Key features of the novel geothermal heat exchanger prototype installed at the Brenner Base Tunnel

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ABSTRACT

The design, installation, and testing of an innovative geothermal heat exchanger, tailored for tunnels excavated by Tunnel Boring Machines, will be presented. The prototype was developed by the joint efforts of BBT SE, involved in the construction of a new railway base tunnel system connecting Italy and Austria, and the University of Bologna, engaged in applied research over various aspects of the BBT system. The geothermal heat exchanger consists in a modular horizontal closed-loop system located in the exploratory tunnel of the BBT system, specifically in the space dedicated to collect the drained water at the lining invert. Due to the type of the heat exchange process, working with the drainage water, and for its compact design and simple installation procedure, the prototype was called "Smart Flowing". Modules were built outside and later moved inside the tunnel, and eventually placed and assembled concurrently to the advancement of the Tunnel Boring Machine. Specific tests were performed to prove the reliability and the efficiency of the system, by simulating the work of a heat pump conditioning system in both heating and cooling modes. Finally, a preliminary assessment of the economic and environmental potential of this innovative prototype was carried out. First results showed the performance of the system for both heat dissipation and extraction. The drainage water flow guarantees a continuous recovery to the natural state, thus improving efficiency compared to classic geothermal heat exchangers. Economic savings and reduction of pollutants and greenhouse gases, as compared to burning fossil fuels, can reach up to 70%.

1. INTRODUCTION

The exploitation of low enthalpy geothermal resource takes advantage of the stable temperature of soil, rock or groundwater and can be obtained by means of foundations, underground structures and even tunnels (Brandl, 2016). These structural elements therefore become an integral part of the geothermal system, being able to provide heating and / or cooling to buildings located in their immediate vicinity (Laloui & Di Donna, 2013). With particular reference to the mountain environment, the users placed near tunnels are limited, thus reducing the potential benefit from geostructures. In such a condition, among the well-known applications of low enthalpy geothermal energy there is the direct exploitation of drainage water, whose temperature values often allow for coupling with heat pumps. Some famous examples can be found especially in Switzerland (Raybach et al., 2003). In the existing applications, the end-users are located near the tunnel portals, while the total usable geothermal heat is limited by long distances from other potential beneficiaries (Stemmle et al., 2022). The current work presents a solution for bringing direct benefits along the tunnel length.

As part of the collaboration between BBT SE, involved in the construction of the Brenner Base Tunnel (BBT), and the University of Bologna, the study of the geothermal potential of the tunnel system on the Italian side of the Brenner is an important research topic that has recently led to the creation of a prototype, named "Smart Flowing" (Spaggiari, 2021; Spaggiari et al., 2022). The prototype aims at investigating the exploitable potential of the heat stored in the drainage water directly inside the tunnel. This research is following previous studies conducted at the same site in the period 2015-2017 related to the estimation of the geothermal potential at different depths, the evaluation of the exploitable potential from drainage water and the practical assessment of an energy lining installation (Boldini et al., 2016; Tinti et al., 2017).

2. CONCEPT, DESIGN AND INSTALLATION

Smart Flowing is a new type of geothermal exchanger, installed in the space dedicated to drainage water collection of the exploratory tunnel of the BBT system (Fig. 1).

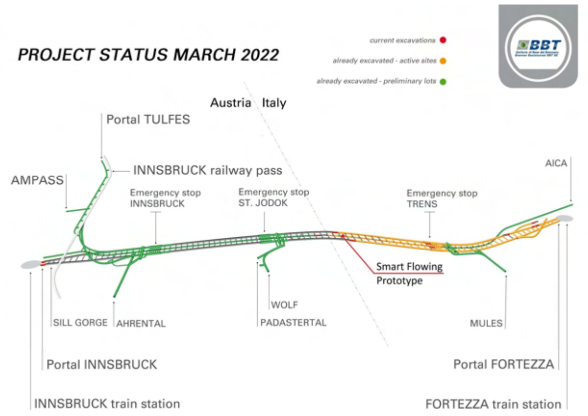

Figure 1: Location of the Smart Flowing prototype in the exploratory tunnel of the BBT system (modified from graphics in bbt-se.com).

Firstly, the exploratory tunnel was identified as the most suitable site for placing the prototype within the Brenner Base Tunnel system. In fact, the exploratory tunnel:

- is designed to convey the drainage water of the entire tunnel system, likely ensuring an adequate flow of water over time;
- has a lining ring characterized by two complementary base inverts where the Smart Flowing can be easily located (Fig. 2);
- was under construction when the prototype was built.

