DEVELOPMENT OF A HEAT-PUMP SNOW-MELTING SYSTEM COUPLED WITH EXHAUST WATER FROM GROUND WATER SPRINKLER

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ABSTRACT

The most commonly used snow-melting system in Japan is the groundwater sprinkler system. Groundwater at approximately 15°C is pumped from the ground and then run through a sprinkler to melt snow covering the ground. Since the temperature of the water from the melted snow is approximately 4°C, this water may be used as a heat source of the heat pump system to melt snow in other areas, such as pedestrian walkways.

The performance of a road heating system that uses a heat pump coupled with exhaust water from a snow-melting sprinkler is experimentally investigated. A prototype heat collection unit was assembled from 10 steel pipes having a length of 4 m and a diameter of 15 mm, placed in a U-shaped ditch of 400 mm in width along the roadside. A heat collection unit was connected to a 6.2 kW heat pump unit, and heated water was fed to a snow-melting radiator having an area of 31.2 m^2. A practical experiment was carried out from February 6 to March 7, 2013. For 4°C water flowing at 92 ℓ/min, the amount of heat collected in the ditch was 4.8 kW, and that radiated from the snow-melting panel was 6.0 kW. The average COP of the system was 5.8, and 10 cm of natural snowfall was cleared over three hours. A heat collector of unit length (1 m) can achieve a heat per unit length of 775 W/m.

1. INTRODUCTION

The rapidly aging society of Japan has led to the desire for clear and safe sidewalks and/or public areas during the winter. Compared to mechanical snow removal, a road heating system may provide a much higher level of snow removal for pedestrian use, even for handicapped individuals. However, the costs, including the initial cost, the operational costs, and the maintenance costs, are considerable. As such, road-heating systems remain unpopular. Moreover, conventional road-heating systems that use warm water heated by a boiler or electrical heater consume enormous amounts of fossil fuels. Therefore, the development of a system that uses naturally available and/or unused energy as a heat source has also been promoted for the past quarter of a century. However, the initial cost of systems such as geothermal systems tend to be much more expensive than conventional systems, and so have not yet been implemented (Uchino et. al, 2005).

The snow-melting sprinkler (SMS) system, which uses pumped groundwater, has been widely used for half a century, especially in the Hokuriku (northwest coast) region of Japan, which has a relatively warm climate. Since the system uses pumped groundwater having a temperature of approximately 15°C sprinkled over the road surface through embedded piping, the initial cost is cheaper than other snow-melting systems. Moreover, the running costs are also low because the system uses natural ground heat energy as a heat source.

However, the volume of sprinkled water can be six times the volume of melted snow, and soaked road surfaces are not convenient for pedestrians.

In order to ensure the personal mobility of persons during winter, including older and wheelchair-bound individuals, an effective snow-melting system with reasonable costs for key areas, such as bus stops, sidewalks, and niche spaces around crossings, is desired. However, there is no suitable key technology that solves the problems of both cost and performance. The water generated by the snow-melting sprinkler must be maintained at 4°C or higher so as not to refreeze when entering the roadside ditch. Because the air temperature is typically below 0°C during snowfall, water maintained around 4°C will be a better heat source than air for a heat pump system. We herein report the results of a performance test conducted at an experimental facility constructed in Nagaoka, Niigata Prefecture.

2. EXPERIMENTAL CONDITIONS

2.1 Concept of the system

The concept of the proposed system is shown in Figure 1. The system is composed of a radiator section, a heat pump unit, and a collection section. The heat collection unit (collector) is placed in a roadside ditch and exchanges heat between brine in the pipe and flowing water (4°C or less), which comes from the snow melting sprinkler embedded in the roadway. Since, in general, the design heat load may be approximately 200 W/m^2 in the Hokuriku region of Japan, a heat pump rated for approximately 6 to 8 kW can be used to melt snow covering an area of 30 to 40 m^2, which corresponds to a bus stop, or three car parking spaces.

