temperature.

Regarding the heat utilization location of case 3-S-HP, it is set to be at the middle and downstream. After a part of the heat recovered by the buildings in the midstream area, there is no additional heat discharged into the sewage and therefore lead to a lower sewage temperature in the downstream area. Thus, from the perspective of sewage heat utilization in the downstream area, the sewage heat utilization system in case-Q-HP will have higher efficiency because of the higher sewage temperature; therefore, there is a high sewage heat utilization potential in this case.

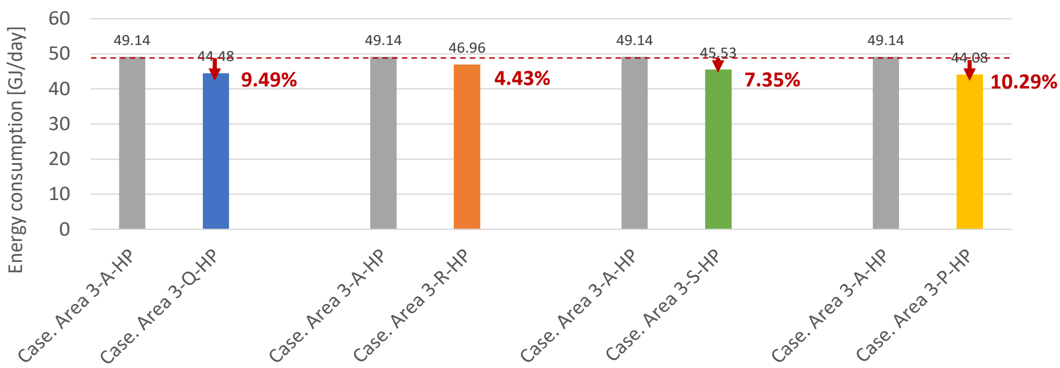

Figure 5- 19 Comparison of sewage heat utilization potential of different cases (February)

5.4 Application in large-scale area

After discussing the possibility of sewage heat utilization potential in a single area (Area3) in the previous section, the study range is expanded to the whole area including Area 3, Area4, Area 5, and Area6 to discuss the temperature variation at the final downstream point (manhole NO. 80270060), and respectively discuss two main scenarios by several cases; for instance, the aspect of impact on downstream temperature and the relationship between utilization penetration rate and sewage heat utilization potential.

5.4.1 Scenario 1: Discussion of impact on downstream temperature

According to Table 5- 4, these seven cases discuss the pattern of respectively utilizing sewage heat in every single area, and the pattern of utilizing sewage heat in multiple regions to clarify the relationship between temperature variation at the downstream area and the sewage heat utilization rates at upstream areas. In addition to the setting condition of each case, the simulation results of sewage heat utilization potential are shown in the table as well.

Regarding the definition of the standard case in this scenario, it is the same as the setting of the former section. In the standard case, the building heat demand is fulfilled by the heat pump of the tap water source.

As the aspect of sewage heat utilization potential of this study area, the result shows that utilizing sewage heat in the whole area has the highest sewage heat utilization potential (case. Whole-D-HP). However, when discussing the utilizing potential of the relative downstream area, it is essential to discuss the final downstream temperature of this study area, because this temperature will make an influence on the next downstream area.

Table 5- 4 Case setting

Case	Whole-A-HP	Whole-E-HP	Whole-F-HP	Whole-G-HP	Whole-H-HP	Whole-I-HP	Whole-J-HP	Whole-D-HP
Utilization rate of Area 3	0%	100%	0%	0%	0%	100%	100%	100%
Utilization rate of Area 4	0%	0%	100%	0%	0%	100%	100%	100%
Utilization rate of Area 5	0%	0%	0%	100%	0%	0%	100%	100%
Utilization rate of Area 6	0%	0%	0%	0%	100%	0%	0%	100%
Sewage heat utilization potential	Standard case	1.53%	6.00%	2.02%	2.61%	7.53%	9.55%	10.38%

As shown in Figure 5- 20, when respectively installed the sewage heat utilization system in the single area, the energy saving potential is related to the scale of the area. Specifically speaking, comparing the results of case. Whole-E-HP, case. Whole-F-HP, case. Whole-G-HP, and case. Whole-H-HP, there is the greatest sewage heat utilization potential in case. Whole-F-HP, which is the case that installed the sewage heat utilization system in Area 4. It is speculated that owing to Area 4 is the largest area within Area 3 to Area 6 which the total building area is the biggest one; therefore, the building numbers of utilizing the sewage heat are more than other areas, and consequently lead to the result.

Concerning the results of installing the sewage heat utilization system in multiple areas, it is shown that when broadly utilize the sewage heat in the whole area including Area 3 to Area 6, the result of sewage heat utilization potential has a more significant effect (Whole-D-HP), and the maximum sewage heat utilization potential in the study area is about 10.38 %.

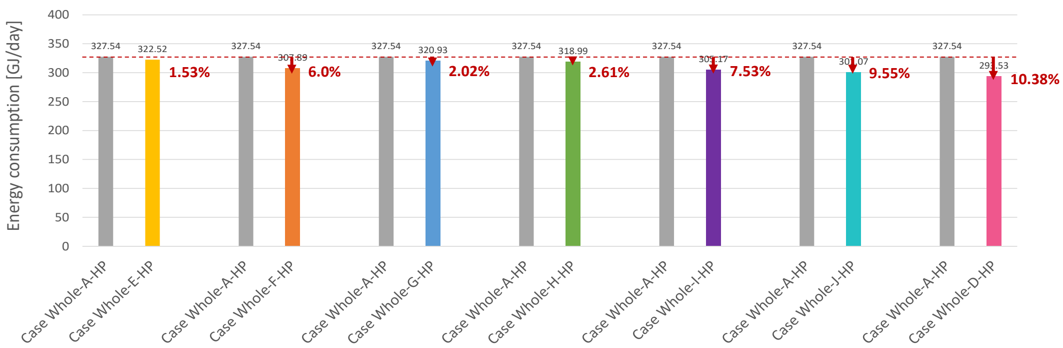

Figure 5- 20 Comparison of sewage heat utilization potential of different cases (February)

Regarding the variation of sewage temperature at the downstream, the simulation results of the sewage temperature at the final downstream manhole (manhole NO. 80270060) under different cases are compared to the sewage temperature before utilizing the sewage heat, and the simulation results are shown in Figure 5- 21 to Figure 5- 26.

According to the simulation results of respectively utilized the sewage heat in a single area, the temperature variation is not obvious in the results of Area 3, Area 4, and Area 5 (case. Whole-E-HP, case. Whole-F-HP, case. Whole-G-HP), only the result of Area 6 (case. Whole-H-HP) shows a noticeable change, it is speculated that due to the manhole NO. 80270060 is located in Area 6, which is the most downstream area; therefore, the variation of sewage temperature is affected by the sewage heat utilization directly. Referring to Figure 5- 21 and Figure 5- 22, the maximum temperature difference between the sewage temperature before utilizing the sewage heat and after using the sewage heat is less than 5 degrees. As for the result shown in Figure 5- 23, the temperature variation is in the range from 0.3 ℃ to 4 ℃, which is not apparent.

Concerning the reason why the variation of sewage temperature is not apparent, it is speculated for two reasons. First of all, based on the sewage heat utilization system model proposed in chapter 4, the effectiveness principle of the heat exchanger leads to the result that sewage heat is unable to be massively recovered by the buildings immediately; in other words, there is a limitation of recovery heat amount related to the heat exchanger model. Therefore, there is no dramatic variation in sewage temperature. Secondly, when utilizing the sewage heat, the wastewater is also discharged from the buildings in the meanwhile. Consequently, when extracting the heat from sewage, the waste heat is exhausted into the sewage through building drainage as well and therefore achieve a certain balance between the heat demand side and the supply side.

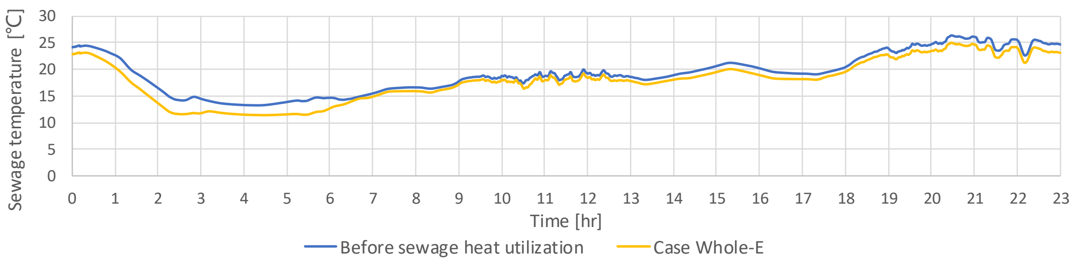

Figure 5- 21 Sewage temperature at manhole NO. 80270060 (case. Whole-E-HP, February)

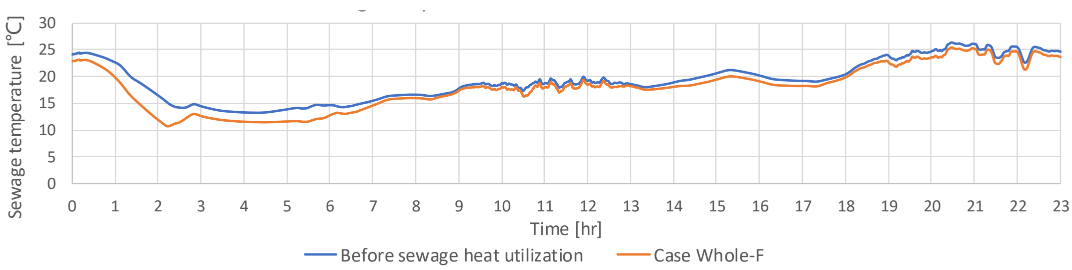

Figure 5- 22 Sewage temperature at manhole NO. 80270060 (case. Whole-F-HP, February)

Regarding the result of utilizing the sewage heat in Area 6 (case. Whole-H-HP), the temperature variation, in this case, is more evident than other results of using sewage heat in a single area. As mentioned above, it is speculated that due to the manhole NO. 80270060 is located in Area 6; therefore, the variation of sewage temperature is affected by the sewage heat utilization directly. Referring to Figure 5- 24, the maximum temperature difference, in this case, is about 5.2 degrees, and the minimum temperature difference is about 1.4 degrees. It is apparent than the results of utilizing sewage heat in Area 3, Area 4, and Area 5.

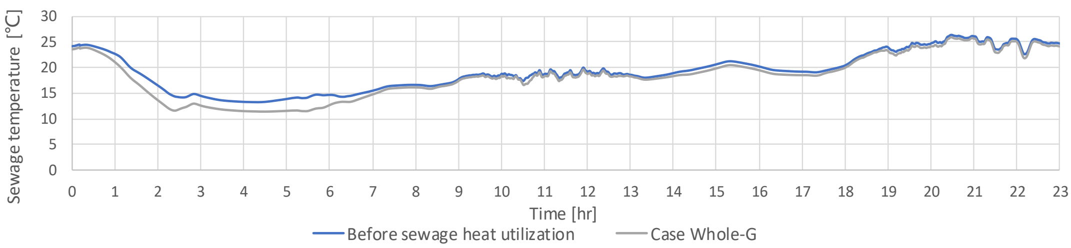

Figure 5- 23 Sewage temperature at manhole NO. 80270060 (case. Whole-G-HP, February)

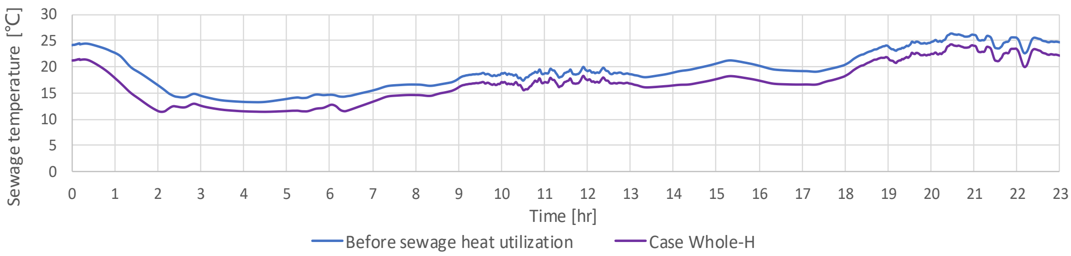

Figure 5- 24 Sewage temperature at manhole NO. 80270060 (case. Whole-H-HP, February)

Concerning the simulation results of utilizing the sewage heat in multiple areas, the variation of sewage temperature in case. Whole-I-HP, case. Whole-J-HP, case. Whole-D-HP is evident than the results of utilizing the sewage heat in a single area owing to the increase of building numbers that extracting the sewage heat. The result of utilizing the sewage heat in Area 3 and Area 4 (case. Whole-I-HP) is shown in Figure 5- 25. The maximum temperature difference, in this case, is about 5.6 degrees, and the minimum temperature difference is about 1.2 degrees; in fact, the range of the temperature difference is similar to the result of utilizing the sewage heat in only Area 6 (case. Whole-H-HP). It is speculated that owing to Area 3 and Area 4 is relatively far from the downstream manhole (manhole NO. 80270060); therefore, within the process of sewage flow from Area3 to the downstream manhole, the building drainage with relatively high temperature discharged into the pipelines and led to the result of inapparent temperature variation.

Regarding the result of utilizing the sewage heat in Area 3, Area 4 and Area 5 (case. Whole-J-HP), the temperature variation between the sewage temperature of before using the sewage heat and after utilizing the sewage heat is noticeable (Figure 5- 26). Specifically, the maximum temperature difference, in this case, is about 6.5 degrees, and the minimum temperature difference is about 1.4 degrees. Owing to this significant decrease in sewage temperature, it may cut down the effect of sewage heat utilization potential in the downstream areas.

