Deicing efficiency and snow melting on roof through heat exchange pipe

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Abstract. The energy pile can support the load of upper buildings and exploit the shallow geothermal energy by embedding the traditional ground-source heat pump in the pile foundation of buildings. The steel roof has a large span and poor load-bearing capacity, and it is easy to collapse in the ice and snow weather. Based on the model test and the numerical model, the differences of deicing efficiency on roof through heat exchange pipe under different heat exchange pipe materials, position of pipe layout and pipe spacing on the roof panel, etc. were analyzed in this paper. Results showed that, when the heat exchange pipes were arranged above the panel, the ice melting time was about 2 / 3 of that when heat exchange pipes were arranged under the panel; The shorter the pipe spacing and the denser the pipe arrangement, the faster the ice melting rate.

1. Introduction
Steel structure is widely used in civil and industrial buildings due to its advantages of light weight, low cost and fast construction speed[1-3]. The ice and snow conditions in winter have a great impact on the steel roof, which could lead to the damage and collapse accidents of the steel roof[4-6]. The main causes of the accident are as follows: first, the safety of the structure
is greatly reduced under the condition of large load of ice and snow; Second, the load of ice and snow is not easy to flow and eliminate, a large number of local accumulation makes the roof bear the load far beyond the scope of structural design\[7\]. Limited to the large span and poor bearing capacity of steel roof, it is hard to deice and melt snow by manual and mechanical means\[8-9\]. Spraying chemical reagent can easily corrode the main body of steel structure, which leads to safety hazards. Other main snow removal methods are too expensive and not suitable for large-area roof deicing and snow melting.

Energy pile is a new kind of ground-source heat pump embedded in the pile foundation of building, which can support the load of the upper building and exploit the shallow geothermal energy at the same time\[10\]. In view of the thermodynamic response of energy piles, scholars have done extensive researches\[11-16\]. However, there are little researches focused on deicing efficiency and snow melting on large-span steel roof with energy piles.

Hence, in this study, based on the model test and numerical simulation method, the differences of deicing efficiency on roof through heat exchange pipe under different heat exchange pipe materials, position of pipe layout and pipe spacing on the roof panel, etc. Were analyzed, so as to provide some reference for practical application.

2. Description of model test

2.1. Introduction of model test
Material of the roof panel was 840 color steel veneer with thickness of 0.6 mm, which was decided by the "Code for Design of Steel Structures" and investigating the actual steel structure workshop. PERT pipe and aluminum-plastic pipe were selected for comparative test. The distance between pipes was 20 cm. Pipes were arranged at the bottom and upper part of roof panel (1m×1m). The photos of pipe layout above and under the panel are shown in Figures 1(a) and 1(b).
2.2. Model tests design

The size of the roof panel model was 1m×1m, the materials of pipes were PRET and aluminum-plastic, respectively. The pipe diameter was 16 mm, the pipe spacing was 20 cm, and the velocity of heat exchange fluid was 0.6 m/s. 2.5 kW power heating device was placed in the thermal insulation water tank for heating, and the heating power is conforms to the thermal characteristics of the energy piles recorded in the reference[11-16]. The circulation loop composed of the heat exchange pipe was fixed at the upper part/bottom of the roof panel with pipe clamp and drilling screw, pipes at the bottom were insulated with 5cm-thick rock wool. Thermometers were arranged at the inlet and outlet of the heat exchange pipe and in the thermal insulation water tank, the water pump was connected between the pipeline and the thermal insulation water tank to provide a steady flow of water.

2.3. Ambient temperature

The ambient temperature of the model test is shown in Figure 2. In the numerical model, taking the ambient temperature recorded in the model test as the benchmark, the continuous ambient temperature was obtained by linear interpolation.

![Ambient temperature of model tests](image)

Fig. 2 Ambient temperature of model tests

3. Establishment of numerical model

3.1. Model size, material and mesh division

In the numerical model, the size of roof panel was 1m×1m×6mm, which was consistent with the model test, 5cm-thick rock wool layer was arranged under the bottom pipe. The layout of the pipe was the same as that of the model test, the pipe spacing was 15 cm, 20 cm, 25 cm and 30 cm, respectively; The pipe diameter was 16 mm, 20 mm and 25 mm, respectively. The thermal conductivity of the pipe materials were adjusted to simulate different actual pipes. When the liquid entered the pipes on roof panel, the non isothermal pipe flow was used to simulate at once. The heat conduction equation is shown in Eq. (1). The numerical model and mesh division are shown in Figure 3, in which the blue parts were the heat exchange pipes arranged under the roof panel.
\[ U_1 = U_t + U_s \] (1)

In which, \( U_1 \) is the total work done by deicing system on ice, \( U_t \) is the heat required for ice temperature change, and \( U_s \) is the heat required for ice phase change (melting heat).

