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Unsteady analysis of subway cabin airflows under piston effects

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Abstract. This is a study on environment inside subway cabin under the effects of piston winds. Subway trains move fast in underground tunnels and induce strong piston winds which will change the atmospheric environment around every cabin. Through a more realistic Computational Fluid Dynamics approach with a full-scale geometry model of tunnel and a subway train made up by four cabins. This paper got conclusions about the spatial distribution of velocity, pressure and temperature in cabins which are helpful to optimize the Environment Control Systems (ECS) in every single cabin and improve the comfort level for commuters.

1. Introduction

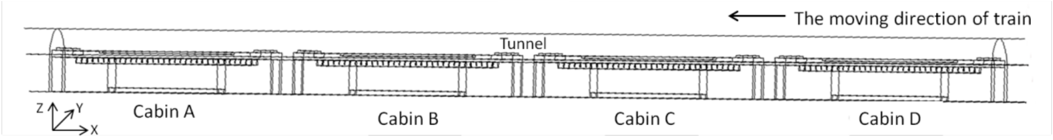
Subway system produce complex spatiotemporal airflow pattern. In an effort to better understand these complex flows, in the 1970s and 1980s, a computer program named Subway Environment Simulator (SES) was developed by American Public Transit Association (APTA) [1].These simulations provided information on the air flow in the subway tunnels by solving linear systems of equations which is not accurate enough for the nonlinear airflow dynamics in most of the cases. Despite of defects, SES was used widely to design and analyze the subway systems.Chi-Ji Lin et al. [2] used SES to simulate the tunnel ventilation for piston effects influenced by draught relief shaft. It investigated parameters that should take into consideration when designing draught relief shafts. As for Computational Fluid Dynamics (CFD) approach, the Commercial CFD package has also been used to model air flow in subway systems. J.Y. Kim and K.Y. Kim [3] used CFX4 to analyze the three-dimensional unsteady flow in the tunnel caused by train. The piston effects have a significant influence on unsteady airflows in subway tunnels also the indoor environment such as air velocity, temperature, pressure in every single subway cabin. In this paper, a full-scaled geometrical model of a subway train assembled by four cabins within a regional tunnel is created based on a real subway system to simulate numerically the piston effect influence on indoor environment of cabins.

2. Methodology

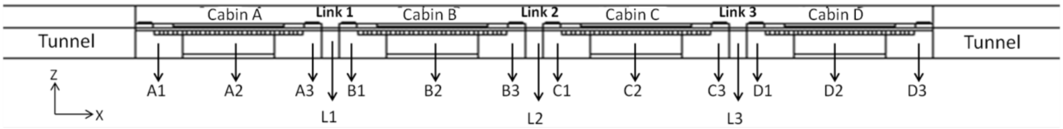
2.1 Geometrical model.

A typical subway train type C-I has four cabins, two driving cabins at both sides and two trailing cabins in the middle (Tc+Mp+Mp+Tc). The piston winds induced by moving train make pressure gradient of airflow in tunnel decrease progressively from the forward direction to the tail. The ventilations on trains such as air inlets and exhaust fans need to exchange airflows with the tunnel environment. This process is influenced by air distribution in tunnel inevitability; hence the environment inside cabins is related closely to piston effect.

Fig. 1 (a) shows the layout of an actual subway system. Every single cabin is 19.5 m(L)×2.6 m(W)×3.8 m(H). Four cabins are named A to D from the front to the terminal and we determine the moving direction of train as the front orientation. There are fifteen locations in a whole train to observe which is shown in Fig. 1 (b). Specifically every cabin has three observation locations: two points located three meters far away from both sides plus the middle one. Besides that, three more points at the middle of link parts between every two cabins are included. All locations are at the middle of width and 1.5m high from the cabin floor.



(a) layout of an actual subway system



(b) Observation locations

Fig. 1 Simplified geometrical model

2.2 CFD analysis.

2.2.1 Turbulence model.

Comparing three turbulence models, Wall-Adapting Local Eddy-viscosity reproduces well the turbulence produced by complex geometries but it cost the computing resources a lot. standard k-ε turbulence model is stable and accurate relatively, but proper Wall Function need to be used. Renormalization Group k-ε (RNG k-ε) turbulence model is better for complex turbulence because of the swirl correction. Summing up, the RNG k-ε turbulence model is the most appropriate one for the simulation in this paper to solve equations on suitable meshes.