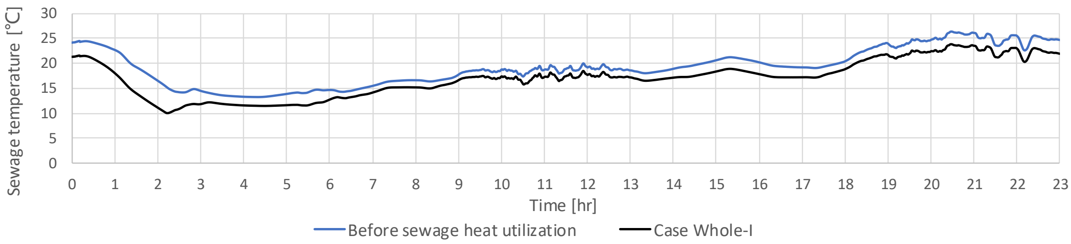

Figure 5- 25 Sewage temperature at manhole NO. 80270060 (case. Whole-I-HP, February)

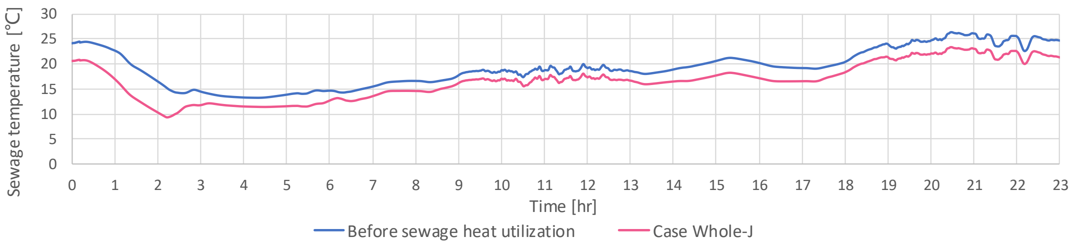

Figure 5- 26 Sewage temperature at manhole NO. 80270060 (case. Whole-J-HP, February)

With regards to the result of utilizing the sewage heat in the whole study area (Figure 5- 27), from the perspective of energy saving potential, it performs the greatest potential of sewage heat utilization. However, the range of the temperature variation, in this case, shows the most significant temperature difference. In other words, after the sewage heat has been utilized in the whole study area, including Area 3 to Area 6, the sewage temperature decreases to a quite low temperature. If there are certain areas located at the relative downstream of the study area that intends to utilize the sewage heat, it may cut down the sewage heat utilization effect in this area. Therefore, when concerning the energy utilization on the regional scale, it is essential to clarify the optimal strategy to achieve the balance of energy saving potential and practical situation from an overall perspective.

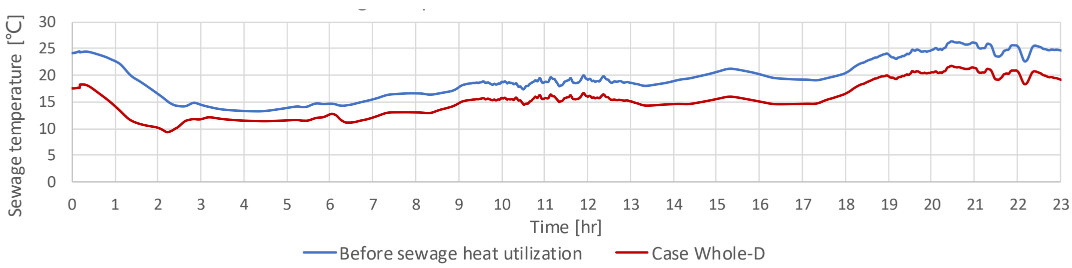

Figure 5- 27 Sewage temperature at manhole NO. 80270060 (case. Whole-D-HP, February)

5.4.2 Scenario 2: Discussion of utilization penetration rate

In this scenario, four cases are set to clarify the relationship between the penetration rate of sewage heat utilization and the sewage heat utilization potential in the study area. The cases set in this scenario are just some simple cases to roughly evaluate and comprehend the effect of sewage heat utilization under different penetration rates.

The setting condition of each case and the sewage heat utilization potential are listed in Table 5- 5. In this section, the definition of the standard case and utilization rate is the same as the setting condition of the previous part. Briefly speaking, the setting condition of the standard case is that the building heat demand is fulfilled by the heat pump of the tap water source. As for the setting of backup system, when the inlet sewage temperature for the heat exchanger is lower than 10 degrees or the recovery quantity of sewage heat is insufficient for the required heat output of the heat pump, the remaining heat will be provided by the backup system which is set as the tap water heat pump.

Table 5- 5 Case setting

Case	Whole-A-HP	Whole-B-HP	Whole-C-HP	Whole-D-HP
Utilization rate of Area 3	0%	50%	80%	100%
Utilization rate of Area 4	0%	50%	80%	100%
Utilization rate of Area 5	0%	50%	80%	100%
Utilization rate of Area 6	0%	50%	80%	100%
Sewage heat utilization potential	Standard case	9.73%	10.69%	10.38%

According to the energy saving potential shown in Figure 5- 28, it is known that there is the most effective sewage heat utilization potential when the utilization rate is 80 %, the energy saving amount is even greater than the case of the sewage heat utilization rate is 100 %. The reason leads to the result is speculated to be related to the inlet sewage temperature for the heat exchanger, which makes an influence on the inlet temperature of the heat pump and affects the performance of the heat pump; eventually, it makes an influence on the energy consumption.

Specifically speaking, if excessively install the sewage heat utilization system and recover the sewage heat densely, the sewage temperature can not be raised to a higher temperature for proper utilization, it may lead to the lower performance of sewage heat utilization system. Owing to the setting condition of this study is that while the inlet sewage temperature for the heat exchanger is lower than 10 degrees, the sewage heat utilization system is assumed to stop operating. However, for instance, when the circumstance that sewage temperature is 10 degrees and the temperature difference between sewage and the circulating water of heat exchanger is 1 degree, the inlet temperature of the sewage source heat pump becomes 9 degrees. Under this situation, the 9 degrees is lower than the temperature of the tap water (9.4℃), which is set as the standard case. Therefore, it leads to the lower performance of the sewage heat pump than tap water source heat pump, which causes the higher energy consumption of the sewage heat pump.

In addition, from the perspective of heat balance, when the penetration rate of sewage heat utilization is 100%, owing to extracting heat from sewage densely, the influence on the decreasing of average sewage temperature in an entire area is more serious than the case of the penetration rate is 80%. Therefore, it leads to worse performance of the sewage source heat pump. Moreover, under the case of the penetration rate is 100%, the numbers of the heat pump with worse performance are more than the case of the penetration rate is 80%. Due to the total required quantity of the building heat demand is fixed, and the numbers of the heat pump with worse performance take a majority proportion in case Whole-D-HP; thus, the energy consumption of case Whole-D-HP is larger than case Whole-C-HP.

Based on the result, it is known that there is still a limitation of maximum utilization rate for achieving more significant sewage heat utilization potential. In other words, the relationship between the sewage heat utilization rate and sewage heat utilization potential is not proportional.

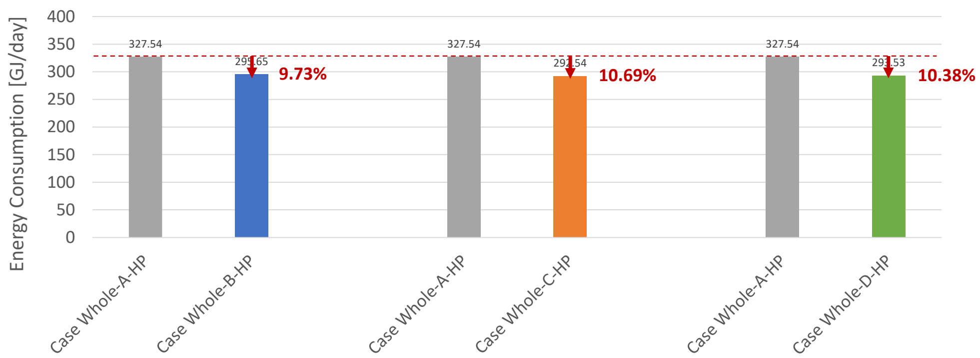

Figure 5- 28 Comparison of sewage heat utilization potential of different cases (February)

5.5 Summary

In chapter 5, the application of the urban sewage state prediction model is applied to an actual urban area to discuss the variation of sewage temperature and the regional energy saving potential after utilizing the sewage heat. Specifically speaking, by integrating the physical sewage model proposed in chapter 2 and the sewage heat utilization system model proposed in chapter 4, the simulation of regional sewage heat utilization potential is conducted through several scenarios from different perspectives. The setting conditions of the cases which are discussed in this chapter are set from a general perspective of approximately comprehend the sewage heat utilization potential in the whole area, and simply discuss the objective result of different setting conditions without considering the optimal strategies.

In this chapter, the application of the urban sewage state prediction model is respectively be discussed the scenario in small-scale areas and large-scale areas. Firstly, the objective area is set as a part of the study area (Area 3) to begin the simulation on a small scale to clarify the energy consumption and sewage heat utilization potential through discussing the utilization strategy, which is decided by building scale and location. Secondly, after discussing the possibility of sewage heat utilization potential in a single area, the study range is expanded to the whole area including Area3, Area4, Area 5, and Area6 to clarify the temperature variation at the final downstream point (manhole NO. 80270060), and respectively discuss two main scenarios to analyze the downstream sewage temperature and the relationship between utilization penetration rate and energy saving potential.

According to the simulation result, it is known that there is an excellent potential of sewage heat utilization in the urban area. Besides, reclaiming the sewage heat in the upstream area indeed makes an influence on the effect of recovering heat in the downstream area. However, when recovering the sewage heat, the buildings are discharging waste heat in the meanwhile; thus, the sewage heat temperature does not dramatically decrease immediately.

Besides, it is notable that according to the scenario of the relationship between penetration rate and sewage heat utilization potential, it is known that there is still a limitation of maximum utilization rate for achieving more significant sewage heat utilization potential, excessively recover the sewage heat may lead to the worse effect, it means the relationship between the sewage heat utilization rate and sewage heat utilization potential is not absolutely proportional.

Based on the approximately comprehending of sewage heat utilization potential and the factors that may make influences utilizing sewage heat proposed in this chapter, the optimal strategies of utilizing sewage heat will be discussed and elaborated in the next chapter.

Chapter 6: Case studies for utilization potential of district sewage heat

Chapter 6: Case studies for utilization potential of district sewage heat

6.1 Introduction and objective

In chapter 6, in order to propose the strategy for the optimal utilization of sewage heat in urban areas, the simulation under different setting parameters and scenarios are conducted to analyze the sewage heat utilization potential. Specifically speaking, within the scenarios proposed in this chapter, the study cases are respectively set up by the specific buildings in the actual study area and the cases of hypothesis building distribution. Owing to the building types in the study area are mainly composed of residence, the diversity of building types is insufficient to discuss the relationship between sewage heat utilization potential and building types under different pattern. Therefore, the cases of hypothesis building types and distribution are also set in this chapter to analyze the optimal strategies and the relationship between the composition of building types and distribution.

Based on the simulation result of the cases suggested in this chapter, the optimal strategies of utilizing sewage heat such as the buildings which are recommended to utilize sewage heat and the proper layout of building distribution can be clarified through the urban sewage state prediction model proposed by this study.

6.2 Overview of the regional sewage heat utilization potential

According to the simulation results proposed in chapter 5, it is shown that the sewage heat utilization potential can achieve a better effect when broadly utilized the sewage heat by more buildings. However, from the perspective of a practical view, it is difficult to install the sewage heat utilization system in most of the buildings scattered in the urban area due to several reasons from the aspect of the economy, initial cost, the willingness of the users, etc. Therefore, it is essential to clarify the optimal sewage heat utilization strategies in order to evaluate the priority of buildings which are recommended to utilize the sewage heat based on building features such as building types and spatial distribution in the urban area in order to achieve efficient sewage heat utilization. Moreover, from the perspective of reducing the environmental load and energy saving in the urban area, the optimal strategies for sewage heat utilization proposed in this study can be applied to urban planning when drawing up the regional energy utilization plan for a new area which is still under developing.

6.3 Influence of different parameters on district sewage heat utilization potential

In this section, the influence of different parameters on district sewage heat utilization potential, for instance, building location and building type, are discussed by two scenarios including the cases of the specific buildings in an actual area and the hypothesis cases. The simulation results are elaborated in the following section.

6.3.1 Scenario 1: Discussion of the sewage heat utilization potential of specific buildings

The discussion in the first scenario begins from the cases of building scale. Two cases are set in this section including case. Off-A and case. Off-B. Specifically speaking, two office buildings located at different location (upstream and downstream) in the study area (Area 3) are set as objectives to compare which building is proper to utilize sewage heat.

Instead of discussing the regional sewage heat utilization potential, the purpose of this scenario is to clarify the sewage heat utilization potential from the perspective of building scale in order to analyze the relationship between different building locations and building energy consumption. Furthermore, the performance of the sewage source heat pump installed in the objective buildings and the variation of the inlet sewage temperature are discussed in detail as well.

As shown in Figure 6- 1, two buildings (Building NO. Off-33162 and Building NO. Off-33091) located in downstream and relative upstream are selected as the study objectives. Regarding the spatial distribution of objective 2 (Building NO. Off-33091) which is defined as the building that located at upstream in this scenario, as shown in the figure, there are some buildings located at relative upstream of objective 2; however, these buildings are set to be unable to recover the sewage heat based on the setting condition of sewage heat utilization proposed in chapter 5. Specifically, when the average amount of sewage retained in the pipelines is less than 10% of water depth, the buildings connected to these pipelines are supposed to be unable to utilize the sewage heat.

Therefore, objective 2 is regarded as a building located at upstream and it is also assumed as the first building which utilizes the sewage heat from the sewage flow process. As for the spatial distribution of objective 1 (Building NO. Off-33162) which is defined as the building that located at downstream, concerning the possibility of utilizing the sewage heat by the buildings that located at the relative upstream of objective 1, after filtering out the buildings that are unable to utilize the sewage heat, there are four buildings is regarded as able to recover the heat from sewage.

