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Evaluation of the Potential Use of Geothermal Heat Exchangers in the CEVA Tunneling Project

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ABSTRACT

The CEVA railway connection is planed in Geneva, Switzerland. Along the pathway, houses, schools and commercial centers will also be built and integrated into a general energy scheme and energy supply. Since considerable parts of railway lines are running in tunnels, the utilization of geothermal energy can be of major interest along sections near well-developed infrastructure. As such heating of buildings in winter and cooling in summer using a heat pump could be performed. The objective of this concept study is to quantify the energy balance obtained from the use of absorber elements integrated into the lateral walls and bottom slab of the CEVA tunnel. The potential of the produced power has been calculated for different tunnel sections and different utilization scenarios. At first, a one-dimensional analytical approach of the system is presented for sensitivity analyses of various parameters variations. Further on, the temperature field is computed in 2D Finite Element models applying the geometry of typical 100 m long tunnel section and using the numerical code FRACTure. Different scenarios for energy utilization and installation variants have been considered. Typical usage of the system (mean temperature of the energy piles is -1°C in winter and 30°C in summer, for combined heating and cooling use) result in total annual energy of 560 MWh for heating and 480 MWh for cooling. The results strongly depend on the temperature level in the tunnel, which in turn depends on the railway transit and the air condition of the trains. Optimum results are obtained for balanced heat load profiles.

1. INTRODUCTION

The construction of the CEVA (Cornavin-Eaux-Vives-Annemasse) train connection should begin in Geneva, Switzerland in the next months. It will ensure a direct connection between Geneva main station and Annemasse, France. As the pathway of the train line takes place in an urban area, most of the line will be realized in tunnels. The project is part of a policy that aims at reducing the car traffic and promoting clean transportation and renewable energy in the town of Geneva. To that purpose, it was decided to study the feasibility of integrating heat exchangers in the tunnel walls and to quantify the energy that could be extracted using such systems. The present paper offers an overview on the works conducted to estimate the geothermal potential of a tunnel section "gare des Eaux-Vives".

The idea is to use geothermal absorber elements, i.e. geothermal heat exchangers integrated in energy piles or energy textiles (geomembrane). Currently, the installation of the energy textiles are investigated that are placed between sealing sheeting at the outer shotcreting and the inner shell of the tunnel construction. The technology has been strongly developed by the Institute for Soil Mechanics and geotechnical engineering at the Vienna University of Technology (Adam and Markiewicz, 2003). Within the CEVA construction the absorber elements should be integrated in the lateral walls and optionally in the bottom slab of the tunnel. In order to quantify the energy that could be produced from such systems, a 1D sensitivity analysis was first realized in order to identify the key parameters that influence the performance of the system. Then, 2D finite elements models are built to simulate the behavior of the tunnel section and of the ground. Finally, the total energy that could be extracted is integrated over the tunnel section.

2. PREREQUISITES: TEMPERATURES AND HEAT TRANSFER COEFFICIENT

2.1 Ground and Tunnel Temperatures

The ground surface temperature is assumed to be constant over the year in the computations (i.e. no seasonal variations are taken in account). The average air temperature in Geneva over the 30 last years is reported to 10.1°C (Meteornorm, 2005). After an altitude correction (Signorelli, 2004), the ground surface temperature average could be estimated to 11.8°C. In order to take in account the urban environment of the tunnel, an average ground surface temperature of 13°C is taken in account into the computations.

The air temperature in a tunnel was studied in Stuttgart (Schlosser et al., 2007). In the following, a tunnel temperature varying between 6°C in winter and 20°C in summer (thus centered on 13°C) will be assumed, with monthly variations. This is reasonable, as the studied section of the tunnel is located at 500 m of the portal of the tunnel. These values are in agreement with previous studies.

2.2 Heat Flow

The heat flow in Geneva can be estimated to vary between 60 $mW \cdot m^{-2}$ and 70 $mW \cdot m^{-2}$ (Medici and Rybach, 2002). These values are representative of the heat flow values met in Switzerland. The heat flow is not expected to play an important role in the following calculations.

