Experimental study of road deicing by using the urban groundwater under the climatic condition of Nuremberg city, Germany

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Abstract

Traffic accidents caused by heavy icing and snowing kept increasing in Germany in recent years, and many deicing methods were therefore developed. These methods either harm the environment (deicing salt) or damage roads (snowplows). As an alternative, the heating of roads using electricity or heated water has been proposed. This study considers the direct use of groundwater for road deicing in urban centers. The climatic and hydrological setting of Nuremberg city is referenced for a testing setup inside a cooling chamber using concrete slabs to test inlet water temperatures under different ambient temperatures. They were designed with 100 mm and 200 mm coil distance and both with an installation depth of around 40 mm. Additionally, an outside test field in a similar fashion is built to validate the measurements inside a chamber. The experiments indicated that a groundwater temperature of 10 °C is sufficient to keep the surface ice-free in typical winter days in the study area. Furthermore, the snow did not accumulate on the outside test field during snowfall events. The usability of this heating method could, therefore, be recommended for road deicing under such climatic condition.

Keywords Deicing · Urban groundwater · Urban heat island · Open-space heating · Roadworks

List of symbols

Q	Heat flux (W)
A	Surface (m ²)
d	Width of body (m)
E	Thermal energy (kJ)
m	Mass of fluid (g)
C_w	Specific heat capacity (J/g K)
ΔT	Temperature difference $T_1 - T_2$ (°C)
v	Volume flow (l/s)
V	Volume (l)
λ	Thermal conductivity (W/m K)

T_m	Surface temperature between pipes
T_{air}	Outside air temperature

Abbreviations

T_{out}	Outlet temperature
T_{in}	Inlet temperature
T_{ref}	Reference temperature
T_C	Temperature of chamber
T_p	Surface temperature above pipe

1 Introduction

In winter, the accident rate in Germany is generally higher than that of other seasons. It was proven that wintry traffic jams have harmful economic effects [1]. The number of accidents in winter fluctuates significantly and is related to the intensity of winter, as can be seen from the documents of the German Federal Statistical Office [2]. Road clearance procedures were established in Germany for many years and enabled fluid traffic in winter. However, these methods are anything but environmentally friendly. As already shown in multiple studies, a direct correlation between the use of road salt and

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the chloride rise in groundwater was proven [3–5]. Also, the use of snowplows damages roads [6].

These findings have led to developments to keep the roads free of snow and ice with different methods. In the United States, some bridges were successfully heated geothermally or electrically [7]. In Europe, a Swiss project was able to prove that geothermal street heating is possible and feasible [8]. Furthermore, due to its unique geological location, Iceland has been a pioneer in the use of geothermal energy for years, including the use of open-space heating. The country currently heats about 70.000 m² of road and pavement with a designed maximum heat output of 180 W/m² [9]. In Germany, the Berkenhthn geothermal bridge was built in 2011 as a pilot project, proving that geothermal energy could be a heat source for deicing road surfaces in Germany is feasible [10].

These projects, except in Iceland, have in common that a heat pump was used to raise the water temperature. Inlet temperatures of up to 55 °C are no exception, but the rule, as various projects show [7, 11, 12]. Thus, additional electrical energy was often used to heat the road surface, usually induced by fossil fuels [8]. Just in recent years, some studies appeared that focus on a more ecologic approach by using low-temperature heating fluids [13, 14]. There is little research in this area, and most systems do still rely on higher inlet fluid temperatures [12]. All studies mentioned are either halfway [14] or completely [7, 8, 11] dependable on additional heating energy.

This study tries to take a different approach: Instead of increasing the water temperature heating the surface, the groundwater is used directly for heating to keep the road surface above 0 °C. Furthermore, instead of using additional energy to heat the surface, an abundant heat source is used that has increased over the last few decades, namely the Urban Heat Island Effect [15]. Some Japanese areas have used this method for years, where water is distributed on the road surface via sprinklers to melt snow [16].

The urban heat island effect has been observed since the 1950s [17]. In 1973, Oke determined it as the maximum temperature difference of the surface air temperature in urban city centers and the rural area around the city [15]. Studies in Germany have shown a sizeable geothermal potential of urban heat islands in Germany and abroad [18–20]. The groundwater temperatures in the cities studied are, on average, 1.9 to 2.4 °C higher than the surrounding groundwater [19].