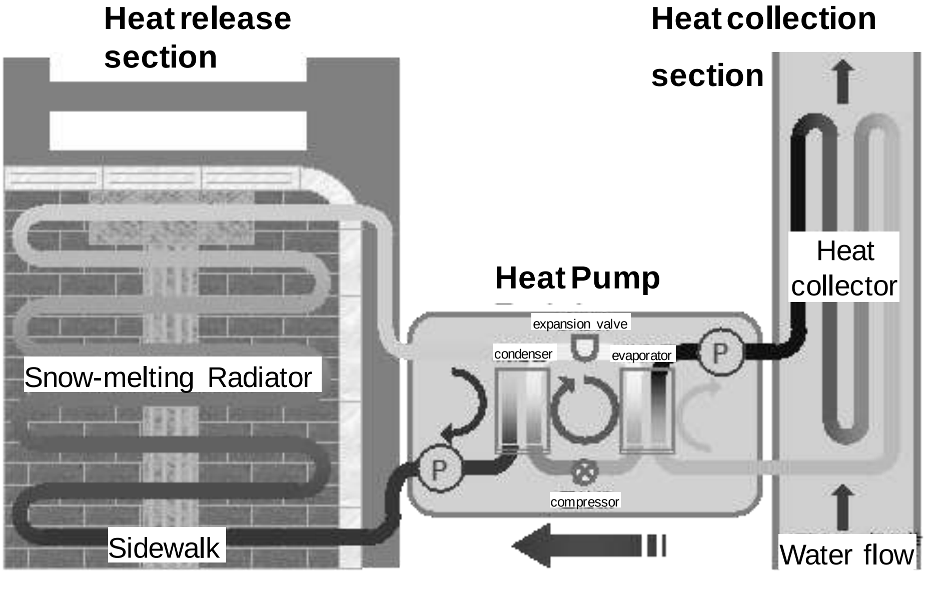


Figure 1 Schematic diagram of HARNESS

2.2 Experimental facility

In the fall of 2012, an experimental facility was constructed in Nagaoka, Niigata Prefecture. The layout of the facility is shown in Figure 1, and the specifications of the facility are summarized in Table 1. Nagaoka is a region having a maximum average snow cover of approximately 1 m. As shown in Figure 2, a heat collection unit is assembled from five steel pipes of 4 m in length and 15 mm in diameter. Two heat collectors were immersed in a 0.4-m wide ditch along the roadside. Snow melting pipe was already installed in the neighboring parking lot, and exhaust water automatically flows into the ditch. The snow melting section is composed of four concrete panels of 2.1 m × 3.7 m with buried polyethylene pipe of 13 mm in diameter. The overall snow-melting area is 31.2 m^2.

Table 1 Specifications of the experimental facility

Heat pump unit	Model: Sunpot, GSHP-701 Declared power: 6.2 kW (0 to 35 °C) COP: 4.0 (0 to 35 °C) Power consumption: 1.5 kW (200V)
Snow-melting section	Heat load: 200 W/m^2 Melting area: 31.2 m^2 Radiation pipe: cross-linked PE, ϕ13 Pump: 20 ℓ/min, 4.0 m
Heat collection section	Ditch: W400 x D350 Radiator: Steel pipe, ϕ15 x40 m Surface area: 2.73 m^2 Pump: 20 ℓ/min, 6.5 m