2.3 Heat Transfer Coefficient

The boundary condition between the air of the tunnel and the concrete of the tunnel wall is mixed:

$$q = -\lambda \frac{\partial T}{\partial x} = \alpha \cdot (T_{Wall} - T_{air})$$

with

q	Heat flow	$[W \cdot m^{-2}]$
α	Heat transfer coefficient	$[W \cdot m^{-2} \cdot K^{-1}]$
λ	Thermal conductivity of the walls	$[W \cdot m^{-1} \cdot K^{-1}]$

Different estimations of the value of this heat transfer coefficient could be found in the literature. The value of 8 $W \cdot m^{-2} \cdot K^{-1}$ is advanced by Schlosser et al. (2007) for a contact air/concrete. In a tunnel a clear relationship could be demonstrated between the values of the heat transfer coefficient and the wind speed in the tunnel. The dependency between these two parameters could be modeled with an empirical law (Oberhauser, 2006):

$$\alpha = 6.2 + 4.2v$$

with:

v wind speed [$m \cdot s^{-1}$]

In the following, a heat transfer coefficient value of 10 W $m^{-2} \cdot K^{-1}$ is assumed, corresponding to an average wind in the tunnel of about 1 m s^{-1}. A sensitivity analysis on this parameter showed that this value could be considered as critical: a greater value of the heat transfer coefficient shows very similar energetic contribution of the tunnel air to the system.

In the 2D numerical models, the heat transfer coefficient is treated by adding a supplementary (dummy) material layer on the tunnel wall in order to simulate the heat transfer between the air and the concrete wall.

2.4 Utilization Scenario

In the original report, several utilization scenarios are investigated, implying different temperature distributions in the heat exchanger located in the tunnel wall. It is here proposed to expose the results obtained with the scenario showed in Figure 1, initially suggested by ENERCRET (Wilhelm, 2006).

3. ONE DIMENSIONAL SENSITIVITY ANALYSIS

3.1 Equations

The problem in 1D (ignoring the contribution of the tunnel air to the system) corresponds to the diffusion equation:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}$$

with

$$\kappa = \frac{\lambda}{\rho c_p}$$

and

ρ	Ground density	[$kg \cdot m^{-3}$]
c_p	Ground heat capacity	[$J \cdot kg^{-1} \cdot K^{-1}$]
λ	Thermal conductivity	[$W \cdot m^{-1} \cdot K^{-1}$]
κ	Thermal diffusivity	[$m^2 \cdot s^{-1}$]

3.2 Solution

The solution of the diffusion equation can be written as:

$$q = -\lambda \frac{\partial T}{\partial x} = -\lambda \cdot (T_{abs} - T_{gr}) \frac{1}{\sqrt{\pi \kappa \cdot t}}$$

with

q	Heat flow on tunnel wall	[$W \cdot m^{-2}$]
T_{abs}	Absorber temperature	[°C]
T_{gr}	Ground temperature	[°C]
t	Time	[s]

3.3 Sensitivity

Thus, as one could expect, these results show that the temperature difference between the ground and the heat exchanger is the most important factor (see Figure 2). The thermal conductivity also play a quite important role in the energy quantification, as it is expected to show relatively heterogeneous values in the area (Morin and DERIAZ S.A., 2008).

4. TWO DIMENSIONAL NUMERICAL MODELS

4.1 Concept

The models are constituted of a tunnel section. Because of symmetry considerations, only one half of the section is modeled, as it can be seen on Figure 3. The different boundary conditions are indicated on the figure.

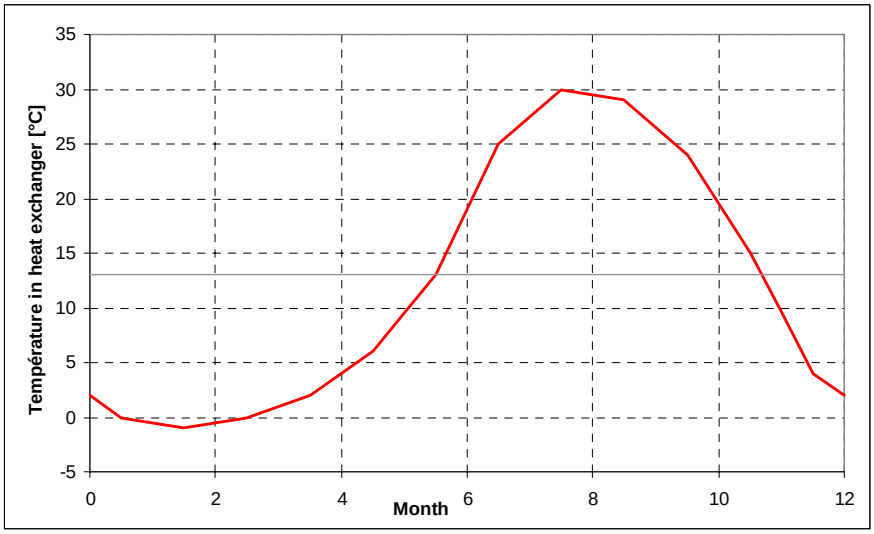


Figure 1: Monthly temperature variations assumed in the heat exchanger for the calculations.

