To utilize air thermal energy for railway facilities, experiments were conducted on snow melting systems equipped with air thermal energy heat pumps at the Kanamaki and Gonen Snow Melting Bases on the Joetsu Shinkansen. In these experiments, system requirements for cold regions were clarified by adjusting the efficiency of defrosting operation, and the CO₂ reduction effect of interlinking heat pumps and boilers was confirmed.

Keywords: Atmospheric heat, Water-sprinkler snow melting method, Heat pump, Boiler, Cold region, CO₂ reduction

1 Introduction

Atmospheric heat is the heat of outdoor air itself. It is difficult to use atmospheric heat alone as a heat source, but atmospheric heat can be collected and radiated as renewable energy by using a heat pump where heat exchange during becomes possible due to the change in state of matter when compressing refrigerant.

Heat pumps use electricity as the power source and are characterized by having a particularly high coefficient of performance (cooling or heating capacity ÷ power consumption, COP). They therefore hold a position as being an important system in achieving a low-carbon society.

Aiming to utilize such air thermal energy for railway facilities, we conducted research on applying air thermal energy heat pumps to water-sprinkler snow melting systems on the Joetsu Shinkansen. On the Joetsu Shinkansen, 31 water-sprinkler snow melting systems are set up in the section between Echigo-Yuzawa and Niigata on the total length of approx. 70 km, not including tunnel sections. The system sprinkles water heated by boilers (quantity of heat generated: 9 to 35 MW per boiler) on the track to melt snow.

The boilers consume a huge annual average of 7,600 kL of kerosene, a kind of fossil oil. We thus decided to replace the heat generated by boilers raising water temperature with that of air thermal energy heat pumps. In this manner, we replace fossil fuel with electric power to reduce fossil fuel consumption, aiming to reduce CO₂ emissions.

2 Overview of Water Sprinkler Snow Melting System Equipped with Heat Pumps

2.1 Water Sprinkler Snow Melting System Equipped with Heat Pumps

Fig. 1 shows an overview of the water sprinkler snow melting system equipped with heat pumps. In this system, heat pumps preheat the water stored in the first tank while the water sprinklers are not operating, reducing the amount of heating by boilers when sprinkling water.

2.2 Issues to Solve in Equipping Heat Pumps to a Water Sprinkler Snow Melting System

(1) Performance deterioration due to frosting

When air temperature falls below the dew point, dew condenses on the heat exchangers of the air thermal energy heat pumps. When air temperature further falls below the freezing point, the dew becomes frost that covers the heat exchangers and deteriorates heat exchanging efficiency. Therefore, the heat pump needs defrosting operation by temporarily changing over from cooling to heating. As the water sprinkler snow melting system is installed under the severe conditions of heavy snow, cold temperature, and high humidity, effects of such conditions have to be sufficiently investigated.

(2) Using heat pumps in conjunction with boilers and time required to raise water temperature

As the water sprinkler snow melting system is designed on the assumption of using boilers alone, we have to study boiler operation taking into account preheating of water to effectively use water heated by heat pumps. Moreover, it takes more time to raise water temperature by heat pumps because those generate a smaller quantity of heat than boilers do. In order to effectively use the heat generated, we have to clarify the relation between the time to raise water temperature and the boiler operation interval in order to design the system and its operation.

2.3 Test System

In the field tests conducted from fiscal 2011 to fiscal 2014, we repeatedly modified the test system according to the details of individual tests. The modification history is as follows.

2.3.1 Kanamaki Snow Melting Base (Fiscal 2011)

Fig. 2 and 3 show an overview of the test system. At the Kanamaki Snow Melting Base, we operated heat pumps alone in fundamental tests to evaluate operation performance of the system under low water and outdoor temperatures in the cold region. The test system was equipped with a cushion tank for defrosting operation. The water heated by the heat pumps was stored in the cushion tank and used as the heat source for defrosting.

(1) Overview of the Kanamaki Snow Melting Base

Length of track water-sprinkled by the base: 2,400 m

Boilers: Six 2.0 Gcal boilers (approx. 14 MW)

First tank capacity: 1,646 m³

(2) Test system

Air-cooled heat pump chiller: 160 kW

Cushion tank: 6.0 m³
2.3.2 Gonen Snow Melting Base (Fiscal 2012 to 2014)

Fig. 4 and 5 show an overview of the test system. Aiming to put the water sprinkler snow melting system equipped with air thermal energy heat pumps into practical use at larger snow melting bases, we equipped the system with three heat pumps and carried out various tests. The purposes of those tests were to look into temperature distribution in the tank, examine defrosting operation methods, and examine control methods when used with the existing boiler system. The unit type heat pump chillers newly added were operated in a unit of two chillers, and they could perform defrosting operation as a single unit alone. In fiscal 2014, we designed a compact test system with just unit type heat pump chillers, without a cushion tank, to carry out tests to check the defrosting limit without a cushion tank.

