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Research Paper

Street-heat: Controlling road temperature via low enthalpy geothermal energy

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HIGHLIGHTS

- Avoid ice formation on streets pavements through low enthalpy geothermal energy.
- Reduce street temperature fluctuations throughout the year.
- Finite element modeling of the proposed anti-icing geothermal system.
- Avoid the use of a working fluid for heating streets.
- Increase streets pavements lifetime and reduce maintenance and operating costs.

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ABSTRACT

In this paper, the authors present an idea to exploit low enthalpy geothermal energy in order to reduce street temperature fluctuations throughout the year and avoid ice formation during the winter season. The key aspect of the proposed system is that it is based on the exploitation of geothermal temperature gradients through materials with high thermal conductivity inserted into the ground, such as piles but without structural function, in order to create a preferable path for the geothermal heat to be spontaneously transferred to the street surface. The authors have carried out long-term dynamic simulations, by using the finite element discretization technique, to analyze the performance of the proposed anti-icing system. The obtained numerical results show that such a system could be effectively utilized for street heating, and proper design of both the system configuration and the thermal properties of the employed materials is important, in relation to the specific site and, as a consequence, to the exterior temperature and the subsoil temperature. A sensitivity analysis on the main geometrical characteristics of the system and thermal properties of the employed materials is presented, in order to assess the effects of these design parameters on the street heating performance.

1. Introduction

Ice formation on streets poses a major problem in terms of both the safety of drivers and the cost of damaged pavement. In addition, dangerous conditions due to ice can lead to road closures, massive traffic jams and ultra-long commutes, state-wide travel bans, delayed start times, declared state-of-emergencies, and business and school closures. All of this adds up to considerable economic loss, up to hundreds of millions of dollars per day depending on the severity of the conditions [1]. In order to address the challenge of icy streets, millions of euros/dollars are spent every year by public and private institutions. The most common de-icing technique in use today is the dispersion of salt or other chemical products, such as calcium chloride, sodium chloride and potassium acetate, able to reduce ice formation on the street surface. However, this comes at a cost as both salt and the other products cause structural damage to the street pavement, as well as other serious detrimental environmental impacts, i.e. contamination of water, subsoil and vegetation [2–4]. Given the magnitude of the problem and the negative effects and significant costs related to the available options, new solutions that are both economically and environmentally sound are highly desirable.

A number of alternatives to salt for de-icing streets have been explored, including the use of renewable energy sources or innovative materials [4–14], such as the use of solar or geothermal energy, or electrically conductive concrete/asphalt. For example,

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traditional silicon photovoltaic cells have been studied as a possible way to warm the surfaces of bridges, preventing icing [5] via concepts similar to radiant floors for home heating, using glycose as a working fluid that is pumped through pipes installed under the pavement; high installation, operating, and maintenance costs pose a severe challenge for such an approach.

The exploitation of geothermal energy – an abundantly available renewable resource – offers another opportunity for de-icing streets [6–8]. At about 8–10 meters below ground, the temperature assumes an almost constant value, roughly equal to the yearly average temperature above ground for a given location. Previous work on the use of geothermal energy to warm streets employed systems similar to that described above (radiant floor), taking geothermal energy as a heat source to heat a working fluid that is then pumped through probes (borehole heat exchangers) inserted into the ground. In particular, geothermal energy can be supplied to the street by using different approaches, that take into account the use of heat pipes, the direct use of the fluid coming from a well or the employment of a heat exchanger at the well head [8].

During summer, the system cools the pavement, storing heat in the ground, to be reused during winter. A crucial aspect and limitation of these types of systems is that a working fluid is required, flowing through kilometers of pipes installed under the roads, with subsequent high costs of maintenance and pumping.

Conductive concrete/asphalt as the street pavement material has also been explored as a possible solution for ice formation [9–15]. Conductive concrete is a cement mixture containing electrically conductive components to obtain high electrical conductivity. Due to its electrical resistance and impedance, a thin conductive concrete layer could generate enough heat to prevent ice formation when connected to a power source. Such an approach is interesting although again the issue of maintenance and operating costs becomes a critical challenge. A comprehensive analysis of the thermal performance of different types of street pavements is available in reference [16].