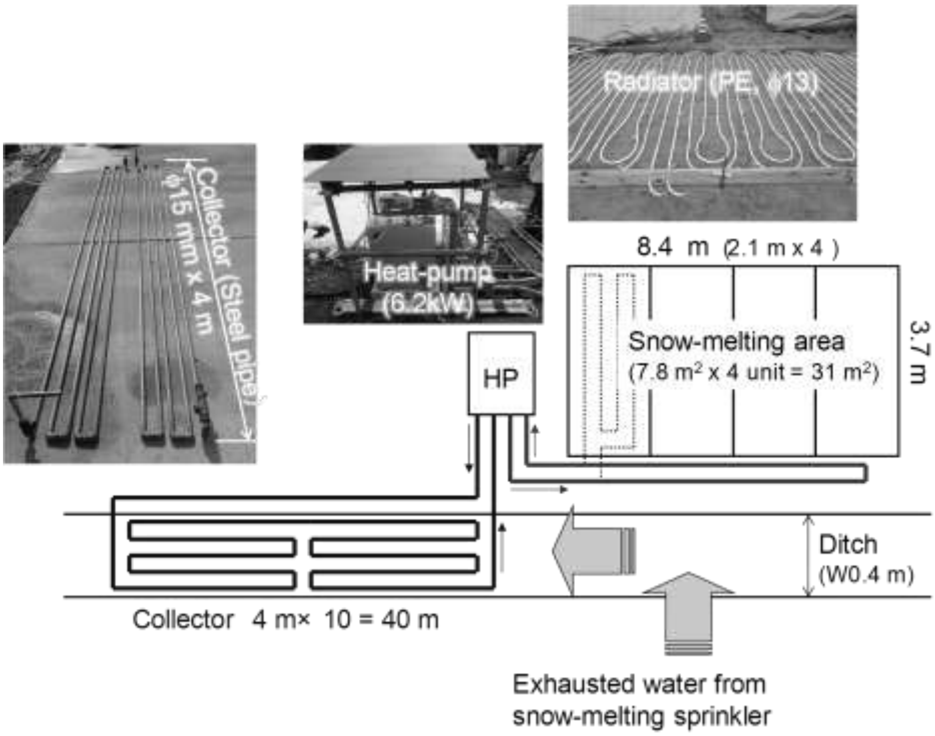


Figure 2 Layout of the experimental facility

2.3 Measurement and analysis

Measurement items are shown in Table 2. The snowfall intensity (depth of snowfall per hour) and atmospheric air temperature were observed. The flow rate and temperature upstream and downstream in the ditch generated by the water from the SMS were measured. The temperatures of the circulating brine in the snow-melting radiator and heat collector were measured at the return and the feed, and the power consumption of the heat pump was also measured.

Table 2 Observation condition

Climate condition	Atmospheric air temperature
	Snowfall intensity
Flowing water from SMS	Temperature at upstream / downstream
	Flow rate
Heat collector	Input/output brine temperature
Snow-melting radiator	Input/output brine temperature
Heat pump	Electricity consumption

The amount of heat radiation, Q_r, and the amount of heat collection, Q_c, can be calculated as the product of the mass flow rate, $\dot{m}$, the specific heat of the brine, C, and the temperature difference, ΔT, between the inlets and outlets of the radiator and collector, respectively, as follows:

$$Q_r = C_b m \; T_{r1} - T_{r2} \; , \qquad Q_c = C_b m \; T_{c2} - T_{c1} \; , \tag{1}$$

where T_{r1} and T_{r2} are the brine temperatures at the inlet (feed) and the outlet (return), respectively, from the heat pump to the radiator, and T_{c1} and T_{c2} are the brine temperatures at the inlet (feed) and the outlet (return), respectively, from the heat pump to the collector.

The coefficient of performance, COP, of the system was determined using the following equation as a ratio of the power consumption, E, and the amount of heat radiation Q_r:

$$COP = \frac{Q_r}{E} \tag{2}$$

The heat transfer rate between the collector pipes for flowing water, k, is calculated as follows:

$$k = \frac{Q_c}{(S\mathrm{C}E_{lm})}, \tag{3}$$

where $\mathrm{C}E_{lm}$ is a logarithmic mean temperature difference, which, in the case of a countercurrent heat exchanger, can be defined as follows:

$$\Delta \mathrm{T_{lm}} = \frac{\mathrm{T_{w1}\text{-}T_{c2}} - \mathrm{T_{w2}\text{-}T_{c1}}}{\log_e \frac{\mathrm{T_{w1}\text{-}T_{c2}}}{\mathrm{T_{w2}\text{-}T_{c1}}}}, \tag{4}$$

where T_{w1} and T_{w2} are the flowing water temperature upstream and downstream, respectively, and S is the surface area of the heat collecting pipes. The total surface area of the pipe that can collect heat in the experimental facility is 27.3 m^2.

