

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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6

## 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.

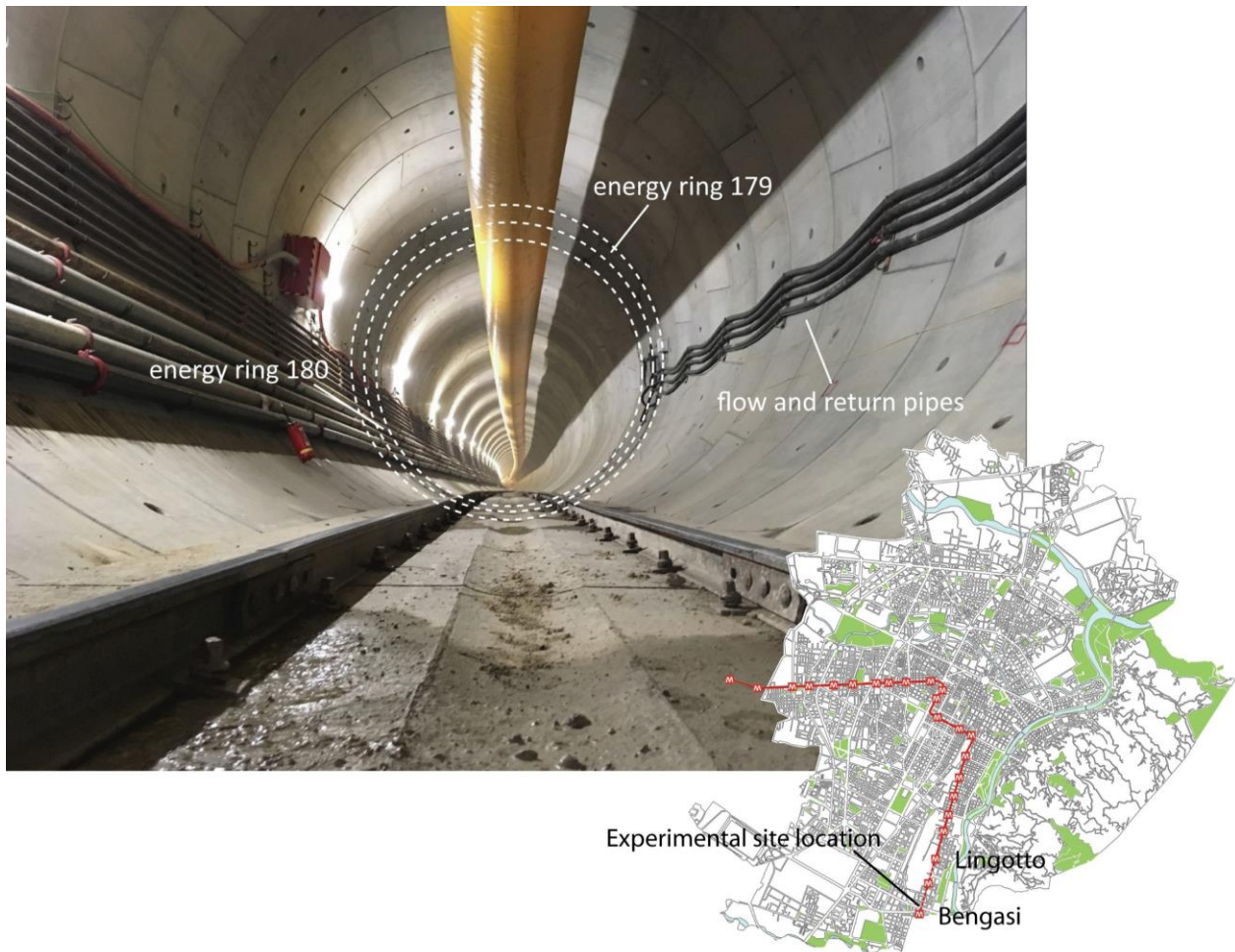
55 Barla and Di Donna (2016b) have proposed a novel segmental lining named Enertun which has been installed  
56 and tested by a real-scale energy tunnel prototype in the tunnel under construction of the Turin Metro Line 1  
57 South Extension (Barla et al., 2019). The prototype allowed collecting a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