In this work, a different approach to street anti-icing, based on the exploitation of low enthalpy geothermal energy, is presented. Specifically, the authors propose the use of a high thermal conductivity material (e.g., aluminum) inserted in the ground as piles (without structural function), to create pathways for the spontaneous transfer of the geothermal energy to the street surface. The piles connect to a thin layer of high thermal conductivity material placed directly under the street pavement, as a substrate of hollow blocks or a large mesh, allowing for adaptation to deformations in the concrete employed in the road package. Depending on the climate conditions of the considered site, it could also be useful to employ a type of concrete with high thermal conductivity for the street pavement, such as that obtained by mixing aggregates as aluminum powder or carbon soot, derived from processing wastes with minimal costs. The key aspect of the proposed technical solution is that maintenance and operating costs are absent, since the system works without a working fluid, and installation costs are lower than those corresponding to the other available geothermal solutions [7].

2. Methods

The proposed anti-icing system is shown schematically in Fig. 1. The geometry considered in the simulations takes into account the presence of the ground, the high thermal conductivity elements inserted into the ground (i.e., the piles), the thermally conductive substrate, and the street pavement. The role of the piles is of course to increase the heat transfer between the soil and the street surface, although to what extent and under what conditions is the question addressed here using a modeling approach. The reference configuration consists of inserting piles 15 cm in diameter and 20 m in length, spaced 1.5 m apart. The substrate is assumed to be 2 cm thick and placed immediately below the street pavement which is taken to be 10 cm thick. A short and narrow two-lane street is considered in the present simulations (10 m × 5.5 m), with a row of piles below each lane, resulting in a total of twelve piles. The soil subdomain extends to a depth of 30 m below the street, that is considered sufficiently deep to assume an undisturbed soil temperature. The main parameters used for this reference configuration are reported in Table 1, although, as discussed below, these parameters have also been varied in the simulations in order to assess their impact on the anti-icing performance.

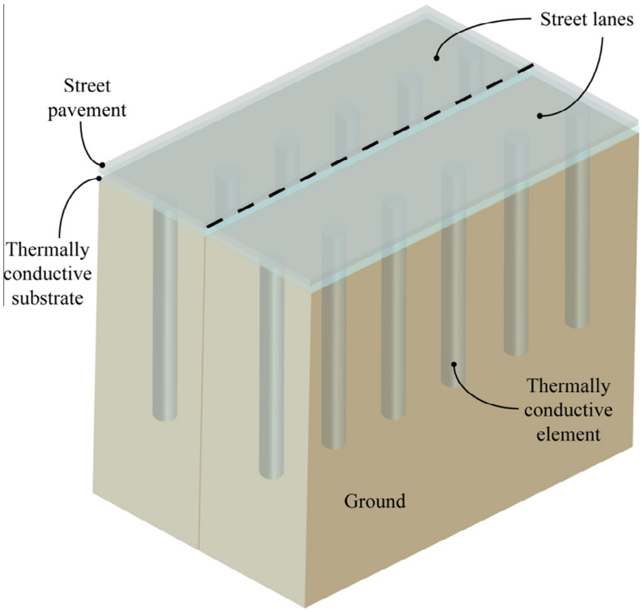

Fig. 1. Sketch of the proposed anti-icing system.

In order to predict whether such a construct would deliver enough thermal energy from the ground to the pavement, and to prevent ice formation on its surface, a series of three-dimensional numerical simulations is carried out employing a heat conduction transient model based on the Finite Element Method (FEM) [17–19], implemented in Comsol Multiphysics environment. Water convection phenomena in the ground (taken into account by one of the authors in another work [20]) have been neglected, leading to an underestimation in the present model of the heat transfer between ground and piles. Data available in the literature for foundation pile ground heat exchangers show that the presence of groundwater flow may lead to an increase of heat transfer performance up to four times [21]. Thus, the present calculations can be considered a conservative estimate of the heat transferred to the

Table 1
Characteristics of the reference configuration of the street anti-icing geothermal system shown in Fig. 1.

