Feasibility study of snow melting system using geothermal energy piles in Canadian Prairies

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ABSTRACT
Snow accumulation on bridge decks during winter causes tremendous inconvenience for drivers and traffic accidents. A traditional approach for snow melting and de-icing of bridge decks is to use salt which can lower the freezing point of water to prevent the formation of ice. Unfortunately, this method can induce some problems. Salt will not only be ineffective for snow melting or de-icing if temperature falls below -3.9 °C, but also penetrate down to the slab and accelerate the corrosion of concrete and steel used in a bridge deck. The pile foundations designed to support the loads of bridge structures can also be used to provide renewable energy heat source for hydronic heating system used for snow melting. In this paper, the feasibility study of snow melting system using geothermal energy pile is performed for Edmonton and Winnipeg based on the typical weather conditions during snowfall and their underground conditions.

RÉSUMÉ
L'accumulation de neige sur les ponts en hiver cause d'énormes inconvénients aux conducteurs. Une approche traditionnelle pour le dégivrage des tabliers de ponts consiste à utiliser du sel qui peut abaisser le point de congélation de l'eau pour empêcher la formation de glace. Le sel ne sera pas seulement inefficace pour le dégivrage si la température tombe en dessous de -3,9 °C, mais aussi pour pénétrer jusqu'à la dalle et accélérer la corrosion de l'acier utilisée dans le tablier. Les pieux conçus pour supporter les charges des structures de ponts peuvent également être utilisées pour fournir une source de chaleur pour un système de chauffage hydronique. Dans cet article, une étude de faisabilité d'un système de fonte des neiges en utilisant des pieux géothermiques est réalisée pour Edmonton et Winnipeg en fonction des conditions météorologiques typiques pendant les chutes de neige et de leurs conditions géologiques.

1 INTRODUCTION

Snow accumulation on the pavement and bridge decks can seriously affect the safety and productivity of the transportation system. The prevalent method for snow removal is mechanical plowing together with spraying deicing salt. However, this method not only consumes huge amount of materials but also induces many environmental issues. In the recent decades, researchers and practitioners have been looking for effective and economical alternatives for the snow melting and de-icing system. One of the most efficient techniques is to use automatically controlled hydronic and electrical melting system (Balbay and Esen 2010). In an electrical system, heat is generated by electrical current flowing through metallic cable that usually is laid out in a serpentine pattern in order to heat bridge deck uniformly (Hoppe 2000). As the cable warms up because of the passage of electrical current, it conveys heat to the surrounding material (Hoppe 2000).In a hydronic system, heat is transferred in the form of convection as the heat carrier fluid circulates through a closed-circuit loop by a hydraulic pump and releases heat to the surrounding medium (Hoppe 2000).

Hydronic heating system is one of the options to supply heat for the snow melting of bridge deck. Circulation of hot fluid provides the heat source for snow melting. Typical pipe spacing ranges from 150mm to 300mm and is usually buried between 50mm and 75mm deep (Spitler and D 2000). Nominal pipe diameters are 18mm to 25mm (Spitler and D 2000). There are also several numerical studies of the bridge deck de-icing system. Rees et al. (2002) developed a two-dimensional numerical model that accounted for the transient effects of the snow melting process on a pavement and one conclusion from this study is that in order to achieve a snow-free area ratio (Ar = 1), system idling will likely be required (Rees, Spitler, and Xiao 2002). Liu et al. (2007) improved the model developed by Rees et al. (2002) to simulate hydronic heating of bridge deck over its lifetime and the entire model consisted of four sub-models: a hydronic heated bridge deck model, a ground loop heat exchanger model, a water to water heat pump model, and a system control model (X. Liu, Rees, and Spitler 2007). The model ability to predict the average bridge surface temperature and fluid exiting temperature was promising but slightly over-predicted the surface temperatures.

A Geothermal energy pile that integrates the heat exchanger in structure foundation is one of the most promising designs because of its relatively low cost comparing with traditional geothermal system. Traditionally, the system requires a certain number of boreholes (independent from the structure foundation) that consists of the majority cost of system. Geothermal energy piles, instead, integrates the heat exchanger in the foundation during construction; in this way, the initial installation cost can be saved (Akrouch, Sánchez, and Briaud 2016). A shallow geothermal system is usually composed of three main components: a geothermal heat pump, a ground heat exchanger and a piping system for different applications (Akrouch, Sánchez, and Briaud 2016). A heat pump has four sub-components which are condenser, evaporator, expansion valve and compressor. Mechanical vapor compression systems are the dominant heat pump technology owing to their reliability, familiarity, and relatively compact size (Chiasson 2016). During winter, because of the existing temperature gradient between refrigerant in evaporator and underground temperature, geothermal heat is absorbed by refrigerant and transfer to the compressor. By compressing refrigerant and increasing its pressure, the temperature will be increased. Finally, refrigerant is circulated to condenser to release heat for snow and ice melting on bridge deck. Then expansion valve acts to reduce pressure and temperature of refrigerant liquid and this system keeps going on.

