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Edgar Experimental Mine as a Geothermal Resources Laboratory

Yu KOIZUMI and Masami NAKAGAWA

Colorado School of Mines, Mining Engineering Department

1600 Illinois Street, Golden, CO 80401, USA

E-mail: mnakagaw@mines.edu

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ABSTRACT

The authors propose a system that can cool buildings in the summer time and melt snow on the pedestrian sidewalks during the winter using an underground mine and a hot spring in Idaho Springs, Colorado. In the proposed system, the mine would be used as cold thermal energy storage, and the heat of geothermal fluid transported from the hot spring would be re-used to melt snow in the historic downtown of Idaho Springs. To assess the feasibility of the proposed system, a series of temperature measurements in the Edgar Mine (Colorado School of Mines' Experimental Mine) and heat transfer analyses of geothermal fluid were conducted. The results of the temperature measurements proved that the temperature of the underground mine was low to be used to store cold groundwater for the summer. Furthermore, the temperature profiles of two different tunnels in the Edgar Mine were discussed to determine the most appropriate place to store cold groundwater. In the heat transfer analyses, the heat loss of the geothermal hot fluid during its transportation was modeled and calculated, and then heat requirement for snow melting was compared with the heat supply from the geothermal hot fluid. It was concluded that the heat supply was not sufficient enough to melt snow on the entire sidewalk area of the downtown. The result, however, indicated the proposed snow melting system could be realized if the required snow melting area were smaller or additional geothermal wells were drilled. This case study should serve as a good example of a sustainable energy system that promotes "local consumption of locally available energy".

1. INTRODUCTION

Geothermal energy is a renewable energy source that can provide reliable base-load power. Therefore, it is suitable for developing a sustainable community. For example, Hachijojima is a volcanic island located 300km south of Tokyo, Japan and has a population of about 9,500 according to Yamashita et al. (2000). The Hachijojima Geothermal Power Station, operated by Tokyo Electronic Power Company since 1999, supplies 3,300kW of electricity, which corresponds to the minimum demand for this isolated community throughout a year. In addition to the power generation, the heat of condensed vapor, the temperature of which is about 40°C, is utilized for space heating and agriculture. This is a good example of local consumption of locally produced energy, which is important for isolated communities to achieve their sustainable living.

Colorado is blessed with geothermal resources. Local residents and tourists enjoy natural hot springs in many places. In Geo-Heat Center Quarterly Bulletins, at least six hot springs have been described as well as case studies showing direct use of geothermal energy such as greenhouses, aquaculture and district space heating in Colorado. In Colorado, there are many underground mines that are no longer used or abandoned. It should be noted that an abandoned mine can be utilized as a thermal storage. Pingjia and Ning (2011) studied three different usages of abandoned mines. One of them is called a "Thermal Accumulator" where cold water stored in the cold mine would be used in summer, and warm water stored in the hot mine would be used in winter to improve heat pump efficiency of buildings nearby. Rodriguez and Diaz (2009) proposed that an abandoned underground mine in Spain at a depth of 500m could be used as a geothermal heat exchanger. According to their measurement, the temperature of the rock mass in the underground mine was 27°C constant. Therefore, they proposed to flow cold water through the underground mine to heat it up to improve the heat pump efficiency of nearby buildings in winter. Furthermore, they conducted economic analysis and proved that the proposed system would be economically viable.

2. EDGAR MINE AS A GEOTHERMAL RESOURCE FOR IDAHO SPRINGS

2.1 General Information about Idaho Springs

The city of Idaho Springs, Colorado is located about fifty kilometers west of Denver in the foothills of the Rockies. The town was founded in 1859 by prospectors and flourished as a mining community. Today, the town has a population of about 1,900 and attracts tourists with its historic downtown, hot spring, and experimental Edgar Mine. Figure 1 shows the map of the city of Idaho Springs and the locations of the historic downtown, the hot spring, and the Edgar Mine.

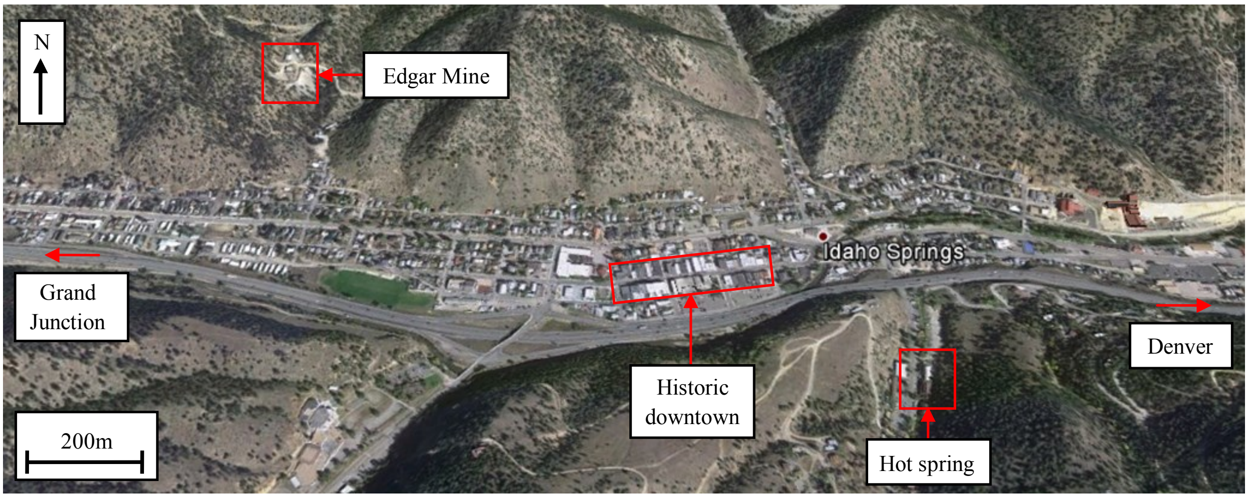

Figure 1: Map of Idaho Springs, Colorado

2.2 Proposed System for heating and cooling

The proposed heating/cooling system for Idaho Springs can be visualized in Figure 2. It is assumed that the rock mass temperature in the Edgar Mine is relatively low because the mine is not located at a great depth. Therefore, cold groundwater would be stored in a closed section of the Edgar Mine in winter and used to cool down condensers of heat pumps in summer as shown in Figure 3 (a). In this way, the efficiency of heat pumps would be improved. In winter, on the other hand, geothermal hot fluid used for bathing at the hot spring would be transported to the historic downtown and used to melt snow on the pedestrian sidewalks. Furthermore, the geothermal hot fluid could improve heat pump efficiency by heating up evaporators as shown in Figure 3 (b) if the fluid is still warm.