The urban area of the city Nuremberg was chosen as a model location to test the suitability of the heating method. It is not only large enough to expect a heat island but also has multiple subway lines and various multi-story car parks, that further heat up the ground.

This study aims to keep an area free of ice successfully under the climatic conditions of the city Nuremberg, Germany. Furthermore, the efficiency of snow melting was observed during the winter of 2018/2019.

2 Materials and methodology

2.1 Testing method

A testing setup was devised and installed in a controllable environment to determine the influence of ambient temperatures on the surface temperature of concrete roadworks. The framework conditions were such that the surface temperature was controlled only by changing the ambient temperature or the heating temperature. Isolated concrete slabs inside a cooling chamber were used. In this way, the heat potential of various groundwater settings was investigated. The energy consumption of the system was then recorded by determining the inlet and outlet temperatures [21]. A similar method was used to determine the thermal conductivity of soils and rocks in thermal response tests [22]. In this case, the thermal conductivity of the heated material was already known. The test was considered successful when the surface temperature was above 0 °C at the lowest chosen ambient temperature step.

This setup, as shown in Fig. 1, should allow it to perform observations about the heat consumption that occurs during the operation of the deicing system. Before the test setup was designed, multiple border conditions for the experimental setting were defined (Fig. 2).

2.2 Geological and hydrological setting

Nuremberg is embedded in the so-called “Nuremberg Basin” and is characterized by depression and saddle structures that alternate in the city area [23].

Geologically, Nuremberg is located in the “Upper Triassic”—strata. Table 1 demonstrates the stratigraphic chart of the city area. In general, the “Blasensandstein,” porous

Fig. 1 Sketch of the testing setup. The tested slabs are inside a cooling chamber while heated by a water source (i.e., groundwater, artificial reservoir)

Fig. 2 Groundwater temperatures in Nuremberg 10 meters below groundwater level. Map by the Nuremberg environmental office [32]

sandstone, is considered the central geological layer in the city area.

Nuremberg has two significant aquifers. Aquifer Ia is considered as the surface near aquifer flowing through the quarternary sands and gravels of the “Pegnitz”—river and its paleo valleys. Aquifer Ib is regarded as a crevasse aquifer through a series of geological strata up to the “Estheriensichten” [24]. As both aquifers Ia and Ib are hydraulically connected, they are generally defined as one aquifer. The “Estheriensichten,” silty claystone, is considered as aquiclude between aquifer I and aquifer II. The latter is based on the “Benker” sandstone and is used as a reservoir for drinking water. Aquifer I is usually high yielding with hydraulic conductivity coefficients of 1×10^{-4} – 1×10^{-5} m/s [24].

Additionally, the groundwater temperature was included in the current measurement program of the city Nuremberg [32]. An urban heat island was suspected. As shown in Fig. 3, groundwater temperatures were usually higher than 9 °C. These temperatures were measured in rural areas around the city. In the city center, temperatures between 14 and 15 °C were observed. The temperature decreased concentrically from the city center. It can, therefore, be assumed that the temperature of aquifer I permanently remain above 10 °C in the urban area. Summing up, the groundwater temperature for the experimental setup was spanning from 8 to 14 °C providing insight into the heating capabilities of average temperatures in the Nuremberg urban area and the rural area surrounding it.

Table 1 A stratigraphic table shows the geological strata in Nuremberg city. Modified after Berger [23] and Spöcker [26]

Aquifer	Hydraulic conductivity (m/s)	Thickness of layer (m)	Stratigraphy [27] /age (Ma) [28]		Comment
Ia (unconfined)	$k_f = 5 \times 10^{-3}$ – 10^{-5}	0–30	Fluvial sands	Quaternary (2.6–0)	Sand and gravel layers; deposited by Pegnitz River and its glacial valleys [29]
Ib (semi-confined)	$k_f = 10^{-4}$ – 10^{-5}	~ 90	Burgsandstein (Mainhardt and Löwenstein—Formation)	Upper Triassic-Norian (226–209)	Sandstone; occurs only in two locations [30]
		~ 40	Blasensandstein l.w.s (Hassberge—Formation)		Sandstone; central stratigraphic unit in the urban area [31]
	$k_f = 10^{-5}$	~ 30	Lehrbergschichten (Steigerwald—Formation)	Upper Triassic—Carnian (237.5–226)	Sand-and Siltstone
		4–30	Schilfsandstein (Stuttgart—Formation)		Sandstone
Aquiclude	$k_f = 10^{-7}$ – 10^{-9}	20–30	Estheriensichten (Benk—Formation)		Separates Aquifer I from Aquifer II
II (confined aquifer)	$k_f = 10^{-5}$	~ 90	Benker Sandstein (Benk—Formation)		Sandstone