In this paper, a feasibility study of snow melting and de-icing system by using geothermal energy piles for bridge decks is carried out for. This paper aims to compare the energy efficiency of the heating system for Edmonton and Winnipeg. For this purpose, two methods can be used: 1) the coefficient of performance (COP) of the system can be used as the indicator of the energy efficiency; 2) by assuming same COP in both cities, the number of piles can be used as the efficiency indicator. The first method has been discussed in details in a companion paper (H. Liu, Maghoul, Bahari, and Kavgic 2018). Therefore, in this paper, constant COP of 3 are assumed and the number of piles for the snow melting was obtained as an indicator of the feasibility of this technology in Winnipeg and Edmonton.

2 MODEL DESCRIPTION

2.1 Energy balance at the surface of bridge slab for snow melting/de-icing

The energy balance equation described in 2007 ASHREA handbook states that the heat flux depends on surface convection, radiation and evaporation whose values are based on five atmospheric factors: rate of snowfall, air temperature, humidity, wind speed near the heated surface and sky temperature. The complete energy balance equation is expressed as:

$$q = q_{conv} + q_s + q_m + q_{solar} \quad [1]$$

where q (W/m^2) represents the heat flux required for snow-melting at the surface; q_{conv} (W/m^2) stands for the surface convection heat flux; q_s (W/m^2) denotes the sensible heat flux; q_m (W/m^2) is the latent heat; q_{solar} (W/m^2) is the short-wave solar radiation. In this equation, the sensible heat flux q_s during snow melting and the latent heat of fusion of snow q_m as well as the short-wave solar radiation q_{solar} introduced into the heat flux equation are time-dependent.

Sensible heat flux q_s is used to increase the temperature of fresh snow to its melting point and then increase the temperature of water to liquid film temperature (0.56 °C). This sensible heat flux can be calculated using the following equation:

$$q_s(\mathrm{t}) = \rho_w\, s(t)[c_{p,i}(T_m - T_a(t)) + c_{p,w}(T_f - T_m) \quad [2]$$

where ρ_w (1000 kg/m3) is the density of the liquid water; s (m/s) is the snowfall rate expressed in water equivalent; $c_{p,i}$ (2100 J/ kg-K) is the specific heat of ice; $c_{p,w}$ (4200 J/ kg-K) is the specific heat of water; T_f (°C) is the liquid film temperature which usually is taken as 0.56 °C; T_a (°C) is the ambient temperature that varies with time and T_m (°C) is the melting temperature taken as 0°C. t (s) denotes time.

Latent heat of fusion of snow q_m is the heat that snow needs to absorb during the phase change:

$$q_m(\mathrm{t}) = \rho_w\, s(t)\, h_{if} \quad [3]$$

where h_{if} is the heat of fusion, usually taken as 3.3 × 105 J/kg.

Short-wave radiation is evaluated by the combination of beam radiation and diffuse radiation on the horizontal plane, where beam radiation, also termed as direct radiation, refers to the component of total solar radiation that travels on a straight line from sun to the surface of earth without changing its direction. Diffuse radiation, on the other hand, describes the sunlight that has been scattered by molecules and partials in the atmosphere but still made it down to the surface of the earth. The data used in this analysis is obtained from Natural Resource Canada.

The convection q_{conv} is temperature-dependent. Because of the huge thermal mass of concrete, temperature of slab takes time to change. In this analysis, the surface convection heat flux can be calculated using the following equation:

$$q_{conv}(\mathrm{t}) = h_{conv}(T_a(\mathrm{t}) - T_s(t)) \quad [4]$$

where T_a (°C) is the air temperature and T_s (°C) is the temperature on the slab surface.