The concept of this system is basically the same as that of a ground-source heat pump (GSHP) system, which utilizes constant ground temperature. GSHP system emits heat from a condenser to the ground in summer and absorbs heat from the ground to heat up an evaporator in winter. However, the system proposed in this paper would improve heat pump efficiency more because the groundwater stored in the Edgar Mine is presumed to be colder than circulating fluid in a GSHP system which emits its heat into the ground in summer, and the geothermal hot fluid transported from the hot spring is presumed to be hotter than circulating fluid in a GSHP system which absorbs heat from the ground in winter. In addition, a GSHP system requires either boring for a vertical loop or excavating a trench for a horizontal loop, the construction cost of which is expensive. In the proposed system, the installation of pipes would be required, but boring or excavating is not required.

As it is reviewed in the previous section, the use of an abandoned mine to improve heat pump efficiency is not a new idea. Moreover, Shiba (2008) reports a case study in which geothermal hot fluid consumed in a public bathing facility is re-used to improve heat pump efficiency of buildings in Japan. However, we have never reviewed a case study in which an abandoned mine and geothermal hot fluid are utilized in one place, which makes Idaho Springs a unique site.

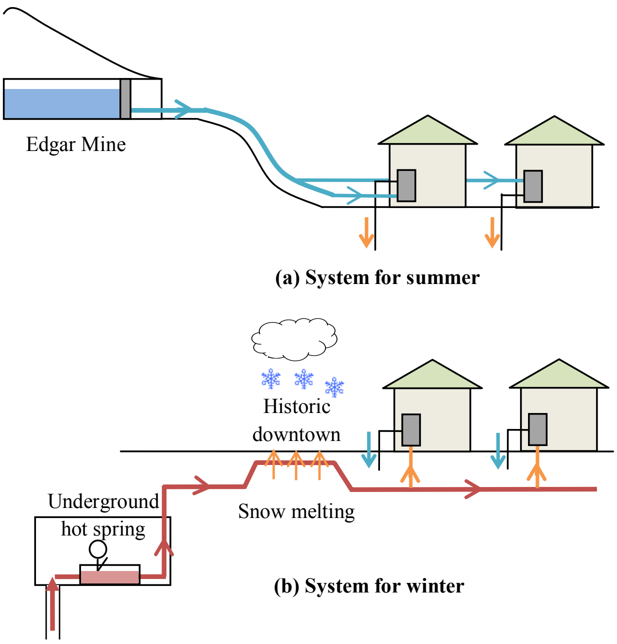

Figure 2: Proposed system for Idaho Springs

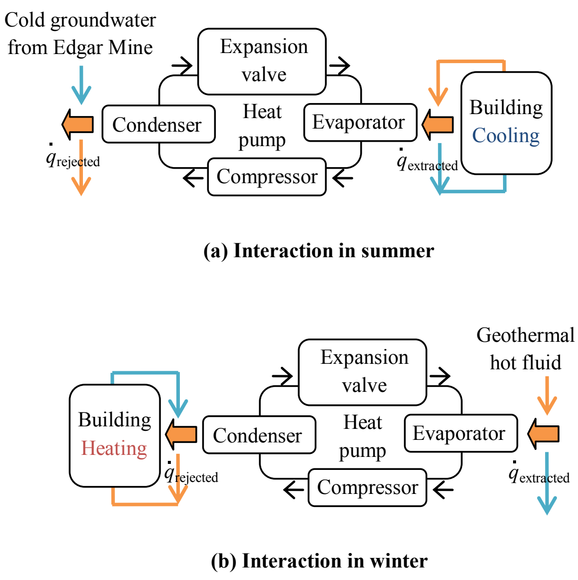

Figure 3: Interaction between proposed system, heat pump, and building

3. TEMPERATURE MEASUREMENT IN EDGAR MINE

In order to validate the feasibility of the proposed system, the temperature environment was investigated in the Edgar Mine. In this section, general information about the Edgar Mine is first provided. Then, the method and the result of temperature measurement in the Edgar Mine are presented.

3.1 General Information about Edgar Mine

The Edgar Mine, also known as the Mines' Experimental Mine, produced high-grade silver, gold, lead and copper in the 1870s. Colorado School of Mines (CSM) acquired the Edgar Mine in 1921 when a bankrupt mining company agreed to lease it to the school and CSM has been using the mine for mining education and research since then. For example, junior students in the Mining Engineering Department take a course entitled "Mining Engineering Laboratory" at the Edgar Mine to receive practical training in operating jackleg drills, jumbo drills, and Load-Haul-Dump machines, etc. In other classes, students gain hands-on experience in underground mine surveying, geological mapping, mine ventilation field studies, mine safety, and so on. Photo 1 shows the entrance of the Edgar Mine (Miami Tunnel) and Photo 2 shows a classroom inside the mine. Research is conducted at the Edgar Mine by numerous academic, government, and industry groups including the CSM Mining Engineering Department, the National Institute for Occupational Safety and Health (NIOSH), the U.S. Army, and others. Research topics cover tunnel detection, blasting, rock mechanics, and development of new mining equipment and methods. For more information, the CSM website is available using the following link: http://inside.mines.edu/Mining-Edgar-Mine.

3.2 Temperature Measurement

We carried out temperature measurements in the Edgar Mine three times, on Sept. 17th, Oct. 24th, and Nov. 25th in 2013. Figure 4 shows the data for temperature, precipitation, and snowfall of Idaho Springs in 2013. The data were obtained from the website of AccuWeather.com. The ambient temperature decreased significantly during the measurement period. We measured the surface temperature of the rock mass, ambient temperature, and humidity at 24 locations shown in Figure 5. As shown in Figure 5, the eastern area of the Edgar Mine is called the Miami Tunnel, and the western area is called the Army Tunnel. The cross section of the Army Tunnel is larger than that of the Miami Tunnel. The height and width of the Miami Tunnel are about 2m and 2m, and those of the Army Tunnel are about 4m and 5m. An infrared thermometer (Maker: Fluke, Model: 62Max) was used to measure the rock surface temperature as shown in Photo 3. The temperature of groundwater accumulated at the location 21 was also measured. The area between the entrance of the Army Tunnel (Location 24) and the location 19 was wet.