3. EXPERIMENTAL RESULTS

The experiments of the present study were carried out for a total of five times from February 6 to March 7, 2013, while varying the flow rate and temperature of the exhaust water and the area of snowmelt. As a representative, the results of the experiment of February 22 and March 7 are shown in Figures 3 and 5, respectively. The target snowmelt area was 31.2 m^2 (all four panels were used) for both experiments. In February 22, an experiment was carried out under standard conditions, i.e., an average exhaust water temperature of 4.6°C, a flow rate of 95 ℓ/min, and natural moderate snowfall. The experiment on March 7 was conducted under the most severe conditions, i.e., an average exhaust water temperature of 0.5°C, a flow rate of 12 ℓ/min, and full snow coverage over the test area.

Table 3 Experimental conditions

	Date	Flowing water in Ditch		Snow melting area (m^2)	Snow condition
		Flow rate (ℓ/min)	Avg. Temp. (°C)		
1	Feb. 6th, 2013	82	4.5	7.8	Natural snowfall
2	Feb. 11th, 2013	85	4.1	15.6	Natural snowfall
3	Feb. 20th, 2013	140	8.4	15.6	Natural snowfall
4	Feb. 22nd, 2013	95	4.6	31.2	Natural snowfall
5	Mar. 7th, 2013	12	0.5	31.2	Forcibly covered snow

In the experiment on February 22, as shown in Figure 3, the brine sent to the collector was below the freezing point of water. The brine returns to the heat pump and is heated to an average temperature of 5.8°C, following the change in the exhaust water temperature. In a radiator circuit, the temperature of brine sent to the radiator was gradually increased to 15°C; the average temperature difference between the radiator and the outlet was 5.3°C between 10 am and 11 am, during which time when the operation was stable. The amount of heat collected in the ditch remained at 4.8 kW during the entire experiment, and the amount of heat radiated from the snow-melting panel was maintained at 6.1 kW, which is approximately equal to the rated power of the heat pump. The average COP of the system calculated based on electricity consumption data using Eqs. (1) and (2) was 5.8. Figure 4 shows time-lapse photographs of the snow-melting panel. Approximately 10 cm of snow fell during the experiment and was completely melted by 1 pm.

