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# Energy consumption and utilization rate analysis of automatically snow-melting system in infrastructures by thermal simulation and melting experiments

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ABSTRACT

The automatically snow-melting system with the electric heating pipes (AS-EHP) is applied in infrastructures (concrete pavement, parking apron, garage entrances and municipal road) in cold regions to mitigate the accumulated snow problem. In order to reduce the energy consumption (EC) and improve the energy utilization rate (EUR) of AS-EHP, the analysis about EC and EUR is investigated. The melting process of AS-EHP is divided into two phases which include preheating the infrastructures and melting. The influence and sensitivity analysis between the inputs (the pipes' embedded spacing and embedded depth, heating power and wind velocity) and the outputs (EC and EUR) are found and compared in two phases by thermal simulation. The applicability and rationality of the simulation are verified by snow melting experiments. According to the simulation, decreasing embedded spacing and depth in phase 1 and phase 2 could reduce EC and improve EUR. In the two phases, the heating power is suggested to be 100 W/m-140 W/m under the condition that the heating pipe' embedded spacing is 0.10 m–0.25 m, the depth is 0.06 m–0.12 m, and the wind velocity is 0 m/s–15 m/s. The results and suggestions could be used to efficiently guide the scheme design and operation control of AS-EHP in infrastructures.


## 1. Introduction

In cold regions, snow and ice on infrastructure (concrete pavement, parking apron, garage entrance, and municipal road) surface significantly hinder transportation and threaten safety. To mitigate this problem, many effective solutions have been investigated. For infrastructure snow-melting, the thermal methods consist of a hydronic heating system (Wang et al., 2010; Liu et al., 2004; Liu et al., 2007; Miróet, 2012), electric heating cables or pipes (Zhao et al., 2011; Lai et al., 2014) electrically conductive concrete (Wu et al., 2015; Gomis et al., 2015; Chu and Chen, 2016) and so on. Minsk (1999) summarized three different technologies (hydronic, heat pipe, and electric) used for heating bridge decks and listed the construction details, cost, operating characteristics, and deicing performance during winter operations. For the electrically conductive concrete, the thermal conductivity, compressive strength, and effectiveness were analyzed by experiments. Zhao validated the effectiveness of the deicing method with carbon fiber heating wires embedded inside concrete slabs. Liu et al. (2015) studied the thermal conductivity of iron ore sand cement mortar, which was applied in the conductive layer of snow-melting pavement. Li et al. (2014) investigated the deicing performance of self-deicing road system through the analytic method.

Besides the above aspects, the energy analysis is also an important part of the infrastructure snow-melting. Energy analysis in pavement had mainly been concentrated in the cool pavement field recently and much progress had been made. Santamouris summarized the actual developments in cool pavements to mitigate the heat island phenomenon (Santamouris, 2013). Qin studied the energy partition at the ground surface and the heat released from the reflective cool pavements surface (Qin and Hiller, 2011; Qin, 2015).

For the energy analysis of the infrastructure snow-melting, Lai studied the temperature and energy distribution along the depth of pavement with carbon fiber grille through field experiments (Lai et al., 2014). Nuijten and H.ylanda (2016) compared the melting processes of dry uncompressed and compressed snow on heated pavements. The difference between the energy used to melt compressed and uncompressed snow was also studied. Adl-Zarrabi et al. (2016) studied the sustainable ice-free roads, and the influences of the space between the pipes and the depth at which the pipe were buried on the system performance are investigated to decrease the energy loses and difference of the seasonal energy storage. Therefore, for the energy analysis

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of the infrastructure snow-melting, the study about the influence of the heating power and wind velocity on the energy consumption and utilization is lacking.

Although the heating methods, the thermal field, the conductive material of infrastructure snow-melting, and the energy analysis of pavement have been investigated, the analyses on EC and EUR for snow-melting especially in different phases and with different influence factors (the pipes' embedded spacing and embedded depth, heating power and wind velocity) are lacking. If the heating scheme of snow-melting is designed unreasonably, it will cause a snow-melting inefficiency or a waste of energy. Therefore, a reliable energy analysis for the infrastructure snow-melting must be conducted to save the energy and maintain the stable operation. In this paper, the numerical simulation and validated experiments are used to analyze EC and EUR for AS-EHP. The experimental results agree with the simulation results very well. Meanwhile, the influence laws and degree of different parameters on EC and EUR are analyzed. The appropriate heating scheme is proposed to guide the structure design and operation of AS-EHP for infrastructures.

## 2. Structure and operation phases of infrastructures with AS-EHP

### 2.1. Structure

The structure of AS-EHP in infrastructures is shown in Fig. 1(a). The electric heating pipes are embedded in the concrete layer above the insulating layer. The insulating layer can slow down the downward heat conduction.