Fig. 3 Stratigraphic column of Nuremberg with additional hydro-geologic information. Modified after Baier et al. [25]

Fig. 4 Mean, maximum, and minimum average daily temperatures in Nuremberg from 1951 to 2018. Data provided by the Climate Data Center of the German Weather Services (Climate Data Center [34])

2.3 Climatic conditions

2.3.1 Temperatures

Nuremberg is a city located in Northern Bavaria, Germany. The Köppen–Geiger classification is “Dfb,” a warm–summer humid continental climate [33]. The winter with average daily temperatures of 2 °C to 4 °C extends from December to

March. In these months, temperatures frequently fall below zero degrees. The average temperatures per month of the last 60 years (1955 to 2015) are depicted in the following Fig. 4. On average, the minimal daily temperatures from December to March ranged between −3 and 0 °C, which indicates that frost events occurred on a regular base. Those averages do not depict the actual measured air temperature in unusually cold events. Even so, temperatures down to −10 °C occurred quite frequently [34]. For the investigation, ambient temperatures between 0 and −10 °C were chosen as this temperature range is most common in freezing conditions (Table 2). Still, in extreme events, the temperature can drop below −10 °C. If that is the case, it is assumed that additional heating power (i.e., electric heating to the water at the inlet, use of heat pump) is used to prevent the surface from freezing. Even so, ambient temperatures lower than −8 °C might not be that harmful. Due to the deficient humidity levels at such low temperatures, the icing of the surface is less likely than at temperatures around the freezing point [35].

2.4 Energy calculation

To determine the heat flux that is provided by the groundwater at different temperature steps, the energy of the heating fluid was calculated. The energy output of the carrier fluid was calculated by the following equation [36, 37]:

$$E = m * C_w * \Delta T \quad (1)$$

where E is the energy measured in joule (J). m is the mass of the carrier liquid in gram (g), C_w is the specific heat capacity of the carrier liquid in J/(g K), and ΔT in kelvin (K) is the temperature difference of the carrier liquid. With this equation, the total energy output of the system is calculated. To calculate the heat output, the energy, derived in (1), was implemented in the following Eqs. (2) and (3):

$$t = \frac{V}{v} \quad (2)$$

$$Q = \frac{E}{t} \quad (3)$$

here, t is the time (s), the water takes to flow through the installed pipes, with v being the volume flow in liters per second (l/s), and V the volume in liters of the used pipes. Q is the calculated heat flux in watts. This allowed the power provided by the energy source to be calculated in Eq. (4):

Table 2 Hourly measured temperatures below 0 °C since 1950 (596,058 h) (Climate Data Center [34])

Temperature	0 °C	−1 °C	−2 °C	−3 °C	−4 °C	−5 °C	−6 °C	−7 °C	−8 °C	−9 °C	−10 °C
Percentage	14.28%	10.97%	8.30%	6.28%	4.81%	3.68%	2.84%	2.21%	1.72%	1.34%	1.03%

$$Q = \frac{(m * C_w * \Delta T) * v}{V} \quad (4)$$

2.5 Definition of variables

After establishing the equations needed for the measurements, the decisive parameters for determining the heating power were defined further and implemented in the test setup. The following parameters were defined.

- m as the mass of the carrier liquid inside the heated pipes. In this study, water was used, with a density of 1 g/cm^3 .
- V as the volume of the carrier liquid
- C_w , the specific heat capacity, was set to $4.2 \text{ MJ/m}^3 \text{ K}$
- ΔT was split up in T_{in} , as the inflow temperature of water and T_{out} , as the outflow temperature

Furthermore, to measure the feasibility of the heating system, additional parameters were defined.