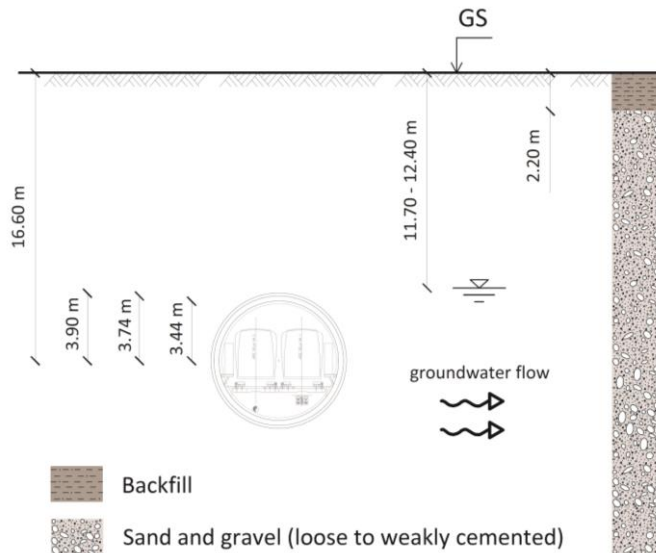
**Figure 1.** View of the Enertun experimental site and its location along the Turin Metro Line 1.

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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 <sup>3</sup> /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  $\Delta T$  (in  $^{\circ}C$ ) between outlet and inlet was computed at any given time  $t_n$   
 131 when data were available

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

- 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

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

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  $\Delta T$  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  $\Delta \dot{Q}(t)$

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

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.

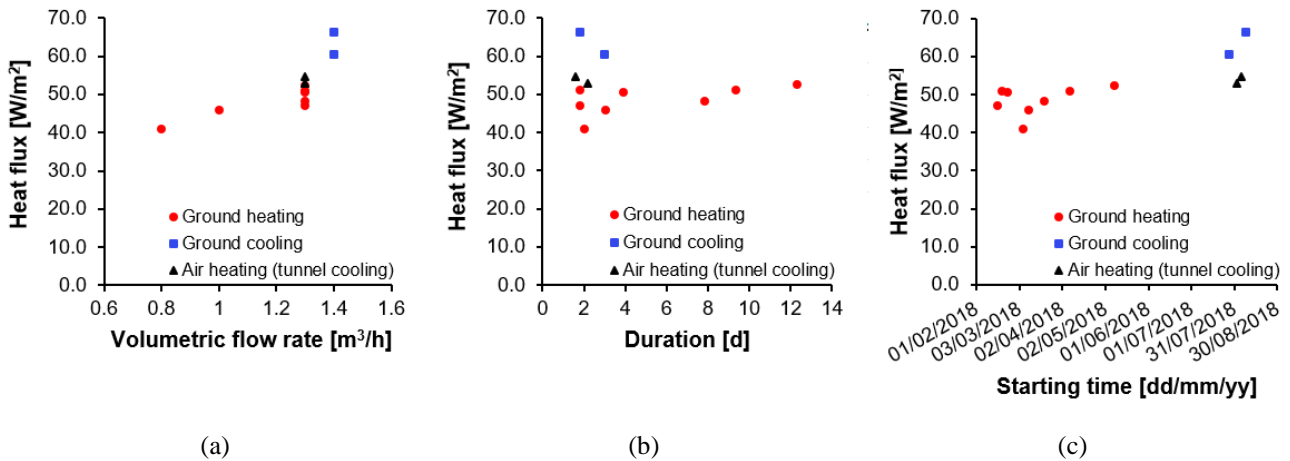
Test code	Thermal power		Thermal energy
	[W/m]	[W/m <sup>2</sup> ]	[kWh]
180215_G_H_T45_179180	1105	47.0	135.35
180218_G_H_T45_179180	1198	51.0	147.25
180222_G_H_T45_179180	1188	50.6	313.75
180305_G_H_T45_179180	959	40.8	129.44
180309_G_H_T45_179180	1076	45.8	222.34
180320_G_H_T45_179180	1135	48.3	601.12
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

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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.



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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.