Photo 1: Entrance of Edgar Mine (Miami Tunnel, Location 1 in Figure 5)

Photo 2: USGS Classroom inside Edgar Mine (Location 9 in Figure 5)

Photo 3: Measurement of rock surface temperature using an infrared thermometer

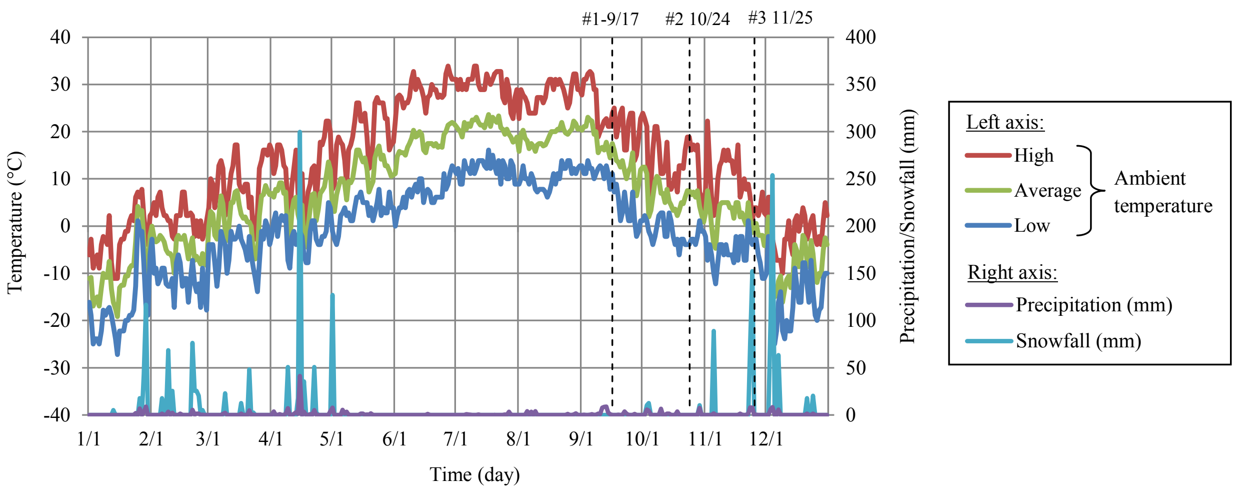

Figure 4: Ambient temperature, precipitation, and snowfall in Idaho Springs

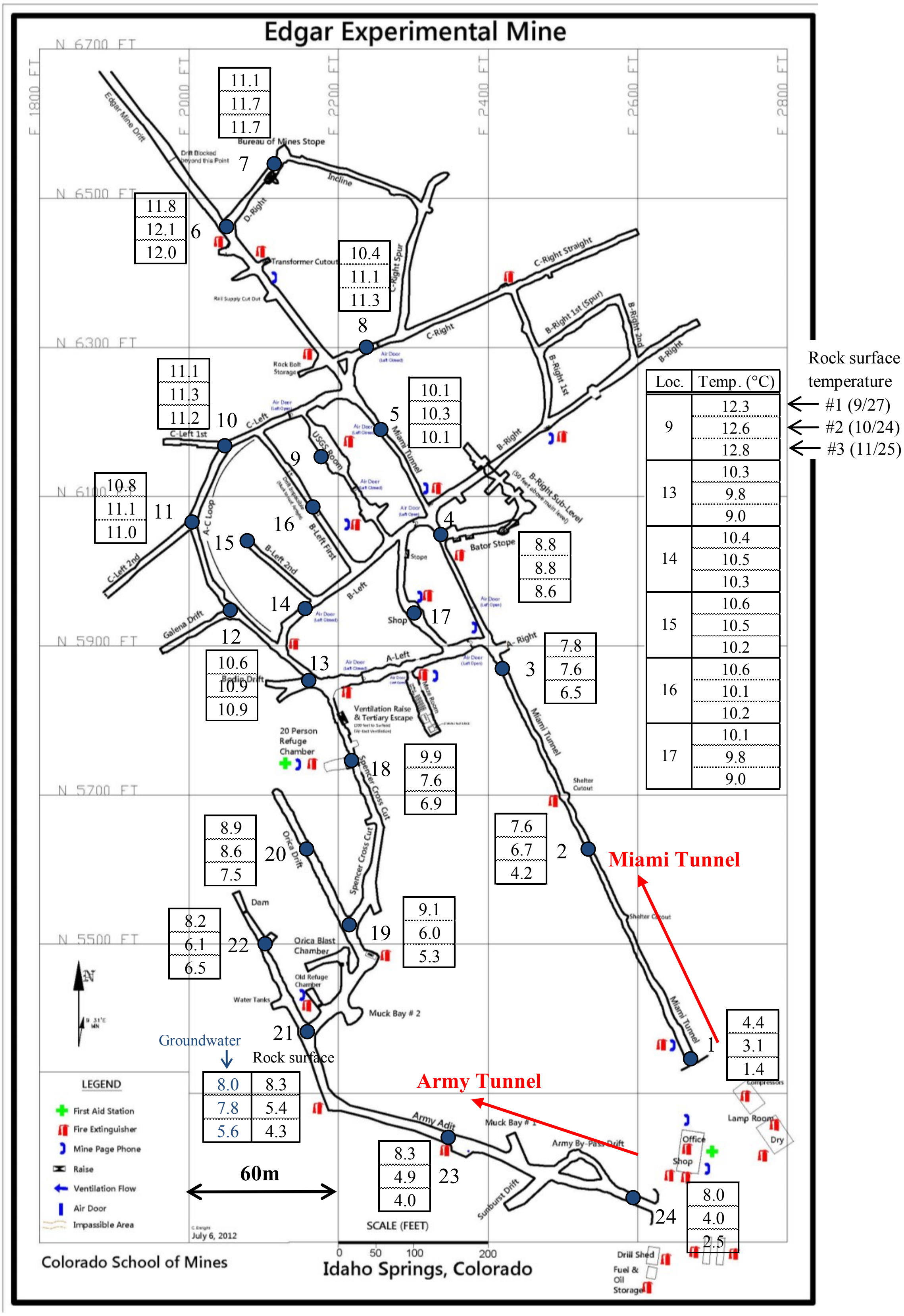

Figure 5: Map of Edgar Mine and rock surface temperatures at 24 locations

3.3 Results

The measured surface temperature of the rock mass at 24 locations is shown in Figure 5. The temperature measured near the entrance of two tunnels decreased during the three measurements because they were easily influenced by the ambient temperature. On the other hand, the temperature inside the mine was stable. The highest surface temperature was always measured at location 9 (USGS classroom), and it was about 12.5°C. The temperature measured at the USGS classroom could have been influenced by the heat emitted from lights there, but this has not been officially confirmed. The second highest temperature measured at location 6 was about 12°C. Considering that the surface temperature of the rock mass was 27°C at a 500m-deep abandoned mine in Spain in the paper by Rodriguez and Diaz (2009), it can be said that the surface temperature of the rock mass in the Edgar Mine is much lower. This could make sense because the measured areas in the Edgar Mine had been excavated horizontally in a mountain so that the typical temperature gradient (20-30 °C/km) is not expected. Besides, it seems the measured area is not influenced by volcanic activity although there is a hot spring at the other side of the town.

