

Experimental and numerical investigations on the energy performance of a thermo-active tunnel

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1 Experimental and numerical investigations on the energy 2 performance of a thermo-active tunnel

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7 Abstract

8 The paper illustrates the experimental and numerical study performed to assess the energy performance of a thermo-active tunnel lining.
9 The experimental data from the real-scale energy tunnel prototype tested in the tunnel of the Turin Metro Line 1 South Extension are
10 considered, by presenting the results of the tests performed in heating and cooling mode through both the ground and air configurations
11 of the novel Enertun layout. Thanks to the availability of the original experimental data collected, it was possible to calibrate and
12 corroborate a thermo-hydraulic numerical model, then used to extend the results to different ground and environmental conditions.
13 Understanding of the role of some of the most important design parameters is illustrated in the form of parametric design charts, that
14 update to the Enertun configuration those already existing in literature. A simple method for preliminary evaluation of the potential of
15 energy tunnels, accounting for the investigated design parameters, is formulated.
16

17 **Keywords: energy tunnel; thermal performance; geothermal energy; tunnel lining; design charts.**

18 Highlights

- 19 - Thermal performance of a real scale prototype of energy tunnel system is evaluated.
- 20 - The role of groundwater flow direction and of other design aspects is studied.
- 21 - Updated preliminary thermal design charts are built and validated.
- 22 - A new procedure to calculate the exchanged thermal power is established.

23 1. Introduction

24 In the next decades new projects involving the use of renewable energy sources will be needed to achieve a
25 noticeable increase in energy production from renewable energy sources (RES) aimed at reducing carbon
26 dioxide emissions and at meeting other targets, such as energy supply security. Every European country agreed
27 to elaborate a National Renewable Energy Action Plan to reach the goal, as required by the EU (Directive
28 2009/28/EC, 2009).

29 In this context a clean, renewable and locally available thermal energy source can be provided by the use of
30 energy geostructures. The multifunctional technology of energy tunnels represents an interesting alternative to
31 traditional shallow geothermal technologies, well fitting in the context of an energy system transition that will
32 bring important modifications to the way homes and other spaces will be heated and cooled. By thermally
33 activating the structural elements of a construction in direct contact with the ground, a low enthalpy geothermal
34 system can be achieved. This is obtained by embedding a circuit of pipes into the concrete members and by
35 circulating a heat carrier fluid along it. This circuit is called the primary circuit and provides heat to a secondary
36 circuit, that of the user. The connection among them can occur directly, as in the case of free heating and free
37 cooling, or through a heat pump, allowing to vary the temperature to the necessary one. These energy
38 geostructures can be used for heating and cooling of adjacent buildings and infrastructures, with a reduction
39 of the initial installation costs, compared to conventional geothermal solutions (Boënnec, 2008; Adam and
40 Markiewicz, 2009; Preene and Powrie, 2009; Bouazza et al., 2011; Barla et al., 2016).

41 In principle, all structures in contact with the ground can be used as energy geostructures (Brandl, 2006; Laloui
42 and Di Donna, 2013; Pahud, 2013; Barla and Di Donna, 2016a; Soga and Rui, 2016). Piles, micropiles,
43 diaphragm walls, anchors, tunnel linings can be mentioned among this technology. Recent studies focused on
44 the application of this technology to tunnels (Barla and Perino, 2014a; Barla et al., 2015, 2016, 2017, 2019;
45 Moormann et al., 2016; Bourne-Webb and da Costa Gonçalves, 2016; Bourne-Webb et al., 2016; Buhmann et
46 al., 2016; Di Donna and Barla, 2016; Barla and Di Donna, 2018). In comparison with other energy

47 geostructures, energy tunnels are characterized by two main differences. Firstly, their much more extensive
48 linear development implies a bigger surface in contact with the ground that could be thermally activated.
49 Secondly, the tunnel's inner side lies in contact with the tunnel air, which could act as a source of heat in winter
50 due to trains circulation. The fundamental three-fold role played by groundwater flow on the surrounding
51 environment temperature, internal air distribution and on thermal performance and heat exchanger systems
52 operation temperature was studied by many authors (Barla and Perino, 2014b, 2014c; Barla et al., 2016; Di
53 Donna and Barla, 2016; Zhang et al., 2016; Bidarmaghz et al., 2017; Bidarmaghz and Narsilio, 2018).
54 Nevertheless, the effect of groundwater flow direction cannot be found in any of these studies.

55 Barla and Di Donna (2016b) have proposed a novel segmental lining named Enertun which has been installed
56 and tested by a real-scale energy tunnel prototype in the tunnel under construction of the Turin Metro Line 1
57 South Extension (Barla et al., 2019). The prototype allowed collecting a large amount of data on the thermal
58 and structural performance of the lining.

59 Few studies have dealt with the thorough investigation of the thermal performance of energy tunnels based
60 both on a monitored, full-scale site and on numerical results. It is the scope of this paper to analyse the original
61 data collected for that pertaining to the thermal performance of the Enertun prototype in both the ground and
62 the air configuration in order to investigate the energy efficiency of thermal activation of tunnels. Monitoring
63 data allowed to calibrate a thermo-hydraulic numerical model and to reproduce the thermal performance in the
64 conditions of the site. Corroboration of numerical models was not possible in previous literature for the Turin
65 case given the unavailability of a testbed (Barla et al., 2014; Barla et al., 2016). Then, the calibrated parameters
66 are used to generalise the results to different ground and environmental conditions, with particular reference
67 to the still unstudied role of groundwater flow direction.

68 **2. Experimental thermo-active tunnel prototype**

69 In order to test the thermal performance of the newly patented energy segment, an experimental site of Enertun
70 segmental lining was installed in the tunnel of Turin Metro Line 1 South Extension under construction, about
71 42 m northwards from Bengasi station, in the Lingotto-Bengasi section (Figure 1).

72 The experimental site is described in detail in Barla et al. (2019). Two rings of segmental lining were fully
73 equipped with a total of 12 Enertun segments, for a total longitudinal length of 2.80 m. Two nets of pipes are
74 included in the segments, one close to the extrados (tunnel surface in contact with the ground), the other close
75 to the intrados (tunnel surface in contact with the air).

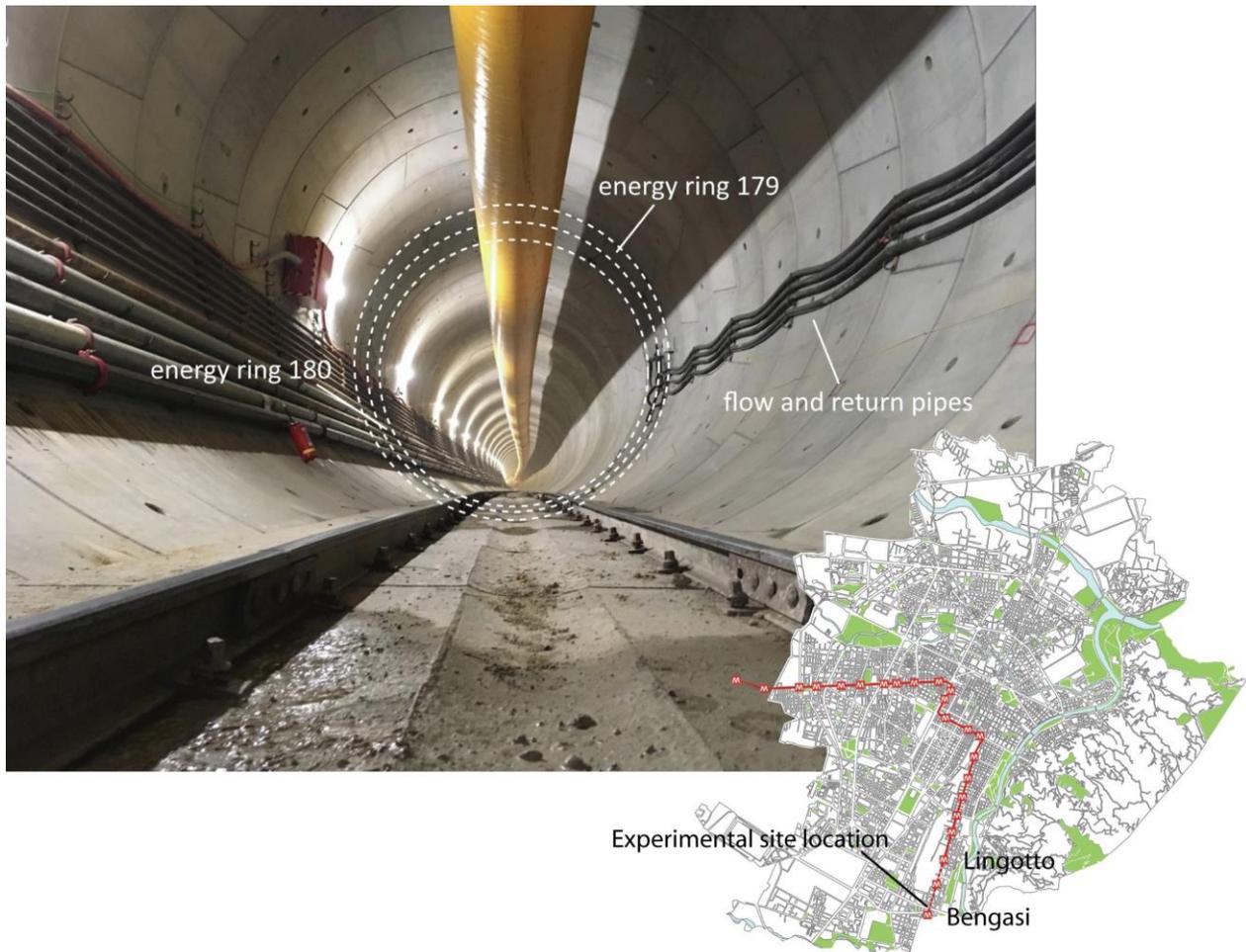


Figure 1. View of the Enertun experimental site and its location along the Turin Metro Line 1.

