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Study of a double subsurface snow-water utilization system for the melting of snow using the waste heat of urban sewage

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ABSTRACT

This study describes technology that melts snow using the waste heat of urban sewage and reclaims snowmelt on site using a double subsurface constructed snow-melting system, allowing the organic integration of snow utilization and landscape design in cities with long winters. This system highlights the thermal energy cycle, in which underground urban sewer pipes and the considerable amount of low-temperature waste heat that they contain are utilized along with a small-temperature-rise heat pump to ultimately melt snow. The temperature of sewage in the winter usually ranges from 4 to 10℃ in cities, representing a high-value resource that can be developed and utilized. In this system, an indirect heat exchanger heat pump, which uses sewage as its heat source, is employed, and the heat is exchanged between the sewage and intermediary water in the heat exchanger. This is followed by heat removal and the emission of radiation into a working substance in the condenser and evaporator, respectively. Then, the water temperature in the assemblies of the heat pipes is increased, thereby increasing the coefficient of performance (COP) to 10 and achieving the concentrated reuse of the distributed waste heat. The double subsurface snow-melting system consists of snow-melting wells and double subsurface tanks. The surface plant residues and frozen layer constitute a natural insulation layer to maintain the water-purification activity of the lower-layer, low-temperature anaerobes. The removed snow is dumped into the snow-melting wells by workers and heated by the hot grate and pipes on the sidewalls and at the bottom of the wells. The snowmelt water flows into the pretreatment tank and grill, and then, it enters the lower layer of the double subsurface tanks. The lower-layer gravel fills are colonized by low-temperature oligotrophic bacteria. The removal of samples for the analysis of BOD_5, COD, and SS is efficient, and the quality of the output thereby satisfies the standards for municipal water use.

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Keywords: Winter cities; Utilization of snow resources; Snow-melting with waste heat; Snow melting technology; Double subsurface constructed tanks

1. Introduction

The removal of snow from roads and parks affects urban transport, daily activities in cities in the winter, environmental protection, and the efficient use of water resources. Storm water management systems and water treatment facilities are unable to maintain continuous operation due to the long winter and harsh climate, thus making water treatment impossible. Snow management technology is still undeveloped. Traditional snow-melting agents continue to be scattered in winter, causing harm to both the artificial and natural environments, such as the reinforced concrete structure of urban roads, underground metal pipelines, plants, and the ozone layer, and increasing the salinity of the soil [1–5]. This method of snow removal has gradually been prohibited or restricted in some cities, including Harbin, China.

Other countries have more options for urban snow removal. In addition to the research and development of advanced snow-sweeping devices, many countries have established better snow-melting systems and positively utilize snow as a resource. For instance, in Japan, heated seawater is transferred through pipes to melt the snow on streets, and another technique involves the use of geothermal energy to melt the snow on streets and parking lots [6,7], which is also adopted in Turkey as an effective measure for snow melting [8]. Well-developed technology can also be found in Canada, the USA, and Northern Europe. Reykjavík, the capital of Iceland, lays sewer pipes to melt the snow on the streets with the waste heat from the sewage. Sweden addresses rainwater and melting snow on site, utilizing the water within the landscape design.

Snow is weak in thermal conductivity and low in surface evaporation, both properties of which are vital to retain water in soil and prevent spring droughts. The potential fresh water that can be gained from melting snow provides an incentive to treat the snow effectively and retain it in the urban environment. Experiences and researches in the past indicate that the composition contained in the snowfall during the early period is close to that in the rainwater. Falling snow efficiently absorbs and coheres contaminants from the atmosphere and concentrates them in a snow cover that acts as a temporary storage medium [9]. Generally, in the early and late periods of snowfall, the turbidity of snowmelt water is similar to that of rainwater, and the quality of water from removed snow is poor, with obviously higher hardness due to dissolved ions. The chemical compositions contained in the snow water become more complex with the environment variation under the input of anthropogenic organic contaminants [10,11]. And what's more, the fate of organic chemicals in urban watersheds is highly complex, especially when snow and snowmelt processes are involved in [12]. Differences between storm water runoff and snowmelt water ablation include the timing of chemical transport and the amplification of concentrations [13]. Especially in cold winter with continuing low temperatures, the snow deposited on roads will be compacted and squeezed by vehicles or pedestrians, which is hard to sweep away. And the contamination of the snow becomes more serious with the coverage of dust and harmful chemical substance for a long time. Therefore, snow should be promptly collected for the purposes of snow water utilization.

