OPERATIONAL CHARACTERISTICS OF THE GAIA SNOW-MELTING SYSTEM IN NINOHE, IWATE, JAPAN

DEVELOPMENT OF A SNOW-MELTING SYSTEM WHICH UTILIZES THERMAL FUNCTIONS OF THE GROUND

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ABSTRACT

The authors have developed the Gaia Snow-Melting System, which utilizes the ground as a heat source and heat storage body. Another characteristic of the Gaia Snow-Melting System is the utilization of the Downhole Coaxial Heat Exchangers (DCHEs) proposed by the authors. In this system, solar heat absorbed in a pavement is recovered and stored in the ground over summertime. Hence, both geothermal heat and solar heat are used for melting snow in winter.

The first Gaia Snow-Melting System was installed in December 1995 in Ninohe, Iwate Prefecture. The system covers an area of 266 m^2. Three DCHEs, each 8.9 cm in outer diameter and 150.2 m long, and a heat pump driven by a 15-kW electric motor were used. Adjustments of the setting parameters of the operation control system were performed during the first winter and first summer of operation. Modifications of the control system were carried out before the second winter.

In winters (not including the first winter), the average coefficients of performance (COP) for the heat pump have been 4.2 to 4.3 and the average specific heat extraction rates 80 to 83 W/m. The Gaia system's annual electric power consumption per unit area has been less than 20% that of the electric heating cable systems used in the same city.

The cumulative heat charged into the ground from the onset of operation until the end of November 1998 was greater than that extracted from the ground during the same period. Temperature profiles measured at an observation DCHE have changed year by year. However, the average temperature in the DCHE before the winter of 1998 was almost the same as that of the initial temperature profile in the DCHE. A more appropriate design and higher performance will be realized in the next system.

INTRODUCTION

The Japan Sea side of Japan from central Honshu through Hokkaido is subject to heavy snowfall. Many snow-melting apparatuses have been used over the past several decades and have been increasing in number. The oldest and most utilized method for melting snow is the sprinkling of groundwater over roads. However, the associated problems of ground subsidence and the dropping of groundwater levels have emerged. Apparatuses using electric heating cables and boilers burning oil or gas have been increasing in number especially in northern Japan, where the sprinkling of groundwater is not applicable. This can lead to an increase in the consumption of fossil fuels, and thereby, the emission of carbon dioxide.

The authors have developed the Gaia Snow-Melting System, which utilizes the ground as a heat source and a heat storage body. This system's main heat source is the geothermal heat contained in the shallow ground and its auxiliary source is summertime solar heat. Another characteristic of the system is the utilization of the Downhole Coaxial Heat Exchangers (DCHEs) proposed by the authors (Morita, et al.,1985; Morita and Tago, 1995). The DCHE utilizes thermally insulated inner pipe and reverse circulation (i.e., cold fluid flows down the annulus and warmer fluid flows up through the inner pipe) for efficient heat extraction.

The first Gaia Snow-Melting System was installed in Ninohe, Iwate Prefecture and has been in operation since December 1995. So far, this Gaia system has functioned effectively and has eliminated accidents due to snow or ice.

THE GAIA SNOW-MELTING SYSTEM

The Gaia Snow-Melting System consists of DCHEs, a heat pump and heating pipes embedded in the pavement (Fig. 1).

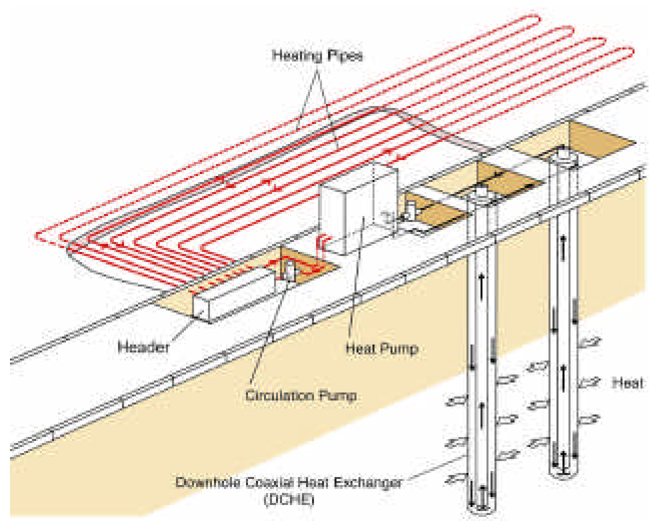

Figure 1. ***Conceptual drawing of the Gaia Snow-Melting System.***

In winter, heat extracted from the ground with the DCHEs is transferred to the heat pump. After the heat pump increases the temperature, the thermal energy is transmitted to a heating medium circulating through a network of heating pipes for melting snow. Antifreeze is used as both a heat extraction medium and a heating medium.