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79 Energy rings were placed on site by the TBM at the beginning of July 2017 about 42 m from the entrance of
80 the station. Installation chainage was decided in accordance with the construction site managers with the
81 intention to minimize impact on the construction operations.

82 The Turin subsoil is constituted by glaciofluvial formations and hosts an unconfined aquifer (Barla and Barla,
83 2012). The geological profile in correspondence of the energy tunnel prototype (Figure 2) was obtained from
84 the inspection of boreholes drilled ad hoc by the construction site along the line and by previous knowledge
85 for the city of Turin (Barla and Barla, 2012). Below a shallow backfill layer, a sand and gravel unit from loose
86 to weakly cemented (cementation included in the range 0-25%) can be highlighted. The tunnel is located within
87 an aquifer, completely below the groundwater table surface whose depth oscillates between 11.7 and 12.4 m.
88 Based on the data recorded by nearby piezometers, it is possible to detect a West-to-East groundwater flow
89 and an hydraulic gradient in the range 0.3-0.5%.

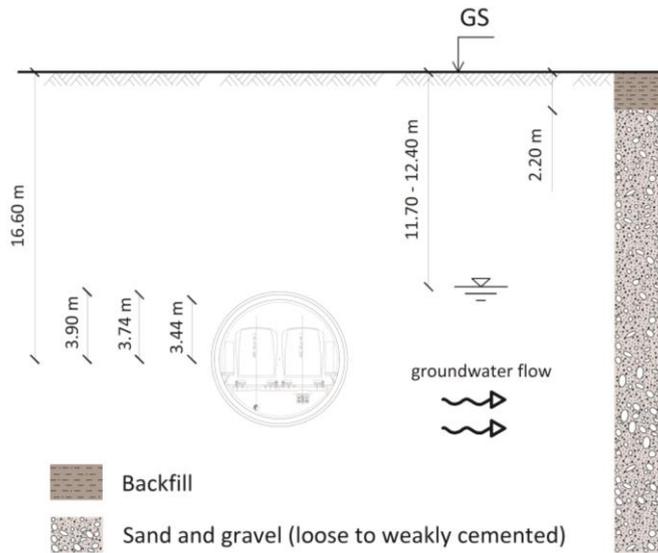


Figure 2. Hydrogeological cross section in correspondence of the energy tunnel prototype.

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93 A heat pump device characterized by a useful thermal power in the range 4.8 and 7.4 kW was installed together
 94 with two hydraulic pumps that circulate the heat carrier fluid along the primary circuit. This fluid is a propylene
 95 glycol mixed with water allowing to work down to a temperature of $-20\text{ }^{\circ}\text{C}$. Because of the experimental
 96 nature of the project, the secondary circuit of the heat pump is represented by a fan coil unit located close to
 97 the heat pump. Therefore, there were no real end users benefitting from the tests, but the heat was dissipated
 98 in or extracted from the air.

99 Given the complexity of the system to be investigated and the experimental nature of the project, a
 100 comprehensive monitoring system was installed to monitor the energy tunnel performance both from a thermal
 101 and a structural point of view (for the sake of brevity the drawings are not reported here, but the interested
 102 reader can refer to Barla et al. (2019)). The two energy rings were instrumented with a specifically designed
 103 monitoring system to observe stresses, strains and temperatures in the lining.

104 The aim of the experimental campaign was to evaluate efficiency and reliability of the prototype thermal
 105 activation together with its possible impacts on the lining. Monitoring started in September 2017 with the
 106 assessment of undisturbed conditions at the site. Differential stresses, differential strains and temperatures in
 107 the lining were recorded under natural fluctuations of tunnel air temperature (it has to be recalled that the site
 108 was still under construction, therefore external air temperatures are reflected in tunnel air).

109 The reversible heat pump made it possible to simulate summer and winter heating and cooling conditions.
 110 Depending on the fluid inlet temperature, this is warmed or cooled by the surrounding ground. During winter
 111 2017/2018 heating mode tests were completed with both rings operating in parallel. At the end of each test the
 112 heat pump was turned off for long enough to ensure returning to the initial undisturbed thermal and mechanical
 113 conditions. Cooling mode test were performed during summer 2018. The total list of tests performed is given
 114 in Table 1, with 8 tests involving the ground circuit in heating mode (both continuous and cyclic), 2 tests where
 115 the ground circuit worked in cooling mode and 2 more tests where the air circuit was used to cool the tunnel
 116 air. Different volumetric flow rates and durations were chosen in order to collect a sound database for
 117 subsequent numerical back-analysis.

118

Table 1. List of the tests performed.

Test code	Circuit	Mode	Volumetric flow rate [m ³ /h]	Fluid velocity [m/s]	Starting time [dd/mm/aa hh:mm]	Ending time [dd/mm/aa hh:mm]	Duration [d]
-----------	---------	------	--	----------------------------	---	---------------------------------------	-----------------

180215_G_H_T45_179180	Ground	Heating	1.3	0.90	15/02/2018 14:13	17/02/2018 09:57	1.82
180218_G_H_T45_179180	Ground	Heating	1.3	0.90	18/02/2018 13:57	20/02/2018 09:50	1.83
180222_G_H_T45_179180	Ground	Heating	1.3	0.90	22/02/2018 14:32	26/02/2018 12:50	3.93
180305_G_H_T45_179180	Ground	Heating	0.8	0.55	05/03/2018 14:05	07/03/2018 14:17	2.01
180309_G_H_T45_179180	Ground	Heating	1.0	0.69	09/03/2018 13:59	12/03/2018 15:47	3.07
180320_G_H_T45_179180	Ground	Heating	1.3	0.90	20/03/2018 14:00	28/03/2018 11:11	7.82
180407_G_H_T45_179180*	Ground	Heating	1.3	0.90	07/04/2018 10:00	16/04/2018 18:00	9.33
180508_G_H_T45_179180*	Ground	Heating	1.3	0.90	08/05/2018 10:04	20/05/2018 18:00	12.33
180727_G_C_T10_179180	Ground	Cooling	1.4	0.97	27/07/2018 11:29	30/07/2018 11:31	3.00
180801_A_H_T55_179180	Air	Heating**	1.3	0.90	01/08/2018 10:56	03/08/2018 15:56	2.21
180804_A_H_T55_179180	Air	Heating**	1.3	0.90	04/08/2018 20:00	06/08/2018 10:00	1.58
180807_G_C_T10_179180	Ground	Cooling	1.4	0.97	07/08/2018 12:22	09/08/2018 07:31	1.80

119 *Cyclic tests with heat pump on between 10:00 and 18:00.

120 **In this case the heat pump heating mode corresponds to tunnel cooling.

121 3. Energy performance of the prototype

122 The tests performed and listed in Table 1 allowed to investigate the energy performance of the experimental
 123 prototype of energy tunnel. The following considerations are then specifically referred to the conditions in
 124 which the prototype was tested, that is during the construction of the tunnel. Nevertheless, the data collected
 125 were particularly valuable to calibrate a thermo-hydraulic numerical model for the purpose of extending the
 126 discussion to other conditions (temperature boundary conditions, thermal ground properties, etc.), as debated
 127 in the following paragraphs.

128 For each test the inlet and outlet temperature over the whole duration were recorded by the heat pump. The
 129 procedure to evaluate the energy performance was as follows:

- 130 - The difference of temperature ΔT (in $^{\circ}C$) between outlet and inlet was computed at any given time t_n
 131 when data were available

$$132 \Delta T(t_n) = |T_{outlet}(t_n) - T_{inlet}(t_n)| \quad (1)$$

- 133 - The heat flow, also called thermal power, $\Delta \dot{Q}$ (in W or J/s) was derived from the first law of
 134 thermodynamics, by computing the enthalpy flow $\Delta \dot{H}$ in the case of convective heat transfer, that is
 135 the main heat transfer mechanism taking place within the pipes

$$136 \Delta \dot{Q}(t_n) = \Delta \dot{H} = \dot{M} c_p \Delta T(t_n) \quad (2)$$

137 where \dot{M} is the mass flow rate expressed in kg/s , c_p is the specific heat capacity at constant pressure
 138 in $J/(kg \cdot ^{\circ}C)$ and ΔT is the temperature difference in $^{\circ}C$

- 139 - The thermal energy extracted or injected for each timeframe $\Delta Q(t_n)$ (in kWh) was computed as the
 140 trapezoidal area under the curve $\Delta \dot{Q}(t)$

$$141 \Delta Q(t_n) = \frac{[\Delta \dot{Q}(t_n) + \Delta \dot{Q}(t_{n-1})] \cdot [t_n - t_{n-1}]}{2} \quad (3)$$

142 - The total energy extracted or injected during the test from the two energy rings was obtained by the
 143 following summation

$$Q = \sum_{t=t_{in}}^{t=t_{fin}} \Delta Q(t) \quad (4)$$

144

145 - The average thermal power \dot{Q} was obtained by dividing the total energy extracted by the test duration.
 146 From \dot{Q} it is possible to calculate the average thermal power extracted or injected per meter of tunnel
 147 lining or per square meter of tunnel lining by using the total longitudinal length of the prototype (2.8
 148 m, in W/m) or its total contact surface area (65.8 m^2 for the ground circuit and 60.5 m^2 for the air
 149 circuit, in W/m^2).

