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Numerical modeling of the piston effect in longitudinal ventilation systems for subway tunnels

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ABSTRACT

This paper analyzes the influence of the piston effect in the longitudinal ventilation system of subway tunnels using numerical methodologies. This aerodynamic effect, highly complex, three-dimensional and unsteady is modeled using Computational Fluid Dynamics (CFD) in order to simulate and analyze in detail the flow patterns associated to this effect. This approach improves the description provided by typical conventional tools, based on 1-D numerical modeling, and constitutes a useful benchmark for calibrating existing tunnel environment simulation software. For this study, a 3-D computational model for a typical subway line between two consecutive stations has been considered. The implemented geometry is a typical configuration that mimics any modern infrastructure with 100 m long stations connected through a two-way tunnel, 500 m in length. The ventilation system is longitudinal, composed of two inlet shafts, with mechanical ventilation for each station, and an exhaust shaft in the middle of the tunnel. Additionally, at the tunnel edges, close to the stations, there are also natural ventilation shafts or draught relief shafts (DRSs) – i.e. without mechanical fans – to attenuate possible pressure fluctuations originating from the piston effect.

The numerical simulation has been conducted using the commercial code, FLUENT, developing an unsteady numerical model with a dynamic mesh technique to simulate the train displacement between the two stations. Different cases have been studied in detail, including a wide range of ventilation conditions, as well as travel frequencies (single train and two trains crossing halfway). The main objective of this analysis has been the definition and quantification of the different parameters influencing the subway ventilation system. Finally, the impact of the piston effect on the global ventilation performance has also been addressed via numerical estimation.

1. Introduction

Nowadays, public transport systems have become an essential service in our modern daily lives. Among all the means of transport available in today's large cities, the subway is the most advantageous in terms of massive capacity, frequency and reliability. However, despite being the most efficient and sustainable option, it regular operation requires large amounts of energy. In particular, underground transportation systems have significant impacts on energy consumption at a regional scale (e.g., London Underground is the largest consumer of electricity in London and rates amongst the top 10 electricity consumers in the UK – London Underground Environment Report, 2006). In contrast to other travel systems, a very important fraction of the total consumption is not directly related to transport, but assigned to secondary subsystems as lighting or ventilation. Large metropolitan areas, like Seoul or Barcelona, may have rail networks with total lengths in the order of 100–150 km, and total annual consumption of energy in the range of 200 million kW h/year (TMB, 2010). Approximately, 30–40% of that network energy is employed for non-traction electricity consumption (Hu et al., 2006; SEAM4US Project, 2011), where ventilation systems represent the largest portion. Table 1 summarizes typical distributions of auxiliary systems in terms of percentage and total amount of energy per passenger and year (adapted from Hong and Kim, 2004).

In modern underground facilities, the energy consumption related to ventilation and HVAC systems represents about 75% of the total energy for non-traction purposes. Consequently, the expense for cities like Barcelona or Seoul can be as high as 50 million kW h, up to 200 million for London (network length of 400 km) and even 500 million for the New York Metropolitan Area (more than 1000 km in length). Obviously, an optimal management of the ventilation system would imply a large energy saving in absolute terms. In addition to these energetic requirements,

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Table 1
Operating metro subsystems (non-traction energy consumptions)[a]. Total annual energy per passenger and per network area.

Facilities in subway stations	Ratio (%)	kJ/pass.	MJ/m^2
Mechanical ventilation	55.0	107	157
HVAC systems in stations	18.5	35	53
Lighting (transformer & electricity rooms)	9.0	17	25
Elevators, escalators	17.5	33	50

[a] Data from Seoul Subway Lines & Stations, with an estimation of the overall energy consumption of the metro stations around 70 million kW h/year and 3.75 million users per day.

ventilation systems are essential to guarantee optimal levels of comfort and safety for the passengers.

Unfortunately, underground tunnel ventilation is complex and inherently related to the dynamic effects generated by the rolling stock on the flow behavior. This means that, usually, a deep and customized analysis has to be performed for the definition of practical guidelines to optimize the overall performance (Lau and Yau, 2007).

There are a wide number of flow effects to be considered during the operation of ventilation systems: pressure variations (from low pressures due to the suction regions to high pressures in stagnation zones), flow currents due to normal ventilation operation, primary and secondary flows due to the three-dimensionality of the domains (Wang et al., 2011), induced flow currents due to changes in boundary conditions (open doors – Yang et al., 2009, train displacements, thermal imbalances, etc.) and even sonic shock in case of high-speed trains (Bopp and Hagenah, 2009, or Uystepruyst et al., 2011). The most important induced flow currents are those provoked by the rapid displacement of the trains in the tunnels, establishing the so-called "piston effect", which is responsible for a significant air recirculation within subway tunnels and connecting stations (Lin et al., 2008). Hence, when a train enters into a tunnel, it induces a notable acceleration of the air in the tunnel, previously at rest. The air is then accelerated to velocities ranging from 3 to 8 m/s, except in the gap between the train and the tunnel where the air flow velocity can be a 30% higher than the train velocity due to the section decrease associated to the train blockage (Chen et al., 1998). This effect, unavoidably associated to the running trains, induces an additional flow rate that enhances the tunnel ventilation and may be considered as a supplementary mechanism to relief the mechanical ventilation. Consequently, this fact justifies the analysis, either numerical or experimental, of the piston effect as a beneficial contributor in the ventilation systems, and evidences its potential to be included in current protocols for the operation and optimization of such systems.