(1) Overview of the Gonen Snow Melting Base
   Length of track water-sprinkled by the base: 3,651 m
   Boilers: Nine 2.0 Gcal boilers (approx. 21 MW)
   First tank capacity: 3,719 m³

(2) Test system
   Air-cooled heat pump chiller: Two 160 kW chillers
   Air-cooled heat pump chiller (unit type): Two 180 kW chillers
   180 kW = 90 kW + 90 kW
   Cushion tank: 6.0 m³

3. Evaluation of Applying the Heat Pumps for the System
3.1 Verification of Operation Performance under Cold Region Conditions

(1) Operation performance evaluation using low-temperature water
   Fig. 6 shows a comparison of measured heating capacity and COP when raising water temperature by 10 ºC from different intake water temperatures using heat pumps. Compared with the result with intake water temperature 25 ºC, heating capacity was higher by 8% and COP higher by 33% with intake water temperature 5 ºC. Under this condition, the heat pumps operated stably.

(2) Operation performance evaluation at low outdoor air temperature
   We investigated the relation between outdoor air temperature and heating capacity [kW/h] and COP. Defining operation with no defrosting operation as 100% capacity operation, we compared actual heating capacity rates achieved at different outdoor air temperatures. Heating capacity was calculated by dividing the cumulative heating capacity (system capacity - cooling capacity during defrosting) in one operation cycle by operation time. One operation cycle was the cycle from start of heating to the next start of heating.

As shown in Fig. 7, each capacity value became lower as outdoor air temperature dropped. The reason was that the impact of frost on the equipment at low outdoor air temperature was great and capacity loss by operation stop and restart increased while heating, resulting in shortened heating time within an operation cycle. Even under this condition of low outdoor air temperature, the heat pumps stably operated.
3.1.2 Temperature Distribution in First Tank

In using water in the first tank after preheating, occurrence of water temperature unevenness and thermal stratification in the tank was expected. In order to check water temperature distribution in the tank, we examined two methods: simulating water temperature distribution and measuring water temperature using thermo sensors attached in the tank. (1) Simulation of water temperature distribution

Table 1 lists the conditions for simulation of water temperature distribution, and Fig. 8 shows the simulation results. When supplying the tank with heated water with an outlet set at the farthest tank corner from the intake, no remarkable unevenness of water temperature was found. We therefore expected that water temperature would rise evenly.

(2) Measurement of water temperature distribution

As we expected even water temperature rise based on the simulation, we measured water temperature in the tank to confirm that. We attached 12 water temperature sensors each to columns in the tank at heights above the bottom of 500 mm (L), 1,750 mm (M), and 3,000 mm (H), as shown in Fig. 9, and measured at a total of 36 points (12 points horizontally at three different heights). Table 2 shows the average water temperature 48 hours after starting operation of heat pumps. The measurement results proved that no temperature unevenness and thermal stratification occurred in the tank, confirming the effectiveness of the simulation.

3.1.3 Examination of Defrosting Operation Methods

Efficiency of the air thermal energy heat pump system is greatly affected by defrosting operation. In the tests, we examined a method using a cushion tank (using heated water for defrosting stored in the cushion tank) and a method of defrosting with heat pump chillers in pairs (defrosting with unit type heat pump chillers in pairs alone). Furthermore, we identified the lower limit to the temperature of heat source water for idle defrosting at starting up of the heat pumps to find the requirements for stable and efficient system configuration.

(1) Comparison of cushion tank method and method of defrosting in pairs

Fig. 10 illustrates the method of defrosting with heat pump chillers in pairs. Forming pairs of heat pumps, if either heat pump in a pair reaches the conditions for defrosting operation, the other heat pump generates and supplies heat source water for defrosting.

This eliminates the need for a water tank to store heated water for defrosting. We compared this with the cushion tank method based on actual operation data. The results are shown in Fig. 11. During the tests, the heat pump system operated stably. Total quantity of heat generated of the method of defrosting with heat pumps in pairs was 12% higher than that of the cushion tank method, while COP of the cushion tank method was higher than that of the method of defrosting with heat pumps in pairs. However, quantity of heat generated in the cushion tank method includes the quantity of heat generated for heating the cushion tank for defrosting. Therefore, when excluding that quantity of heat, the cumulative heating capacity of the cushion tank method is 2,261 kWh and COP is 3.74. Looking at those values, the method of defrosting with heat pumps in pairs and the cushion
tank method are equal in terms of operation stability and capacity, suggesting that a heat pump system configuration without a cushion tank could be designed.