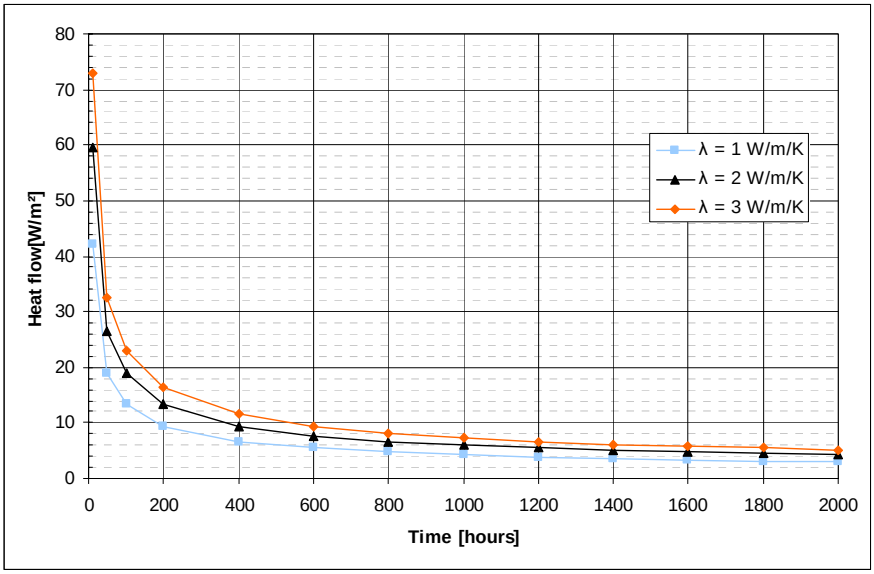


Figure 2: influence of the thermal conductivity of the ground λ on the thermal heat flow on the tunnel wall.

4.2 The Mesh

The meshing is based on geotechnical sections provided by DERIAZ SA (2008). The work was done using intern meshing capabilities from GEOWATT AG. It is constituted of over 15'000 elements (triangles and squares). The model extent is important, in order to avoid the influence of the boundary conditions: 500 m in the lateral direction and 100 m depth (see detail of the mesh on Figure 4).

4.3 Boundary and Initial Conditions

The following boundary conditions are applied to the model (see figure 2):

- A Dirichlet boundary condition at the surface: 13°C
- A Neumann boundary condition at the base of the model: q= 60 mW·m^{-2}
- A Dirichlet boundary condition in the tunnel in order to force the tunnel temperature, varying between 6°C and 20°C.
- A Dirichlet boundary condition in the heat exchangers in the tunnel wall

The initial state of the model is computed without the boundary condition in the heat exchanger. The tunnel lightly disturbs the initial ground temperature (Figure 5).

4.4 Parameters

The thermal conductivities of the material constituting the underground vary between 1.57 W·m^{-1}·K^{-1} and 3 W·m^{-1}·K^{-1} (heat capacity average value: 2.3·10^{6} J·kg^{-1}·K^{-1}). The thermal conductivity of the concrete is taken to 1.8 W·m^{-1}·K^{-1}, and its heat capacity is similar to the undergrounds. Thermal transport within the heat exchanger and of the tunnel air is assumed to be that effective that it does not represent any thermal resistance. By this a homogeneous temperature distribution in the tunnel and in the heat exchangers is obtained. The thermal conductivity of the heat transfer layer was computed to 0.2 W·m^{-1}·K^{-1}.

5. RESULTS

5.1 Temperature Distribution in the Underground

The temperature computed perpendicular to the tunnel (see figure 6) shows up different interesting points:

- The steady-state regime is reached from the second year of utilization, and
- The thermal disturbance due to the heat exchanger is limited to maximum 15 m from the tunnel.

The underground around the tunnel plays the role of a heat (or cold) register as it can be observed on the Figure 7; for example during August, the tunnel is used in order to produce cold, thus warming the underground. One sees on the temperature distribution that, despite a temperature increase near the tunnel wall, the underground is still cold because of the cooling down during the previous winter.