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

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

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

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

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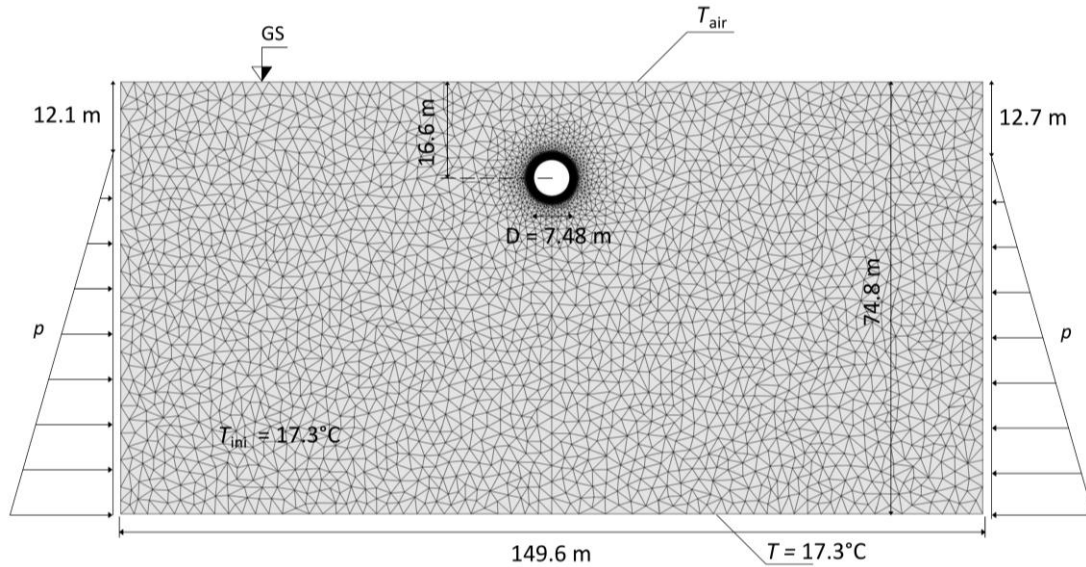
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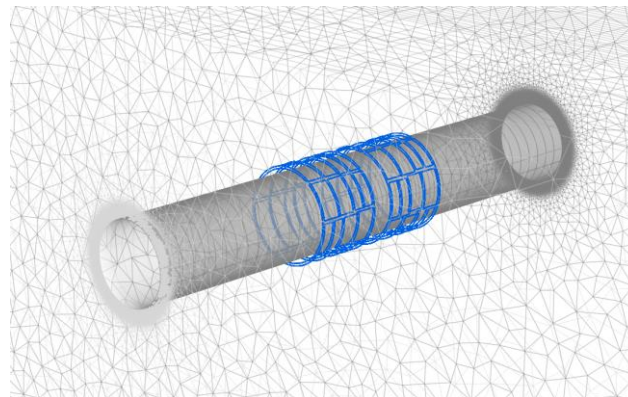
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Both thermal and hydraulic boundary conditions were set. As shown in Figure 4, the initial temperature throughout the model was set at 17.3°C, as resulting from the interpolation of three measurements in the area of the experimental site (two piezometers and an extensometer well). The time series of the external air temperature was applied on the upper boundary of the model, which represents the free surface, whereas a constant value of 17.3°C was assigned to the lower boundary. On the tunnel internal boundary, the temperature 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.



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

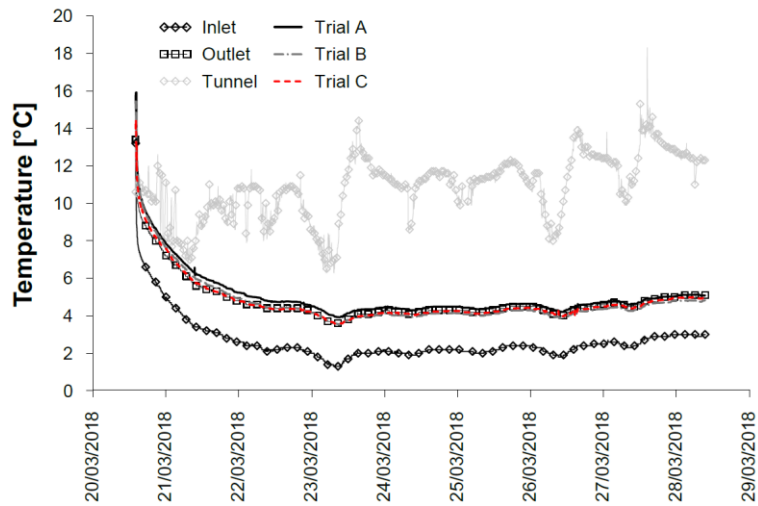
233 evaluation, until reaching a good superposition of simulation and monitoring outlet temperature. In particular,  
 234 grout thermal conductivity was first assumed equal to the one for concrete and then reduced to 0.655 W/mK,  
 235 as found by Allan and Kavanaugh (1999) for a cement & bentonite 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.

