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# Exergetic Aspects of Snow Melting Using a Geothermal Heat Pump System

NurdanYildirim and Arif Hepbasli

Department of Energy Systems Engineering, Faculty of Engineering, Yasar University, 35100 Bornova, Izmir,Turkey

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**ABSTRACT**

In recent years, traffic accidents have occurred frequently in most of cold regions in Turkey due to the snowy and icy weather conditions. It is desirable to remove the ice and snow effectively to keep normal traffic operations. At present, chemical salts have been used extensively around the world. Hydronic snow melting on pavement has been applied as an alternative solution to the conventional chemical method. It has a remarkable advantage in using a low temperature heat sources including geothermal tail water, solar energy, and industrial waste heat. It is of great significance to save energy and reduce $CO_2$ emissions.

Exergy analysis has been considered as a powerful tool for assessing the performance of various energy systems. Energy analysis method has been widely used for simulation, design, and modelling and performance evaluation of snow melting systems.

This study deals with modelling and analyzing the performance of a snow melting heating system from the power plant through the heating system to the roadbed using exergy analysis method, the so-called low exergy or LowEx approach, which has been and is still being successfully used in sustainable buildings design. Particularly, a geothermal-based snow melting system was designed for melting of ice on a road of a university campus in the eastern region of Turkey. Differing from the previous studies, exergetic analysis method was applied to this system to evaluate the performance of the system through exergy efficiency. The lowest and highest exergy demand rates of the snow melting system were calculated to be about 110 kW and 186 kW at dead state temperatures of – 6.7 °C and – 11.9 °C respectively, while their corresponding exergy efficiency values varied between 2.08%-3.69%.

## 1.INTRODUCTION

Traffic accidents occur frequently in many cold northern regions. In normal traffic maintenances, effective removal of ice and snow plays an essential role. For this purpose, chemical salts have been widely utilized around the world, causing negative impacts including the concrete corrosion and environmental pollution (Wang et al, 2010). Salt is an inexpensive deicing agent while it is efficient in melting snow and ice except when the surface temperature is lower than 0°C. However, ice will not be melted by the most popularly used salt (sodium chloride) if the temperature falls below -3.9°C (Chen et al, 2011).

Hydronic or electric sub-surface heating systems have been applied to road/bridge pavements as an effective alternative method for ice and snow control in Iceland, America, Japan and other countries since the late 1950s. These kinds of systems use a heated fluid, which is circulated through a series of pipe circuits laid below the surface (Wang et al, 2008). Melting snow or ice by supplying heat to the exposed surface has been realized in many applications, which include sidewalks, roadways, ramps, bridges, access ramps, and parking spaces for the handicapped, and runways (Ashrae, 2003).

Melting snow and preventing icing through a heating system have been proposed in the past decades as an alternative to spreading salt. In popular snow melting systems, electrical heating wires buried under the pavement are utilized. On the other hand, hot water piping systems heated by kerosene or gas boilers are also commonly used for not only residential front yards, but also big parking spaces and precipitous roads. Snow melting systems consume much larger amount of thermal energy than most people think due to a large amount of heat loss to the ambient. An addition heat is required for melting snow (Nagano et al. 2006; Liu et. al, 2007 Part I).

The hydronic heating based on low temperature fluid, such as geothermal tail water, solar energy, and industrial waste heat, seems to be a better alternative method of snow melting. Obviously, this method is very essential in terms of energy saving. Most commonly snow melting is done using a glycol solution (Wang and Chen, 2009), hot water, or steam circulated in pipes within or below the pavement, using either heat pipes or geothermal fluids. However, in one instance, hot water has been sprinkled directly onto the pavement, roadways, etc. (Lund, 2000). Compared to the electrical heating method, the snow-melting energy load is lower. It usually varies between 320 $W/m^2$ and 600 $W/m^2$, due to the smaller thermal-conduction resistance of materials (Wang and Chen, 2009). In a district heating system, the snow melting system may be tied to the return piping of the district, which increases the overall temperature drop in the district heating system (Brown, 1999).

Liu et al. (2007, Part I) presented a transient and two-dimensional numerical model for the snow-melting process occurring on a hydronically-heated pavement. They predicted the surface conditions and temperatures over the heated surface including the degree of snow cover under the given system heat flux (or fluid temperature of the hydronic heating system) and weather data. A newly developed numerical model of the snow melting process on heated pavement surfaces was also experimentally validated (Liu et al. 2007, Part II). Hamada et al. (2007) proposed a hybrid system for snow storage/melting and air conditioning by using renewable energy-resources, and investigated the effects of an actual realized application. Wang and Chen (2009) studied the mechanism of critical free-area ratio and its influencing factors. They presented a simplified theoretical model to describe the heat and mass transfer process on pavement. Chen et al. (2011) examined both experimentally and numerically a snow melting process on asphalt pavements as solar collector. They reported that especially, it was feasible to use low temperature water of about 25 °C for snow melting.