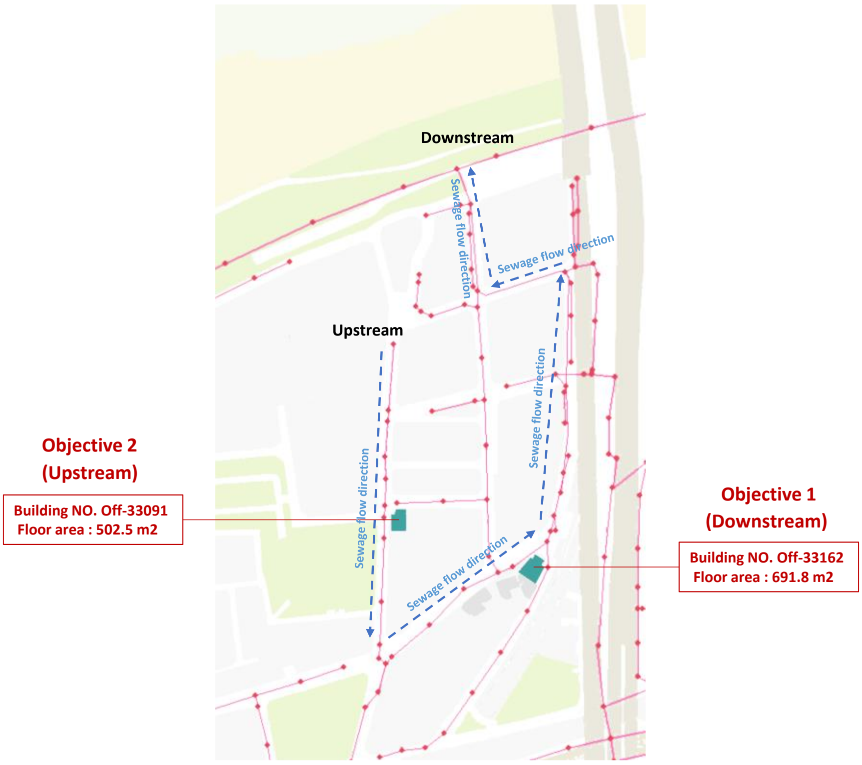

Figure 6- 1 Spatial distribution of objective buildings

The simple diagram and the building information of the two cases are shown in Figure 6- 2 and Figure 6- 3. Regarding the setting condition of the case. Off-A, the sewage heat utilization system is installed in objective 1 and all the buildings located at the relative upstream of objective 1; the buildings located at the relative upstream of objective 1 are four residences, from upstream to downstream are Building NO.Res-3421, Building NO.Res-3423, Building NO. Res-33061, and Building NO. Res-33062. As for case. Off-B, the situation of other buildings located at the downstream of objective 2 are ignored, due to the main purpose of this scenario is focusing on the sewage heat utilization potential of the two objective buildings, whether other buildings that located at downstream utilize sewage heat or not does not make influences on the sewage heat utilization potential of objective 2, therefore, the setting conditions of other buildings in case. Off-B can be ignored.

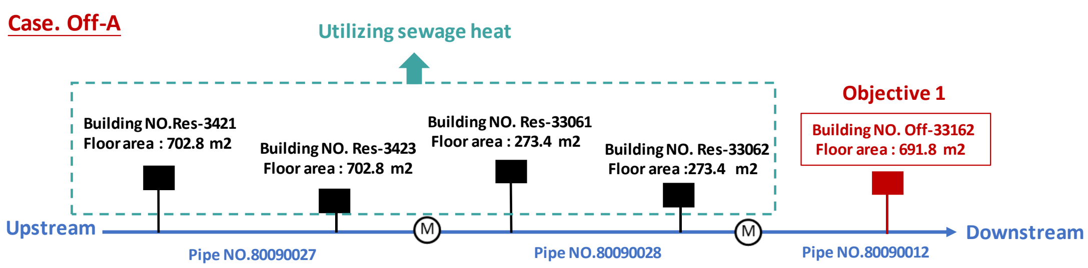

Figure 6- 2 Diagram of case. Off-A

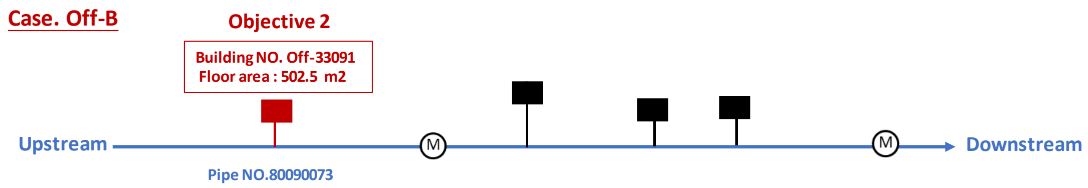

Figure 6- 3 Diagram of case. Off-B

- Simulation result

With regards to the simulation results, the results from two perspectives will be discussed in this section, including the sewage side and building side. For instance, the variation of sewage heat amount that retained in the pipelines which are connected to the study buildings and the variation of sewage temperature; as for the building side, building heat demand, heat demand of heat pump, total energy consumption, heat pump energy consumption, and the performance of sewage source heat pump are all be elaborated. In addition, not only the two objective buildings, but the simulation results of the buildings located at upstream of objective 1 are also analyzed in order to clarify the variation of sewage heat amount that retained in the pipelines and the variation of sewage temperature from upstream to downstream. Eventually, the energy consumption, performance of sewage source heat pump, and the inlet sewage temperature of two objective buildings are mainly discussed.

Figure 6- 4 to Figure 6- 7 show the simulation results of case.off-A, which represent the daily operation of the sewage heat utilization system of building NO.Res-3421, 3423, 33061 and 33062, respectively.

As shown in Figure 6- 4, due to the building NO.Res-3421 is a residence located at the most upstream, the drainage temperature of the building is high and lead to the relatively high sewage temperature. Therefore, as shown by the solid blue line in Figure 6- 4, there is a great amount of sewage heat retained in the connected pipelines, and reached the highest amount at night.

Comparing to other buildings, the sewage heat that can be recovered by building NO.Res-3421 is the highest of all cases, and the average value per hour at night time reaches 120 kJ. On the other hand, because there is more retained heat in the sewage, high-efficiency sewage source heat pumps can be used to fulfill most of the heat demands of the building. In addition, the total energy consumption of building NO.Res-3421 is smaller than that of building NO.Res-3423, which is similar in size but located relatively downstream.

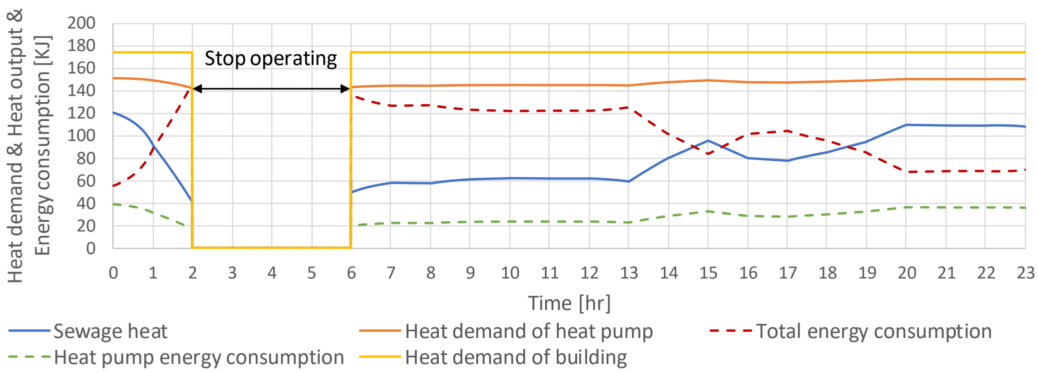

Figure 6- 4 Daily operation of the sewage heat utilization system of Building NO.Res-3421 (February)

Besides, It is worth noting that in addition to the amount of retained heat in sewage, the lower sewage temperature in the downstream leads to the worse performance of the sewage source heat pump, and therefore leads to a relatively increasing energy consumption of the building NO.Res-3423 (Figure 6- 5). However, due to the similar location, the previous building is discharging hot water while recovering heat in the meanwhile. The variation of sewage temperature is not obvious when the sewage flows through the next building. Therefore, according to the results, there is not much difference in energy consumption between the two buildings.

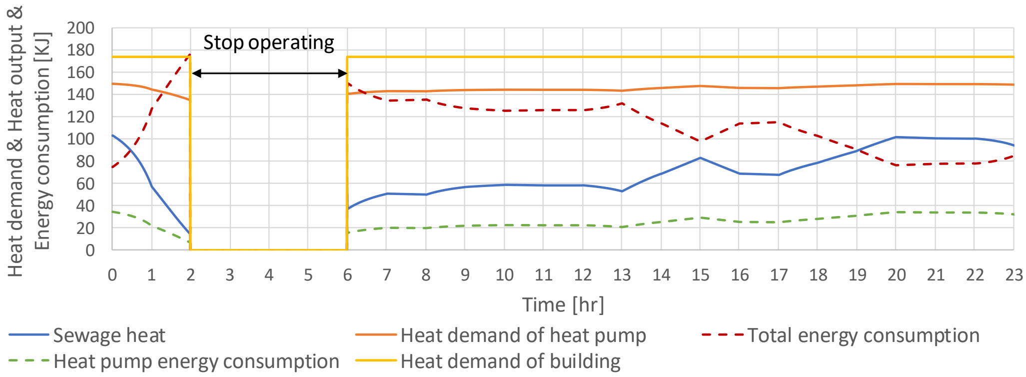

Figure 6- 5 Daily operation of the sewage heat utilization system of Building NO.Res-3423(February)

The building located in the relative downstream is represented by the building NO.Res-33061 (Figure 6- 6) and NO.Res-33062 (Figure 6- 7). As shown by the solid yellow line in the figure, owing to the scale of these two buildings are small, the overall heat demand of the buildings are correspondingly reduced compared to the previous two buildings. Comparing to the buildings in the upstream, the simulation results show that the sewage heat amount that can be recovered by the buildings located downstream is significantly reduced, due to a large amount of sewage heat has been recovered by the large-scale buildings located upstream, and caused the decrease of sewage temperature. In the other words, there is no sufficient heat remaining in the sewage when it flows by the downstream buildings. The lower sewage temperature leads to the worse performance of sewage source heat pump installed in the downstream buildings. Therefore, comparing to the result of building NO.Res-3421 and building NO.Res-3423, the retained sewage heat in the pipelines indicated by the green dotted line significantly reduced.

Besides, due to the building NO.Res-33061 is a small scale building, the sewage heat that can be recovered at night can still meet its heat demand, so it is still possible to make use of the sewage source heat pump for supplying heat. However, it is worth noting that during the same night time period, the sewage heat that can be recovered by the most downstream building NO.Res-33062 cannot meet the heat demand of it due to the heat extraction from the three upstream buildings. Under this situation, the required heat is provided by the backup system, and the total energy consumption higher than building NO.Res-33061.

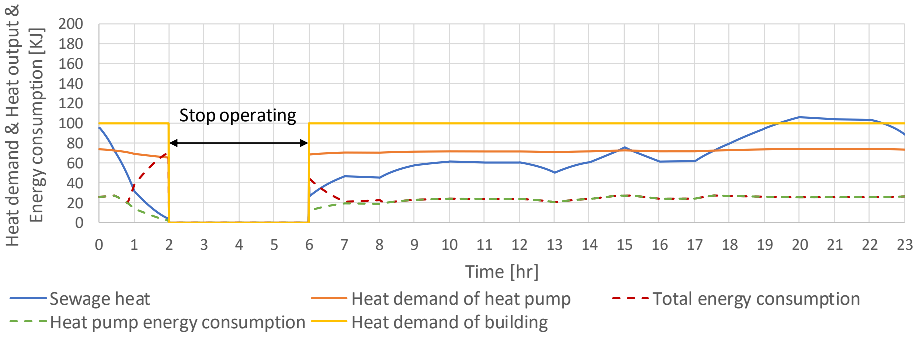

Figure 6- 6 Daily operation of the sewage heat utilization system of building NO.Res-33061(February)

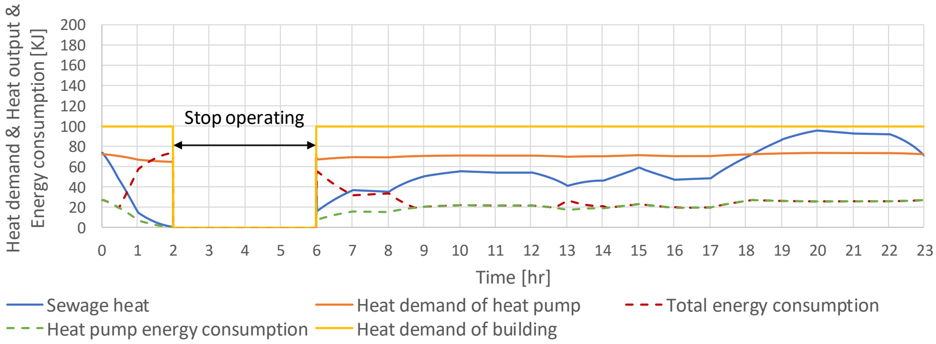

Figure 6- 7 Daily operation of the sewage heat utilization system of building NO.Res-33062(February)

Comparing the results of the four buildings, we can know that under the circumstance that when the building types are all residence, and all the buildings are set to recover the sewage heat, the buildings located upstream have the best condition to recover the sewage heat, due to there is higher temperature at upstream, which means there is a greater amount of heat can be provided by the sewage at upstream. In the meanwhile, the higher temperature means the sewage source heat pump can operate with better efficiency, and lead to the reduction of total energy consumption of the building. On the other hand, although the buildings located at downstream can only recover the less heat amount from the sewage, there are still opportunities to meet the heat demand of the buildings depending on the building scale.

Figure 6- 8 to Figure 6- 12 show the results of objective 1 and objective 2. As shown in Figure 6- 8, as explained in the previous section, the variation of the heat amount that can be recovered form the sewage is affected by the building drainage. There are two peaks of the retained heat in the sewage flowing by the building objective1 in a day. As the building drainage increases, the first peak appears at 10:00, and the second peak appears at 20:00. Building Objective 2 has the same variation trend.

The value of the retained heat in the sewage flowing by the two buildings is different due to the different location of the pipelines.

It is also worth noting that the red dotted line and the solid blue line in the figure are almost in the opposite trend. The reason is that as the retained heat in the sewage increases, the heat provided by the high-efficiency sewage source heat pump increases, and therefore lead to the overall energy consumption of the building decreases.

