A solar-collecting system for tunnel thermal storage

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Summary

Despite being resilient geostructures, a non-negligible amount of tunnels worldwide are approaching the end of their service life. This is mainly evident in Italy due to the agedness of most of the underground built environment. To address this issue, a plan to renovate existing motorway tunnels is underway to extend their serviceability. In this framework, a novel energy tunnel based anti-icing solar-collecting system is being implemented on a full scale in a motorway tunnel undergoing renovation. This envisages a geothermal serpentine embedded in the rehabilitated lining connected to other heat exchanger piping placed within the motorway pavement. Working in free-cooling mode, the system can take advantage of the thermal inertia of the ground behind the lining to store the solar heat collected through the motorway pavement, acting as a solar collector. The aim is to use this heat for anti-icing operations during the harshest periods of winter seasons.
This paper will illustrate the laboratory testing and numerical modelling needed to preliminarily assess the functionality of the energy tunnel based anti-icing solar-collecting system.

1 Introduction

The global transition to renewable energy sources is at a critical juncture, needing immediate and innovative solutions to address the climate impacts associated with historical energy practices. In this regard, shallow geothermal energy emerges as a renewable, reliable and easy-to-access solution offering decentralized, low-carbon heating and cooling. This technology may be vital in aligning with the objectives outlined in recent climate agreements, just as the Paris Agreement of 2015, the European Green Deal of 2019 and the Glasgow COP26 of 2021. Notably, energy geostructures (EGs) deserve noteworthy attention, as these can promote the sustainability of the carbon-intensive construction industry, thereby advancing environmental goals.
Among them, energy tunnels (ETs) have gained considerable attention in recent years due to the large ground-contact volume and the possibility of exploiting heat also from inside the underground environment. However, recent ET implementations have only been related to new tunnelling projects, and the possibility of instrumenting existing tunnels for heat exchange has only recently been investigated [1]. In this regard, the ageing of the existing tunnels, many of which are centenary or even older [2],[4], and the increasing need for refurbishment interventions aimed at extending their service life can pave the way for developing green solutions for converting existing tunnels into EGs. This paper will briefly describe an ET-based anti-icing solar-collecting system implemented during the renovation of an existing motorway tunnel in Italy and the laboratory testing and numerical modelling needed to preliminarily assess its functionality.

2 The ET-based anti-icing solar-collecting system

As part of the structural renovation of the right tube of the Olimpia tunnel (located on the A26 motorway, between Casale Monferrato and Alessandria, Italy), an ET-based anti-icing solar-collecting system is under construction. The system is designed to prevent the formation of hoar frost on the surface of the motorway pavement during winter, while also storing solar thermal energy within the ground surrounding the Olimpia tunnel in summer. Such energy can then be reused in the following cold periods.
The system is composed of a closed-loop circuit consisting of a 14.0 m long ET installation coupled with a 3.6×27.0 m hydronic heated pavement (HHP)/pavement solar collector (PSC) through insulated collectors. The Olimpia tunnel is instrumented for geothermal exploitation, setting up 20.0 mm diameter PE-Xa heat exchanger pipes at the interface between the existing and the newly built linings. These are hand-fixed with metallic clamps spaced 40.0 cm apart and embedded within the shotcrete regularisation layer, which also accomplishes a protective aim. Analogously, the HHP/PSC is instrumented with the same type of pipes as above, arranged within the pavement structure under the wearing and binder layers with a spacing of 30.0 cm and embedded in a concrete protection slab. The ET-based system does not envisage the aid of a ground source heat pump, thus working in free-heating and free-cooling mode in winter and summer, respectively.

3 Preliminary assessment of the solar-collecting potential

To preliminarily assess the solar-collecting potential of the ET-based system, two distinct thermo-hydraulic numerical models were developed through the finite element code FeFlow© ver. 7.5 [5], which reproduce separately the ET and PSC installations. However, these are interconnected with a Python script that enables communication between them at each time step. The models were supplied with the outcomes from thermal laboratory testing aimed at ascertaining the thermal properties of the construction materials involved in the Olimpia tunnel renovation process.

