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Geothermal usage in inner city tunnels - A study of the Fasanenhof subway tunnel in Stuttgart Germany

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Abstract

Few technical modifications are required to use a tunnel as a geothermal source or sink. This idea is realized with two geothermal test sections inside the Fasanenhof subway tunnel in Stuttgart, Germany. The sections are equipped with absorber pipes along a length of 10 meters each. The tunnel is equipped with measuring devices to determine the temperature distribution in the ground, the tunnel lining and the tunnel air.

The first stationary measurements with fixed inlet temperatures for the tunnel absorbers showed variations between 5 W/m² and 37 W/m² in cooling effect per absorber heat exchange area. The highest power output was obtained at the beginning of the phase. The thermal output decreased with time, partly due to the temperature increase of the absorber section surroundings. An influence of the tunnel air temperature could also be seen.

In order to see how the system behaves under transient conditions an emulation is performed with a coupling between the geothermal tunnel system and the simulation environment TRNSYS. A fictive office building is modeled and the annual heating and cooling load are calculated. A cooling phase is performed with the cooling load as input for the tunnel system. Transient results once again show an influence of the tunnel air temperature. The thermal output is however also influenced by the cooling load. 77% of the supplied cooling energy could in the end be obtained through direct cooling. This shows a potential for the method to further establish itself in the energy sector.

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Keywords: Ground source; Tunnel; TRNSYS; Emulation; Cooling

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1. Introduction

1.1. Targets of the European union

The European Union strives for that 20% of its overall energy consumption should be covered by renewable energy sources by 2020. Renewable energies are not only attractive due to their low impact on the climate but they would also make the union less dependent on importing fuels, such as fossil fuels, which today covers 79% of its gross inland energy consumption [1]. Buildings are today responsible for more than 40% of the global energy use and one third of the global greenhouse gas emissions, both in developed and developing countries [2]. There is a great potential for renewable energies to increase their market shares and to establish themselves as cost effective and widely used alternatives for this sector.

Geothermal power comprises both solutions utilizing thermal energy stored at down to several kilometers of depth in the earth crust for electricity generation to shallow applications with heat pumps for the heating and cooling of buildings. The later solution shows potential for the building sector due to its low technological, environmental and economic costs. Cooling can be performed either in combination with a heat pump or direct as free cooling [3]. The use of shallow geothermal energy has the potential of playing a key role in the transformation of the European energy market.

1.2. Shallow geothermal energy

Various techniques exist today which use shallow geothermal energy as an energy source. The most common method in central and northern Europe is the borehole heat exchanger. Heat exchanger tubes are installed into vertical boreholes and heat transfer fluid is circulated to supply or extract heat from the ground. The thermal storage capacity of the ground can then be utilized for heating and cooling purposes. The heat exchangers are usually connected to a heat pump. Several boreholes can be installed to meet the requirements of larger buildings. Other possibilities are ground absorbers, horizontal collectors and energy baskets. These methods all have high capital costs for the installation, due to the requirement of drilling and additional space for construction, but low running costs. They also require additional underground space for bore holes. Efforts are made to reduce initials investments. The use of geostructures, such as pile foundations, has caught of attention during recent years. Already required ground contact elements for the transfer of construction loads are thereby used as additional heat exchanger elements in order to save investment costs.

1.3. Thermally activated tunnels

Tunnels can be used as geostructures. A large ground volume and surface can be activated for heat exchange. Inner city tunnels have the advantage of being close to possible end users. An essential difference compared to other geostructures is that the heat is not only extracted from the ground but also from the tunnel air. Previous studies have shown an influence of the tunnel air on the thermal output, accounting for around 20% to 30% of the energy output [4]. A number of heat exchanger solutions exist for tunnels. Along the bored energy piles there are also diaphragm walls and foundations as well as energy anchors. There is also the possibility to integrate the heat exchangers into the tunnel lining. Two main methods for thermal activation of tunnel linings are present today. The first one uses geotextiles to attach the pipes between the outer and inner lining. The other method uses prefabricated tunnel lining segments. The prefabrication reduces the installation efforts in the tunnel and keeps the investment costs down. The units can be integrated during the installation of the tunnel without any need for additional drilling of boreholes. Previous forecasts indicate that the increased costs for the shell caused by the geothermal activation amount to circa 2% [5].