5.2 Computed Thermal Energy

The energy balance is computed according to 3 main heat flows:

- Flux 1: horizontal, from the underground to the tunnel wall;
- Flux 2: horizontal, from the underground to the tunnel wall, under the tunnel;
- Flux 3: horizontal, from the air of the tunnel to the tunnel wall.

A comparison with the 1D analytical solution (i.e. flux 1, computed with a constant temperature in the heat exchanger) showed that, after 2000 hours, the value of the flux 1 computed with the model is from 8.5 W·m^{-2}, whereas the analytical solution results in a value of 6 W·m^{-2}. The two solutions are comparable. The differences obtained come from the 2D solution obtained with the numerical models; the heat fluxes are not perfectly horizontal between the underground and the wall. Indeed, part of the energy captured by the tunnel wall come from deeper underground, what is not taken in account in the 1D solution.

In case of using the scenario with variable temperature in the heat exchangers, the monthly energy that could be taken from the heat exchangers structures is represented on the Figure 8.

During one year, the geothermal exploitation of two 14 m depth tunnel walls over 100 m tunnel bring 290 MWh of warmth and 260 MWh of cold. These results can be multiplied by a factor 2 using he bottom slab of the tunnel.

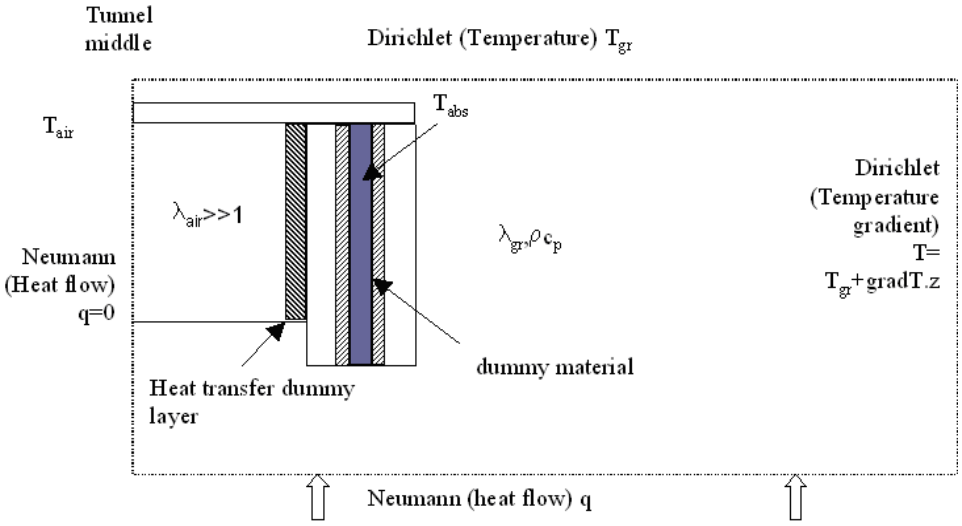


Figure 3: Concept of the numerical bidimensional models. The heat exchanger is located at the center of the wall.

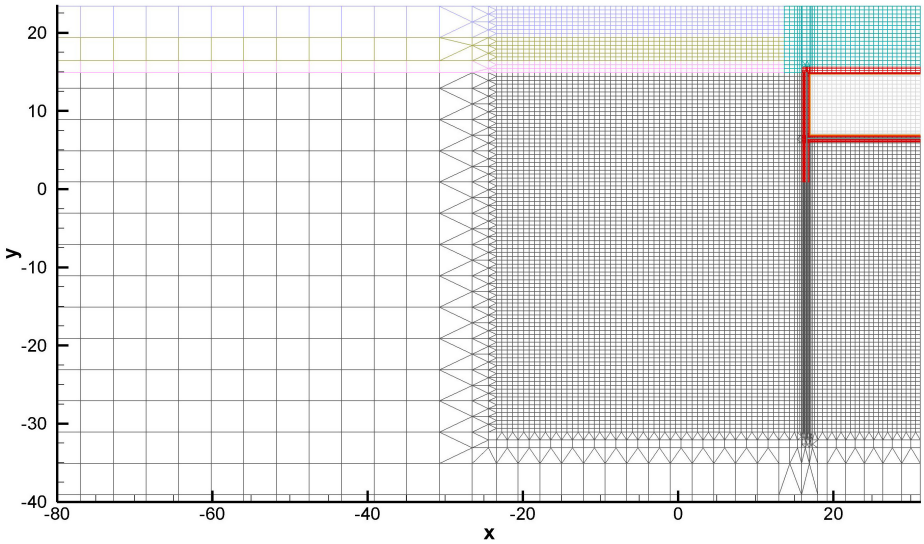


Figure 4: Mesh of the model (detail); the air, the tunnel wall and the ground are meshed.