2.2.3 Numerical simulation setup.

The spatial-temporal air flow dynamics in subway cabins is influenced by transient piston effects. It’s necessary to use User-Defined Functions to describe the boundary conditions of model. According to the field measurements and on base of reasonable simplification, train is accelerated from rest to a speed of 10 m/s in the first twenty seconds, after that it traveled faster to a speed of 17 m/s for the second twenty more seconds. It was then accelerated to maximum speed 20 m/s in the last twenty seconds. At the same time, the rate of train-induced piston winds was much lower than the train. The rate changed from zero to 1m/s at the first twenty seconds and then increased continuously to 3.5 in the next twenty seconds. In the last time interval, piston winds reached maximum speed 7m/s approximately [4]. We can define a series of functions by separate sixty seconds into three time intervals to simplify the time sequence of velocity-inlet condition which is on the front side of tunnel in the numerical simulation model. The opposite airflow-outlet setting on the back side of tunnel is selected the type of outflow to describe the outlet condition. Besides the inlet and outlet on the both side of tunnel, there are intake-fans and exhaust-fans on the top of every cabin to simulate the real air circulation between the cabins and tunnel.

3. Result and discussion

3.1 Velocity field.

Fig. 2 shows the variations of air flow velocity magnitude. The airflow rate increase with time due to the accelerated movement of subway train. In the last time interval 40 s-60 s train is moving fast enough to maximum speed and the piston effects induced by moving train is at the strongest phase, the airflow rate is much faster than earlier.

All the stages share a same tendency of airflow velocity magnitude: the fastest area is around cabin C and the lowest area is around cabin A. The airflow velocity in cabin B is between A and C and decrease extremely in cabin D from a high level to the lowest point D3 which approximate point A1. In brief, the velocity in a whole train decreases from the center part to both sides. As for every single cabin, in cabin A, B and C the peak velocity is shown at the center A2, B2 and C2 while in cabin D velocity just decreases from front to tail.

Three link parts between every two cabins are worth of attention because of the drastic step. The velocity at point L1, L2 and L3 is much faster than the points located inside cabins around them such as A3 and B1, B3 and C1, C3 and D1.

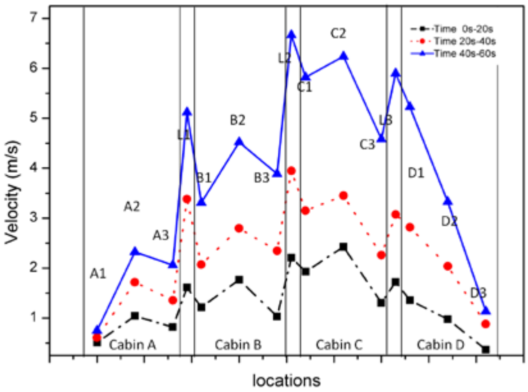
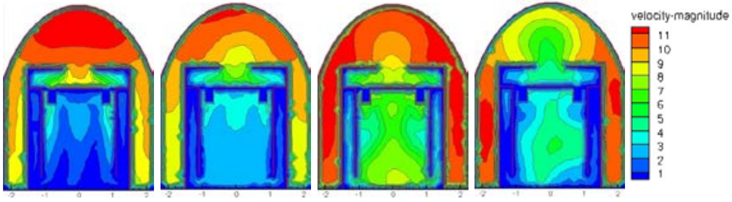


Fig. 2 Spatial distribution of velocity



(a) Cabin A (b) Cabin B (c) Cabin C (d) Cabin D

Fig. 3 velocity field vertical distributions

Fig. 3 shows a time snapshot viding supra. Figures (a) to (d) represent respectively the section for axis Z of the length center locations in different cabins. Absolutely, the velocity of airflows in tunnel is much faster than inner space and the severely affected area is around cabin C, which is the reason why the strongest inner airflows appear at this cabin.

3.2 Pressure field.

In order to analyze pressure field objectively, this paper introduce a pressure coefficient P_c [5]

$$P_c = \frac{P}{0.5 \cdot \rho \cdot v_{\max}} \tag{1}$$

Where P is the average pressure in a particularly time interval, ρ is the air density, $v_{\max}$ is the maximum subway velocity.