As can be seen from a literature survey, snow melting has been studied by many investigators in terms of design, modelling and energetic aspects while some handbooks on snow melting (e.g., Kurschner et al., 2008; USDA, 2004; Ashrae, 2003) have been published. To the best of the authors` knowledge, no study on exergetic modelling of snow melting has appeared in open literatures. This was the main motivation of the present study.

## 2. SYSTEM DESCRIPTION

The snow melting system is considered to construct in Malatya city, located in the upper Firat river basin area of the Eastern Anatolian Region of Turkey. Malatya city has several geothermal resources with temperatures of 24-29 °C (MTA, 2005). Geothermal exploration studies have gained momentum in recent years.

Heat pumps are heat transfer devices which, by using an input of work or heat, are able to reverse the normal direction of passive heat transfer and absorb heat at a low temperature and reject it at a higher temperature. Heat pumps can be used in low-temperature geothermal heating schemes to generally boost the heat output of the fluid, but their particular role in any specific scheme will depend upon the temperatures of the fluids which are being used (Zwarycz, 2002). The ground source geothermal heat pump is selected as snow melting system since there are a few geothermal resources with low temperature in Malatya. The schematic diagram of the proposed snow melting system is shown in Figure 1. To provide necessary heat from ground, vertical downhole heat exchanger is planned in heat pump system.

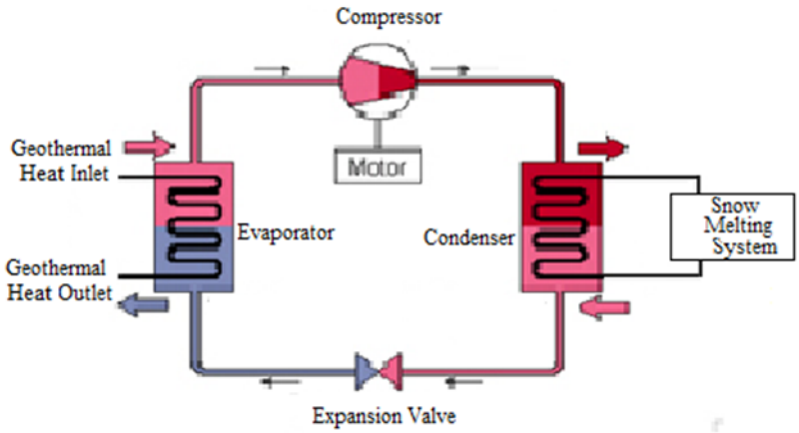



**Figure 1: The schematic diagram of the snow melting system.**

The snow melting system is designed to melt the snow on the road at the main building entrance in the university campus. Hydronic snow melting system is planned for the road with 300 $m^2$ (6mx50m) surface area.

Hydronic snow melting systems utilize a mixture of hot water and propylene glycol (anti-freeze) that circulates through a closed loop flexible polymer (Pex) tubing that is installed in the road (concrete, asphalt, or just about any medium). The hot liquid is circulated from a centrally located water heater through the Pex tubing to warm the road (Facility Management, 2014). Some examples of piping installation of road snow melting systems are shown in Figure 2.

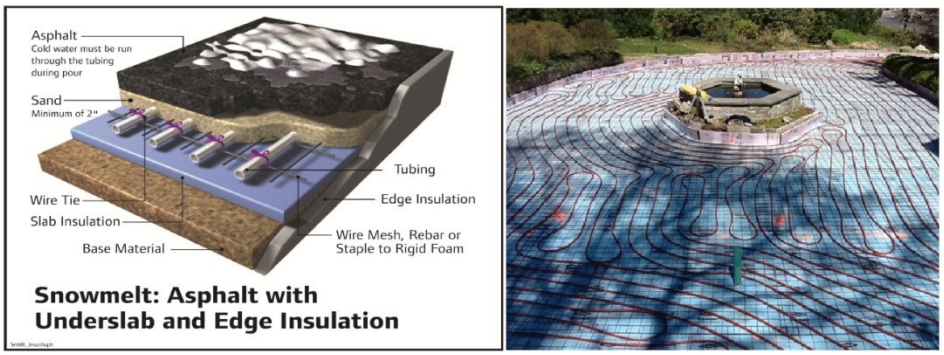



**Figure 2: Examples of piping installation for road snow melting system (Facility Management, 2014; Radiant Floor, 2014)**

### 2.2 Climate Data

The weather in Malatya is hot and dry during summers and cold and snowy in winters. The monthly average, high average and low average outside temperatures are shown in Figure 3. The general climatic information of Malatya city is summarized in Table 1 (Weatherbase, 2014). The monthly average temperature is in the range of (-4)-7 °C during winters. But the lowest temperature recorded reached -25 °C at the coldest days. According to the data of Weatherbase (2014), there are 64 days per year in which the outside air temperature is below 0°C. The average wind speed of air during winter is approximately 3 m/s.