In summer, solar heat raises the temperature of the pavement, in which the heating pipes are embedded, up to between 30 to 50EC. The solar heat is recovered from the pavement and charged into the ground by directly connecting the DCHEs and heating pipes, and by circulating antifreeze in this loop. Forward circulation is employed for efficient heat charging.

Thus, geothermal heat and summertime solar heat are used for melting snow in winter.

A newly developed control system operates the Gaia system automatically when road conditions meet specified criteria for melting snow or charging heat.

A numerical simulation code has been developed for predicting the operational behavior and performance of the system including DCHEs and a heat pump. This code was used for designing the Gaia system in Ninohe and for predicting its performance. Another code for analyzing temperature behavior in the pavement and the roadbed surrounding the heating pipes has been developed after the installation of the first Gaia Snow-Melting System. These two codes make it possible to design the system appropriately, meeting specific site conditions, and to predict the performance of the system.

THE GAIA IN NINOHE

Ninohe City is located about 500 km north of Tokyo. The Gaia system was installed at the downhill section of a curved road with a 9% gradient in order to prevent accidents caused by skidding and sliding vehicles in winter. The area covered by the snow-melting system is 4 m wide and 65 m long, covering a total area of 266 m^2.

The formation consists of Tertiary sandy tuff. Preliminary numerical simulations for the first winter's operation indicated the effective thermal conductivity of the formation to be 1.3 W/m•K. The temperature at the bottom of one of the DCHEs, 150.8 m in depth, was 22.5EC before the initial operation of the system, at one month after the completion of the DCHE.

Three DCHEs (Fig. 2), each 8.9 cm in outer diameter and 150.2 m long, a heat pump driven by a 15-kW electric motor and two 0.75-kW circulation pumps are used. Polybutene pipes of 16 mm in inner diameter are used as heating pipes and were embedded in the asphalt concrete pavement at 20 cm intervals. The depth of the top of the heating pipes is 10 cm from the surface of the pavement. The thermal capacity of the Gaia System is approximately 50 kW_t.

Snow-Melting Operation

In the current control system, the operation of the Snow-Melting System in the snow-melting mode is controlled utilizing information from a road surface temperature sensor and two road surface water detectors, one water detector with a heater inside and another without a heater. The heater is for melting snow or ice on the surface of the detector, and thus, snow or ice can be detected as water. The system begins its operation when the road surface temperature becomes lower than a specified value and one or both water detectors detect water. When the road surface temperature is higher than the specified value or when neither water detectors detect water, the system doesn't operate or its operation is stopped. The