The convection heat transfer mode is comprised of two mechanism: diffusion and advection (DeWitt, Bergman, and Lavine 2007). The convection heat transfer coefficient, h_{conv}, mainly depends on conditions on the boundary layer, for example, wind speed and ambient temperature (DeWitt, Bergman, and Lavine 2007) . The convective heat transfer coefficient for external flow on a horizontal surface can be calculated by the following formula:

$$h_{conv} = 2\frac{k}{L}\left(\frac{0.3387\, Pr^{\frac{1}{3}} Re_L^{0.5}}{(1+\left(\frac{0.0468}{Pr}\right)^{2/3})^{1/4}}\right) \quad if\ Re_L \le 5 \times 10^5 \quad [5]$$

$$h_{conv} = 2\frac{k}{L}\, Pr^{\frac{1}{3}}\left(0.037\, Re_L^{\frac{4}{5}} - 871\right) \quad if\ Re_L > 5 \times 10^5 \quad [6]$$

where k (W/m-k) is thermal conductivity of air at t_a; L (m) is characteristic length of slab in the direction of wind; Pr stands for Prandtl number of air, the ratio of thermal diffusivity to viscosity, taken as 0.7. And Re_L is Reynolds number based on characteristic length L, calculated as follows:

$$Re_L = VL/\nu_{air} \quad [7]$$

where V (m/s) is design wind speed near slab surface and ν_{air} (m^2/s) is the kinematic viscosity of air.

The design weather is a very important parameter for sizing heat pump so that the system can handle most of snowy situation. In this analysis, the design weather is not the worst weather condition since it will unnecessarily overdesign the system and therefore dramatically increase the cost. However, the design weather should at least handle 90% snow melting load.

Environment and Climate Change Canada (http://climate.weather.gc.ca/) offers the statistic information based on at least 15 years' weather data. It showed that there are 96% and 97% of daily snowfall that are smaller than 10cm for Winnipeg and Edmonton respectively. Therefore, the design weather is a day with approximately daily snow of 5-10cm and moderate wind speed.

In this analysis, the net heat flux is defined as:

$$q_{net} = q_{solar} - (q_m + q_s) \quad [8]$$

where q_{net} (W/m^2) represents the heat flux that should be provided by hydronic heating system on the pavement surface.

By using the modified heat flux model together with the design weather, the results for Edmonton and Winnipeg can be seen in the Figure 1 and Figure 2, respectively.

2.2 Hydronic heating system in bridge deck

The modeling of the hydronic heating system is performed considering the heat transfer in pipe and concrete materials used for bridge decks. The important assumptions applied in this model are: a) the velocity profile is fully developed with entire pipe section; b) the average bulk mean velocity remains constant along the pipe; c) all velocity components normal to pipe axis is assumed to be 0. The governing equation for the heat transfer in the pipe used to determine the temperature distribution profile in the fluid flow is:

$$\rho_w A C_p \frac{\partial T}{\partial t} + \rho_w A C_p v_s \cdot \nabla T = \nabla \cdot (A k \nabla T) + Q \quad [9]$$

while the heat transfer in adjacent pavement materials is described as follows:

$$\rho C_{pc} \frac{\partial T}{\partial t} = \nabla \cdot (k_c \nabla T) - Q \quad [10]$$

where A (m^2) is the cross sectional area of pipe; ρ_w (kg/m^3) is the density of fluid; ρ (kg/m^3) is the density of pavement materials; ρ_w is the density of fluid. u(m/s) is the fluid velocity; C_p (J/(kg-K)) is the heat capacity of fluid at constant pressure; C_{pc} (J/(kg-K)) is the heat capacity of pavement materials at constant pressure; T is the temperature (K); k and k_c (W/(m-K)) are the thermal conductivity for fluid and concrete, respectively. Q (W/m) is a source/sink term due to heat exchange with the surrounding materials.

The boundary conditions at the top surface of bridge slab include the forced convection (q_{conv}), short-wave radiation (q_{solar}), sensible heat (q_s) and latent heat (q_m) during the phase change. The bottom and side surfaces are assumed to be insulated to make sure no heat loss occur. However, the effect of insulation has been studied in another companion paper. It is concluded that the energy consumption rate is expecting to increase by 29% without insulating the bottom and sides of a bridge (H. Liu, Maghoul, Bahari, and Shahmohammadi 2018).

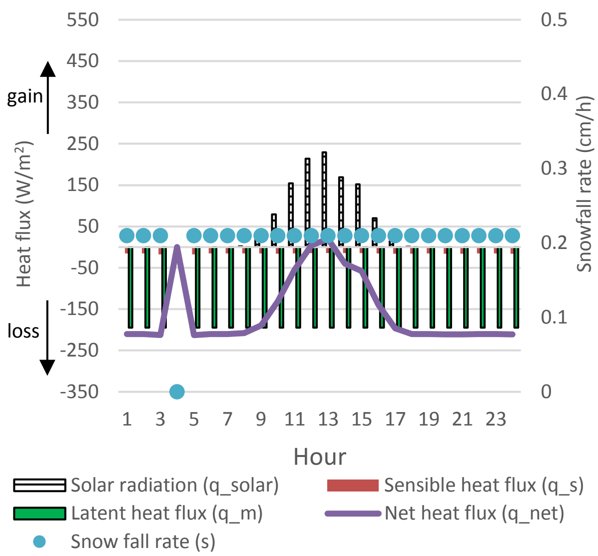


Figure 1. Heat Flux summary and snowfall rate distribution for Edmonton in 11/17/2010