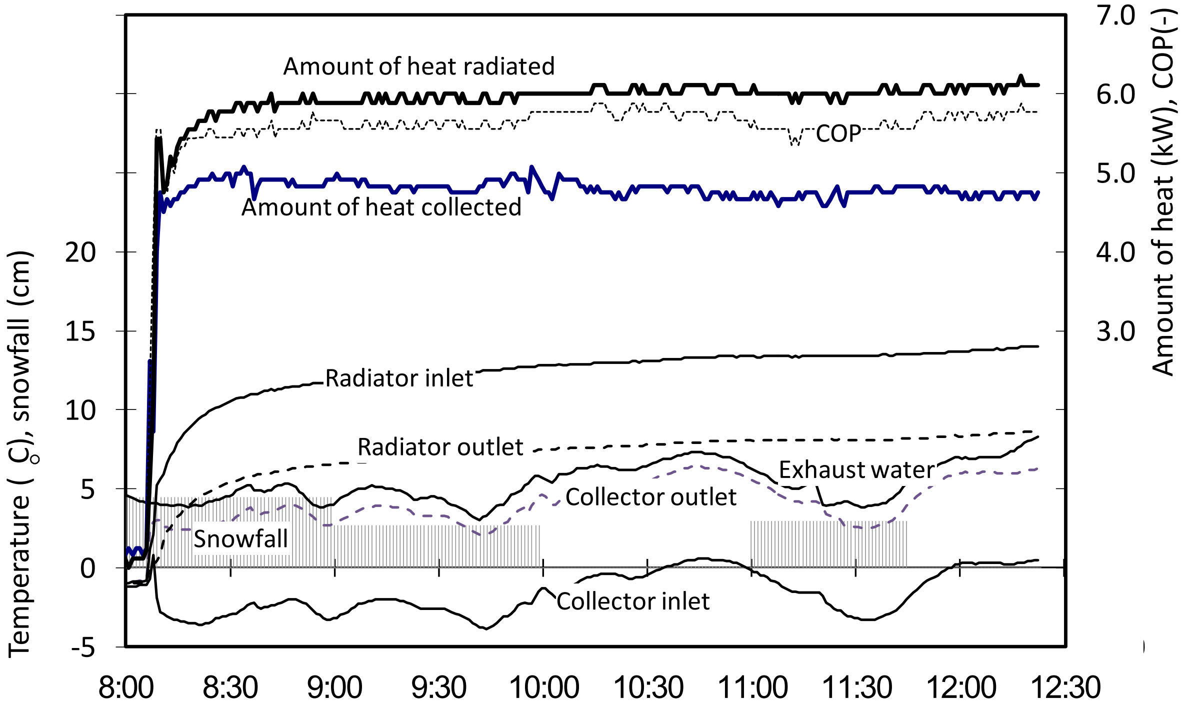
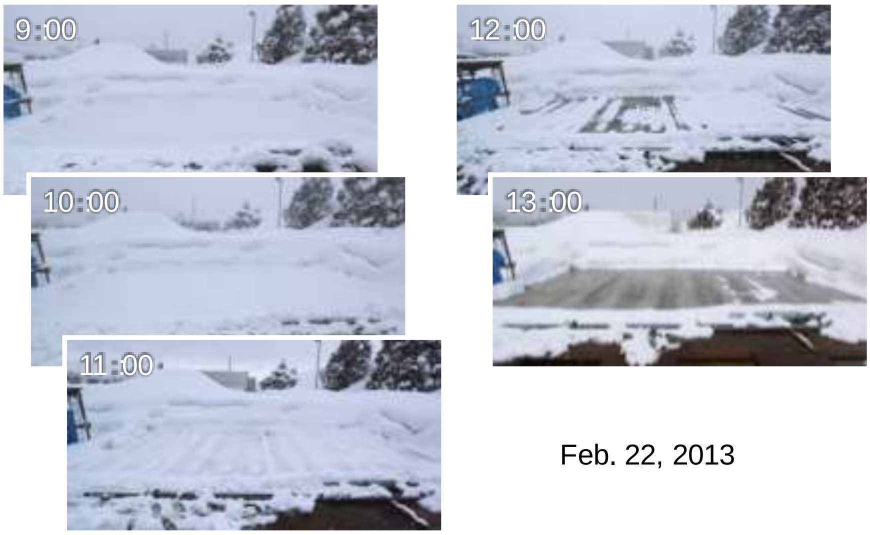


Figure 3 Experimental results for February 22, 2013.



Feb. 22, 2013

Figure 4 Melting process of snow on the radiator on February 22, 2013.

