Numerical simulation of heat transfer performance and reliability design of road snow-melting system based on inorganic heat pipe

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Abstract. In order to study the optimal design parameters of the heat pipe system in the heat pipe snow-melting road structure, a finite element analytical model of the snow-melting road is established based on the heat transfer theory. And based on the analysis of internal heat transfer and surface convective heat transfer of the road, the author set suitable boundary conditions of temperature field according to the actual situation of the road pavement and made quantitative research on the influence of factors such as the evaporating section burial depth and arrangement distance of the heat pipe on the pavement temperature field. The results show that the optimal arrangement distance of the heat pipes is 300-500mm, and when the heat pipe distance is 500mm, the temperatures of the road surface increased slowly, the isotherm of 0℃ will no longer continue, and the snow-melting time would become longer; heat pipe burial depth should be determined according to the road structure, the shallower the burial depth the better the snow-melting effect.

1. Introduction
Snow on highways is one of the important factors of the occurrence of traffic accidents in rain and snow. According to statistics, in the winter, snow and ice will directly affect about 70% of China's highways, and a lot of major traffic accidents resulted from ice and snow every year have caused a large number of casualties and property damage[1]. Developing effective snow melting technology is an important issue to ensure the safety of road traffic in winter. At this stage, the traditional methods of snow and ice clearing, splashing snow-melting agents and others are also no longer adapt to the intelligent high-speed road network construction requirements due to excessive reliance on manpower and their great damages to the road structure[2]. Today, it is an inevitable trend to use new energy, new materials, and other new snow-melting technologies to achieve the goal of ensuring highway transportation wisely and safely. Inorganic heat pipe melting-snow technology is green, efficient, active, which specifically belongs to the category of energy conversion road.

By doing so, it allows the author to deeply studies the unsteady heat conduction mechanism of heat pipe technology in snow melting, forms a perfect series of theoretical basis of heat pipe snow-melting
system, and proposes the optimal design parameters of the heat pipe system, so that provides theoretical support to solve this engineering problem of highway snow melting\[3\].

In this paper, by establishing a finite element model based on heat transfer theory, the author analyzed minutely the time required for snow melting on the road surface under the conditions of 0℃, -5℃, -10℃ combined with the snowfall of 2mm, 5mm and 10mm, and the snow melting effect under the heat pipes arrangement distance of 100mm, 200mm, 300mm, 400mm and 500mm. The author combines the numerical simulation and his analysis of engineering test results, and finally determines the optimal parameter design of highway heat pipe snow-melting system.

2. Numerical model for roads snow melting with inorganic heat pipe

2.1. coupled governing equations of a numerical model for heat pipe snow melting system

The snow melting process of the heat pipe snow melting system is complex which includes mass and heat transfer and energy dynamic transfer\[4\]. Based on the research of the mechanism of heat transfer with heat pipes and snow melting mechanism, and on the overall consideration of ambient temperature, wind speed, snowfall speed and relative humidity, the author proposed a road snow melting model, and the corresponding differential equations of heat conduction control are as follows.

\[ \lambda_{\text{ice}} \nabla T_{\text{ice}} = -h(T_{\text{amb}} - T_{i-s}) - \varepsilon \sigma (T_{i-s} - T_{\text{sky}}) \]  

(1)

(2) Coupling surface equation

The coupling surface equation describes the energy transfer when two materials with different properties are in contact. It means that the heat output from the high-temperature surface is equal to the heat input of the opposite low-temperature surface, and the generalized form is given in equation (2).

\[ \lambda_{\text{ice}} \left( \frac{\partial T_{i-s}}{\partial x} + \frac{\partial T_{i-s}}{\partial y} + \frac{\partial T_{i-s}}{\partial z} \right) = \lambda_{\text{ice}} \left( \frac{\partial T_{\text{amb}}}{\partial x} + \frac{\partial T_{\text{amb}}}{\partial y} + \frac{\partial T_{\text{amb}}}{\partial z} \right) \]  

(2)

Where: \( \lambda_{\text{ice}} \) is the heat conductivity coefficient of snow; \( T_{\text{amb}} \) is the ambient temperature; \( T_{i-s} \) is the temperature of the outer surface of the snow layer; \( T_{\text{ice}} \) is the temperature of the snow layer; \( T_{\text{sky}} \) is the radiation temperature of sky; \( \varepsilon \) is the emissivity of the ice surface; \( \sigma \) is the Stephen-Boltzmann constant; \( h \) is the convective heat transfer coefficient of the natural flow of air; \( v \) is the flow velocity of ambient air.