Figure 6 (a) and (b) show how the measured rock surface temperature and the ambient temperature change with the distance from the entrance. More specifically, the temperature measured at locations 1, 2, 3, 4, 5 and 6 is shown in Figure 6 (a), and the temperature measured at locations 24, 23, 21, 19 and 18 is shown in Figure 6 (b). Comparing the two trends, it is found that the surface temperature increases as the distance from the entrance becomes greater inside the Miami Tunnel from Figure 6 (a). Furthermore, the surface temperatures at locations 4, 5 and 6 show no significant difference between the three measurements though the ambient temperature decreases. Figure 6 (b), on the other hand, indicates that the surface temperature does not increase as the distance becomes greater in the Army Tunnel. The surface temperatures shown in Figure 6 (b) are significantly different between the three measurements.

In order to understand the differences in the temperature profiles between the Miami Tunnel and the Army Tunnel, the relationships between the cover (= ground surface elevation - tunnel elevation) and the distance from the entrance of the Miami Tunnel and the Army Tunnel are shown in Figure 7. From Figure 7, it is found that the cover above the Army Tunnel does not increase while the cover above the Miami Tunnel increases almost linearly with the distance from its entrance. The heat is transferred through the rock mass by conduction since no significant wind blows inside the underground mine. Therefore, as the cover becomes larger, the surface temperature of the rock mass is less influenced by the ambient temperature outside the Edgar Mine. The rock surface temperatures at locations 4, 5 and 6, with the cover greater than 150m, is considered to be independent of the ambient temperature outside the mine. Figure 7 also shows the different topography above the Miami Tunnel and the Army Tunnel, which should explain why the Miami Tunnel is dry and the Army Tunnel is wet. The thin and relatively flat cover above the Army Tunnel should catch more water on the surface, which could easily permeate the tunnel. Moreover, the larger perimeter of the Army Tunnel could draw groundwater into the tunnel.

In conclusion, it is found that the temperature of the rock mass in the Edgar Mine is relatively low due to its shallow depth. Therefore, the mine would be suitable for thermal energy storage in which cold groundwater would be stored in winter and used in summer as proposed in Figure 2. It would be easier to store groundwater in the Army Tunnel as the groundwater flows into the tunnel naturally. In addition, due to its thin cover, the Army Tunnel was colder than Miami Tunnel while the three measurements were conducted. However, the thin cover can also indicate that the Army Tunnel could be warmer than the Miami Tunnel in summer. Therefore, the temperature measurement should be continued to determine which part of the mine would be used for cold thermal energy storage more effectively.

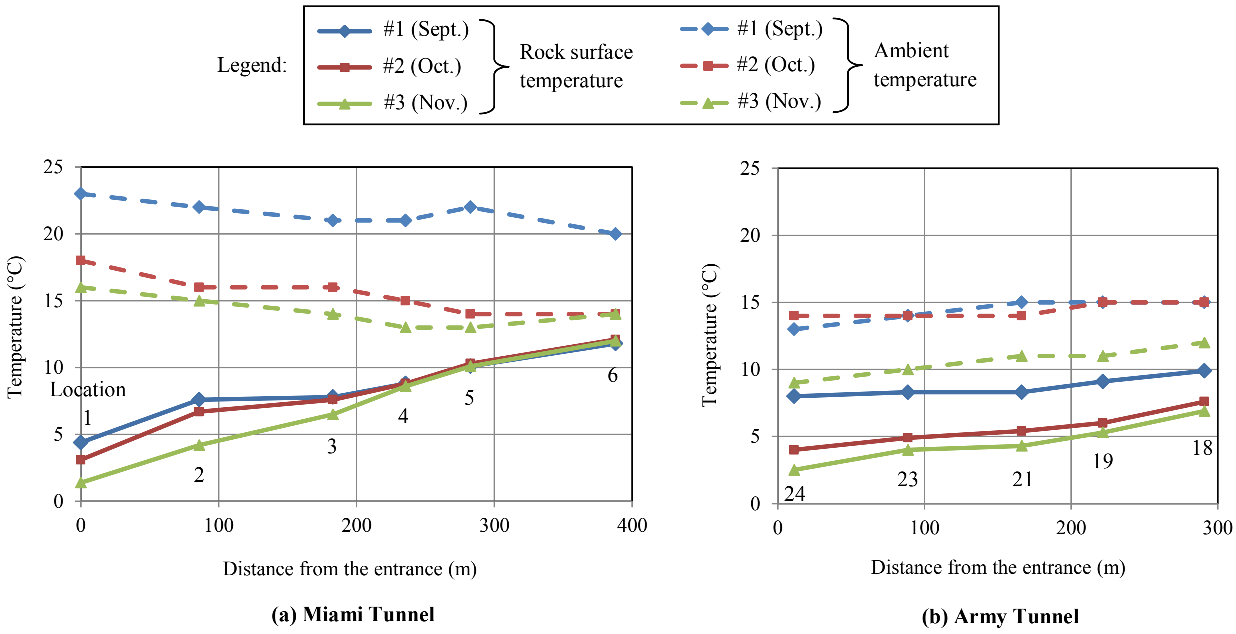

Figure 6: Relationship between temperature and distance from the entrance

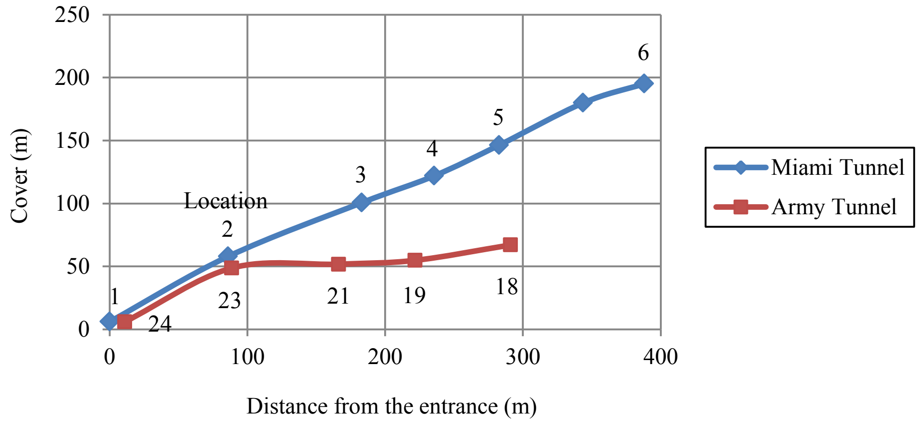

Figure 7: Relationship between cover and distance from the entrance

4. TEMPERATURE LOSS OF TRANSPORTED GEOTHERMAL HOT FLUID

In the proposed system shown in section 2.2, geothermal hot fluid would be transported from the hot spring to the east end of the historic downtown through a pipe buried in the ground. In this section, the temperature loss of the transported geothermal hot fluid is calculated.