(2) Identifying the lower limit to temperature of heat source water for idle defrosting

When starting up at the beginning of the season or after recovery from operation suspension due to power outage and the like, the heat pumps start operation at cooling setting even if set to heating (idle defrosting). The test system was equipped with auxiliary heaters that generate heated water in idle defrosting to secure system stability. In order to design a compact system configuration while securing system stability, we have to identify the limit temperature of heat source water for idle defrosting of the system. We thus checked the limit temperature by varying system control parameters of idle defrosting in the tests.

As a typical sample of the test results, test data of heat pump HP-1-1 is shown in Table 3. In this test, we found that idle defrosting needs heat absorption of around 4 °C from the heat source water. And, in the test of reducing heat charging by half from operation suspension due to lower water temperature dropping to the lower limit. This result confirmed that no problem would be caused, even in heat pump system operation only with one of two built-in compressors, when the heat source water temperature for idle defrosting by heat pumps alone is higher than 3 °C (2 °C for heat charging + 1 °C for margin). Based on this result, we concluded that the lower limit temperature of heat source water for idle defrosting is 5 °C or higher (4 °C for heat charging + 1 °C for margin) in ordinary operation and 3 °C in operation with only one built-in compressor, and that auxiliary heaters should be equipped as needed to secure the temperature.

[Test details]
1) Operate heat pumps at stable heating.
2) Check heat pump system behavior in defrosting operation (idle defrosting) in automatic recovery after the breaker is tripped and reset.

[Condition for ending idle defrosting (condition for changing over to heating circuit)]

When either of the following conditions is met, the system switches over to heating operation.
1) A 0.4 MPa or greater difference in pressure of built-in compressors is secured.
2) 180 seconds have passed after idle defrosting started.

[Condition for system suspension (system protection)]
1) Abnormal lower limit temperature of heat source water (set value) zero degree.

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**Table 3** Limit Test Results of Heat Source Water for Idle Defrosting (HP-1-1)

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Idle defrosting test data</th>
<th>HP-1-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Compressor (MHz)</td>
<td>Time-initial frequency (MHz)</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
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<td>30</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>

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**Fig. 11** Comparison of Quantity of Heat Generated in Method of Defrosting Using Heat Pumps in Pairs and in Cushion Tank Method

**Fig. 12** Water Temperature Change in First Water Tank of Gonen Snow Melting Base

**Fig. 13** Quantity of Heat Generated by Boilers and Heat Pumps

**Fig. 14** Annual CO₂ Reduction Effect

3.1.4 Quantity of Heat Generated and CO₂ Emissions Reduction

Fig. 12 shows data of water temperature rise in the first tank and operation results for the Gonen Snow Melting Base (February 20 to 27, 2013). When the base was not in operation, heating by heat pumps gradually raised water temperature in the first tank. Thus, the quantity of heat needed for heating by boilers was reduced by that temperature rise. Fig. 13 shows the quantity of heat generated in the above-mentioned period. The heat pumps generated 23.8% of the total quantity of heat in that period. CO₂ emissions were reduced by 12.9% by replacing kerosene with electric power to generate some of the heat. Assuming the ratio of the heat sources of the quantity of heat remains the same, annual reduction of CO₂ emissions will be 56 t-CO₂ as shown in Fig. 14.
3.2 Evaluation of Operation in conjunction with Boilers

3.2.1 Investigation of Operation Control Considering Preheating of the Water Tank

The water sprinkler snow melting system starts up when the snow detector detects snowfall over a specified intensity and certain conditions are met. The temperature at which water the sprinkling command is issued (hereinafter, “water sprinkling command temperature”) is calculated based on the temperature of returned water, but the initial water sprinkling command temperature is according to settings (9 ºC in winter, 10 ºC in midwinter). In order to control the number of boilers to start up, the number of boilers is calculated using the parameters of each snow melting base based on the difference between the water sprinkling command temperature, and the water temperature in the first water tank with the number of boilers to initially start up (the setting) is added to that. As the water in the first tank is preheated in the water sprinkler snow melting system equipped with heat pumps, we might be able to reduce the number of boilers to initially start up if the water temperature in the first tank is high enough at startup.

Fig. 15 shows the operation status of the snow melting bases before changing the boiler system control and Fig. 16 shows that after the change. Fig. 15 demonstrates that the water temperature in the first tank did not drop for approx. 30 minutes after system start up. Furthermore, we confirmed that one of the boilers started up and operated unnecessarily in this period, even though the water temperature in the first tank was higher than the set water sprinkling command temperature.