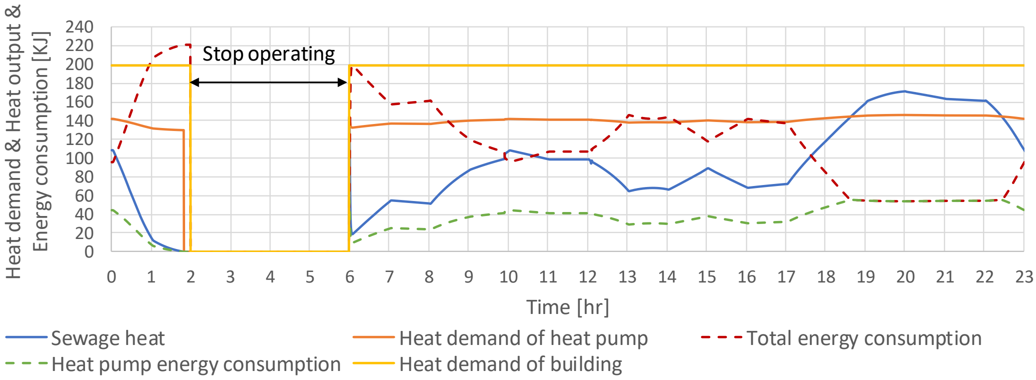

Figure 6- 8 Daily operation of the sewage heat utilization system of Objective1 (February)

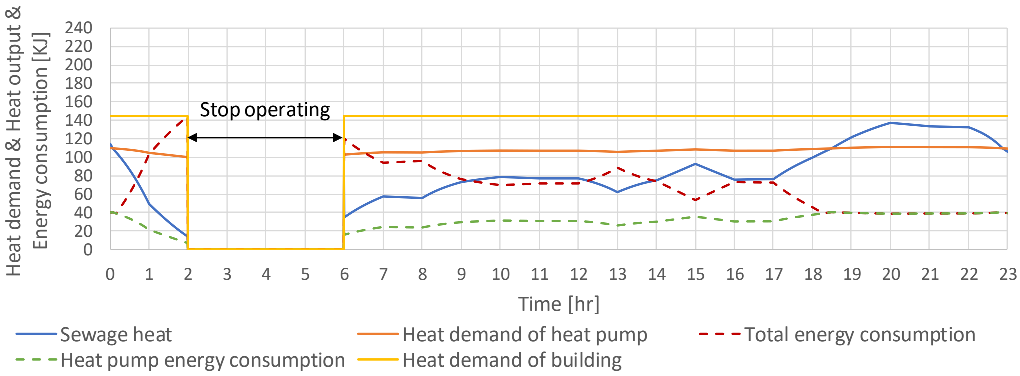

Figure 6- 9 Daily operation of the sewage heat utilization system of Objective2 (February)

Figure 6- 10 shows the performance of every sewage source heat pumps installed in the buildings of case.off-A. As shown in the figure, the solid green line is the result of the objective office building (objective 1) located downstream, which indicates a relatively lower COP than buildings at upstream. Simultaneously, comparing all the COP curves, we can know that the COP of the sewage source heat pump in the upstream building is higher than the downstream buildings. The reason is that the sewage temperature gradually decreases from the upstream pipeline to downstream due to the heat is recovering by buildings. The highest temperature in the upstream indicates that the sewage source heat pump of the building in the upstream has the greatest operating efficiency.

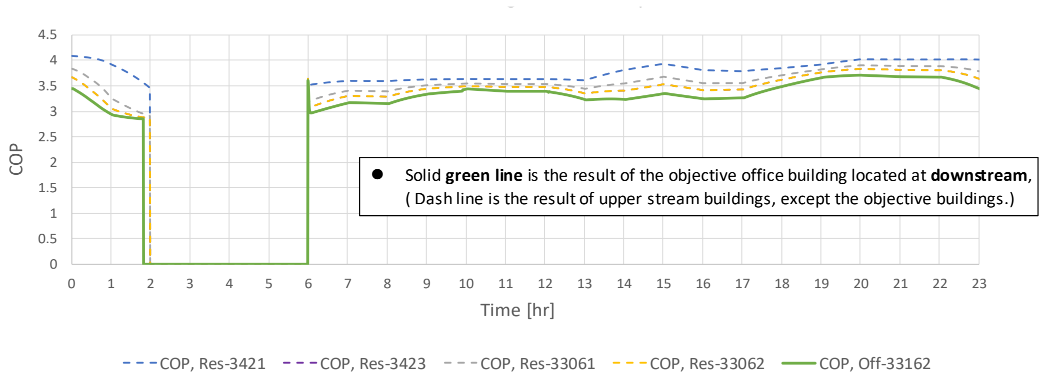

Figure 6- 10 Simulation result of the performance of the sewage source heat pump (February)

Figure 6- 11 shows the relationship between inlet sewage temperature and COP of sewage source heat pump in objective 1 and objective 2. Due to the objective 1 is located at downstream, and the buildings at the upstream of it are recovering sewage heat in the meanwhile; therefore, the inlet sewage temperature at objective 2 is lower than objective 1 which is located at upstream. Besides, the relatively low sewage temperature also makes influence on the COP of the sewage source heat pump. Figure 6- 12 shows the energy consumption of objective1 and objective2. Corresponding to the results in Figure 6- 11, the lower inlet sewage temperature of objective1 which located at downstream leads to the low efficiency of the sewage source heat pump operation and eventually result in an increased of energy consumption.

The sewage source heat pump of the objective2 located at the upstream has higher efficiency; therefore, the energy consumption of the building is relatively lower. However, due to the different scale of the buildings, the performance of the sewage source heat pump is not the only factor leading to this result. The scale of the building objective1 is relatively large, and the sewage heat that can be recovered in this case is relatively less than objective2. Therefore, more heat needs to be provided by the backup system with lower efficiency in order to meet the heat demand.

Although the floor area of objective 1 is about 1.4 times than the floor area of objective 2, the energy consumption of objective1 is about 1.75 times than objective2. This result proves that the reduction of sewage temperature still makes a considerable influence on building energy consumption when utilizing sewage heat.

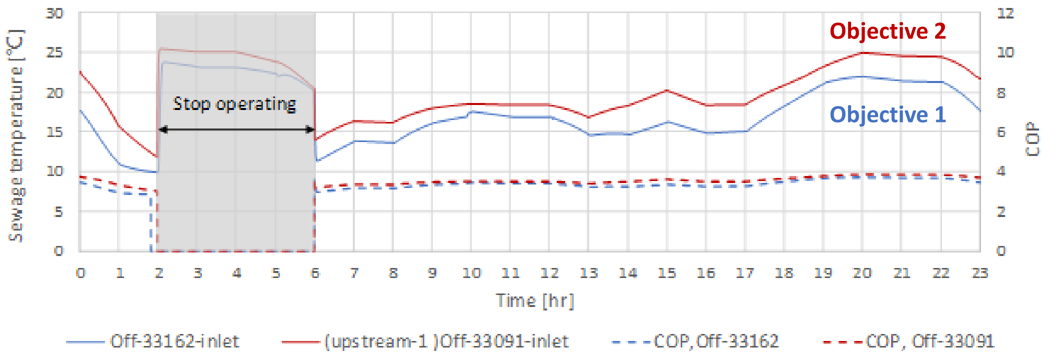

Figure 6- 11 Relationship between inlet sewage temperature and sewage source heat pump COP (February)

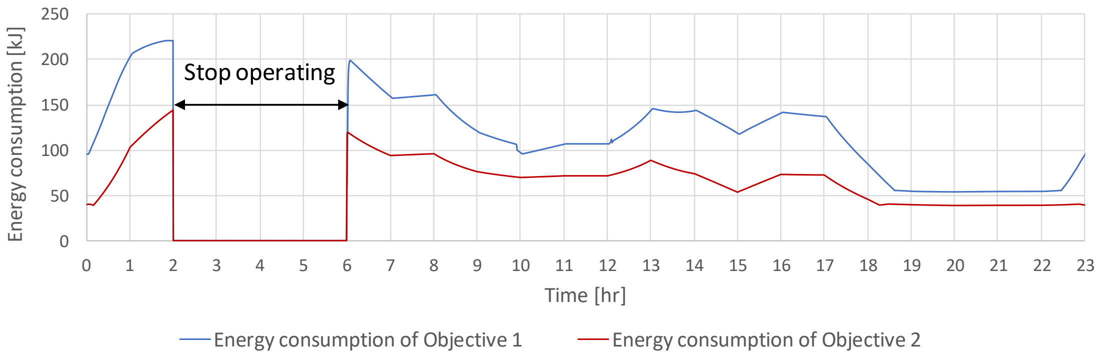

Figure 6- 12 Energy consumption of Objective 1 and Objective 2 (February)

6.3.2 Scenario 2: Discussion of building type and location

In this scenario, the relationship between sewage heat utilization potential, building type, and building location is discussed from the perspective of the features of drainage and heat demand of different building types through setting up several objective buildings in hypothesis areas.

Based on the results of these simulation cases, it is expected to clarify the heat demand and drainage characteristics of different building types in order to suggest the proper layout in the urban areas. Specifically speaking, according to the building drainage and heat demand characteristics, buildings can be classified that which building types are proper to act as the role of offering waste heat, and which building types are the priority types of utilizing sewage heat. Furthermore, it is able to propose an optimal layout for building distribution in urban areas from the aspect of sewage heat utilization potential.

First of all, from the perspective of discharging waste heat from buildings, the features of drainage from different building types are shown in Figure 6- 13, which is calculated by the sewage physical model proposed in chapter 2. Regarding the drainage temperature, it is calculated based on the using water temperature and the using ratio of hot and cold water. The results shown in Figure 6- 13 are calculated based on the hot water temperature of 60°C and the cold water temperature of 9.4°C. Specifically speaking, as mentioned in chapter 2, concerning the drainage temperature of residence, it is calculated by the daily using frequency, hourly using ratio of each water using behavior, and hot and cold water using ratio [46]. As for other building types (office, retail, hotel, and hospital), the drainage amount and temperature is calculated by the original unit of water consumption, hot water consumption unit, and hourly using frequency [45]. After calculating the hourly drainage amount and temperature, the average values are shown in Figure 6- 13. According to the figure, it is known that the daily accumulate drainage amount from the hotel is the largest one within all the building types, followed by the hospital, residence, retail, and office. The daily average wastewater temperature of the hotel is also the highest one, followed by the residence, hospital, office, and retail. As shown in the figure, the daily average wastewater temperature of retail is the lowest one for barely 15 degrees which is much lower than other building types.

Regarding the result, it is speculated that the using behaviors in hotel and residence such as taking shower and bath or water using in the kitchen are the behaviors that the hot water consumption takes a majority proportion; in addition, the hot water using ratio in hotel and residence keep a relatively stable trend during a whole day and therefore lead to the higher drainage temperature.

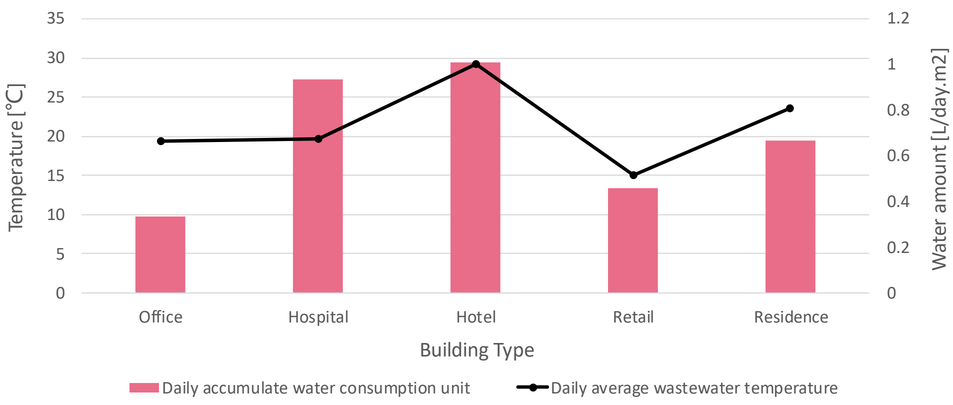

Figure 6- 13 Features of drainage from different building types

Secondly, as for the heat demand for different building types, the average heat demand for different building types are shown in Figure 6- 14. According to the figure, it is known that the heat demand for the hotel is the largest one, followed by hospital retail, office, and the residence is the smallest one within all the building types.

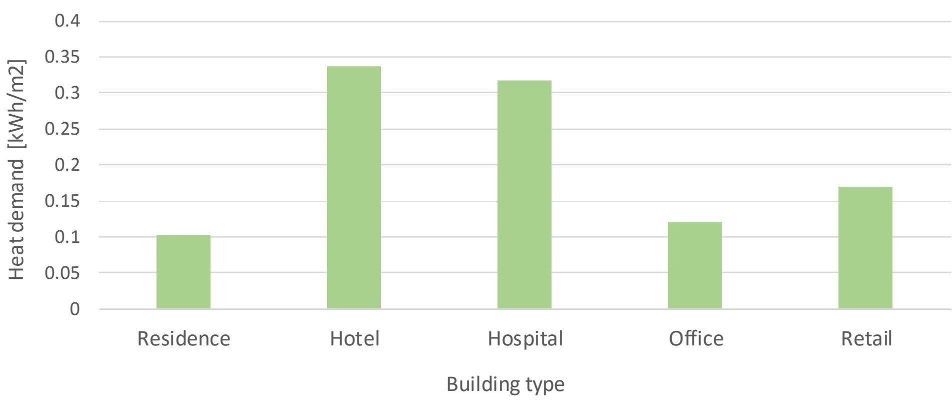

Figure 6- 14 Average heat demand for different building types

Integrating the building drainage and heat demand features of different building types mentioned above, it is sequenced form level 1 to level 5, and the sequence is listed in Table 6- 1 and Figure 6-15. According to the sequence, the relationship and balance between heat demand and heat discharged of different building types can be clarified. Specifically speaking, take the building type of hotel for example, hotel is a building type which has the highest heat demand than other building types; in the meanwhile, the drainage temperature and amount from the hotel are also the highest one. Therefore, the hotel is regarded as a building type that can discharge a great amount of heat, and a large amount of heat is required by the hotel as well.