Current snow removal technologies include cable or electric wire regeneration, solar regeneration, the burial of pipe systems for a ground-sourced heat pump, mechanical operation, and chemical agents. Unfortunately, the utilization of these techniques has their own problems, respectively, resulting in the difficulties to application and promotion of them. Cable regeneration requires significant investment and intends to weaken the stability of road pavement; photovoltaic conversion efficiency is low and difficult for solar regeneration, hardly forming the matured technology; the utilization of pipe systems will lead to large quantity of work and improve the cost; the snow-melting agent is commonly prohibited due to the severe environmental problems. Therefore, in China, many cities still use inefficient human labor to remove snow and to transport and discard it in the suburbs, which consumes substantial manpower and materials, causing waste gas and carbon emission. In winter, green spaces and courtyards are usually used as a place to pile up the snowpack, leaving snow melt themselves. The melted snow, which is mixed with dust throughout the winter, will freeze and thaw repeatedly when the spring comes, flowing everywhere. This scenario results in environmental pollution and the wasting of valuable water, which can affect daily life.

Snowfall is greater in terms of water quality and quantity in cities with an extensive winter. For instance, in Harbin, the capital of Heilongjiang Province, there is generally 33 snowfall days, with a high rate of snow. The average snow depth is approximately 20 cm, and the snow is on the ground up to 105 days of the year [14]. The reutilization of the snow as a resource could yield beneficial results if the relevant technology and techniques were developed. The waste heat from sewage, bath, and heat-supplying system pipes is a useful resource. A large amount of this heat is unfortunately wasted and could be an ideal means for melting snow. The development of a heat-recycling device and the associated reduction in energy utilization is practical. Even in the cold northeastern areas of China, the temperature of the pipes is approximately 10℃; therefore, the pipes could be directly used to melt snow [15,16]. The thermal energy from the sewage could be extracted and transferred with a small-temperature-rise heat pump to recycle the qualified snow water, preserving an urban water resource while melting the snow and maintaining separation between the sewage and melt water. In this study, a small-temperature-rise heat pump was applied to extract waste heat to melt snow, and the snowmelt water was treated and stored in a double subsurface constructed tank built under urban green space to be used as a public water source and in landscape construction in the spring, with a promising prospect.

2. The heat cycle of the double snow-melting system

2.1. *Technical aspects of the double snow-melting system*

The key to snow treatment in the winter is to remove the influence of the cold temperature during the process of snow melting in an environmentally sound way using an appropriate structure. To satisfy the above requirements, the proposed double snow-melting system applies the planning model of a scattered network and uses its own structural characteristics for heat insulation and self-gravity circulation. The components of this system include thermal melting wells, heating and snow-melting assemblies, double subsurface constructed tanks, and independent or inter-connected networks along the lower greenbelts of streets, forming an integrated process of snow collection, treatment and storage (see Fig. 1).

The size of thermal melting wells is usually 1.5 m × 3 m. Square or rectangular wells are convenient for maintenance, preservation and melting operations and suitable for snow storage to a depth of 2.5–3 m. The double subsurface constructed tank connected to the wells is relatively large, with the width reaching 6–12 m and the length reaching 10 m or miles, depending on the size of the available green space. The height of the thermal operation door is limited to 0.6–0.9 m for the filler operation. The upper horizontal landscape tank is operated in spring, summer, and autumn and can be used as a flowerbed, a lawn, planting tanks for aquatic plants or landscape water pools to collect rainwater. In winter, the melting snow in the collection well overflows after sedimentation and then flows into the lower horizontal tanks through the drainage pipes. This system operates continuously throughout the year. The drainage pipes should be set up below the permafrost line and on top of the double subsurface constructed tank to facilitate self-gravity circulation.

The snow should be collected immediately after snowfall and be dumped directly into the disposal wells in the green belt on both sides of the road. The heat tubes are circumferentially placed at the bottom

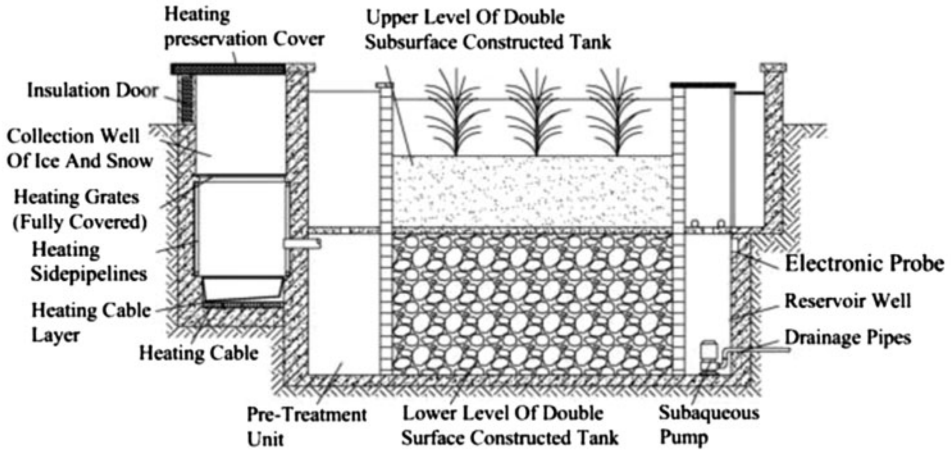

Fig. 1. Illustration of the snow-melting system with double subsurface constructed tank.

