Circular models of air distribution due to piston effect in subways

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Abstract. Subways as places of stay of many people are imposed with higher standards of microclimate at platforms and in tunnels, including the dust criterion. To reduce dust concentrations in tunnel air to MAC values, the authors suggest installation of filters at ventilation connections nearby platforms. Aimed to find operational parameters of the filtering facilities, the authors determine the air velocities at ventilation connections. An original approach is proposed to the air distribution analysis using circular models as they considerably diminish the subway test area size without the loss of the computational accuracy and reduce the computation time.

1. Introduction
The mission of the subway ventilation is maintenance of the interio microclimate standards. The standards for the metro stations and tunnels set the maximal allowable concentrations of dust [1, 2]. In the meanwhile, some investigations [3, 4] reveal that dust concentrations in tunnel air exceed MAC. For example, dust concentrations at workplaces of personnel in subways exceed the standard 1.3-3.4 times [3]. High concentrations of fine and dispersed dust trigger respiratory diseases [5]. Dust steeled on the surfaces inside subway tunnels and stations is a favorable environment for pathogenic bacteria, which contribute to the bacterial contamination of subways [6]. Thus, additional dust filtration and suppression is required. This paper authors propose installation of filtering facilities at ventilation connections in subways as much air passes through ventilation connections due to the piston effect [7] generates a circulation loop, and the rate of air flow involved in the circulation increases with increasing number of opposing trains. To determine structural and operational parameters of filtering facilities, it is required to identify regular variations in the tunnel air flow initiated by the piston effect through the ventilation connections depending on the positions of rains in tunnels.

This study aims to find the value and direction of the tunnel air velocity at subway ventilation connections with a view to developing proper activities on tunnel air dedusting.

2. Design model and methods
In aerodynamic modeling of long transportation lines, selection of a test site for the results to be most accurate should take into account influence of adjacent areas outside the design model. For example, in air exchange modeling in a station–tunnel–station test site, it is required to include the influence of
four to eight neighbor stations. Otherwise, in case of setting atmospheric pressure (as an outlet to the atmosphere) at the boundaries of the computational domain, the value of air exchange in the domain will be unreasonably overstated as air resistance of the whole subway line is neglected. The ANSYS-based techniques applicable to the finite volume method calculations allow inclusion of air resistance along the whole subway network in modeling a single test area of a subway line [8]. Such methods include: (a) setting an equivalent opening at the test site boundary, such that the air resistance of the opening equals the air resistance of the network outside the design model; (b) setting a ventilation connection of a certain cross-section and one more tunnel arranged in parallel to the test tunnel; (c) setting a porous body with a preset resistance at the test site boundary; (d) use of a circular model of the subway line, such that the boundaries of a test area make a circle. The revealed shortages of these methods are: (a) air flow undergoes structural rupture near portals of the model tunnel site; (b) the FEM mesh size and the computational time increase; (c) smoothing of the velocity fluctuations near the test site portals due to the static pressure waves in train movement. Method (d) has no such disadvantages and allows the most correct modeling of the subway line resistance. To reduce the curvature of the test tunnel, the design model should include not less than two spans to 1000 m long.

The assumed test site includes two island platforms and two spans of single-track tunnels. The geometry of the design model is shown in Figure 1. There two trains moving at the maximal velocity of 12 m/s in opposite directions from one platform to the other platform. The station time is 20 s. The air velocities are calculated in ANSYS Fluent.

![Figure 1. Design model geometry: \( V_t \) —velocity and direction of train.](image)

ANSYS Fluent uses the method of finite volumes [9]. The model is split into a set of elements (computational mesh). For each element, a system of laws of conservation of mass, momentum and energy is described in an integral form and is then transformed to a system of algebraic equations relative to the unknown values at the centers of the mesh cells. In this 2D problem, the velocities are found from the numerical solution of the Navier–Stokes equations together with Poisson’s equation for pressures and realizable \( k-\varepsilon \) turbulence model.
In ANSYS Meshing environment, the finite element meshing is carried out. There were 43053 elements. Orthogonality and asymmetry are within the recommended ranges [10]. In the framework of the assumed realizable $k$-$\varepsilon$ model, the value of the dimensionless distance $t$ the model wall $y^+$ should be within a range from 30 to 300. Based on this requirement, using the procedure from [11], the size of the wall cells is 0.015 m. The problem was solved in the nonstationary formulation. The time step was chosen from the Courant number formula $\nu \tau = \Delta \cdot s / V_n = 1$, where $s$ is the cell size along the train movement, $\Delta \tau$ is the time step, $s$; $V_n$ is the train velocity, m/s. The time step is 1.25 s. The total time of the train movement is 765 s (6 arrival and departure cycles of train to and from the platform).

3. Results
The calculated changes in the tunnel air flow velocity and its components along the X and Y axes at ventilation connections are shown in Figure 2.
(a) Air flow velocity at ventilation connection No. 1

(b) X and Y components of air flow velocity at ventilation connection No. 1

(c) Air flow velocity at ventilation connection No. 2
(d) X and Y components of air flow velocity at ventilation connection No. 2

(e) Air flow velocity at ventilation connection No. 3

(f) X and Y components of air flow velocity at ventilation connection No. 3

(g) Air flow velocity at ventilation connection No. 4
Figure 2. Air velocities at ventilation connections. The vertical lines denote the times of the train arrivals and departures to and from the platform.

Figure 3. Vectors and field of velocities in train pass by ventilation connection No. 1; the arrows show the direction of the train movement.

4. Discussion
The obtained air velocity patterns show that the air velocities at ventilation connections directed differently subject to the train position relative to the connection: in front of it or behind it. This fact is well traced in Figure 3. As the train approach the ventilation connection (Figure 3a), it displaces air through the connection to the neighbor tunnel. As the rain passes by the connection, rarefied air is
generated behind the rear car, flow reversal takes place, and air flows through the connection from the neighbor tunnel (Figures 3c and 3d). From Figure, it follows that air flow reversal takes places within a short time of 10 s as the train passes by the ventilation connection. The rest of time, the air flow direction at the ventilation connection is steady, and only absolute value of air flow rate changes. For this reason, the tunnel air filtering facilities to be installed at ventilation connections should be resistive to sharp but short-term changes in air flow direction. This can be achieved by closing louvered griller in front of the filters for the time of train passage by the ventilation connections.

It is also found that the maximal air flow velocity along the ventilation connection is 4.9 m/s, and the air flow rate per 1 train movement cycle is 21150 m³.

5. Conclusions
1. The new approach to the topology of a design model of air distribution in subways has been justified. The approach consists in using circular models. This approach allows taking into account air resistance of the subway line, considerably diminishes the computation domain size without loss of accuracy and reduces the computation time.
2. The regular patterns of change in the tunnel air velocities at ventilation connections are determined. They allow substantiating the required operational parameters of air filtering facilities at ventilation connections.
2. It is found that the maximal air flow velocity along the ventilation connection is 4.9 m/s, and the air flow rate per 1 train movement cycle is 21150 m³.

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