Two modes can be distinguished for the operation of thermally activated tunnels. By the first mode, energy is either extracted or supplied to the ground, which leads to a constant cooling or heating of the soil over time. The other mode operates alternating seasonal and the thermally activated tunnel is used for both heating and cooling. The ground is thereby used as a thermal energy storage. The second mode can produce energy equilibrium over time leading to a stable ground temperature over the year after a complete heating and a cooling period [6].

1.4. Previous research projects

The use of thermally activated tunnels as an energy source is still in its research phase and few prior projects have explored this solution before.

A previous study with different methods for the thermal activation of tunnels was performed in the metro line U2 in Vienna, Austria [7]. The absorbers were positioned in the foundation slabs, bored piles and the diaphragm walls of the subway tunnels and some sections were equipped with an energy fleece. It could be shown that the temperature variations from the absorbers have negligible effects on the structural performance of the tunnel. Effects on the groundwater could only be seen within 5 meters from the diaphragm walls. The thermal regeneration increased with an increasing groundwater flow.

A 54 m long tunnel section in Jenbach, Austria was equipped with lining segments to be used as a geothermal source or sink [8]. The absorber pipes were integrated into prefabricated reinforcement cages in steel mould for the tunnel structure. The geothermal plant was dimensioned to cover the heat demand of the town council, from which 15 kW is to be extracted from the ground.

In [9] a test bed of six pilot energy textile modules with various configurations was constructed in an abandoned railroad tunnel in South Korea. Field monitoring was performed to measure the heat exchange capacity of each energy textile module by applying intermittent and artificial heating and cooling loads corresponding to typical office buildings.

Tunnel lining heat exchangers have been installed in the Linchang tunnel in Inner Mongolia [10]. Performed experiments focused on how factors, such as the flow rate, the inlet temperature and the pipe distances of the absorber modules, affect the heat transfer of the tunnel lining heat exchangers.

The possibility of thermally activating a new section of the metro Torino in Italy was numerically investigated in [11]. A thermal output equal to 53 W and 74 W per square meter of tunnel lining heat exchange area was predicted for the winter and summer respectively. It could be shown that the thermal activation of the tunnel lining would be 41% less expensive than using vertical piles in combination with a heat pump. The payback was calculated to be less than 5 years.

1.5. Investigating the Fasanenhof subway tunnel in Stuttgart, Germany

The project described in this paper is performed at the Fasanenhof Subway Tunnel in Stuttgart, Germany. The tunnel has a length of approximately 380 meters, a height of 9.2 meters and width of 7.4 meters. It contains two parallel train tracks for traffic in both directions [12]. The tunnel ceiling is situated 15 meters below surface at the deepest part of the tunnel. A geothermal tunnel system was installed inside the tunnel in 2011. It contains two thermally activated tunnel sections, connecting pipes and a test rig containing a heat pump, an electrical heater, a heat exchanger for cooling purposes and a main pump for the circulation of heat exchanger fluid.

The 10 m long tunnel lining sections were equipped with absorber elements to extract and supply heat from the surroundings. The absorber fluid consists of a water/monoethylene glycol mixture. The prefabricated absorber units contain pipes, which are included into a geotextile for easier mounting. This prefabrication method has been used before in the Lainzer Tunnel in Vienna, Austria [7]. The geotextiles were mounted on the external shotcrete tunnel lining and integrated into the sprayed concrete used for the inner tunnel lining. 800 meters of polyethylene pipes are distributed on the two tunnel lining sections with a combined surface of 360 m² [13]. The left side of Fig. 1 shows how the absorber pipes were positioned in the tunnel lining before the final concreting.

Fig. 1. Left: Tunnel section with absorber pipes before completion of tunnel lining, Right: Test rig inside control room

A main pipe going to and from the two absorber blocks is connected to the test rig, situated in a control room nearby. The first tunnel section is situated 90 meters from the control room. The two sections are separated by a distance of 80 meters and are located in layers of sandstone and shale [5]. The heat pump inside the control room can be used to raise the absorbed heat to a higher temperature level. The reversed process can be used for cooling purposes. Different load profiles can be generated for the heating and cooling in order to examine the interaction between the absorbers, the ground, the tunnel and potential end users. The right side of Fig. 1 shows the test rig inside the control room.