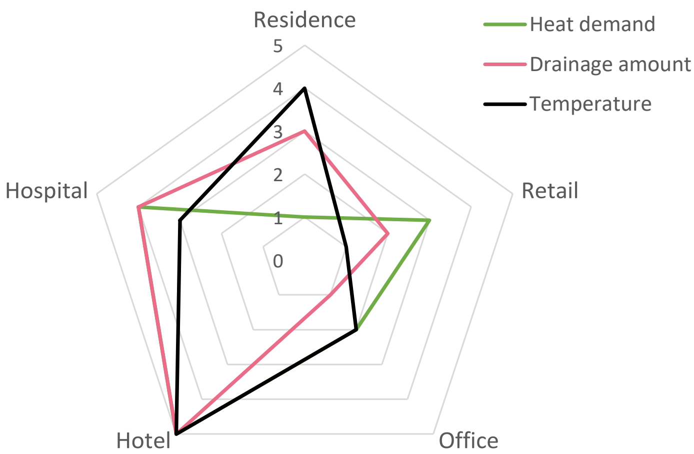

Figure 6- 15 Features of heat demand and discharging heat

Table 6- 1 Features of Heat Demand and Discharging Heat

	Features of Heat Demand and Discharging Heat (From level 1 to 5)		
	Heat demand	Drainage amount	Temperature
Residence	1	3	4
Retail	3	2	1
Office	2	1	2
Hotel	5	5	5
Hospital	4	4	3

- Setting condition of scenario 2

After describing the features of building drainage and heat demand of all the building types, the cases of different building locations including upstream and downstream are set by building types to discuss the sewage heat utilization potential. In these cases, in order to discuss the overall sewage heat utilization potential in a regional scale, residences are assumed as existed in all the cases due to there is usually a great amount of residence in urban areas. In other words, the residence is assumed as the basic building type in the hypothesis area set in this scenario, and then assembled with another building type. In order to clarify the relationship between heat demand of different building types and their location, all the building scale in this scenario is assumed as the same. In addition, the setting condition of the standard case is that the building heat demand is fulfilled by the heat pump of tap water source. As for the backup system, when the recovery quantity of sewage heat is insufficient for the required heat output of the heat pump, or the circumstance that inlet sewage temperature for the heat exchanger is lower than 10 degrees, the sewage heat utilization system is assumed to stop operating, and the remaining heat will be provided by the backup system which is set as the tap water heat pump.

The setting condition and simulation results of each case discussed by different building types are elaborated in the following contents.

- Simulation result of retail

In this section, the simulation is set to discuss the sewage heat utilization potential of two building distribution patterns including the situations that the retail is located in a relatively upstream and downstream area than the residences. The setting condition and the simulation result of sewage heat utilization potential are list in Table 6- 2. According to Table 6- 2, the definition of the utilization rate of 100% means the condition that the heat pump numbers of sewage source heat pump installed in the building are the numbers that can fulfill the numbers required by the building. As mentioned above, when the recovery quantity of sewage heat is insufficient for the required heat output of the heat pump, or the circumstance that inlet sewage temperature for the heat exchanger is lower than 10 degrees, the remaining heat will be provided by the backup system which is set as the tap water heat pump.

Table 6- 2 Case setting

	Case.Hypo-L	Case.Hypo-M		Case.Hypo-L	Case.Hypo-N
Utilization rate of NO.Hypo-Ret2 (Upstream)	0%	100%	Utilization rate of NO. Hypo-Res1	0%	100%
Utilization rate of NO. Hypo-Res1	0%	100%	Utilization rate of NO. Hypo-Res2	0%	100%
Utilization rate of NO. Hypo-Res2	0%	100%	Utilization rate of NO. Hypo-Res3	0%	100%
Utilization rate of NO. Hypo-Res3	0%	100%	Utilization rate of NO. Hypo-Res4	0%	100%
Utilization rate of NO. Hypo-Res4	0%	100%	**Utilization rate of NO. Hypo-Ret3 (Downstream)**	0%	100%
Sewage heat utilization potential	Standard case	**3.96%**	Sewage heat utilization potential	Standard case	**12.04%**

Table 6- 2 shows the simulation settings and calculation results of retail buildings. Case hypo L is the standard case, and all buildings do not utilize the sewage heat utilization system. In case hypo-M and case hypo-N, all buildings are set to utilize the sewage heat utilization system. The difference between cases M and N is that the target retail building in case M is located upstream, while in case N the target building is located downstream. Therefore, we discuss the impact of different locations of building with same type on the the overall sewage heat utilization potential.

Figure 6- 16 shows the simulation results of cases M and N. Compared with the standard case, the total energy consumption of cases M and N is respectively reduced by 3.96% and 12.04%. At the same time, compared to case M, when the target retail building is located downstream, the total energy consumption is reduced by 8%. Regarding the reason, we argue that due to the drainage characteristics of retail buildings, the drainage temperature of it is not high, so it can not discharge the sufficient heat into the sewage. Briefly, the retail buildings discharge moderate amounts of low-temperature water, and its heat demand is also at the middle level.

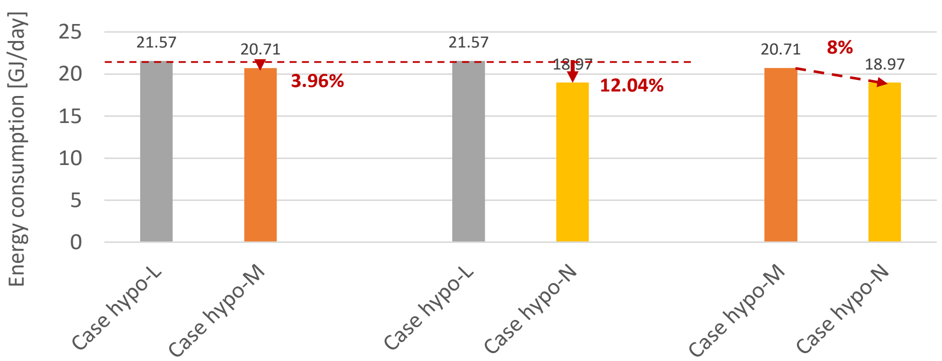

Figure 6- 16 Comparison of sewage heat utilization potential of different cases (February)

On the other hand, even the retail building itself intend to utilize the sewage heat from the pipelines connected to it, the sewage heat pump may not efficiently operate with good performance, due to the temperature of building drainage from retail buildings is relatively low.

According to the result, it is known that when the retail building is placed upstream, it can not achieve optimal efficiency for the entire area, due to its drainage characteristics, neither itself nor other buildings located downstream can obtain a good effect of sewage heat utilization potential. On the contrary, under the circumstance that the retail building is placed downstream (Case.Hypo-N), the heat demand of the upstream residential is not significant, so it may not recover too much heat from the sewage. Besides, because of the drainage characteristics of the upstream residence discharge high-temperature wastewater into the sewage, it increases the heat retained in the sewage, and the downstream retail buildings can accordingly recover more sewage heat. In addition, the sewage with a higher temperature increases the efficiency of the sewage source heat pump, so the total energy saving of buildings in the area will be significantly improved. Through the simulation results, it is known that when the retail building is placed downstream, the energy saving of the case increased by about 2 times than the cases that it is placed upstream.

- Simulation result of office

In this section, the simulation is set to discuss the sewage heat utilization potential of two building distribution patterns including the situations that the office is located in a relatively upstream and downstream area than the residences. The setting condition and the simulation result of sewage heat utilization potential are list in Table 6- 3. In these case, the definition of utilization rate and the setting of backup system are same as the cases of retail mentioned above.

Table 6- 3 Case setting

	Case.Hypo-O	Case.Hypo-P		Case.Hypo-O	Case.Hypo-Q
Utilization rate of NO.Hypo-Off1 (Upstream)	0%	100%	Utilization rate of NO. Hypo-Res1	0%	100%
Utilization rate of NO. Hypo-Res1	0%	100%	Utilization rate of NO. Hypo-Res2	0%	100%
Utilization rate of NO. Hypo-Res2	0%	100%	Utilization rate of NO. Hypo-Res3	0%	100%
Utilization rate of NO. Hypo-Res3	0%	100%	Utilization rate of NO. Hypo-Res4	0%	100%
Utilization rate of NO. Hypo-Res4	0%	100%	**Utilization rate of NO. Hypo-Off2 (Downstream)**	0%	100%
Sewage heat utilization potential	Standard case	**5.08%**	Sewage heat utilization potential	Standard case	**15.52%**

Table 6- 3 shows the case settings. Same as the retail buildings, case P and case Q indicate the situation when the office building is located upstream and downstream respectively. As shown in Figure 6- 17, when all the buildings are set to utilize the sewage heat, and the office buildings are located upstream and downstream, the total energy consumption of the area is reduced by 5.08% and 15.52%.

According to the drainage features of the office building, the office buildings discharge small amounts of low-temperature wastewater, and the heat demand feature of office buildings is similar to the retail buildings. Due to the characteristics of drainage, the drainage temperature of the office is usually low. On the other hand, owing to the office buildings do not have a large heat demand, comparing to the upstream retail buildings of the same scale, the total energy saving of the whole region is 5.08%, which is higher than 3.96% of retail buildings.

It is worth noting that if the office building is located downstream, its drainage temperature is higher than retail buildings, and there is high-temperature building drainage from upstream residences; therefore, a considerable amount of sewage heat discharged into the pipelines from upstream to downstream. In the meanwhile, the high-temperature sewage also ensures the high-efficiency operation of the sewage source heat pump; thus, comparing to the retail buildings, the overall energy saving of office buildings is higher. Similar to retail buildings, when office buildings are located downstream, energy savings are increased by approximately 2 times than the case of located upstream.

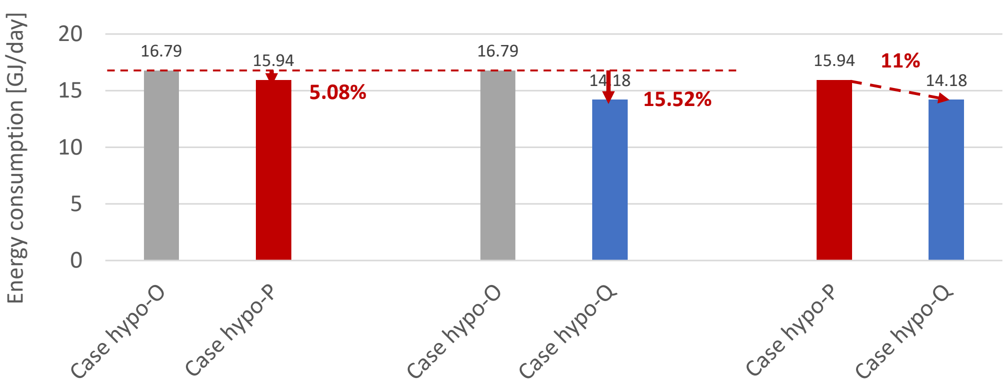

Figure 6- 17 Comparison of sewage heat utilization potential of different cases (February)

- Simulation result of hospital

In this section, the simulation is set to discuss the sewage heat utilization potential of two building distribution patterns, including the situations that the hospital is located in a relatively upstream and downstream area than the residences. The setting condition and the simulation result of sewage heat utilization potential are list in Table 6- 4. In this case, the definition of utilization rate and the setting of the backup system are the same as the cases of retail mentioned above. As shown in Table 6- 4, case S and case T respectively represent the case setting when the hospital is located upstream and downstream. No building in the standard case R utilize the sewage heat, while all buildings in case S and T recover the sewage heat.

The results are shown in Figure 6- 18. When the hospital is located upstream, the energy savings compared to the standard case is 2.41%; when the hospital is located downstream, the energy savings reached 7.36%. In other words, the energy saving when the hospital is located downstream

Table 6- 4 Case setting

	Case.Hypo-R	Case.Hypo-S		Case.Hypo-R	Case.Hypo-T
Utilization rate of NO. Hypo-Hospital1 (Upstream)	0%	100%	Utilization rate of NO. Hypo-Res1	0%	100%
Utilization rate of NO. Hypo-Res1	0%	100%	Utilization rate of NO. Hypo-Res2	0%	100%
Utilization rate of NO. Hypo-Res2	0%	100%	Utilization rate of NO. Hypo-Res3	0%	100%
Utilization rate of NO. Hypo-Res3	0%	100%	Utilization rate of NO. Hypo-Res4	0%	100%
Utilization rate of NO. Hypo-Res4	0%	100%	**Utilization rate of NO. Hypo-Hospital2 (Downstream)**	0%	100%
Sewage heat utilization potential	Standard case	**2.41%**	Sewage heat utilization potential	Standard case	**7.36%**

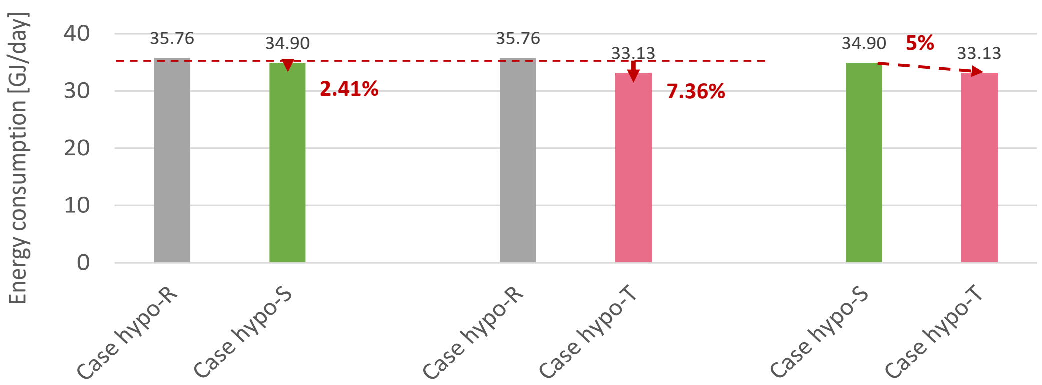

Figure 6- 18 Comparison of sewage heat utilization potential of different cases (February)

increased about 5% than the case located upstream. The hospital discharges a lot of medium-temperature building drainage; however, the heat demand of the hospital is significant. Therefore, due to the heat demand of the hospital itself is huge, if the hospital is located upstream, it may recover a large amount of sewage heat from the pipelines, which leads to a dramatic drop of sewage temperature and heat. As a result, the possibility of the sewage heat utilization for the residences downstream reduced, and the energy saving of the entire area reduced as well.

On the other hand, if the hospital is located downstream, although there is no great amount of sewage heat recovered by the upstream residence, the heat demand of the hospital is very significant. In addition, due to the limitation of the capacity of the heat exchanger (heat exchanger effectiveness), it cannot completely rely on the sewage heat to supply the required heat demand of the hospital, it means the hospital can not recover all the sewage heat immediately to fulfill its entire heat demand. Therefore, comparing to other building types with smaller heat demands, although they are all located downstream, the total energy saving has not been significantly improved in the case of hospital. In brief, according to the results, the total energy saving in this case is 2.41%, which is less than 3.96% in retail buildings and 5.08% in office buildings.