of the wells to melt the snow, and the upper snow melts naturally, forming an insulation layer to guarantee the completion of the melting of the lower levels of snow. The melting snow water enters the conditioning tank in the weir pool after pretreatment and is admitted to the lower subsurface constructed tanks by gravity or an elevator pump. After being established, the filter and oligotrophic bacteria with resistance to low temperatures, such as effective organic degradation bacteria, PSB or low-temperature bacteria will constitute a biofilm to increase the filtration effect [17,18]. The oil-contaminated mixed snow collected from roads and walkways can be pretreated with special techniques and then discharged into the lower tanks [19].

The method used to supply energy through recycling should be determined based on the climate characteristics, geographical advantage, and surrounding conditions due to the large latent heat of fusion and high energy consumption during snowmelt. This snow-melting system thus combines the technology of a low-temperature heat pump with the heating energy of underground sewage (usually at 5℃) to melt the snow in the wells. This method is simple to apply in an environmentally conscious manner without yielding any waste emissions, which seems ideal.

The steps used to collect the snow with the double snow-melting system are as follows: (a) collect the snow in the city; (b) place the collected snow into the melting wells through the thermal operation door; and (c) discharge the overflowing water, which is the melting water obtained from sedimentation, by gravity into the double subsurface constructed tanks through the drainage pipes for anaerobic treatment [20].

2.2. The key technology used to control the double snow-melting system

To guarantee the continuous operation of the melting system, several measures are taken to control the stability of the process and improve the efficiency of the system.

(1) First, large, hard snow blocks are selected against by a single- or double-layered grate (0.3–0.5 m grid), avoiding bump and scratches to the bottom.
(2) Sand, small stones, waste papers, withered leaves, and other debris on the road are inevitably covered by ice and snow and thus transported into the wells, forming precipitant at the bottom of the wells, clogging the pipelines, and reducing the efficiency of the system. Ultimately, the entire system will be influenced by this debris and should therefore be cleaned regularly. The cover of the melting wells can be opened for convenient manual cleaning. An electric elevated sedimentation groove is also acceptable.
(3) For use in conjunction with the well, an infrared detector will signal when the quantity of snow submitted for treatment is below the effective standard height, which suggests the need for refilling by the ground workers.
(4) Heating coils are placed at the fillister and the bottom of the sidewalls, and the heating water enters from the top and returns at the bottom. The coils at the bottom enter from the center and return along the outside rings to mitigate the freeze risk and maximally extend the snow-melting area.
(5) The heating coils on the sidewalls enhance the natural convection of the air between the sidewalls and the blocks, thereby increasing the melting rate. The flow is maintained at approximately 2 m/s to avoid partial freezing.

Antifreeze is added to the coils to avoid the buildup of frost when the heat pump stops or is checked [21]. For maximal antifreeze utilization and effectiveness of the heating pump, the optimal temperature of the supply water is 20℃, and the optimal temperature drop is 5℃.

2.3. Layout and operation management of the double snow-melting system

The snow-melting system is located beneath the streets and the greenbelts of courtyards and constitutes a continuously operating system that performs collection, preliminary sedimentation, and treatment of snow-water, partnering with the landscape pools of double subsurface constructed wetlands. The area of the melting wells can be a few to hundreds of square meters. The thermal operation doors and covers are placed at the material-filling gate to push the snow into the wells. The snow-melting wells are connected to the top of the lower input water regulating tanks of the double subsurface constructed tanks below the permafrost line. Water that overflows from the melting snow water following sedimentation enters the double subsurface constructed tanks by gravity. The thermal cover separates the inside and outside of the snow-melting wells to improve the efficiency of the heating assemblies and to reduce heat loss. The sedimentation tank is placed at the bottom of the wells to collect the mud and debris from the snow water and can be regularly elevated to the surface to be treated. The objectives of the double snow-melting system are to minimize the area required and to collect and dispose of the snow through continuous operation.

