CFD model to assess parameters influencing piston wind in a subway tunnel and station

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Abstract. Quantifying the train-induced wind affecting the climate of subway stations can be applied to improve underground networks air quality. In this paper, numerical simulations of train-induced airflow in a subway station are performed, using a CFD model with dynamic meshing techniques. A preliminary study is done in a double-track tunnel with blockage ratios of 0.30, 0.37 and 0.46 with a train running at constant speed in the order of 10 m/s. The tunnel length necessary to obtain a stable flow around the train body is determined, and this upstream tunnel length is included in a subway station model. Two different architectures and three train speeds are simulated, and the effect of these configurations on the station airflow is evaluated through the air velocity and the mass flow rate at a location on the platform. The results evidence an increase in air circulation with blockage ratio and train speed.

1. Introduction and research context

Subway stations are a peculiar type of built environment in terms of climate, since they connect the overground ambient environment with the underground network formed by the tunnels and the stations. Therefore, subway stations are exposed to a lot of different factors influencing indoor airflow. The broad aim of this project is to model and predict numerically the airflow into a subway station, using a commercial Computation Fluid Dynamics (CFD) software. The comprehensive understanding and the quantification of the train-induced wind arriving on the subway platforms can be applied to improve the air quality and passengers’ thermal comfort in underground subway networks, as well as to design passive ventilation strategies in more complex stations.

1.1. Piston effect in tunnels and stations

Monitoring Particulate Matter (PM) concentration levels in a Parisian station during a full week, Walther et al. [1] observed that the PM concentration follow closely the frequency of trains. Waymel [2] used a validated numerical model in another Parisian subway station and evidenced the link between the trains crossing the station and mass flow rates variations. Most of the studies including train operation indeed agree on the fact that a major contribution to ventilation in subway stations is performed by the piston wind.

In tunnels, this phenomenon has been extensively studied. Piston effect occur when a train travels through a narrow tunnel, and the air pushed by the train cannot completely flow to the rear end of the
train; a positive pressure volume is formed at the front, while a negative pressure and highly turbulent region appears behind the train [3]. In their highly cited article, Kim and Kim [4] used a 1/20 scale model of a single-track tunnel to monitor pressure and air velocity variations due to a train accelerating, running at constant speed and decelerating. They found a good agreement with their numerical model. Cross et al. [5] further investigated the effect of blockage ratio with numerical models of varying tunnel dimensions and train speeds. They observed that during acceleration and deceleration phases, higher blockage ratios translate into steeper and earlier variations in the velocities, and that the maximum attained velocity is higher. During the constant velocity phase, increasing blockage ratio from 0.65 to 0.85 results in a 36% increase of the outlet velocity.

In subway stations, substantial experimental work has been carried out to characterize the effect of trains on airflow. Moreno et al. [6] conducted an air quality monitoring campaign in 10 stations in Barcelona of varying architectures and under different ventilation conditions. They found out that narrow platforms with single-track tunnels are hardly ventilated by piston effect only, while wider stations benefit more of this effect to improve air quality. They also identified platform ends as areas with the greatest accumulation of particles, especially when no exits are present in those areas. However, the realization of these experimental measurements is often costly and allow only a limited number of parameters to be controlled. Fortain [7] has pointed out source discrimination as a limit to the measurement and modeling of particles in a Parisian subway station at night, including when a train is running, and that obtaining reproducible signals is a challenge.

1.2. The need for numerical investigation

To the best of the authors’ knowledge, the numerical evaluation of how this piston effect propagates in the station and affects the platform flow field is mainly limited to case studies. Xue et al. [8], Jia et al. [9] and Camelli et al. [10] have used transient CFD techniques to simulate a scenario of a train passing through a model station, with a train arriving through a tunnel, braking, stopping in the station, and departing. Experimental validation was sought through measurements in the stations or through literature and resulted in good matches. Despite requiring high computational resources, numerical models allow to visualize and retrieve quantitative data about airflow conditions affecting passengers comfort, health and safety, such as the air velocity distribution on a line along the platform length [9], contaminant dispersion into the station [10] and best location for draught relief shafts [8].

In this study, emphasis is given to train movement and tunnel layout in order to assess their contribution to the climate of the station. Although this project is based also on a real-life case, its parameters are varied in an attempt at generalizing how station airflow is affected by different factors, provided in a non-dimensional form as the blockage ratio, velocity coefficient and Reynolds number.