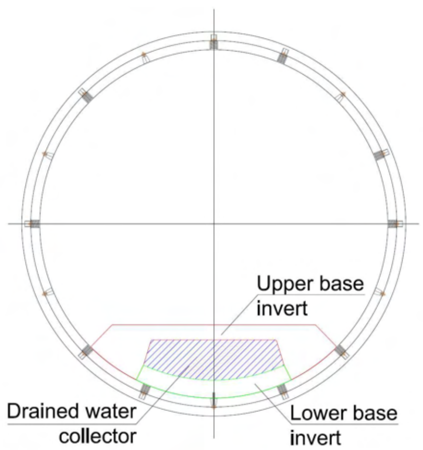

Figure 2: Section of the exploratory tunnel and prototype location (modified from Spaggiari et al., 2022)

Secondly, the system was conceptualized to be easily integrated, and quickly installed, as a modular system, during the construction operations of the tunnel.

The layout is similar to a horizontal heat exchanger, generally disposed 1-2 m below ground surface in trenches.

Each of the seven manufactured modules consists of a PE-Xa absorber pipe arranged in a coil configuration over a horizontal rigid support formed by a welded wire mesh placed on four steel profiles. Considering that seven modules were installed, each with dimensions of 1.5 m per 2 m, the total length of the system is 10.5 metres. Each module is connected to the following one through steel plates and bolts to connect the profiles, and hydraulic fittings so as to form a continuous circuit in which the heat-carrier fluid flows. The PE-Xa pipe with an outside diameter of 25 mm and a thickness of 2.3 mm guarantees durability. The consecutive modules provide a 76 m length of pipes (Fig. 3).

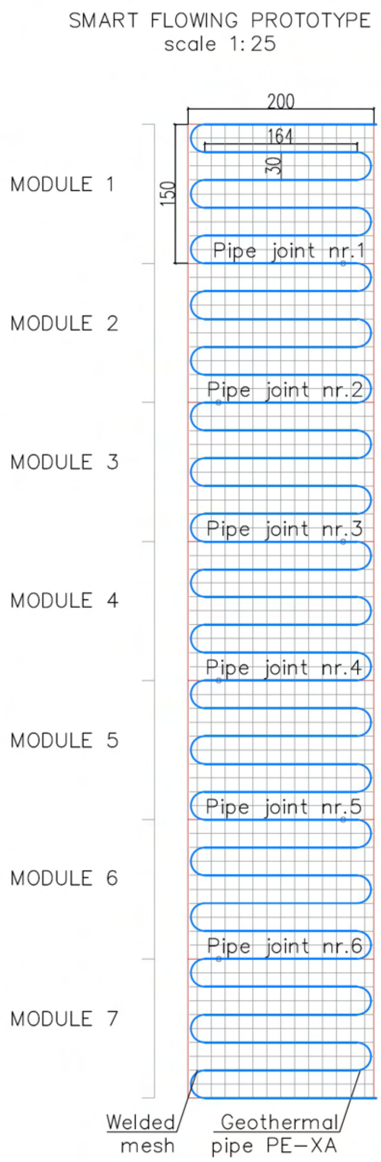

Figure 3: Scheme of the Smart Flowing prototype (modified from Spaggiari et al., 2022)

The installation of the system required 6 hours and 40 minutes, of which 2 hours and 20 minutes were dedicated exclusively to the placement and connection in series of geothermal modules, while the rest included standard activities of mechanized excavation, such as the placing of the base inverts. As a result, Smart Flowing was installed simultaneously with the advancement of the Tunnel Boring Machine, producing very limited interference with the excavation (Fig. 4).

Figure 4: Installation of Smart Flowing during TBM advancement.

3. TESTING AND RESULTS

In order to evaluate the exploitable heat from the drainage water, an air source heat pump (ASHP), a buffer tank and a circulation pump were connected to Smart Flowing, bringing the entire circuit to a length of 90 metres (Fig. 5).

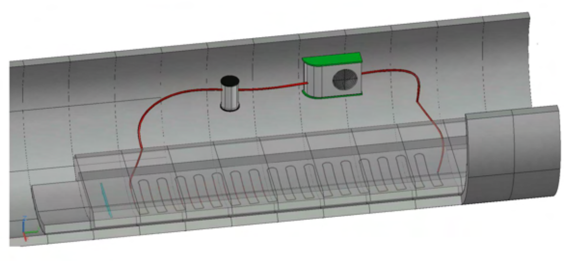

Figure 5: Simplified scheme of the closed loop circuit, including the heat pump.

The chosen ASHP is capable of providing a heat extraction capacity of 6.0 kW and a heat injection capacity of 7.3 kW. The buffer tank has a volume of 80 l, while the external circulation pump has a head of 7.7 m. The heat pump is equipped with sensors to measure and record temperature and flow of the heat transfer fluid entering and leaving the circuit.

Smart Flowing was tested for two consecutive months, under both heat injection and extraction conditions. Eleven tests were conducted, in which the heat pump limit temperature (i.e. the manual set-point of the ASHP), the hours of operation and the head of the auxiliary pump were varied (Table 1).

