Heat transport analysis in a district heating system applying waste heat from GTHTR300, a commercial design of high-temperature gas-cooled reactor

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Abstract

A district heating system for household heating and road snow melting utilizing waste heat from Gas Turbine High-Temperature Reactors of 300 MW (GTHTR300s), a high-temperature gas-cooled reactor design, was analyzed. The application area was set in Sapporo and Ishikari, cities with heavy snowfall in northern Japan. The heat transport analyses were performed by modeling heat-transfer components in the system to estimate the system's overall heat supply profile. These components included the pipelines of the secondary water loops between the GTHTR300s and the heat-application area; heat exchangers to transfer the heat from the secondary loops to the tertiary water loops of the district-heating pipes; and the district-heating pipes of the tertiary loops between the heat exchangers and houses and roads. Single- and double-pipes for the secondary loops were compared. Although the double-pipes were advantageous for having less heat loss and a smaller excavation area, these advantages did not compensate for the higher construction cost of the pipes. To satisfy the heat demand of the application area in the month of maximum requirement, 520–529 MW of heat were supplied by 3 GTHTR300s and delivered by 6 secondary loops, 3,450 heat exchangers about 90 m long, and 3,450 tertiary loops. More efficient designs for the heat exchangers and improvements to the tertiary loops applying branched flow networks are desired to reduce the number of heat exchangers and tertiary loops and to make the heat exchangers smaller. Heat lost to the ground from the tertiary loops comprised 80%–90% of the heat loss. Applications of the larger pipe or loops using the branched flow network or double-pipe are required for more efficient heat utilization. More than 90% of the construction cost went into thermal insulators. The thickness and properties of the insulator must be reevaluated for economical heat delivery.

Key words : High-temperature gas-cooled reactor, GTHTR300, Waste heat application, District heating, Heat-transfer modeling

1. Introduction

The Gas Turbine High-Temperature Reactor of 300 MW (GTHTR300) is a high-temperature gas-cooled reactor; this type of nuclear reactor uses helium gas as a coolant (Kamiji et al., 2014) and is under development by Japan Atomic Energy Agency. Waste heat rejection from GTHTR300 is at a higher temperature range, up to 200°C, than the typical 40°C waste heat from conventional light water reactors. The high-quality waste heat is suitable for various applications; for example, desalination requires temperatures of 120°C (Kamiji et al., 2014), and the temperature requirements for household heating and road snow melting are 70°C and 40°C, respectively (Minase and Hirano, 1975).

District heating is a system for delivering heat through hot water or steam to many separate houses or buildings from a few concentrated heat sources. Road snow melting involves heating roads from the outside to prevent and remove snow, keeping traffic safe in heavy snowfall regions. Though the temperature requirement is low, a large

amount of heat is necessary to melt snow over large areas. Waste heat from industry and unutilized environmental heat can be used. Scale merit of heat sources is expected because a large-scale heat source is used instead of using separate heating equipment for each house, building, or road.

Waste heat from a nuclear power plant can be, and is, used for this purpose. District heating using waste heat from two pressurized water reactors in Beznau power plant, Switzerland, has operated since 1985. 154,000 MW_t (subscript _t denotes heat, same hereafter) of heat were delivered to 2,360 users in the winter season of 2004/2005. The farthest area was 16 km away from the plant (Sugiyama et al., 2006). The Augusta plant, a pressurized heavy water reactor in a suburb of Stockholm, Sweden, supplied 55 MW_t of heat to a heat-demand area 3.2 km away (Nakajima et al., 2005). Cities with high population density and heavy snowfall are suitable for nuclear household heating and road snow melting because large amounts of heat are required and the heat delivery area is narrow. Sapporo and Ishikari, constituting an urban area in Hokkaido, the northern island of Japan, are considered as a candidate for such a system. The area requires a large amount of heat because of its cold winter and heavy snowfall. Though district heating using natural gas, woody biomass, and waste heat from garbage combustion is already being applied in Sapporo, the amount (Hoku Netsu Corp., 2015; Ministry of Land, Infrastructure, Transport and Tourism, 2014a; City of Sapporo, 2014a; Sapporo Energy Supply, 2015) is far smaller than the total heat demand of the area. A nuclear district heating system can supply the total heat requirement due to the large scale of nuclear power plants. In addition, electricity is supplied to the cities.

This study examines a combined power generation, household heating, and road snow melting system for Sapporo and Ishikari utilizing waste heat from GTHT300. The availability of the waste heat temperature for the application was confirmed by heat balance in heat transportation analyzed by heat-transfer modeling. The scale of the system is shown by the numbers of process components. Improvement ideas are proposed from the result for more efficient and economical heat usage.

2. Modeling

Figure 1 illustrates a schematic diagram of a nuclear district heating system. The reactor supplies heat to helium in the primary loop of the helium pipe. Electricity is generated in the gas turbine using the heat in the helium. The remaining heat in the helium is transferred to water in the secondary loop of the heat-transfer pipe through the heat exchanger. The secondary loop carries the heat to the distant heat-application area and then to the tertiary water loops through district heat exchangers. The heat in the tertiary loops is delivered first to households, and residual heat is then used to melt road snow in the adjacent areas through the loops of antifreeze solution between the tertiary loops and the road.

Here, a static simulation of the district heating system was performed to design a model. The numbers of units of GTHT300 and heat supply components were determined, and the overall heat supply profile of the system was

Fig. 1 Schematic diagram of a nuclear district heating system.

Fig. 2 Monthly heat demand of Sapporo and Ishikari. JFY denotes Japanese fiscal year which is from April in a year and March in the next year.

estimated through the analysis.

2.1 Heat-application area

The heat and electricity requirements of Sapporo and Ishikari over each month were estimated as follows. The total annual livelihood and snow melting heat requirements are 1,359 Tcal/y and 319 Tcal/y, respectively (Furumichi et al., 1998). The livelihood heat consumption was distributed to each month under the assumption that the monthly heat demand was proportional to the monthly kerosene cost for heating (Hokkaido prefecture, 2011). Similarly, the monthly heat demand for snow melting was assumed to be proportional to the data of electricity consumption for snow melting (City of Sapporo, 2014b). Figure 2 summarizes the heat demand per second in each month. The total heat demand of 434.7 MW_t in January was the largest. Heat demand for livelihood and snow melting were 303.3 MW_t and 131.3 MW_t in this month, respectively. The total electricity demand was the sum of the demands in Sapporo and Ishikari. The former was taken from the literature (City of Sapporo, 2014b); the latter was estimated assuming that the demand was proportional to population (City of Sapporo, 2014c; Ishikari city, 2014). The total demand was estimated to be 1,464.9 MW_e (subscript _e denotes electricity, same hereafter). Table 1 summarizes the heat and electricity demand. Heat and electricity supplied by a GTHTR300 (Kamiji et al., 2014) is also shown.

The location of the GTHTR300 site was determined by considering the following points. Hokkaido prefecture set its urgent protective action planning zone, in which preparation for a nuclear disaster should mainly be done, within a radius of 30 km of a nuclear power plant (Hokkaido prefecture, 2015a). The GTHTR300 site should be placed more than 30 km away from any city to ensure that they are out of this zone. In addition, the site should be set away from the sea to prevent tsunami hazards. The GTHTR300 site was located as indicated in Fig. 3, keeping a distance of at least 30 km from the cities of Sapporo, Ishikari, and Iwamizawa. The distance between the site and the center of Sapporo was about 40 km. The city of Ishikari was considered to be at the same place as Sapporo, even though it is about 13 km away. The influence of the distance between the cities was negligible in the evaluation because heat and electricity demand in Sapporo was far larger than that in Ishikari.

