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GEOTHERMAL DEICING IN A MINE TUNNEL

Aniko Toth

University of Miskolc
Miskolc-Egyetemvaros, 3515 Hungary
e-mail: toth.aniko@uni-miskolc.hu

ABSTRACT

The floor of the entrance tunnel to an underground waste deposit system in Hungary is exposed to frost and icing in winter. This is rather dangerous for the heavy vehicle traffic. To avoid this danger, a floor deicing system was installed. This consists of a heating grid system placed in the floor of the tunnel entrance section. Initially, a fuel oil system was utilized to heat the incoming air. More recently geothermal heat pumps were recommended for the expansion of the facility. In this case geothermal energy is utilized indirectly by two different systems. The first is air-water heat pumps utilizing the heat content of the warmed up air as it flows out of the mine tunnel. The other source is the heat content of the drained water from the deep part of the mine. The benefit of this system is multiplied: decreasing of the thermal power as compared to the original fuel oil heating system, eliminating of the use of fuel oil, and decreasing the CO_2 emissions.

BACKROUND

In the southwestern part of Hungary in the Bátaapáti region a small-to-medium-level underground radioactive waste deposit system was built. The storage space is connected by two 1800 m-long mine tunnels. The storage area was constructed through these tunnels, and afterwards they were used for the operational traffic and ventilation. If the outside temperature is less than -5C, then to improve the workplace climate and prevent the icing of the entrance section to the mine tunnel, it is necessary to warm the intake air to the tunnels. The original design included the use of traditional oil burners to warm the air. During the construction period 80 m^3/s of air-flow was used. This was the maximum air demand. During normal operations 25 m^3/s air-flow is utilized. Regardless of the season these airflow had to be heated to between +2^{o}C and +5^{o}C. In case of an extreme weather condition, (for example -18^{o}C), the air temperature must be increased to between +20^{o}C and +22^{o}C. In this latter case, 2,316kW of heating capacity is required. This requires 247 l/h of fuel for the oil burners. The next phase of the development of the waste deposit system would have required the installation of two more oil burners. Instead of this expensive solution, and to decrease of the huge CO_2 emission from the oil burners, I recommended a geothermal solution for the floor and the roof heating. Deicing the floor of the tunnel and avoid the formation of icicle on the roof.

USING GEOTHERMAL ENERGY

Tempering the air of the mine tunnels is necessary on the one hand to ensure that the facility's climate is comfortable for the workers, and on the other hand deicing the floor of the entrance section. Geothermal energy has always had a dominant role in the climate of underground facilities and mine tunnels. The wall temperature of the mine tunnel is about +17^o to +18^{o}C, which is much higher than the inflowing air temperature in winter. The surface of the tunnel walls is a very large heat transfer area. The air intake tunnel walls with the floor and the roof constitute 36,000 m^2 of surface area over the length of 1,800 m. The heat flow is constant over this major surface and thus, heats the air flow in the mine tunnel. This can be determined by a simple calculation.

Heating requirement for the icing intake tunnel

It is enough to heat the first 300 m section of the intake-air tunnels just where the icing appears. The heating system uses hot water and glycol solution being circulated in pipes loops below the floor and on the roof of the mine tunnel. Similar installation like sidewalk, roadway, and bridge deicing systems have been demonstrated in several countries, including Argentina, Japan and the United States. In our case the heating requirement can be met by two sources. The first is air-water heat pumps utilizing the heat content of the warmed up air as it flows out of the mine tunnel. The other source is the heat content of the drained water from the deep part of the mine.

Chapman (1952) derives and explains equations for the heating requirement of a snow-melting system. Chapman and Katunich (1956) derive the general equation for the required heat output (q) in W/m^2. We can use it for the tunnel floor.

$$q_o = q_s + q_m + A(q_e + q_h) \quad (1)$$

where

q_s = sensible heat transferred to the ice (W/m^2),
q_m = heat of fusion (W/m^2),
A = ratio of snow-free area to total area (dimensionless),
q_e = heat of evaporation (W/m^2),
q_h = heat transfer by convection (W/m^2).

The sensible heat q_s to bring the ice to 0 °C (32 °F) is:

$$q_s = s \cdot h \cdot \rho_i \qquad (2)$$

where

s = rate of taken in snow layer on the floor (0.0025 m/day)
ρ = density of ice (917 kg/m^3),
c_p = specific heat of snow (J/kg °C)
h = enthalpy of fusion for water (J/kg),
c_1 = conversion factor (86,400 s).

