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Analysis of gravity heat pipe for anti-icing and snow melting on road surface

QING Qian, ZHANG Deng-chun, CHEN Da-wei

(School of Civil Engineering, Hunan University of Science and Technology, Xiangtan Hunan 411201, China)

corresponding author's e-mail address: dczhang2000@126.com

Abstract. Road icing is a serious hazard to highway traffic safety, so it is necessary to develop the anti-icing and de-icing technology. In this paper, theoretical and simulation analysis was carried out based on the idea that the gravity heat pipe uses shallow geothermal energy to meet the requirements of highway de-icing. The maximum heat transfer limit of different working media was calculated, and the two-dimensional pavement heat transfer model and thermal resistance model were established. The effect of different pipe diameters, pipe spacing and length of evaporation and condensation section on the heat transfer efficiency of gravity heat pipe to the surface of road was considered. It is concluded that ammonia can maximize the heat transfer limit of heat pipe due to its high latent heat, which is the best working fluid for preventing ice and snow melting of gravity heat pipe. When the pipe spacing is 150mm, the road surface temperature can be more than 2 °C. Considering the maximum heat transfer per unit area, the optimal length of the gravity heat pipe is 30m for the evaporation section and 10m for the condensation section, and the unit heat transfer is 205W/m².

1. Introduction

Thin ice on the surface of pavement is easy to form in wet and rainy winter in the southern China, which has a serious impact on road traffic safety and material transportation. At present, salt deicing is the main way of road deicing in our country, which causes serious damage to pavement structure and ecological environment. How to achieve environmental protection and efficient de-icing effect has always been the research direction of the majority of scholars. In recent years, the deicing methods of heat pipe and heating cable have been studied by many scholars^[1-5]. Heat pipe has been widely used in all walks of life because of its high thermal conductivity^[6-9]. The heat pipe deicing technology was first used in New Jersey in 1969^[10]. The system was operated with a mixture of ethylene glycol and water as a phase change material cycle inside. The gravity heat pipe was studied by Nydahl et al.^[11] in 1984. The tube was filled with gas-liquid two fluid. It was found that the temperature around the evaporating section was higher than that in the condensing section when the heat pipe was self-heated at any time. The complete heat pipe deicing project took place at the highway ramp in West Virginia, with 177 heat pipes, each 36 meters long, with 7% of the slope angle heating the pavement. The first bridge using heat pipe deicing^[12] began in 1995 with a planned heat production of 700W/m² and a total of 241 heat pipes with a heating area of 567m². Tanaka et al.^[13] studied the possibility of geothermal utilization near the volcano, and analyzed the temperature distribution of the heat pipe and the surrounding ground temperature considering the heat transfer and thermal resistance model. Ozsoy et al.^[14] found the effects of heat pipe diameter, length of evaporation and condensation section, surface temperature of ground and air temperature on heat transfer. It is concluded that geothermal



heat can be used as a heat source for road anti-icing under the weather conditions in Tokyo. Zorn et al.^[15] used carbon dioxide as the phase change material for heat pipe and tested it in real time at the exit of a fire station in Germany. The results show that the heat pipe is effective in deicing and deicing. The thermodynamic analysis of the superlong heat pipe deicing system has been carried out by Wang et al.^[16]. The results show that the optimum filling rate of the heat pipe is 62%, and the heat yield of the single gravity heat pipe is from 850 to 1200W. In order to explore the possibility of using shallow heat energy by gravity heat pipe to prevent ice and snow in Xiangtan area, according to the reference^[19], we find that the average annual temperature in Xiangtan area is 17 °C, which is selected as the constant temperature of the absorbed shallow geothermal energy. Based on the requirements of the entrainment limit of the heat pipe, the most suitable fluid medium and the diameter of the heat pipe are analyzed in this paper, the different buried pipe spacing is discussed, and the effect of different wind speed on heat transfer of heat pipe is also studied. The temperature of each section of the heat pipe is determined by the thermal resistance model, and the effect of the length of evaporation section and condensation section on heat transfer is studied. The most suitable combination of heat pipe length is selected according to the different heat transfer and the heat flux required to prevent ice and melt snow on the road surface.