4.1 Temperature Distribution in the Ground

Ground temperature, T (°C) is known as a function of time and the depth below the surface and is obtained by the following equation suggested by Kasuda and Archenbach (1965),

$$T = T_{mean} - T_{amp} \times \exp\left[-D\left(\frac{\pi}{365\alpha}\right)\right] \times \cos\left\{\frac{2\pi}{365}\left[t - t_{shift} - \frac{D}{2}\left(\frac{365}{\pi\alpha}\right)\right]\right\} \tag{1}$$

where, T_{mean}, T_{amp}, D, α, t, t_{shift} are mean surface temperature (average air temperature throughout a year = 6.7°C), amplitude of surface temperature ((maximum air temperature (29.9°C in July) minus minimum air temperature (-17.5°C in January))/2 = 23.7°C), depth below the surface (m), thermal diffusivity of the ground (1.19×10^{-2} m^2/day), time (day), and day of the year of the minimum surface temperature (15 days (January 15th)), respectively.

Figure 8 shows the temperature distribution in the ground and indicates that the ground temperature becomes 6.7°C more or less at the depth of approximately 6m. Considering its expensive cost, it is not realistic to bury a pipe at the depth of 6m. The depth of the buried pipe would be approximately 2m, at which the ground temperature is not perfectly constant. However, it is approximated that the temperature of the ground which the pipe contacts a constant 6.7°C to simplify the calculation hereafter.

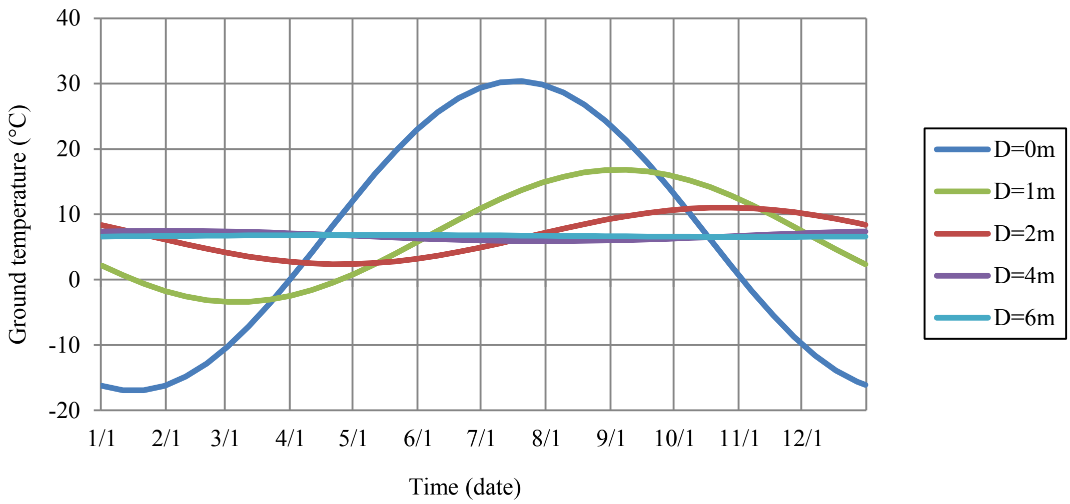

Figure 8: Ground temperature as a function of time and depth

4.2 Temperature loss due to transportation of geothermal hot fluid from hot spring to historic downtown

Figure 9 shows the schematic representation of the geothermal hot fluid flowing from the hot spring to the historic downtown. According to Repplier et al. (1982), the flow rate of the geothermal well used by the hot spring is 136 ℓ /min. Considering 25% loss of the flow, the flow rate is assumed as 100 ℓ /min. Under the conditions shown in the figure, the temperature loss was calculated by the following steps. The heat transfer textbook by Bergman et al. (2011) was used.

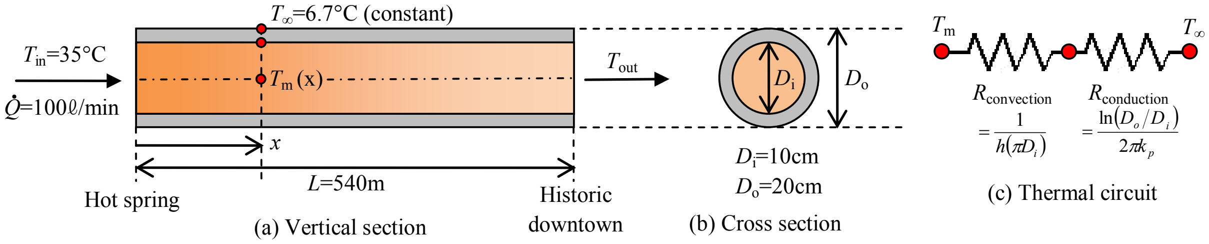

Figure 9: Schematic representation of the geothermal hot fluid flowing from hot spring to historic downtown

The Reynolds number of the internal flow through a pipe, Re_D is

$$\mathrm{Re}_D = \frac{\rho u_m D_i}{\mu} = \frac{995.0 \times 0.212 \times 0.1}{7.69 \times 10^{-4}} = 27{,}430 \tag{2}$$

where, ρ, μ, u_m are density (kg/m^3) and viscosity (N-s/m^2) of the fluid, and internal flow rate (m/s).

Re_D is larger than 2,300, therefore the flow is turbulent. As the temperature of the fluid is higher than the surrounding ground temperature in this case, the following equation can be applied to calculate the Nusseldt number, Nu_D

$$Nu_D = 0.023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.3} = 0.023 \times 27430^{0.8} \times 5.2^{0.3} = 134.0 \tag{3}$$

where, Pr is Prandtl number.