150 Table 2 summarizes the energy performance expressed in terms of thermal power (in W/m and in W/m^2) and
 151 of total thermal energy (in kWh) obtained for each of the tests listed in Table 1. It is pointed out that water,
 152 with 10% glycol was assumed in the computations, therefore c_p was equal to 4070 $J/(kg \cdot ^\circ C)$ and water density
 153 to 1009.6 kg/m^3 .

154 **Table 2.** Energy performance of the prototype in terms of heat flux and thermal energy for each of the tests performed.

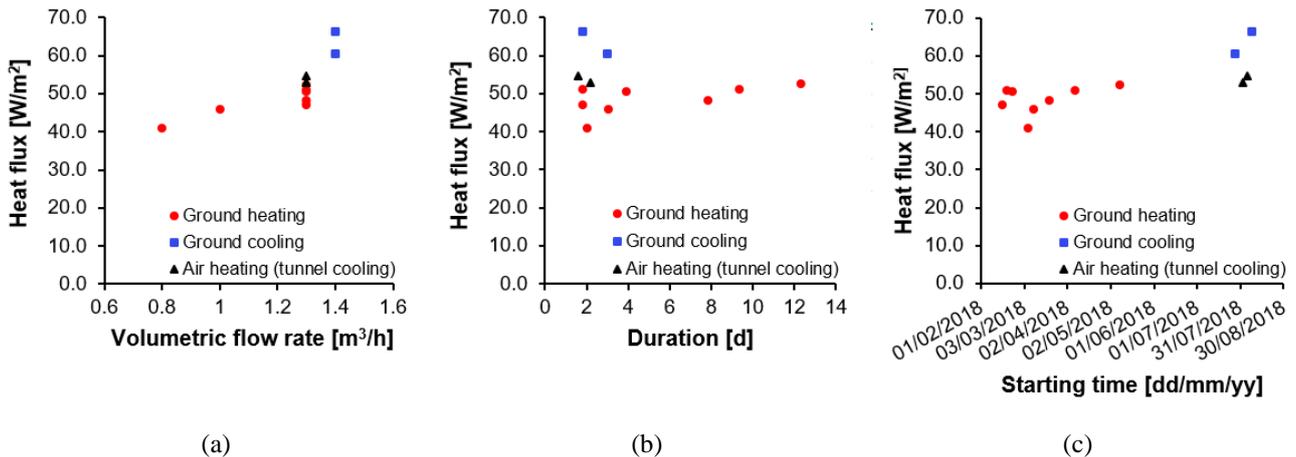
Test code	Thermal power		Thermal energy
	[W/m]	[W/m ²]	[kWh]
180215_G_H_T45_179180	1105	47.0	135.35
180218_G_H_T45_179180	1198	51.0	147.25
180222_G_H_T45_179180	1188	50.6	313.75
180305_G_H_T45_179180	959	40.8	129.44
180309_G_H_T45_179180	1076	45.8	222.34
180320_G_H_T45_179180	1135	48.3	601.12
180407_G_H_T45_179180	1198	51.0	250.50
180508_G_H_T45_179180	1233	52.5	340.64
180727_G_C_T10_179180	1421	60.5	286.59
180801_A_H_T55_179180	1142	52.8	169.47
180804_A_H_T55_179180	1179	54.6	125.48
180807_G_C_T10_179180	1559	66.4	86.85

155

156 Although the total number of tests is limited and do not allow for a statistical analysis, some additional
 157 considerations can be given by observing Figure 3a-c. From Figure 3a a nearly linear relationship between the
 158 volumetric flow rate of the fluid within the pipes and the heat flux is shown, that is heat flux increases with
 159 increasing flow rates. Heat fluxes between 41 and 53 W/m^2 were obtained considering both the continuous and
 160 the two cyclic tests. The energy performance was higher for ground cooling mode, mainly due to the higher
 161 flow rate and to the higher distance in temperature between the ground and the heat carrier fluid. When the air
 162 circuit was operated in tunnel cooling mode, heat flux values were similar to those of the ground heating and
 163 cooling tests. However, it has to be remarked that higher ranges of inlet and outlet temperatures occurred in
 164 this case, with a beneficial effect on the coefficient of performance of the heat pump.

165 In Figure 3b heat flux is plotted versus the test duration. No particular trends can be highlighted; therefore, the
 166 energy efficiency does not depend on the test duration and comparable thermal powers were obtained also in
 167 the case of longer tests, allegedly due to the favourable groundwater thermal recharge.

168 Figure 3c is intended to investigate any induced effect of the period of the year during which the test was
 169 carried out. The performance is seen only marginally affected leading to the conviction that it will be
 170 negligible during real operation of the tunnel, when the influence of external climatic conditions will be even
 171 lower than during the construction of the tunnel.



172

173
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Figure 3. Energy tunnel thermal performance dependence on (a) heat carrier fluid volumetric flow rate, (b) test duration and (c) period of the year.

175 4. Numerical investigation of the thermal behavior of the prototype

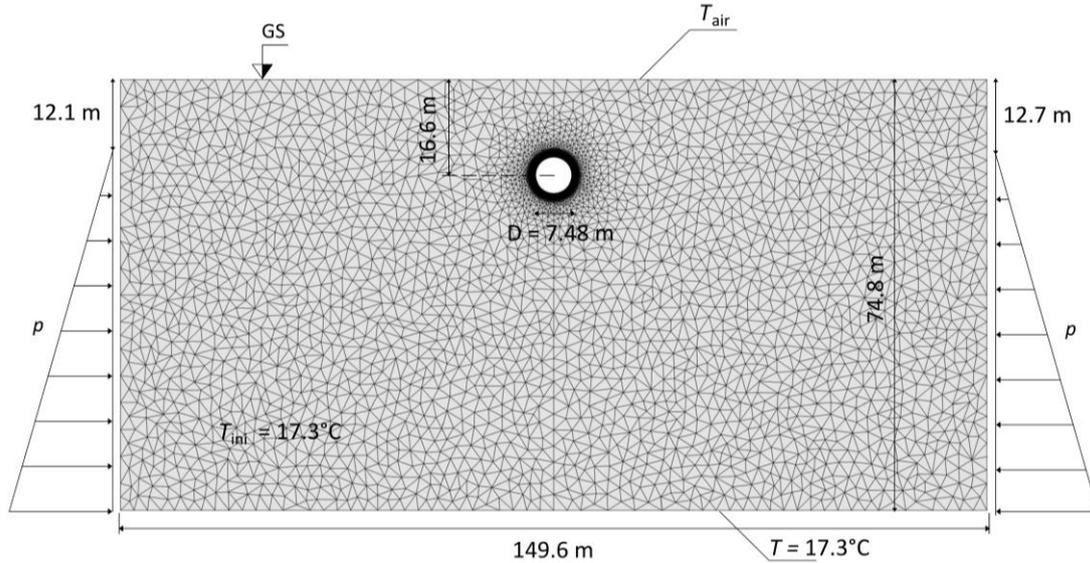
176 The collection of experimental data concerning the real thermal behaviour of the energy tunnel prototype was
 177 used to draw some conclusions about its thermal performance. This is of particular relevance as no such results
 178 are available in literature for Italy and for hydrogeological conditions such as those existing in Turin. However,
 179 the conditions of the experimental campaign carried out are not fully representative of the general case of an
 180 operational tunnel, mainly because of the different temperature variations of the tunnel internal air.
 181 Nevertheless, this situation can be investigated by taking advantage of a three-dimensional, time-dependent,
 182 coupled thermo-hydraulic numerical model, that was first calibrated and then validated on the experimental
 183 results. This task is described in the following and is aimed at developing some updated design charts, in the
 184 path of the ones depicted in Di Donna and Barla (2016).

185 A 3D numerical model was built with the FEM software Feflow (Diersch, 2009) to reproduce the combined,
 186 transient thermo-hydraulic behaviour of the two Enertun rings installed in the experimental site. The TH
 187 problem is governed by mass conservation, energy conservation equations, and Darcy's velocity law, written
 188 in the Eulerian coordinate system for a saturated medium composed of a solid and a liquid (water) phase.
 189 The model, whose cross section is shown in Figure 4, is 74.8 m high and 149.6 m wide, with a thickness of
 190 8.4 m, for a total of 6 rings (the two middle rings are the energy rings). The external diameter of the tunnel is
 191 7.48 m, with a 30 cm-thick concrete lining. An 11 cm-thick layer of grout all around the lining is also
 192 reproduced. A preliminary assessment of the appropriate boundary conditions to be adopted at the intrados of
 193 the tunnel to reproduce the influence of internal air was carried out. First, a 30-cm thick air layer was included
 194 in the model by assigning moving air thermal properties. Then, this layer was deactivated and a heat transfer
 195 boundary condition was applied, by computing the corresponding heat transfer coefficient. For the subsequent
 196 analyses the second boundary condition was adopted to reduce the total number of finite elements in the model.