The main research goal is to investigate the capacity of the geothermal tunnel system and the range of its effect on the ground temperature. Another research priority is to investigate how the tunnel air influences the amount of extracted energy [4]. The first stationary measurements with fixed inlet temperatures for the tunnel absorbers showed variations between 5 W/m² and 37 W/m² in cooling effect per absorber heat exchange area. The highest power output was obtained at the beginning of the cooling phase. The thermal output decreased with time, partly due to the temperature increase of the absorber module surroundings. Numerical analyses showed that abstraction rates of 3 W/m² to 8 W/m² can be expected for heating and cooling with long term operation states [14]. An influence could also be seen of the tunnel air temperature on the thermal output [15]. The results show that geothermal tunnel systems can play an important role for sustainable heating and cooling of buildings. This with having only a small influence on surrounding ground temperatures.

2. Method

2.1. Introduction

An emulation is performed to investigate the interaction of the tunnel system with potential end users, such as residential or office buildings. The simulation environment TRNSYS is used to generate cooling load profiles, which can be transferred to the test rig inside the control room of the Fasanenhof tunnel. TRNSYS is capable of modeling various heating, cooling and air conditioning units. Load profiles that are generated from building models change according to the weather conditions and the internal building loads. This makes them more realistic than intermittent artificial load profiles since load fluctuations can be captured more precisely. They also give more insight on which assumptions that are being made for the load generation.

The emulation is performed on a real time basis. This means that one simulated hour in TRNSYS lasts one hour and that the simulated time of the year is the current time of the year. Weather data from Stuttgart is used to simulate the climatic conditions for the building model.

2.2. Generating the cooling load

One office floor is created in TRNSYS for which a cooling load is generated. This cooling load can be multiplied in order to simulate buildings with more than one single floor. The office floor contains seven office rooms, one conference room, one kitchen, two bathrooms and one corridor. A schematic representation of this fictive office floor can be seen in Fig. 2.

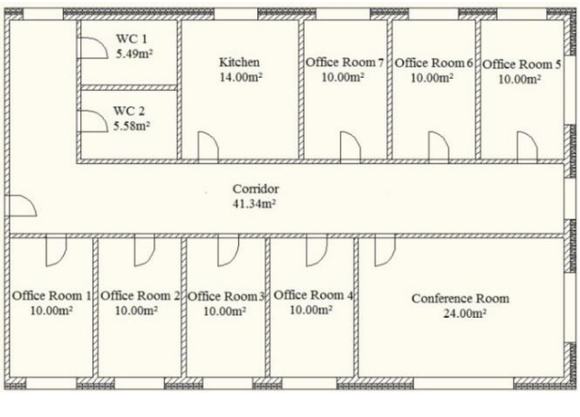

Fig. 2. Office model created in TRNSYS

All bureaus have one person working in them during office hours and they all contain one computer and artificial lightning. The conference room and kitchen both have a varying amount of people present during the work days. These internal heat loads play an important role for the thermal condition inside the rooms.

The external walls and windows have an overall heat transfer coefficient equal to 0.199 W/(m²K) and 1.270 W/(m²K) respectively. The windows are equipped with outdoor shades in order to decrease the solar radiation gain during the warmer days of the year. The heat transfer coefficients for the walls and windows fulfill the German energy saving ordinance from 2014 (EnEV 2014), which contains requirements for the primary energy demand of new buildings [16]. The office floor is mechanically ventilated and the flow rates for the office rooms are calculated according the German guideline for air conditioning in office buildings (VDI 3804) [17].

The building is equipped with ceiling cooling panels in every room in order to remove heat from the building and thereby sustaining a comfortable indoor temperature. Cooling ceilings can be operated with a fluid inlet temperature which is close to room temperature. This makes them compatible with shallow geothermal energy sources. A model based on the finite difference method is implemented into TRNSYS, which describes the transient thermal performance of such panels and their geometrical design [18]. The inlet temperature of the cooling panels is restricted to 17°C to avoid the occurrence of condensation. The cooling panels are activated, if the room temperature, T_{Room}, exceeds 26°C during office hours or 28°C for non-work hours. The floor has a constant maximal permitted room temperature equal to 28°C.