### 2.2. Operation phases

When there is accumulated snow and no continuous snowfall on the infrastructure's surface, the melting process is named static melting. From Fig. 1(b), there are two operation phases in static melting. The snow starts to be melted when the temperature of infrastructure's surface reaches 0 °C. Therefore, the period that the infrastructure's surface temperature heated up to 0 °C is regarded as phase 1, and the period in which all the snow on the infrastructure's surface is melted into water is regarded as phase 2. The duration of phase 1 and phase 2 is described as $t_1$ and $t_2$ respectively.

## 3. Thermal simulation of the melting process in infrastructures with AS-EHP

### 3.1. Simplified model of infrastructures with AS-EHP

The two-dimensional model of AS-EHP in infrastructure with compacted snow is depicted in Fig. 2(a). The heating pipes are distributed symmetrically, therefore the two-dimensional model shown in Fig. 2(a) can be further simplified to a half model shown in Fig. 2(b). The modeling is performed under the following assumptions:

(1) The bottom boundary is adiabatic because concrete layer rests on a thermal insulation layer. The surface of the half model has a convective and radiative boundary condition. The left and right boundaries both are thermally insulated. There are two reasons for the adiabatic boundaries: 1) The heating pipes are distributed symmetrically (Wang and Chen, 2009); 2) The thermal conductivity of concrete in AS-EHP is higher than the typical concrete closing to AS-EHP, and there is somewhat heat transfer between the concrete in AS-EHP and the typical concrete. Therefore, the heat transfer is weak and can be ignored, and the boundaries are assumed to be the adiabatic boundaries (Li et al., 2014).
(2) The electric heating pipes are uniform. There is no energy loss in heat transfer from the electric heating pipes to concrete.
(3) The concrete and compacted snow in the model is uniform, isotropic, and homogeneous.

The energy equation in the half model can be written by using Fourier's law as follows:

$$\frac{\partial^2 T_i}{\partial x^2}+\frac{\partial^2 T_i}{\partial y^2}+\frac{q}{\lambda_i}=\frac{1}{\alpha_i}\cdot\frac{\partial T_i}{\partial t} \tag{1}$$

The governing equation is subject to the following initial conditions.

$$T_i(x,y,t)|_{t=0}=T_0 \;,\quad i=1,2,3 \quad 0\le x\le s/2,\quad 0\le y\le D+D_s \tag{2}$$

The boundary conditions of four sides are expressed as Eq. (3)–(4).

$$\left.\frac{\partial T_i}{\partial x}\right|_{x=0}=\left.\frac{\partial T_i}{\partial x}\right|_{x=s/2}=\left.\frac{\partial T_i}{\partial y}\right|_{y=0}=0 \tag{3}$$

$$\left.\frac{\partial T_3}{\partial y}\right|_{y=D+D_s}=h(T_3-T_a)+\varsigma\varepsilon\left(T_{sky}^4-T_3^4\right) \tag{4}$$

The continuous conditions between the electric heating pipe and the concrete, and between the concrete and the compacted snow are expressed as Eq. (5)–(8).

$$T_1=T_2 \;,\; x^2+[y-(D-d)]^2=(D_p/2)^2 \tag{5}$$

$$\frac{\partial T_1}{\partial x}\lambda_1=\frac{\partial T_2}{\partial x}\lambda_2 \;,\; x^2+[y-(D-d)]^2=(D_p/2)^2 \tag{6}$$

$$T_2=T_3 \;,\; 0\le x\le s/2, y=D \tag{7}$$

$$\frac{\partial T_2}{\partial x}\lambda_2=\frac{\partial T_3}{\partial x}\lambda_3 \;,\; 0\le x\le s/2, y=D \tag{8}$$

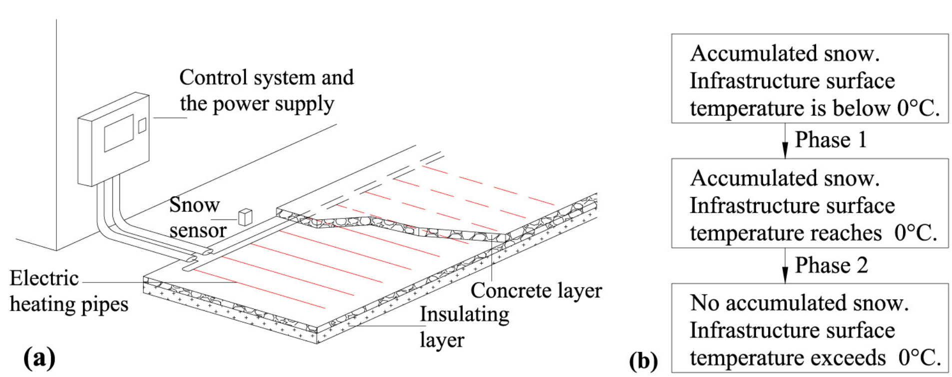


**Fig. 1.** Structure and operation phases of the infrastructure with AS-EHP: (a) three-dimensional (3D) structure; (b) two operation phases.