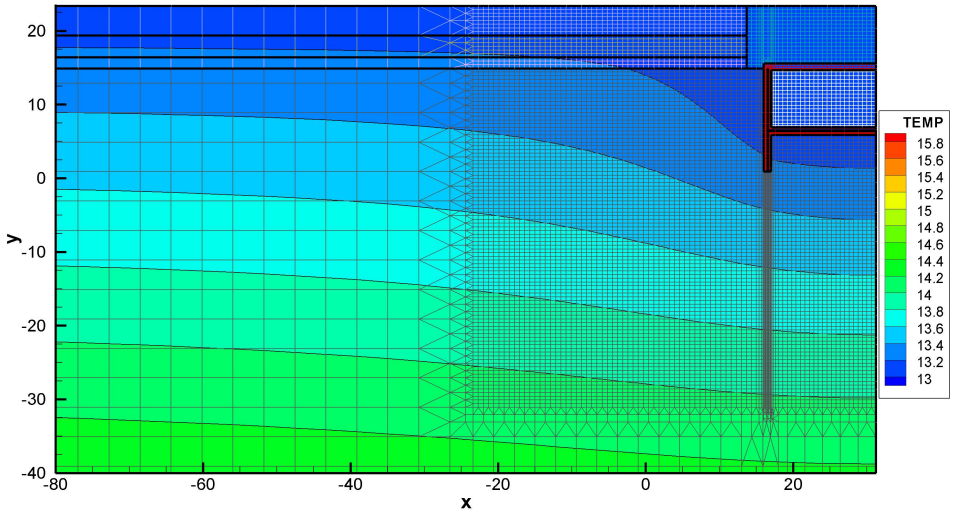


Figure 5: Initial temperature distribution in the model.

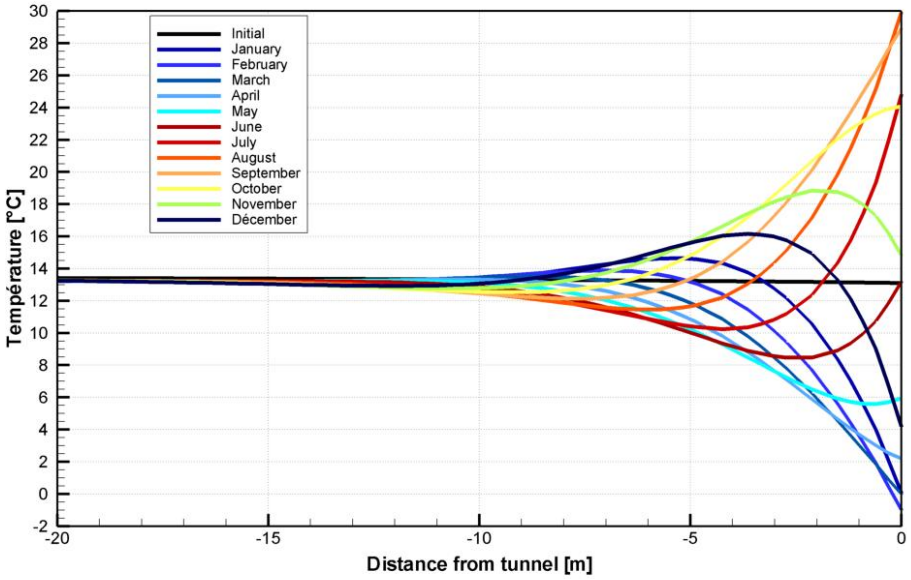


Figure 6: Temperature distribution perpendicular to the tunnel.