Whenever the maximum allowed temperature is exceeded in one of the rooms its cooling ceiling activates. The fluid inside the cooling ceiling will extract heat from the room and the room temperature will be lowered. Consequentially, the fluid temperature inside the cooling ceiling will be raised. The total mass flow required for the whole building, $\dot{m}_{Load}$, is the sum of all cooling ceiling mass flows:

$$\dot{m}_{Load} = \sum_{1}^{n} \dot{m}_{n}, \tag{1}$$

where n is the amount of rooms with a cooling ceiling and $\dot{m}_n$ is the mass flow rate for the ceiling in room n. The total return temperature from the buildings cooling ceilings, $T_{Out,Building}$, is obtained with:

$$T_{Out,Building} = \frac{\sum_{1}^{n} T_{Out,Room,n} \cdot \dot{m}_{n}}{\dot{m}_{Load}}, \tag{2}$$

where $T_{Out,Room,n}$ is the return temperature for the cooling panel in room n. A load profile containing $\dot{m}_{Load}$ and $T_{Out,Building}$ can then be generated for the emulation time period.

2.3. Emulation

The geothermal tunnel system will cool down a stratified fluid storage, which is modelled in TNRSYS. The storage is discretized into 50 vertical nodes and is thereby able to capture the effects of thermal stratification [19]. It is modeled with a volume of 250 m³ and contains water. A schematic representation of the emulation containing the building model load profile, the stratified storage and the connection with the geothermal tunnel system in Fasanenhof is displayed in Fig. 3. The left hand side of the vertical line symbolizes the numerical part, which is modeled in TNRSYS. This contains the load profile of the building, described earlier in Section 2.2, and the storage with its auxiliary cooler and heat exchanger. The right hand comprises the test rig, the tunnel heat exchangers and the various measurement units situated inside the actual Fasanenhof tunnel and its control room.

Whenever the load profile signals that a mass flow rate is needed for the cooling ceilings inside the office building ($\dot{m}_{Load}$ > 0), fluid is extracted from the bottom of the fluid storage. The bypass on the left side of the storage in Fig. 3 is used if the fluid temperature is lower than 17°C. The returning water from the cooling ceilings is supplied back to the top of the storage with the same mass flow rate and the return temperature $T_{Out,Building}$, which is also given by the load profile.

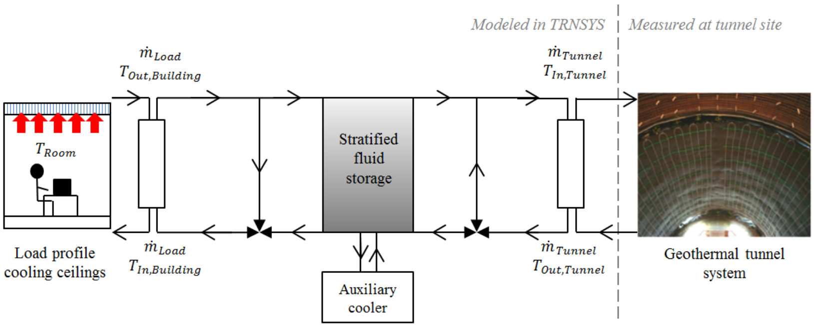

Fig. 3. Structure of emulation

The storage is cooled down by the geothermal tunnel system and the auxiliary cooler situated at its bottom. The geothermal tunnel system cools the storage through a mantle heat exchanger, which enables stratified charging. The water that is lead to the geothermal tunnel system is extracted from the top of the storage, with the temperature $T_{In,Tunnel}$. The fluid which is fed to the two tunnel sections inside the actual tunnel in Fasanenhof will be heated to this temperature using the test rig inside the control room. The test rig is controlled with the software Labview. A connection is created between TRNSYS and Labview to pass on information between them. The heat transfer fluid, now with the same temperature as the fluid extracted from the top of the storage, will then flow through the two tunnel sections inside the Fasanenhof tunnel and cool down. After the heat transfer fluid has passed through the tunnel absorbers it is led back to the control room. The measured return temperature, $T_{Out,Tunnel}$, is then imported into TRNSYS as the inlet temperature for the mantle heat exchanger inside the fluid storage. The storage is thereby cooled by the tunnel system.