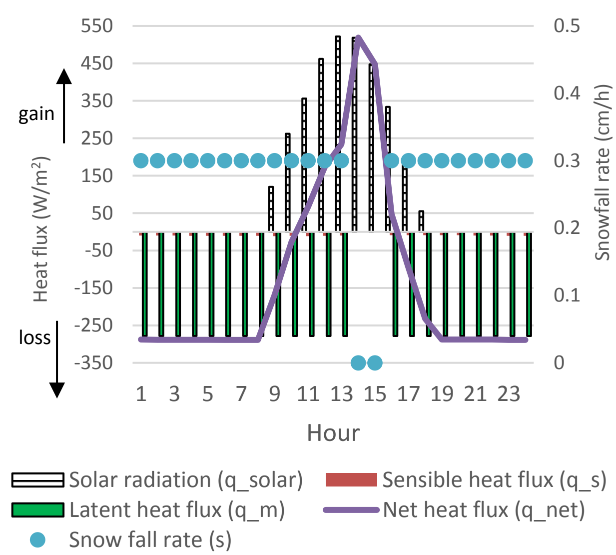


Figure 2. Heat Flux summary and snowfall rate distribution for Winnipeg in 02/15/2007

According to ASHREA (2011) handbook, the satisfactory standard installation place of pipe is at least 5cm from the top and bottom of the slab. The typical spacing between pipes ranges from 150mm to 300mm (Spitler and D 2000). Nominal pipe diameters are 18mm to 25mm (Spitler and D 2000). The parameters used in the model is shown in the table 1:

Table 1. Snow melting parameters used for the bridge slab

Item	Parameter	Description
Hydronic heating system	Diameter of pipe	2 cm
	Space	0.2 m
	Depth of pipe	5 cm
Bridge deck	length	7 m
	Width	4 m
	Height	0.2 m
Constant parameters value	Heat capacity of air	1004 J/kg*K
	Viscosity of air	0.000011 Pa*s
	Air conductivity	0.02 W/m*K
	Melting point	0 °C
	Film temperature	0.56 °C
	Pr number of air	0.7
	Sc number of air	0.6

2.3 Geothermal energy pile

The first few meters of geothermal piles are usually insulated because of the freezing and thawing effect of the ground. The governing equation for the heat transfer in geothermal heat exchanger fluid can be expressed as:

$$\rho_w A C_p \frac{\partial T}{\partial t} + \rho_w A C_p v_g \cdot \nabla T = \nabla \cdot (Ak\nabla T) + Q_2 \qquad [11]$$

where Q_2 (W/m^3) is the heat sink term due to the phase change in the evaporator of the heat pump; v_g (m/s) is the velocity of the geothermal heat exchanger pipe flow.

The heat transfer in the soil and concrete pile are described as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\mathrm{k}\, \nabla T) - Q_2 \qquad [12]$$

where C_p (J/kg-K) is the heat capacity for concrete or soil; k (W/m-K) is the thermal conductivity for concrete or soil; ρ (kg/m^3) stands for the density of soil or concrete.

The Equation 9 and 10 are fully coupled to estimate the required energy during snow melting. In addition, the equation 11 and 12 are fully coupled to obtain the amount of energy extracted from ground. The governing equation of 9 to 12 are solved using finite element method through COMSOL software. Tetrahedral mesh with various of size from 0.3m to 2.4m are adopted.

Constant underground temperature is used as the boundary condition for the geothermal energy pile. It should be noted that soil medium should be large enough so that the constant soil temperature can be considered as a valid boundary condition. The heat exchanger pipe is assumed to be polyvinyl chloride (PVC) with an inner diameter of 2cm and wall thickness of 4mm. The computational domain of the surrounding soil medium is set to be a cylinder with a diameter of 12m and 1.2m for concrete pile.

The performance of the geothermal energy pile requires a good understanding of the ground temperature distribution at various depth. Also, the buried depth as well as the length of the heat exchanger pipe could have tremendous impact on its working efficiency.