2. Calculation of entrainment limit of gravity heat pipe

The entrainment limit of the heat pipe means that when the axial heat flux is large enough, the relative velocity between the upward steam flow and the downward condensate leads to a significant increase of shear strength at the interface, and the evaporator is dried out in the end because of the condensate downward is carried away by the upward steam. For the purpose of avoiding this, the heat flux during heat pipe operation must be less than the maximum heat flux at the entrainment limit, which can be calculated as^[17]:

$$Q_{Imura} = 0.64 \left(\frac{\rho_l}{\rho_v} \right)^{0.13} \left(\frac{D_e}{4l_e} \right) r [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{0.25} \quad (1)$$

Where, Q_{Imura} is the maximum heat flux, W/m²; D_e is the inner diameter of heat pipe; σ is the surface tension, N/m.

The physical parameters of different fluids at different temperatures are obtained through literature^[20] to select the best working fluid of the gravity heat pipe anti-ice system. Suppose the inner diameter of the heat pipe and the length of the evaporation section are the same under different temperature, the entrainment limit of different working fluids at different operating condition is calculated by Matlab software, as shown in Fig. 1.

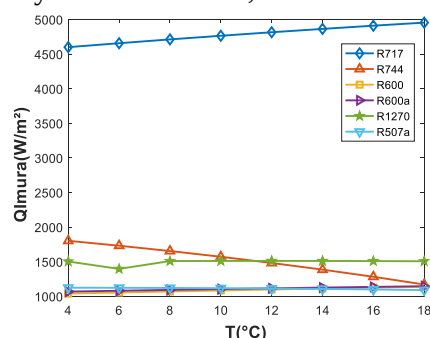


Fig. 1. Entrainment limit of different working fluid

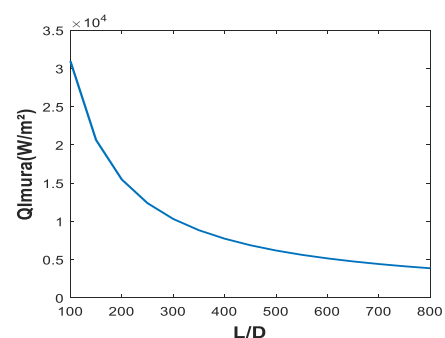


Fig. 2. Entrainment limits at different aspect ratios

Fig. 1 presents clearly that the entrainment limits of R717 (ammonia) is the biggest over the others. In the working temperature of 4 ~ 18 °C, the value of entrainment limit of R717 is from 4500 to 5000 W/m². The value of other fluid media within the operating temperature ranges from 1000 to 2000W/m². That's because of the characteristics of high latent heat and pressure, ammonia can release a large amount of latent heat at the condition of a lower temperature. Therefore, ammonia is the best working fluid for road anti-ice and snowmelt with the help of shallow geothermal energy. Considering the condition of Xiang Tan area, taking the annual average temperature of 17 °C as the working

condition of the system, finding out the physical parameters of ammonia under this temperature, it is concluded that the heat transfer limit Q_{Imura} relations with heat pipe length to diameter ratio L/D as shown in Fig. 2.

We can know distinctly from Fig. 2 that the entrainment limits of heat pipe Q_{Imura} decreases with the increase of aspect ratio L/D . When the aspect ratio is less than 200, the entrainment limit decreases sharply with the increase of aspect ratio. When the L/D is greater than 200, with the increase of length-diameter ratio, the heat transfer limit gradually decreases slowly. As the thermostatic layer is generally more than ten meters below the ground, we take an assumption that the length of the evaporation section of heat pipe is 20m. Under the limitation of the heat transfer Q_{Imura} , the optimal heat transfer pipe diameter is determined to be $\phi 36\text{mm} \times 2\text{mm}$.