- T_c was defined as the temperature of the testing chamber, simulating the ambient temperature.
- T_p was the surface temperature of the heated slab above the heating pipes.
- T_m was the surface temperature of the heated slab between pipes.
- T_{ref} was defined as the reference temperature of the surface, providing a comparison between the heated and unheated slab.

2.6 Testing setup inside the cooling chamber

Three concrete slabs with a surface area of 1.4 m^2 were designed for testing and were installed in a cooling chamber to provide a controllable ambient temperature. The temperature inside was adjustable down to -10°C with

a precision of $\pm 0.3^\circ \text{C}$. An artificial reservoir provided the water supply for the experiment and was adaptable to the desired inlet temperature by several heating rods and a thermostat. A submersible pump circulates the water through the heated slabs. The water circuit flow was controlled by a valve and led to the respective concrete bodies by two separately adjustable inlet valves. A flowmeter measured the flow rate during each test run at the separate inlet. For the experiment, air-entrained concrete, commonly used in street works, was used for the slab body. The thermal conductivity was measured to be approximately $2.8\text{--}3.1 \text{ W/m K}$. Foam insulation plates isolated the slabs with a width of 5 cm on the sides and the underside to provide an exchange of heat predominantly through the surface. In two of them, "RAUTitan stabil" heating pipes made of composite materials with aluminum sheathing were installed with 10 and 20 cm horizontal distances at a depth of 40 mm . The inner width of the pipes was 17.6 mm . Literature states a typical spacing of the pipes at around 30 cm or even 40 cm [11, 12]. In this study, 100 mm and 200 mm pipe separation was used. It was assumed, as stated in reviews before [10, 13, 38], that the heating ability of pipes at higher separations is not ideal, especially when using low-temperature heating fluids. Table 3 describes additional information, including the length of the pipes and the volume. The third concrete slab was designed as a reference with no heating equipment installed (Fig. 5). For the temperature measurements, PT100 resistance temperature sensors were used. With the uncertainty of $\pm 0.1^\circ \text{C}$, they provided a sufficient measuring resolution for this study. The measurements were logged every 10 s to measure the slightest fluctuations in the temperature at the testing site. The temperature sensors were arranged as follows (Fig. 5).

- Two sensors were placed in front and rear of the cooling chamber measuring the mean chamber temperature (T_{C1} and T_{C2})

Table 3 Parameters of the heated slabs

Attribute name	Attributes	
	Slab 10	Slab 20
Material	Air-entrained concrete	Air entrained concrete
Thermal conductivity	$2.8\text{--}3.1 \text{ W/mK}$	$2.8\text{--}3.1 \text{ W/mK}$
Area	1.4 m^2	1.4 m^2
Height	0.3 m	0.3 m
Pipe material	Pe-Xa with aluminum	Pe-Xa with aluminum
Width	17.6 mm	17.6 mm
Installation depth	40 mm	40 mm
Horizontal pipe separation	100 mm	200 mm
Length	12 m	8 m
Volume of pipes	2.9 l	1.9 l

Fig. 5 Concrete slabs inside the cooling chamber. Each blue dot is one PT100 thermal sensor. T_c : sensors measuring chamber temperature; T_p : sensors measuring the surface temperature directly above the pipe; T_m : sensors measuring surface temperature in between

the pipes; T_{ref} : sensor measuring the surface temperature of the reference slab; T_{in} : sensors measuring the inlet temperature. T_{out} : sensor measuring the outlet temperature

- One sensor was placed on the surface of the reference slab measuring T_{ref}
- One sensor was placed outside of the chamber to measure T_{air} to measure the influence of the outside temperature on the chamber performance, one
- Two sensors were placed in each heated slab inlet and outlet pipe measuring T_{in} and T_{out} .
- One sensor was placed on the surface of each heated slab directly above the pipe (T_{p10} and T_{p20}). The other sensor was placed on the surface in between two pipes (T_{m10} and T_{m20}).

Table 4 Description of the measuring setup

Measurement Nr.	Inlet temperature (°C)	Chamber temperature (°C)	Temperature step	Timestep (h)
1	8	−1 to −10	2 K per step	24
2	10	−1 to −10	2 K per step	24
3	12	−1 to −10	2 K per step	48
4	14	−1 to −10	2 K per step	24

2.7 Measurement inside the cooling chamber

The measurements in the cooling chamber were carried out according to the following parameters mentioned in the chapters above (Table 4).