3. Working principle of the low-temperature heat pump snow-melting system

There are two snow-melting methods that utilize the waste heat of urban sewage. One method is to dump the snow into the sewage channels directly, thus melting the snow by direct heat [22]. This method is simple to apply without investment or operation costs, but the combination of snow water and sewage wastes the water resource, which is unacceptable in water-limited areas. The other method is to extract the heat from the sewage by using a heat pump to transfer the heat to the snow; the snow water is then reutilized with some investment and operation costs. This is the snow-melting system presented in this paper. Fig. 2 shows the principle of a low-temperature heat pump snow-melting system.

The low-temperature heat pump system has three components:

(1) Heat extraction from sewage includes the exposure of the heat-exchanging coils to the sewage, the water pump, and pipes.
(2) Heat pump host includes the evaporator, condenser, throttle valve, and compressor.
(3) Heating of the melting snow includes the heating pipes on the sidewalls and the bottom, the water pump, and pipes.

The sewage coils, where the low-temperature cold-water (which was evaporated from the heat pump host) flows, are immersed in the sewage channels. The temperature of the cold water is lower than the sewage, and the low-temperature heating water will absorb the heating energy from the sewage because of the difference in temperature [23]; the heating energy will then be transferred to the evaporator. After the temperature of the heat pump host is elevated, the heating water flows through the condenser and then through the coils of the snow-melting wells to heat the wells and ultimately cause the snow to melt. The final effect of this process is that a slight input of electricity causes the heat pump to transfer the heating energy to the snow-melting wells, and the temperature rises from 10 to 20℃.

The heat pump motor room can be placed in either the underground wells or the surface structure. The limiting factor for the low-temperature heat pump snow melting system is the distance between the sewage source and the melting wells. A distance of 500 m is economical and suitable from the perspective of transferred energy consumption, and this condition is realistic. The landscape snow-melting system described in this paper is usually located on roadsides, and sewer pipes are generally buried underground; thus, these positions are close together.

The heat pump of the snow-melting system operates at a low temperature with a small temperature rise. Carnot's theorem shows that the heating coefficient of performance (COP) can be estimated using the following equation [23]:

$$\mathrm{COP} = \frac{t_g - \delta t/2 + 278}{t_g - \delta t/2 - t_w + 15} \times \eta \tag{1}$$

where t_g is the supplying temperature of the heating water, in ℃; δt is the temperature drop of the heating water; t_w is the temperature of the sewage, in ℃; and η is the overall efficiency, usually approximately 70%, considering the transmission losses, compressor efficiency, interception loss, and heat loss.

The trend and range of the heat coefficient of the low-temperature heat pump used for snow melting are presented in Fig. 3. The COP of the heat pump

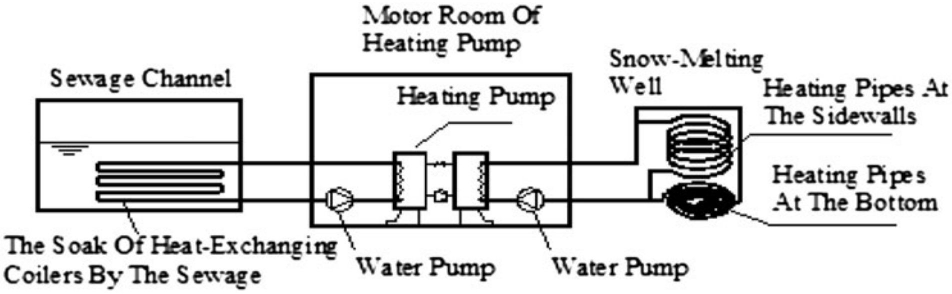

Fig. 2. The components and principle of a snow-melting system using a low-temperature heat pump.

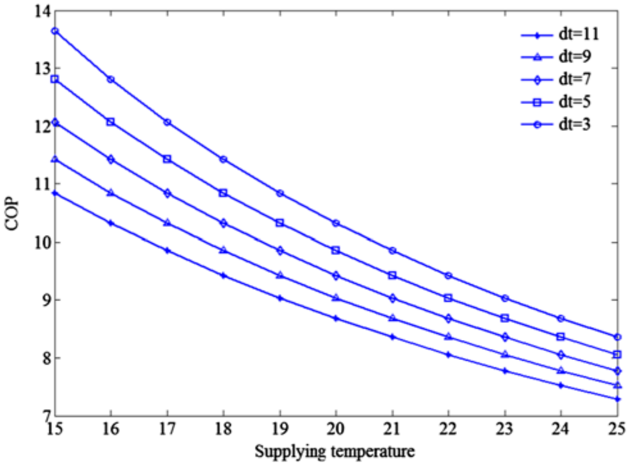

Fig. 3. The variation of the heating coefficient of the snow-melting heat pump with the changes of the temperature of the supply water and the temperature drop of the hot water.