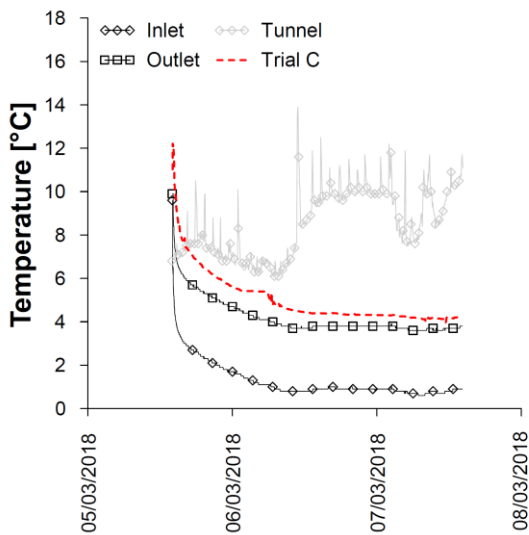
Material	Property	Symbol	Unit	Trial A	Trial B	Trial C
<b>Ground</b>	Horizontal hydraulic conductivity	$K_{xx}, K_{zz}$	m/s	4.150E-03		
	Vertical hydraulic conductivity	$K_{yy}$	m/s	2.075E-04		
	Specific storage	$S_y$	1/m	1.0E-04		
	Porosity	$n$	-	0.25		
	Fluid-phase thermal conductivity	$\lambda_w$	W/mK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

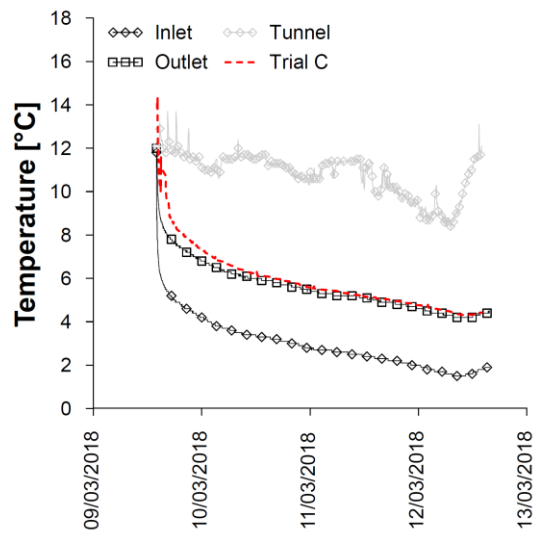
252



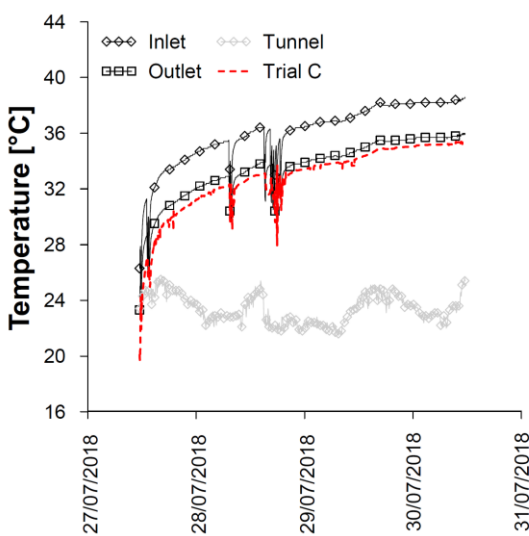
253  
254 **Figure 6.** Comparison between measured and computed circuit outlet temperature: test 180320\_G\_H\_T45\_179180  
255 (calibration phase).