A temperature range of 8 °C–14 °C was selected for the inlet temperatures. This range covered the temperatures occurring in groundwater in the Nuremberg area.

Chamber temperatures of −1 °C to −10 °C were selected for the respective measurement series. This range included the frequently occurring outdoor temperatures in winter.

The chamber temperature was lowered by 2 K every 24 h until −10 °C was reached. This period was considered adequate to achieve a thermal equilibrium between the chamber temperature and the heating temperature.

The water temperatures were raised by 2 K after each set of tests. The water temperatures of the test series were designated to 8 °C, 10 °C, 12 °C, and 14 °C.

2.7.1 Field test

Multiple concrete slabs with a similar water supply and heating installations were built in the backyard of the university facilities (Fig. 5; Carl—Thiersch—Strasse 16, 91054 Erlangen, Germany) to evaluate the thermal efficiency of this heating system in an in situ environment. The measurements of the outside test field are conducted with a similar arrangement of sensors as inside the cooling chamber. Furthermore, installation depth and coil distances remained identical. For further results, a slab with a coil distance of 15 cm was built as well. The area of each was 4 m² or 2 × 2 m, representing a two-lane highway on a scale of 1 to 5. The experiment was carried out between January 15 and March 10, 2019, and only one slab was measured at a time (Fig. 6).

Fig. 6 Sketch of Test field: 1: 100 mm coil distance, concrete; 2: 200 mm coil distance, concrete; 3: coil distance 150 mm; concrete; 4: reference field; concrete; all heat pipes are installed at a depth of approx. 40 mm

Fig. 7 Exemplary measurement of the concrete slab with 100 mm coil distance at $-1\text{ }^{\circ}\text{C}$ ambient temperature and $10\text{ }^{\circ}\text{C}$ water temperature. The defrosting cycles of the chamber are visible as small peaks at T_c and the surface temperatures. T_c : combined measurements of chamber temperature. T_p : surface temperature above the pipe. T_m : surface temperatures between pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

3 Results and discussion

3.1 Temperature development in the cooling chamber

3.1.1 Slab 100 mm

An exemplary measurement step is shown in Fig. 7. This figure shows how the measurements were structured and what similarities existed between the individual measurement steps. The hourly average of all values was calculated for better presentation. In general, the temperatures fluctuated to equilibrium within one hour

after the start of the measurement. T_{ref} required about 3 h adjusting to the chamber temperature. At regular intervals of four hours, a slight increase of the surface temperatures (T_p and T_m) and the chamber temperature T_c was observed. These peaks were due to the defrosting cycles of the cooling chamber. Figure 8 shows the mean values of all measurement series.

A linear decrease of all surface temperatures of the samples was observed in the measurement series. As expected, T_{ref} decreased linearly to the ambient temperature. The reduction in the outlet temperature with a cooler chamber temperature was also observed. Conversely, this meant that the heating power connected to the system increased with decreasing chamber temperature. Higher water temperature also increased the heat output in the sample. The surface temperatures of the heated surface were significantly higher than those of the unheated surface. At water temperatures of $8\text{ }^{\circ}\text{C}$, the surface temperature dropped below the freezing point at a chamber temperature of $-9\text{ }^{\circ}\text{C}$. At $-10\text{ }^{\circ}\text{C}$, the temperature of T_p also dropped below $0\text{ }^{\circ}\text{C}$, indicating that heating the surface with $8\text{ }^{\circ}\text{C}$ water temperature cannot provide enough heat for the defined temperature window. All other water temperatures guaranteed surface heating above the freezing point.

Another observation made was the increased spread of surface temperatures between T_p and T_m . These were also observed in other studies [39]. The power output consumed per heated square meter is shown in Table 5.