Table 1: List of performed experimental tests.

Test no.	Date	Duration	Heat mode	Circulation pump head (m)	Set-point return temperature T_{in} HP limit (°C)
1	01/06/2021	2h30	Injection	4	52
1bis - repeated	07/06/2021	3h30			
2	10/06/2021	3h40	Injection	4	40
2bis - repeated	14/06/2021	4h			
3	17/06/2021	3h	Extraction	4	10
4	24-25/06/2021	24h	Extraction	4	10
5	29/06/2021 - 02/07/2021	70h	Extraction	2	10
6	06-09/07/2021	74h	Extraction	2	5
7	09-13/07/2021	100h	Extraction	2	5
8	13-14/07/2021	16h	Injection	2	52
8bis	19/07/2021	2h40			

The temperature of the drainage water was also measured during the tests, showing a fairly stable range of values, between 31.3 and 31.7 ° C.

Measurements allowed the calculation of the power extracted / dissipated by the system, using the following equation:

$$P = c_p \, \rho \, q \, \Delta T \qquad [1]$$

where P is the exchanged heat, c_p and ρ are the heat capacity and density of the thermovector fluid, q is the flow and ΔT is the difference between inlet and outlet fluid temperature.

Observation of experimental tests reveals that, after an initial phase of temperature increase and decrease, depending on the test mode, the temperature of the Smart Flowing circulation fluid tended to stabilize without ever reaching the set temperature limit of the heat pump. This result is a consequence of the continuous drainage water flow, which moreover makes it possible to quickly recover temperatures to initial values (Fig. 6).

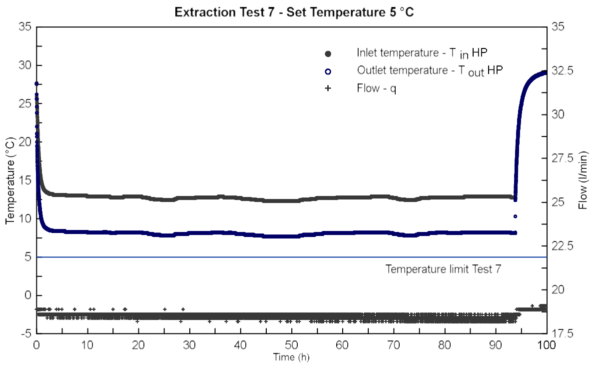

Figure 6: Example of a performed test in extraction mode: to provide the whole heat required (6 kW), return fluid temperature from Smart Flowing stabilised at around 13.5°C, much higher than the heat pump threshold set at 5°C.

The full cooling capacity in injection mode is achieved with fluid temperature stabilization at 49.5°C return temperature, while in extraction mode the full heating capacity is achieved with stabilization at a 13.5°C return temperature. As the drainage water temperature is around 31.5° C, the temperature gap is the same for both injection and extraction (18.5°C). On the other hand, the coupling of Smart Flowing with a ground source heat pump (GSHP) would lead to a higher seasonal performance factor (SPF) by extracting rather than by injecting heat: $SPF_{heating}$ is expected to be around 5 with constant heat pump inlet temperature at 13.5°C, while $SPF_{cooling}$ is expected to be around 3 with constant heat pump inlet temperature at 49.5°C.

At such performance values, thanks to the effect of long-term temperature stabilization due to drainage water flow, Smart Flowing provides a constant specific heating power of 80 W/m of pipe length and 285 W/m^2 of base invert surface. On the other hand, the constant specific cooling power is about 97 W/m of pipe length and 348 W/m^2. of base invert surface.

4. CONCLUSIONS

Smart Flowing is a prototype of a modular type geothermal exchanger made up of seven elements connected in series to form a single horizontal pipe installed in the drainage water channel of tunnels during TBM advancement.

The system was installed in the exploratory tunnel of the BBT tunnel system where the cover reaches about 1000 m and the drainage water is at a temperature of around 31.5 ° C.

The following conclusions can be drawn with reference to the implementation and testing of the system:

- the installation sequence can be perfectly integrated in the mechanized excavation activities without significant slowdowns, requiring only around 20 minutes per module;
- the drainage water flow allows the temperature stabilization of the heat transfer fluid and fast heat recovery once the heat extraction/injection is stopped;
- the specific power for both heat extraction/injection is higher than that of common vertical geothermal exchangers (80 W/m against 50 W/m) and significantly higher than that of horizontal geothermal collectors with equivalent surface in green field (285 W/m^2 against 40 W/m^2);
- the extraction/injection efficiency is generally high, but strongly dependent on the temperature level of the drainage water.

The market uptake of the developed prototype still requires additional insights related to convenient uses along the tunnel length; however, it can be concluded that Smart Flowing has proved to be a geothermal system capable of exploiting the heat released by the drainage water in an effective way.

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