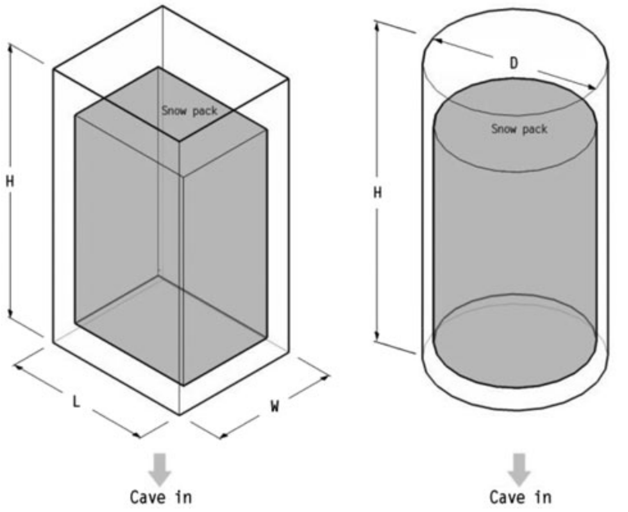

Fig. 4. Illustration of the dimension of the snow-melting wells.

host decreased as the initial temperature and temperature drop of the hot supply water increased. The value of the COP reached 10 at 20℃ when the temperature drop was 5℃. Higher COP values are required for the economical operation of the snow-melting system. Although the low temperature and small temperature rise improve the COP of the heat pump, these conditions prolong the time required for the melting of snow and increase the flow, ultimately increasing the total power consumption. The initial temperature and temperature drop recommended in this paper are 20 and 5℃, respectively.

4. The snow-melting process of the heat pump and an analysis of energy consumption

The length, width, and height of the rectangular snow-melting wells are L, W, and H, respectively. The diameter and height of the cylinder are D and H, respectively (see Fig. 4). The characteristic size of the snow-melting wells is therefore defined as the ratio of the volume and surface. For the rectangular snow-melting wells:

$$L_{cc} = \frac{3V}{A} = \frac{3LWH}{2(LW + LH + WH)} \tag{2}$$

For the cylinder wells:

$$L_{cr} = \frac{3V}{A} = \frac{3D^2H}{2(2DH + D^2)} \tag{3}$$

The temperature of the supply water is t_g, the temperature rise is δt, and the average temperature difference required to melt the snow with hot water is

$$\Delta t = t_g - \frac{\delta t}{2} \tag{4}$$

The distance, melting width S, between the ice surface and the heating coils becomes greater as the snow blocks melt, decreasing the coefficient of the heat transfer. The coefficient is K_0 at the beginning of the melting process, which is determined by the flow rate of the heating water, the thermal resistance of the sidewall materials and the thermal resistance of the gap. The relationship between the coefficient of heating transfer and the melting width S as the snow melts is as follows:

$$K = K_0\left(1 - \frac{S}{L}\right) \tag{5}$$

The following is the differential equation between the melting width and the duration based on the thermal equilibrium:

$$K_0\left(1 - \frac{S}{L_c}\right)\left(t_g - \frac{\delta t}{2}\right)d\tau = \rho\gamma dS \tag{6}$$

In the equation, S is the melting width; m is the melting duration; s is the initial coefficient of heat transfer, in W/(m^2℃); L_c is the feature size, in m; t_g is the temperature of the supply water, in ℃; δt is the temperature rise of the hot water, in ℃; ρ is the density of the snow and ice, with a commonly used value of 730 kg/m^3; and γ is the latent heat of the snow-melting process, namely 334,400 J/kg.

The initial condition at $\tau = 0$ is $S = 0$. The variation in the snow-melting width over time is represented by:

$$\frac{S}{L_c} = 1 - \exp\left[-\frac{K_0(2t_g - \delta t)}{2L_c\rho\gamma} \times \tau\right] \tag{7}$$

The value of $\varphi = \frac{S}{L_c}$, which corresponds to the percentage of the snow melted, indicates the snow-melting width.

For a general snow-melting well of dimensions 1.5 m × 3.0 m × 2.5 m, the temperature of the supply water is 20℃, the temperature drop of the hot water is 5℃, and the initial coefficient of heat transfer is 50 W/(m^2℃). The relationships between the melting process and the size of the wells, the initial coefficient of heat transfer, the temperature of the supply water, and the temperature rise of the snow-melting wells are shown in Figs. 5–8.