3.1 Thermal laboratory testing

The thermo-physical properties of the existing and newly built linings, as well as the shotcrete regularisation layer and the concrete slab within which the heat exchanger piping is embedded, were determined through thermal laboratory testing using *Thermtest*™ devices. In particular, a needle (TLS-50) and a planar (TPS-EFF) probe were used to measure the thermal conductivity λ [$Wm^{-1}K^{-1}$] and effusivity ζ [$Ws^{1/2}m^{-1}K^{-1}$]. The latter was used to compute the thermal diffusivity α [m^2s^{-1}] and the volumetric capacity c_v [$Jm^{-3}K^{-1}$] of the samples through the following relationships:

$$\zeta = (\lambda\, c_v)^{1/2} \tag{1}$$

$$\alpha = \lambda\, c_v^{-1} \tag{2}$$

The results of the experimental campaign, which was performed in compliance with the ASTM D5334-22 and ASTM D7984-16, are detailed in Tab. 1 along with their uncertainties. These were computed according to the theory of measurements, which proves the empirical mean value is the best estimation of the actual quantity being measured and rules the propagation of the uncertainties for computed ones.

Table 1: Results of the thermal laboratory testing campaign.

Thermal properties	Existing tunnel lining	Newly built tunnel lining	Regularisation layer	Protection slab
λ [$Wm^{-1}K^{-1}$]	1.86 ± 0.20	1.59 ± 0.08	1.43 ± 0.08	1.46 ± 0.07
ζ [$Ws^{1/2}m^{-1}K^{-1}$]	2284.9 ± 136.7	2058.5 ± 100.9	1884.5 ± 96.7	1774.7 ± 62.7
α [m^2s^{-1}]	2.81 ± 0.64	2.67 ± 0.39	2.48 ± 0.40	2.16 ± 0.26
c_v [$Jm^{-3}K^{-1}$]	0.66 ± 0.22	0.59 ± 0.11	0.58 ± 0.13	0.67 ± 0.11

3.2 Interdependent numerical modelling

The thermo-hydraulic numerical models developed for the sake of this research are shown in Fig. 1 and Fig. 2 and are completely analogous to those described in [6] in terms of geometric features, boundary conditions, material properties and the interdependent running methodology.

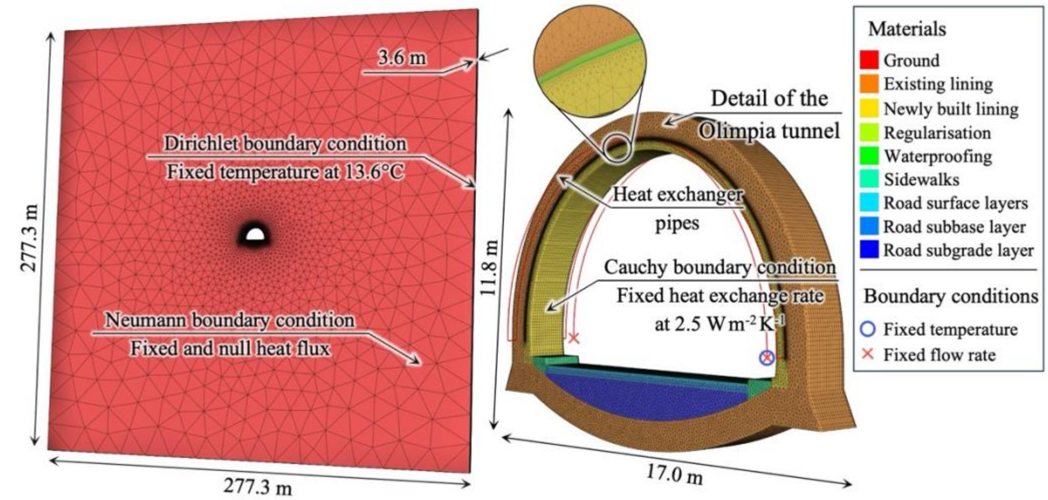

Figure 1: Thermo-hydraulic numerical model of the ET installation in the Olimpia tunnel.