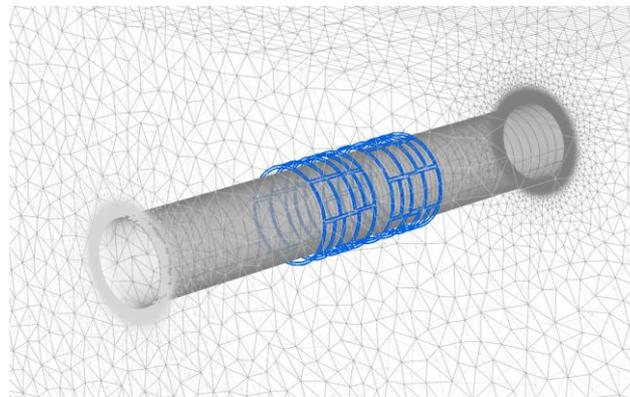
197 The model is discretized into 2760016 triangular prismatic elements (49286 per layer) with 1420953 nodes
 198 (24929 per slice). The pipes, both ground-side and air-side, in the two equipped rings were accurately modelled
 199 reproducing the real geometry (segments rotated from one ring to another, asymmetric pipes layout along the
 200 longitudinal direction, segments different shapes and size) with one-dimensional elements, the so called
 201 "discrete features" (shown in blue in Figure 5), with a cross section area of 201 mm², corresponding to an
 202 external diameter of 20 mm and a thickness of 2 mm.

203 Both thermal and hydraulic boundary conditions were set. As shown in Figure 4, the initial temperature
 204 throughout the model was set at 17.3°C, as resulting from the interpolation of three measurements in the area
 205 of the experimental site (two piezometers and an extensometer well). The time series of the external air
 206 temperature was applied on the upper boundary of the model, which represents the free surface, whereas a
 207 constant value of 17.3°C was assigned to the lower boundary. On the tunnel internal boundary, the temperature
 208 was fixed following the data coming from the monitoring system. It should be remarked that the dual contact

209 of energy tunnel linings with the ground on one side and with the air on the other side is a peculiarity typical
 210 of tunnels and diaphragm walls. This is not an issue for energy piles, for example, and adds a degree of
 211 complexity and uncertainty to the boundary conditions that should be applied at the intrados to best recreate
 212 thermal conditions existing in situ. The hydraulic boundary conditions consist of a constant hydraulic head on
 213 the left and right sides, with different values on the two sides to allow a groundwater flow of 1.5 m/day from
 214 East to West and representative of a groundwater table depth of about 12.4 m at the tunnel centerline location,
 215 as measured in situ. Above the phreatic surface, air thermal properties were assigned.



216
 217 **Figure 4.** Cross section of the 3D FEM model with indication of thermal and hydraulic boundary conditions.
 218



219
 220 **Figure 5.** 3D view of the pipes circuit (expansion factor along longitudinal axis for a better view of the pipes network).

221 The numerical model was calibrated by considering the continuous ground heating mode test
 222 180320_G_H_T45_179180, involving both rings working in parallel and characterized by a longer duration
 223 (see Table 1). To initialize the model and obtain a representative thermo-hydraulic state at the beginning of the
 224 test, a 30-days preliminary simulation was carried out with no thermal activation of the lining. At the end of
 225 this stage, a constant fluid velocity (0.9 m/s, Table 1) and a variable inlet temperature were imposed at the
 226 pipes inlets (velocity was also imposed at the outlets to keep it constant through the pipes), based on the
 227 monitoring data, for the whole length of the test.

228 First-trial hydraulic and thermal properties were obtained by previous studies (Barla et al., 2015, 2018), with
 229 the exception of the concrete thermal conductivity, which was obtained by means of hot guarded plate tests
 230 performed in the laboratory on the same concrete used for the precast Enertun segments. The calibration
 231 involved a number of trials. The values of a couple of thermal parameters, i.e. grout thermal conductivity and
 232 intrados heat transfer coefficient, were slightly modified, in the unavailability of any direct experimental

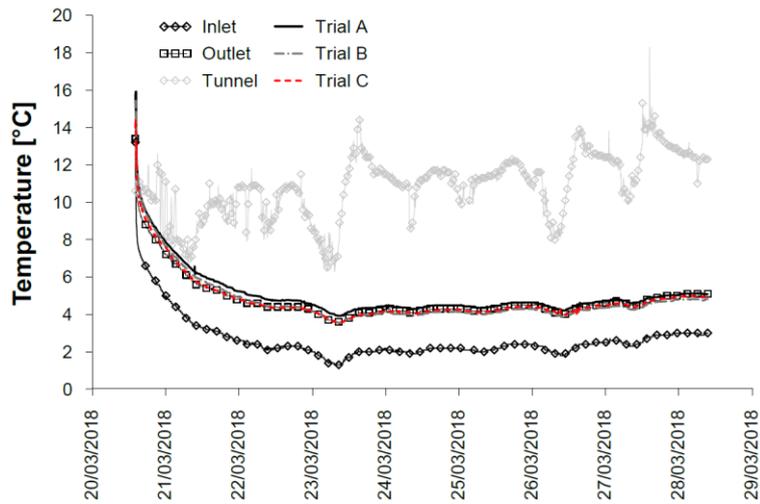
233 evaluation, until reaching a good superposition of simulation and monitoring outlet temperature. In particular,
 234 grout thermal conductivity was first assumed equal to the one for concrete and then reduced to 0.655 W/mK,
 235 as found by Allan and Kavanaugh (1999) for a cement & bentonite grout (the same grout composition adopted
 236 for Turin ML1 rings), to better fit experimental data. The adopted thermal conductivity value appears
 237 reasonable as no special mix design enhanced for thermal performance was adopted for the grout by the
 238 contractor. Material properties used in the numerical model are listed in Table 3 (note that blank cells mean
 239 that the same value as in Trial A was assumed), while Figure 6 exemplifies calibration results. The ground
 240 around the tunnel was assumed thermally isotropic and homogeneous.

241
 242 **Table 3.** Material properties used during the calibration phase of the numerical model.

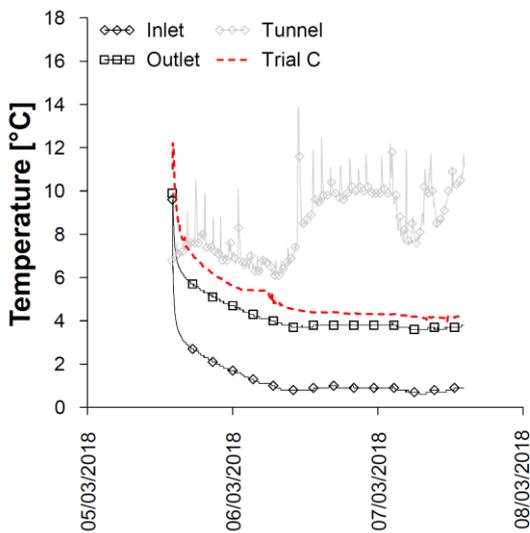
Material	Property	Symbol	Unit	Trial A	Trial B	Trial C
Ground	Horizontal hydraulic conductivity	K_{xx}, K_{zz}	m/s	4.150E-03		
	Vertical hydraulic conductivity	K_{yy}	m/s	2.075E-04		
	Specific storage	S_y	1/m	1.0E-04		
	Porosity	n	-	0.25		
	Fluid-phase thermal conductivity	λ_w	W/mK	0.65		
	Solid-phase thermal conductivity	λ_s	W/mK	2.8		
	Fluid-phase volumetric thermal capacity	$\rho_w c_w$	MJ/(m ³ K)	4.2		
	Solid-phase volumetric thermal capacity	$\rho_s c_s$	MJ/(m ³ K)	2		
	Transverse aquifer thermal dispersivity	α_T	m	0.31		
	Longitudinal aquifer thermal dispersivity	α_L	m	3.1		
Tunnel lining	Specific storage	S_y	1/m	1.0E-04		
	Solid-phase thermal conductivity	λ_s	W/mK	1.12		
	Solid-phase volumetric thermal capacity	$\rho_s c_s$	MJ/(m ³ K)	2.19		
	Horizontal hydraulic conductivity	K_{xx}, K_{zz}	m/s	1.0E-16		
	Vertical hydraulic conductivity	K_{yy}	m/s	1.0E-16		
	Porosity	n	-	0		
	Transverse thermal dispersivity	α_T	m	0.5		
Longitudinal thermal dispersivity	α_L	m	5			
Pipes	Specific storage	S_y	1/m	1.0E-04		
	Fluid-phase thermal conductivity	λ_w	W/mK	0.542		
	Fluid-phase volumetric thermal capacity	$\rho_w c_w$	MJ/(m ³ K)	4.11		
	Longitudinal thermal dispersivity	α_L	m	5		
	Cross-sectional area	A	m ²	2.01E-04		
	Hydraulic aperture	b	m	0.8		
Grout	Specific storage	S_y	1/m	1.0E-04		
	Solid-phase thermal conductivity	λ_s	W/mK	1.12	0.655	0.655
	Solid-phase volumetric thermal capacity	$\rho_s c_s$	MJ/(m ³ K)	2.19		
	Horizontal hydraulic conductivity	K_{xx}, K_{zz}	m/s	1.0E-16		
	Vertical hydraulic conductivity	K_{yy}	m/s	1.0E-16		
	Porosity	n	-	0		
	Transverse thermal dispersivity	α_T	m	0.5		
Longitudinal thermal dispersivity	α_L	m	5			
Air layer	Heat transfer coefficient	Φ	W/m ² K	1.77	1.77	5.30

243
 244 In Figure 6 it is possible to notice that the measured outlet temperature and the computed one are highly
 245 comparable, both in trial B and C, testifying a good calibration of the numerical model. However, trial C is the
 246 one that best fits also other tests, as demonstrated in Figure 7a-d that analyzes the results obtained during the
 247 validation phase for four more tests (two ground heating tests with different volumetric flow rates, one ground
 248 cooling test and one air heating test). The same procedure (30 days-initialization and test simulation) was
 249 followed also for the validation analyses. It is pointed out that a number of combinations of thermal and
 250 hydraulic parameters could yield a good match with the experimental outputs, but it stands to reason that the
 251 found set is fairly appropriate as comparison with a number of tests was undertaken.