One of the most important properties of the soil is its very high thermal mass, which causes a slow response to temperature variations at the ground surface. The constant underground temperature and soil thermal conductivity for different cities in Canada is provided by Natural Resource Canada, as can be seen in Figure 3 and Figure 4 respectively. In this study, the constant underground temperature considered for Edmonton and Winnipeg is 5°C and 7°C, respectively. The detailed parameters used in the analysis can be seen as table 2:

Table 2 Geothermal pile heat exchanger parameters

Parameter	Description
Geothermal heat exchanger pipe arrangement types	Spiral shape
Pile depth	30m
Pile diameter	1.2m
Pipe material	PVC
Pipe inner diameter	2cm
Pipe wall thickness	4mm
Total pipe length	180m
Pipe wall (PVC) thermal conductivity	0.46 W/m/K
Borehole backfilling Concrete	Concrete
Ground properties	Soil
Fluid inlet temperature	-4 C
Fluid in the pipe	Water
Fluid flow rate	0.2 m/s-0.4m/s
Concrete thermal conductivity	1.65 W/m/K
Concrete specific heat capacity	837 J/kg/K
Concrete density	2300kg/m3
Ground specific heat capacity	1000 J/kg/K
Soil density (for clay)	1600 kg/m3

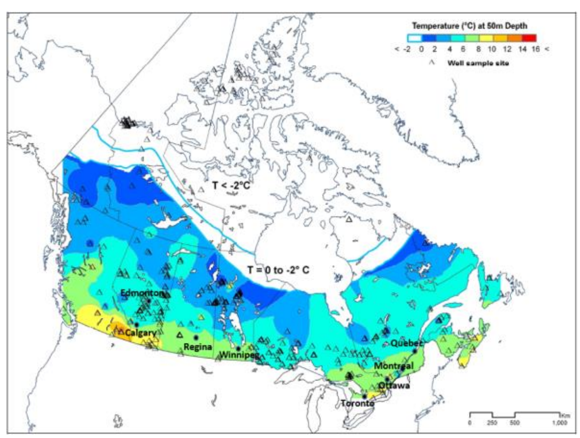


Figure 3. Underground temperature distribution across Canada (Grasby et al. 2012)

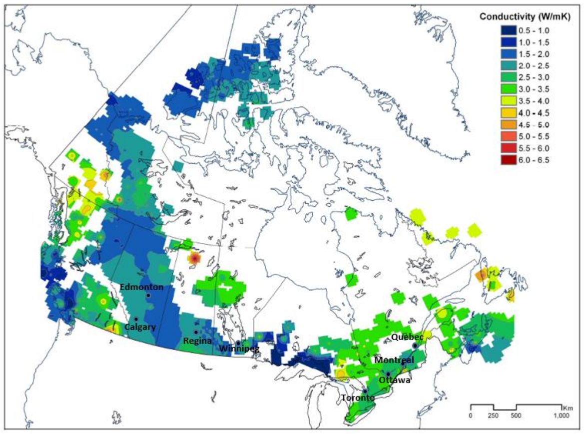


Figure 4 Thermal conductivity distribution of soils or rock across Canada (Grasby et al. 2012)

3 RESULTS

3.1 The effect of initial fluid temperature in geothermal energy pile

The influence of initial temperature of fluid exchange in U, W, and spiral shape loops is analyzed by performing a parametric study. Figure 5 shows the outlet temperature distribution with inlet temperature of -4°C and initial temperature of -10°C, -7°C, -1°C and 2°C.