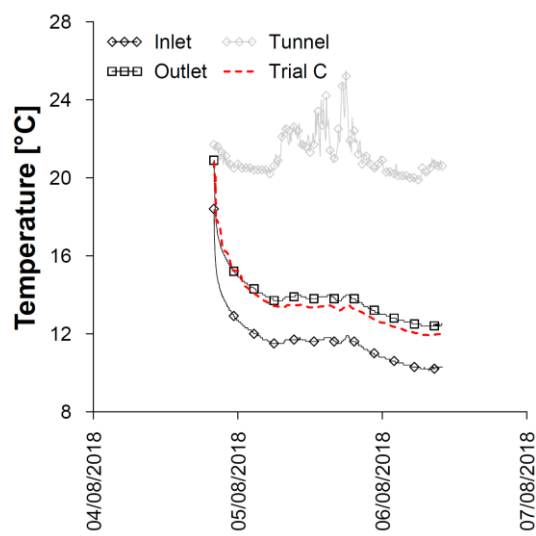
256 (a)



257 (b)



258 (c)



259 (d)

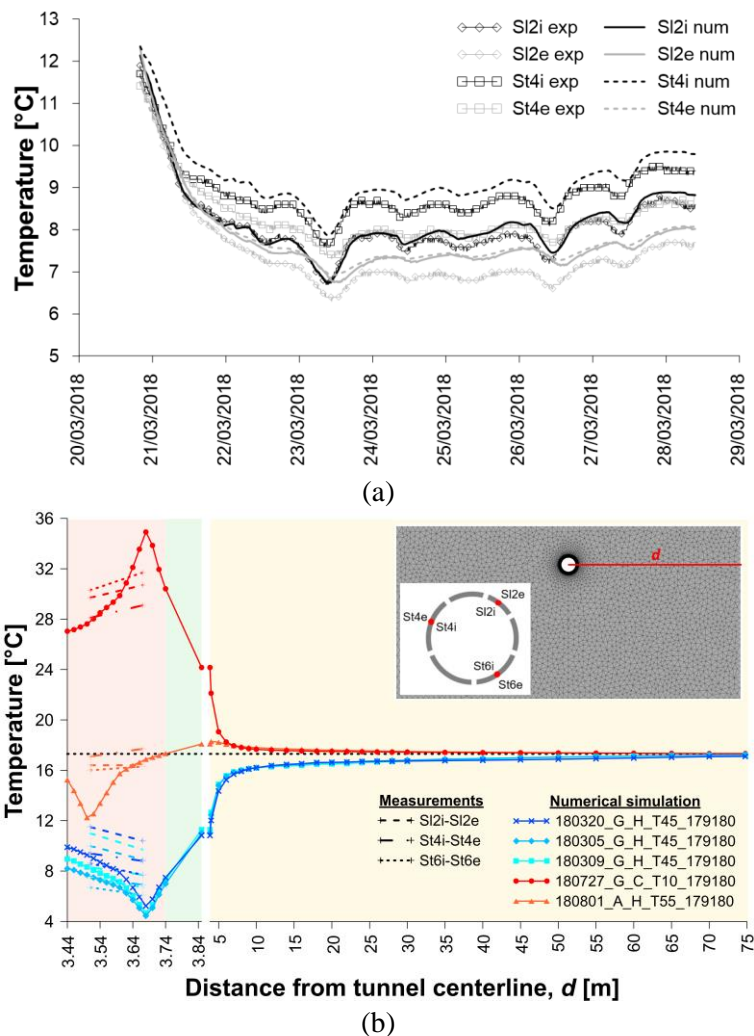
260 **Figure 7.** Comparison between measured and computed data: (a) test 180305\_G\_H\_T45\_179180, (b) test  
 261 180309\_G\_H\_T45\_179180, (c) test 180727\_G\_C\_T10\_179180 and (d) 180804\_A\_H\_T55\_179180 (validation phase).