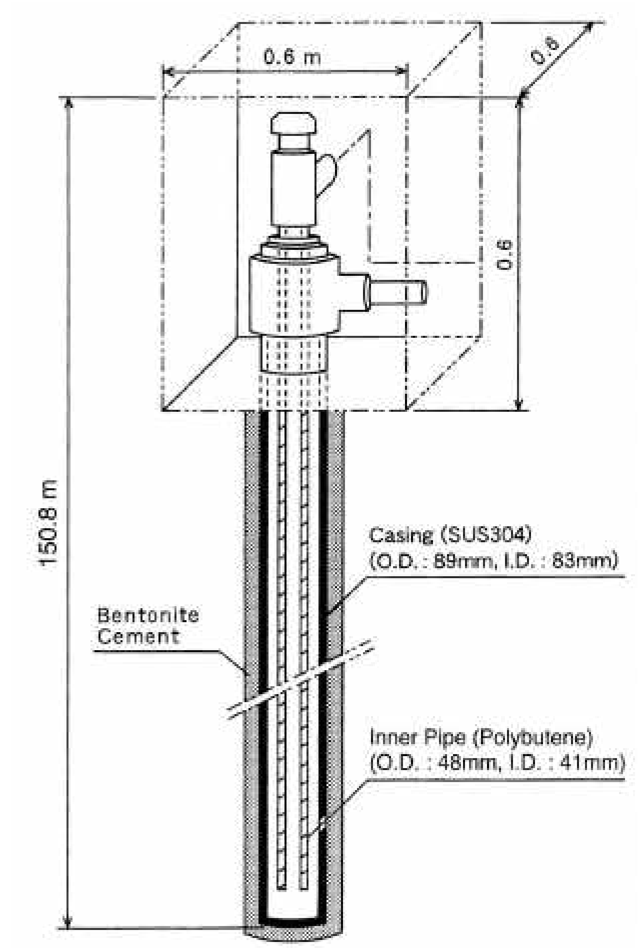

Figure 2. Structure of the DCHE.

sensitivity of these water detectors is so high that the operation of the system begins immediately after the onset of snowfall.

It has been demonstrated that the Gaia system is an effective method to melt snow on roads. Figures 3 and 4 show the snow-melting conditions on February 13, 1996. So far, four snow-melting seasons have passed since the installation of this system. The operational characteristics of the system in the snow-melting mode are introduced here mainly using data from the winter of 1997. The average low temperature for the month of January was –8.3EC in that winter in the city.

Figure 5 shows the daily snowdepth differences in the winter of 1997 measured by a weather station of the AMeDAS (Automated Meteorological Data Acquisition System) located in Ninohe City. This station is located about 10 km east of the Gaia system. The daily snowdepth difference is a positive difference between the snowdepth of a certain day and that of the previous day. Hence, the number of actual snowfall days is greater than the snowfall days shown in Figure 5.

In Ninohe City, snow-melting operations begin at the beginning of December and end at the end of March (hereinafter, this period shall be called the snow-melting season). The total snowdepth difference for the 1997 snow-melting season was 223 cm.

Figure 3. ***Snow-melting condition at the upper section of the road on February 13, 1996.***

Figure 4. ***Snow-melting conditin at the lower section of the road on February 13, 1996.***

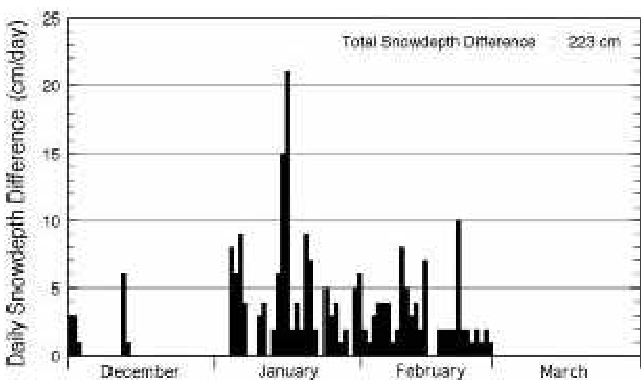

Figure 5. ***Daily snowdepth differences at the weather station in the 1997 snow-melting season.***

Figure 6 shows the changes in the daily operation times over the 1997 snow-melting season. The number of operation days in Figure 6 is greater than the snowfall days shown in Figure 5. This is because of the nature of the daily snowdepth difference and limitations in the resolution of the AMeDAS, which is 1 cm. Also, the system sometimes goes into operation because of rain or condensation of water in the air on the road surface. The total operation time of the system over the 1997 snow-melting season was 491.9 hours.

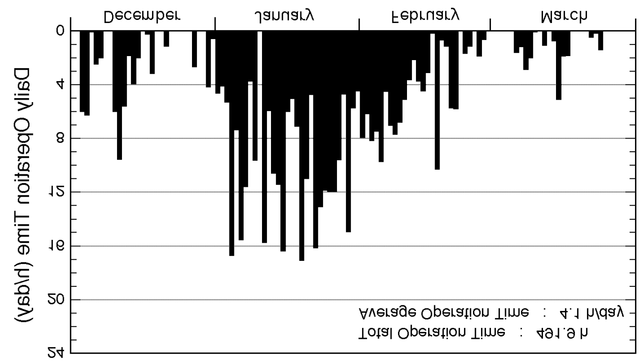

Figure 6. ***Daily operation time of the system in the 1997 snow-melting season.***

Figure 7 shows the changes in the antifreeze temperature at the outlet of the observation DCHE and in the ambient temperature at the weather station. The Gaia snow-melting system normally works in an ambient temperature range between the average and the low temperatures. Hence, the ambient temperature ranges shown in Figure 7 are ranges between the average and low temperatures. It can be seen that the outlet temperatures of the DCHE are higher than the ambient temperatures by 1.4 to 20.4EC.