Fig. 3 Pipe layout and mesh division

3.2. Boundary conditions and initial conditions

The initial temperature of the pipes and panel in numerical model were consistent with the ambient temperature of the model test at the first moment; The inlet water temperature was consistent with the records of model test. The continuous inlet water temperature was obtained by interpolation based on the inlet water temperature recorded in model test at each moment. There was no heat exchange between pipes and air (radiation heat exchange), and the heat only exchanged between the pipes and the materials above (corresponding to the heat insulation measures took in model test). The temperature of the upper and lower part of the top panel was the same.

4. Test scheme and working condition

The E-B model was used due to the heat exchange pipe and panel were considered as linear thermoelastic. Table 1 shows the thermomechanical properties of two kinds of heat exchange pipes and the parts of roof panel used in the numerical model, which were measured in the laboratory using the KD2 Pro device.

| Material           | \( \lambda \) (W/(m·K)) | \( C_p \) (J/(kg·K)) | \( \rho \) (kg/m³) | \( \mu \) (Pa·s) | \( v \) |
|--------------------|--------------------------|-----------------------|-------------------|------------------|------|
| Water              | 0.613                    | 4179                  | 997               | 0.001            | 1    |
| Ice                | 2.31                     | 2052                  | 918               | —                | —    |
| Rock wool          | 0.035                    | 0.75                  | 100               | —                | —    |
| PERT               | 0.40                     | —                     | —                 | —                | —    |
| Aluminum-plastic pipe | 0.45                  | —                     | —                 | —                | —    |

In which: \( \lambda \) is the heat transfer coefficient, \( C_p \) is the heat capacity at constant pressure, \( \rho \) is the density, \( \mu \) is the dynamic viscosity, \( v \) is the specific heat rate.

The working conditions are shown in Table 2, in which, the heating power of all conditions was the same as the model tests (2.5 kW).

Table 2. Working condition of roof deicing
5. Results and analysis

5.1. Inlet water temperature of model test

Records of inlet water temperature of each condition are shown in Figure 4. The deicing time with pipes arranged above the panel was obviously shorter than that with pipes arranged under the panel. There was a little difference in the initial inlet water temperature among the four groups of tests, which was influenced by the ambient temperature and surrounding conditions. Under the condition of pipes arranged under the panel, when the thickness of ice was 5 cm, in 0-100 min, the rate of temperature rise of the inlet water (i.e. the temperature of the water tank) was obviously faster than that of the condition where the ice was 3 cm thick, and it means that the deicing power \( P_1 \) of the system decreases with the decrease of the ice layer thickness in the initial stage of the test, which is related to the difference of heat transfer coefficients between ice and water. Under the condition of standard atmospheric pressure and 0 °C, the heat transfer coefficient of ice is about 4 times that of water. As the ice layer is thicker, the time for ice to reach the melting point is longer, the heat transfer coefficient of the ice layer is higher, and the corresponding deicing power is higher. When the ice layer is thin, the time for ice to reach the melting point is short, and the ice quickly reaches the state of ice water mixture, the increase of water in the system makes the mixed heat transfer coefficient decreases, and the corresponding deicing power decreases. After 100 min, the curves of the inlet water temperature of groups with pipes arranged under the panel were roughly the same, that is, the deicing power of the system gradually tends to be the same. The reason is that, as time increases, a large amount of water is produced at the bottom of the ice layer, separating
the ice layer from the panel, thus the heat transfer coefficient of different tests tends to be the same. Under the condition of 3 cm ice layer, PERT pipe / aluminum-plastic pipes arranged under the panel, the inlet water temperature curve was almost the same, and the temperature rising speed of aluminum-plastic pipe condition was slightly higher than that of PERT pipe condition; It could be considered that there was no obvious difference due to the difference of initial inlet water temperature and the ambient temperature in tests.

![Fig. 4 Temperature change diagram of water inlet in model tests](image)

5.2. Heat conversion ratio of model test
In the four kinds of roof deicing model tests, the difference between the inlet and outlet water temperature of the roof panel was small due to the small size of the model panel (1m×1m) and the short length of the pipeline (7m). It was impossible to calculate the heat transfer power based on the inlet and outlet water temperature, so the "Heat conversion ratio" index was introduced for comparison:

$$\sigma = \frac{U_1 + U_2}{W}$$  \hspace{1cm} (2)

$$W = P \cdot t = U_1 + U_2 + U_3$$  \hspace{1cm} (3)

In which, $\sigma$ is the heat conversion ratio, $W$ is the total work of the system, $U_1$ is the total work of deicing system on the ice layer, $U_2$ is the heat dissipation work, and $U_3$ is the total work needed by the water temperature rise in the model test system.