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



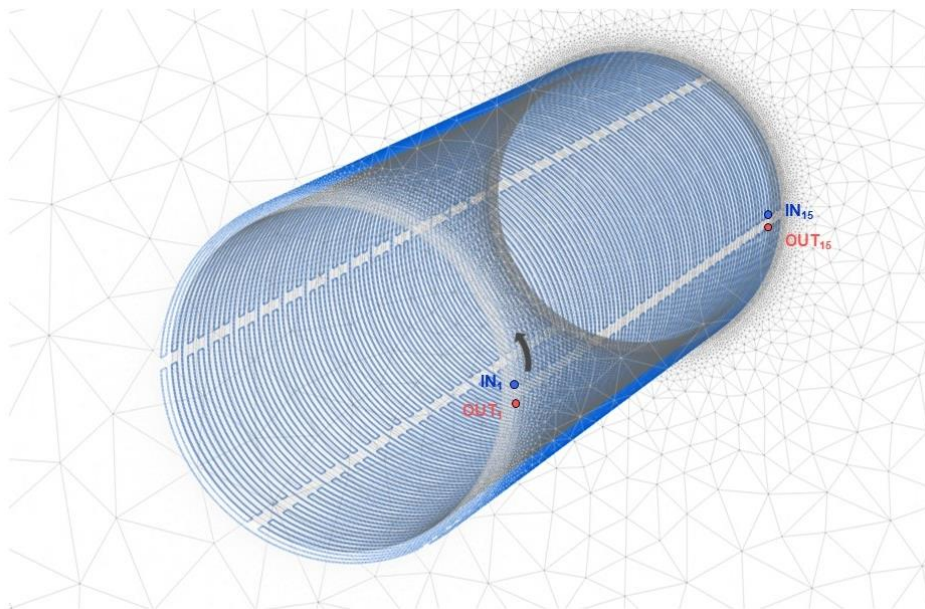
279 **Figure 8.** (a) Comparison between measured and computed lining temperature at the extrados and at the intrados: test  
 280 180320\_G\_H\_T45\_179180 (calibration phase); (b) Computed downstream temperature at the end of the simulated tests.  
 281

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

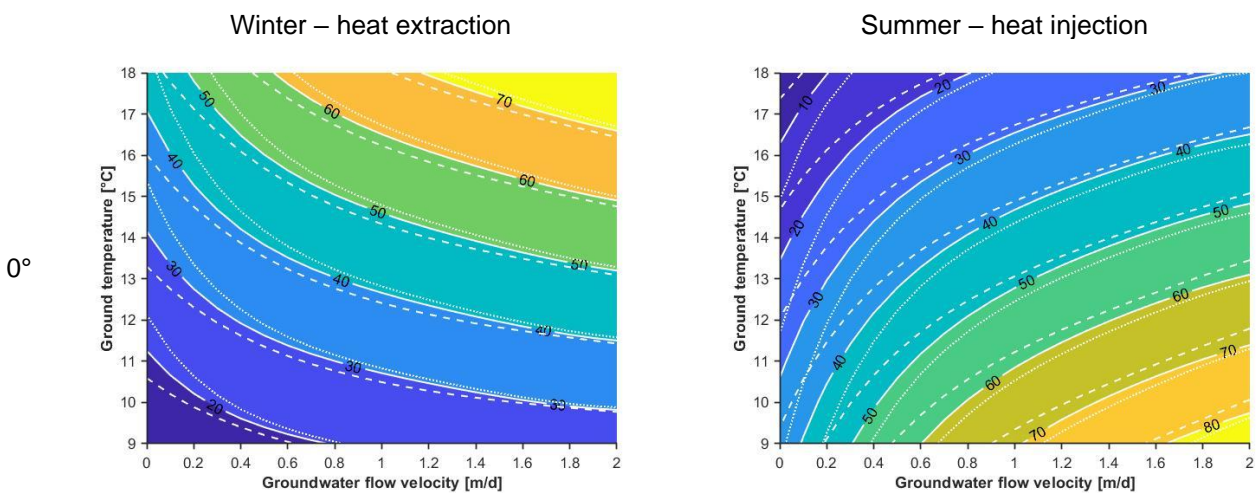
Characteristic	Unit	Value
Pipes size	mm	20x2
Inlet temperature (winter)	°C	4
Inlet temperature (summer)	°C	28