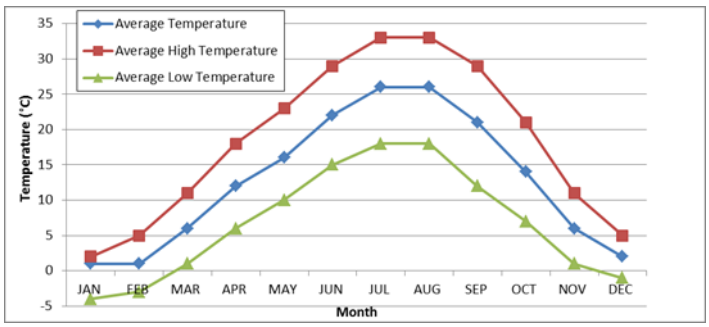



**Figure 3: The average outside temperatures of Malatya city.**

**Table 1: The general climatic data of Malatya city.**

| | | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Temperature | °C | 1 | 1 | 6 | 12 | 16 | 22 | 26 | 26 | 21 | 14 | 6 | 2 |
| Average High Temperature | °C | 2 | 5 | 11 | 18 | 23 | 29 | 33 | 33 | 29 | 21 | 11 | 5 |
| Average Low Temperature | °C | -4 | -3 | 1 | 6 | 10 | 15 | 18 | 18 | 12 | 7 | 1 | -1 |
| Lowest Recorded Temperature | °C | -20 | -25 | | -3 | | 6 | 10 | 7 | | -3 | -10 | -18 |
| Average Number of Days Below 0°C | Days | 26 | 20 | 13 | 2 | | | | | | 1 | 12 | 20 |
| Average Wind Speed | m/s | 2.2 | 2.2 | 5.6 | 4.4 | 2.5 | 5.3 | 5.6 | 5.6 | 2.5 | 2.2 | 1.7 | 1.7 |

The design winter outside temperature is -11.9 °C for Malatya. But design outside temperatures can be taken as -8.4 °C and -6.7 °C with 99.6% and 99% frequency, respectively (Yılmaz and Bulut, 2001). -8.4 °C means the heating system will provide thermal comforting 99.6 percent of the time but may fail to do so during 0.4 percent of the time.

## 3.THERMODYNAMIC ANALYSIS

### 3.1 Energetic Analysis

Heating requirements for snow melting depend firstly on atmospheric factors and secondly on the demand for effectiveness. Atmospheric factors are rate of snowfall, air temperature, relative humidity and wind velocity. Effectiveness of snow melting or melting area means how quickly snow is melted. Heat output and melting rate are dependent on the distance between pipes, the depth of pipes in the ground, fluid flow and the drop in temperature of the fluid in pipes, conductivity of the slab, etc. (Zwarycz, 2002).

The dimensions of the snow melting slab affect heat and mass transfer rate at the surface. Other factors such as back and edge heat losses must be considered in complete designs (Ashrae, 2003).

The total heat load per unit surface area, which consists of sensible heat load, melting heat load, convective and radiative heat load and evaporative heat load, is calculated by using following equation.

$$\dot{q}_{snow\,mel} = \dot{q}_s + \dot{q}_m + A_r(\dot{q}_h + \dot{q}_e) \tag{1}$$

Sensible and latent (melting) heat loads occur on the entire slab during snowfall. On the other hand, heat and mass transfer at the slab surface depend on whether there is a snow layer on the surface. Any snow accumulation on the slab partially insulates the surface from heat losses and evaporation. Because snow may cover a portion of the slab area, the ratio of uncovered or free area $A_f$ to the total area $A_t$ is the snow-free area ratio $A_r$ (Eq. 2).

$$A_r = \frac{A_f}{A_t} \qquad 0 \leq A_r \leq 1 \qquad A_t = A_s + A_f \tag{2}$$

To satisfy $A_r = 1$, the system must melt snow fast enough so that no accumulation occurs. For $A_r = 0$, the surface is covered with snow of sufficient thickness to prevent heat and evaporation losses. Practical snow-melting systems operate between these limits. Earlier studies indicated that sufficient snow-melting system design information is obtained by considering three values of the free area ratio:0, 0.5, and 1.0 (Chapman, 1952).

**Sensible and Latent Heat Loads:** The sensible heat load is the heat load required to raise the temperature of snow on the slab to the melting temperature plus, after the snow has melted, to raise the temperature of the liquid to the assigned temperature $T_f$ of the liquid film. The snow is assumed to fall at air temperature $T_a$. The sensible heat load per unit surface area is calculated by Eq. 3.

$$\dot{q}_s = \rho_{water}.s.\left[c_{p,ice}.(T_s - T_a) + c_{p,water}.\left(T_f - T_s\right)\right]/c_1 \quad (3)$$

**Melting Heat Load:** The melting heat load $q_m$ is the heat load required to melt the snow per unit surface area. And it is directly proportional to the snowfall rate $s$ under steady-state conditions.

$$\dot{q}_m = \rho_{water}.s.h_{if}/c_1 \quad (4)$$

**Convective and Radiative Heat Flux from a Snow-Free Surface:** The corresponding heat load is given by the following equation (Eq. 5):

$$\dot{q}_h = h_c.\left(T_f - T_a\right) + \sigma.\varepsilon_s.\left[\left(T_f + 273.15\right)^4 - (T_{MR} + 273.15)^4\right] \quad (5)$$