3.1.2 Slab 200 mm

The measurement results with a horizontal pipe distance of 200 mm behaved comparably to that of 100 mm (Fig. 9). The most significant differences were the lower surface temperature and the higher outlet temperature, which is due to the shorter pipe length. Since the same volume flow was used for both concrete slabs, the water could not cool as much as in the other pipe system, which was 4 m longer. Figure 10 shows a comparison of the 4-measurement series. Like the results of the previous chapter, the surface temperature decreased almost linearly with decreasing ambient temperature. At a water temperature of $8\text{ }^{\circ}\text{C}$, the freezing point on the surface was reached at around $-8\text{ }^{\circ}\text{C}$ of chamber temperature. In contrast to a horizontal distance of 100 mm, it was not possible to guarantee reliable ice-free operation with water temperatures of $10\text{ }^{\circ}\text{C}$. The freezing point was reached at an ambient temperature of around $9\text{ }^{\circ}\text{C}$. Only at water temperatures of $12\text{ }^{\circ}\text{C}$ and $14\text{ }^{\circ}\text{C}$, it was ensured that no ice is formed. Also, an increasing difference was observed between the surface temperature above the pipe and between, comparable to that of 100 mm horizontal distance. The heat

Fig. 8 Mean measured temperatures of the different tests for coil distance 10 cm. **a** 8 °C Inlet temperature (the volume flow has been adjusted to better measure the difference from T_{in} to T_{out}); **b** inlet Temperature of 10 °C; **c** inlet temperature of 12 °C; **d** inlet temperature of 14 °C (temperature step at -3 °C had faulty data and was

not used for this study). T_C : combined measurements of chamber Temperature. T_p : surface temperature above the pipe. T_m : surface temperatures between pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

output in this setting was not calculated at most measured steps due to multiple errors that occurred with the thermal sensor at the water outlet.

3.2 Temperature development at the test field

3.2.1 General observation

For a general overview, the following Fig. 11 shows a 7-day segment of the outside measurement test.

An evident day–night fluctuation was discernible. During the day, the temperatures of the air and the surface rise with a maximum in the afternoon. After sunset, temperatures dropped below freezing point, with a minimum of heat just before sunrise. The reference temperature acted with delay to the decreasing ambient temperatures, but in some cases also dropped below the freezing point. The temperature of the heated surface remained above 0 °C throughout the measuring period. In the course of the day, the increased solar radiation leads to considerable heating

Table 5 Heat output of coil distance 100 mm. T_{in} : inlet temperature; T_c : set chamber temperature

Temperature step T_c (°C)	Power Output per square meter (W/m ²)			
	T_{in} 8 °C	T_{in} 10 °C	T_{in} 12 °C	T_{in} 14 °C
−1	40	48	64	76
−3	55	57	84	n.a
−5	70	69	109	122
−7	75	96	132	140
−9	90	112	152	177
−10	97	128	168	197

Fig. 9 Exemplary measurement of the concrete slab with 200 mm coil distance at -1 °C ambient temperature and 10 °C water temperature. T_c : combined measurements of chamber temperature. T_p : surface temperature directly above the pipe. T_m : surface temperatures between pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

of the air temperature sensor. The surface temperature was temporarily higher than the inlet temperature. Cooling of the surface was observed. Due to the fluctuating daily outside temperatures, a direct comparison of data collected from the test field and the measurements in the cooling chamber was difficult. However, for some measurements, a stable and comparable temperature condition was found. On February 25, 2019, for example, a relatively stable outdoor temperature between 12:00 AM and 7:00 AM was observed, as can be seen in Fig. 12. Thus, the surface temperature settled at around 3 °C at a -5 °C ambient temperature. These data were measured on test field 2 with a 200 mm coil distance. When the data of the chamber are compared (Fig. 10; #1), a similar temperature was measured.

To conclude, the central heating load generally was needed shortly before sunrise. During the daytime, a

reduced heat output was required (Fig. 13). Even so, during midday, cooling of the surface was observed, which lead to the recirculation of heat energy into the subsurface. Based on the comparisons that were made between the cooling chamber and the outside test field, the measurements from the cooling chamber could be validated. Besides, the slab remained at surface temperatures above 0 °C throughout the time of the experiment. The lowest ambient temperature recorded was -9 °C.

3.2.2 Snow melting performance

Two snowfall events, with a snow height of about 5 cm, were recorded during the tests. In both cases, the surface of the tested slab remained free of snow (Fig. 14). The measurements are shown in Fig. 15.