The time constant of the melting process in Eq. (7) is

$$\tau^* = \frac{2L_c\rho\gamma}{K_0(2t_g - \delta t)} \tag{8}$$

As shown in Figs. 5–8, the speed of melting of the snow is close to the time constant, and as the constant decreases, the speed of the melting process decreases and the melting time decreases. Four factors influence the time constant of the snow-melting process:

(1) Feature size. The feature size is directly proportional to the time constant of the snow-melting process and is thus unfavorable to this process. A suitable form and size of the snow-melting well can therefore be determined based on the melting effect and investment of the snow-melting wells. Two parameters are considered to control the feature size: the superficial area of the wells and the minimized size of one dimension.

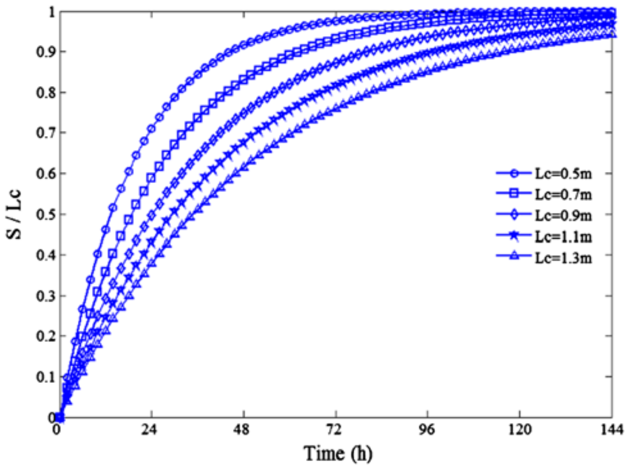

Fig. 5. The effect of the size of the snow-melting well on the melting process.

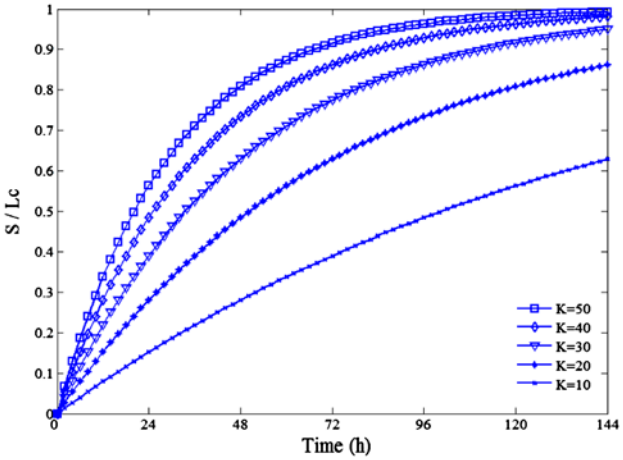

Fig. 6. The effect of the initial coefficient on the melting process.

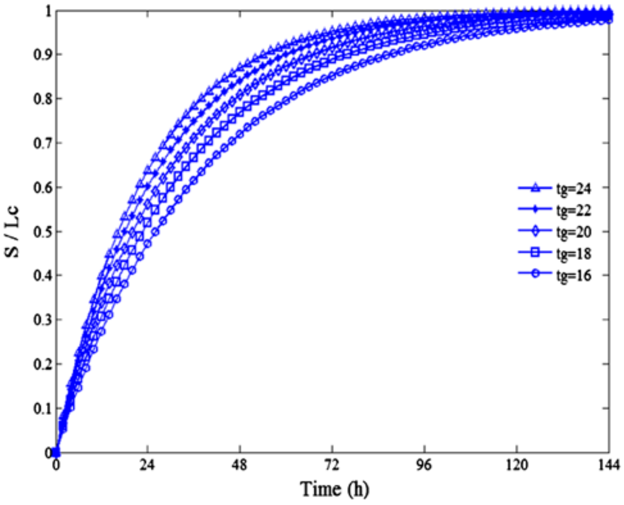

Fig. 7. The effect of the temperature of the supply water on the melting process.

(2) Initial coefficient of heat transfer. The coefficient is inversely proportional to the time constant, which is more favorable to snow melting. The flow speed inside the heating pipes can be altered to improve the efficiency and the clean condition, and air circulation around the heating pipes should be ensured.

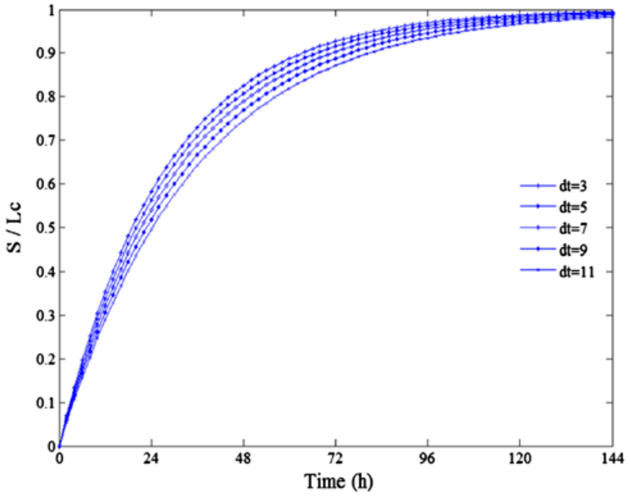

Fig. 8. The effect of the temperature rise of the hot water on the melting process.

