Influence of airflow conditions and convective heat transfer coefficient on urban energy tunnels performance

Margaux Peltier[1 *], Alessandro Rotta Loria[1], Lyesse Laloui[1] , Loïc Lepage[2] , Etienne Garin[2] , Guillaume Massard[2] , Nima Nilipour[2] , Julien Lepine[2]

[1] Laboratory of Soils Mechanics, Ecole Polytechnique Fédérale de Lausanne, Switzerland
[2] BG Consulting Engineers, Lausanne, Switzerland
* margaux.peltier@epfl.ch

Introduction

The relatively recent development of energy geostructures such as energy piles widens geothermal energy sources at the city scale while significantly reducing the technical and cost constraints of conventional geothermal technologies. If energy piles currently represent the most widely used earth contact structures that are employed to provide structural support and energy supply to any type of built environment, the thermal activation of infrastructures such as tunnels is particularly interesting for energy applications at the urban scale. Many urban environments benefit from a large amount of heat stored in the subsurface that could be used for satisfying their annual heating and cooling requirements. In this respect, energy tunnels are a promising technology to increase the renewable energy supply at the city scale, reduce fossil fuel dependency and provide energy storage opportunities for cities.

A key aspect characterising the geothermal operation of energy tunnels, similar to other non-isothermal internal flow problems, is the heat exchange occurring at the air-wall interface. Air-to-wall heat exchange is mainly driven by the airflow conditions in the tunnel and depends on two parameters: the air temperature and the convective heat transfer coefficient, h_c (Bergman et al. 2011). The airflow conditions strictly interact with the development of the so-called velocity and thermal boundary layers, which define the extent of the hydrodynamic and thermal entrance regions with respect to the associated fully developed regions (Bergman et al. 2011). In the context of problems involving internal flows such as in tunnels, the considered boundary layers develop along the longitudinal direction of the system. Within the entrance region, the velocity and temperature profile change with the axial distance. In the fully developed regions, the considered quantities, and thus the coefficient h_c, do not change anymore with the axial distance.

Based on previous investigations for non-isothermal external flow problems, some correlations between the airflow velocity and the heat transfer coefficient have been discussed in the context of energy tunnels (Bourne-Webb et al. 2016). Despite these advances, the understanding of the airflow conditions in the context of the geothermal capacity of energy tunnels remains a complex problem, and the influence of the considered conditions on the actual heat exchange that can be harvested from the tunnels represents a major research gap.

To address this lack of knowledge, the present paper investigates the development of the hydrodynamic and thermal entrance regions in energy tunnels, and the consequent influence of the development of these regions on the variation of the coefficient h_c. This research is part of a broader investigation on the geothermal capacity of an urban tunnel that is planned to be constructed in Lausanne, Switzerland.

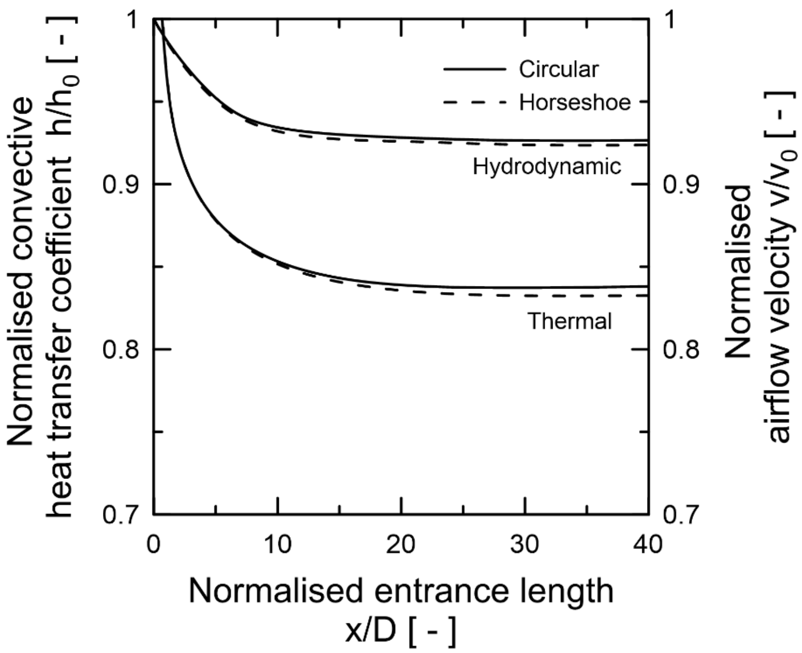
Case study

Situated in the Canton of Vaud, Lausanne is the fourth largest city of Switzerland and has been committed to sustainable development since many years. The new urban metro line m3, planned for 2025, connects the railway station to the north of the city. This line aims not only to absorb the growing quantity of travellers transiting through the railway station, but also to support the urban development of the north of the city. Given its urban location, the m3 is surrounded by several buildings, commercial centres, an exhibition and congress centre and a new eco-district.

The tunnel line is 4500 meters long and serves seven underground stations. The tunnel is most likely to be characterised by a horseshoe-shaped cross-section with an equivalent diameter of approximately 7.2 m, excavated through conventional excavation methods. The average soil cover of the tunnel is of 10 m, except for a 250 m long section that intersects an existing metro line. Varying subsoil conditions characterise the tunnel line, including shallow layers of alluvial deposits and a sandy-gravelly moraine layer, overlying a bottom molasse layer mainly composed of sandstone. Based on the available geotechnical and hydrological investigations, groundwater flow is insignificant. As ventilation is guaranteed thanks to several shafts that inject external air, the tunnel climatology depends on natural and forced convection.

Methodology and discussion

For the purpose of this study, numerical analyses are performed with the Computational Fluid Dynamics solver FLUENT (Fluent, 2009) to analyse crucial features of the airflow conditions in energy tunnels. The influence of tunnel cross-section geometry, tunnel length, Reynolds number and tunnel wall roughness are investigated. As can be appreciated referring to Figure 1, the tunnel geometry has limited influence on the variation of the velocity and temperature fields characterising tunnels of different cross-sections with the same equivalent diameter. In fact, a circular section remains an accurate estimation of the horseshoe section, while considerably decreasing computational time. In general, the fully developed thermal region starts before the hydrodynamic one. Within the hydrodynamic and thermal entrance regions, larger variations of the coefficient h_c compared to the airflow velocity v are observed. Results not presented hereafter show that tunnel length and Reynolds number have no influence on the hydrodynamic and thermal entrance lengths, which is in agreement with the theory of non-isothermal flows mainly developed for pipes. The wall roughness has a significant influence on the extent of the entrance regions as well as on the value of h_c. An increasing roughness leads to a larger h_c value and a shorter thermal entrance region, which is particularly relevant for energy tunnel design.



(h_0: inlet heat transfer coefficient, v_0: inlet velocity)

Fig. 1: Hydrodynamic and thermal entrance lengths characterising an energy tunnel

Concluding remarks

The convective heat transfer coefficient h_c is essential for an accurate estimation of the thermal potential, especially regarding energy tunnels. The present study aims to increase knowledge about the significance and magnitude of the coefficient h_c in urban energy tunnels as well as the relationship between this coefficient and typical physical and design variables governing tunnel environments.

References

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