Figure 1. Air velocity measured experimentally in the station.

Figure 2. Station floor plan, with experimental measurement location in red, and CFD results location in purple.

2. Methodology

In this paper, a simplified geometrical model of a subway station is created according to one existing subway station in a Belgian major city. In this parallelepiped station, there are no corridors, and the ventilation is only realized by the piston effect caused by the train movements and temperature-gradient induced wind. The station is 95 meters long and include 6 exits spread on both platforms (see Figures
2, 3 and 4), all connecting the station to the outside with straight staircases (not modeled). The doors are 2.4 m wide and 2.1 m high and the train is 90 m long. Model T1 in Table 1 and S1 in Table 2 correspond to the real test case.

The blockage ratio $\beta$ of the train in the tunnel or in the station, and the Reynolds number $Re$ based on the hydraulic diameter $D_h$ of the tunnel are used to characterize the different geometries and velocity inputs as defined below, where $\rho = 1.225 \text{ kg$\cdot$m}^{-3}$ is the density and $\mu = 1.7894 \text{ kg$\cdot$s}^{-1} \cdot \text{m}^{-1}$ is the dynamic viscosity of air at 288K temperature:

$$\beta = \frac{A_{\text{train}}}{A_{\text{domain}}} \quad (1); \quad D_h = \frac{2 Y_t Z_t}{Y_t + Z_t} \quad (2); \quad Re = \frac{\rho U_{\text{tr}} D_h}{\mu} \quad (3)$$

![Figure 3. Vertical cross-section of the train in the tunnel with result line in dashed red.](image3.png)

![Figure 4. Vertical cross-section of the train in the station, with the platforms on the side.](image4.png)

Experimental measurements of air velocity were performed with a hot wire in the station [11]. The data in Figure 1 represents the air velocity, at the location displayed in Figure 2, averaged for 7 trains going through the station on that side (from left to right). It is to be noted that the flow in the station is already affected several seconds before the train reaches the station entrance. In the CFD model, as the train starts at its beginning position, all of the air surrounding it is stationary, while in reality the airflow around the body would be completely developed as the train has been travelling long enough through the tunnel. The numerical domain far-field limits – in our case, the upstream tunnel length – necessary to ensure a boundary independent solution are hence studied and determined in a first part. In a second part, two station geometries are studied for three different initial train speeds.

### 3. Study of upstream tunnel length

Çengel and Cimbala [12] define a fully developed flow as the flow state when the time-averaged velocity profile remains unchanged. In a circular pipe, the length necessary to obtain this fully developed flow, called entry length, is a function of the pipe diameter. To determine that necessary tunnel length, a first study was performed on a case composed only of a train running at constant speed in a 1000 m long tunnel for different configurations.

#### 3.1. Description of the cases and numerical model

The tunnel dimensions, as defined in Figure 3, and train speed are varied according to Table 1 below. In addition to variations around the mean train speed of 10.22 m/s measured in the station, 3.85 m/s and 20.68 m/s cases are studied for model T1, to offer data comparable to [5, 8]. For models T2 and T3, the second velocity is chosen to have the same Reynolds number as the 10.22 m/s configuration of model T1.

The station architecture is reproduced numerically using a Computer Aided Design (CAD) software. The internal domain of the station is meshed using the integrated mesher of ANSYS Workbench (2020 R2) with a tetrahedral unstructured grid of cell size 0.3 m, and a face refinement of 0.2 m on the train walls. A mesh sensitivity analysis performed with a 0.15 m grid size has provided the similar results. The computational model was solved using the commercial CFD software ANSYS Fluent (2020 R2),
with mass conservation and RANS equations for incompressible, transient flow. The tunnel extremities are set to atmospheric pressure inlets/outlets and the initial flow velocity and turbulence intensity are set to zero. The $k$-$\varepsilon$ turbulence model is chosen as it was previously used for the simulation of train-induced airflows where it performed well [8]. A dynamic mesh approach, allowing the fluid calculation area delimited by the station walls and the train car boundaries to change as the train moves, is adopted, similar to [5, 8]. A time step of 0.001 seconds is found to be sufficient to permit a correct remeshing process while the train is moving.