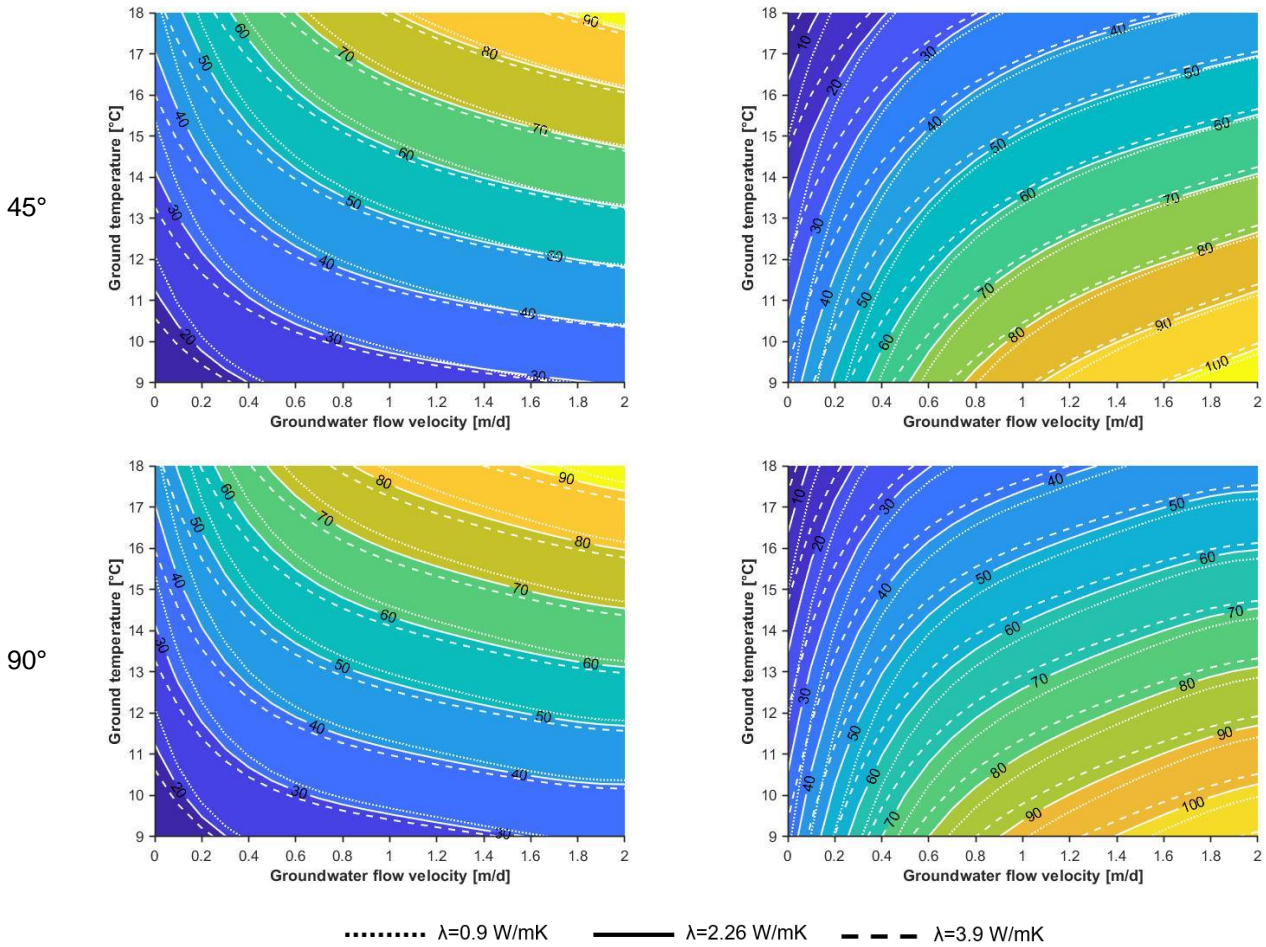
Heat carrier fluid velocity	m/s	0.9
Grout thermal conductivity	W/mK	2
Concrete thermal conductivity	W/mK	1.5
Grout thickness	cm	11
Ground temperature	°C	9-12-15-18
Heat transfer coefficient	W/(m <sup>2</sup> K)	5.3
Tunnel temperature (winter)	°C	Variable with ground temperature 7.1-10.1-13.1-16.1
Tunnel 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/m<sup>2</sup> 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/m<sup>2</sup>, while summer energy performance falls between 10-110 W/m<sup>2</sup>.,  
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 ( $0^\circ$ ,  $45^\circ$  and  $90^\circ$ ).