The convection heat transfer coefficient over the slab on a plane horizontal surface is (Incropera and DeWitt, 1996):

$$h_c = 0.037.\frac{k_{air}}{L}.Re_L^{0.8}.Pr^{1/3} \quad (6)$$

$$Re_L = \frac{V.L}{v_{air}} \quad (7)$$

The mean radiant temperature ($T_{MR}$) is the equivalent blackbody temperature of the surroundings of the snow melting slab and it is calculated as:

$$T_{MR} = \left[(T_{cloud} + 273.15)^4 F_{sc} + \left(T_{sky,clear} + 273.15\right)^4 (1 - F_{sc})\right]^{1/4} \quad (8)$$

Temperature of clear sky is calculated (Ramsey et al., 1982):

$$T_{sky,clear} = 1.6\,T_a - 18.5 \quad (9)$$

**Evaporation Heat Load:** The heat load required to evaporate water from a wet surface is given by:

$$\dot{q}_e = \rho_{dry,air}.h_m.\left(W_f - W_{air}\right).h_{fg} \quad (10)$$

*where* $W_f$ is the humidity ratio of saturated air at film surface temperature, $kg_{vapor}/kg_{air}$

Mass transfer coefficient, $h_m$, is calculated by Eq. 11.

$$h_m = \left(\frac{Pr}{Sc}\right)^{2/3} \frac{h_c}{\rho_{dry,air}.c_{p,air}} \quad (11)$$

The both humidity ratios in the atmosphere and at the surface of the water film are calculated using the standard psychometric relation given in the following equation:

$$W = 0.622\left(\frac{P_v}{P_{air} - P_v}\right) \quad (12)$$

Atmospheric pressure above sea level can be calculated as (Cengel and Boles, 2011).

$$P_{air} = 101.325(1 - 2.25577\,Exp^{-5}.z)^{5.25588} \quad (13)$$

The average fluid temperature, required to provide for the total snow melting heat load per unit surface area ($\dot{q}_{snow\,mel}$), is calculated from Eq. 14

$$T_m = 0.08806.\dot{q}_{snow\,mel} + T_f \quad (14)$$

### 3.2. Exergetic Analysis

LowEx systems are defined as heating or cooling systems that allow the use of low valued energy as the energy source. In practice, this means systems that provide heating and cooling energy at a temperature close to room temperature. The exergetic modeling of snow melting here is done using the low exergy (the so-called LowEx) approach (Hepbasli, 2012). This approach is developed for buildings while it is adapted to snow melting using a geothermal heat pump.

The relations used in the analysis are comprehensively given elsewhere (Hepbasli, 2012) while some key ones are given below. In the first section, the general project data and boundary conditions are used. $A_t$ is the surface area, $T_a$ is the outdoor air temperature and $T_i$ is the internal temperature under the design conditions. The outdoor temperature is taken as the reference temperature $T_{ref}$ for analysis purposes.

The overall energy and exergy load rates of the building are expressed in the required primary energy and exergy input rates. For the fossil or non-renewable part of the primary energy, the result becomes

$$\dot{E}_{p,tot} = \dot{Q}_{HP}.F_P + (P_{aux,HP} + P_{aux,dis} + P_{aux,HS}).F_{p,el} \tag{15}$$

where Fp is the primary energy factor.

If the heat production system utilizes a renewable energy source or extracts heat from the environment, as heat pumps or solar collectors do, the additional renewable energy load rate is estimated by

$$\dot{E}_R = \dot{Q}_{HP}.F_R + \dot{E}_{env} \tag{16}$$

The total exergy load rate of the snow melting system becomes

$$\dot{E}x_{tot} = \dot{Q}_{HP}.F_p.F_{q,s} + (P_{aux,HP} + P_{aux,dis} + P_{aux,HS}).F_{p,el} + \dot{E}_R.F_{q,R} \tag{17}$$

The total energy input rate per area is calculated by

$$\dot{E}''_{tot,pa} = \frac{\dot{E}_{tot}}{A_t} \tag{18}$$

The total energy input rate per volume is calculated by

$$\dot{E}''_{tot,pv} = \frac{\dot{E}_{tot}}{\forall_N} \tag{19}$$

The total exergy input rate per area is calculated by

$$\dot{E}x''_{tot,pa} = \frac{\dot{E}x_{tot}}{A_t} \tag{20}$$

The total exergy input rate per volume is calculated by

$$\dot{E}x''_{tot,pv} = \frac{\dot{E}x_{tot}}{\forall_N} \tag{21}$$

The total energy efficiency of the system is expressed as follows:

$$\eta_{sys} = \frac{\dot{E}_{snowmel}}{\dot{E}_{tot}} \tag{22}$$

The total exergy efficiency of the system is expressed as follows:

$$\psi_{sys} = \frac{\dot{E}x_{snowmel}}{\dot{E}x_{tot}} \tag{23}$$

The exergy destruction rate of the system can be calculated from:

$$\dot{E}x_{dest} = \left(1 - \psi_{sys}\right)\dot{E}x_{tot} \tag{24}$$

The exergy flexibility factor is calculated by,

$$F_{flex} = \frac{\dot{E}x_{HS}}{\dot{E}x_{tot}} \tag{25}$$

These are key parameters and can be used for a ranking in a specific value, for comparing snow melt systems and their efficiency and quality of exergy utilization, and for evaluating the success of the exergy optimization.