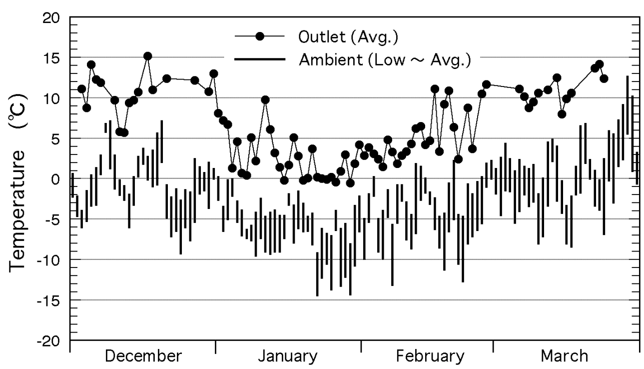

Figure 7. ***Daily average outlet temperatures of DCHE and ambient temperatures in the 1997 snow-melting season.***

Figure 8 shows the changes in the delivery temperatures of the heating medium from the heat pump to the heating pipes. Except in the case of short daily operation times, daily high temperatures of delivery temperatures roughly ranged from 28 to 36EC and daily average temperatures 25 to 30EC.

Figure 9 shows the changes in the extracted heat with DCHEs and delivered heat from the heat pump to the heating pipes in the 1997 snow-melting season. The total supplied heat with this system was 21.8 MW$_t$h and extracted heat with the DCHEs was 16.6 MW$_t$h (about 76% of the total supplied heat of the system).

Figure 10 shows the changes in the thermal output rate of the system and the heat extraction rate of the DCHEs. Normally, both rates decrease after the onset of operation with the progress of the season and recover after late January or early February. This tendency is associated with the decrease and recovery in the outlet temperature of the DCHEs. Therefore, this figure indicates that the heat pump is mostly

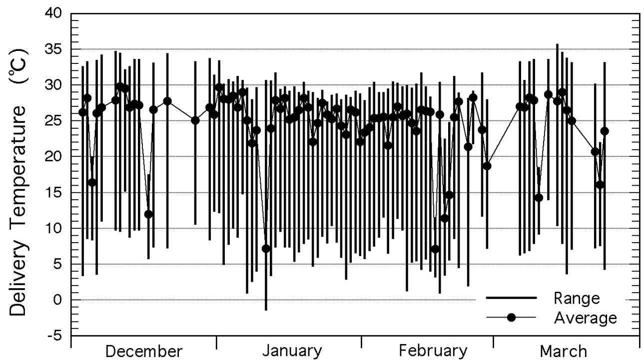

Figure 8. ***Change in delivery temperatures in the 1997 snow-melting season.***

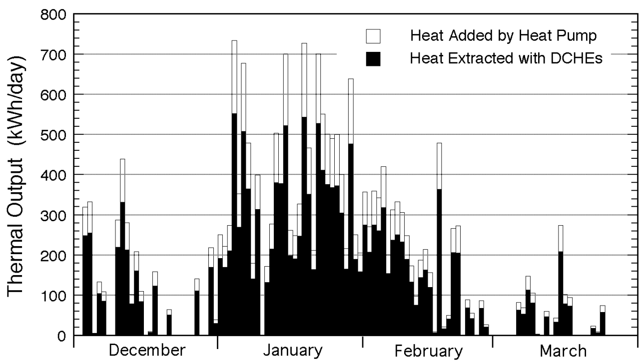

Figure 9. ***Thermal output of the system in the 1997 snow-melting season.***

at full load in January and February, and thus, the selected heat pump for the Gaia system was appropriate from the view point of capacity.

