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Cooling underground substations worldwide using heat pumps

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The use of underground space in urban environments has increased at an accelerated rate over the past few years, particularly to satisfy transport infrastructure needs. Transport tunnels are being constructed at increasingly greater depths in the already congested subsurface. While transport tunnels have demonstrated significant potential as sustainable heat sources for heating under - and above-ground spaces, due to the large area in contact with the ground [4,5], cooling the substations that serve the tunnels, containing plants and machinery, is a task that poses a significant economic and environmental challenge. To tackle this, a new method that takes advantage of airflow in the tunnels and the thermal mass of the ground surrounding the tunnels has been recently introduced [2]. Similar to energy tunnels [1], these systems use water-filled high-density polyethylene (HDPE) pipes integrated into the tunnel space to exchange heat, however using the pipes to reject heat from the substations to the tunnels. This work adopts four cities, namely Sydney in Australia, Guangzhou in China, London in the UK, and Stuttgart in Germany, and investigates the suitability of this approach to cool substations for different meteorological and geological conditions around the world. Moreover, varying heat exchanger lengths and tunnel air temperatures are incorporated in the analysis, to assess the impact of these key parameters on system efficiency and performance.

A detailed 3D finite element heat and mass transport model is utilised in this work, simulating the tunnel lining, surrounding soil, the airflow within the tunnel, the pipes attached to the tunnel linings (tunnel air side), and the circulating fluid within the pipes [2]. The location farfield temperature and material properties are shown in Table 1, for the soil conditions in the four locations and for the common materials (shaded in grey). A parametric analysis is undertaken to investigate the performance of these systems under varying conditions. For each of the locations, five different pipe leg length values are used: 50 m, 100 m, 150 m, 200 m, and 300 m and the air velocity is assumed as 0.5 m/s, typical of these tunnels. In addition, two different distributions for the temperature of the air entering the tunnel are used: the estimated tunnel air temperature (T_{air}) distributions based on available literature and measurements [3, 6, 7], as well as the surface air temperatures ($T_{surface}$), both shown in Figure 1-left. The latter is used to understand the impact of natural ventilation of tunnels on the system, which could inform the placement of the pipes with respect to the positions of ventilating shafts along the tunnel length.

Table 1: Ground farfield temperature and soil properties for the four cities, and general material properties.

Parameter	Sydney	Guangzhou	London	Stuttgart	Concrete	Water	Air
Farfield temperature [$°C$]	20.1	23.8	12.5	9.0	-	-	-
Thermal conductivity [W/(m K)]	2.2	2.2	1.7	2.0	2.1	0.58	0.026
Density [kg/m^3]	2000	1950	2000	2400	2200	998	1.225
Specific heat capacity [J/(kg K)]	850	1538	870	1100	900	4186	1005

The results are shown in Figure 1-right, in terms of the cooling thermal power that a single pipe loop can provide (total pipe loop length being 2x$L_{pipe\ leg}$), when operating constantly over 20 years – to replicate the real conditions in cooling substations. These

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values are obtained such that the temperature of the fluid does not reduce below 5 °C, such that the heat pump efficiencies remain high. The locations are shown based on the line colour and the air temperature distribution used for each location is represented by the line type (solid:T_{air}, dashed:$T_{surface}$). The results show that the cooling provided can vary significantly based on the investigated parameters and suggest that the temperature of the air flowing in the tunnel is very influential to the system performance. The most favourable outcome is achieved for Stuttgart (green), which has the lowest tunnel air and farfield temperature, and the least favourable for Guangzhou (red), which has the higher air and farfield temperature. Comparing the two air temperature distributions used (solid vs dashed), using $T_{surface}$ instead of T_{air}, which is lower in all cases, increases the performance of the system. This is most obvious for the case of London, with an increase between 2.5 kW and 5 kW, likely due to the low value of the farfield temperature as opposed to the significantly high tunnel air temperatures (T_{air}). The length of the pipes used in all cases increases the amount of energy, however that increase is logarithmic in nature and therefore after about 150 m to 200 m the investment might not be justified. Overall, this work shows that there is significant potential to utilise heat pump technologies to cool tunnel substations, especially in cooler climates such as central-northern Europe.

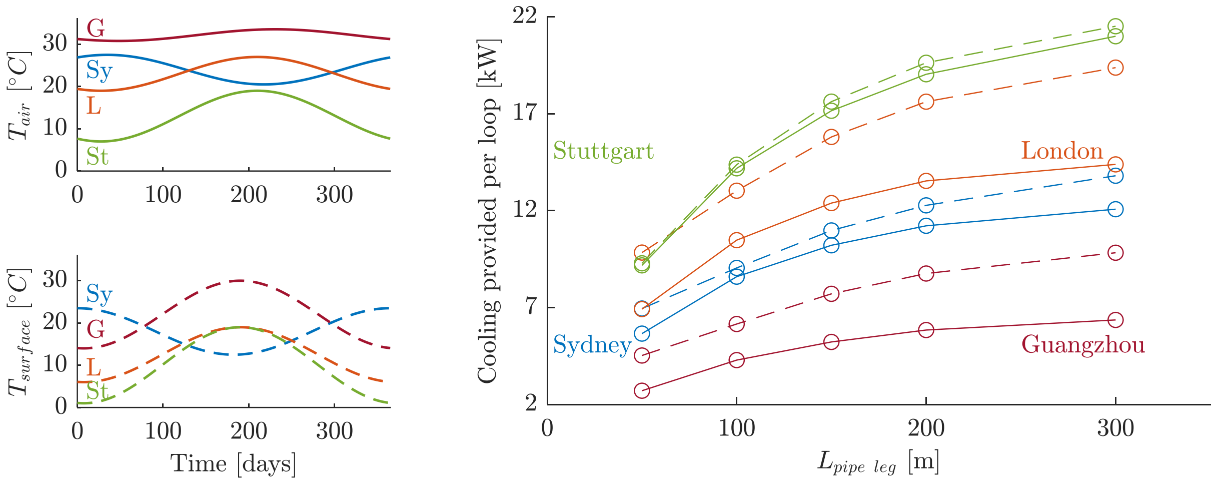

Figure 1: The left panel shows the air temperature distributions for the tunnel air (T_{air}) and the surface temperature ($T_{surface}$), for the four investigated locations, Sydney (Sy), Guangzhou (G), London (L), and Stuttgart (St, colour-coordinated). The resulting cooling thermal power per pipe loop that can be provided is shown (right panel) for the two entering air temperature distributions (solid: T_{air}, dashed: $T_{surface}$), varying with length of activated tunnel.

Contributor statement

N. Makasis: Formal Analysis, Investigation, Methodology, Visualisation, Writing. A. Bidarmaghz: Conceptualisation, Investigation, Methodology, Writing– Review & Editing, W. Fei: Methodology, Writing – Review & Editing, G.A. Narsilio: Methodology, Writing – Review & Editing.

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