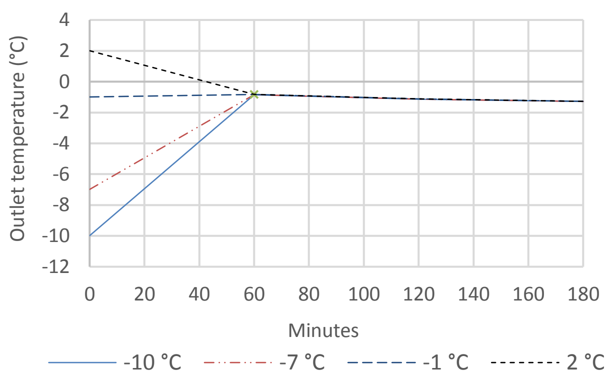


Figure 5. Outlet temperature with various initial temperature for U shape

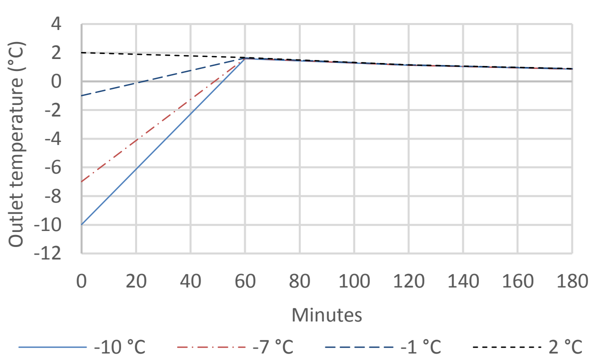


Figure 6. Outlet temperature with various initial temperature for W shape

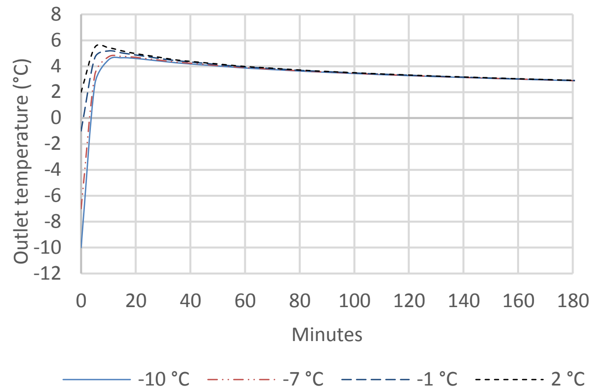


Figure 7. Outlet temperature with various initial temperature for spiral shape

The results show that the initial temperature of fluid is more important for loops with shorter length and it does not affect the performance of the heat exchanger after one hour.

3.2 The effect of flow rate in geothermal energy pile

The flow rate of fluid inside the geothermal heat exchanger pipe is an important parameter in terms of the heat absorption rate. A higher flow rate intends to achieve a faster heat exchange rate. However, the larger flow rate is also accompanied with a greater cost of electricity consumption from water pump. Therefore, it is important to determine the optimum flow rate. In this study, the impact of the flow rate for different loop arrangements is studied.

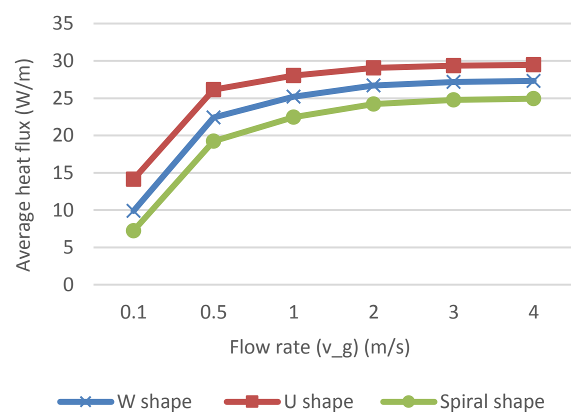


Figure 8. Average heat exchange rate for various flow rate

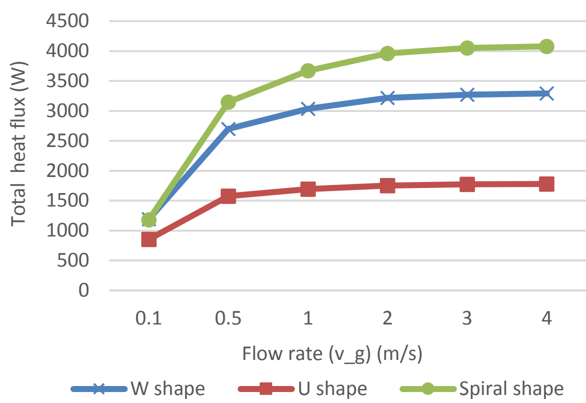


Figure 9. Total heat exchange rate for various flow rate

From Figure 6 and Figure 7, one can see that the average heat exchange rate between the soil and heat exchanger inside the energy pile increases with flow rate and this efficiency decreases dramatically for flow rates lower than 0.5 m/s and almost reaches a plateau for flow rates higher than 1.25 m/s. A higher mass flow rate (v_g) will lead to a decrease of the outlet temperature since the traveling time of fluid is reduced in one cycle.

The numerical results show that not only the length of the heat exchanger pipe affect the heat exchange rate, but also the available heat source of the surrounding soil. For example, having 200m of heat exchanger pipe instead of 180m does not improve the efficiency but increases the cost. It can be concluded from Figure 7 that the flow rate of fluid has the most significant impact on spiral loops. The total heat exchange rate by using U shape, W shape and spiral shape is increased by 2 times, 2.7 times and 3.4 times respectively from a flow rate of 0.1 m/s to 4 m/s. Therefore, the flow rate tends to play a more important role when loop becomes longer.