- Simulation result of hotel

In this section, the simulation is set to discuss the sewage heat utilization potential of two building distribution patterns, including the situations that the hotel is located in a relatively upstream and downstream area than the residences. The setting condition and the simulation result of sewage heat utilization potential are list in Table 6- 5. In this case, the definition of utilization rate and the setting of the backup system are the same as the cases of retail mentioned above. As shown in Table 6- 5, case V and case W respectively represent the case setting when the hotel is located upstream and downstream. No building in the standard case R utilize the sewage heat, while all buildings in case V and W utilize the sewage heat.

Figure 6- 19 shows the total energy consumption and energy savings of the area when the hotel is located upstream and downstream. When the hotel is located upstream, the total energy saving is 2.37%, when the hotel is located downstream, the total energy saving increases to 7.19%. Different from the previous building types, the building drainage of the hotel has the characteristics of high

temperature and a significant flow rate. In the meanwhile, the heat demand of the hotel is also huge; it is expected that the hotel will have a considerable impact on the overall energy consumption of the area. Since the heat demands of the hotel and the hospital are very high, the simulation results of the two types are very similar. When the hotel is located upstream, the drainage temperature of the hotel is high; however, simultaneously, its heat demand is also very significant, and therefore leads to the phenomenon that after the hotel recovering the sewage heat, the sewage temperature dropped significantly; besides, the flow rate of low-temperature water discharged from the hotel (after recovering sewage heat) is also significant, although the downstream residence discharges high-temperature water, its flow rate is lower than hotel relatively. Therefore, it is difficult to discharge sufficient heat into the sewage to raise the sewage temperature.

Table 6- 5 Case setting

	Case.Hypo-U	Case.Hypo-V		Case.Hypo-U	Case.Hypo-W
Utilization rate of NO.Hypo-Hotel1 (Upstream)	0%	100%	Utilization rate of NO. Hypo-Res1	0%	100%
Utilization rate of NO. Hypo-Res1	0%	100%	Utilization rate of NO. Hypo-Res2	0%	100%
Utilization rate of NO. Hypo-Res2	0%	100%	Utilization rate of NO. Hypo-Res3	0%	100%
Utilization rate of NO. Hypo-Res3	0%	100%	Utilization rate of NO. Hypo-Res4	0%	100%
Utilization rate of NO. Hypo-Res4	0%	100%	**Utilization rate of NO. Hypo-Hotel2 (Downstream)**	0%	100%
Sewage heat utilization potential	Standard case	**2.37%**	Sewage heat utilization potential	Standard case	**7.19%**

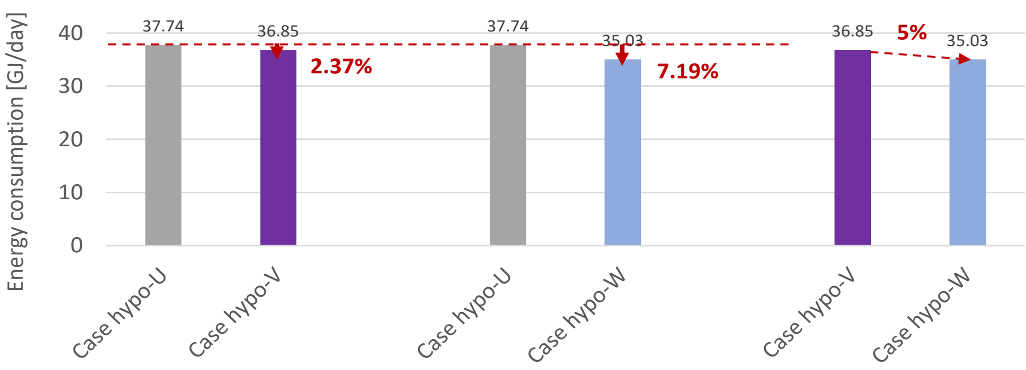

Figure 6- 19 Comparison of sewage heat utilization potential of different cases (February)

- Simulation result of all the building types

Figure 6- 20 shows the comparison results for all cases. According to the results, the numbers of residence are the largest in the urban area; besides, its drainage temperature is high, the flow rate is relatively stable, and the heat demand of the residence is small. Comprehensively, residence is a building type that suitable to act as a heat provider in the urban area.

As for hotel or hospital, although both of them are the building types that highly exhausted heat, their heat demand is also significant. If they are placed upstream, it is easy to recover a large amount of sewage heat, and lead to a rapid drop of sewage temperature. Therefore, based on the result, they are recommended to be placed downstream so that the upstream buildings with small heat requirements can utilize the sewage heat as well, and eventually achieve a greater sewage heat utilization potential in an entire area.

It is worth noting that the energy saving of buildings with great heat demand can significantly increase the total energy saving potential of the entire area. Therefore, if the buildings located upstream do not utilize the sewage heat, the building types with higher heat demand are also suitable to be placed in the downstream in order to utilize the sewage heat preferentially.

Additionally, based on the comparison result of retail and office buildings, the drainage features of these two building types are small drainage amount with relatively low temperature; however, it is known that due to the much lower drainage temperature of retail buildings, the total energy saving potential of the area is less than the case of the office building.

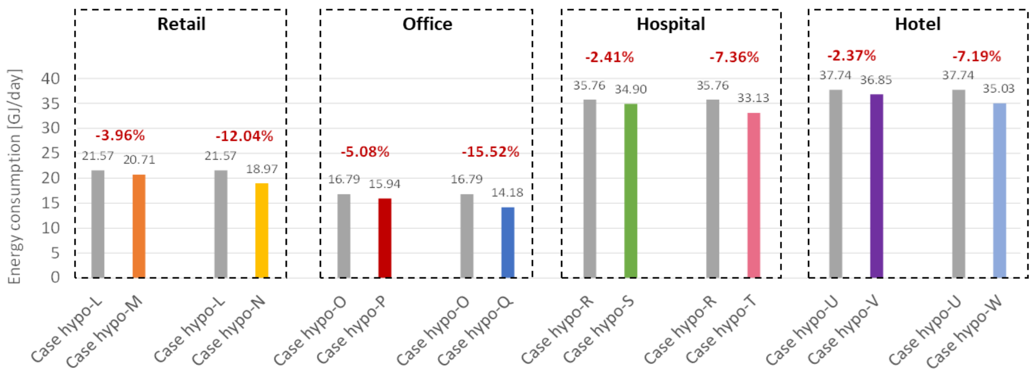

Figure 6- 20 Comparison of sewage heat utilization potential of all cases (February)

6.4 The optimal strategy of district sewage heat utilization

In chapter 5 and the former section of chapter 6, several scenarios and cases under different patterns are set to clarify the effect of some parameters that possibly make influences on district sewage heat utilization potential; besides, the study cases are set up from the scale of buildings, small area to the whole study area. Specifically speaking, for instance, the study cases of specific buildings located at upstream and downstream in the actual area are set to clarify the performance of sewage heat utilization systems installed in the buildings, which the study objective is focused on the building scale. As for the urban scale, several scenarios are set to discuss the factors that generally make influences on the sewage heat utilization potential of the whole area; for instance, the influences on the sewage temperature of the downstream area while the sewage heat is utilizing at upstream buildings in the meanwhile, utilizing sewage heat by different building types, and utilizing sewage heat by the buildings located at different locations.

After analyzing the cases which are set up to clarify the influence of different parameters on district sewage heat utilization potential through realistic and hypothesis area, the study cases in this section are set up in the actual area from the practical perspective to discuss the optimal strategies of sewage heat utilization potential.

In the following two sections, the study cases are set up by the strategies of utilizing sewage heat by different building types and different building locations in two study objective areas. Briefly speaking, Area 6 which is located at downstream of the entire study area is firstly set as an objective area to analyze the influences on sewage heat utilization potential of the downstream area when there are different sewage heat utilization strategies at upstream areas. In the final section, the optimal strategies which are generalized by the study are eventually applied to the entire study area by an optimal case to discuss the district sewage heat utilization potential.

6.4.1 Scenario 1: Discussion of sewage heat utilization potential of the downstream area

In this scenario, the simulation of district sewage heat utilization potential is conducted in the actual area. Area 6, which is located in downstream of the whole study area (Figure 6- 21) is selected as the study objective to analyze the influences on sewage heat utilization potential of the downstream area when there are different sewage heat utilization strategies in upstream areas. Owing to the purpose of this scenario is focusing on the sewage heat utilization potential of the downstream area, it is essential to clarify which patterns of sewage heat utilization in the upstream areas can lead to the greatest heat utilization potential for the downstream area. Briefly speaking, the following case studies are classified by two main strategies of utilizing sewage heat, including the strategy decided by building types and the strategy decided by the heat demand scale of areas.

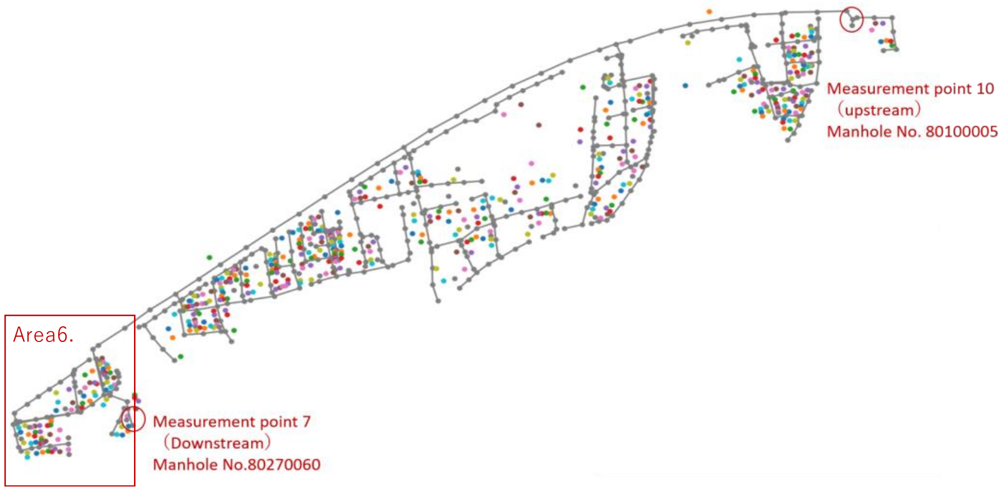

Figure 6- 21 Spatial distribution of Area 6 in the study area

- Sewage heat utilization strategy decided by building types

First of all, the sewage heat utilization strategy is decided by building types. Based on the setting condition proposed in chapter 4, physical sewage conditions are used to determine the objective buildings which are proper to utilize sewage heat at the initial step of the simulation. Within the 460 buildings in the whole study area, there are 146 buildings determined to be able to utilize the sewage heat from the pipelines connected to them.

Specifically, the composition of building types in the study area is shown in Figure 6- 22, only the composition of building types in Area 3 to Area 6 is discussed due to the buildings in Area 1 and Area 2 are filtered out and assumed as unable to utilize sewage heat. After filtering out the buildings which are unable to utilize the sewage heat, the composition proportion of the remaining building types is shown in Figure 6- 22. In other words, the proportion of building types shown in the figure is sorted based on the buildings that are set to utilize the sewage heat. As shown in the figure, the residence is the majority building type within all the building types that are set to utilize the sewage heat, followed by office, retail, and hotel.

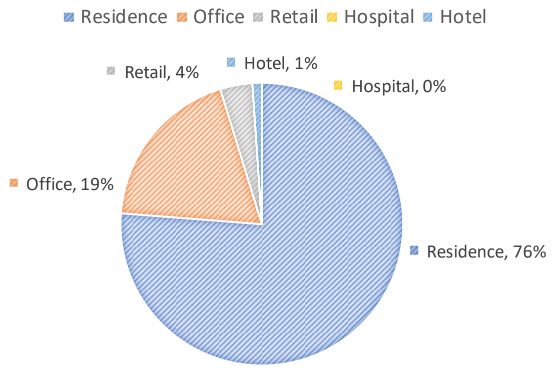

Figure 6- 22 Composition of building types for utilizing sewage heat in the study area

After clarifying the building composition in Area 3 to Area 6, the study cases discuss the strategy of different utilization rates of different building types in the upstream area (Area 3, Area 4, and Area 5) in order to analyze the sewage heat utilization potential in the downstream area (Area 6). The setting condition and the simulation result of sewage heat utilization potential are shown in Table 6- 6. As shown in Table 6- 6, in order to clarify the sewage heat utilization potential in Area 6, the setting condition of the standard case is that buildings of all the building types located in the upstream areas are assumed to utilize the sewage heat. By comparing to the standard case, it is able to analyze that installing the sewage heat system in what kinds of buildings makes the greatest influence on the sewage heat utilization potential in the downstream area.

As shown in Table 6- 6, the utilization rate of the sewage heat source heat pump system in all types of buildings in the standard case of whole-K is 100%. The setting of case whole L, M, N is to discuss the influence of retail building, residential, and office building separately. By utilizing the sewage heat in certain building types, the influence factor can be determined based on the value of sewage heat utilization potential.

Table 6- 6 Case setting

Case	Whole-K	Whole-L	Whole-M	Whole-N
Retail	100%	0%	100%	100%
Office	100%	100%	100%	0%
Residence	100%	100%	0%	100%
Sewage heat utilization potential in Area 6	Standard case	0.03%	1.50%	0.10%

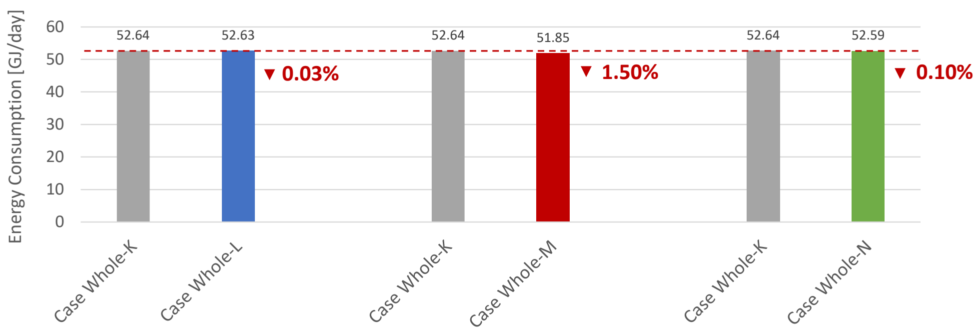

Figure 6- 23 Comparison of sewage heat utilization potential in Area 6 (February)

Figure 6- 23 shows the calculation results of 4 cases, including the standard case. Comparing to the standard case, when retail buildings and office buildings stop recovering heat from sewage, the heat utilization potential of sewage decreased by 0.3% and 0.1% respectively. However, when the residence stopped recovering heat from the sewage, the potential for sewage heat utilization decreased by 1.5%. Since the buildings in the study area are mostly residence, retail buildings account for only a small proportion, when retail buildings stop recovering heat from sewage, the variation of sewage heat utilization potential is not so noticeable.