Convection heat transfer coefficient, h (W/m^2-K) is

$$h = \frac{Nu_D \times k}{D_i} = \frac{134.0 \times 0.62}{0.1} = 830.8 \tag{4}$$

where, k is the thermal conductivity of the fluid (W/m-K).

Total thermal resistance per unit length, R_{tot} (m-K/W) is

$$R_{tot} = R_{conv} + R_{cond} = \frac{1}{h(\pi D_i)} + \frac{\ln(D_o/D_i)}{2\pi k_p} = \frac{1}{830.8 \times (\pi \times 0.1)} + \frac{\ln(0.2/0.1)}{2 \times \pi \times 0.16} = 0.306 \tag{5}$$

where, k_p is the thermal conductivity of a pipe (W/m-K).

$$\frac{T_\infty - T_x}{T_\infty - T_{in}} = \exp\left(-\frac{x}{\dot{m} c_p R_{tot}}\right) \Leftrightarrow T_x = 6.7 - \exp\left(-\frac{x}{1.66 \times 4178 \times 0.306}\right) \times (6.7 - 35) \tag{6}$$

where, T_x, T_∞, T_{in}, m, c_p are mean temperature at x=x (°C), constant surface temperature (°C), inlet temperature (°C), mass flow rate (kg/s), and specific heat of the fluid (J/kg-K).

Figure 10 shows the relationship between the mean temperature of the geothermal hot fluid and its travel distance. It is found that the temperature would decrease from 35°C to 28.6°C while it is transported from the hot spring to the historic downtown. In this

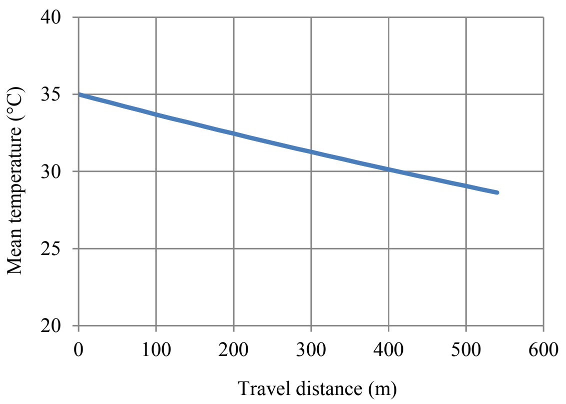

Figure 10: Relationship between mean temperature of geothermal hot fluid and travel distance

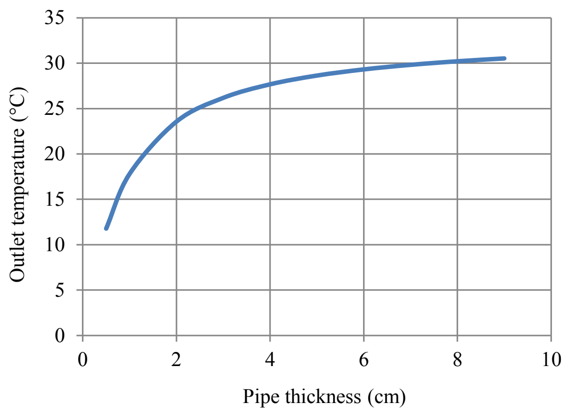

Figure 11: Relationship between outlet temperature of geothermal hot fluid and pipe thickness

calculation, the thickness of a pipe is assumed to be 5cm. Figure 11 shows the result of a parametric study when the thickness of a pipe is changed from 1cm to 9cm. Figure 11 indicates that the outlet temperature is higher when the pipe is thicker. However, there is no linear correlation between them, and an inflection point exists when the pipe thickness is approximately 2cm. Considering its high cost and the difficult work caused by too thick pipe, 5cm-thickness assumed in the calculation above is the most reasonable.

5. HEAT BALANCE ANALYSIS FOR SNOW MELTING

The heat of the hot geothermal fluid, the temperature of which is 28.6°C, is used to melt snow and to improve heat pump efficiency of buildings in the historic downtown. In this section, the feasibility of the designed snow melting system is discussed by comparing heat supply and heat requirement for snow melting.

5.1 Heat supply of geothermal hot fluid to pedestrian sidewalks

Figure 12 shows the design of the proposed snow melting system in the historic downtown. The geothermal hot fluid transported from the hot spring flows below both of the north and south pedestrian sidewalks. The depth, the spacing, and the size of buried pipes are determined appropriately by reviewing two case studies in which similar snow melting systems were installed. One case study covers the system in Klamath Falls, Oregon, reported by Lund (1999) and the other covers the system in Sapporo, Japan, reported by Sato and Sekioka (1979).

In order to calculate the heat supply of the geothermal hot fluid to the pedestrian sidewalks, the temperature decrease of the geothermal hot fluid flowing through the historic downtown was calculated in the same way as the calculation of the temperature loss in section 4. However, the buried depth of the pipes shown in Figure 12 is only 8cm while that of the pipe in the previous section was assumed to be 2m. Therefore, the geothermal hot fluid would be significantly influenced by cold ambient temperature in this calculation. Thus it is assumed that the flow is cooled down by the constant temperature, -7.7°C as shown in Figure 13. The average temperature of the ground surface in 2013 was -7.7°C between November 1st and April 30th, the average months of snowfall in Idaho Springs as shown in Figure 4.

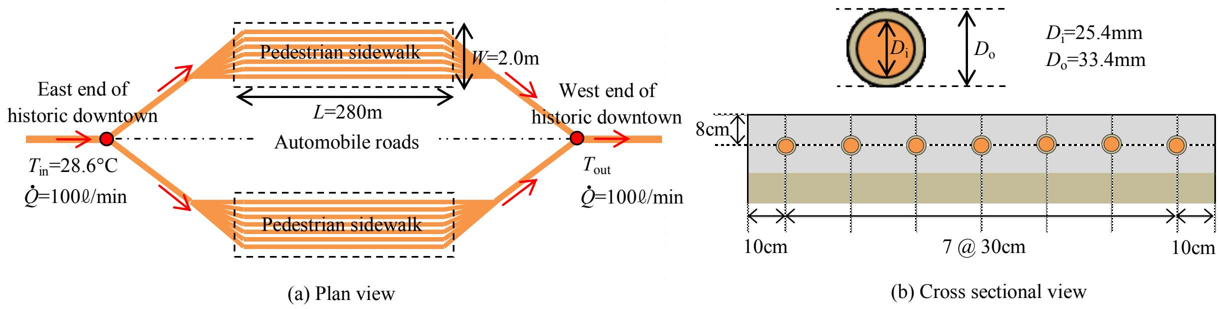

Figure 12: Schematic representation of the geothermal hot fluid flowing from hot spring to historic downtown