The pump that circulates the heat exchanger fluid inside the Fasanenhof tunnel can only be adjusted manually on site. The bypass on the right side of the stratified storage in Fig. 3 is therefore activated during the time periods when no cooling can be provided by the geothermal system. This means that the fluid is circulated at the tunnel site without any cooling or heating, which gives time for thermal regeneration for the surrounding ground. No fluid is extracted from the storage by the geothermal tunnel system in the TRNSYS model.

2.4. Investigated cooling period

The emulation was initiated 8th of June 2016 and lasted until the 23rd of October the same year. The number of offices was varied for the load profile in order to see how the system reacts on different magnitudes of cooling loads. Table 1 and Fig. 4 show how the cooling load was varied during the different emulation phases.

Table 1. Cooling load profile for the emulation phases

Phase	Initialization date	Number of offices	Peak cooling load [kW]
1	8th of June 2016	1	5.7
2	23rd of June 2016	3	16.2
3	30th of June 2016	7	50.0
4	9th of August 2016	5	39.4
5	15th of September 2016	7	33.1

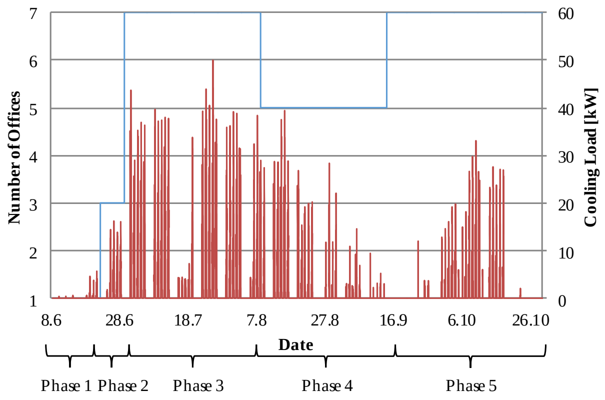

Fig. 4. Cooling load profile

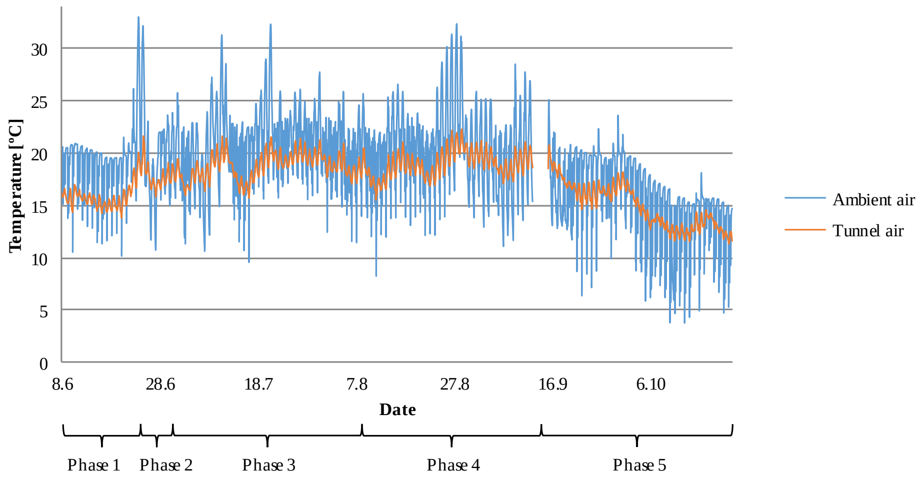

Fig. 5. Temperature variation of ambient and tunnel air during emulation time period

The temperature variation for the ambient and the tunnel air are shown in Fig. 5 for the emulation time period. The temperature fluctuation is significantly lower for the tunnel air compared to the ambient air. The tunnel air is generally colder than the ambient air with an average temperature of 17.3ºC compared to 18.9ºC for the emulation time period. These results show that even though a lot of energy is supplied from the tunnel air to the absorbers (as earlier discussed in section 1.3), the tunnel air temperature level is more beneficial than the temperature level of the ambient air. The lower the temperature is around the absorber sections, the more cooling energy can be used for the direct cooling of the thermal storage and thereby the building.