(3) Temperature of the supply water. Higher supply water temperatures lead to a smaller time constant for snow melting, which is beneficial to the snow-melting process. However, higher temperatures may reduce the operation effectiveness of the heat pump. The recommended temperature is approximately 20℃ to control the entropy production of the entire thermodynamic system.

(4) Temperature drop of the hot water. A decrease in the ratio of the temperature drop to the time constant is unfavorable to the snow-melting process. A lower temperature drop will inevitably cause greater flow and a greater operation cost of the pump. Therefore, the recommended temperature drop is approximately 5℃.

Based on Eq. (7), the relationship between the melting time and the melting process is shown in Eq. (9).

$$\tau = -\tau^* \times \ln(1-\varphi) \tag{9}$$

As illustrated in Fig. 9, near the end of the melting process, the melting rate was lower, the time was longer, the constant was larger, and the time consuming required to reach the same temperature was also greater. This rule can also be viewed in terms of the melting speed of the snow, which is determined by a formula that follows from Eq. (7).

$$U_\varphi = \frac{1}{\tau^*} \times \exp\left(-\frac{\tau}{\tau^*}\right) \tag{10}$$

Eq. (10) reveals an important characteristic of the melting process; namely, the melting rate was gradually slower as the melting process progressed. Thus, the capacity for snow melting does not remain constant with the same time, heating pump, and electrical consumption of the water pump; in the later period of snow melting, this capacity appears to be inadequate. Therefore, new snow should be added to the melting wells when the melting speed is 1/3 of the initial speed to ensure higher melting effectiveness when the melting time is $\tau_s = 1.1\tau^*$.

The heat capacity of the heat pump is modeled based on the initial heat; thus, the heat capacity of the heat pump is

$$Q = K_0 A\left(t_g - \frac{\delta t}{2}\right) \tag{11}$$

New snow is added at time τ_s and the melting time is n times the time constant, which equals $n = \frac{\tau_s}{\tau^*}$. The average electrical consumption of the heat pump per unit volume of snow is as follows

$$E = \frac{K_0(2t_g - \delta t)\tau_s}{2 \times \mathrm{COP} \times L_c\varphi(\tau_s)} = \frac{n\rho\gamma}{\eta[1-\exp(-n)]}\left(\frac{t_g - \delta t/2 - t_w + 15}{t_g - \delta t/2 + 278}\right) \tag{12}$$

The crucial index needed to measure the efficiency of snow melting is the ratio of the electricity consumption of snow melting per volume and the latent heat of the snow melting. The electricity ratio of snow melting refers to the ratio of the heat quantity transferred from the electrical consumption of the

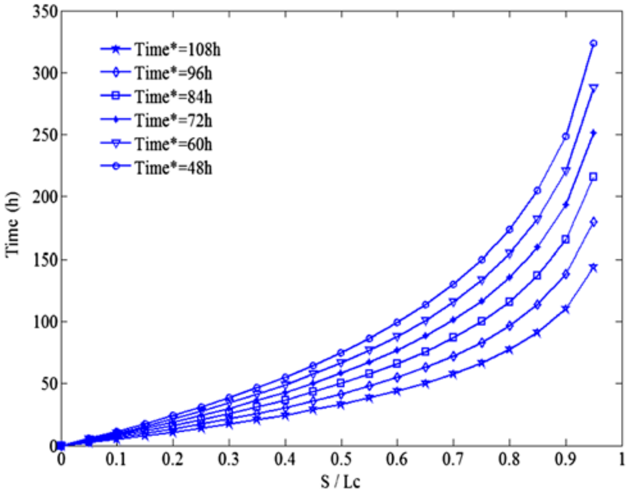

Fig. 9. Relationships among the melting time, melting process, and time constant.