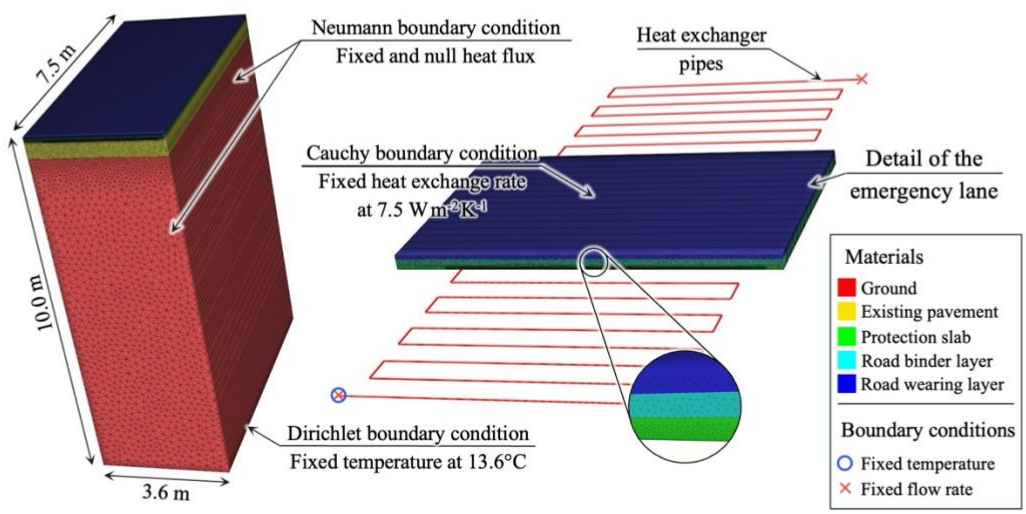

Figure 2: Thermo-hydraulic numerical model of the PSC installation outside the Olimpia tunnel.

The solar-collecting potential of the ET-based system was assessed against a 16.0 h design meteorological event outlined as follows:

- during the first 5.0 h, ambient air heats up and solar irradiance increases from, respectively, 20.0°C to 30.0°C and 0.0 Wm^{-2} to 650.0 Wm^{-2};
- during the middle 6.0 h, ambient air and solar irradiance are constant at 30.0°C and 650.0 Wm^{-2}, respectively;
- during the last 5.0 h, ambient air cools down and solar irradiance decreases from, respectively, 30.0°C to 20.0°C and 650.0 Wm^{-2} to 0.0 Wm^{-2}.

Meteorological data come from the nearest weather stations to the Olimpia motorway tunnel. Accordingly, in the last five years, the average air temperature and solar radiation in the hottest hours of summer days are, on average, 30.0° and 650.0 Wm^{-2}.

4 Conclusion

As per Fig. 3, the numerical modelling results testified to the solar-collecting functionality of the ET-based system, which was demonstrated to collect 60.0 kWh_t during the design meteorological event, thereby also diminishing the possibility of rutting damage by cooling the motorway pavement up to 5.0°C.

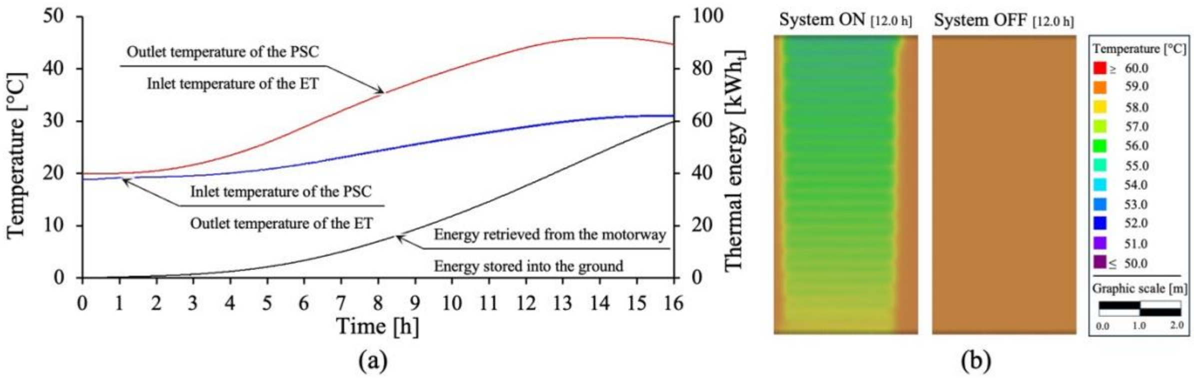

Figure 3: a) Inlet and outlet fluid temperatures and solar thermal energy collected by the ET-based system and b) corresponding temperature of the PSC after 12.0 h of operation.

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