2.2 Heat-transfer pipes

Heat loss and electricity demand for pumps in the secondary loops of the heat-transfer pipes were evaluated. The temperature at the district heat exchangers was also investigated to clarify that there was no significant temperature decrease by heat loss through the transportation of water over a long distance because the district heating demanded a certain level of temperature. The excavation area for burying the pipes was considered as an indicator of the requirement for land. Here, single-pipes and double-pipes were compared as candidates for heat-transfer pipes.

2.2.1 Single-pipe model

Table 1 Demand and supply of heat and electricity.

		Unit		Ref.	Note
Heat	Supply from a GTHTR300	MW _t	220.0	Kamiji et al., 2014	
	Demand for household heating	MW _t	303.3	Furumichi et al., 1998, Hokkaido pref., 2011	1)
	Demand for road snow melting	MW _t	131.3	Furumichi et al., 1998, City of Sapporo, 2014b	2)
Electricity	Supply from a GTHTR300	MW _e	280.0	Kamiji et al., 2014	
	Demand of the heat application area	MW _e	1,464.9	City of Sapporo, 2014b, c Ishikari city, 2014	3)

1) January, 2009

2) January, 2012

3) January, 2012. Electricity demand per person in Ishikari is assumed as the same as in Sapporo.

Fig. 3 Location of the GTHTR300 and the heat-application area. This map is referred from Technocco Image Factory Website, 2016. This map is made from GSI digital map 25000 with permission of Geospatial Information Authority of Japan.

Table 2 Specifications of a heat-transfer pipe (single-pipe).

Parameter	Symbol	Unit	Ref.	Note
Radius of the heat-transfer pipe	$r_{s,1}$	m	0.3223	1)
Thickness of the heat-transfer pipe	$r_{s,2} - r_{s,1}$	m	0.0079	1)
Thickness of the thermal insulator	$r_{s,3} - r_{s,2}$	m	0.2 Imamura, 2009	
Linear flow rate at the outlet of the heat exchanger with the primary loop	$u_{hx,C,out}$	m/s	1	2)
Temperature at the outlet of the heat exchanger with the primary loop	$T_{hx,C,out}$	K	383.15 Kamiji et al., 2014	3)
Temperature at the outlet of the district heat exchanger	$T_{x,H,out}$	K	313.15	4)
Temperature of the ground	T_g	K	275.15 Hamada et al., 1998	5)
Thermal conductivity of the heat-transfer pipe	$k_{s,1}$	W/(m·K)	53 Imamura, 2009	6)
Thermal conductivity of the thermal insulator	$k_{s,2}$	W/(m·K)	0.036 Imamura, 2009	7)
Total length		km	40	8)
Distance between pumps		km	4 Sugiyama et al., 2006	
Unit length	L_s	m	10	9)
Excavation depth		m	1.35 Furumichi et al., 1998	10)
Pump efficiency	η_{pump}	%	100	9)

1) STPG 370 650A, the largest carbon steel pipe for pressurized condition in Japan Industrial Standards (JIS)

2) General flow rate in pipes

3) Assumed as the same as brine temperature receiving heat of the helium primary loop

4) Estimated from the temperature of 15°C for snow melting (City of Sapporo, 2011)

5) Measurement at 1 m underground in Sapporo in January, the month of the lowest temperature

6) Carbon steel

7) 16K in high performance glass wool thermal insulator in JIS A9521

8) Linear distance from the GTHTR300 site and the district heat exchangers

9) Assumption

10) Deeper than freezing depth in Sapporo and Ishikari of 0.6 m (Hokkaido prefecture, 2015b)

Water in a secondary loop receives heat from a helium primary loop. A small portion of the heat was lost through the pipe and the thermal insulator to the ground in both the outward flow and the returning flow. The other portion of the heat was transported into a district heat-exchanger. Table 2 summarizes the specification parameters in a model of the single-pipe.

Figure 4 shows a schematic of a unit length of the single-pipe model. Outward flow from the GTHTR300 site to the heat-application area and returning flow move through different pipes. The heat balance in the single-pipe model was calculated as follows. Heat loss from water to the ground was calculated by Eq. (1) led from a heat-transfer model of a circular pipe. Table 2 and Fig. 4 show symbols with subscript numbers.

$$q_{s,C-g} = \frac{T_{s,in} - T_g}{R_s} = (T_{s,in} - T_g) \times \frac{2\pi L_s}{\frac{1}{\alpha_{s,1} r_{s,1}} + \frac{1}{k_{s,1}} \cdot \ln\left(\frac{r_{s,2}}{r_{s,1}}\right) + \frac{1}{k_{s,2}} \cdot \ln\left(\frac{r_{s,3}}{r_{s,2}}\right)} \quad (1)$$

Equations (2) and (3) were used to determine $\alpha_{s,1}$:

$$\alpha_{s,1} = \frac{Nu_s \cdot k_w}{2r_{s,1}} \quad (2)$$

$$Nu_s = 0.023 \cdot Re_s^{0.8} Pr_s^{0.3} \quad (3)$$

Equation (3), the Dittus-Boelter equation, was applicable under the conditions that $0.7 < Pr_s < 160$, and $10^4 < Re_s$; Re_s and Pr_s , as used in the equation, were determined from their definitions using u_s , μ , ρ , C_p , and k_w . The change of ρ with temperature influenced u_s .

Fig. 4 Heat-transfer pipe (single-pipe).

Table 3 Specifications of a heat-transfer pipe (double-pipe).

Parameter	Symbol	Unit	Ref.	Note
Inner radius of the outer pipe of the outward flow	$r_{d,1}$	m	0.3223	1)
Thickness of the outer pipe of the outward flow	$r_{d,2} - r_{d,1}$	m	0.0079	1)
Thickness of the thermal insulator between the outward and returning flows	$r_{d,3} - r_{d,2}$	m	0.2 Imamura, 2009	
Thickness of the inner pipe of the returning flow	$r_{d,4} - r_{d,3}$	m	0.0079	2)
Inner radius of the outer pipe of the returning flow	$r_{d,5}$	m	0.6272	3)
Thickness of the outer pipe of the returning flow	$r_{d,6} - r_{d,5}$	m	0.0079	2)
Thickness of the thermal insulator between the returning flow and the ground	$r_{d,7} - r_{d,6}$	m	0.2	4)
Linear flow rate at the outlet of the heat exchanger with the primary loop	$u_{hx,C,out}$	m/s	1	5)
Temperature at the outlet of the heat exchanger with the primary loop	$T_{hx,C,out}$	K	383.15 Kamiji et al., 2014	6)
Temperature at the outlet of the district heat exchanger	$T_{x,H,out}$	K	313.15	7)
Temperature of the ground	T_g	K	275.15 Hamada et al., 1998	8)
Thermal conductivity of the heat-transfer pipes; outer pipe of the outward flow, inner pipe of the returning flow, and outer pipe of the returning flow, respectively	$k_{d,1}, k_{d,2}, k_{d,3}$	W/(m·K)	53 Imamura, 2009	9)
Thermal conductivity of the thermal insulator; the insulator between outward and returning flows, the insulator between outward flow and ground, respectively	$k_{d,4}, k_{d,5}$	W/(m·K)	0.036 Imamura, 2009	10)
Total length		km	40	11)
Distance between pumps		km	4 Sugiyama et al., 2006	
Unit length	L_d	m	10	12)
Excavation depth		m	1.35 Furumichi et al., 1998	13)
Pump efficiency	η_{pump}	%	100	12)