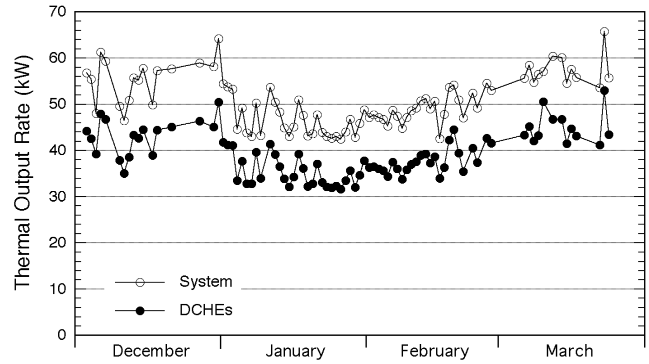

Figure 10. ***Changes in thermal output rate of the system and DCHEs in the 1997 snow-melting season.***

Table 1 summarizes the major characteristic values of the system in snow-melting operations for four winters. Despite a smaller total daily snowdepth difference, the supplied heat in the 1996 snow-melting season was greater than that of the previous season. This is because of a modification in the temperature control unit and an increase in the heat supply rate with this modification.

In winters (except for the first winter), the average supplied heat to the heating pipes per unit area of the snow-melting area over a snow-melting season ranged from 178 to 185 W/m^2, and the average specific heat extraction rates of the DCHEs ranged from 80 to 83 W/m. These high specific heat extraction rates at a low effective thermal conductivity of the formation is mainly due to the small operation rate of the system. Coefficients of performance (COP) ranged from 4.2 to 4.3 for the heat pump and 3.4 to 3.6 for the whole system.

Table 1. **Major Characteristic Values for Snow-Melting Seasons**

Snow-Melting Season	1995	1996	1997	1998
Total Snowdepth Difference (cm)	234	149	223	323
Avg. Low Temp. for January (^{o}C)	-7.1	-4.6	-8.3	-6.2
Operation Time of System (h)	460.0	417.7	491.9	597.2
Operation time of HP (h)	381.5	393.4	460.7	507.3
Avg. Inlet Temp. of DCHE (^{o}C)	1.7	2.1	0.2	1.1
Avg. Outlet Temp. of DCHE (^{o}C)	4.8	5.3	3.4	4.3
Avg. Delivery Temp. of HP (^{o}C)	26.2	26.6	26.2	25.4
Avg. Return Temp. to HP (^{o}C)	19.3	19.4	19.2	18.5
Extracted Heat (kW_th)	12,330	14,740	16,600	18,870
Supplied Heat (kW_th)	16,230	19,360	21,810	24,650
Avg. Outlet of HP (kW_t)	42.5	49.2	47.3	48.6
Heat Supply Rate per Unit Area (W_t/m^2)	160	185	178	183
Specific Heat Extraction Rate (W_t/m^w)	71.8	83.2	80.0	82.5
Electric Power Consumption (kW_eh)	5,164	5,939	6,641	7,363
Power Consumption of HP (kW_eh)	3,899	4,617	5,211	5,779
Avg. COP of HP (-)	4.16	4.19	4.19	4.27
Avg. COP of Total System (-)	3.42	3.59	3.57	3.60
Seasonal Performance Factor (-)	3.14	3.26	3.28	3.33

Note: Data for each winter are for a period from the first of December to the end of March except for the 1995 snow-melting season. Data for 1995 are for a period from December 27, 1995 to March 31, 1996.

Heat-Charging Operation

In heat-charging mode, the system kicks into operation when the difference between the pavement temperature and a bottom-hole temperature of the observation DCHE becomes greater than a specified value. The heat-charging operation is stopped when the difference between the inlet temperature and the outlet temperature of the DCHE becomes smaller than a specified value.

Here, the operational characteristics over the 1998 heat-charging season, the season after the 1997 snow-melting season, are introduced.

Figure 11 shows changes in operation time at Japanese Standard Time. As shown in Figure 13, the daily average heat charging rates were almost constant over most of the heat charging period. Hence, the daily charged heat was essentially proportional to the daily operation times. The length of daily operation time was closely related to the total daily insolation, and most non-operation days in the period from May to the middle of October coincided with the days when no sunshine were observed at the weather station.