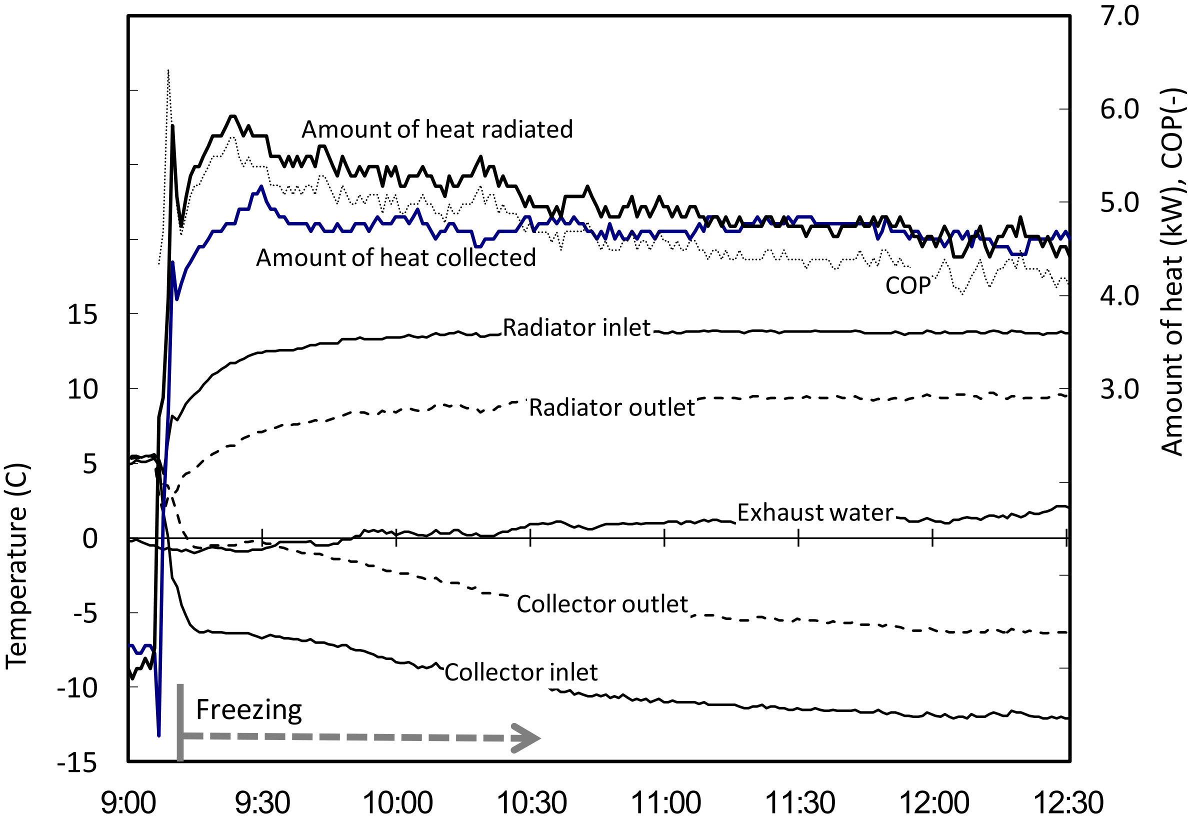


Figure 5 Experimental results for March 7, 2013.

In the experiment on March 7, as shown in Figure 5, the temperature of the brine at the collector inlet immediately decreased to -5°C or less just after the start of the system operation and then continued to decrease gradually. The temperature of the return brine from the collectors also quickly fell below the freezing point. Ice formed around the collector pipes, as shown in Figure 6. The feed temperature of the radiator increased to approximately 15°C, which is the operating temperature of the heat pump. The amount of heat radiated initially reached approximately 6 kW just after the start of operation, but then gradually decreased to 4.5, and the COP started at approximately 5.7 and then gradually decreased to 4.1. Considering the actual operational conditions, the experiment results may be for the most severe conditions of a water temperature of 0.5°C and a flow rate of 12 ℓ/min. Even under these severe conditions, the performance of the snow-melting system was adequate. Although the performance decreased with the growth of ice around the collector pipes, it is believed that the performance of this device will be sufficient for practical use.

Figure 7 shows the results for the heat transfer coefficient. The squares indicate the results of laboratory experiments conducted previously using a scale model. The lines indicate the results of the calculation of the heat transfer model based on the experimental results. The solid circles indicate the results of the experiment of the present study. Since the experimental results of February 22 are generally consistent with those of the laboratory experiment and the theoretical calculations, the results of the February 22 experiment are determined to be reasonable. In contrast, the results of the experiment conducted on March 7 were quite different from those of the laboratory experiment because of the formation of ice around the collector pipe.