In the model test system, the constant heating power $P$ is 2.5 kW, and the difference between ambient temperature was small, it could be considered that the power of heat dissipation is the same and constant in different tests, therefore:

$$\sigma = \frac{1 - U_1}{W} = \frac{U_1 + U_2}{P_t} = A + \frac{U_1}{P_t} = A + \frac{P_1}{P}$$  \hspace{1cm} (4)

$$P_1 = \frac{\sigma - A}{P} = \frac{\sigma}{P} - C$$  \hspace{1cm} (5)
In which, \( A \) and \( C \) are constant, \( P_1 = \frac{U_1}{T} \) is the deicing power of the model test, which is proportional to \( \sigma \).

The change of heat conversion ratio versus time is shown in Figure 5. In the model test, the time for complete ice melting was different due to the different environmental temperature and different test conditions. Figure 5 shows that, when the thickness of ice was 1.5 cm and the PERT pipes were arranged above the panel, the heat conversion ratio increased fastest with time, and the ice melted fastest, the complete melting time was 145 min; In the other three tests, pipes were arranged under the panel, the slopes of heat conversion ratio were similar, and the changing trends versus time were similar. It could be seen that when the heat exchange pipes were arranged above the panel, the time of ice melting was obviously shorter than that when the pipes were arranged under the panel; The deicing power \( P_1 \) increased faster when pipes were arranged above the panel, and the rising rates of deicing power \( P_1 \) were similar when pipes were arranged under the panel.

In the three groups of tests whose pipes were arranged under the panel, when the thickness of the ice layer was 1.5 cm, the heat conversion ratio was significantly higher than that when the ice was 3 cm thick. When the ice thickness increases, the total work required for deicing increases (the latent heat required for melting is 333.5 kJ/kg). What’s more, the heat transfer coefficient of water (0.613 W/(m·K)) is about 1/4 that of ice (2.31 W/(m·K)) at 0°C, therefore, with the increase of water in the system, the heat transfer efficiency will decrease, and the deicing power \( P_1 \) of the system will also decrease.

In the two groups of comparative tests, pipes were arranged under the panel and the ice thickness was 3 cm, other arrangements were the same. The heat transfer coefficient of PERT pipe was 0.40 W/(m·K) and that of aluminum-plastic pipe was 0.45 W/(m·K). Figure 4 shows that there was little difference in heat transfer efficiency between these two groups of tests; The value and slope of heat conversion ratio, the ice melting time of the two groups were almost the same. The curve of heat conversion ratio of aluminum-plastic pipe condition was slightly higher than that of PERT pipe condition, that is, with the increase of heat transfer coefficient of heat exchange pipe, the deicing power \( P_1 \) of model test system will increase slightly. When the heat transfer coefficient of pipes are similar, different pipes have little effect on the deicing power \( P_1 \) of the system, which could be ignored.
5.3. Verification of numerical model

In the model test, the heating power was 2.5 kW; In the numerical model, in order to get the same heating power, variable inlet water temperatures were set at the inlet of the pipe, which was consistent with model test conditions. The continuous inlet water temperature was obtained by piecewise interpolation based on the temperature recorded in model tests. When the running time of the numerical model was out of the model test, the corresponding temperature was obtained by using linear function simulation.

The proportion of ice melting (i.e. phase change ratio) in the numerical model was compared with that in the model test to verify the correctness of the numerical model, which was verified by the time required for complete ice melting. Taking the numerical model condition of “1.5 cm thick ice layer, PERT pipe under the panel” as example, Figure 6 shows the phase change of the ice layer in the numerical model, in which the blue area represents ice and the red area represents water. Figure 6 (a) shows the phase change distribution at 30 min, and Figure 6 (b) shows the phase change distribution at 210 min. The numerical model could be used to simulate the ice phase change at different times.

![Fig. 6 Scale nephogram of ice phase change in numerical model](image)

(a) 30 min  (b) 210 min

The numerical results of model test under four conditions are shown in Figure 7. The time of complete ice melting of two conditions: “1.5 cm ice layer-PERT pipe-under/above the panel” agreed well with the model test (249 min, 155 min, respectively). When the thickness
of ice was 3 cm, the deicing time of two numerical models was slightly faster than that of the model tests.