Reference case	Piles (aluminum)	Street substrate (aluminum)	Street pavement (concrete)
Thermal conductivity (W/(m · K))	237	237	1.40
Density (kg/m^3)	2700	2700	2400
Specific heat capacity (J/(kg · K))	897	897	720
Thickness/pile diameter (cm)	15.0	2.00	10.0

street surface. The governing Partial Differential Equation (PDE) can be written as:

$$\rho c \frac{\partial T}{\partial \vartheta} = \lambda \nabla^2 T \tag{1}$$

where ρ, c and λ are density (kg/m^3), specific heat capacity (J/kg·K) and thermal conductivity (W/(m·K)), respectively. The boundary and initial conditions associated with the above governing PDE are: variation of temperature with depth as a function of time on the vertical surfaces of the ground domain [22], undisturbed (constant) ground temperature on the bottom surface of the ground domain, convection heat transfer on the street surface, and initial variation of temperature with depth. The boundary conditions employed are as follows:

$$\begin{aligned}
&T(x,y,z,\vartheta=0)=T_0(z) \quad \text{in the whole computational domain}\\
&T(x,y,z,\vartheta)=T_g(z,\vartheta) \quad \text{on the lateral surfaces of the ground domain}\\
&T(x,y)=T_{g,\infty} \quad \text{on the bottom surface of the ground domain}\\
&h_c[T_\infty(\vartheta)-T(x,y,\vartheta)]=-\lambda\tfrac{\partial T(x,y,\vartheta)}{\partial z} \quad \text{on the street surface}\\
&\tfrac{\partial T(x,y,z,\vartheta)}{\partial n}=0 \quad \text{on the remaining lateral surfaces of the street}
\end{aligned} \tag{2}$$

where $T_0(z)$ is the initial temperature, $T_g(z,\vartheta)$ is the ground temperature that is dependent on depth and time [22], $T_{g,\infty}$ is the undisturbed ground temperature (equal to the yearly average temperature of the given location), h_c is the convective heat transfer coefficient (calculated here on the basis of wind speed data for the given location), and $T_\infty(\vartheta)$ is the time-dependent exterior air temperature. Solar radiation has been neglected in the present model, as it would cause an increase in the superficial street temperature which, while beneficial for anti-icing, would not allow to isolate the effects of the proposed geothermal system. Therefore, the operation of the system has been studied in the worst possible conditions. The simulations have been carried out for one quarter of the geometry shown in Fig. 1, as it is possible to take advantage of the symmetry of the problem. A mesh with 245,681 tetrahedral elements has been used.

As a test case, the authors consider here the values for the time-dependent exterior air temperature for the city of Bolzano in northern Italy, on the basis of the technical standard [23], that reports the methodology to be employed for the definition of the reference year to be used to reproduce the climate conditions. In particular, the simulations have been carried out for a fourteen months period from January 1st to February 28th of the following year, in order to analyze the performance over long-term operation. The first two months (January and February) can be considered an equilibration period as the dynamic operation of the system is still affected by initial conditions. The following 12 months, from March 1st to February 28th, are taken as production data and used to analyze the proposed concept. The climate conditions used here (average yearly low = −5.4 °C, average yearly high = ±14.8 °C) are representative of many cold cities around the globe where snow phenomena are present.

3. Numerical results

The time-dependent temperature is calculated for two different points on the street surface: one directly on top of a pile and one between the two lanes, i.e. the farthest point from the piles. The exterior air temperature is also reported. As can be seen in Fig. 2, the reference case leads to a substantial increase in the superficial street temperature, keeping it above freezing both in the center of each lane (where the line of piles is installed) and between the lanes. This result is due to the high thermal conductivity of the piles that create a preferable path for the heat from the ground.