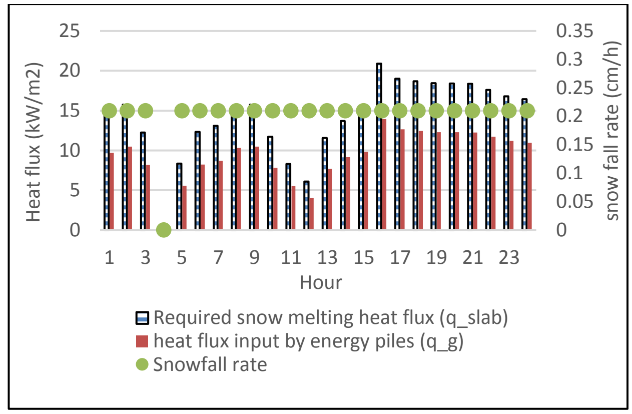
3.3 The number of pile

By performing 3D transient analysis using Equations 9 and 10 together with boundary conditions presented in Figures 1 and 2, the required heat output (q_{slab}) from hydronic heating system can be determined, as shown in Figures 8 and 9 for Edmonton and Winnipeg respectively. The required snow melting heat flux in this analysis is able to maintain the average surface temperature of pavement above 0 °C. The slab dimension is presented Table 1.

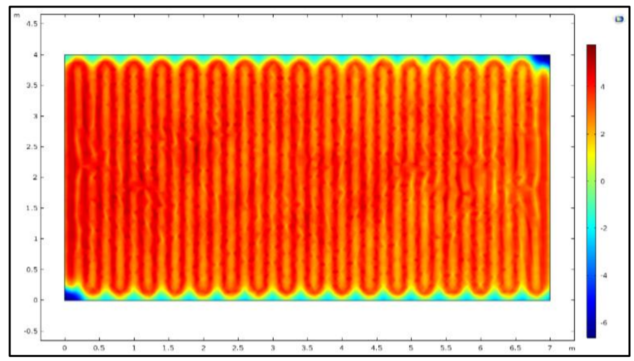
By assuming the COP of 3, the amount of energy required from geothermal energy pile (q_g) can be evaluated by:

$$q_g = \frac{(COP-1)\, q_{slab}}{COP} = \frac{2}{3}\, q_{slab} \qquad [13]$$

It is noted that the total energy consumed for snow meting during a snowfall that lasted for 23 hours is 338 kW*h in Edmonton. Similarly, 217 kW*h for a snowfall that lasted for 22 hours in Winnipeg. The average energy consumption rate (q_{slab}) for the slab is 14.7 kW and 9.9 kW for Edmonton and Winnipeg, respectively. Therefore, the required energy input for geothermal energy pile becomes 9.8kW and 6.6kW for Edmonton and Winnipeg respectively.

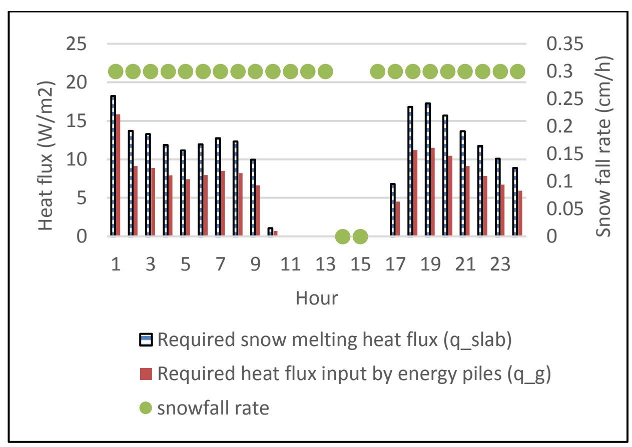


(a) Required heat flux for COP of 3

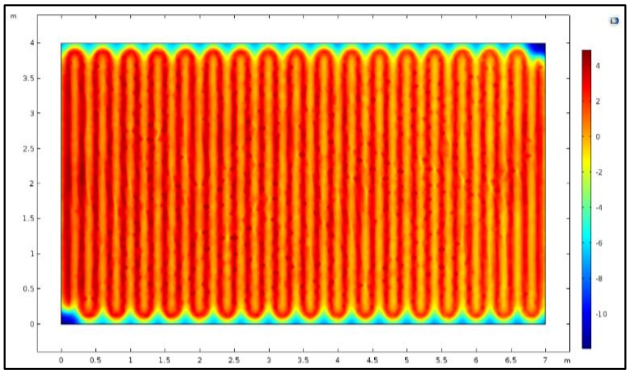


(b) Surface temperature distribution of bridge slab

Figure 10. The required heat flux input (q_g) for COP of 3 (a) and the temperature distribution of bridge slab after 12h of the start of snowfall (b) in Edmonton



(a) Required heat flux for COP of 3



(b) Surface temperature distribution of bridge slab

Figure 11. The required heat flux input (q_g) for COP of 3 (a) and the temperature distribution of bridge slab after 7h of the start of snowfall (b) in Winnipeg

The required number of piles can be simply calculated by:

$$N = q_g / P \quad [14]$$

Where N is the required number of piles; q_g (W) is the required energy input rate for geothermal energy pile to achieve COP of 3; P (W) is the energy input rate for a single pile.