1) STPG 370 650A, the largest carbon steel pipe for pressurized condition in Japan Industrial Standards (JIS)

2) Same as the outer pipe of inner stream

3) Determined to set flow rates of the outward flow and returning flow same

4) Same as that of thermal insulator between outward and returning flows

5) General flow rate in pipes

6) Assumed as the same as brine temperature receiving heat of the helium primary loop

7) Estimated from the temperature of 15°C for snow melting (City of Sapporo, 2011)

8) Measurement at 1 m underground in Sapporo in January, the month of the lowest temperature

9) Carbon steel

10) 16K in high performance glass wool thermal insulator in JIS A9521

11) Linear distance from the GTHTR300 site and the district heat exchangers

12) Assumption

13) Deeper than freezing depth in Sapporo and Ishikari of 0.6 m (Hokkaido prefecture, 2015b)

When the $q_{s,C-g}$ was obtained, $T_{s,out}$ was calculated from the heat balance in the unit length. Heat loss from the next unit length was calculated using the $T_{s,out}$ as the next length's $T_{s,in}$. The procedure was repeated all the way from the GTHTR300 site to the district heat exchangers to find $T_{x,H,in}$ at the inlet of these exchangers. The returning flow was similarly investigated from the outlet of the heat exchanger to the GTHTR300 site to find the temperature $T_{hx,C,in}$. The total heat loss from the loop was the sum of the $q_{s,C-g}$ values all throughout the loop.

Pressure loss over a unit length was calculated using Eqs. (4) and (5):

$$\Delta P_s = \lambda_s \cdot \frac{L_s}{D_s} \cdot \frac{\rho u_s^2}{2} \quad (4)$$

$$\lambda_s^{-0.5} = 1.74 - 2.0 \cdot \log_{10} \left(\frac{2k_w}{D_s} \right) \quad (5)$$

Equation (4) is called the Darcy-Weisbach equation. Equation (5) is the Kaman-Nikuradse equation for a turbulence stream with a rough surface. This equation is applicable for Re_s values of over 4,000. The value of D_s is equal to $2r_{s,1}$. The pressure loss calculation was

Fig. 5 Excavation widths of pipes and a heat exchanger.

repeated all throughout the loop. Equation (6) was used to obtain $\Sigma w_{s,pump}$ to compensate for the total pressure loss:

$$\sum w_{s,pump} = \frac{\pi r_{s,1}^2 \sum_{loop} (\Delta P_s u_s)}{\eta_{pump}} \quad (6)$$

The excavation area was defined as the product of $L_{s,excav.}$, as shown in Fig. 5 (Furumichi et al., 1998), and the distance between the GTHTR300 site and the district heat exchangers. A pair consisting of an outward flow pipe and a returning flow pipe was considered as a unit.

2.2.2 Double-pipe model

Water in a second loop receives heat from a helium primary loop. Heat loss from the outward flow is recovered in the returning flow. Heat loss to the ground is only from the returning flow. The remaining heat is transported into a district heat exchanger. Table 3 summarizes specification parameters for the evaluation of the double-pipe model.

Figure 6 shows the schematic of a unit length of the double-pipe model. The outward flow is in the inner pipe, and the returning flow is in the annular channel between the two pipes. The heat balance in the double-pipe model was designed as follows: equation (7) was applied to calculate $q_{d,H-C}$; similarly, $q_{d,C-g}$ was calculated as in Eq. (8):

$$q_{d,H-C} = \frac{T_{d,H,in} - T_{d,C,out}}{R_{d,H-C}} = (T_{d,H,in} - T_{d,C,out}) \times \frac{2\pi L_d}{\frac{1}{r_{d,1}\alpha_{d,1}} + \frac{1}{k_{d,1}} \cdot \ln\left(\frac{r_{d,2}}{r_{d,1}}\right) + \frac{1}{k_{d,4}} \cdot \ln\left(\frac{r_{d,3}}{r_{d,2}}\right) + \frac{1}{k_{d,2}} \cdot \ln\left(\frac{r_{d,4}}{r_{d,3}}\right) + \frac{1}{r_{d,4}\alpha_{d,2}}} \quad (7)$$

$$q_{d,C-g} = \frac{T_{d,C,out} - T_g}{R_{d,C-g}} = (T_{d,C,out} - T_g) \times \frac{2\pi L_d}{\frac{1}{r_{d,5}\alpha_{d,3}} + \frac{1}{k_{d,3}} \cdot \ln\left(\frac{r_{d,6}}{r_{d,5}}\right) + \frac{1}{k_{d,5}} \cdot \ln\left(\frac{r_{d,7}}{r_{d,6}}\right)} \quad (8)$$

Heat-transfer coefficients $\alpha_{d,1}$ and $\alpha_{d,3}$ were calculated by the same method in the modeling of the single-pipe. Meanwhile, $\alpha_{d,2}$ was obtained by Eqs. (9)–(11), assuming heat transfer to an annular pipe with no heat transfer to the outer pipe of the returning flow (Japan Society of Mechanical Engineers, 1993):

$$\alpha_{d,2} = \frac{Nu_{d,C} \cdot k_{d,w,C}}{D_{d,C}} \quad (9)$$

$$Nu_{d,C} = 0.019 \cdot \left(\frac{r_{d,4}}{r_{d,5}}\right)^{-0.16} \cdot Re_{d,C}^{0.8} \cdot Pr_{d,C}^{0.5} \quad (10)$$

$$D_{d,C} = \frac{4 \cdot (\pi r_{d,5}^2 - \pi r_{d,4}^2)}{2\pi r_{d,4}} = \frac{2(r_{d,5}^2 - r_{d,4}^2)}{r_{d,4}} \quad (11)$$

Equation (10) is called the Dalle-Donne equation and can be used under the condition of $0.5 < Pr_{d,C} < 1.0$. Just as in the case of the single-pipe model, $Re_{d,C}$ and $Pr_{d,C}$, as used in the equation, were determined from their definitions using $u_{d,C}$, $\mu_{d,C}$, $\rho_{d,C}$, $C_{p,d,C}$, and $k_{d,w,C}$; $u_{d,C}$ depended upon a change in $\rho_{d,C}$ by temperature.

Temperatures of $T_{d,H,out}$ and $T_{d,C,in}$ in Fig. 6 were clarified by the heat balance calculated by $q_{d,H-C}$ and $q_{d,C-g}$. Heat balance in the next unit length was calculated using these temperatures as $T_{d,H,in}$ and $T_{d,C,out}$. The calculation was repeated to obtain the temperature profile and heat balance from the GTHTR300 to the district heat exchanger. The temperatures $T_{hx,C,in}$ and $T_{x,H,in}$ were obtained as a result of the analysis. The total heat loss

Fig. 6 Heat-transfer pipe (double-pipe).

Table 4 Specifications of a district heat exchanger (common in single- and double-pipe cases).