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  $\Phi$ , 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
$\Phi$	$W/m^2K$	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

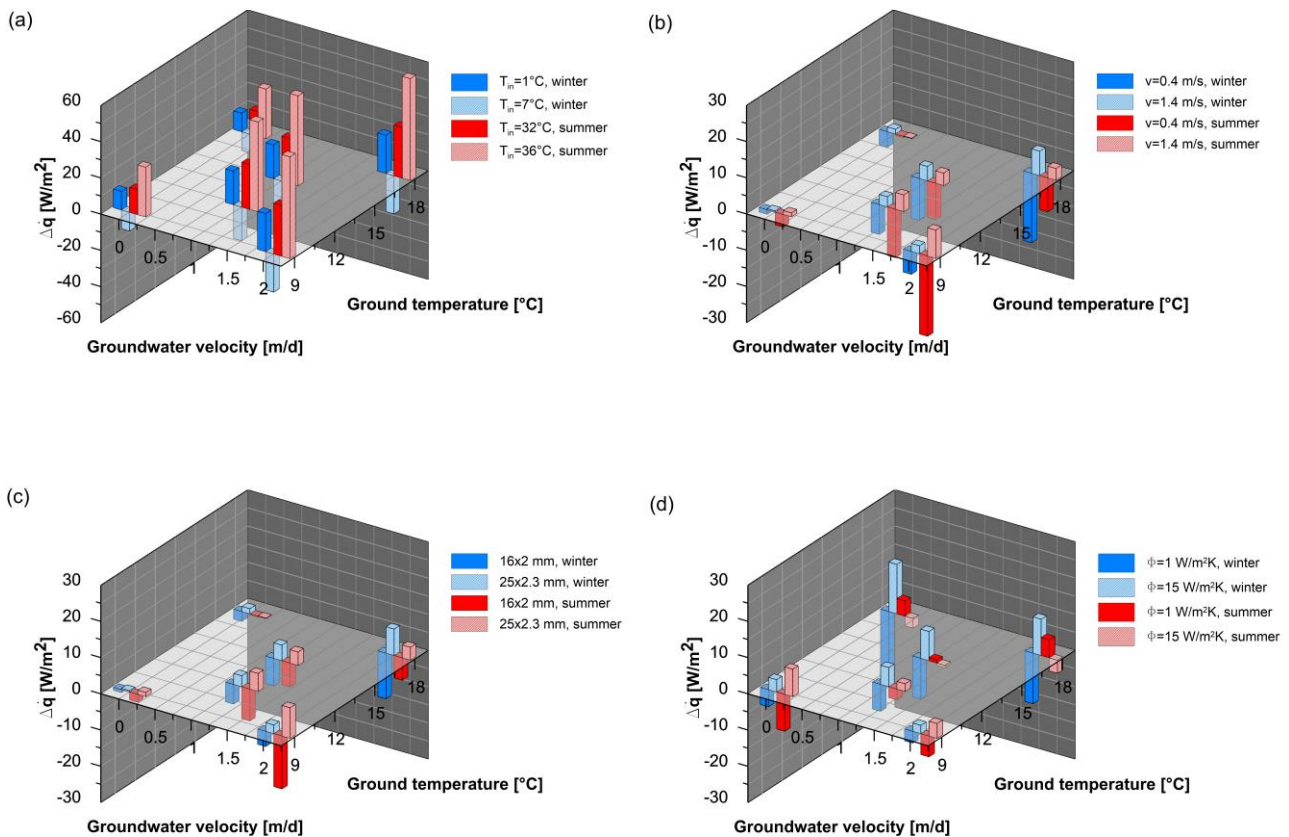
350 temperature (ground thermal conductivity kept to 2.26 W/mK) so that all the chart area is spanned. In the  
 351 following each aspect is explored and commented in detail.

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  $56 \text{ W/m}^2$  in summer  
 355 when using the highest inlet 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  $15 \text{ W/m}^2\text{K}$ , the heat flux increases by a maximum of  
 367  $14 \text{ W/m}^2$  in winter and by  $8 \text{ W/m}^2$  (or decreases by  $4 \text{ W/m}^2$ ) in summer. When the heat transfer coefficient is  
 368  $1 \text{ W/m}^2\text{K}$ , the heat flux decreases by a maximum of  $19 \text{ W/m}^2$  in winter and by  $10 \text{ W/m}^2$  (or increases by  $5 \text{ W/m}^2$ )  
 369 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  $\Delta T$  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  $\pm 10$  W/m<sup>2</sup> correction to the above obtained value of W/m<sup>2</sup> 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/m<sup>2</sup>K  
 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 <sub>gw</sub> [m/d]	T <sub>g</sub> [°C]	λ [W/mK]	q [W/m <sup>2</sup> ]			
					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/m<sup>2</sup>, 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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470

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