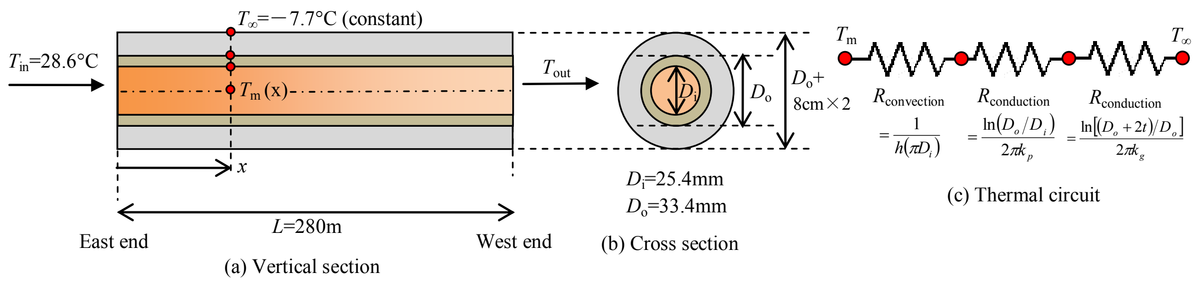

Figure 13: Schematic representation of geothermal hot fluid flowing from hot spring to historic downtown

As a result of the calculation, the outlet temperature was found to be 3.1°C. Therefore, the heat supply from the geothermal hot fluid to the surrounding ground, q (W) is

$$q = \dot{m} c_p (T_{in} - T_{out}) = 1.66 \times 4184 \times (28.6 - 3.1) = 177{,}108\ \mathrm{W} = 177.1\,\mathrm{kW} \tag{7}$$

According to Adlam (1950), 70% of the heat is usefully consumed for snow melting, because approximately 8-10% is emitted to the atmosphere and approximately 20-22% is lost downwards to the ground. Therefore, the available heat for snow melting is

$$q_{available} = 0.7 \times q = 0.7 \times 177.1 = 124.0\,\mathrm{kW} \tag{8}$$

The outlet temperature of the geothermal fluid (3.1°C) is so cold that it could not be used to heat up an evaporator of a heat pump. Therefore, the proposed system shown in Figure 2 (b) is not realistic and should be modified. The geothermal hot fluid flows 8cm under the pedestrian sidewalks only on snowy days. Otherwise, it is transported to a heat pump of each building directly so that the heat can be used more effectively.

5.2 Heat requirement for snow melting

Chapman and Katunich (1956) described required total heat flux for snow melting, q_0 (W/m^2) as the following equation,

$$q_0 = q_s + q_m + A_r(q_h + q_e) \tag{9}$$

where, q_s, q_m, A_r, q_h, q_e are sensible heat flux (W/m^2), latent heat flux (W/m^2), snow-free area ratio, convective and radiative heat flux from snow-free surface (W/m^2), and heat flux of evaporation (W/m^2), respectively. According to Chapman and Katunich (1956), when A_r is 1.0, the system melts snow rapidly enough that no accumulation of snow occurs. However, this condition requires the maximum energy supply. When A_r is 0, the surface is covered with snow of sufficient thickness. This condition is not desirable but could be tolerable when time for snow clearance is not critical. Chapman and Katunich (1956) mentioned that an intermediate value of A_r = 0.5 would be used for many non-critical situations. Thus, in this calculation, three required total heat fluxes for snow melting were calculated when A_r is 0, 0.5 and 1.0, and the required heat with A_r = 0.5 is considered to be the most important value in practice. The document prepared by ASHRAE (2011) is used to calculate each heat flux as shown below.

Sensible heat flux, q_s (W/m^2) is

$$q_s = \rho_{water} s\left[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)\right]/c_1 = 1000\times\frac{2.36}{3.6\times10^6}\left[2100\times(0+6.2) + 4290\times(0.56-0)\right] = 10.1 \tag{10}$$

where, ρ_{water}, s, $c_{p,water}$, $c_{p,water}$, t_a, t_f, t_s, c_1 are density of water (kg/m^3), snowfall rate water equivalent (mm/hr), specific heat of ice (J/kg-K), specific heat of water (J/kg-K), ambient temperature coincident with snowfall (°C), liquid film temperature (°C), melting temperature (°C), and conversion factor. We find that it snowed in Idaho Springs for 34 days in total in 2013. Therefore, ambient temperature coincident with snowfall is assumed -6.2°C, which is the average of ambient temperature of the 34 snowy days. Snowfall rate water equivalent is assumed 2.36 mm/hr as the average snowfall rate per day is 56.6 mm/day in Idaho Springs.

Latent heat flux, q_m (W/m^2) is

$$q_m = \rho_{water} s h_{if}/c_1 = 1000\times\frac{2.36}{3.6\times10^6}\times334000 = 219.0 \tag{11}$$

where, h_{if} is heat of fusion of snow (J/kg).

Convective and radiative heat flux from a snow-free surface, q_h (W/m^2) is

$$q_h = h_c(t_s - t_a) + \sigma\varepsilon_s\left(T_f^{\,4} - T_a^{\,4}\right) = 12.3\times(0.56+6.2) + \left(5.67\times10^{-8}\right)(0.9)\left(273.7^4 - 264.9^4\right) = 110.7 \tag{12}$$

$$h_c = 0.037\left(\frac{k_{air}}{L}\right)\mathrm{Re}_L^{\,0.8}\,\mathrm{Pr}^{1/3} = 0.037\left(\frac{k_{air}}{L}\right)\left(\frac{VL}{\nu_{air}}c_2\right)^{0.8}\mathrm{Pr}^{1/3} = 0.037\left(\frac{0.0235}{6.1}\right)\left(\frac{10.0\times2.0\times0.278}{1.3\times10^{-5}}\right)^{0.8}(0.7)^{1/3} = 12.3 \tag{13}$$

where, h_c, T_f, T_{MR}, σ, ε_s, k_{air}, L, Re_L, Pr, V, ν_{air}, c_2 are convection heat transfer coefficient for turbulent flow (W/m^2), liquid film temperature (K), mean radiant temperature of surroundings (K), Stefan-Boltzmann constant (=5.67$\times10^{-8}$ W/m^2-K^4), emmitance of surface (=0.7 assumed), thermal conductivity of air at t_a (W/m-K), characteristic length of slab in direction of wind (m), Reynolds number based on characteristic length L, and Prandtl number for air (=0.7), design wind speed near slab surface (=10km/hr assumed), kinematic viscosity of air (m^2/s), and conversion factor (=0.278), respectively.