3. The simulation of heat transfer via ground

3.1 The model of heat transfer

The heat transfer model of the heat pipe laid on the pavement is established with the Tongping expressway in hunan as the reference pavement structure, as shown in Fig. 3. The condensation section of the gravity heat pipe is laid on the middle layer. After mesh division, this model is imported into Fluent 14.5. for simulation with the total cell of 47923. The pavement material includes the surface layer SMA-13 with a thickness of 40mm and the middle layer AC-20 with a thickness of 60mm, and its physical parameters are measured experimentally as shown in table 1.

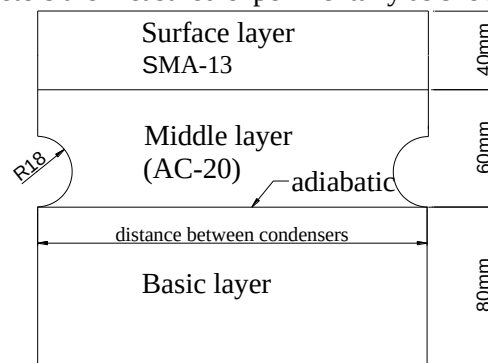


Fig. 3. The model of heat transfer via ground

Table 1. Related parameters of SMA-13 and AC-20.

Material	Density(ρ) $\text{kg}\cdot\text{m}^{-3}$	Heat conductivity coefficient(λ) $\text{W}\cdot\text{m}^{-1}\cdot^{\circ}\text{C}^{-1}$	Heat capacity(c) $\text{J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$	Thickness(δ) mm
SMA-13	2300	1.244	1000	40
AC-20	2300	1.583/1.674	700	60

3.2 Boundary conditions

A 2D physical model is developed assuming the pavement layers are uniform. Annual average temperature in Xiangtan is 17°C , which is applied to the constant temperature boundary of evaporation section. Considering the heat loss from the evaporator to condenser is about 5°C temperature difference, so 12°C is set as the outer wall temperature of condenser. Symmetrical boundary is set on the surrounding sides, and adiabatic boundary condition is set as the baseline of the heat pipe. Pavement natural convection temperature take extreme minimum temperature when the weather -2°C , the surface heat transfer coefficient is a function of wind speed, according to the Eq. (2) ^[18]:

$$h_a = 5.7 + 3.8v_a \quad (2)$$

Where, h_a is the surface heat transfer coefficient, $\text{W}/(\text{m}^2\cdot\text{K})$; v_a is wind speed, m/s .

3.3 Thermal resistance model

From a theoretical point of view, we can calculate the heat loss in every part of the transfer process by many empirical formula. The thermal resistance model of the heat transfer from the evaporator of gravity heat pipe to the pavement is established to study the heat transfer capacity of a single gravity heat pipe. The thermal resistance in the heat transfer process are: heat conduction of wall of evaporator, namely R_1 , R_2 of evaporation section is the convection between working medium and inner wall of evaporator, resistance R_3 is of heat transfer with liquid film in evaporation section, R_4 is of heat transfer with liquid film in condenser, the convective heat resistance R_5 is between gaseous medium and the inner wall of the condenser, R_6 is heat conduction of condenser wall, and the last one R_7 is the resistance from the outer wall of condenser to the air contacted with pavement, respectively. The heat transfer resistance model is shown as Fig. 4, specifically.

In this paper, the following assumptions are made before calculating the heat transfer capacity of the heat pipe taken from the soil: (1) the ground temperature does not change with the increase of depth; (2) soil temperature is considered to be a constant value; (3) there is no heat loss or pressure loss in the heat pipe; (4) the influence of thermal resistance of liquid film is ignored.

The total heat transfer capacity by the heat pipe is determined by the thermal resistance of the heat transfer process, and its expression is as follow:

$$Q = \frac{\Delta T}{R_t} \quad (3)$$

Where, Q is heat throughput, W; ΔT is the temperature difference of the outer wall of evaporation section and the air temperature; R_t is the total thermal resistance in the heat transfer system, °C/W, which can calculate by the equation as follow:

$$R_t = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 \quad (4)$$

Where, the expressions of thermal resistance R_1 , R_2 , R_3 , R_4 , R_5 and R_6 are shown in Table 2.