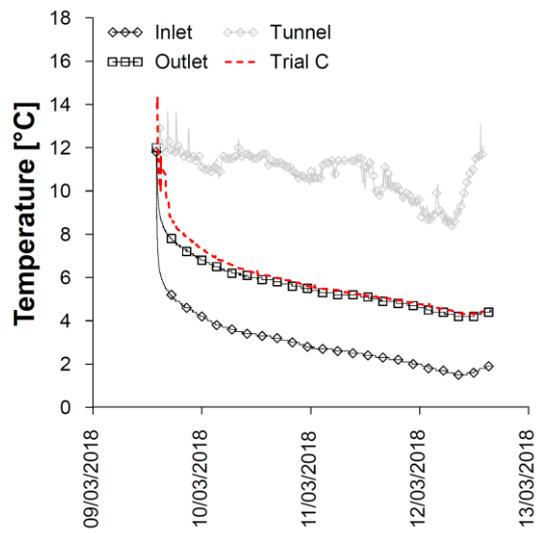
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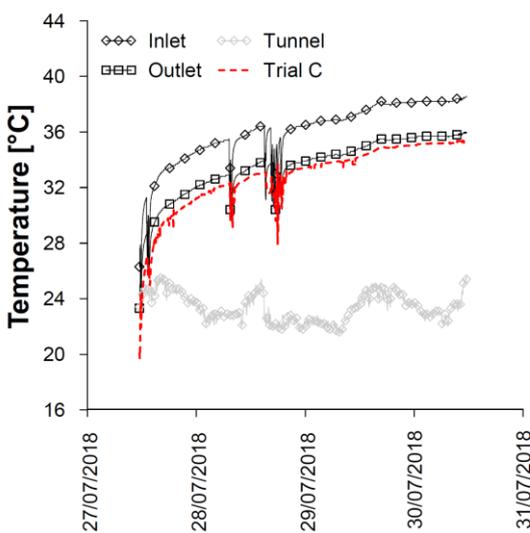
253
254 **Figure 6.** Comparison between measured and computed circuit outlet temperature: test 180320_G_H_T45_179180
255 (calibration phase).



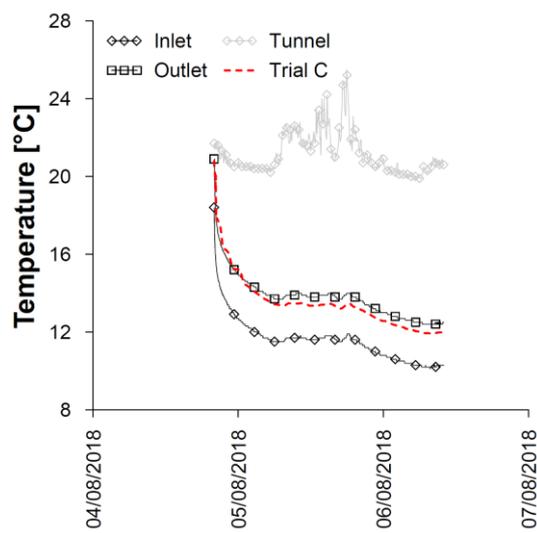
(a)



(b)



(c)



(d)

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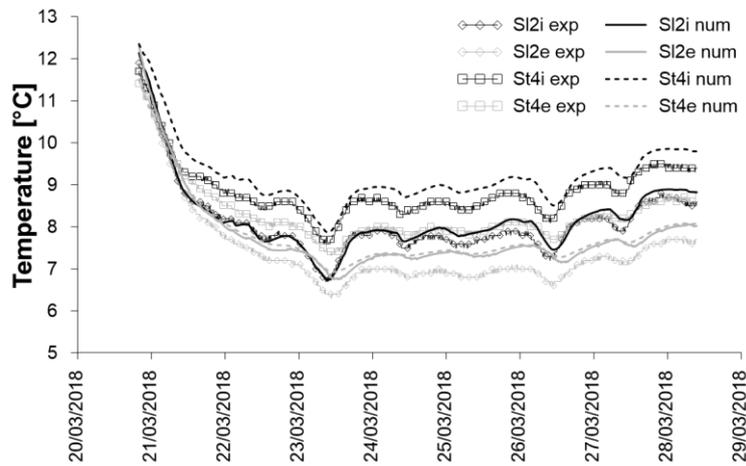
260 **Figure 7.** Comparison between measured and computed data: (a) test 180305_G_H_T45_179180, (b) test
 261 180309_G_H_T45_179180, (c) test 180727_G_C_T10_179180 and (d) 180804_A_H_T55_179180 (validation phase).

262 This is even more true noting that the temperatures computed numerically during the calibration phase, at four
 263 different locations in the lining, well reflect those measured by vibrating wire strain gauges at the intrados and
 264 at the extrados of the lining (see Figure 8a), considering that the embedded thermistor accuracy is 0.5°C.

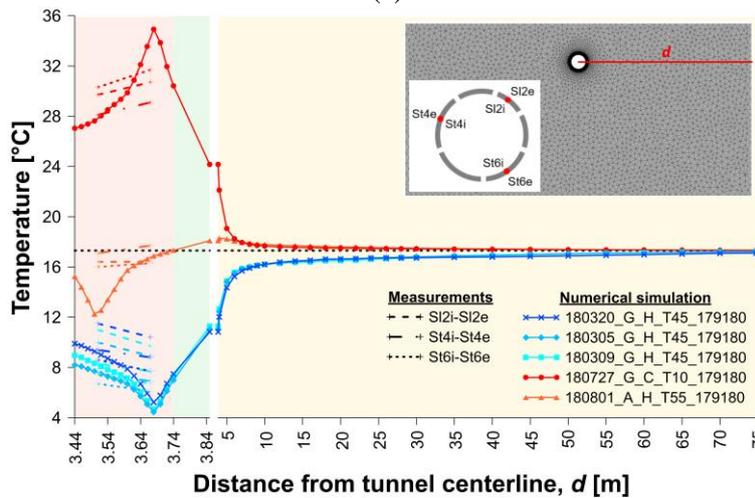
265 Figure 8b depicts the computed downstream temperature from the tunnel lining intrados to the model right
 266 boundary at the end of the simulated tests, as well as the monitored temperature within the lining in
 267 correspondence of the location of three pairs of strain gauges with embedded thermistors (note that two
 268 different scales are used to better visualize the lining thermal profile and that the different background colours
 269 indicate the concrete layer, the grout layer and the ground; in SI2i, SI2e, St4i, St4e, St6i St6e *i* means intrados
 270 and *e* means extrados). A good match between computed and recorded results emerges. Moreover, it can be
 271 noted that for the test 180309_G_H_T45_179180 the thermal alteration is smaller than 1°C at 14 m distance,
 272 while it is even lower in the other tests. Unfortunately, monitoring data of surrounding rock temperature are
 273 not available. Indeed, during the design phase, it was ascertained that no downstream existing wells were
 274 available perpendicularly to the tunnel axis along the location of the energy tunnels. On the other hand, ad hoc
 275 wells could not be drilled for economic reasons as well as logistic constraints (the construction site is in the
 276 middle of a congested roads crossing).