Evaporation heat flux, q_e (W/m^2) is

$$q_e = \rho_{dryair} h_m\left(W_f - W_a\right)h_{fg} = 1.33\times0.0102\times(0.00393 - 0.00160)\times2499\times10^3 = 79.2 \tag{14}$$

$$h_m = \left(\frac{\mathrm{Pr}}{Sc}\right)^{2/3}\frac{h_c}{\rho_{dryair}c_{p,air}} = \left(\frac{0.7}{0.6}\right)^{2/3}\frac{12.3}{1.33\times1005} = 0.0102 \tag{15}$$

where, h_m, W_a, W_f, h_{fg}, $\rho_{dry\ air}$, Sc are mass transfer coefficient (m/s), humidity ratio of ambient air, humidity ratio of saturated air at film surface temperature, heat of vaporization (J/kg), density of dry air (kg/m^3), and Schmidt number (=0.6).

As a result, the required total heat flux for snow melting is 229.1, 324.0, and 418.9 W/m^2 when A_r is 0, 0.5, and 1.0, respectively. The area of the pedestrian sidewalks is 1,120m^2 (=280m$\times$2m$\times$2); therefore, the required total heat is 256.6, 362.9, and 469.2 kW when A_r is 0, 0.5, and 1.0.

Comparing the heat supply from the geothermal hot fluid (124.0 kW) with the required total heat shown above, it is found that the heat supply would be insufficient to melt snow even when A_r is 0. As shown in eq. (7), the heat supply depends on mass flow rate and the difference between inlet and outlet temperature. As it is difficult to make the temperature difference larger, the required heat would be supplemented by drilling roughly two additional geothermal wells to satisfy the required total heat with A_r = 0.5, 362.9 kW. Or the snow melting area should be limited to approximately one-third of the total area of the pedestrian sidewalks.

6. CONCLUSION

In this study, the authors proposed and designed a system which would improve heat pump efficiency of buildings and melt snow in the historic downtown in Idaho Springs, Colorado, using an abandoned mine and geothermal resources. We investigated the feasibility of the proposed system by conducting temperature measurements in the Edgar Mine and heat transfer analyses of the geothermal hot fluid. As a result, the following is discussed and concluded.

The results of temperature measurements showed that the rock surface temperature was approximately 12°C at maximum in the Edgar Mine. It can be said that the mine is relatively cold and suitable for cold thermal energy storage. As the Army Tunnel was wetter and colder than the Miami Tunnel when the measurements were conducted, the Army Tunnel is more suitable to store cold groundwater from winter to summer. Unlike the Miami Tunnel, however, the rock surface temperature in the Army Tunnel was not constant because of its thinner cover. Therefore, temperature measurement in the Army Tunnel should be continued throughout a year to design a cold thermal storage system in the Edgar Mine in more detail.

The heat transfer analyses showed that the temperature of the geothermal hot fluid decreases from 35°C to 28.6°C when the thickness of a pipe was assumed to be 5cm while it is transported from the hot spring to the historic downtown. In order to minimize this temperature loss, the thickness of a pipe should be much larger than 5cm. However, as there is no simply linear correlation between the pipe thickness and the temperature loss, the pipe thickness has to be chosen appropriately considering the cost and ease of construction work.

The heat balance analyses showed that the proposed system would not melt snow-covered pedestrian sidewalks effectively, because the heat supply was smaller than the heat requirement. In order to satisfy the heat requirement with $A_r = 0.5$, the heat supply has to be increased approximately three times, which would be achieved by drilling additional geothermal wells. However, this should be considered carefully in terms of the effect of the pre-existing geothermal well, the cost, and so on.

As it is concluded above, the proposed system would not work perfectly without additional data and analysis for summer and supplementary heat for winter. So far in the town, however, abandoned mines have been ignored, and the geothermal hot fluid has been thrown away after it is used for bathing and pool. Similarly, it is considered that many communities in the world do not fully utilize locally available thermal resources. We hope this case study can serve as an example of “local consumption of locally available energy”. If communities start utilizing economically viable local energy in a socially and environmentally responsible manner, it will contribute to sustainable development for mankind.

REFERENCES

AccuWeather.com: Local weather record of Idaho Springs, CO, http://www.accuweather.com/en/us/idaho-springs-co/80452/december-weather/337419?monyr=12/1/2013&view=table, accessed Jan. 1, 2014.

Adlam, T.N.: Snow Melting, The Industrial Press, (1950).

ASHRAE: Snow Melting and Freeze Protection, *2011 ASHRAE Handbook – HVAC Applications*, **51**, (2011), 51.1-51.20.

Bergman, T.L., Lavine, A.S., Incropera, F.P., and Dewitt, D.P.: Fundamentals of heat and mass transfer (seventh edition), Willey, (2011).

Chapman, W.P. and Katunich, S.: Heat Requirements of Snow Melting Systems, *ASHRAE Transactions*, **62**, (1956), 359-372.

Kasuda, T. and Archenbach, P.R. :Earth Temperature and Thermal Diffusivity at Selected Staions in the United States, *ASHRAE Transactions*, **71**, Part 1, (1965).

Lund, J. W.: Reconstruction of a Pavement Geothermal Deicing System, *Geo-Heat Center Quarterly Bulletin*, Vol.20, No.1, (1999), 14-17.

Pingjia, L. and Ning, C.: Abandoned Coal Mine Tunnels: Future Heating/power Supply Centers, *Mining Science and Technology (China)*, **21**, (2011), 637-640.

Repplier, F.N., Zacharakis, T.G., and Ringrose, C.D.: Geothermal Resource Assessment of Idaho Springs, Colorado, Colorado Geological Survey, (1982).

Rodriguez, R. and Diaz, M.B.: Analysis of the Utilization of Mine Galleries as Geothermal Heat Exchangers by Means a Semi-empirical Prediction Method, *Renewable Energy*, **34**, (2009), 1716-1725.

Sato, M. and Sekioka, M.: Geothermal Snow Melting at Sapporo, Japan, *Geo-Heat Center Quarterly Bulletin*, Vol.4, No.3, (1979), 16-18.

Shiba, Y.: Ground-Source Heat Pump System, *Building Utilities and Piping Work*, **2**, (2008), 20-24 (in Japanese).

Yamashita, M., Majima, T., Tsujita, M., and Matsuyama, K.: Geothermal Development in Hachijojima, *Proceedings*, World Geothermal Congress 2000, Kyusyu-Tohoku, Japan (2000).