	Parameter	Symbol	Unit	Ref.	Note
Size	Inner radius of the outer pipe of the inner flow	$r_{x,1}$	m	0.0136	1)
	Outer radius of the outer pipe of the inner flow	$r_{x,2}$	m	0.0170	1)
	Inner radius of the outer pipe of the outer flow	$r_{x,3}$	m	0.0206	2)
	Outer radius of the outer pipe of the outer flow	$r_{x,4}$	m	0.0243	2)
	Outer radius of the thermal insulator	$r_{x,5}$	m	0.2243 Imamura, 2009	
Thermal conductivity	Thermal conductivity of the heat-transfer pipes; outer pipe of the inner flow, and outer pipe of the outer flow, respectively	$k_{x,1}, k_{x,3}$	W/(m·K)	53 Imamura, 2009	3)
	Thermal conductivity of the thermal insulator	$k_{x,4}$	W/(m·K)	0.036 Imamura, 2009	4)
Others	Temperature of the ground	T_g	K	275.15 Hamada et al., 1998	5)
	Excavation depth		m	1.35 Furumichi et al., 1998	6)

1) STPG 370 25A Sch40, a carbon steel pipe for pressurized condition in Japan Industrial Standards (JIS)

2) STPG 370 40A Sch40, a carbon steel pipe for pressurized condition in Japan Industrial Standards (JIS)

3) Carbon steel

4) 16K in high performance glass wool thermal insulator in JIS A9521

5) Measurement at 1 m underground in Sapporo in January, the month of the lowest temperature.

6) Same as excavation depth of a heat-transfer pipe. This is deeper than freezing depth in Sapporo and Ishikari of 0.6 m (Hokkaido prefecture, 2015b).

from the loop was the sum of the $q_{d,C-g}$ values from only the returning flow.

The pressure loss of the outward flow was calculated by the same method as in the single-pipe model. The loss of the returning flow was calculated using $D_{d,C}$ as defined by Eq. (12), instead of $2r_l$ in the single-pipe model:

$$D_{d,C} = 4 \times \frac{\pi \cdot (r_{d,5}^2 - r_{d,4}^2)}{2\pi \cdot (r_{d,4} + r_{d,5})} = 2 \cdot (r_{d,5} - r_{d,4}) \quad (12)$$

The total electricity demand in the pumps for the outward flow was obtained in the same manner as for the single-pipe model. The electricity demand for the returning flow was calculated by Eq. (13):

$$w_{d,C,pump} = \frac{\pi(r_{d,5}^2 - r_{d,4}^2) \cdot \sum_{return} (\Delta P_{d,C} u_{d,C})}{\eta_{pump}} \quad (13)$$

The excavation area for burying the heat-transfer pipes was given by the product of $L_{d,excav.}$ and the distance between the GTHT300 site and the district heat exchangers. Figure 5 defines $L_{d,excav.}$ (Furumichi et al., 1998). A double-pipe was a unit in the model.

2.3 District heat exchanger between a heat-transfer pipe and a district-heating pipe

Figure 7 illustrates the district heat-exchanger model. A double tube-type counter-current heat exchanger was used for simplification of the model. One heat-transfer pipe connects many district-heating pipes by the same number of district heat exchangers. The water in the heat-transfer pipe was split uniformly between the heat exchangers, and heat was transferred from each of the split flows to water in a district-heating pipe. The heat-exchanger model was common for the single-pipe case and the double-pipe case in section 2.2. The water on the heat-transfer pipe side lost $q_{x,H-C}$ heat; within the heat, $q_{x,H-C} - q_{x,C-g}$ was received in the water in the district-heating pipe, and $q_{x,C-g}$ was lost to the ground. It should be noted that the q in this section is the heat per district heat exchanger or per district-heating pipe; the q value in section 2.2 is measured for each heat-transfer pipe. Table 4 summarizes the specification parameters of the heat exchanger.

The calculation method for the heat exchange was similar to that of the double-pipe model of the heat-transfer pipe. A layer of pipe, a thermal insulator, and another pipe was placed between the

Fig. 7 District heat exchanger.

outward flow and returning flow in the double-pipe model; here, in the heat-exchanger model, only a pipe was placed between the inner and outer flows to enhance heat transfer. Equation (14) was used to determine $q_{x,H-C}$:

$$q_{x,H-C} = \frac{\Delta T_{x,H-C}}{R_{x,H-C}} = \Delta T_{x,H-C} \times \frac{2\pi L_x}{\frac{1}{r_{x,1}\alpha_{x,1}} + \frac{1}{k_{x,1}} \cdot \ln\left(\frac{r_{x,2}}{r_{x,1}}\right) + \frac{1}{r_{x,2}\alpha_{x,2}}} \quad (14)$$

The symbol $\Delta T_{x,H-C}$ denotes the logarithmic mean temperature-difference between water on the heat-transfer pipe side and on the district-heating pipe side. Similarly, $q_{x,C-g}$ was obtained by Eq. (15):

$$q_{x,C-g} = \frac{\Delta T_{x,C-g}}{R_{x,C-g}} = \Delta T_{x,C-g} \times \frac{2\pi L_x}{\frac{1}{r_{x,3}\alpha_{x,3}} + \frac{1}{k_{x,3}} \cdot \ln\left(\frac{r_{x,4}}{r_{x,3}}\right) + \frac{1}{k_{x,4}} \cdot \ln\left(\frac{r_{x,5}}{r_{x,4}}\right)} \quad (15)$$

where $\Delta T_{x,C-g}$ denotes the logarithmic mean temperature difference between the water on the district-heating pipe side and the ground.

The heat-transfer coefficients $\alpha_{x,1}$, $\alpha_{x,2}$, and $\alpha_{x,3}$ were obtained by the same method as for the double-pipe model of the heat-transfer pipes.

The operational conditions of $T_{x,C,out}$ were estimated by modeling to maintain the temperature difference between the heat exchanger and the heat balance at a constant value in a district-heating pipe. The values of $T_{x,C,in}$ and $u_{x,C}$ were calculated in the district-heating pipe model shown in section 2.4.

In addition, L_x was chosen to match $q_{x,H-C}$ calculated in Eq. (14) with $q_{x,H-C}$ calculated by Eq. (16):

$$q_{x,H-C} = \pi r_{x,1}^2 u_{x,H} \rho_H \int_{T_{x,H,in}}^{T_{x,H,out}} C_p dT \quad (16)$$

The former was obtained by the heat-transfer calculation; the latter was the enthalpy difference between the inlet and outlet of heat-transfer pipe side.

Pressure loss in the heat exchanger was negligible because L_x was short compared with the heat-transfer pipes and district-heating pipes. The excavation area was estimated as the product of L_x and $L_{x,excav.}$, which were obtained just as for the values of double heat-transfer pipes, as shown in Fig. 5.

2.4 District-heating pipes

Figure 8 illustrates a unit length of the district-heating pipe model. A single-pipe model was applied for the tertiary loop, with the aim of simple and inexpensive heat delivery. The model of the district-heating pipe was the same in both the single-pipe case and the double-pipe case. The water in the pipe received heat in the district heat exchanger; some part of the heat was lost during transportation to houses and roads ($q_{a,C-g}$). Some of the remaining heat was used for household heating (q_{house}). The rest was utilized to melt road snow through a small loop of antifreezing liquid (q_{snow}). Table 5 summarizes the specification parameters in the pipes.

Equations (1)–(3) were used to estimate $q_{a,C-g}$ just as for the single pipe model of a heat-transfer pipe. The procedure was repeated all throughout the loop to estimate the temperature profile including $T_{house,H,in}$ and $T_{x,C,in}$ and the total heat loss, just as in section 2.2. The q in this section was the heat per district-heating pipe. The linear flow velocity, u_a , depended on the change of ρ_a as a function of temperature.

The outlet temperate of household heating ($T_{house,H,out}$) was determined to match the heat ratio of q_{house} to q_{snow} supplied from the model estimation with their heat demand ratio over the whole heat-application area in Table 1 ($303.3/131.3 = 2.309$).