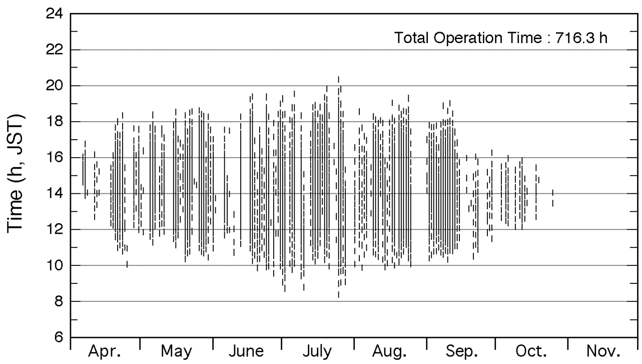

Figure 11. ***Operation time of the system at Japanese Standard Time in the 1998 heat-charging season.***

Figure 12 shows changes in inlet temperature of the observation DCHE and its bottom-hole temperature at 9 a.m. The bottom-hole temperature changed in a similar manner to that of the inlet temperature. Gradual decrease in the bottom-hole temperature after the last heat-charging operation might have been due to self-circulation of the working fluid in the DCHEs.

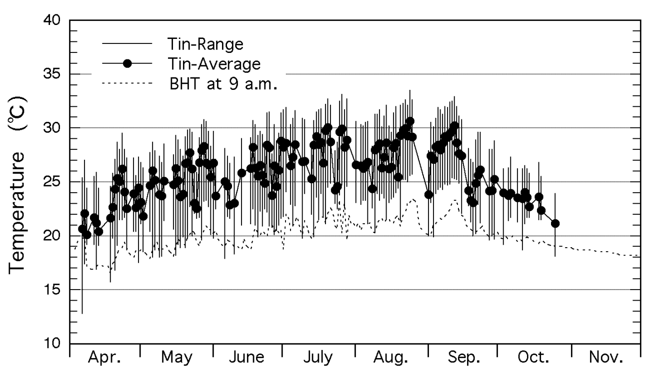

Figure 12. ***Changes in inlet temperature of the observation DCHE and its bottom-hole temperature in the 1998 heat-charging season.***

Figure 13 shows changes in the heat charging rate. The reason for the high heat charging rate in April, despite the low inlet temperature of the DCHE, was mainly due to the low formation temperature caused by heat extraction in the preceding winter. An increase in the formation temperature follows that of the inlet temperature, and the temperature difference between the working fluid in the DCHEs and the surrounding formation is limited in a narrow range. Therefore, the increase in the heat charging rate was very small from April to August.

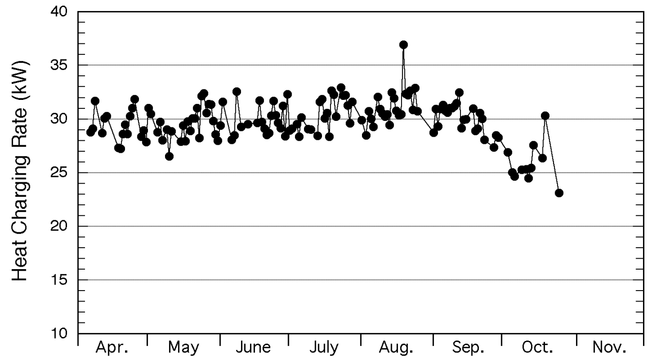

Figure 13. ***Changes in heat charging rate in the 1998 heat-charging season.***

Table 2 summarizes the major characteristic values of the system over three heat-charging seasons. Because adjustment of setting parameters of the operation control system was performed, values for the first season did not fully reflect weather conditions. The average heat recovery rate per unit area of the snow-melting area was 92 to 113 W/m^2. The average specific heat charging rates of the DCHEs ranged from 54 to 67 W/m. Heat charging rates per unit electric power consumption over a heat-charging season were 13.4 to 23.8 kW$_t$h/kW$_e$h.

System's Behavior and Performance

<u>Heat Balance</u>

Figure 14 shows the seasonal extracted and charged heat since the onset of the operation of the system.