It is worth noting that for residence, the heat demand of the residence is not high, however the building drainage temperature is high. Simultaneously, the numbers of residence are the largest in the urban area, so it is suitable to act as a heat provider. Besides, it can also be seen from the results that if upstream residences do not recover the sewage heat, the sewage heat utilization potential of

Area 6 can be increased the most. It can be known from the results that if the downstream area needs to recover more heat from sewage, it should prevent the residences located upstream from recovering the sewage heat to achieve a greater effect in the downstream area. Due to the residence account for the largest proportion in the study areas, it makes an great influence on the sewage heat. According to the results, we can also know that for retail buildings and office buildings, because there is a small proportion of these two building types, the impact on the downstream is not obvious.

- Sewage heat utilization strategy decided by the heat demand amount of areas

Secondly, the sewage heat utilization strategy is decided by the heat demand amount of the upstream areas. In fact, sewage heat utilization potential is not only affected by the scale of building area which related to the heat demand but the heat recovery locations. Therefore, there is a need to discuss the cases that combining the parameters of the heat demand of the area and the sewage heat recovery location. The heat demand proportion from upstream to downstream (Area 3 to Area 6) is shown in Figure 6- 24. Regarding the definition of heat demand mentioned here, it is the total building heat demand of all the building types. As shown in Figure 6- 24, it is known that the heat demand of area 4 is the largest one, followed by Area 5, Area 6 and Area 3. After clarifying the heat demand proportion of each area, four cases are set to discuss the relationship between the sewage heat utilization potential of Area 6 and the scale of the upstream areas.

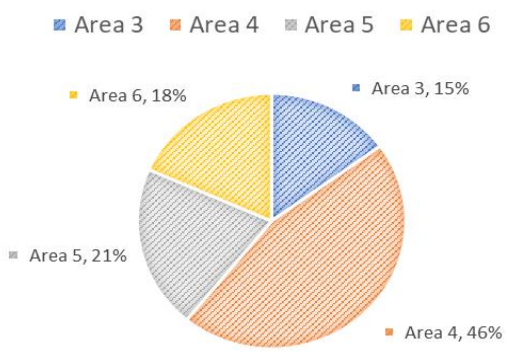

Figure 6- 24 Heat demand proportion of Area 3 to Area 6

The setting conditions and the simulation result of the sewage heat utilizing potential in Area 6 are shown in Table 6- 7. According to Table 6- 7, the setting condition of the standard case is similar to the former section that all the buildings in the study area are assumed to utilize the sewage heat. Regarding the case Whole-P, it is set to discuss the sewage heat utilization potential of the downstream area under the situation that when the upstream area with the largest heat demand does not utilize the sewage heat. The case whole-Q is set to discuss the impact on the downstream area when only the area with the greatest heat demand in the upstream recovers heat from the sewage. The case whole-R is set to discuss the impact on the downstream area when the upstream area recovered the minimal heat amount from sewage. The final case whole-S is set to discuss the sewage heat utilization potential in area 6 when there is no sewage heat recovery in the upstream area. Figure 6- 25 shows all calculation results, including the standard case. As shown in the figure, the result indicates that when none of the upstream areas recover the sewage heat, the sewage heat utilization potential in Area 6 shows the greatest result due to the sewage heat does not recover in the upstream. Therefore, there

Table 6- 7 Case setting

Case	Whole-O	Whole-P	Whole-Q	Whole-R	Whole-S
Utilization rate of Area 3	100%	100%	0%	100%	0%
Utilization rate of Area 4	100%	0%	100%	0%	0%
Utilization rate of Area 5	100%	100%	0%	0%	0%
Utilization rate of Area 6	100%	100%	100%	100%	100%
Sewage heat utilization potential in Area 6	Standard case	0.98%	0.88%	1.3%	1.9%

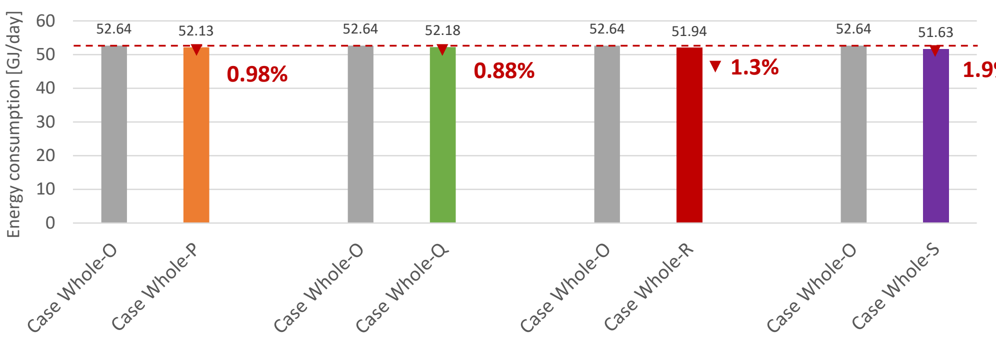

Figure 6- 25 Comparison of sewage heat utilization potential in Area 6 (February)

is the sewage with high temperature flowing into Area 6, and leads to the considerable amount of sewage heat. Besides, the higher sewage temperature ensures the high efficiency of the sewage source heat pump as well, and therefore increases the sewage heat utilization potential.

If the sewage heat does not be recovered in Area 4, which is the area of the largest scale, the sewage heat utilization potential of Area 6 is only 0.98%. It is speculated that Area 5 which is right next to Area 6 is recovering the sewage heat, and the low-temperature sewage caused by the Area 5 makes an influence on the sewage temperature of Area6; therefore, the sewage heat utilization potential is not obvious.

By comparing case whole-P with case whole-Q, it can be seen that if the largest Area 4 recovers heat from the sewage and the neighboring Area 5 dose not utilize the sewage heat, the sewage heat utilization potential of Area 6 is lower than the case whole-P. The reason is that the large amount of low-temperature sewage produced by Area 4 after recovering heat from sewage makes an influence on the downstream area. Besides, Area 5 is a small scale area, even if the sewage heat does not be recovered in Area 5, it still cannot provide sufficient heat to balance a large amount of low-temperature sewage from the upstream. Therefore, this pattern leads to the sewage heat utilization potential of Area 6 decreased.

It is also worth noting that owing to the office accounts for nearly 50% in Area6, if Area 4 and 5, which is mainly composed of residence does not recover heat from sewage, and accumulate the heat in sewage to the downstream area, the sewage heat utilization potential of Area 6 can be increased to 1.3%.

In this section, the relationship between the sewage heat utilization potential of the downstream area and the sewage heat utilization patterns in upstream areas is clarified by discussing the strategy decided by building types and heat demand scale of upstream areas. Through the results of sewage heat utilization potential, the impacts of the utilization patterns in upstream areas are clarified.

6.4.2 Scenario 2: Discussion of sewage heat utilization potential of the entire study area

As mentioned in section 6.2, according to the simulation results proposed in chapter 5, it is known that the sewage heat utilization potential can achieve a better effect when broadly utilized the sewage heat by more buildings. However, from the perspective of a practical view, it is difficult to install the sewage heat utilization system in most of the buildings scattered in the urban area. Therefore, in the final section of the study, a case that applied the optimal strategies suggested by the study is set up to conduct the simulation. In other words, the sewage heat utilization strategies summarized by the former sections are set as the conditions of this optimal case in order to propose and clarify the district sewage heat utilization potential of the study area from a practical perspective.

In addition, another case that the setting conditions are contrary to the optimal case is also proposed to compare the sewage heat utilization potential with the optimal case.

- Setting condition of the optimal case

Based on the simulation results of the study cases and the analysis of sewage heat utilization potential under different circumstances, it can be clarified by two main points to suggest the optimal strategies of sewage heat utilization, including the recommend building types and their spatial distribution. Specifically speaking, regarding the recommended building types of utilizing sewage heat, it is known that the building types with great heat demand such as hotel and hospital are suggested to be as the priority building types to utilize sewage heat, especially when these types of buildings are located in the downstream area, the effect of regional sewage heat utilization can achieve a greater potential.

As for the residence, which is the majority building type in the urban areas, it is recommended to act the role as offering its waste heat due to the stable and large amount of drainage with high temperature. In fact, it is suggested that utilizing sewage heat to more buildings can achieve better regional sewage heat utilization potential, and there is a great amount of residence in the study area. Therefore, it is regarded that the sewage heat utilization system can be reasonably installed in the residences; besides, the heat demand of residence is small, and it can discharge more waste heat than the heat it needs.

Briefly speaking, regarding the setting condition of this optimal case (Table 6- 8), it is assumed that all the buildings located in the downstream area are set to utilize the sewage heat. The reason why the residences located in the downstream area are also determined to utilize the sewage heat is owing to that when the sewage heat recovered by these residences in the downstream area will not make an obvious influence on the utilization potential of other building types because the residences are discharging a great amount of waste heat in the meanwhile. Regarding the situation of the upstream area, when the retail is located at the upstream, it is assumed not to utilize the sewage heat due to its low drainage temperature; the residence and office are the building types with small heat demand, when residence and office located at the upstream, they are also assumed not to utilize the sewage heat in order to storage more sewage heat for the high heat demand building types in the downstream area. As for the hotel and hospital, which the high heat demand building types, no matter they are located in the upstream or downstream area, they are always assumed to utilize the sewage heat.

Comprehensively speaking, in the study area, as mentioned in the former chapter, there are 146 buildings that are able to utilize sewage heat based on the physical sewage state of the pipelines that connected to the buildings. Under the setting condition of the optimal case, 94 buildings, which include different building types and locations, are recommended as the priority buildings for utilizing the sewage heat to clarify the sewage heat utilization potential of the optimal case.

Regarding the definition of the buildings that are belonging to the upstream or downstream area, it is respectively classified in each area (Area 3 to Area 6) based on the GIS map of the sewer system and determined by this study. The proportion of total building area in the upstream and downstream area are shown in Figure 6- 26 ~ Figure 6- 29, and the composition of building types in the upstream and downstream are respectively shown as well (Figure 6- 30 ~ Figure 6- 37).

Table 6- 8 Case setting

	Residential		Retail		Office		Hotel		Hospital	
	Up*	Down*	Up	Down	Up	Down	Up	Down	Up	Down
Case T	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Case U	0%	100%	0%	100%	0%	100%	100%	100%	100%	100%
Case V	100%	0%	100%	0%	100%	0%	0%	0%	0%	0%

*Up means upstream, Down means downstream.

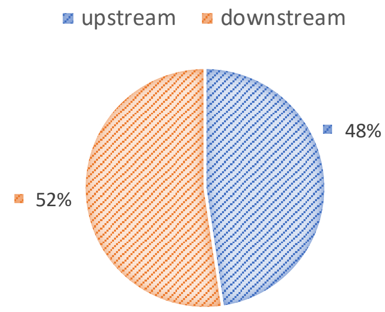

Figure 6- 26 Proportion of building area at different location (Area 3)

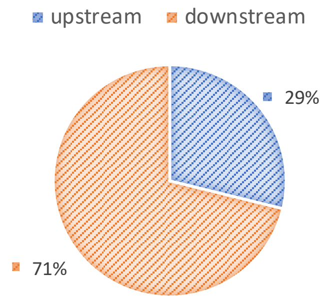

Figure 6- 27 Proportion of building area at different location (Area 4)

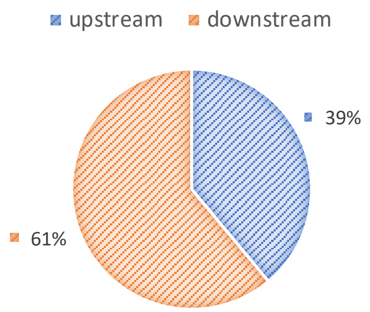

Figure 6- 28 Proportion of building area at different location (Area 5)

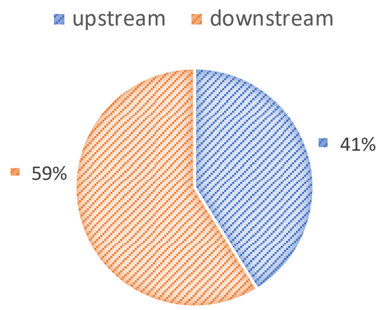

Figure 6- 29 Proportion of building area at different location (Area 6)

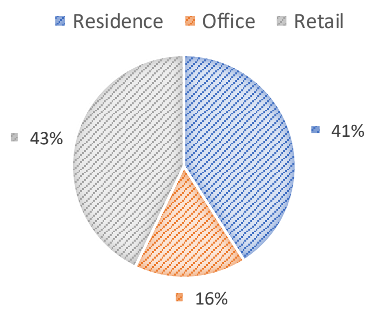

Figure 6- 30 Composition of building types (Area 3, upstream)

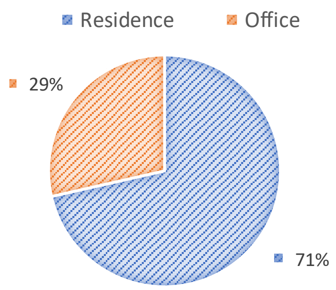

Figure 6- 31 Composition of building types (Area 3, downstream)

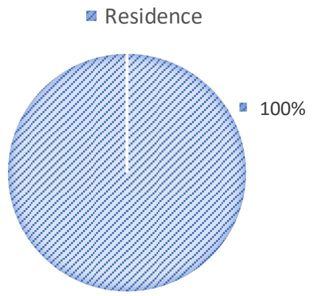

Figure 6- 32 Composition of building types

(Area 4, upstream)

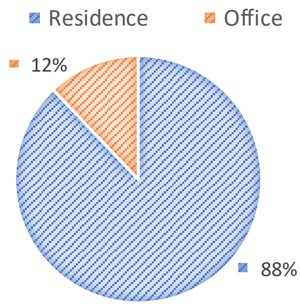

Figure 6- 33 Composition of building types

(Area 4, downstream)