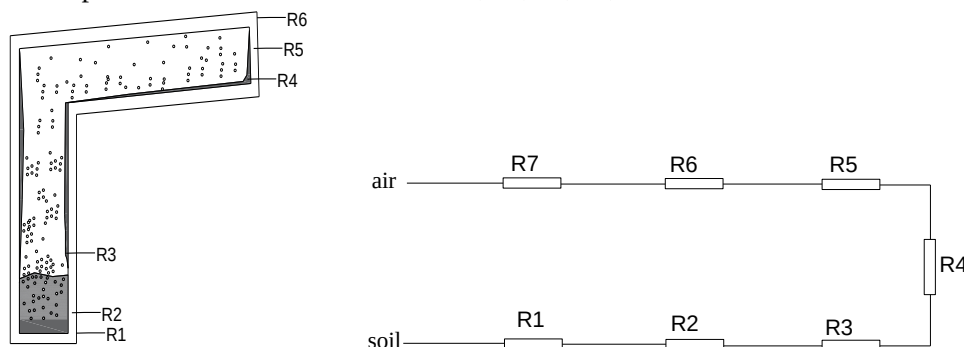


Fig. 4. Heat resistance model

Table 2. Thermal resistance equations in heat transfer system.

Heat resistance	Equations
R_1	$R_1 = \frac{\ln \frac{D_o}{D}}{2\pi l_e \lambda_x}$
R_2	$R_2 = \frac{1}{h_e A_e}, \quad h_e = 0.32 \left(\frac{\rho_l^{0.65} \lambda_l^{0.3} c_{pl}^{0.7} g^{0.2} q_e^{0.4}}{\rho_v^{0.25} h_{lv}^{0.4} \mu^{0.1}} \right) \left(\frac{p_{sat}}{p_a} \right)^{0.3}$
R_5	$R_5 = \frac{1}{h_c A_c}, \quad h_c = 0.729 \left[\frac{\rho_l (\rho_l - \rho_v) g h_{lv} \lambda_l^3}{D_i \mu_l (T_{sat} - T_{ci})} \right]^{1/4}$
R_6	$R_6 = \frac{\ln \frac{D_o}{D}}{2\pi l_c \lambda_x}$

Nomenclature			
A	area, m ²	ρ	density, kg/m ³
C_{pl}	heat capacity of liquid, J/(kg·°C)	μ	Dynamic viscosity, Pa·s
D	diameter, m	Subscripts	
g	Gravitational acceleration, m/s ²	a	air
h	heat transfer coefficient, W/(m ² ·°C)	c	condenser section
h_{lv}	latent heat, J/kg	ci	condenser inner wall
l	length, m	e	evaporator section
p	pressure, Pa	i	inner
q	heat flux, W/m ²	l	Liquid phase
T	temperature, °C	o	outer
λ	thermal conductivity, W/(m·°C)	sat	saturation state
l	length, m	v	vapor phase

4. Results and discussion

When the distance between condenser is 200mm, the effect of different wind speeds on pavement temperature is shown in Fig. 5(a). When the wind speed is 8m/s, the effect of different heat pipe spacing on the pavement temperature is shown in Fig. 5(b). As can be seen from Fig. 5(a), the higher the wind speed is, the lower the road surface temperature is. That is because that the increase of wind speed causes the greater the surface heat transfer coefficient h_a , which enhance the heat transfer between the pavement surface and the surrounding air environment. The increase of h_a leads to the heat loss to environment, which is presented in the form of pavement temperature. Fig. 5(b) shows that with the increase of heat pipe spacing, the heat transfer rate to the pavement surface gradually decreases, and the temperature difference of the surface between the adjacent condensers increases. As we can see that the road surface temperature was distributed as a triangular-function manner. The surface temperature of the position right on the condenser was the highest, and the temperature at the center of two condensers was the lowest, which showing a symmetrical distribution. The temperature difference of the road surface increased with the increase of the distance between condensers.