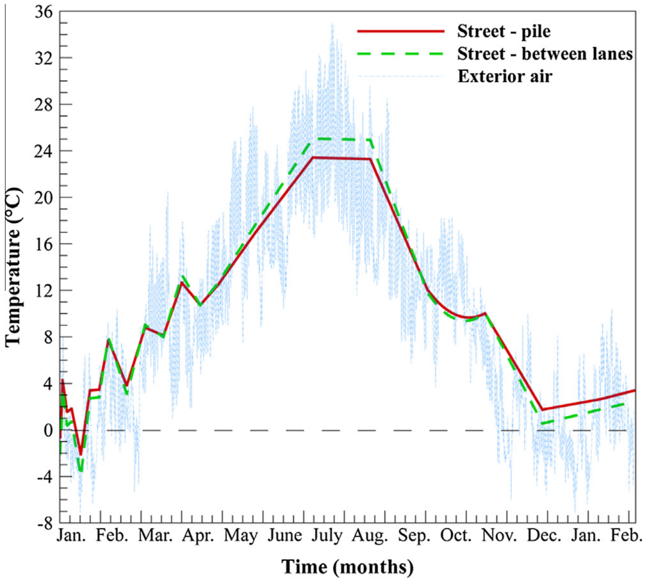

Fig. 2. Fourteen months operation: temperature of two points on the street surface, one on the top of a pile and one between the lanes, for the reference case.

Again, it is possible to note that the first two months should be considered an equilibration period, during which time the system has not yet accumulated enough heat to dampen the effects of oscillations in exterior air temperature. After one year of operation, the obtained results show that it is possible to maintain the street temperature above the freezing point as the system has reached equilibration. In particular, the street temperature ranges from 0.7 to 25.1 °C, between March 1st and February 28th, as reported in Table 2, while outside air temperatures fluctuate from −7.8 to +35 °C.

Table 2 also reports the results obtained for a normal street, without installation of any anti-icing system. From the analysis of the table, it is possible to understand the benefits deriving from the installation of the proposed anti-icing system with respect to a normal street in terms of increase of street temperature during winter and decrease during summer. By using the proposed system, it is possible to obtain an increase in the minimum street temperature values ranging between 4.6 °C and 6.6 °C, and a decrease in the maximum temperature values ranging between 3.8 °C and 7.5 °C.

Fig. 3 shows two temperature fields for the reference case, one at a specific time instant of a hot day during summer and another of a cold day during winter. The presence of the geothermal gradient and the positive effects of the proposed system are clearly evident.

Additional benefits from this type of system, beyond street ice prevention, are related to the reduction of thermal stress during the year. During hot months, the street is cooled and its temperature is largely unaffected by the peaks of the exterior air temperature. The increased stability and lower values of the street temperature reduce the number and dimensions of ruts that form, which in turn increases the lifetime of the pavement and lowers maintenance costs [24]. Similar considerations apply for the cold season.

In order to analyze the sensitivity of the proposed geothermal system to the variation of some of the important material parameters, Fig. 4 shows the calculated temperatures considering a thicker thermally conductive substrate (5 cm as opposed to 2 cm in the reference case), referred to as Case 1, which should lead to a more even distribution of heat across the road surface. The present simulations do show this to be the case: the gap between

Table 2
Minimum and maximum street temperature values obtained employing the different configurations of the proposed anti-icing system and for a normal street without any anti-icing system.

	Street temperature (between the lanes)		Street temperature (on the top of a pile)		Air temperature	
	Minimum (°C)	Maximum (°C)	Minimum (°C)	Maximum (°C)	Minimum (°C)	Maximum (°C)
Street without any anti-icing system	−4.5	+28.9	−4.5	+28.9	−7.8	+35
Street employing the proposed anti-icing system						
Reference case	+0.7	+25.1	+1.8	+23.4		
Case 1	+0.1	+24.0	+0.6	+23.1		
Case 2	+0.6	+23.9	+0.9	+23.4		
Case 3	+0.6	+23.8	+0.9	+23.4		
Case 4	+1.1	+22.3	+2.1	+21.4		