## 4. RESULTS AND DISCUSSION

In this study, the hydronic snow melting system is proposed for the road with the dimension of 60 x 50m (300m$^2$ surface area) in the University Campus of Malatya city. Ground source heat pump system is selected as snow melting system with vertical downhole heat exchanger. As a first step, the required heat load and fluid temperature of snow melting system is calculated in energetic analysis, then exergetic analysis have been conducted by using the main results of energetic analysis.

The general assumptions and constant parameters of representative snow melting system are listed in Table 2.

**Table 2: The general assumptions and constant parameters of the system.**

| Parameter | Unit | Value |
|---|---|---|
| $T_f$ | °C | 0.556 |
| $T_s$ | °C | 0 |
| $\sigma$ | W/(m$^2$K$^4$) | 5.6703x10$^{-8}$ |
| $\varepsilon_s$ | - | 0.9 |
| L | m | 6 |
| Pr | - | 0.7 |
| $F_{sc}$ | - | 0.5 |
| $h_{if}$ | J/kg | 334000 |
| Sc | | 0.6 |
| z | m | 998 |

### 4.1 Energetic Results

According to the climatic data, the design winter outside temperature is -11.9 °C for Malatya. But design outside temperatures can be taken as -8.4 and -6.7°C with 99.6% and 99% frequency, respectively (Yılmaz and Bulut, 2001). Thus, the required heat load and average fluid temperature are calculated for various outside temperatures at the wind speed of 3 m/s, snowfall rate 2 mm/h and snow-free area ratio of 1. The results are summarize in Table 3.

**Table 3: The required heat load and fluid temperature of the snow melting system at various outside temperatures**

| $T_a$ (°C) | $\dot{q}_s$ (W/m$^2$) | $\dot{q}_m$ (W/m$^2$) | $\dot{q}_h$ (W/m$^2$) | $\dot{q}_e$ (W/m$^2$) | $\dot{q}_{snow\ mel}$ (W/m$^2$) | $\dot{Q}$ (W) | $T_m$ (°C) |
|---|---|---|---|---|---|---|---|
| -11.9 | 15.09 | 185.2 | 236.9 | 87.69 | 524.9 | 157.5 | 46.78 |
| -8.4 | 11.04 | 185.2 | 187.5 | 74.13 | 457.8 | 137.3 | 40.87 |
| -6.7 | 9.066 | 185.2 | 163.7 | 66.41 | 424.3 | 127.3 | 37.92 |

Table 3 indicates that with an increase in outside temperature 1°C, total unit heat load is reduced by approximately 19.2 W/m$^2$.

The wind speed, snowfall rate, snow-free area ratio and outside temperatures are the main design parameters of the snow melting systems. In order to examine the effect of the snowfall rate on unit heat load of the snow melting system, the parametric study has been conducted. The unit heat load of the system is calculated with five different snowfall rates, which are in the range of 1-5 mm/h (Figure 4). There is a linear proportionality between snowfall rate and unit heat load of the system. The unit heat load is increased by 100W/m$^2$ with an increase of 1 mm/h in snowfall rate.

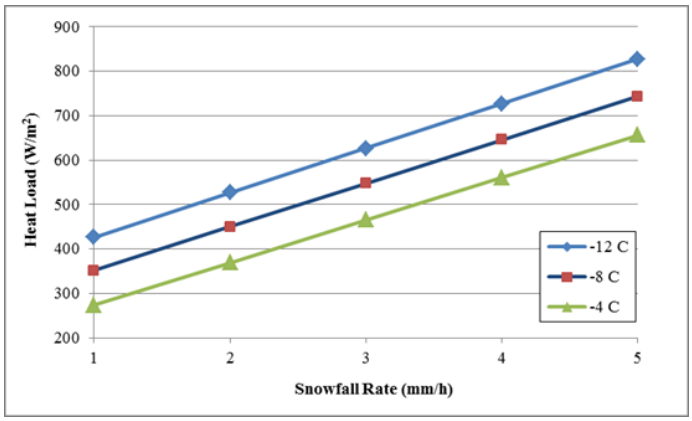



**Figure 4: Total required heat load per unit surface area versus snowfall rate for various outside temperature.**

The unit heat load of the snow melting system is calculated at various wind speeds, snowfall rates, snow-free area ratios and outside temperatures and the results are given in Table 4. The results show that the unit heat load increases with increasing wind speed and snow-free area ratio as well.