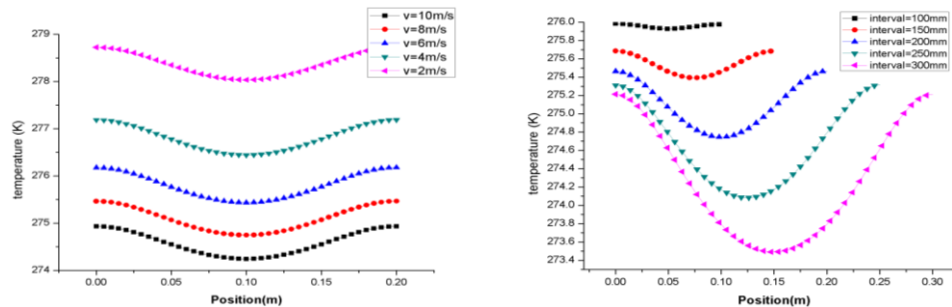


Fig.5. The temperature on surface of pavement: (a)with different wind speed; (b)with different intervals between adjacent condensers.

Due to the characteristics of low temperature and high humidity day and night in winter in Hunan province, preventing pavement from ice forming, it is necessary to keep pavement temperature above 2 °C. Fig. 5(b) shows that the optimal spacing of condensers is 150mm at this time.

The output heat flow q is calculated by Fluent 14.5 with different heat transfer coefficient h_a and temperature difference ($T_{co}-T_a$), and its relationship is shown in Fig. 6. As can be seen from the Fig. 6, heat flow q increases with the increase of heat transfer coefficient and temperature difference. The corresponding calculation results under different working conditions in Fig. 6 are input into Matlab for formula fitting. The heat transfer process from the outer wall of condenser to the air includes the conduction of the condenser outer wall to the pavement and the convection heat transfer between the pavement surface and the air. The part of conduction is taken into account in the convection heat transfer. The basic formula is $q=A \cdot h_a^B \cdot (T_{co}-T_a)$, where A and B are constants to be determined. After

fitting in Matlab, the relationship between heat flow q and the independent variable h_a , $(T_{co}-T_a)$ is shown in equation (5).

$$q = 2.236 \times h_a^{0.4529} \times (T_{co} - T_a) \quad (5)$$

Where, q is the output heat flow, W/m^2 ; T_{co} is the outer wall surface temperature of the heat pipe condensation section, $^{\circ}C$; T_a is air temperature, $^{\circ}C$.

According to equation (5), the thermal resistance R_7 of the condenser outer wall to the air in the thermal resistance model can be obtained as equation (6).

$$R_7 = \frac{T_{co}-T_a}{Q} = \frac{1}{2.236 \times h_a^{0.4529} \times A_p} \quad (6)$$

Where, A_p is pavement protection area, m^2 , and its value is equal to the product of the optimal heat pipe spacing of 0.15m multiply by the length of condensation section l_c .