The curve of “1.5 cm ice layer, PERT pipe, under the panel” shows a certain phase change in the initial period, which was related to the initial ambient temperature; In addition, it tended to grow in a straight line within 0-100 min, and the growth rate gradually slowed down within 100-249 min, which meant that the deicing power kept stable at first, and then decreased gradually; This was consistent with the analysis that the heat transfer efficiency decreased gradually with the increase of meltwater in the model test. The curve of “1.5 cm ice layer, PERT pipe, above the panel” tended to be a straight line within 0-155 min, which meant that the output of deicing power was almost constant and the effect was better when the pipes were arranged above the panel; It verified the conclusion that the ice melting time of piping above panel was much shorter than that of piping under panel (based on the conditions in this paper), and the accuracy of the numerical model was also proved.

When the thickness of ice was 3 cm, the results of the two numerical models were very close, which was consistent with the results of the model test. It verified that when the heat transfer coefficient was close (0.40 W/ (m·K)) (the difference is less than 10%), the pipe material had little affect on the deicing results, and the accuracy of the numerical model was further verified.

5.4. Deicing efficiency versus different liquid velocity

In tests, the boundary condition of constant temperature heating was adopted, the inlet water temperature was 40 °C, the ambient temperature was -2 °C, and the initial temperature of ice layer, roof panel and heat exchange pipe was -2 °C. The numerical model condition of the control group was: pipes under the panel, 1.5cm-thick ice layer, PERT pipe, pipe outer diameter of 16 mm, pipe spacing of 20 cm.

![Phase change ratio of ice versus time](image-url)

Fig. 7 Phase change ratio of ice versus time
5.5. Deicing efficiency versus different pipe diameters

The deicing efficiency of the numerical models was compared and analyzed when the pipe diameter was 16 mm, 20 mm, 22 mm and 25 mm, respectively under the specified boundary conditions (the same as Section 5.4). Figure 9 shows the phase change ratio of ice versus different pipe diameters. The curves of phase change ratio versus different pipe diameters were distinct. When the pipe diameter was 16 mm, the ice melting rate was the fastest, and the ice melting rate under the condition of 20 mm pipe diameter was the slowest. Take the curve of “16 mm pipe diameter” as reference, with the increase of pipe diameter, the deicing power of the system first decreased and then increased, and reached the lowest point when the pipe diameter was around 20 mm. It could be analyzed that, the initial temperature of the pipe itself was low, which affected the initial heat transfer efficiency of the system, with the
increase of pipe diameter, the negative effect increased. What’s more, the contact area between the pipe and the roof panel was small, the increased energy provided by the increased flow due to the increased pipe diameter at the initial stage was not enough to offset the increased negative effect of the pipe itself. However, with the further increase of the pipe diameter, the contact area between the pipe and the roof panel increased, which made the deicing power of the system rise again.

![Phase change ratio of ice versus different pipe diameters](image)

**Fig. 9** Phase change ratio of ice versus different pipe diameters

5.6. **Deicing efficiency versus different pipe spacing**

The deicing efficiency of the numerical models was compared and analyzed when the pipe spacing was 15 cm, 20 cm and 25 cm, respectively under the specified boundary conditions (the same as Section 5.4). Figure 10 shows the phase change ratio of ice versus different pipe spacing. From which, with the decrease of pipe spacing, the melting rate of ice layer was obviously accelerated. When the pipe spacing was 25 cm, 20 cm and 15 cm, the ice layer completely melted in 162 min, 100 min and 72 min, respectively. Taking the curve of “20 cm pipe spacing” as reference, when the total length of pipe increased by 33% per unit area (15 cm pipe spacing), the complete melting time of ice decreased by 28%; When the total length of pipe decreased by 20% per unit area (25 cm pipe spacing), the complete melting time of ice increased by 62%. Therefore, the shorter the pipe spacing and the denser the pipe arrangement, the faster the ice melting rate, and the deicing efficiency would be higher.
6. Conclusion

The deicing efficiency and snow melting on roof through heat exchange pipe were carried out. Some conclusions can be obtained as follows:

(1) In model tests, when the heat exchange pipes were arranged above the panel, the ice melting time was about 2/3 of that when the pipes were arranged under the panel. The deicing power $P_1$ of model tests increased rapidly versus time when the pipes were arranged above the panel. With the increase of heat transfer coefficient of pipe, the deicing power of model test system increased slightly. When the heat transfer coefficient of pipes were close (within 10%), the influence of different pipes on the deicing power of system was small and could be ignored.

(2) In the numerical model, the ice melting speed was gradually accelerated with the increase of inlet water velocity, but the increase of deicing efficiency was not obvious. Taking the condition of “20 cm pipe spacing” as reference, the ice melting time decreased by 28% when the total length of pipe in unit area increased by 33%. The ice melting time increased by 62% when the total length of pipe in unit area decreased by 20%. Hence, the ice melting rate was increased with the decreasing of pipe spacing and the denser the pipe arrangement.

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