**Table 4: The main results of energetic analysis.**

| | | | $T_a$=-16°C | | $T_a$=-12°C | | $T_a$=-8°C | | $T_a$=-4°C | |
|---|---|---|---|---|---|---|---|---|---|---|
| V (m/s) | s (mm/h) | $A_r$ | $\dot{q}_{snow\ mel}$ (W/m$^2$) | $T_m$ (°C) | $\dot{q}_{snow\ mel}$ (W/m$^2$) | $T_m$ (°C) | $\dot{q}_{snow\ mel}$ (W/m$^2$) | $T_m$ (°C) | $\dot{q}_{snow\ mel}$ (W/m$^2$) | $T_m$ (°C) |
| 1 | 1 | 0.5 | 222.2 | 20.1 | 201.3 | 18.3 | 179.6 | 16.4 | 156.8 | 14.4 |
| | | 1 | 341.9 | 30.7 | 302.4 | 27.2 | 261.4 | 23.6 | 218.1 | 19.8 |
| | 2 | 0.5 | 324.7 | 29.2 | 301.5 | 27.1 | 277.5 | 25.0 | 252.4 | 22.8 |
| | | 1 | 444.4 | 39.7 | 402.6 | 36.0 | 359.2 | 32.2 | 313.7 | 28.2 |
| | 3 | 0.5 | 427.2 | 38.2 | 401.7 | 35.9 | 375.4 | 33.6 | 348.0 | 31.2 |
| | | 1 | 546.9 | 48.7 | 502.8 | 44.8 | 457.1 | 40.8 | 409.2 | 36.6 |
| 3 | 1 | 0.5 | 300.5 | 27.0 | 263.4 | 23.8 | 225.0 | 20.4 | 184.7 | 16.8 |
| | | 1 | 498.5 | 44.5 | 426.6 | 38.1 | 352.1 | 31.6 | 273.9 | 24.7 |
| | 2 | 0.5 | 403.0 | 36.0 | 363.6 | 32.6 | 322.9 | 29.0 | 280.3 | 25.2 |
| | | 1 | 601.0 | 53.5 | 526.7 | 46.9 | 450.0 | 40.2 | 369.5 | 33.1 |
| | 3 | 0.5 | 505.5 | 45.1 | 463.8 | 41.4 | 420.8 | 37.6 | 375.9 | 33.7 |
| | | 1 | 703.5 | 62.5 | 626.9 | 55.8 | 547.9 | 48.8 | 465.1 | 41.5 |
| 5 | 1 | 0.5 | 368.1 | 33.0 | 316.9 | 28.5 | 264.2 | 23.8 | 208.8 | 19.0 |
| | | 1 | 633.6 | 56.4 | 533.7 | 47.6 | 430.5 | 38.5 | 322.1 | 28.9 |
| | 2 | 0.5 | 470.6 | 42.0 | 417.1 | 37.3 | 362.1 | 32.4 | 304.4 | 27.4 |
| | | 1 | 736.2 | 65.4 | 633.9 | 56.4 | 528.3 | 47.1 | 417.7 | 37.3 |
| | 3 | 0.5 | 573.1 | 51.0 | 517.3 | 46.1 | 459.9 | 41.1 | 400.0 | 35.8 |
| | | 1 | 838.7 | 74.4 | 734.1 | 65.2 | 626.2 | 55.7 | 513.3 | 45.8 |

### 4.2 Exergetic Results

Figure 5 shows the energy flows from primary energy transformation to the environment. The process begins with the power plant, through the production of heat, via a distribution system, to the heating system and from there, across the roadbed surface to the outside environment.

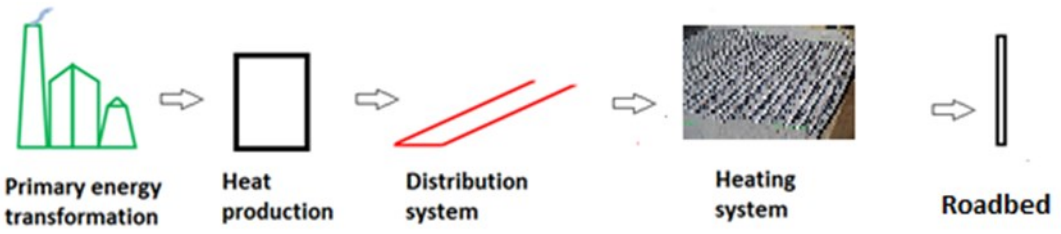



**Figure 5: Energy flows from primary energy transformation to the environment.**

For the snow melting heating system, the project data and boundary conditions are as follows: volume is 30 m$^3$, net surface area is 300 m$^2$, while the melting temperature is 0 ºC and two outside air temperatures -11.9 and -6.7 ºC are considered. In analyzing the generation stage (ground-source heat pump), the distribution stage, and the heating system, some data are necessary, as indicated in Table 5.