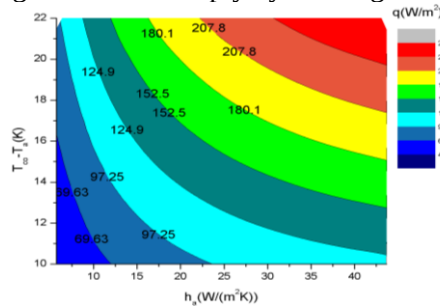


Fig. 6. The relationship between heat flux q with $T_{co}-T_a$ and h_a

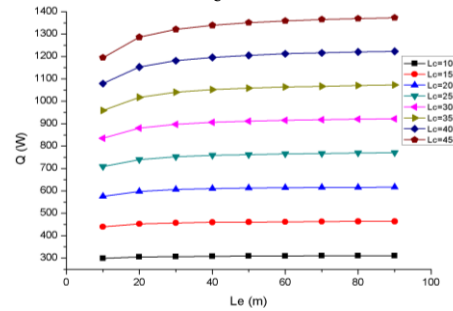


Fig. 7. The relationship between Q with l_e/l_c

Thermal resistance model is used to calculate the temperature of every section of heat pipe, which determine the physical parameters of working medium. Taking the most adverse temperature $-2^{\circ}C$ in Xiangtan, the most unfavorable wind speed 8 m/s as the working condition of the road. All these parameters are taken into the resistance expression. Firstly, suppose a heat transfer rate Q , and a new Q' can be calculated by equation (3). If the absolute error is less than 1W, then we can think that Q is considered to be the corresponding heat transfer rate with the given evaporator and condenser length. Based on this idea, The heat transfer rate of heat pipe corresponding to the lengths of different evaporator and condenser sections can be calculated by compiling this program through Matlab. The calculation results are shown in Fig. 7.

It can be seen from Fig. 7 that the heat transfer rate Q increases slowly with the increase of the length of evaporator l_e and significantly with the increase of the length of condenser l_c . Compared with the length of evaporator section, the length of condenser has more influence on the heat transfer of heat pipe. The variation range of heat transfer growth rate caused by every 10m change in evaporation section length is 0.06%~ 7.6%, while that caused by every 5m change in condensation section length is 10.8%~49.5%. The thermal resistance R_7 from the condenser outer wall to the pavement is the main thermal resistance in the thermal resistance model, while the length of the condensing section mainly affects the heat transfer rate by affecting the pavement protection area. With the increase of condenser length l_c , the area protected by heat pipe increases, R_7 decreases, and heat transfer rate Q increases significantly. When the length of evaporator is between 10m and 40m, and the length of condensation section is between 10m and 30m, the heat transfer rate Q of gravity heat pipe ranges from 299W to 906W. Moreover, the evaporator length l_e has the greatest effect on heat transfer rate mainly between 10 and 30m, and after being larger than 30m, the evaporator length has little influence on heat transfer, so the optimal length of the evaporator section is 30m.

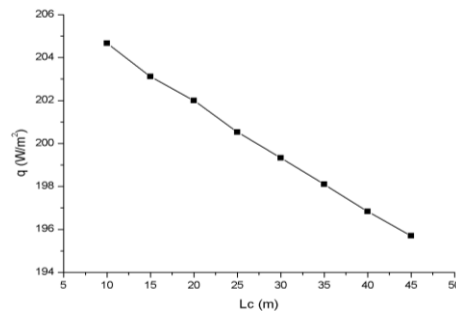


Fig. 8. The heat flux q with different l_c

When the length of evaporation section l_e is 30m, the relationship between the heat flux q and the length of condenser section l_c is shown in Fig.8. As can be seen from Fig. 8, heat flux q decreases gradually with the increase in the length of the condenser l_c , which is because with the increase of the length of the condenser, the surface area that the heat pipe needs to protect increases. It also reflects that although the total heat transfer of the heat pipe increases as the length of the condenser increases, the heat transfer flux of per unit area decreases. Therefore, in order to maximize the heat transfer flux of per unit, the length of the condenser is selected to be 10m. At this time, the heat transfer flux of per unit area that the gravity heat pipe can reach the pavement is $205W/m^2$.

5. Conclusion

Based on the theoretical analysis of the gravity heat pipe using shallow heat energy to resist ice, the influence of different working media, the distance between condensers of heat pipes, and the length of evaporator section and condenser section on the efficiency of gravity heat pipe deicing system are considered, and the following conclusions are drawn:

- When choosing the working fluid of the gravity heat pipe for anti-ice and snow melting, ammonia has the characteristics of high latent heat and pressure compared with other working medium, which can make the heat transfer limit of the gravity heat pipe reach the maximum. Therefore, ammonia is the best working medium for the anti-ice and snow melting of the gravity heat pipe.
- Considering spacing influence on heat transfer, in order to ensure the pavement temperature is higher than $2^{\circ}C$, the optimal distance between condensers is 150 mm.
- In order to maximize the heat pipe rate of the deicing system, the optimal length of evaporator section is 30m, the length of condenser section is 10m, and the heat transfer flux of per unit area is $205W/m^2$.

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