Electricity consumption for pumps to circulate water was calculated using Eqs. (4)–(6), just as in the single-pipe model. The excavation area for burying the pipes was calculated just as in the single-pipe case.

2.5 Heat balance of the total district heating system and the number of heat-delivery components

Table 5 Specifications of a district-heating pipe (common in single-pipe and double-pipe cases).

Parameter	Symbol	Unit	Ref.	Note
Radius of the district-heating pipe	$r_{a,1}$	m	0.0206	1)
Thickness of the district-heating pipe	$r_{a,2} - r_{a,1}$	m	0.0037	1)
Thickness of the thermal insulator	$r_{a,3} - r_{a,2}$	m	0.2 Imamura, 2009	
Temperature of the ground	T_g	K	278.15 Hamada et al., 1998	2)
Thermal conductivity of the district-heating pipe	$k_{a,1}$	W/(m·K)	53 Imamura, 2009	3)
Thermal conductivity of the thermal insulator	$k_{a,2}$	W/(m·K)	0.036 Imamura, 2009	4)
Total length		km	2 Furumichi et al., 1998	5)
Unit length	L_a	m	10	6)
Excavation depth		m	3	7)
Pump efficiency	η_{pump}	%	100	6)

1) STPG 370 40A Sch40, a carbon steel pipe for pressurized condition in Japan Industrial Standards (JIS)

2) Measurement at 3 m underground in Sapporo in April, the month of the lowest temperature.

3) Carbon steel

4) 16K in high performance glass wool thermal insulator in JIS A9521

5) Range of district heating from a heat source

6) Assumption

7) Deeper than freezing depth in Sapporo and Ishikari of 0.6 m (Hokkaido prefecture, 2015b)

The depth was larger than heat-transfer pipes because the lower temperature water in the pipes was easier to be frozen.

The numbers of the GTHTR300s, heat-transfer pipes, district-heating pipes, district heat exchangers, and pumps were determined by the heat balance in the total system and the heat demand of the application area. The amounts of heat transfer and heat loss in the total system (Q) were determined to supply the heat demand in the application area. The heat balances in each pipe and heat exchanger (q) were multiplied to make consistent heat balance all throughout the system.

The number of loops and heat exchangers was estimated by comparing corresponding values of q and Q . The number of pumps was determined from the number of loops and the distance between pumps. Tables 2 and 3 show the distance for heat-transfer pipes: one pump was applied for a district-heating pipe due to the short distance between the heat exchangers and houses and roads.

2.6 Construction cost of the heat-delivery system

The cost of constructing the system was roughly estimated to compare the single- and double-pipe cases in terms of economics. The costs of pipelines, thermal insulators, heat exchangers, pumps, water in the pipes, and labor to bury the pipes were considered. GTHTR300s, heat exchangers from the helium pipe to the heat-transfer pipe and from the district-heating pipes to the antifreezing liquid loops, the antifreezing loops themselves, and the road snow-melting components were not investigated.

The unit prices of the pipelines, thermal insulators, heat exchangers, and pumps were estimated from data concerning chemical plants in the literature (Saito, 2000). The unit price of a double-pipe was assumed to be the sum of the prices of the inner and outer pipes, not considering the cost of integration of these pipes. The number of components estimated in section 2.5 was applied to this computation. The unit price of the water was taken to be that of industrial water in the area of Ishikari Bay New Port, near Ishikari (Hokkaido prefecture, 2015c). The price of labor for burial of the pipeline per excavation unit volume was taken from standard price data for civil engineering work (Ministry of Land, Infrastructure, Transport and Tourism, 2014b). The required amount of water was determined as the inner volume of the pipes. The excavation volumes calculated in sections 2.2, 2.3, and 2.4 were used in this estimation.

3. Results

The results of the heat-transfer analysis are shown in this

Fig. 8 District-heating pipe.

chapter. Tables 6–8 summarize heat-transfer and heat-exchange properties. Tables 9 and 10 show the overall heat supply profile and electricity consumption, respectively, while Table 11 describes the number of heat-transfer components in the district heating system with heating properties to estimate the numbers. Table 12 shows excavation width and excavation area in the system. Table 13 summarizes the cost-estimation of the system. Details of the results are discussed as follows.

3.1. Comparison of types of heat-transfer pipes

Table 6 summarizes the temperatures at representative points and the change of temperatures in the heat-transfer pipes. The flow temperature changed linearly with the distance from the GTHTR300 site in both cases. The ratios of the temperature change to the distance were on the order of 10^{-2} K/km. The temperature decrease at the district heat exchanger 40 km away from the GTHTR300 site was 1.02 and 1.57 K in the single- and double-pipe cases, respectively, because of the small ratio. The large size of the pipe and the thick thermal insulator prevented heat loss and maintained the temperature of the water. Waste heat from GTHTR300s was applicable to district heating 40 km away from the nuclear site. The temperature decrease was smaller in the double-pipe model due to smaller heat loss, as shown in Table 6. Recovery of the heat loss from the outward flow by the returning flow contributed to a smaller heat loss to the ground in the double-pipe case.

As shown in Table 6, $\Sigma\Delta P$ in the double-pipe model was 2.8 times that in the single-pipe model. Flow resistance in

Table 6 Heat-transfer properties in a heat-transfer pipe.

Parameter	Symbol	Unit	Single-pipe case	Double-pipe case	Note
Inlet temperature of the heat exchanger with the primary loop	$T_{hx,C,in}$	K	312.59	313.20	1)
Outlet temperature of the heat exchanger with the primary loop	$T_{hx,C,out}$	K	383.15	383.15	3)
Inlet temperature of the district heat exchanger	$T_{x,H,in}$	K	381.58	382.13	1)
Outlet temperature of the district heat exchanger	$T_{x,H,out}$	K	313.15	313.15	2)
Temperature decrease ratio of outward flow per unit distance from GTHTR300		K/km	3.9×10^{-2}	2.5×10^{-2}	1)
Temperature decrease of the returning flow per unit distance from the district heat exchanger		K/km	1.4×10^{-2}	-1.4×10^{-3}	1, 4)
Total pressure loss all through the secondary loop	$\Sigma\Delta P_s, \Sigma\Delta P_d$	MPa	0.58	1.59	1)

1) Result of the calculation of the heat-transfer pipe

2) Estimated from the temperature of 15°C for snow melting (City of Sapporo, 2011)

3) Assumed as the same as brine temperature receiving heat of the helium primary loop (Kamiji et al., 2014)

4) Minus value means flow temperature increases as the water flowed toward GTHTR300.

Table 7 Heat exchange properties in a district heat exchanger.

	Parameter	Symbol	Unit	Single-pipe case	Double-pipe case	Note
Inner flow (heat transfer pipe side)	Inlet temperature	$T_{x,H,in}$	K	381.58	382.13	1)
	Outlet temperate	$T_{x,H,out}$	K	313.15	313.15	2)
	Linear flow rate	$u_{x,H}$	m/s	0.976	0.977	3)
Outer flow (district heating pipe side)	Inlet temperature	$T_{x,C,in}$	K	300.92	300.92	4)
	Outlet temperature	$T_{x,C,out}$	K	371.58	372.13	5)
	Linear flow rate	$u_{x,C}$	m/s	0.408	0.408	4)
Size	Length of the heat exchanger	L_x	m	91.0	91.6	6)

1) Result of the calculation of the heat-transfer pipe

2) Estimated from the temperature of 15°C for snow melting (City of Sapporo, 2011)

3) Average of flow rate at the inlet and outlet of the heat exchanger of the result of calculation of the heat-transfer pipe

4) Result of the calculation of the district-heating pipe

5) 10 K lower than the inlet temperature of the water in the heat-transfer pipe at the heat exchanger, $T_{x,H,in}$

6) Calculated from area for heat transfer from a heat-transfer pipe to a district-heating pipe

Table 8 Heat-transfer properties in a district-heating pipe.