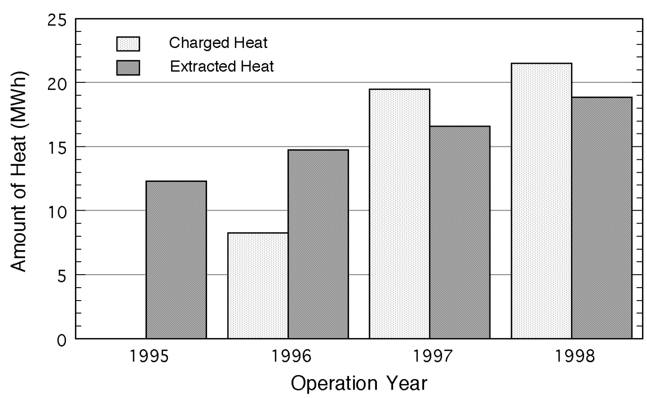

Figure 14. ***Charged heat and extracted heat up to March 31, 1999. Operation year is from the first of April to the end of March in the next year.***

Table 2. Major Characteristic Values for Heat-Charging Seasons

Heat-Charging Season	1996	1997	1998
Total Insolation (kW$_t$h/m^2)	892	925	870
Operation time of the System (h)	339.2	691.6	716.3
Avg. Inlet Temp. of DCHE (°C)	26.7	28.4	27.1
Avg. Outlet Temp. of DCHE (°C)	22.3	23.4	21.8
Charged Heat (kW$_t$h)	8,270	19,490	21,510
Recovered Heat per Unit Area (kW$_t$h/m^2)	31.1	73.3	80.9
Heat Recovering Rate (W$_t$/m^2)	92	106	113
Heat Charging Rate (kW$_t$)	24.4	28.2	30.0
Specific Heat Charging Rate (W$_t$/m)	54.1	62.5	66.6
Electric Power Consumption (kW$_e$h)	619	872	903
Seasonal Performance Factor (-)	13.4	22.4	23.8

The cumulative charged heat into the ground up to the end of November 1998 was greater than the cumulative extracted heat over the same period. It seems that the greater the extracted heat in preceding season, the greater the charged heat in the successive season.

Changes in Temperature Profiles in a DCHE

Figure 15 shows measured temperature profiles in the observation DCHE at the beginning of the snow-melting season. As can be seen in this figure, temperature profiles have changed year by year. However, average temperatures in the DCHE over a section from 10 m in depth to the bottom-hole have remained almost the same. The average temperatures for 1995, 1996, 1997 and 1998 were 17.04, 16.95, 16.88 and 17.07EC, respectively. It is clear that the heat charging operation has been effective in preventing deterioration of the ground's function as a heat source.

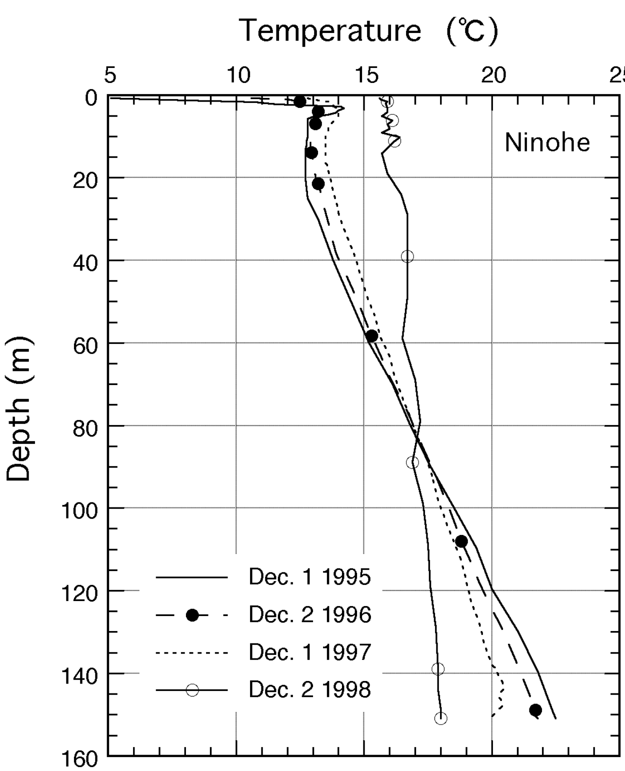

Figure 15. Change in temperature profiles in the observation DCHE.