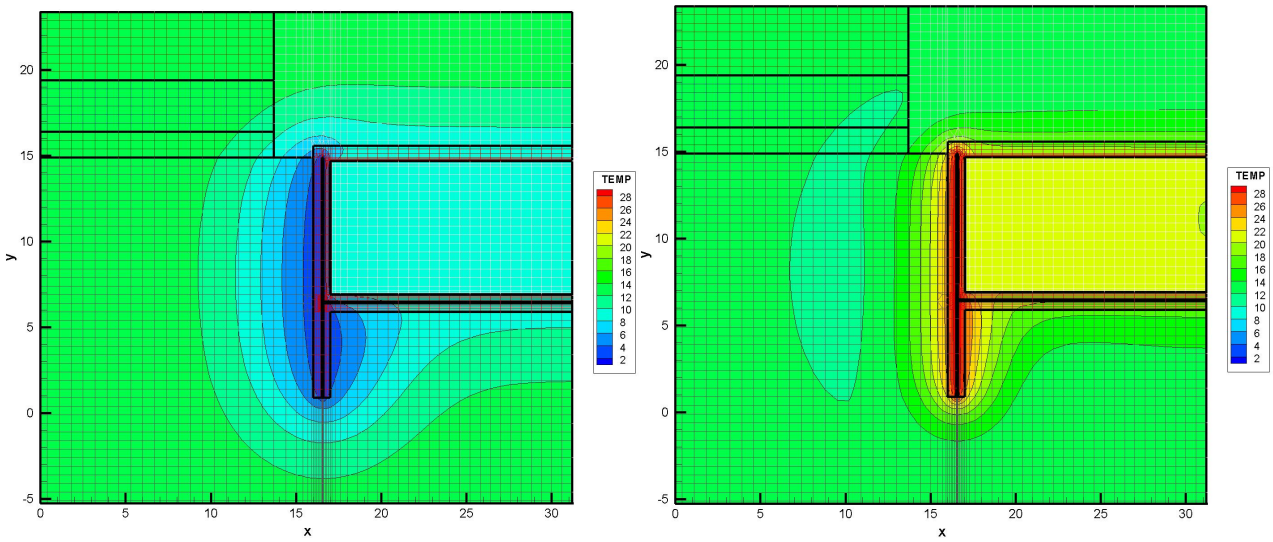


Figure 7: Temperature distribution in the underground in April (letf) and August (right).

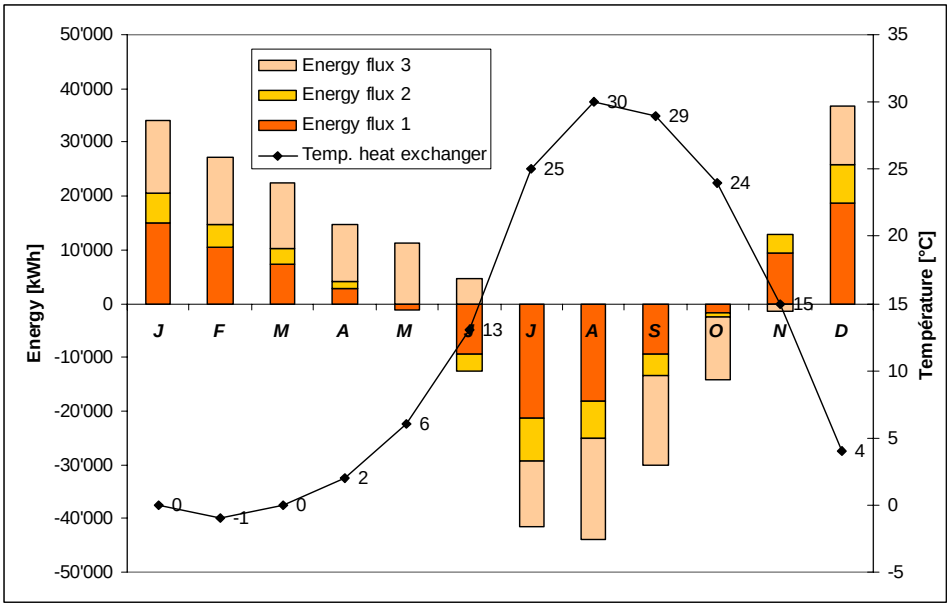


Figure 8: Geothermal energy computed during the 10th year of utilization. Results are given for one wall, and integrated over the 14 m depth of the wall and over 100 m tunnel length.

6. CONCLUSION

Between one third and one half of the energy comes from the air of the tunnel. Different climatic conditions in the tunnel (temperature or wind speed) could have a great impact on the results here presented. Detailed investigations on the tunnel conditions could consolidate the results of these computations.

It is also possible to optimize the energy demand of the heat pumps by imposing relatively high temperatures in the heat exchangers in winter (up to 5°C). But it was proven that the cold production in summer without heat pump (free-cooling) using low circulation temperatures in the heat exchangers might not be possible; in that case, the elevated air temperature in the tunnel counterbalances the cold produced by the underground.

This study shows that the use heat exchangers in a tunnel wall to produce warm and cold can be of high interest and contribute to reduce CO_2 emissions due to building heating. This is particularly true in the case of the CEVA tunnel, which is located in an urban area with direct proximity to buildings showing complementarily energy demands.

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