3. Results

Fig. 6 shows the cooling power that is provided by the geothermal tunnel system and the auxiliary cooler during the emulation phases. Fig. 7 displays the temperature distribution inside the thermal storage at the beginning of each phase.

During Phase 1, which is characterized by its low peak cooling load, the storage is cooled down from its initial temperature of 20ºC. This is done almost exclusively by the geothermal tunnel system. The cooling power of the tunnel system decreases from 11 kW, which is equal to approximately 30 W per square meter absorber heat exchange area, down to 0 W as the temperature sinks inside the storage. The mean provided cooling power is equal to 2.5 kW during this phase, which is equal to 7 W per square meter absorber heat exchange area. At the end of Phase 1 the storage has been cooled down to its lowest temperature level for the emulation. Only the supplied hot water returning from the cooling ceilings has to be further cooled down. This can be done entirely by the geothermal tunnel system. The storage has its lowest temperature level as Phase 2 begins, which is shown qualitatively in Fig. 7.

Since the geothermal tunnel system has potential to provide more cooling the amount of offices is tripled in Phase 2. The storage temperature rises during this phase. However, Fig. 6 shows that the provided cooling energy from the geothermal tunnel system still is quite low. The temperature raise between the start of Phase 2 and Phase 3 is therefore quite low inside the storage.

The amount of offices is further increased to 7 in Phase 3. This phase is characterized by a high cooling load and a high tunnel air temperature level. The stored cooling energy is consumed and the temperature rises inside the stratified fluid storage due to the higher cooling load. A comparison between the temperature distribution inside the storage at the beginning of Phase 3 and Phase 4 shows this. The now higher tunnel air temperature lowers the amount of free cooling that can be provided by the geothermal tunnel system. The tunnel system reaches a peak cooling power of 5.6 kW, which is equal to 16 W per absorber heat exchange area. The auxiliary cooler has to be activated to secure a maximum temperature of 17ºC at the lowest part of the storage. The mean cooling power provided by the geothermal tunnel system is equal to 2.8 kW, which is equal to 8 W per square meter absorber heat exchange area. The mean cooling power provided by the auxiliary cooler equals 1.6 kW.

The amount of offices is slightly lowered in Phase 4 which gives time for regeneration inside the storage. The resulting temperature decrease inside the storage between the beginning of Phase 4 and Phase 5 can be seen in Fig. 7. The provided cooling power by the geothermal tunnel system decreases as the building cooling ceiling load decreases and the storage temperature sinks.

In Phase 5, the amount of offices is once again raised to 7. The tunnel air temperature decreases during this phase which means that the heat transfer fluid can be further cooled by tunnel absorbers. This, in combination with the higher cooling load, leads to that the cooling power increases to its highest values since the beginning of Phase 1. The tunnel system reaches a peak cooling power of 7 kW, which is equal to 20 W per absorber heat exchange area. The mean provided cooling power is equal to 2.2 kW, which is equal to 6 W per square meter absorber heat exchange area.

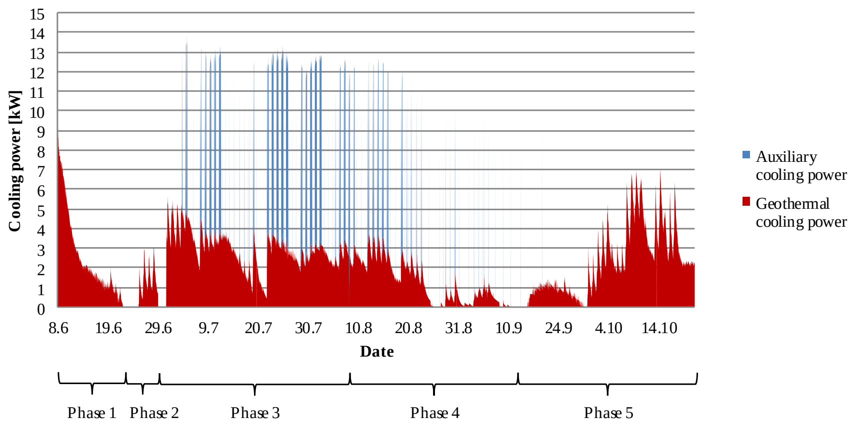

Fig. 6. Supplied cooling power from geothermal tunnel system and auxiliary cooler