The piston effect is basically the consequence of a stagnation pressure in the front area and the low pressure in the rear, as the train moves along the tunnel (see sketch in Fig. 1). The higher pressure at the front pushes the air ahead, while the low pressure developed at the rear establishes a suction flow when the train has passed away. As a consequence, a ventilation shaft in the central part of the tunnel experiences an outflow when the train advances towards the shaft (positions A, B in Fig. 1) and an inflow once the train passes by (locations C and D in the sketch). A similar response is found in the pressure at the central point of the tunnel, with a sudden increase of the pressure when the train nose reaches the central shaft, followed by an abrupt pressure decay induced by the train wake.

The time-resolved evolution of the instantaneous flow rate in the draught relief shaft (DRS) is a perfect indicator of the impact of the piston effect on the ventilation system. Recently, both experimental and numerical approaches have been considered in the literature to observe the overall trends associated with the piston effect in different underground configurations. Experimentally,

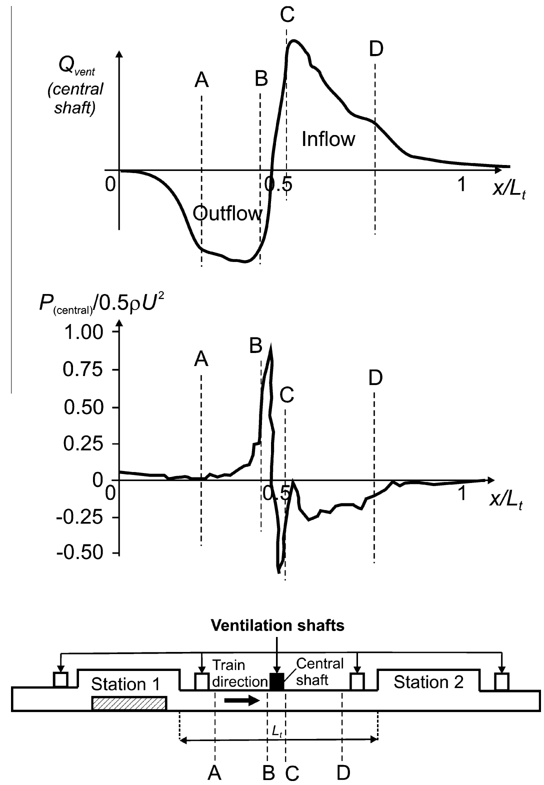

Fig. 1. Instantaneous flow rate and static pressure in the central shaft of a typical longitudinal ventilation system due to the piston effect (adapted from Krasyuk and Lugin (2007) and Kim and Kim (2009)).

Lin et al. (2008), have addressed the influence of DRS performance with intensive measurements of the unsteady velocity and temperature in a real station. Complementarily, Krasyuk and Lugin (2007), have also characterized a real station of the Novosibirsk Metro and proposed an hydraulic correction that considers the influence of the piston effect as a moving pressure loss for low-speed trains in subway environments. Ping et al. (2006), employed a similar methodology to estimate the wind velocities due to the piston effect using ventilation network theory. Other works, like those by Kim and Kim (2007), have employed scaled models to reproduce the train aerodynamics in a controlled environment in the laboratory and computational simulations to study the flow through compensating shafts. Numerically, CFD methodologies have begun to be considered for the optimization and design of operating practices in the daily management of subway stations. For instance, Huang et al. (2010), or Hai-Tao (2010), have employed a layering algorithm to analyze the train-induced unsteady airflow for natural ventilation; while Ke et al. (2002), used computational tools to optimize the design of control systems in a subway environment. Other authors, like Yang et al. (2008), have introduced the analysis of temperature distributions in underground platforms with an immersed mesh technique, and even provided validation with flow patterns and temperature distributions measured experimentally (El-Bialy and Khalil, 2010). Furthermore, the influence of train-induced motion over emergency ventilation in fire scenarios has been also recently considered in the literature (Yuncel et al., 2008, or Karaslan et al., 2010).

In this paper, different cases of ventilation have been evaluated, including the superimposed effect of the airflow induced by the train movement, allowing the estimation of the total amount of air displaced by the piston effect during a typical operating cycle of a scheduled train. In particular, several cases have been defined to study the influence of different parameters on the performance of the piston effect over longitudinal ventilation systems. The