2.2. Definite conditions and physical parameters

2.2.1. Definite conditions

With the use of ground sources as a renewable energy source, determining soil temperature is also important for the efficiency of the ground source heat pump and buried heat pipe. We will take the environmental parameters of Jinan at 0:00 on January 1 as an example to calculate the soil temperature varies with depth. The calculation results are shown below\[5\].

Figure 1. Variation of soil temperature with depth.
Figure 1 shows that when y = 8m, the soil temperature amplitude has been reduced to the extent that can be generally ignored in engineering calculations. Therefore, 8m was set as the boundary of isothermal layer, in the layers above 8m, initial values of soil temperature varying with depth are set at 1m intervals, and below 8m, premising the soil temperature does not change with the change of depth, set the temperature to the same value in the simulation calculation.

2.2.2. Determination of physical parameters
In the snow-melting calculation model, there will be a phase change process from snow to water. And in the solution of the phase change heat transfer model, there are mainly the effective capacity method and the enthalpy method to deal with the phase change process of materials[6]. In this study, the author used the effective capacity method to simulate the phase change from snow to water. In the process of phase change, the thermal conductivity will change greatly. The physical parameters of specific heat capacity and thermal conductivity during the melting of snow are shown in Table 1.

| Object                        | Density (kg·m⁻³) | Specific heat capacity (J·kg⁻¹K⁻¹) | Thermal conductivity (W·m⁻¹K⁻¹) |
|-------------------------------|-----------------|-----------------------------------|--------------------------------|
| Asphalt upper layer           | 2300            | 1000                              | 0.83                           |
| Asphalt middle and lower layers | 2300            | 700                               | 1.67                           |
| Lime soil subbase             | 2100            | 900                               | 1.11                           |
| Soil foundation               | 1800            | 900                               | 1.25                           |
| Polyurethane                  | 45              | 1800                              | 0.026                          |
| Heat pipe medium              | 1000            | 4000                              | 14×10⁷                         |
| Snow                          | 125             | Eq.(14)                           | Eq.(13)                        |

2.3. Model building and model validation
The whole physical model is shown in Fig. 2. The model is divided from top to bottom into snow layer, asphalt surface layer, lime soil sub-base, soil layer, and the heat pipes and their polyurethane insulation components running through it. In addition, the vertical pipe depth of the heat pipes is 13000mm, the length of the cross pipes of the heat dissipation section is 2800m, and the diameter of the pipe is 32mm; the insulation material of heat pipe is laid on the uppermost side of the vertical section of the heat pipe. The outer diameter of the insulation materials is 100mm, the inner diameter is 32mm, and the laying length is 1000mm. The entire computational region of this model is divided into 1.5 million meshes, and the distortion rate of the meshes is less than 0.8.

3. Numerical model results and system reliability design

3.1 Snow-melting model validation for asphalt roads
The heat pipe snow melting experiment is conducted on February 14 and 15, 2019. During the experiment, the snowfall starts from 10:00 on February 14 and ends at 6:00 on February 15, and its temperature changes during the whole process are shown in Figure 3. According to the actual average
temperature of snow melting is -0.23℃, we can determine the ratio of snowfall and snow thickness is 1:5. Taking the snowfall intensity of 2mm as an example, the snow thickness can be determined as 10mm.

![Figure 3. Simulated snow melt temperature variation.](image)

3.2 Numerical model structure

3.2.1 The analysis of heat transfer law in single heat pipe model

In order to better explore the asphalt pavement heating range of heat pipe heat dissipation in the heat pipe snow melting process, the author established a three-dimensional snow melting model of a single pipe. Figure 4 shows the temperature distribution of the road surface from 0 to 20h.

![Figure 4. The road surface temperature distribution of single heat pipe model in snow melting process.](image)

During the 0 ~ 20h, the temperature radiation range of heat pipes to the road surface is roughly half of the tube spacing, that is, when the tube spacing is 400 ~ 500mm, the temperature of the road surface is more average. From Figure 4.2.3, we can found that during the 0~20h process of melting snow, when the temperature of the road surface lies within the axle wire of 200 ~ 250mm (tube spacing 400 ~ 500mm) the temperature is relatively higher, and the snow-melting performance is better.