**Table 5: Some necessary design data for the system components.**

| | $T_a$ = - 11.9 °C | | $T_a$ = - 6.7 °C | |
|---|---|---|---|---|
| | **$A_r$ = 1** | **$A_r$ = 0.5** | **$A_r$ = 1** | **$A_r$ = 0.5** |
| Generation (Ground-source heat pump) | | | | |
| COP | 3 | 3 | 3 | 3 |
| $F_p$ | 3.0 | 3 | 3 | 3 |
| $F_{q,s}$ | 1 | 1 | 1 | 1 |
| $T_{max}$ (°C) | 58 | 55 | 55 | 55 |
| $p_{aux,HP}$ [W/kW$_{heat}$] | 2 | 2 | 2 | 2 |
| $F_R$ | 3 | 3 | 3 | 3 |
| Distribution system | | | | |
| Heat loss / efficiency, $\eta_{dis}$ | 0.91 | 0.91 | 0.91 | 0.91 |
| $p_{aux,dis}$ [W/kW$_{heat}$] | 22.36 | 22.36 | 22.36 | 22.36 |
| Heating system (Floor heating) | | | | |
| $T_{supply}$ (°C) | 56 | 50 | 50 | 50 |
| $T_{return}$ (°C) | 48 | 40 | 40 | 40 |
| Heat loss / efficiency, $\eta_{HS}$ | 0.99 | 0.99 | 0.99 | 0.99 |

In this study, the data taken from the energy analysis are utilized to analyze and evaluate the performance of the melting system considered. The data utilized are listed in Table 6. Using the relations given in the exergetic analysis section as well as the values presented in Tables 5 and 6, the total exergy efficiency of the system, $\psi_{sys}$ and the exergy flexibility factor, $F_{flex}$ are calculated.

**Table 6: Total exergy efficiency and flexibility factor values of the system at various outdoor air temperatures**

| | $T_a$ = - 11.9 °C | | $T_a$ = - 6.7 °C | |
|---|---|---|---|---|
| | **Case 1 ($A_r$ = 1)** | **Case 2 ($A_r$ = 0.5)** | **Case 3 ($A_r$ = 1)** | **Case 4 ($A_r$ = 0.5)** |
| $\dot{Q}$ (kW) | 157.5 | 108.8 | 127.3 | 92.78 |
| q (W/m$^2$) | 524.9 | 362.6 | 424.3 | 309.3 |
| $T_{m,fluid}$ (°C) | 46.8 | 32.5 | 37.9 | 27.8 |
| $T_{max}$ (°C) | 58 | 55 | 55 | 55 |
| $T_{supply}$/$T_{return}$(°C) | 56/48 | 50/40 | 50/40 | 50/40 |
| Calculated values | | | | |
| $\dot{E}x_{tot}$ (W) | 186 085 | 128 547 | 150 404 | 109 619 |
| $\psi_{sys}$ (%) | 3.69 | 3.69 | 2.08 | 2.08 |
| $F_{flex}$ (%) | 27.51 | 25.11 | 22.22 | 22.22 |

Figure 6 indicates energy/exergy flow diagrams of the snow melting heating system for Case 3 only. The total exergy demand rate is determined based on the methodology as followed in the energy demand calculation, but using exergy analysis approach. The largest exergy demand rate is calculated to be about 186 kW for Case 1. The largest energy and exergy loss rates take place in the

primary energy transformation. On the other hand, it is clear from Figure 6 that exergy is consumed continually in each component for all cases. While the flow of energy leaves the snow melting system roadbed, there is still a remarkable amount of energy left, but this is not true for exergy. At the reference environment conditions, exergy has no potential of doing work; so all exergy has been consumed. The exergy flow on the right side of the diagram is required to be zero.

In Table 6, the highest exergy efficiency values are obtained to be 3.69% for Cases 1 and 2. By comparison, Caliskan and Hepbasli (2010) reported in a tabulated form that the whole exergy efficiency in the heating of various buildings with floor areas ranging from 35 to 2202 $m^2$ varied between 0.40 and 9.5%, mostly being over 3.5%. The overall exergy efficiency values of the greenhouse systems studied are in the range of 0.18-11.5% at dead state temperatures varying from -10 to 15$^oC$.

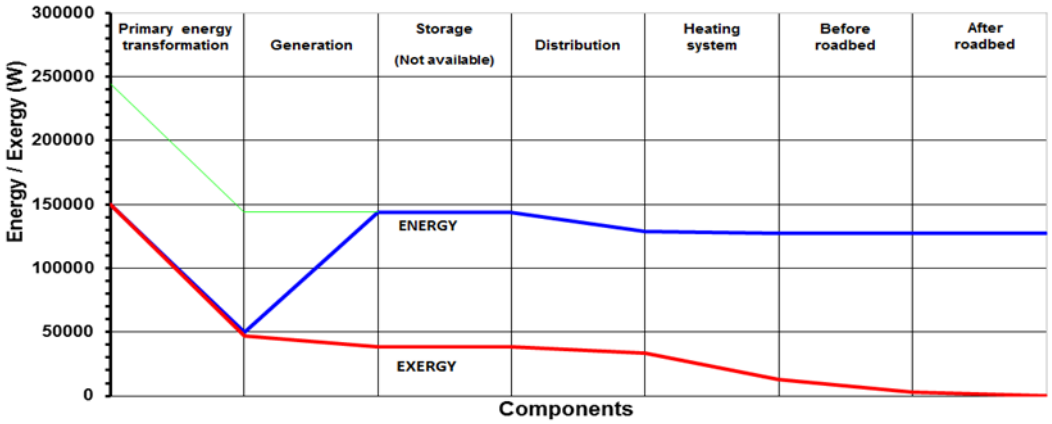



**Figure 6: Energy/exergy flow diagrams of the snow melting heating system for Case 3.**

## 5. CONCLUSIONS

In this study, we have a comprehensive energy and exergy analysis of a snow melting system performed and assessed its performance through energy and exergy efficiencies. We have also indicated energy and exergy flows.