277 According to the previous observations, the set of parameters C in Table 3 was adopted in the following.

278



(a)



(b)

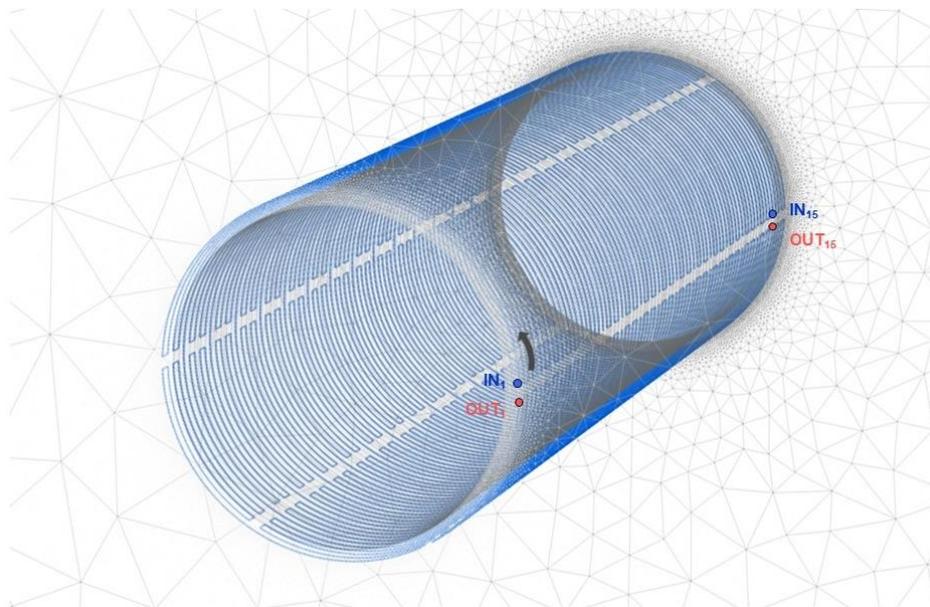
279 **Figure 8.** (a) Comparison between measured and computed lining temperature at the extrados and at the intrados: test
 280 180320_G_H_T45_179180 (calibration phase); (b) Computed downstream temperature at the end of the simulated tests.

282

283 **5. Generalization to different ground and environmental conditions**

284 **5.1. Developing design charts**

285 The experimental data collected during the campaign accomplished in 2017-2018 along Turin ML1 South
286 Extension were essential to demonstrate the robustness and reliability of the coupled numerical model. This
287 had not been possible so far, which is why preliminary analyses had been described in literature. However, the
288 feasibility and efficiency of energy tunnels could be legitimately argued when examining site-specific
289 conditions different from that of the prototype described. To try to provide a comprehensive estimation of the
290 thermal performance of the technology in a number of environmental situations, the design charts presented in
291 Di Donna and Barla (2016), referred to previous configurations of the net of pipes, were updated for the
292 Enertun scenario and for three different groundwater flow directions, that is parallel, forming an angle of 45°
293 and running perpendicular to the tunnel axis. The analysis of the groundwater flow direction is an aspect of
294 novelty in the framework of energy tunnels in comparison to previous literature. To this aim, a new thermo-
295 hydraulic numerical model was built, made of 15 rings working in parallel and of six hypothetical energy
296 segments of equal size (Figure 9). With special reference to the cases of parallel and oblique groundwater flow,
297 results are pertaining to the eighth intermediate ring. The geometry of the tunnel is that of Turin ML1 SE. Of
298 course, this could differ for other projects, but the size under study is quite representative of most typical urban
299 tunneling situations. Further characteristics of the models are summarized in Table 4 (material properties not
300 listed here can be found in Table 3). Temperature was fixed equal to the ground value at the top and bottom
301 boundary, without considering the influence of atmospheric temperature oscillation. Different ground
302 temperatures and corresponding tunnel temperatures were adopted to study various climatic conditions (Table
303 4). Average winter and summer temperatures measured in an already operational section of Turin Metro Line
304 1, that is 13.1 and 26.7°C respectively, were related to a ground temperature of 15°C. The seasonal analyses
305 carried out involved 30 days of thermal initialization followed by 30 days of thermal activation. A sensitivity
306 study was also performed by varying one by one fluid inlet temperature, fluid velocity, pipes size and heat
307 transfer coefficient at the intrados elements.



308
309 **Figure 9.** Geometry of the network of pipes embedded in the model adopted for the construction of design charts (only
310 inlets and outlets of rings 1 and 15 are highlighted for illustrative purposes).

311 **Table 4.** Main properties of the base and sensitivity analyses models

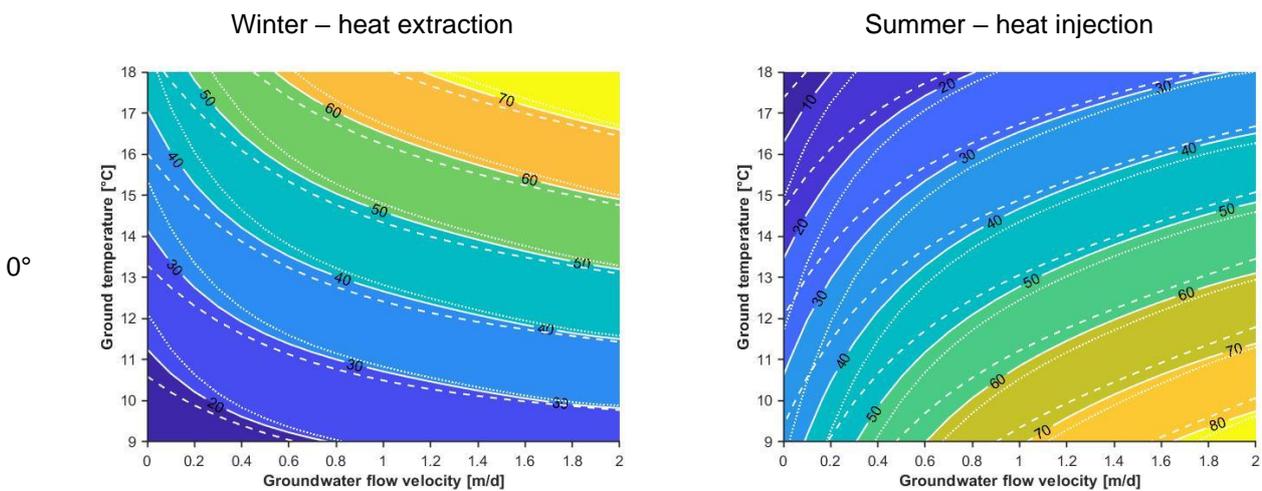
Characteristic	Unit	Value
Pipes size	mm	20x2
Inlet temperature (winter)	°C	4
Inlet temperature (summer)	°C	28

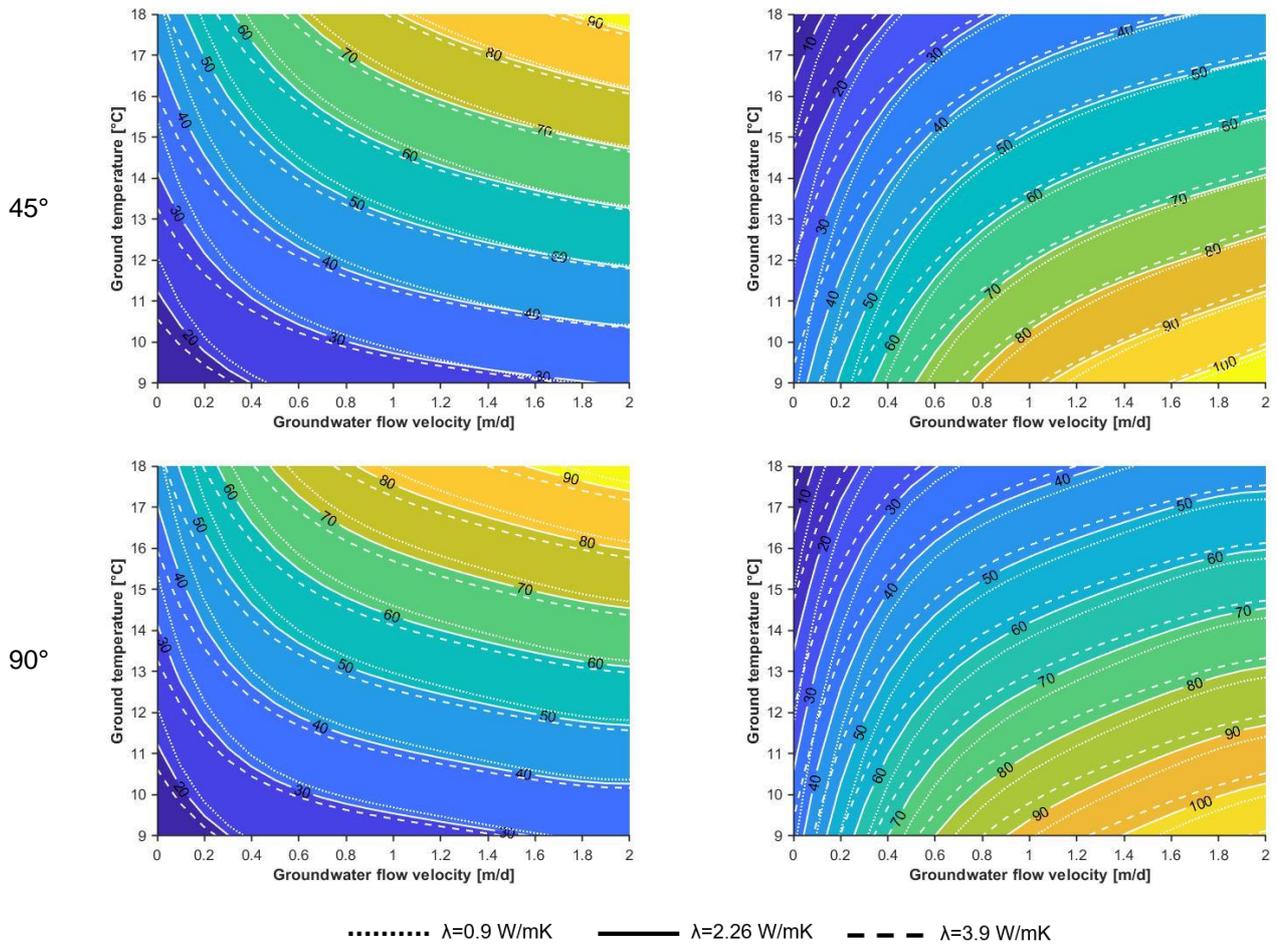
Heat carrier fluid velocity	m/s	0.9
Grout thermal conductivity	W/mK	2
Concrete thermal conductivity	W/mK	1.5
Grout thickness	cm	11
Ground temperature	°C	9-12-15-18
Heat transfer coefficient	W/(m ² K)	5.3
Tunnel temperature (winter)	°C	Variable with ground temperature 7.1-10.1-13.1-16.1
Tunnel temperature (summer)	°C	Variable with ground temperature 20.7-23.7-26.7-29.7
Ground thermal conductivity	W/mk	0.9-2.26-3.9
Groundwater flow	m/d	0-0.5-1-1.5-2