![Figure 5. Model monitoring point temperature](image)

According to the analysis of the dynamic temperature field data in asphalt pavement snow melting, the heat transfer of a single heat pipe can maintain the pavement surface temperature above 0℃ within 200-250mm from the axle wire of the heat pipe without considering the superimposed influence of the temperature field between heat pipes. According to the simulated data of the heat transfer between the
heat pipe and the asphalt pavement, the sphere of effective influence of a single heat pipe on the pavement is within 250 mm from its axle wire.

3.2.2 Heat transfer law analysis of heat pipe snow melting model with different pipe spacing
In the actual engineering application of heat pipe snow melting, the spacing of heat pipe plays a crucial role in the effect of snow melting and engineering investment. When the spacing of the heat pipe is too small, the snow melting efficiency and reliability will be improved, but the cost will also be significantly increased, so it is very necessary to determine the optimal spacing of the heat pipe. The condition setting of Numerical simulation was done under the full consideration of matching with the condition setting of the new inorganic heat pipe snow-melting test platform. And, at the same time, considering different environmental conditions, the author sets the following numerical model test with different conditions combinations.

![Figure 6. -5 ℃, when snowfall is 5 mm, the road surface temperature area map.](image)

Fig. 6 shows that the temperature field of the road surface is symmetrical along the axle wire, and the temperatures decrease along the axle wire toward the outer side. Analysis of the road surface temperatures at different pipe spacing shows that with the increase of pipe spacing, the temperature gradient at the road surface decreases and the maximum temperature at the intersection decreases, too.

3.2.3 Analysis of the effect of heat pipe burial depth on snow melting performance
Based on the burial depth setting in the experimental platform, in order to analyze the effect of the burial depth of the heat pipe on the snow melting performance, the author chose two burial depths of 10cm and 18cm to calculate and explain.

![Figure 7. Temperature field at ambient temperature -5℃, snowfall 5mm, snow melt 20h.](image)

From Figure 7, we can see that when heat pipe spacing is 400mm, the temperature is -5 ℃ and snowfall is 5mm, the temperature change of the interface of road surface and snow under the conditions of heat pipe burial depth of 10cm and 18cm respectively. From the temperature changes, the temperature changes in the two cases are basically the same, but the shallower the burial depth is, the faster the pavement heating rate is. Besides, with the increase in time, the road temperature warms up faster, which thus can ensure that the road snow melt in a faster way. This law has the same performance when the heat pipe laying spacing is 400mm.
3.3 Engineering Validation
This project selected K235 + 700 section to lay the inorganic heat pipes to carry out snow-melting engineering applications. On 28th December 2018, the test section saw moderate snow, the snowfall thickness is 6-8cm, and the highest temperature is only -4 ℃. The infrared imaging result of the pavement temperature in that time shows that the temperature of the road section with heat pipes is basically maintained at about 0 ℃, while the ordinary road surface temperature is as low as -9 ℃. Infrared imaging results demonstrated that, on the road image-able area, the temperature differences on the heat pipe road and the ordinary road is as high as 9 ℃, the heat pipes warmed up the road obviously. Meanwhile, the right picture shows that there was basically no snow on the heat pipe road, and the snow on the ordinary road was not likely to melt because of the low temperature.

Figure 8. Engineering verification of snow melting system in the test section.

4. Conclusion
(1) This paper, based on the research of heat transfer mechanism of the heat pipe and the mechanism of snow melting, considering the ambient temperature, wind speed, snowfall speed and relative humidity, proposed an accurate model of road snow melting. This model is fully combined with the actual environmental conditions of road and simplified the evaporation load and convection heat transfer load on the road surface in the process of snow melting.

(2) Based on the analysis of internal heat transfer and surface convection heat transfer, the author set suitable temperature field boundary conditions according to the actual condition of the road pavement, and applied numerical simulation software to simulate the temperature field of the road pavement to quantitatively study the influence of the heat pipes’ evaporation section depth, arrangement distance, diameter, inclination angle and other factors on the temperature field of the road pavement. Finally, through analyzing the results of numerical simulation, the author determined the optimal design parameters of the heat pipe system under different temperature field boundary conditions.

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