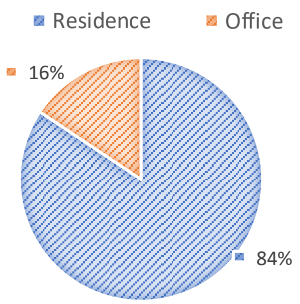

Figure 6- 34 Composition of building types

(Area 5, upstream)

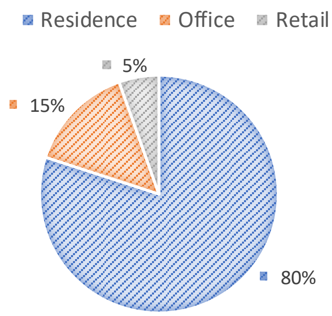

Figure 6- 35 Composition of building types

(Area 5, downstream)

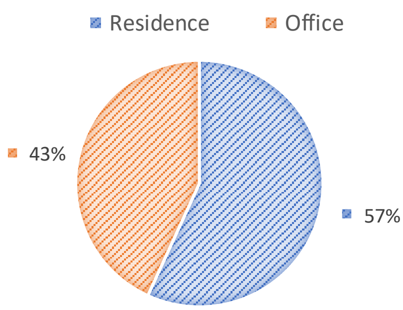

Figure 6- 36 Composition of building types

(Area 6, upstream)

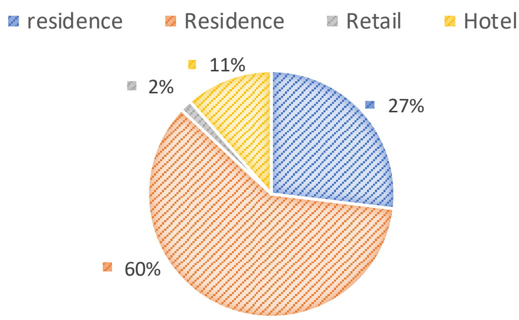

Figure 6- 37 Composition of building types

(Area 6, downstream)

- Simulation result

Figure 6- 38 shows the calculation results of case T, U, and V. Where T is a standard case. In case T, which is the standard case, all types of buildings in the study areas do not recover the sewage heat. Regarding case U, the utilization rate in residences, retail buildings, and office buildings, as well as all hotels and hospitals in the downstream, is set as 100%, and other buildings are set as 0%. Compared with the standard case, the sewage heat utilization potential of case U reached 8.6%.

The setting in case V is the opposite of case U. Concerning the setting condition of case V, the utilization rate in residential buildings, retail buildings, and office buildings in the downstream, as well as all hotels and hospitals are all 0%, and other buildings are 100%. In this situation, the heat utilization potential of case V reached 3.7%, which is less than 8.6% of case U.

Briefly speaking, comparing the result of the optimal case and the contrary case, the sewage heat utilization potential of the optimal case is significantly greater than the contrary case. This result proves that the optimal strategies proposed previously in the study are reasonable.

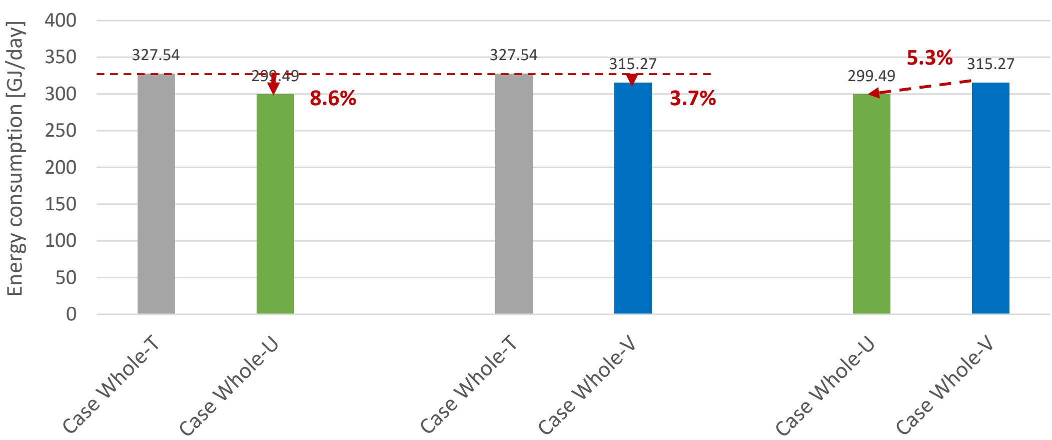

Figure 6- 38 Comparison of sewage heat utilization potential of optimal case and the contrary case (February)

6.5 Summary

In this chapter, in order to propose the strategies for the optimal utilization of sewage heat in urban areas, the simulation under different setting parameters and scenarios are conducted to analyze the sewage heat utilization potential from the practical perspective. Specifically speaking, within the scenarios proposed in this chapter, the study cases are respectively set up by the specific buildings in the actual study area and the cases of hypothesis building distribution.

Owing to the building types in the study area is mainly composed of residence, the diversity of building composition is insufficient to discuss the relationship between sewage heat utilization potential and building types under different pattern. Therefore, the cases of hypothesis building types and distribution are also set in this chapter to analyze the optimal strategies and the relationship between the composition of building types and distribution.

Based on the simulation results, we can know that for hotels or hospitals, although both are high heat exhaust types, their heat demand is also significant. If they are placed upstream, it is easy to recover a large part of the available heat in the sewage, resulting in a rapid drop of sewage temperature. Therefore, based on the result, they are more suitable to be placed in downstream area, so that the upstream buildings with small heat requirements can also utilize the available heat in sewage.

It is worth noting that the energy saving of buildings with significant heat demand can significantly increase the total energy saving potential of the whole area. Therefore, if the buildings located in the upstream do not recover the sewage heat, buildings with higher heat demand are also suitable to be placed in the downstream area to utilize the sewage heat preferentially.

From the perspective of practical view, it is difficult to install the sewage heat utilization system in most of the buildings scattered in the urban area. Therefore, in the final section of the study, a case that applied the optimal strategies suggested by the study is set up to conduct the simulation in order to propose and clarify the district sewage heat utilization potential in the entire study area. In addition, another case that the setting conditions are contrary to the optimal case is also proposed to compare the sewage heat utilization potential with the optimal case.

According to the simulation result of the optimal case and the contrary case, it is known that the sewage heat utilization potential of the optimal case is significantly greater than the contrary case. This result proves that the optimal strategies proposed by the study are reasonable and effective.

Chapter 7: Conclusion and future work

Chapter 7: Conclusion and future work

7.1 Conclusions

This thesis proposed an estimation methodology to evaluate the sewage heat utilization potential and suggested the optimal strategies for utilizing sewage heat in urban area by the urban sewage state prediction model.

Chapter 1 elaborated on the research background, literature review, research objective, the originality of this research, and the overall structure of this thesis. From the perspective of reducing the environmental load and energy saving in the urban area, an estimation methodology for evaluating the sewage heat utilization potential based on the urban sewage state prediction model is proposed in this thesis in order to suggest the optimal plan for utilizing sewage heat. In addition, the evaluation methodology can be applied to urban planning when drawing up the regional energy utilization plan for not only the existed areas but new areas that are still under development.

Chapter 2 build up a theoretical sewage physical model which is close to the realistic situation of sewage pipeline in order to clarify the sewage physical state in pipelines at the step before utilizing the sewage heat utilization system. Specifically specking, the timely variation of sewage physical state including flow rate, temperature, and flow velocity can be simulated through the partially full pipe model which is based on the thermal equilibrium, Manning-Strickler formula, and finite difference method. Moreover, the factors that make the influence on retained heat amount in pipelines are all taken into consideration such as heat loss in the pipeline, the volumetric specific heat of raw wastewater.

Chapter 3 verified the sewage physical model by the measurement data in an actual area in Osaka city to confirm the adequacy of the model; besides, the synopsis of verification area and the provided measurement data have been overviewed to make an overall understanding for readers to comprehend the data which was utilized in the study.

According to the verification results proposed in chapter 3, the sewage physical model is considered as a reasonable model for simulating the sewage physical state including sewage flow rate, temperature and flow velocity. Consequently, the sewage physical conditions are able to be simulated through the sewage physical model proposed in chapter 2 which provides the databases of sewage flow rate and sewage temperature before conducting the simulation of sewage heat utilization.

Chapter 4 build up a sewage heat utilization system model. From the aspect of building heat demand which is the energy demand side to the sewage water of the energy supply side, the connection between energy demand and supply side is all taken into consideration in the sewage heat utilization system model.

According to the sewage heat utilization system model, the pivotal factors of evaluating the regional sewage heat utilization potential can be simulated. For instance, the outlet temperature which makes an influence on the sewage water temperature after utilizing the sewage heat, the sewage heat amount that can be recovered from sewage, and the required heat amount of building side. Moreover, the building energy consumption is calculated at the final step of the simulation based on the required heat amount for heat pump operation which is provided by sewage heat utilization system and backup system if needed.

Chapter 5 applied the urban sewage state prediction model to an actual urban area in order to discuss the variation of sewage temperature and the regional energy saving potential after utilizing the sewage heat. Specifically speaking, by integrating the sewage physical model proposed in chapter 2 and the sewage heat utilization system model proposed in chapter 4, the simulation of regional sewage heat utilization potential is conducted through several scenarios from different perspectives. The setting condition of the cases which are discussed in this chapter is set from a general perspective of approximately comprehend the sewage heat utilization potential in the whole area, and simply discuss the objective result of different setting conditions without considering the optimal strategies.

According to the simulation result, it is known that there is a great potential of sewage heat utilization in the urban area. Besides, reclaiming the sewage heat in the upstream area indeed makes an influence on the effect of recovering heat in the downstream area. However, when recovering the sewage heat, the buildings are discharging waste heat in the meanwhile; thus, the sewage heat temperature does not dramatically decrease immediately. In addition, it is notable that according to the scenario of the relationship between penetration rate and sewage heat utilization potential, it is known that there is still a limitation of maximum utilization rate for achieving greater sewage heat utilization potential, excessively recover the sewage heat may lead to the worse effect and lead to the increase of energy consumption.

Chapter 6 proposed the strategies for the optimal utilization of sewage heat in urban areas through several case studies and eventually proves by an optimal case. Based on the approximately comprehending of sewage heat utilization potential and the factors that may make influences on utilizing sewage heat proposed in chapter 5, the optimal strategies of utilizing sewage heat are discussed from the perspective of a practical view in chapter 6.

Specifically speaking, the sewage heat utilization strategies summarized by the former sections are set as the conditions of an optimal case in order to propose and clarify the district sewage heat utilization potential of the study area. In addition, another case that the setting conditions are contrary to the optimal case is also proposed to compare the sewage heat utilization potential with the optimal case. According to the simulation result of the optimal case and the contrary case, it is known that the sewage heat utilization potential of the optimal case is significantly greater than the contrary case. This result proves that the optimal strategies proposed by the study are reasonable and effective.

7.2 Recommendations for future work

The utilization of sewage heat is a novel issue within the field of the development of renewable energy in the world. However, the features and the utilization potential of sewage heat have not been completely explored so far; therefore, there is still the possibility to draw up the sewage heat utilization plan and strategies in detail to efficiently take advantage of the sewage heat which abundantly exists in urban areas, and eventually reduce the environmental load.

Consequently, this thesis proposed an evaluation methodology to estimate the regional sewage heat utilization potential; furthermore, the optimal strategies for utilizing the sewage heat are proposed as well. However, there are still some issues and limitation that can be improved, including improving the precision of the model and the evolutionary study of sewage heat utilization and regional energy planning.

According to the issues listed in the following article, it is expected to utilize the sewage heat more accurately without extra profligacy.

First of all, the sewage physical model proposed in the study is based on several kinds of statistical data; however, the statistical databases applied in this study are sorted by an hour. According to the urban sewage state prediction model proposed in the study, for the purpose of conducting the simulation that closes to the realistic situation of the fluid features, the value of input data which is provided by the statistical databases are interpolated by second; therefore, it may lead to certain calculation errors during the calculation. In order to accurately estimate the sewage heat utilization potential, if there are the high accuracy input databases for the simulation, it is expected to make the results more precise.

Secondly, the setting condition of the flow-in point of building drainage is under the assumption set by the study, due to the information of the connection between private service lateral and the public sewer system is not provided by the GIS map of sewer ledger. Therefore, the inflow position of building drainage in the model is determined by the study which is set as flowing into the nearest pipelines. In fact, the sewer ledger provides the sewage flow direction of a wide range of the block, so it is regarded that the setting condition proposed by the study is a reasonable assumption that does not far from the actual situation. However, there might still exist certain impact and lead to the calculation errors of retained heat on the pipelines although the eventual simulation of sewage physical state shows acceptable results. Similar to the previous point mentioned above, if there is precise information of the pipeline network which includes the private drainage pipelines, it is expected to conduct an accurate simulation.

Thirdly, as for the development of sewage heat utilization and regional energy planning, the comprehensive evaluation method which including social impacts, such as economic effect, the initial cost, and the construction techniques are expected to be implemented in future studies to complete the evaluation methodology.

Fourthly, the integrated evaluation method which including multiple types of renewable energy such as sewage heat, solar energy is expected to be developed. According to this integrated evaluation method, the overall regional energy plan can be upgraded.

Moreover, regarding the application of the evaluation methodology proposed in this study, it is particularly expected to be applied to the frigid zone. Specifically speaking, the evaluation methodology is proper to be used for the sewage heat utilization type that recovers the heat at its original generated location to lessen the loss of heat within the heat transportation. Especially in the frigid zone, in order to maximum utilize the heat without additional heat loss, it is considered to exploit the heat efficiently through the sewage pipelines to recover the sewage heat directly. As a result, the methodology suggested by the thesis is looking forward to being expanded and applied to especially the frigid zone for drawing up the energy plan.

According to the points mentioned above, if the issue can be improved, it is expected to utilize the sewage heat and other types of renewable energy more accurately without extra profligacy.

Comprehensively, the evaluation methodology proposed by this thesis can be also applied to urban planning for a whole new area at the design phase in order to discuss the spatial distribution of different building types for analyzing the optimal sewage heat utilization potential and furthermore draw up the effective regional energy utilization strategies.

Based on the evaluation methodology of sewage heat utilization potential proposed in this thesis, it is expected to take better advantage of sewage heat in the future and realize the ultimate goal of energy conservation.

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