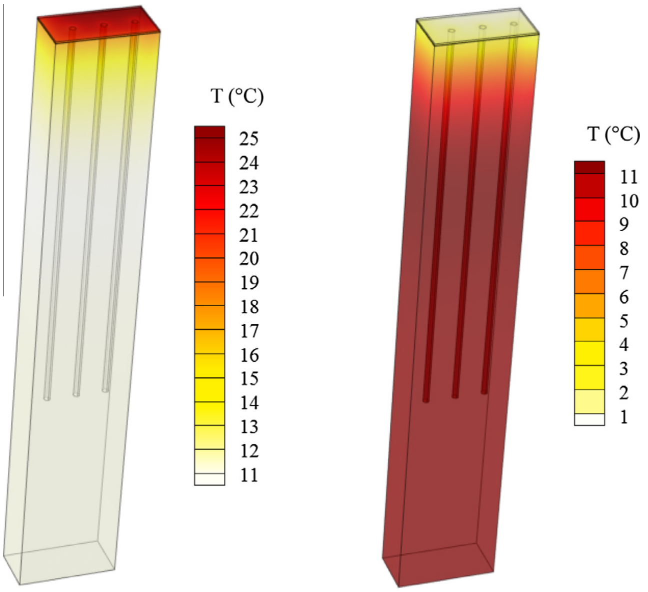

Fig. 3. Temperature field in a time instant of: a hot day during summer (left) and a cold day during winter (right).

the minimum temperature at the top of the pile and between the two lanes is reduced in the case of a 5 cm substrate by 55% (from 1.1 °C in the reference case to 0.5 °C in Case 1). Similar considerations can be applied for the maximum temperatures (see Table 2). However, the more uniform temperature distribution on the road surface for Case 1 comes at the cost of a reduction of the minimum street surface temperature values (down to 0.1 °C and 0.6 °C in the two considered points of the road surface), making this configuration less appealing for anti-icing. This behavior is due to the increased thermal resistance of the street package, with a consequent slower transfer of geothermal energy towards the street's surface.

Another variable that has been explored in the present model is the thickness of the street pavement, which varies in practice with different road packages and materials. In Case 2, the thick street substrate (5 cm) of Case 1 is maintained, but now with a thicker street pavement (20 cm instead of 10 cm). Fig. 5 shows that in this case the system is more responsive to the fluctuations of the exterior air, and the uniformity of the temperature distribution on the street surface is more pronounced, with a gap of only 0.3 °C in the minimum temperatures (see Table 2). Importantly, the minimum temperature of the street is increased with respect to Case 1 by 0.5 °C, illustrating that if temperature uniformity is important, both a thicker substrate as well as thicker pavement may be suitable.

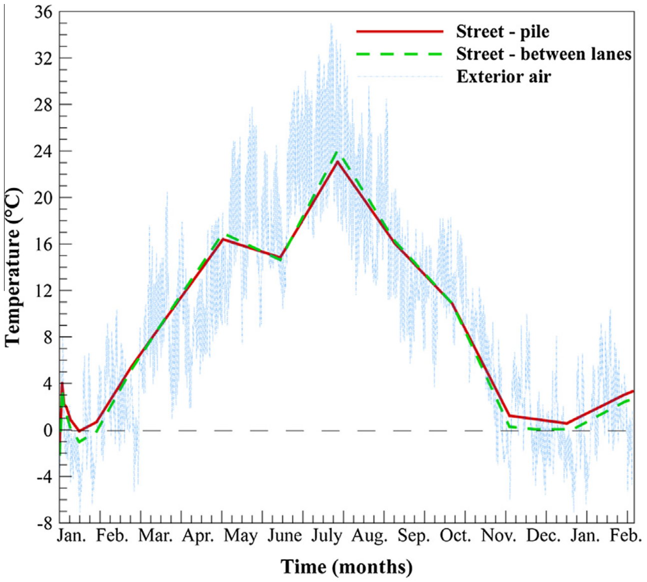

Fig. 4. Fourteen months operation: temperature of two points on the street surface, one on the top of a pile and one between the lanes, when street substrate is thicker (5 cm) – Case 1.