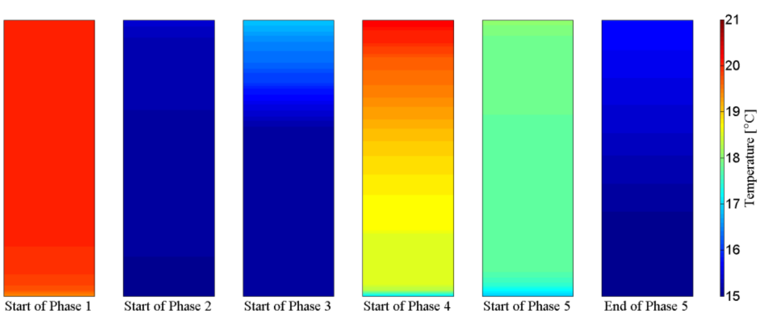

Fig. 7. Qualitative temperature distribution inside stratified thermal storage in the beginning of the phases

Table 2 shows the building cooling demand, the amount of stored cooling energy and the amount of supplied cooling energy from the geothermal tunnel system and the auxiliary cooler for the different phases. The accumulated amount of provided energy is displayed qualitatively in Fig. 8 together with the amount of cooling energy that is subtracted from the stratified storage to meet the cooling demand of the office building.

The geothermal tunnel system manages to cover the whole energy need for the first two phases. The storage can be cooled down since the cooling load is low. This can be seen by the difference in demanded and supplied energy for Phase 1 and Phase 2 in Table 2 and Fig. 8. This stored amount of cooling energy is then used in the beginning of Phase 3. As the cooling load increases more cooling has to be performed by the auxiliary cooler to secure a temperature of 17ºC for the cooling ceilings. Less cooling energy can therefore be stored in Phase 3. The storage cooling load is lower in Phase 4 and the storage has time for regeneration. The storage regenerates further in Phase 5 although the load is once again increased. This is due to the decrease in tunnel air temperature. 77% of the cooling energy is in the end supplied by the geothermal tunnel system which is equal to 6771 kWh.

Table 2. Building cooling demand, stored cooling energy and supplied cooling energy by the geothermal tunnel system and auxiliary cooler

Phase	Cooling demand [kWh]	Stored cooling energy [kWh]	Supplied cooling energy [kWh]	
			Geothermal tunnel system	Auxiliary Cooler
1	29	786	815	0
2	212	721	147	0
3	4896	84	2731	1528
4	1247	300	1022	441
5	1234	1075	2003	6
Total	7618	1075	6718	1975