It can be assumed that the ice and snow carried by vehicles immediately starts to melt, resulting that it does not cool below 0°C. Thus, in the q_s member can be ignored.
Suppose that the thickness of snow cover entered into the tunnel is 2.5mm by day. The heat of fusion q_m to melt the snow is:

$$q_m = \frac{s}{c_1} \cdot c_p \cdot \rho = 0.8835 \frac{W}{m^2} \qquad (3)$$

The heat of evaporation of the molten snow q_e:

$$q_e = \frac{s}{c_1} \cdot c_m \cdot \rho_w = 7.238 \frac{W}{m^2} \qquad (4)$$

where

ρ_w = density of water (1000 kg/m^3),
c_m = heat of evaporation (2,512 kJ/kg)

The heat transfer q_h between the water film on the floor and the intake air. We can calculate the heat transfer coefficient by turbulent flow. In this case the heat transfer coefficient depends on the Reynolds number.

$$q_h = h \cdot (T_w - T_1) = 39.24 \frac{W}{m^2} \qquad (5)$$

where

T_w = water film temperature (°C), usually taken as 1 °C (33 °F)
T_1 = intake air temperature at the entrance cross section in winter (-5°C)

Summing the fluxes, give:
q_o=47.35 W/m^2. (6)

The heated area in the length of 300 m is 1,800 m^2, thus the needed thermal power on the floor of the tunnel is:

$$Q_f = A \cdot q_o = 85.23\,kW \qquad (7)$$

where

Q_f = thermal power for the floor heating (kW),

In winter time, where some water is appear from the roof of the mine tunnel the icing is from occurs as icicle. It is appear only the first 300m part of the tunnel. If we can warm the roof surface over the freezing point (0 °C) couldn't develop icicle, and the water drops could disperged in the intake air flow. If we heat the 6m arch of the tunnel roof, in the length of 300m get 1,800 m^2 areas. Thus the needed thermal power on the roof is:

$$Q_r = h \cdot A \cdot \Delta T = 70.63\,kW \qquad (8)$$

where

ΔT = 6 °C temperature difference between the freezing point and the intake air (1-(-5)) °C,
Q_r = thermal power for the roof heating (kW).

The floor and the roof heating demand together is

$$Q_T = Q_f + Q_r = 85.23 + 70.63 = 155.86kW \qquad (9)$$

where

Q_T = total thermal power demand (kW).

Geothermal sources for Heating the mine tunnel

Enthalpy of the warmed up air

The maximum inflowing air is 80 m^3/s which occurred during construction. In this case the cross-sectional average velocity is:

$$c = \frac{Q}{A} = \frac{80\frac{m^3}{s}}{30\frac{m}{s}} = 2.67\frac{m^2}{s} \qquad (10)$$

where

c = cross-sectional average velocity (m/s)
Q = maximum inflowing air (m^3/s)
A = cross-section of the tunnel (m^2)

The hydraulic radius of the tunnel:

$$R_H = \frac{A}{K} = \frac{30.3}{20.1} = 1.51\,m \qquad (11)$$

where

K = hydraulically active perimeter (Bobok, 1992)

The Reynolds number

$$Re = \frac{c \cdot 4R_H}{\nu} = \frac{2.67\frac{m}{s} 4 \cdot 1.51m}{10^{-5}\frac{m^2}{s}} = 1612680 \qquad (12)$$

The Prandtl number:

$$Pr = \frac{\rho \nu c_p}{k} = 0.541 \qquad (13)$$

Where

ρ = air density (1.292kg/m^3)
ν = kinematics' viscosity coefficient (0.024m^2/s)
c_p = specific heat (1005J/kg°C)

k = thermal conductivity (0.024W/m°C)

The Nusselt number can be calculated from the Reynolds number and the Prandtl number.

$$Nu = 0.015 \cdot Re^{0.83} \cdot Pr^{0.42} = 1645.5 \quad (14)$$

The heat transfer coefficient on the wall:

$$h = \frac{Nu \cdot k}{4R_H} = 6.54 \frac{W}{m^2\ {}^oC} \quad (15)$$

Bobok(1992) derives and explains equations for the temperature distribution along the length.

$$T = T_{wall} - (T_{wall} - T_1) e^{-\frac{4R_H \pi L h}{\dot{m} c_p}} \quad (16)$$

where

L = length of the air in the tunnel (m),
T = warmed up air temperature after the length L (°C),
T_{wall} = tunnel wall temperature (°C),
T_1 = outside air temperature (°C),
$\dot{m}$ = mass flow rate of air (kg/s).