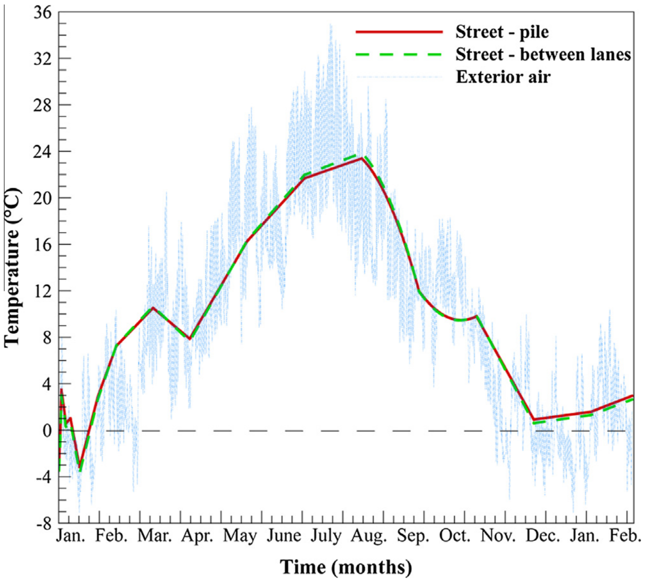

Fig. 5. Fourteen months operation: temperature of two points on the street surface, one on the top of a pile and one between the lanes, when street substrate and pavement are thicker (5 cm and 20 cm, respectively) – Case 2.

Another way to modify the set-up is to consider both street substrate and pavement of larger thickness as in Case 2, coupled to a material with larger heat capacity than aluminum for the street substrate, such as steel (referred to as Case 3). As can be seen in Table 2, the results for this case are nearly identical to the previous example (also in terms of dynamic temperature profiles, that have not been reported again), illustrating that an increased heat capacity of the substrate material does not influence the behavior of the proposed system in the specific configuration considered (with thicker street substrate and pavement). The reason for this behavior could be related to the massive pavement: an increase of heat capacity of the substrate does not influence the system operation because the street package has a significant value of thermal mass, due to its increased thickness with respect to the reference case.

The effects of increasing the thermal conductivity of the road package have been also explored. Fig. 6 shows the calculated temperatures considering the thicker street substrate and pavement as used in Case 2 (5 cm and 20 cm, respectively), although now with a concrete mixture for the street pavement with a larger thermal conductivity $(10\ \mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$, referred to as Case 4. These values of thermal conductivity for concrete can be obtained using tailored materials, such as concrete with aluminum powder, carbon soot or graphene/graphite as aggregates. For this case, the minimum/maximum temperature peaks are substantially increased/reduced with respect to the previous cases, with street surface temperatures ranging, from March 1st to February 28th, from +1.1 to +22.3 °C, while outside air temperatures fluctuate from −7.8 to +35 °C. This increased stability and reduced seasonal fluctuation of the street surface temperature would lead to further reduction of the street thermal stresses. However, as the other cases show, the use of such tailored materials is not necessary to achieve anti-icing and other beneficial effects.

It is possible to note again that the present simulations can be considered quite conservative in their estimates of these benefits, since convective phenomena in the ground and the influence of solar radiation – both of which would lead to further improvements in the performance of the proposed design – have been neglected.

Another aspect of a cold climate to consider is the effect of snow. The behavior of snow on streets pavements is quite complex, and dedicated models to reproduce accumulating and melting phenomena for heated pavements, taking into account the amount of snow falling on the pavement, the temperature values and the different heat transfer mechanisms involved, have been developed and experimentally validated [25,26]. Since the proposed system is based on pure heat conduction with the ground and external driving forces are absent, the superficial street temperature could be maintained slightly above the freezing point, from 0.6 °C to 2.1 °C based on the present simulations (excluding case 1). Therefore, if there is a significant snowing phenomenon and a big amount of snow per unit of time touches the street, the above values of the superficial street temperature may not be high enough to obtain a fast melting, and snow accumulation could occur. When snow accumulates on the pavement, the surface temperature of the street could reach higher values with respect to those that have been reported above. This is because the snow on the pavement acts as an insulation layer between the street and the exterior air, due to the low density and low thermal conductivity of snow (100–200 $\mathrm{kg/m^3}$ and 0.06–0.23 W/m·K, respectively), which in turn reduces the heat dissipation due to convection with the exterior air. Taking into account this insulation layer effect would lead to a larger increase in the pavement temperature, further improving the ability of the proposed system to avoid ice formation. Therefore, icing would be avoided thanks to the temperature values above freezing point, and the snow could gradually melt after accumulating. The melting process does absorb heat, but the proposed system is always active and the street surface temperature should be continuously maintained above the freezing point.