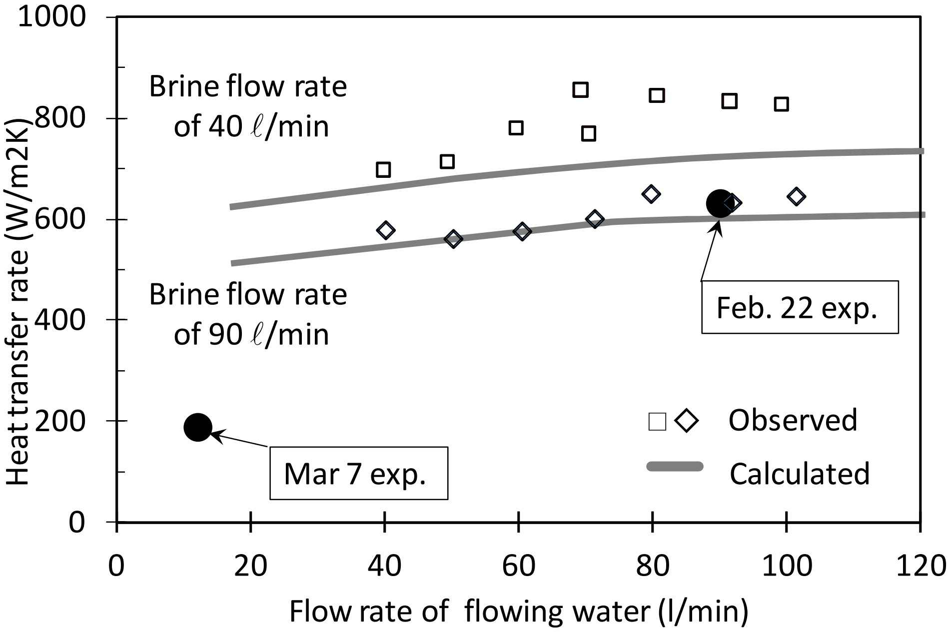


Figure 7 Heat transfer rate of radiator.

4. CONSIDERATIONS

In the system considered herein, approximately 775 W of heat can be collected per meter of ditch (amount of heat radiated [6.2 kW] divided by two 4-m-long collectors). For an area of 10 m^2, only 2.4 m of ditch is required in order to handle the resulting melted snow. In the case of a sidewalk along a road having a snow melting sprinkler system, a melting power of 775 W/m is sufficient for clearing snow along a 3.8-m-wide sidewalk.

In the case of a geothermal heat source heat pump, a heat source temperature of 15°C can be expected. However, heat transfer efficiency depends on the thermal conductivity of the soil (solid material), and the persistence of heat collection is not good (Kamimura et al., 2000). Moreover, drilling costs generally result in high initial costs. In the case of an air-source heat pump, the air temperature during snowfall is below the freezing point of 0°C. In addition, since air is a low-density material, a large volume of air must be moved using a fan to exchange heat, and a periodic defrosting operation is also necessary, during which the system must be stopped. The temperatures of 0°C to 5°C for the flowing water are lower than that of the ground but higher than that of air. The liquid heat source has advantages with respect to the density of a gas and the heat conductivity of a solid. If there is a sufficient amount of non-recirculating flowing water, the sustainability of the heat source performance will be guaranteed.

Within urbanized areas, small rivers or ditches connected to the snow melting sprinkler may be able to provide the required flow rate, so that nearby sidewalks can be cleared of snow. Advances in technology have led to a significant reduction in the price of heat pumps as well as improved performance, especially for mid-range units (6 to 8 kW). Although practical application of the proposed system will require the development of a collector with enhanced durability and higher heat collection efficiency, this technology is considered to be promising.

5. CONCLUSION

The performance of a road heating system that uses a heat pump coupled with flowing water, in particular the exhaust water from a snow-melting sprinkler, was experimentally investigated. A prototype heat collection unit was assembled from 10 steel pipes of 4 m in length and 15 mm in diameter, and the prototype was placed into a roadside U-shaped ditch of 400 mm in width. The heat collection unit was connected to a 6.2-kW heat pump unit, and heated water was fed to a 31.2-m^2 snow-melting radiator. An experiment using a practical model was carried out from February 6 to March 7, 2013.

For flowing water of approximately 4°C and a flow rate of 92 ℓ/min, the amounts of heat collected in the ditch and radiated from the snow-melting panel were 4.8 kW and 6.0 kW, respectively. At that time, the average COP of the system was 5.8, and a snowfall of 10 cm was cleared over the course of three hours. Under the most severe conditions of flowing water of approximately 0.5°C and a flow rate of 12 ℓ/min, the COP remained at 4.5, and the amount of heat radiated was maintained at 4.5 kW, even with the formation of ice around the heat collecting pipe.

The unit length (1 m) of the heat collector was able to provide heating at 775 W/m. As an example, a 10-m^2 bus stop can be cleared of snow using a 2.4-m collector situated in a ditch. Although the development of a collector with enhanced durability and higher heat collection efficiency is necessary, the proposed system is considered to be an effective and promising technology for snow removal in cities that receive heavy snowfall.

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