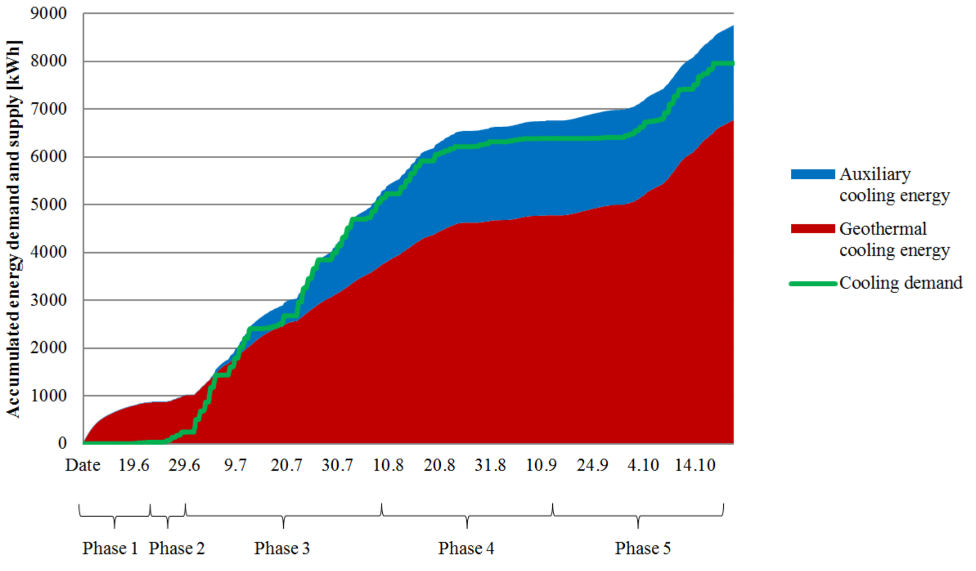

Fig. 8. Accumulated energy demand and energy supply from geothermal tunnel system and auxiliary cooler

4. Discussion

The geothermal tunnel system is influenced by the tunnel air, the cooling load and the storage temperature. A decrease in tunnel air temperature leads to a higher supplied cooling power, which leads to a decrease in storage temperature. The system reached its highest cooling power in Phase 1 and Phase 5 since the tunnel air temperature is low and there is a possibility to further cool the storage. Although the cooling ceiling load is higher in Phase 3 and Phase 4, the higher tunnel air temperature leads to less supplied cooling power. The mean supplied cooling power is however the highest for Phase 3, due to continuously high cooling load. This leads to that the storage temperature remains high and that there is constantly a possibility to supply cooling energy. Both Phase 1 and Phase 5 contain time spans where the cooling load is lower, which decreases the mean value of the supplied cooling power. These results give a deeper insight to the behavior of the tunnel system compared to the stationary measurements, which already showed the influence of the tunnel air.

A large amount of cooling energy can be obtained by the tunnel system merely through direct cooling. The geothermal tunnel system had a mean cooling power of 2.1 kW for the whole emulation time period, which is equal to 6 W per square meter absorber heat exchange area. This shows agreement with the previous numerical analyses that predicted abstraction rates of 3 to 8 W per square meter absorber heat exchange area for long term operation. This also shows that the higher extraction rates that were obtained at the first stationary measurements are not to be expected over longer time periods. This could be seen in Phase 1 as the abstraction rate decreased quickly from its initial value of 30 W/m². 77% of the cooling energy was in the end supplied by the geothermal tunnel system which is equal to 6718 kWh. This shows that there is a potential for the method to increase its market share and to establish itself in the energy sector.

An auxiliary source is needed to ensure the required cooling temperature for the cooling ceilings. This is provided during the warmer months of the year due to the higher tunnel air temperature. The mean cooling power provided by the auxiliary cooler was equal to 1.6 kW for Phase 3, which was characterized by its high cooling demand and tunnel air temperature level. The mean cooling power provided by the geothermal tunnel system was equal to 2.8 kW for the same phase. The system can either be combined with an auxiliary cooling source, as shown in this example, or better through a heat pump, which can be integrated on the right side of the stratified storage in Fig. 3. The numerical part of the model will therefore be expanded by including a heat pump model. The performed measurements however show which amount of energy that can be expected from such a geothermal tunnel system for a realistic end user, such as an office building.

The results show the difficulty in matching the energy output of the geothermal tunnel system with the cooling load of a building. If the load is too low the geothermal tunnel system is left unused during longer time periods, which is not beneficial from an economic point of view since the system only provides a modest amount of cooling energy. When the load is higher, the geothermal tunnel system runs more frequently and delivers more energy. If the load is too high compared to the geothermal tunnel system output there is a need for a lot of auxiliary power. Otherwise a larger part of the tunnel lining has to be thermally activated. This shows the need of better prediction models regarding the energetic output and the economic benefits of geothermal tunnel systems. Although the tunnel air temperature fluctuates less compared to the ambient air temperature, a higher temperature fluctuation can be suspected around the tunnel absorbers compared to geostructures that solely use the ground as a heat source. The tunnel air temperature at the absorber blocks is furthermore influenced by the geometry of the tunnel and additional local factors. These have to be determined to generate reliable prediction models.

Acknowledgements

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