Parameter		Symbol	Unit	Single-pipe case	Double-pipe case	Note
District heat exchanger	Inlet temperature	$T_{x,C,in}$	K	300.93	300.93	1)
	Outlet temperate	$T_{x,C,out}$	K	371.58	372.13	2)
Heat application area	Inlet temperature of household heating	$T_{house,H,in}$	K	363.31	363.82	1)
	Outlet temperate of household heating	$T_{house,H,out}$	K	321.33	321.48	3)
	Outlet temperate of snow melting	$T_{snow,H,out}$	K	303.15	303.15	4)
	Total pressure loss all through the tertiary loop	$\Sigma\Delta P_a$	MPa	0.13	0.13	1)

1) Result of the calculation of the district-heating pipe

2) 10 K lower than the inlet temperature of the water in the heat-transfer pipe at the district heat exchanger, $T_{x,H,in}$

3) The temperature to fit the ratio of heat for household (q_{house}) and the one for snow melting (q_{snow}) from the pipe to the ratio of heat demand of the district

4) Estimated from the temperature of 15°C for snow melting (City of Sapporo, 2011)

the returning pipe in the double-pipe model was large because of flow resistance on the inner and outer pipe surfaces and the small annular channel width. As a result, $\Sigma W_{d,pump}$ was 2.7 times $\Sigma W_{s,pump}$, as shown in Table 10.

As shown in Table 12, $L_{d,excav.}$ was smaller than $L_{s,excav.}$ for one loop. Though the outermost radius of the double-pipe was larger than that of the single-pipe, only one pipe was required for one loop by integrating the outward flow and the returning flow in a pipe. As a result, the excavation area in the double-pipe case was 0.77 times that in the single-pipe case.

Table 9 Overall heat demand and supply in the nuclear district heating system.

		Symbol	Unit	Single-pipe case	Double-pipe case	Note
Heat-transfer pipe	Heat transfer from the GTHTR300	$Q_{x,H-C} + \Sigma Q_{s,C-g}, Q_{x,H-C} + \Sigma Q_{d,C-g}$	MW _t	528.9	519.8	
	Heat transfer to the district heat exchanger	$Q_{x,H-C}$	MW _t	512.9	512.6	
	Heat loss to the ground	$\Sigma Q_{s,C-g}, \Sigma Q_{d,C-g}$	MW _t	16.0	7.2	
District heat exchanger	Heat from the heat-transfer pipe	$Q_{x,H-C}$	MW _t	512.9	512.6	
	Heat to the district-heating pipe	$Q_{x,H-C} - Q_{x,C-g}$	MW _t	511.2	510.9	
	Heat loss to the ground	$Q_{x,C-g}$	MW _t	1.6	1.7	
District-heating pipe	Heat from the heat-transfer pipe	$Q_{x,H-C} - Q_{x,C-g}$	MW _t	511.2	510.9	
	Heat used for household heating	Q_{house}	MW _t	303.3	303.3	
	Heat used for road snow melting	Q_{snow}	MW _t	131.4	131.4	
	Heat loss to the ground	$\Sigma Q_{a,C-g}$	MW _t	76.6	76.3	
Total heat demand		$Q_{house} + Q_{snow}$	MW _t	434.7	434.7	1)
Heat utilization ratio of the heat from GTHTR300			%	82.2	83.6	

1) January, 2009 for household heating, January, 2012 for snow melting

Table 10 Overall electricity demand and supply in the nuclear district heating system.

	Symbol	Unit	Single-pipe case	Double-pipe case	Note
Electricity generation in the GTHTR300s		MW _e	840.0	840.0	
Supply for use in the district		MW _e	838.7	836.9	
Consumption for the pumps in the heat-transfer pipes	$\Sigma W_{s,pump}, \Sigma W_{d,pump}$	MW _e	1.07	2.87	
Consumption for the pumps in the district-heating pipes	$\Sigma W_{a,pump}$	MW _e	0.23	0.23	
Electricity demand		MW _e	1,464.9	1,464.9	1)
Coverage ratio to the electricity demand		%	57.3	57.1	

1) January, 2012. Electricity demand per person in Ishikari is assumed as the same as in Sapporo.

3.2 District heat exchanger

Table 7 summarizes the properties of the district heat exchanger. The temperature profile is similar in both cases. The $u_{x,C}$ of 0.408 m/s was acceptable for a common heat exchanger; the L_x of around 90 m was large in both cases. Reduction of L_x is desired through enhancement of heat transfer by, for example, using fins.

As shown in Table 9, heat loss was negligible compared with the transferred heat; the thickness of the thermal insulator at the outermost layer was sufficient. Both heat loss and excavation area were similar between the single- and double-pipe cases.

3.3 District-heating pipes and heat-application area

As shown in Table 8, a temperature range of 48–90°C was applied to household heating and 30–48°C was utilized in road snow melting in both the cases. In fact, the heat for snow melting was transferred to antifreezing liquid loops and the temperature was reduced by, for example, 10°C due to heat transfer. The $T_{house,H,out}$ was similar to 50°C in the literature (Minase and Hirano, 1975). The distribution of heat to household heating and road snow melting in this study was reasonable.

Table 9 shows that heat loss to the ground accounted for 15% of the heat from the heat-transfer pipe. The reason for the high heat loss ratio was that the total contact area between the pipes and the ground was large due to the small radius and large number of pipes. Though increasing the thickness of a thermal insulator is effective for decreasing the heat loss, such a thicker thermal insulator would increase the construction cost greatly because the ratio of the thermal insulator in the construction cost was large, as shown in Table 13. Many narrow pipes from a district heat exchanger to houses and roads were assumed in this model aiming at simple heat delivery. The heat-delivery system should be

Table 11 Number of heat-transfer components in the nuclear district heating system.

		Unit	Single-pipe case	Double-pipe case	Note
Heat	Supplied from a GTHTR300	MW _t	220.0	220.0	1)
	Received in a heat-transfer pipe	MW _t	88.5	89.2	2)
	Transferred to district heat exchangers from a heat-transfer pipe	MW _t	88.2	89.0	2)
	Received in a district-heating pipe	MW _t	0.154	0.155	2)
Number	Loops of district-heating pipes per heat-transfer pipe		575	575	3)
	GTHTR300s		3	3	4)
	Loops of heat-transfer pipes		6	6	5)
	Loops of district-heat exchangers		3,450	3,450	6)
	Loops of district-heating pipes		3,450	3,450	7)
	Pumps in heat-transfer pipes		120	120	
	Pumps in district-heating pipes		3,450	3,450	

1) Referred from Kamiji et al., 2014

2) Result of this study

3) Ratio of heat to the district-heating pipes from a heat-transfer pipe to heat received in a district-heating pipe rounded up from zero.