On the basis of the present numerical results, the proposed system appears promising for street anti-icing. In any practical application of this concept, it would be important to analyze the local climate conditions and type of street under investigation, in order to design a system that best fits with the specific case. The work presented here is meant as a proof-of-concept; in order to achieve optimal conditions, the design process should take into account the variation of the number of piles, diameter, distance, materials and different combinations of all the design parameters, among other factors. Nonetheless, the obtained results are quite encouraging towards the possibility of an anti-icing road system that operates in the absence of an external energy source and working fluid.

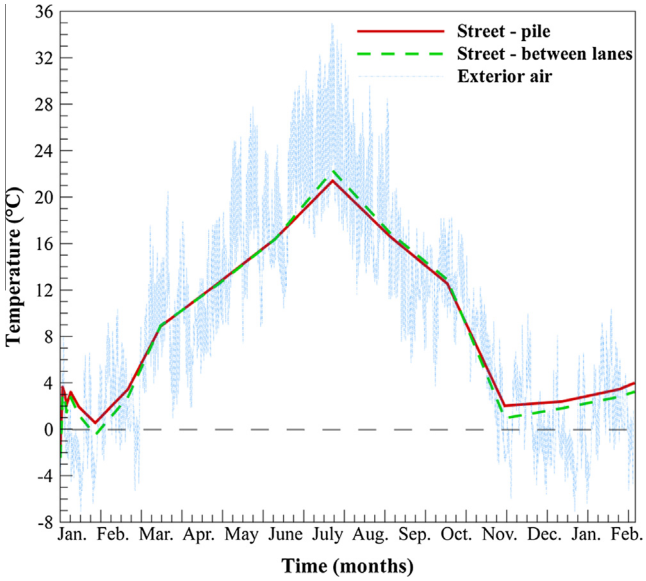

Fig. 6. Fourteen months operation: temperature of two points on the street surface, one on the top of a pile and one between the lanes, when street substrate and pavement are thicker (5 cm and 20 cm, respectively) and the street pavement is more thermally conductive $(10\ \mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$ - Case 4.

4. Cost considerations

While a detailed cost analysis has not been carried out here, it is estimated that the up-front installation costs of the proposed low enthalpy geothermal based anti-icing system are lower than those corresponding to other technical solutions. For example, the cost of a tested system based on solar-geothermal coupled principles, employing heat exchange tubes embedded in the asphalt and energy storage apparatus within the ground, is reported to be around 2500 $\mathrm{Euro/m^2}$ [7].

The cost of the full system proposed here should take into account costs related to the aluminum (or other thermally conductive material) used for the piles and for the street substrate (of different thicknesses), the ground perforations, the installation and, in the case of tailored concrete obtained by using high thermal conductivity aggregates, the additional costs for the aggregates and for the mixture preparation. The authors estimate that taking such items into account, the global cost per square meter of street for the configurations analyzed in this paper could be within the range of 850–1250 $\mathrm{Euro/m^2}$. However, this cost could be further decreased to around 450 $\mathrm{Euro/m^2}$, via materials optimization that would allow to reduce the length, diameter and/or number of piles, or employing hollow piles. Future work will take into account the exploration of these options. Furthermore, one of the most important economic benefits of the proposed system is the savings related to the (essentially complete) lack of maintenance and operating costs compared to other anti-icing strategies.

5. Conclusions

In the present paper, the authors have demonstrated the feasibility of a novel idea for anti-icing of streets, using a three-dimensional dynamic numerical modeling approach based on the finite element method. The concept is based on the exploitation of low enthalpy geothermal energy, without using a working fluid or additional energy sources. The immediate consequence of such a design is that the maintenance and operating costs are absent.

The proposed system is based on the insertion of thermally conductive elements (piles without structural function) into the ground, and the use of a thermally conductive street substrate. This concept has been assessed using different configurations of materials and designs, showing that, in all cases, temperatures of the street's surface can be maintained above freezing throughout the year. This would not only lead to effective anti-icing, but also increase the pavement lifetime due to the lower temperature fluctuations during the year. Using the proposed system with the configurations analyzed here, it is possible to obtain an increase in the minimum street temperature values during winter ranging between 4.6 °C and 6.6 °C, and a decrease in the maximum temperature values during summer ranging between 3.8 °C and 7.5 °C.

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