When water temperature in the first tank is higher than the water sprinkling command temperature, boilers do not need to be lit during the above-mentioned 30 minutes before returned water comes back. We therefore changed the setting for the number of boilers to initially start up to zero and tested the system. Fig. 16 demonstrates that the water temperature in the first tank did not drop for approx. 30 minutes after system start up. Therefore, we changed the water sprinkling command temperature such that the water temperature in the first tank was maintained (30 min., hereinafter, “time at initial boiler number”). If the water temperature in the first tank did not drop for approx. 30 minutes after system start up, the water sprinkling command temperature was set to zero, we were able to eliminate unnecessary boiler operation. Moreover, even when the number of boilers to initially start up was set to zero, we were able to confirm that the sprinkled water temperature followed the water sprinkling command temperature, so that did not interfere the water sprinkling system of the snow melting base.

[Settings on February 6]
- Number of boilers to initially start up: 0
- Minimum number of boilers to be lit: 1

[Settings on March 2 (after change)]
- Number of boilers to initially start up: 0
- Minimum number of boilers to be lit: 1

(Initial boiler number time: 30 minutes)

3.2.2 Effect of Preheated System Operation

(1) Preheated system operation and temperature rise time at the snow melting base

Since heat pumps just have small heating capacity in contrast with the scale of the water sprinkler snow melting system, preheating takes time. We thus have to know the estimated heating time of each snow melting base if we are to achieve effective preheating. Based on the operation data for three years from fiscal 2012 to fiscal 2014 at the Gonen Snow Melting Base, we checked the operation interval time [h] for the base and estimated the heating time that can be expected from the rate of the number of times the base was operated (times operated).

Fig. 17 shows the rate of the number of times operated for the individual operation intervals of the Gonen Snow Melting Base for three years. From this data, we can probably estimate the operation interval time (heating time) that can be expected at a given rate. For example, from the rate of number of times operated, interval time is longer or shorter than 11 h in 50% of the total number of times operated. In other words, in 50% of
the total number of times operated, heating time longer than 11 h can be expected. However, we have to statistically obtain the value for each snow melting base based on more samples as that value varies according to environment and weather conditions.

(2) Relation between heating time and amount of CO\(_2\) reduction

We investigated the relation between heating time and CO\(_2\) reduction effect when heat pumps and boilers were both used. Based on test data in fiscal 2014, we set calculation conditions as follows and verified the relationship.

[Calculation conditions (Gonen Snow Melting Base)]

Heat pump capacity (actual): 125 kW/h \(\times\) 2 heat pumps, COP: 3.56
Quantity of heat generated from kerosene: 8,216 kcal/L
First tank capacity: 3,719 m\(^3\)

Temperature raised \(\Delta t\): 5 °C

CO\(_2\) emissions coefficient:
2.49 kg-CO\(_2\)/L (released by the Ministry of the Environment)
Electric power: 0.59 kg-CO\(_2\)/kWh (Tohoku Electric Power Co., Inc., 2013)

[Calculation: Heating time required to raise water temperature in the tank by 5 °C (by heat pumps)]

(Quantity of heat required) / (Heat pump capacity)
21,622 kW / 250 kW/h = 86.5 h \(\approx\) 90 h

In order to raise water temperature in the first tank by 5 °C under the calculation conditions above, approx. 90 h heating time is required. Fig. 18 shows the relation between the heating time and the CO\(_2\) emissions amount in that case. Assuming heating time of 90 h is secured, the CO\(_2\) reduction amount per operation is 1,971 kg-CO\(_2\), meaning a 35% reduction from with no heating.

### 4 Conclusion

In order to verify the applicability of air thermal energy heat pumps to water sprinkler snow melting bases, we carried out field tests at Kanamaki and Gonen Snow Melting Bases on the Joetsu Shinkansen. The results are as follows.

(1) Applicability to water sprinkler snow melting bases

- Heat pumps worked stably under the conditions of cold water and low outdoor temperature.
- The lower the outdoor temperature is, the lower the efficiency became due to frosting.
- Water temperature in the first tank became almost even when heat pumps were used.

- In defrosting operation, efficiency of the method of defrosting using heat pumps in pairs and the cushion tank method were almost equal to each other, thus a system configuration without a cushion tank is feasible.
- In this heat pump system, temperature of heat source water needs to be kept higher than 5 °C in ordinary idle defrosting operation and higher than 3 °C in operation using only one compressor.
- At the Gonen Snow Melting Base, heat pumps generated 23.8% of the total quantity of heat in the test period.
- At the Gonen Snow Melting Base, the CO\(_2\) reduction rate was 12.9%.

(2) Evaluation of heat pump operation in conjunction with boilers

- With sufficient preheating, the number of boilers to initially operate can be reduced.
- We demonstrated the concept of estimating heating time based on the operation interval time.
- We demonstrated the relation between heating time and CO\(_2\) reduction amount.

As facility capacity and the weather conditions vary among snow melting bases, we have to consider and specify the details for introducing the heat pump system according to the installation environment of each snow melting base. However, the system can make a great contribution to reducing environmental burden. We will actively work to deploy the system as a measure for utilizing renewable energy.