4) Ratio of $(Q_{x,H-C} + \Sigma Q_{C-g})$ in Table 9 to heat supply from a GTHTR300 rounded up from zero5) Ratio of $Q_{x,H-C}$ in Table 9 to heat received in a heat-transfer pipe rounded up from zero

6) Product of the number of the heat-transfer pipes and the number of district-heating pipes per heat-transfer pipe

7) Same number of the district heat exchangers

rearranged to reduce the large heat loss, even if the system becomes a little complicated. A branched network of district-heating pipes is an idea. In the pipeline, the number of district-heating pipes at a district heat exchanger is small. Instead, the radius of the pipes is large. One pipe is split into several pipes of narrow radius on the way to servicing houses and roads. The heat-delivery system is expected to reduce the heat loss by reducing the contact area with the ground. As an alternative, double-pipes to recover heat loss from outward flow to the houses and roads are also effective at reducing heat loss.

Table 8 shows that the properties of the district-heating pipes were very similar between the single- and double-pipe cases. The pressure decrease all through the loop was almost the same in both cases. As shown in Table 10, electricity consumption by the pumps was almost the same as a result. Table 12 shows that the excavation area of a district-heating pipe loop was the same in both cases.

3.4 Total nuclear district-heating system

Tables 9 and 10 summarize the overall heat and electricity supply profiles, respectively, of the total nuclear district-heating systems determined to be necessary to supply heat demands to the application area. The heat-utilization ratio was defined as the ratio of the total heat demand to the heat transferred from GTHTR300. The ratios in the single- and double-pipe cases were 82.2% and 83.6%, respectively. Heat recovery from the outward flow to the returning flow in the double-pipe configuration contributed to the higher heat-utilization ratio. The total electricity consumptions in the single- and double-pipe cases were 1.30 MW_e and 3.10 MW_e, respectively. Flow resistance in the returning annular channel in the heat-transfer pipes caused larger electricity consumption in the double-pipe case. As shown in the next paragraph, 3 GTHTR300s were used in the

Table 12 Excavation width and excavation area.

		Symbol	Unit	Single-pipe case	Double-pipe case	Note
Excavation width	Heat-transfer pipes	$L_{s,excav.}$	m	3.3208	2.5703	
		$L_{d,excav.}$				
	District heat exchangers	$L_{x,excav.}$	m	1.3486	1.3486	
	District-heating pipes	$L_{a,excav.}$	m	2.0972	2.0972	
Excavation area	Heat-transfer pipes		km ²	0.80	0.62	1)
	District heat exchangers		km ²	0.42	0.42	1)
	District-heating pipes		km ²	14.47	14.47	1)
	Total		km ²	15.69	15.51	

1) Number of heat-transfer pipes and district-heating pipes are round up from zero.

system. Considering the electricity consumption for the pumps, 57.3% and 57.1% of the electricity demand in the area was covered by the GTHTR300s.

Table 11 shows the number of GTHTR300s and heat-transfer components in the system. The small difference between the heat transportation profiles of the two cases had no effect on the component number. The numbers of GTHTR300s and heat-transfer pipes were reasonable. On the other hand, optimization of the

number of district heat exchangers and district-heating pipes is required through means such as increasing the radii of these components. This modification would be advantageous for reducing heat loss from district-heating pipes. In both the cases, 120 pumps were used in the heat-transfer pipes, and 3,450 pumps were applied to the district-heating pipes. Many pumps were required for district-heating pipes due to their large number. Smaller numbers of pipes are desirable to reduce the number of pumps.

Table 12 shows the excavation area for burying pipes and heat exchangers over the total system. The total excavation area for the double-pipe case was smaller by 1.1% than that for the single-pipe case, only because the excavation area of the heat-transfer pipes was smaller. More than 90% of the excavation area was that of district-heating pipes. Improvement of the heat-delivery system in the heat-application area, for example, using branched network pipes or double-pipes as suggested in section 3.3, is required to reduce the excavation area for the district-heating pipe.

Table 13 summarizes the construction cost of the total heat-delivery system. The total construction cost in the double-pipe case was 6.7% higher than that in the single-pipe case. The heat-utilization ratio in the double-pipe case was 1.7% higher, which was smaller than the difference in the total construction cost. The single-pipe case was advantageous because the increase in the heat-utilization ratio by the application of double-pipe was smaller than the increase of the construction cost. The costs of the pipelines and thermal insulators were higher in the double-pipe case because larger pipes were used for heat transfer. The thermal insulators occupied over 90% of the cost in both cases. The thickness and properties of the insulators must be re-evaluated to reduce the cost. The trade-off between construction cost and heat loss should be considered in future investigations.

4. Conclusions

A nuclear district heating system for household heating and road snow melting by application of waste heat from GTHTR300 high-temperature gas-cooled reactors was analyzed by heat-transfer modeling. Sapporo and Ishikari were assumed to constitute the heat-application area, and the GTHTR300s were set about 40 km away from the district to avoid nuclear disaster.

The components of the system included a secondary loop of heat-transfer pipes to transport heated water from the GTHTR300 site to the district heat exchangers in the heat-application area, a district heat exchanger to transfer the heat in the heat-transfer pipe into district-heating pipes, and a tertiary loop of district-heating pipes to transport water from the district heat-exchanger to houses and roads. Heat transportation in and between these components was modeled. Single- and double-pipe models for the secondary loop were evaluated.

The waste heat from the GTHTR300 was available for household heating and snow melting 40 km away from the nuclear power plant in both the cases, due to small heat loss from the large diameter of the heat-transfer pipes and thick thermal insulators around them.

The double-pipe system was more advantageous than the single-pipe system, in that it had a smaller heat loss due to heat recovery in the pipes. The heat-utilization ratios from the GTHTR300 were 82.2% and 83.6% in the single- and double-pipe cases, respectively. However, this advantage did not compensate for the disadvantage of the double-pipe case in terms of construction cost due to the larger scale of the pipes and thermal insulators. The total construction cost

Table 13 Construction cost of the nuclear heat-delivery system.

	Unit	Single-pipe case	Double-pipe case	(Double-pipe case) / (Single-pipe case)
Pipelines	10 ⁸ JPY	189.9	305.3	1.608
Thermal insulators	10 ⁸ JPY	4,429.6	4,633.7	1.046
Heat exchangers	10 ⁸ JPY	18.3	18.4	1.002
Pumps	10 ⁸ JPY	6.6	6.7	1.019
Water	10 ⁸ JPY	0.1	0.1	1.000
Labor	10 ⁸ JPY	145.1	144.5	0.996
Total construction cost	10 ⁸ JPY	4,789.6	5,108.6	1.067
Heat utilization ratio of the heat from GTHTR300	%	82.2	83.6	1.017

JPY denotes Japanese yen.

was higher by 6.7% in the double-pipe case. This difference was larger than the relative advantage of 1.7% in heat-utilization ratio. A single-pipe was more advantageous under the present sizes of pipes and thermal insulators.

To supply heat in January, the month of maximum demand, 3 GTHTR300s were needed. The district heating systems had 6 loops of heat-transfer pipes and 3,450 district heat exchangers and district-heating pipes. The number of pumps was 120 for the heat-transfer pipes and 3,450 for the district-heating pipes. All component numbers were the same in both the single-pipe case and the double-pipe case. The length of the heat exchangers was about 90 m. The number and length of the heat exchangers must be reduced by applying more efficient ones such as fin-type heat exchangers. Improvement of the district-heating pipe system, for example through the application of branched network pipes, is also needed to reduce the number of pipes and pumps.

Across the system, 80%–90% of the heat loss to the ground occurred in the district-heating pipes. The large contact areas with the ground for many of the narrow pipes caused heat loss. Increasing the radius of the pipes or improving the district-heating pipes, for example through branched network pipes or double-pipes, is required to increase the heat-utilization ratio. More than 90% of the construction cost went into thermal insulation. The thickness and properties of the insulator must be re-evaluated to consider the trade-off between cost and heat loss for economical heat delivery. The modification of the district-heating pipes would enable more economical heat delivery through smaller heat loss and lower construction costs.