The temperature profiles are becoming more vertical year by year. This is mainly due to self-circulation in the DCHE and vertical redistribution of heat in it and in the surrounding formation. Collected data from a flow meter in the snow melting seasons indicate that self-circulation occurs after the end of each operation of the system.

Power Consumption and Electric Power Costs

Table 3 shows the annual power consumption of the Gaia System per unit area of the snow-melting area for the operation years of 1996 to 1998, and the coinciding electric power costs. Values for electric heating cable systems in the city installed by the Iwate prefectural government are also shown in the table.

Table 3. Annual Power Consumption and Power Cost of the Gaia Snow-Melting System along with Those of Electric Heating Cable Systems in Ninohe City (operation year is from the first of April to the end of March in the next year).

Operation Year	Power Consumption (kWh/m^2/y)		Power Cost (Vm^2/y)	
	Electric Heating Cable	Gaia	Electric Heating Cable	Gaia
1996	145.4	24.7 (17.0%)	4,1082.4	771.6 (18.9%)
1997	154.7	28.3 (18.3%)	4,259.5	809.8 (19.1%)
1998	168.9	31.2 (18.5%)	4,201.0	792.3 (18.9%)

The power consumptions of the Gaia System were 17 to 19% those of the electric heating cable systems. This means that more than an 80% decrease in fossil fuel consumption or carbon dioxide emission can be obtained by replacing electric cable systems with the Gaia System. Annual electric power costs, including those for electric capacity and for power consumption, were about 19% those of the electric cable systems.

Modifications of the Control System

Based on the experiences of the first snow-melting season, modifications of the control system were made before the second winter.

Modification of the Operation Control Unit

In the initial control system, the operation of the Gaia system was controlled using information from one road surface temperature sensor and one road surface water detector with a heater inside. In the first winter, it was observed several times that the system stopped before the road surface completely dried up and the surface froze instantly. This occurred on very cold days. The cause of this phenomenon was that the water detector's surface dried up earlier than the road surface, because of the heater installed in the detector. Hence, another water detector without a heater was added to prevent the above phenomenon.

Modification in the Manner of Adjusting the Capacity of the Heater in the Water Detector

The capacity of the heater inside the water detector used to be manually adjustable at three degrees. In the first winter, the capacity was fixed at the medium degree. The major problem associated with this system was the freezing of the water detector's surface at very low ambient temperatures. In the modified control system, the degree of the capacity is adjusted automatically referring to the ambient temperature.

Modification of the temperature control unit

Initially, it was designed so that the heat pump operates to keep the return temperature of the antifreeze, from the heating pipes to the heat pump, at a specified temperature. In the modified control system, the heat pump is operated so that the temperature of the pavement is kept at another specified temperature. The major purposes of this modification were:

- To increase the temperature of the pavement up to a sufficient temperature level for melting snow as fast as the system's capacity allows, and
- To avoid intermittent operation of the heat pump. In actuality, frequent and intermittent operation of the heat pump was observed in the first snow-melting season.

FUTURE IMPROVEMENTS

In order to achieve higher performance than that attained with the first system, the following modifications will be made in the next Gaia Snow-Melting System.

- Plastic pipes more thermally conductive than polybutene pipes will be used as heating pipes.
- The interval between heating pipes will be shortened from 20 cm in the first system to 15 cm.

These two modifications will enable the supply of required heat flux for melting snow at lower heating medium temperatures by several degrees. This will result in a higher heat pump performance.

Also, a more efficient heat pump than that used in the first system will be employed, because the authors have learnt that is available on the commercial market.

CONCLUSIONS

Through several years of operation, it has been demonstrated that the Gaia Snow-Melting System is an effective system for melting snow and is environmentally benign. Also, an economic analysis, which was carried out separately, indicated that the Gaia System is economical.

The high load factor of the heat pump and a high specific heat extraction rate attained with this system indicated that the design of the system was adequate. A more appropriate design and higher performance will be realized in the next system.

The authors' primary purpose is to promote the utilization of the thermal functions of the ground in Japan. Currently, the authors are carrying out the design and economic evaluation of systems. These systems are applied for melting snow, space heating and cooling, and for indoor swimming pools. Some of them will be realized within the next several years.

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