### Table 1. Geometrical and dynamical settings for the tunnel cases.

| Tunnel width $Y_t$ [m] | Tunnel height $Z_t$ [m] | $\beta$ [-] | $D_h$ [m] | Train speed $U_{tr}$ [m/s] | $Re$ [-] |
|---|---|---|---|---|---|
| **T1** | 6.17 | 4.1 | 0.37 | 4.93 | 3.85 | $1.30 \times 10^6$ |
| | | | | | 7.5 | $2.53 \times 10^6$ |
| | | | | | 10.22 | $3.45 \times 10^6$ |
| | | | | | 12.5 | $4.22 \times 10^6$ |
| | | | | | 15 | $5.06 \times 10^6$ |
| | | | | | 20.68 | $6.9 \times 10^6$ |
| **T2** | 6.50 | 4.8 | 0.30 | 5.52 | 9.12 | $3.45 \times 10^6$ |
| | | | | | 10.22 | $3.86 \times 10^6$ |
| **T3** | 5.00 | 4.1 | 0.46 | 4.50 | 10.22 | $3.15 \times 10^6$ |
| | | | | | 11.17 | $3.45 \times 10^6$ |

### 3.2. Results

The velocity profile along the red line shown in Figure 3 and placed 20 meters away from the train head is exported from the simulations every 0.5 s (Figure 5). The correlation coefficient between the successive profiles is then computed (Figure 6), and the flow is considered sufficiently stable when the correlation coefficient stays above 0.95. The time meeting this condition is reported in Figure 7. Although no clear link with the blockage ratio or speed variation appears, it is found that 30 m of travel through the tunnel will be sufficient for all configurations to achieve a fully developed flow around the moving train at constant speed.

### 4. Station airflow

#### 4.1. Description of the cases and numerical model

130 additional meters are also added to the domain, to allow taking into account the effect of piston wind on the platform before the train reaches the station for all considered speeds. The full geometry hence includes 250 m of upstream tunnel and 150 m of downstream tunnel. For all station geometries, the tunnel T1 is used, and variations of the platform size are done according to Table 2. The numerical settings are the same as for the tunnel case, with the six exits set to atmospheric pressure outlets.
### Table 2. Geometrical and dynamical settings for the station cases.

|         | Platform width \(Y_p\) [m] | Platform height \(Z_p\) [m] | \(\beta\) [-] | Train speed \(U_{\text{max}}\) [m/s] | \(Re\) [-] |
|---------|-----------------------------|-----------------------------|----------------|----------------------------------|------|
| **S1**  | 4                           | 2.50                        | 0.21           | 7.5                               | \(2.53 \times 10^6\) |
|         |                             |                             |                | 10.22                             | \(3.45 \times 10^6\) |
|         |                             |                             |                | 12.5                              | \(4.22 \times 10^6\) |
|         |                             |                             |                | 7.5                               | \(2.53 \times 10^6\) |
|         |                             |                             |                | 10.22                             | \(3.45 \times 10^6\) |
|         |                             |                             |                | 12.5                              | \(4.22 \times 10^6\) |
| **S2**  | 2.50                        | 2.50                        | 0.25           | 7.5                               | \(2.53 \times 10^6\) |
|         |                             |                             |                | 10.22                             | \(3.45 \times 10^6\) |
|         |                             |                             |                | 12.5                              | \(4.22 \times 10^6\) |

In [4,5] work, the distance travelled vary with the train maximum speed. Here, the distance is fixed by the station dimensions, as the train must stop while fully in the station to let passengers go in and out. The train velocity through the tunnel and station is controlled by a User-Defined Function (UDF), as shown in Figure 8. At the beginning of the simulation, the train head is placed 158 m away from the station entrance, and will travel 250 m until reaching its stop position (hence 92 meters away from the station entrance). The Reynolds number of the train in the tunnel is given, and \(U_{\text{max}}\) refers to the train maximum speed, i.e. its cruise speed in the tunnel.

**Figure 8.** Schedule of train run through the station for the 3 different cruise speeds. The deceleration and acceleration coefficients are linearly derived from the breaking and acceleration time measured experimentally, and are of \(-0.68\) m\(\cdot\)s\(^{-2}\) and \(1\) m\(\cdot\)s\(^{-2}\) respectively. The position at which the train starts braking depends on \(U_{\text{max}}\), and the stop time is always of 30 seconds.