Nomenclature

C_p :	Heat capacity of water at constant pressure, $J/(kg \cdot K)$
D :	Characteristic length, m
k :	Thermal conductivity, $W/(m \cdot K)$
L :	Unit length of heat-transfer pipe, district-heating pipe, or length of heat exchanger, m
Nu :	Nusselt number, dimensionless
q :	Heat transfer per unit time in a heat-transfer pipe, district heat exchanger or district-heating pipe, W_t
Q :	Heat transfer per unit time for total heat demand in the heat-application area, W_t
Pr :	Prandtl number, dimensionless
r :	Radius, m
R :	Thermal resistance, K/W_t
Re :	Reynolds number, dimensionless
T :	Temperature, K
u :	Linear flow velocity of water, m/s
w :	Electricity consumption in pumps in a heat-transfer pipe or district-heating pipe, W_e
W :	Electricity consumption in pumps in the heat-application area, W_e
α :	Heat-transfer coefficient, $W/(m^2 \cdot K)$
ΔP :	Pressure loss, Pa
ΔT :	Logarithmic mean temperature difference, K
η_{pump} :	Pump efficiency, dimensionless
μ :	Viscosity of water, $Pa \cdot s$
ρ :	Density of water, kg/m^3
λ :	Darcy friction factor in Eq. (4), dimensionless

Subscripts

a :	District-heating pipe in the heat-application area
c :	Cold side flow in double-pipe, heat exchanger
$c-g$:	Heat transfer from cold side to the ground
d :	Double-pipe model
e :	Electricity
$excav$:	Excavation
g :	Ground
h :	Hot side flow in double-pipe, district heat exchanger, and heat application for household heating and snow melting
$h-c$:	Heat transfer from hot side to cold side
$house$:	Household heating
hx :	Heat exchanger between primary helium loop in a GTHTR300 and a heat-transfer pipe

<i>in</i> :	Inlet flow in a unit length of a heat-transfer pipe or heat exchanger
<i>out</i> :	Outlet flow in a unit length of a heat-transfer pipe or heat exchanger
<i>pump</i> :	Pump
<i>s</i> :	Single-pipe model
<i>snow</i> :	Snow melting
<i>t</i> :	Heat
<i>w</i> :	Water
<i>x</i> :	Heat exchanger model

References

- City of Sapporo website, Road heating, available from
http://www.city.sapporo.jp/kensetsu/dorouji/works/workshop/road_heating.html, (2011), (in Japanese), (accessed on 28th January, 2016).
- City of Sapporo website, Answers for the question about the competition on town planning for future Makomanai, available from <https://www.city.sapporo.jp/keikaku/kougai/makomanai/documents/compekaitou140703.pdf>, (2014a), (in Japanese), (accessed on 28th January, 2016).
- City of Sapporo website, Statistics on City of Sapporo, available from
<http://www.city.sapporo.jp/toukei/tokeisyo/13energy25.html>, (2014b), (in Japanese), (accessed on 28th January, 2016).
- City of Sapporo web site, available from
<http://www.city.sapporo.jp/toukei/jinko/juuki/juuki.html>, (2014c), (in Japanese), (accessed on 28th January, 2016).
- Furumichi, N., Fujiwara, Y., Ochifuji, K. and Satoh, K., Study on the problems in the introduction of a wide area district heating system to cold-climate cities and the effects on environmental load control, Proceedings of Symposium on Global Environment, Vol. 6 (1998), pp. 129-134 (in Japanese).
- Hamada, Y., Nakamura, M., Yokoyama, S., Nagano, K., Nagasaka, S. and Ochifuji, K., A study on earth temperature in a snowy region for underground thermal energy storage (UTES), Transactions of the Society of Heating, Air-Conditioning Sanitary Engineers of Japan, Vo. 68 (1998), pp. 91-100 (in Japanese).
- Hokkaido prefecture website, Report on energy problems in Hokkaido, available from
http://www.pref.hokkaido.lg.jp/kz/kke/grp/h22enemon/03_minsei_jittai.pdf, (2011), (in Japanese), (accessed on 28th January, 2016).
- Hokkaido prefecture website, Hokkaido nuclear disaster prevention plan, available from
<http://www.pref.hokkaido.lg.jp/sm/gat/bousai/bousai.htm>, (2015a), (in Japanese), (accessed on 28th January, 2016).
- Hokkaido prefecture website, Freezing depth, available from
<http://www.pref.hokkaido.lg.jp/kn/ksd/kijun/touketsushindo.htm>, (2015b), (in Japanese), (accessed on 28th January, 2016).
- Hokkaido prefecture website, Corporation Bureau, Industrial Water Section, available from
<http://www.pref.hokkaido.lg.jp/kg/kgs/cost-and-entry.htm>, (2015c), (in Japanese), (accessed on 28th January, 2016).
- Hoku Netsu Corporation, the 47th Annual Report, Hoku Netsu Corporation, (2015), (in Japanese).
- Imamura, M., Development of a small scale nuclear reactor system for district heating, Master Thesis of Hokkaido University, (2009), (in Japanese).
- Ishikari city website, Population of Ishikari City, available from
<http://www.city.ishikari.hokkaido.jp/soshiki/shimin/584.html>, (2014), (in Japanese), (accessed on 28th January, 2016).
- The Japan Society of Mechanical Engineers (eds.), JSME Heat Transfer Handbook (1993), Japan Society of Mechanical Engineers. (in Japanese).
- Kamiji, Y., Noguchi, H., Terada, A. and Yan, X., Flowsheet study of a multistage flash desalination system for cogeneration with high temperature gas-cooled reactor, Proceedings of 2014 22nd International Conference on Nuclear Engineering (ICONE22), (2014), Paper No. ICONE22-30142.

- Minase, K. and Hirano, M., Investigation on heat application of waste heat from power plants [partial citation from a report on a large scale energy base plan in N district], Denryoku Keizai Kenkyuu, Vol. 7 (1975), pp. 81-131 (in Japanese).
- Ministry of Land, Infrastructure, Transport and Tourism, 50 cases of district heating areas, available from <www.mlit.go.jp/common/001113135.pdf>, (2014a), (in Japanese), (accessed on 28th January, 2016).
- Ministry of Land, Infrastructure, Transport and Tourism, Standard Unit Price List for Civil Engineering Works (2014b), Ministry of Land, Infrastructure, Transport and Tourism (in Japanese).
- Nakajima, N., Takahashi, H., Kusunoki, T. and Mitomo, N., Examination of a distributed small reactor system with the social acceptability –The district heat supply small reactor system using deep underground cave-, JAERI-Tech, (2005), 2005-057 (in Japanese).
- Saito, Y., Cost Estimation Handbook for Chemical Engineers, 3rd edition (2000), Kogyo Chosakai Publishing (in Japanese).
- Sapporo Energy Supply, the 29th Annual Report, Sapporo Energy Supply Co. LTD., (2015), (in Japanese).
- Sugiyama, K., Shimazu, Y., Kumaki, J. and Ishitani, N., Nuclear district heating in Switzerland, Journal of Atomic Energy Society of Japan, Vol. 48, No. 2 (2006), pp. 119-124 (in Japanese).
- Technocco Image Factory website, available from, <http://technocco.jp/n_map/n_map.html>, (2016), (in Japanese), (accessed on 28th January, 2016).