312

313 The resulting design charts can be seen in Figure 10 for winter and summer modes and for different
314 groundwater flow directions with respect to the tunnel axis. With different colors the ranges of thermal flux in
315 W/m² are indicated for each triplet of ground temperature, groundwater flow velocity and ground total thermal
316 conductivity. The analyses were carried out for specific triplets, organized on a grid, and then interpolated by
317 using an appropriate polynomial law able to match satisfactorily the discrete, scattered numerical results. The
318 charts related to the case of perpendicular flow are in line with the existing ones, although a one-to-one
319 quantitative comparison is not possible due to different model inputs (presence of grout, different concrete
320 thermal conductivity, pipes size, heat carrier fluid velocity, intrados boundary condition). Considerations
321 drawn by Di Donna and Barla (2016) are confirmed here. No matter the flow direction, the highest performance
322 is obtained with maximum ground thermal conductivity, maximum groundwater flow, due to the thermal
323 recharge mechanism that allows the ground to return more rapidly to its undisturbed temperature, and with
324 maximum ground temperature in winter and vice versa in summer. As groundwater flow velocity decreases,
325 thermal conductivity starts playing a role, since the dotted and dashed lines representing boundaries between
326 heat flux ranges move away from the continuous ones. For perpendicular groundwater flow winter energy
327 performance is in the range 10-95 W/m², while summer energy performance falls between 10-110 W/m².,
328 slightly higher than in summer. By observing the effect of groundwater flow, it is possible to notice that a
329 substantial increase in performance occurs when going from 0° to 45°, whereas little improvement is
330 attributable to perpendicular flow in comparison to the oblique case. It is reasonable to think that thermal
331 performance does not increase linearly with increasing groundwater tilt angle, but with a gradually decreasing
332 gradient.

333





334

335 **Figure 10.** Updated preliminary design charts showing geothermal potential in W/m^2 for winter and summer conditions
 336 and for different groundwater flow directions with respect to the tunnel axis (0° , 45° and 90°).

337 These charts are particularly useful for the designer interested in evaluating whether it may be worth or not to
 338 invest in the feasibility study of the thermal activation of a tunnel. It is clear that a more detailed study should
 339 be conducted at the design analysis stage, as described for example in Barla and Di Donna (2018) and Baralis
 340 et al. (2018).

341 5.2. Sensitivity analyses

342 To investigate the validity and range of application of the design charts, it is of interest to assess the effect of
 343 other possibly varying design parameters on thermal efficiency. For this reason, some sensitivity analyses were
 344 carried out to explore the influence of different values of fluid inlet temperature T_{in} , fluid velocity v_f , pipes
 345 size d, t (diameter and thickness) and heat transfer coefficient Φ , as shown in Table 5.

346

Table 5. Parameters investigated in the sensitivity analyses.

Design parameter	Unit	Values	
$T_{in,winter}$	$^\circ C$	1	7
$T_{in,summer}$	$^\circ C$	32	36
v_f	m/s	0.4	1.4
$d \times t$	mm	16x2	25x2.3
Φ	W/m^2K	1	15

347

348 The range of variation of the heat transfer coefficient was based on the table reported in Di Donna et al. (2016).
 349 The analyses were conducted for six relevant combinations of groundwater flow velocity and ground

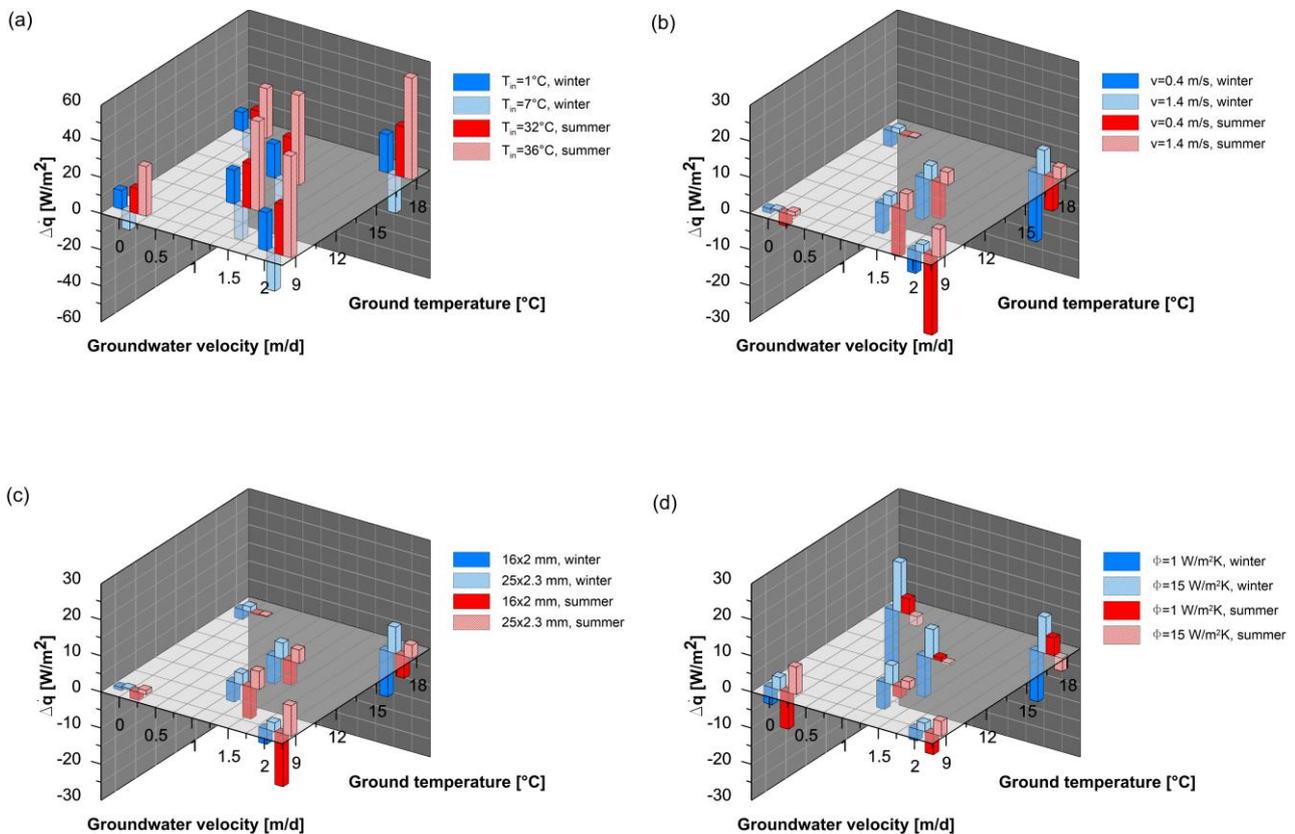
350 temperature (ground thermal conductivity kept to 2.26 W/mK) so that all the chart area is spanned. In the
 351 following each aspect is explored and commented in detail.

352 **Fluid inlet temperature.** The paramount importance of fluid inlet temperature emerges clearly in Figure 11a in
 353 comparison to the other investigated aspects (it is highlighted that in this chart the range is two times that of
 354 the other charts) as it highly affects heat transfer, with variations of the heat flux reaching 56 W/m² in summer
 355 when using the highest temperature. This parameter appears to be strictly dependent on groundwater flow
 356 velocity, as the mechanism of thermal recharge avoids heating or cooling of the surrounding ground thus
 357 improving thermal performance.

358 **Fluid velocity and pipes size.** It can be seen from Figure 11b that the minimum variation in the heat flux occurs
 359 when thermal exchange is minimum (low groundwater flow and low ground temperature in winter, low
 360 groundwater flow and high ground temperature in summer), whereas the maximum variation occurs in the
 361 opposite case. This last is not negligible, hence care should be taken when falling in this area (upper right and
 362 lower right corner of the design chart in winter and summer, respectively). The same goes when assessing the
 363 effect of pipes dimension (Figure 11c), although the maximum variations are lower than in the previous case.

364 **Heat transfer coefficient.** Quite different is the case of sensitivity analyses on the heat transfer coefficient value
 365 (Figure 11d). This coefficient has an effect on the amount of heat flowing from/to the tunnel environment
 366 to/from the lining. When the heat transfer coefficient is 15 W/m²K, the heat flux increases by a maximum of
 367 14 W/m² in winter and by 8 W/m² (or decreases by 4 W/m²) in summer. When the heat transfer coefficient is
 368 1 W/m²K, the heat flux decreases by a maximum of 19 W/m² in winter and by 10 W/m² (or increases by 5
 369 W/m²) in summer. The overall ranges of variation are not too different from that of fluid velocity and pipes
 370 size.