#### 4.2 Results

The air velocity \(u\) is given for a point on the platform, at location indicated in Figure 2, 1 m away from the platform edge and at a height of 1.5 m. The mass flow rate is given through a surface of 10 cm \(\times\) 10 cm in the ZX plane at the same location but at height 1.6 m. These locations would correspond, respectively, to the torso and the face of someone standing on the platform. The vertical dashed lines show the moments the front and the tail of the train are passing the sample point.

**Figure 9.** Air velocities at sampling point.  
**Figure 10.** Mass flow rates at sampling point.

It is noticeable in Figure 9 that the relative intensity of the highest peak, when the train passes the point, does not vary with the blockage ratio, but that the air circulating while the train reaches its stop position is faster when the blockage ratio increases. Similar behavior happens when the train leaves, but with less intensity: in fact, at the platform entrance, the train is at the beginning of its deceleration and therefore still fast, whereas at the end of the simulation the train starts its acceleration and is rather slow. In Figure 10, mass flow rates show that at the train arrival, the air is pushed in front of the train, and as the train leaves, the sample surface first perceives the air carried by the train, before the air gets sucked in by the rear of the train. Experimental data such as in Figure 1 confirm that the train arrival and
departure are the two main events affecting the flow field in the station. Additional measurements of air velocity at several points across the platform would allow to observe similarities between the numerical and experimental results.

5. Conclusion and perspectives

Similar to what have been observed in the literature for tunnels, both velocities and mass flow rates indicate that the air tends to circulate at a higher velocity and at a higher rate as blockage ratio and speed increase. Observing the results on different sampling locations and for a wider range of blockage ratios or train speeds would bring a full understanding of piston wind effect in a subway station as a train crosses it.

The station shape, the presence and the location of exits, the absence of mechanical ventilation, still limit this work to some type of cases. However, replicating this CFD model could be used to match existing station architectures and to confirm the trends found. Performant public transportation system being a major concern in increasingly populated cities, reliable models will allow to design safer and healthier subway transport networks.

References

[1] Walther E and Bogdan M 2017 A novel approach for the modelling of air quality dynamics in underground railway stations Transportation Research Part D: Transport and Environment 56 33–42
[2] Waymel F 2010 Modélisation des effets thermiques et aérauliques dans les stations de métro, Ph.D. thesis Université de La Rochelle
[3] Cross D, Hughes B, Ingham D and Ma L 2017 Enhancing the piston effect in underground railway tunnels Tunnelling and Underground Space Technology 61 71 – 81
[4] Kim J Y and Kim K Y 2007 Experimental and numerical analyses of train-induced unsteady tunnel flow in subway Tunnelling and Underground Space Technology 22 (2) 166–172
[5] Cross D, Hughes B, Ingham D and Ma L 2015 A validated numerical investigation of the effects of high blockage ratio and train and tunnel length upon underground railway aerodynamics Journal of Wind Engineering and Industrial Aerodynamics 146 195–206
[6] Moreno T et al. 2014 Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design Atmospheric Environment 92 461–468
[7] Fortain A 2010 Caractérisation des particules en gares souterraines, Ph.D. thesis Université de La Rochelle
[8] Xue P, You S, Chao J and Ye T 2014 Numerical investigation of unsteady airflow in subway influenced by piston effect based on dynamic mesh Tunnelling and Underground Space Technology 40 195–206
[9] Jia L, Huand P and Yang L 2009 Numerical simulation of flow characteristics in a subway station Heat Transfer–Asian Research 38 (5) 275–283
[10] Camelli F E, Byrne G and Löhner R 2014 Modeling subway air flow using CFD Tunnelling and Underground Space Technology 43 20–31
[11] Faugier L, Laboureur D, Bosschaerts W, Marinus B G and Limam K 2021 Elaboration of numerical and experimental models for airflow in a subway station Review of the VKI Doctoral Research 2020-2021 Magin T and Debeer C, Rhode-Saint-Genèse: von Karman Institute for Fluid Dynamics, ISBN 978-2-87516-164-2
[12] Çengel Y A and Cimbala J M 2006 Fluid mechanics: fundamentals and applications (3rd ed.) McGraw Hill Higher Education, Boston 350–353

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