At around 1:00 AM, snowfall started, and tightly after that, the temperature of the surface dropped from about 3 to 1 °C. Additionally, the temperature of the outlet decreased from 7.5 to 6.6 °C, while the inflow temperature remained constant at 8 °C resulting in higher heat output. The heat output per square meter increased from 60 W/m² to up to 180 W/m². After the end of the snowfall event, a slow increase in surface temperature and outlet temperature was observed, resulting in a decreasing heat output down to again 60 W/m². The maximum heat output of the deicing system (100 – 200 W/m²) could be compared well with other projects with 100 W/m² in Switzerland [8], 130 W/m² in Iceland [9] and 180 W/m² in Japan [16].

4 Conclusions

The measurements from the cooling chamber provided promising results for the deicing ability of the tested heating installation. A horizontal distance of 100 mm is preferable, as water temperatures of 10 °C were sufficient to keep the temperature of the tested surface above the freezing point in the tested climatic conditions. Based on the results, it might also be feasible to use coil distances up to 200 mm, if the inlet temperature is at least 12 °C. However, there have been several studies, as mentioned earlier, that emphasize a coil distance of 10 cm, especially when concerning the temperature distribution on the surface [10, 38].

The results of the outside test field also demonstrated that it is possible to provide snow-free conditions without resorting to additional heating. It must be pointed out

Fig. 10 Mean measured temperatures of the different tests for winding distance 200 mm. 1: 8 °C inlet temperature (here, the volume flow has been adjusted to be able to better measure the difference from T_{in} to T_{out}); 2: inlet temperature of 10 °C; 3: inlet temperature of 12 °C; 4: inlet temperature of 14 °C; all data points are

mean temperature readings from at least 24 h of collected data. T_c : combined measurements of chamber temperature. T_p : surface temperature above the pipe. T_m : surface temperatures between pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

that further, long-term investigations are obligatory as the recent winter was quite mild.

Finally, it can be concluded that heating road surfaces in Nuremberg's urban environment with groundwater temperatures of at least 10 °C is possible and feasible. In more severe periods of frost, the system can provide a lasting deicing capability if the ambient temperature does not sink below -10 °C. If that is the case, the system should continue running, preventing the freezing of

the water inside the pipes. Depending on the groundwater temperature and the expected climatic conditions, this method could be useful in other environments, as groundwater temperatures in different German urban centers like Munich, Berlin [19], and Cologne [20] are increased. On a larger scale, the use of this method could help to limit the usage of deicing salt in the future and to counter the further heating of cities' groundwater reservoirs.

Fig. 11 7-day segment of the field test. Input water temperature 10 °C. The horizontal distance of pipes: 20 cm. For a better overview, the water temperatures are plotted on a secondary y axis. T_{air} : measurements of air temperature. T_p : surface temperature directly above pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

Fig. 12 Measurement on the morning of 25.02.2019 at test field #2 (coil distance: 20 cm). A relatively stable outside temperature can be observed here over a more extended period. The minimum is -5 °C outside temperature and about 3 °C surface temperature at around 6:00 AM. After sunrise (~ 7 AM), the temperatures rise rapidly. T_{air} : measurements of air temperature. T_p : surface temperature directly above the pipe. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

Further studies on this subject should implement field tests in different climatic locations in Germany, as well as numeric models implementing such parameters as snowfall and high humidity levels. Some research has been done on this topic already [11, 40], on which further studies can be based. Furthermore, a long-term observation of the field test in Erlangen is planned, providing information about the possible heat energy extraction in summer in comparison to the heat energy demand in winter, even possibly measuring the performance during a prolonged cooling period or more severe snowing events.

Fig. 13 Heat output of the 25.02.2019 as an example of the fluctuating power output at the outside test field. Negative measurements mean that heat is transported from the concrete slab. The maximum heat output is 67 W/m², the maximum heat input while cooling is 48 W/m². T_{air} : measurements of air temperature. T_p : surface temperature above the pipe. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

Fig. 14 heated slab after snowfall event on the 26th of January 2019 (Slab #1). The heated area is free of snow

Fig. 15 Measurements of the snowfall event on January 26th of 2019 (Field #2, 20 cm coil distance). The inlet temperature was set to 8 °C and was stable throughout the event. The snowfall starts at around 1:00 AM and lasts until about 5:00 AM. T_{air} : measurements of air temperature. T_p : surface temperature directly above pipes. T_{ref} : surface temperature of reference slab; T_{in} : inlet temperature; T_{out} : outlet temperature

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Compliance with ethical standards

Conflict of interest The author(s) declare that they have no competing interests

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