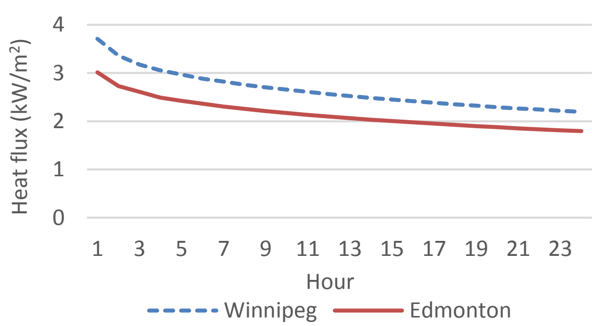


Figure 12. Geothermal energy piles thermal performance for spiral configuration

It can be seen from Figure 10 that the average energy input rate for a single pile (P) is 2.16 kW and 2.64 kW for Edmonton and Winnipeg, respectively. Furthermore, the thermal performance of geothermal energy pile decays with time due to the smaller temperature difference between fluid temperature and surrounding soils.

Therefore, the required number of piles to achieve a COP of 3 for a bridge slab with the length of 7m and width of 4m are 7 and 3 for Edmonton and Winnipeg, respectively.

It should be mentioned that the value of q_g mainly depends on the weather conditions (wind speed, air temperature, snowfall rate and solar radiation). The higher wind speed and snowfall rate will lead to a higher energy input rate (q_g), whereas the higher air temperature and solar radiation will cause a decrease in the energy input rate (q_g). The value of P (W) is dependent on the ground temperature.

4 CONCLUSION

In this paper, we developed a transient snow melting model which evaluates the required heat flux for the instantaneous snow melting based on typical Canadian weather. By performing a 3D transient heat transfer analysis, we evaluated the required energy consumption (q_{slab}) to achieve a desired snow melting performance for the bridge slab and the energy input (q_g) provided by geothermal energy piles.

By assuming a COP of 3 for the geothermal energy system, some important conclusions can be drawn as follows: a) the initial temperature of fluid does not affect the performance of the heat exchanger after one hour; b) the average heat exchange rate between the soil and heat exchanger increases with flow rate. The heat exchange rate decreases dramatically for flow rates lower than 0.5 m/s and almost reaches a plateau for flow rates higher than 1.25 m/s; and c) less pile number is required for Winnipeg in comparison with Edmonton.

In the companion paper (H. Liu, Maghoul, Bahari, and Kavgic 2018), cost analysis has been performed to compare snow melting system using pile-based geothermal energy versus electrical based system. It is concluded that Edmonton is likely to have more relative savings at the end of 30-year operation (H. Liu, Maghoul, Bahari, and Kavgic 2018). Therefore, the snow melting system using geothermal energy pile is more efficient in Winnipeg than in Edmonton. However, the system generates more savings in Edmonton due to higher heating load.

5 ACKNOWLEDGMENT

This research was partially supported by University Research Grants Program (2018) and Strat-Up Fund (2015-2018), University of Manitoba. The authors would like to acknowledge the software platform provided by COMSOL Inc. and CMC Microsystems.

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Table 3 Nomenclature

q	Required heat flux for snow melting, W/m^2
q_s	sensible heat flux, W/m^2
q_m	Latent heat in heat flux, W/m^2
q_{conv}	Convective heat flux, W/m^2
q_{solar}	Short-wave radiation, W/m^2
q_{slab}	energy consumption rate during snow fall, W/m^2
q_{net}	Required heat flux excluding convection, W/m^2
q_g	Energy extraction rate in energy pile, W/m^2
ρ_w	Density of water, kg/m^3
C_p^w	Specific heat capacity of water,$J/(kg*K)$
C_p^i	Specific heat capacity of ice,$J/(kg*K)$
T_f	Liquid film temperature, °C
T_a	Air temperature, °C
T_m	Melting temperature, °C
T_s	Surface temperature of bridge deck, °C
v_s	Velocity of fluid in hydronic system, m/s
v_g	Velocity of fluid in energy pile, m/s
V	Wind speed, m/s
h_{conv}	convective heat transfer coefficient, $W/(m^2*K)$
Pr	Prandtl number of air
Re	Reynolds number
Q	source/sink term for hydronic system, W/m
Q_2	source/sink term for energy pile, W/m
k	Thermal conductivity, $W/(m*K)$