The main conclusions we have drawn from the results of the present study may be listed as follows:

- The specific heat load of the system is calculated as 524.9 W/$m^2$ at snow-free area ratios of 1, wind speed of 3 m/s, and snowfall rate of 2 mm/h at -11.9 °C outside temperature.
- The specific head loads of the system considered vary from 310 to 524.9 W/$m^2$ at the snow-free area ratios of 0.5 and 1 and at the outside air temperatures of -6.7 °C and -11.9 °C.
- The specific heat load is increased by 100W/$m^2$ with an increase of 1 mm/h in snowfall rate.
- With an increase in outside temperature by 1°C, total unit heat load is reduced by approximately 19.2 W/$m^2$.
- The lowest and highest exergy demand rates of the snow melting system are about 110 kW and 186 kW at dead state temperatures of – 6.7 °C and – 11.9 °C, respectively.
- The exergy efficiency values range from 2.08 % to 3.69 %.
- For a future work, it is recommended to conduct a detailed cost accounting and exergoeconomic analysis (which is a combination of exergy and economics) for various types of snow melting systems for comparison purposes.

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**NOMENCLATURE**

| | |
|---|---|
| $A_f$ | equivalent snow-free area, $m^2$ |
| $A_r$ | snow-free area ratio, dimensionless |
| $A_s$ | equivalent snow-covered area, $m^2$ |
| $A_t$ | total area, $m^2$ |
| $c_1$ | unit conversion factor (=3,6.$10^6$) |
| $c_p$ | specific heat, J/kg.K |
| $\dot{E}$ | energy rate (W) |
| $\dot{E}x$ | exergy rate (W) |
| $F$ | factor (-) |
| $F_{sc}$ | fraction of radiation exchange that occurs between slab and clouds |
| $h_c$ | convection heat transfer coefficient for turbulent flow, W/$m^2$·K |
| $h_{fg}$ | heat of vaporization (enthalpy difference between saturated water vapor and saturated liquid water), J/kg |
| $h_{if}$ | heat of fusion of snow, J/kg. |
| $h_m$ | mass transfer coefficient, m/s |
| $k_{air}$ | thermal conductivity of air at ta, W/m.K |
| $L$ | characteristic length of slab in direction of wind, m |
| $P$ | power (W) |
| $P_{air}$ | atmospheric pressure, kPa |
| Pr | Prandtl number for air, taken as Pr = 0,7 |
| $P_v$ | partial pressure of water vapor, kPa |
| $\dot{Q}$ | heat transfer rate (kW) |
| $\dot{q}_e$ | heat load of evaporation, W/$m^2$ |
| $\dot{q}_h$ | convective and radiative heat flux from snow-free surface, W/$m^2$ |
| $\dot{q}_m$ | melting heat load, W/$m^2$ |
| $\dot{q}_s$ | sensible heat load, W/$m^2$ |
| $\dot{q}_{snow\ mel}$ | heat load required at snow-melting surface, W/$m^2$ |
| $Re_L$ | Reynolds number based on characteristic length $L$ |
| $s$ | snowfall rate water equivalent, mm/h |
| Sc | Schmidt number |

| | |
|---|---|
| T | temperature, K |
| $T_a$ | outside temperature coincident with snowfall, °C |
| $T_f$ | liquid film temperature, °C |
| $T_m$ | average liquid temperature, °C |
| $T_s$ | melting temperature, °C |
| $V$ | design wind speed near slab surface, m/s |
| W | humidity ratio $kg_{vapor}/kg_{air}$ |
| z | elevation, m |

*Greek letters*

| | |
|---|---|
| $\eta$ | energy efficiency (-) |
| Ψ | exergy efficiency (-) |
| $\forall$ | volume ($m^3$) |
| $\varepsilon_s$ | emittance of surface, dimensionless (0,9) |
| ν | kinematic viscosity of air, $m^2/s$ |
| ρ | density, $kg/m^3$ |
| σ | Stefan-Boltzmann constant (= 5,6703*10^(-8)) $W/m^2.K^4$ |

*Subscripts*

| | |
|---|---|
| *air* | *air* |
| *aux* | auxiliary energy requirement |
| cloud | cloud |
| *dest* | *destruction* |
| *dis* | distribution system |
| dry,air | dry air |
| *el* | electricity |
| *env* | environment |
| *flex* | flexibility |
| *HP* | heat production system |
| *HS* | heating system |
| ice | ice |
| MR | mean radiant |
| *p* | primary energy |
| *pa* | per area |
| *pv* | per volume |
| *q* | quality |
| *R* | renewable energy |
| skyclear | clear sky |
| snow mel | snow melting |
| *sys* | system |
| *tot* | total |
| water | water |

*Superscripts*

over dot rate2

*Abbreviations*

| | |
|---|---|
| COP | coefficient of performance |
| LowEx | low exergy |