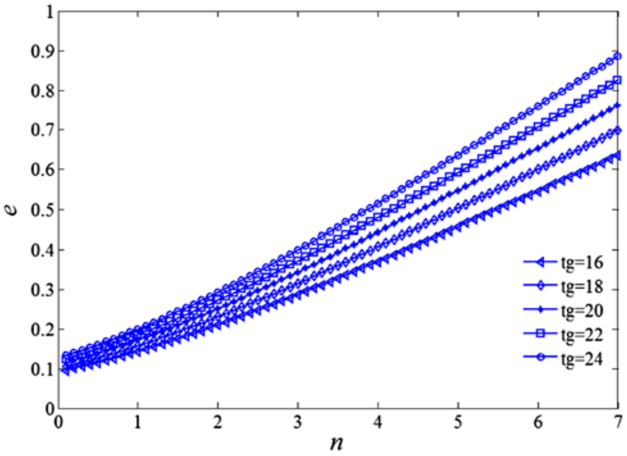

Fig. 10. Relationships among the electrical consumption of the heating pump, latent heat ratio, and the temperature of the supply water.

heating pump to the total heat required to melt the snow. The cost is proportional to the ratio associated with a more desirable efficiency. From Eq. (12), we can obtain the electricity ratio of snow melting.

$$e = \frac{E}{\rho\gamma} = \frac{n}{\eta[1-\exp(-n)]}\left(\frac{t_g - \delta t/2 - t_w + 15}{t_g - \delta t/2 + 278}\right) \tag{13}$$

Fig. 10 shows that the electrical consumption per unit volume increases with the increasing temperature of the supply water. The electrical consumption increases sharply after a prolonged snow-melting time. For instance, when the temperature of the supply water is 20℃, the temperature drop is 5℃ and the melting time is equivalent to the time constant, 13% of the needed heat will be supplied by the electrical consumption of the heat pump; if the melting time is three times the time constant, 32% of the required heat will be derived from the electrical consumption. As mentioned, when the melting time is 1.5 times the time constant, the final melting rate will be 1/3 of the initial speed, which will ensure the best average melting speed throughout the ensure process. The electrical consumption required to control the melting is less than 15% of the total heat.

5. Conclusion

The simulations conducted in this study indicate that the waste heat of the underground pipelines can support the operation of the double subsurface constructed snow-melting system. The snow-melting time, which relates to the size of the melting wells; the temperature of the supply water; the temperature drop of the hot water; and the initial heat transferred depend on the melting time constant. An increase in the size of the wells will reduce the effectiveness of the snow-melting process. A suitable temperature of the supply water is 20℃, and the most efficient temperature drop is 5℃. New snow should be added when the melting time is 1.1 times the time constant to ensure the best average melting speed. The electrical consumption required to control the snow melting is only 15% of the total heat, thus maintaining the economic advantages of this method of snow melting. The technology applies the heating pump with small difference between evaporation temperature and condensation temperature and the temperature fluctuation is between 10 and 20℃. The smaller the temperature rises, the higher COP and the economic benefit it is. This method is also acceptable for the treatment of rainwater in different seasons to enhance the operation effectiveness and the suitability. The planning and layout of the facilities are in accordance with the structure of urban roads and public spaces, demonstrating the close association and multiple constructions, functional and esthetic values of these municipal facilities. The advantageous scattered layout allows for a more flexible design and recycling and treatment of the ice and snow on site, shortening the pipeline arrangement positively which will adapt to different spatial structure and topographical requirements. That lower tank body is controlled below frozen ground line therefore takes advantages of the frozen water body and planting layers due to the construction features of this system to make the natural heat preservation available for use in the snow-melting process, thereby reducing the construction cost. The most important feature of this system is the use of waste heat and the recycling of geothermal energy as the heating source for snow melting to reduce heat consumption. The higher demand for COP increases difficulties in economy; however, this direction is still valuable ecologically and economically, considering the environmental problems and large amount of carbon emission caused by clumsy traditional snow-melting ways.

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Symbols

t — temperature, ℃
δt — temperature drop, ℃
Δt — average temperature difference of heat transfer, ℃

η — overall efficiency of heating pump, %
L — length of snow-melting wells or characteristic dimension of snow-melting wells, m
W — width of snow-melting wells, m
H — height of snow-melting wells, m
D — diameter of snow-melting wells, m
S — width of snow melting, m
K — coefficient of heat transfer, $W/(m^2 °C)$
ρ — density of ice and snow, kg/m^3
γ — melting latent heat of ice and snow, kJ/kg
τ — time, s
τ^* — time constant, s
n — time multiplier
φ — snow-melting percentage, %
U — relative speed of ice and snow melting, %/s
Q — thermal output of heating pump, kW
E — average power consumption of heating pump per unit volume of snow, kJ/m^3
e — power-to-heat ration of snow melting, kJ/kJ

Subscripts

g — water supply
w — sewage
c — characterized or cuboid snow-melting wells
r — cylindrical snow-melting wells
0 — initial
s — continued

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