If the length of the tunnel is 1,800m and the outside temperature is -5 °C, the air temperature at the end of the intake tunnel can be calculated.

$$T_L = 18 - (18 - (-5)) \cdot e^{-\frac{4 \cdot 1.51 \cdot \pi \cdot 1{,}800 \cdot 6.54}{103 \cdot 1005}} = 15.3^o C \quad (17)$$

This calculated temperature was checked by the measured temperature at the end of the intake tunnel, when the outside temperature was -5°C. The result was very close. The measured temperature was 16 °C**.** In an average winter day the air temperature after passing through the intake tunnel is warmed from -5 °C to +15.3 °C. It means: ΔT= 20.3 °C.

During the construction period 80 m^3/s (103 kg/s) of air-flow is used. This is the maximum air demand.

In this case the maximum thermal power $\dot{Q}_{max}$ is:

$$\dot{Q}_{max\ power} = \dot{m} c_p (T_L - T_1) = 2{,}101\ kW \quad (18)$$

It can be seen the thermal power from the tunnel wall is almost as much as the thermal power of traditional oil burner at 2,310 kW at the maximum air demand.
In order to heat the mine tunnel, it is not possible to use all of the maximum heat power. It can be exploited the enthalpy difference between the inlet and outlet air of the heat pump, belonging to the temperature drop: ΔT=15.3-5=11.3 °C.
In this case the useful thermal power from the air is:

$$\dot{Q}_{airmax} = \dot{m} c_p (T_L - T_2) = 1138.7\ kW \quad (19)$$

where

T_2 = outlet air temperature (5 °C),

During normal operations 25 m^3/s (32.3kg/s of) air-flow is utilized.

In this case the thermal power $\dot{Q}_n$ is:

$$\dot{Q}_n = \dot{m} c_p (T_L - T_1) = 652.8\ kW \quad (20)$$

The useful power in the normal operation is:

$$\dot{Q}_{airmin} = \dot{m} c_p (T_L - T_2) = 357\ kW \quad (21)$$

Enthalpy of the collected mine water

Every day in the mine tunnel about 500 m^3/day of water is produced, which means $\dot{m} = 5.79 \frac{kg}{s}$ mass flow rate. After a long term test the temperature of this mine water is about 15 °C. This temperature doesn't depend on the season, as it is the same in winter or summer. At normal operations this water is collected in a sump under the surface in the mine. From time to time this water is pumped to a creek on the surface. Since the flow rate of this inflowing water is steady, and its temperature is constant, we can use its thermal power as a natural geothermal source. The heat power from the mine water is then:

$$Q_w = \dot{m} c_w (T_w - T_2) = 242.4\ kW \quad (22)$$

where

$\dot{m}$ = mass flow rate of the collected mine water (57.9 kg/s),
c_w = specific heat of water (4.187kJ/kg °C),
T_w = mine water temperature (15.3 °C),
T_2 = outlet water temperature (5 °C).

It can be seen that the heating demand is 156kW. The heat supply from the air is 357kW and from the mine water is 242kW. Thus either heat source is enough to satisfy the heating demand of the mine tunnel deicing.

Loop system for the mine tunnel

To collect the mine water a 100 mm diameter pipe is used. Every day about 500m^3/day (0.00578 m^3/s) is produced in the mine tunnel. The cross sectional average velocity in the pipe is:

$$v = \frac{4Q}{D^2 \pi} = \frac{4 \cdot 0.00579 \frac{m^3}{s}}{0.1^2 \cdot \pi\, m^2} = 0.737 \frac{m}{s} \quad (23)$$

$$Re = \frac{v \cdot D}{\nu} = \frac{0.737 \frac{m}{s} \cdot 0.1\, m}{10^{-6} \frac{m^3}{s}} = 73700 \quad (24)$$

The Reynolds number is high and in this case the flow is turbulent.

A heating loop system is designed on the floor and on the roof for the first 300 m section in the mine tunnel. Present practice is to use plastic pipe, with the typical being polyethylene according to Lund (2000). The relative roughness (the ratio between pipe diameter and absolute roughness) of the PE pipe is D/k = 10,000. These Reynolds number and relative roughness values determine a hydraulically smooth behavior of the flow. In this case the friction factor (Karman 1930) is

$$\lambda = \frac{1}{\left(2\lg \frac{Re\sqrt{\lambda}}{2,51}\right)^2} \qquad (25)$$

From this implicit form by iteration we get λ = 0.01919.

The total pressure loss is the sum of the pressure loss from the tube and the pressure losses from the resistance of the 1500 elbows by Varga (1970). The tube spacing is 0.4 m in the 750 loops and along the 300 m length. The procedure is similar to running radiant heat in a building's floor slab.

$$\Delta p' = \lambda \frac{L}{D}\rho\frac{v^2}{2} + \Sigma\xi_k \rho \frac{v^2}{2} \qquad (26)$$

where

- λ = friction factor (0.01919 dimension less),
- L = total length of the tube (15000m),
- ρ = water density (1000 kg/m^3),
- v = cross sectional average velocity (0.732 m/s),
- D = pipe diameter (0.1 m),
- ξ_k = 0.3 elbow loss coefficient.

$$\Delta p' = 903833 \frac{N}{m^2} \qquad (27)$$

Which is about 9 bar.