371 The results obtained above, considering a perpendicular groundwater flow, were confirmed by running a
 372 number of relevant analyses for oblique and parallel flow.



373

374 **Figure 11.** Effect of (a) fluid inlet temperature, (b) fluid velocity, (c) pipes size and (d) heat transfer coefficient on
 375 geothermal potential during winter and summer conditions expressed in terms of heat flux variations in the case
 376 perpendicular flow.

377 Based on the sensitivity analyses one can conclude that fluid inlet temperature is the parameter that mostly
 378 affects heat transfer. Hence, to evaluate geothermal potential the following procedure can be followed:

- 379 - assess local groundwater flow direction and choose the appropriate chart;
- 380 - assess local groundwater flow velocity, ground undisturbed temperature and thermal conductivity;
- 381 - based on the previous inputs, evaluate the exchangeable heat \dot{q}^* from the design chart;
- 382 - if an inlet temperature different from 4°C in winter and 28°C in summer is expected, correct \dot{q}^* based
 383 on the following relationship

$$\dot{q} = \dot{q}^* + \Delta\dot{q} \quad (5)$$

384 with

$$\Delta\dot{q}/\Delta T = 3.44 - \frac{v_{gw}^{2.01}}{3.09} + 4.44 * \ln(1 + v_{gw}) \quad \text{in summer} \quad (6)$$

$$\Delta\dot{q}/\Delta T = - \left[3.44 - \frac{v_{gw}^{2.01}}{3.09} + 4.44 * \ln(1 + v_{gw}) \right] \quad \text{in winter} \quad (7)$$

385

386 in the case of perpendicular and oblique groundwater and

$$\Delta\dot{q}/\Delta T = 3.44 - \frac{v_{gw}^{0.74}}{3.05} + 2.75 * \ln(1 + v_{gw}) \quad \text{in summer} \quad (8)$$

$$\Delta\dot{q}/\Delta T = - \left[3.44 - \frac{v_{gw}^{0.74}}{3.05} + 2.75 * \ln(1 + v_{gw}) \right] \quad \text{in winter} \quad (9)$$

387

388 in the case of parallel groundwater, where ΔT is the difference between the actual inlet temperature
 389 and the theoretical one (4 or 28°C depending on the season) and v_{gw} is the groundwater flow
 390 velocity expressed in m/d. The equations above were obtained by direct interpolation of the
 391 computed data.

- 392 - consider a ± 10 W/m² correction to the above obtained value of W/m² to take into account different
 393 fluid velocity, pipes size and heat transfer coefficient.

394 Considering all the above, the design charts can be reliably adopted for a wide range of conditions. Having
 395 said this, it is clear that they cannot be considered as a general and unique indication for the evaluation of the
 396 geothermal potential of an energy tunnel and that a more detailed study should be conducted at the design
 397 analysis stage, by site-specific thermo-hydraulic numerical modelling that include detailed aspects of ground
 398 conditions, site installation and working conditions.

399 As an example, aspects such as the intermittent ratio (i.e. the ratio of interval time to running time as defined
 400 by Ogunleye et al. (2020) and Zhang et al. (2014)) are not explicitly taken into account in the parametric design
 401 charts, especially for the cases of slow or absent groundwater flow. For the cases with a major groundwater
 402 flow, the intermittent ratio is not expected to play a relevant role. Instead, when no groundwater flow is present
 403 at the site, it could be crucial in assessing the feasibility of an energy tunnel project. Specific thermo-hydraulic
 404 analyses should be performed at a later design stage to find an optimization strategy of the intermittent ratio
 405 so that the geothermal resource is not depleted and is properly used. Similarly, different tunnel climates arising
 406 from particular operation conditions (e.g. “hot” tunnels) should be specifically analyzed. Moreover, as winter
 407 and summer cases are considered separately, thus leading to two seasonal design charts, possible unbalanced
 408 heat situations do not emerge and cannot be caught. Long-term yearly analyses should be performed to assess
 409 this issue, both in the case of heating only, cooling only or heating and cooling (this is particularly true for

410 unfavourable hydrogeological conditions and for single-mode operation, i.e. continuous heating only or
 411 cooling only).
 412

413 6. Validation against existing data

414 The design charts here presented were validated against available literature data. A summary of the obtained
 415 results can be observed in Table 6. A very good match is obtained in most of the cases with the actual values
 416 falling within the ranges anticipated by the design charts. This applies to cases based on numerical studies as
 417 well as to real monitored data.

418 Smaller values are shown for the Grand Paris Express B with respect to the computed ones. Here Cousin et al.
 419 (2019) have considered a tunnel temperature as high as 18.96°C and a heat transfer coefficient of 15.13 W/m²K
 420 which certainly has a positive effect on the heat exchange. It is noted that this also leads to substantially
 421 different results from those reported in Bracq et al. (2017) and Fouché et al. (2018) for a similar case study.
 422 Minor difference is also shown for the case of Warsaw NE metro. However, in this case the Authors have
 423 considered adiabatic boundary conditions in the tunnel.

424 The case of Turin ML1 is shown to be slightly more favourable when using the design charts than in the
 425 previous study performed by Di Donna and Barla (2016) and Barla et al. (2016). The reason lies on the fact
 426 that the more efficient Enertun configuration has been used here.

427 **Table 6.** Validation of the design charts against available data of energy tunnels thermal power exchanged with the
 428 ground.

Case study	R/N*	v _{gw} [m/d]	T _g [°C]	λ [W/mK]	q [W/m ²]			
					Result of the study		Design charts	
					Winter	Summer	Winter	Summer
Crossrail (Nicholson et al., 2013, 2014)	N	0	14.8	1.8	10-30	-	22-42	-
Grand Paris Express A (Bracq et al., 2017; Fouché et al., 2018)	N	0	12	1.6-2.4	15-30	10-20	13-33	15-35
Grand Paris Express B – case 2.1 (Cousin et al., 2019)	N	0	13	2.1-2.3	50	-	24-44	-
Jenbach (Frodl et al., 2010; Mayer and Franzius, 2010; Franzius and Pralle, 2011; Buhmann et al., 2016; Moormann et al., 2016)	R	1	10	3.3	18-40	-	18-38	-
Katzenbergtunnel (Franzius and Pralle, 2011)	R	0	13	3	17-25	-	19-39	-
Turin ML1 SE (Di Donna and Barla, 2015; Barla and Di Donna, 2016b, 2018; Barla et al., 2016)	N	1.5	14	2.26	53	74	53-73	58-78
Warsaw NE metro - model 1 (Baralis et al., 2018)	N	0	12	1.61	13	30	11-31	10-30
Warsaw NE metro - model 2 (Baralis et al., 2018)	N	0.09	12	2.40	15	42	17-37	19-39

429 *R=real case study N=numerical study

430 7. Conclusions

431 A comprehensive study on the energy performance of energy tunnels was carried out with the aim of providing
432 quick and effective tools to designers who want to quantify heat exchange in a preliminary phase of the project.
433 The main conclusions are as follows:

- 434 - Thanks to a real scale prototype constituted by a pair of energy rings Enertun-type recently tested for
435 the first time in Italy, an experimental campaign allowed to assess the thermal performance of tunnels
436 in a variety of conditions (different durations and flow rates, heating case, cooling case). From the
437 processing of data collected, it was possible to infer that winter extraction thermal power amounts to
438 47-52.5 W/m², while in summer a range of 60.5-66.4 was obtained. Despite the longest test lasted
439 more than 12 days, long-term tests are not available yet but are planned to be performed during tunnel
440 operation.
- 441 - A 3D time-dependent thermo-hydraulic numerical model was calibrated and validated on the
442 monitored data pertaining to the two experimental Enertun rings so that it was proved to be able to
443 adequately simulate the conditions existing in situ. With respect to previous studies, consideration of
444 a grout layer was included whose thermal conductivity was calibrated ad hoc. Heat transfer coefficient
445 was also deduced by matching local temperatures measured in the lining and resulted to be slightly
446 higher than the one used in previous models referred to the Turin case.
- 447 - The system operational behaviour was investigated in conditions different from the tested ones to
448 generalise the results. Design charts were presented with the intention of updating to the Enertun layout
449 those already existing in literature. In this new version, different groundwater flow directions as well
450 as the influence of fluid inlet temperature, fluid velocity, pipes size and heat transfer coefficient were
451 also considered. A substantial increase in performance occurs when water flow direction increases
452 from 0° to 45°, whereas little improvement is attributable to perpendicular flow in comparison to the
453 oblique case. The paramount importance of fluid inlet temperature emerges in comparison to the other
454 investigated aspects.
- 455 - A new simplified procedure to calculate the exchanged thermal power by using the design charts was
456 suggested. It can be reliably adopted for a preliminary evaluation in a wide range of conditions. It is
457 clear, however, that a more detailed study should be conducted at the design analysis stage, which
458 includes site-specific thermo-hydraulic numerical modelling, and that caution should be adopted when
459 site conditions differ substantially from those considered in the sensitivity analysis herewith described.

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