The temperature distribution along the length is

$$T = T_0 + (T_1 - T_0)e^{-\frac{4UL}{\rho c v D}} \qquad (28)$$

where

- T_0 = wall temperature of the mine tunnel (^{o}C),
- T_1 = intake water temperature in the tube (^{o}C),
- U = overall heat transfer coefficient (W/m^2 ^{o}C),
- c_w = specific heat of water (kJ/kg ^{o}C).

We can calculate the overall heat transfer coefficient.

$$\frac{1}{U} = \frac{1}{h} + \frac{R_{in}}{k_{tube}}\ln\frac{R_{out}}{R_{in}} + \frac{R_{in}}{k_{cement}}\ln\Phi \qquad (29)$$

where

- h = heat transfer coefficient between the flowing water and the tube wall (W/m^2 ^{o}C),
- R_{in} = internal diameter of the tube (m),
- R_{out} = external diameter of the tube (M),
- k = thermal conductivity of the PE tube (W/m ^{o}C),
- ϕ = shape coefficient.

The shape coefficient can be used for consideration the asymmetric heat flow pattern around the heating pipe (Bobok, 1993).

$$Nu = 0,015 \cdot Re^{0.83} \cdot Pr^{0.42} = 372.4 \qquad (30)$$

$$h = \frac{Nu \cdot k}{D} \qquad (31)$$

$$h = 2234 \text{ W/m}^{2o}\text{C}, \quad \frac{1}{h} = 0,00045 \frac{m^{2o}C}{W} \qquad (32)$$

$$\Phi = \left[2\left(\frac{x}{R_{out}}\right)^2 - 1 - 2\frac{x}{R_{out}}\sqrt{\left(\frac{x}{R_{out}}\right)^2 - 1}\right]^{\frac{1}{2}} \qquad (33)$$

where

x = distance between the floor surface and the centerline of the tube (m).

$$\Phi = 0,2679 \qquad (34)$$

Finally the overall heat transfer coefficient is

$$U = \frac{1}{0.0045 + 0.00455 + 0.07901} = 11.90 \frac{W}{m^{2o}C} \qquad (35)$$

If the temperature of the wall tunnel is T_{wall}=2^{o}C and the outlet temperature of the heat pump is T_{hp}=24 ^{o}C, then the outlet water temperature from the tube is

$$T_2 = T_{wall} + (T_{hp} - T_{wall})e^{-\frac{4 \cdot U \cdot L}{\rho \cdot c \cdot v \cdot D}} \qquad (36)$$

$$T_2 = 2 + (24-2)e^{-\frac{4 \cdot 11.90 \cdot 15000}{1000 \cdot 4187 \cdot 0.737 \cdot 0,1}} = 4.175\ ^oC \qquad (37)$$

The thermal power from the heating loop is

$$\dot{Q} = \dot{m} \cdot c(T_1 - T_2) \qquad (38)$$

$$\dot{Q} = 5.79 \frac{kg}{s} \cdot 4.187 \frac{KJ}{kg^oC} \cdot (24 - 4.18) = 488 \text{ kW} \qquad (39)$$

CONCLUSION

The tunnel floor of the entrance section of an underground waste deposit system in Hungary is exposed to frost and icing in winter. This is rather dangerous for the heavy vehicle traffic. To avoid this danger, an ins-situ floor deicing heating loop system is designed. This floor heating system is much more effective than the originally designed intake air heating by traditional oil burners. There are two heat sources of the geothermal energy. One of them is the heat content of the surrounding rock, which warms up the ventilated air. The other is the heat content of the collected mine water. The temperature of the mine water and the circulated air is the same. It is about 15 ^{o}C. The floor heating system from the warmed intake air is a two-stage geothermal direct use. The first stage is the geothermal heating of the intake air by the rock through the huge heat transfer surface of the tunnel walls. The second stage is an air-water heat pump exploiting the enthalpy of the circulated air and transfers it to the heating loop system. Using the thermal power of the mine water makes necessary to apply a water-water heat pump. Both thermal sources are enough to satisfy the deicing heat demand. In this case the geothermal potential of the mine tunnel is proven greater than the deicing heat demand. The benefits of the geothermal solution in spite of the oil burners are lower heating power, elimination of the use of fuel oil, and decreasing the CO_2 emissions radically.

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