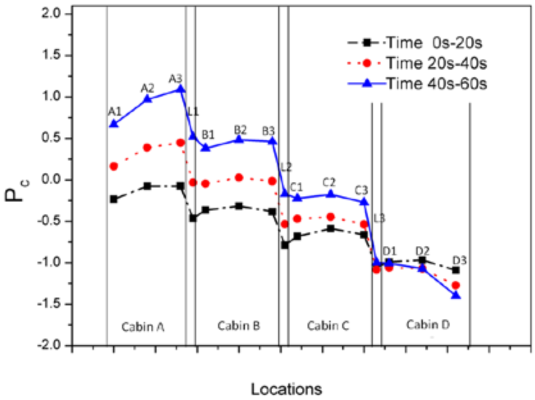


Fig. 4 Spatial distribution of average pressure

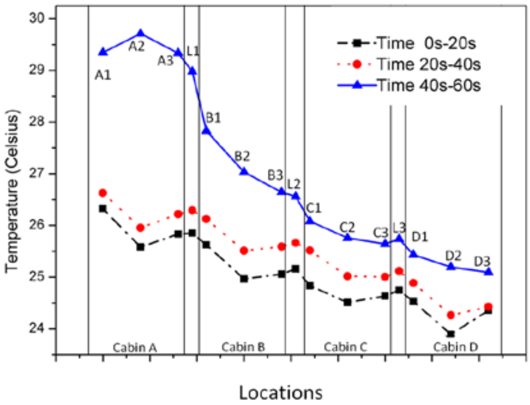


Fig. 5 Spatial distribution of average temperature

Fig. 4 is a time snapshot of the average pressure.The piston winds impact cabins' environment by influencing the ambient pressure which is surrounding train and then changing the conditions of inlets and outlets located on the top of every cabin. Ambient pressure in tunnel reduces continually from the front to tail leading to an easier inflow along with a harder outflow in the front part of the train and reverse in tail.

3.3 Temperature analysis.

In summer, temperature of piston wind in tunnel is hotter than cabins. The HVAC systems (heating, ventilation and air conditioning) in subway train are working high-loaded to cold the hot air flow from the tunnel and outside environment

Fig. 5 is a time snapshot of the temperature field viding supra. As it’s shown in Fig. 5, the coldest area is cabin D and the warmest area is at the link of cabin A and B. The most comfortable temperature for human is around 296. Therefore, cabin D is more comfortable than other areas.

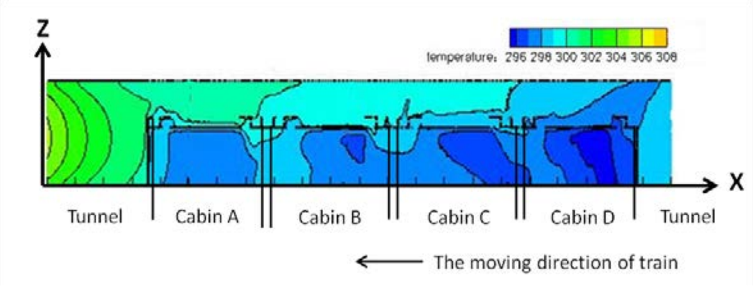


Fig. 6 Temperature field horizontal distributions

Fig.6 shows the spatial distribution of average temperature in three time intervals. The overall trend of temperature is reducing from the front part to tail. In the time interval 0 s to 40 s, subway inner environment is under control of the HVAC systems but in the third time interval 40 s to 60 s, the piston effect is the most important factor influencing the inside environment and the temperature sharply raise in all cabins especially in cabin A. For single cabins, the center temperature is lower than sides.

4. Conclusions

This study used the numerical methods to discuss the subway inside environmental influenced by piston effects. Analyses include the spatial distribution of velocity, pressure and temperature. Tendency of airflow velocity magnitude is the fastest area is around the center part of the train and the lowest areas are head and tail. As for pressure field, ambient pressures in tunnel reduce continually from head to tail of a train. This can lead to an easier inflow along with a harder outflow in the front of the train, reverse trend in the tail. Temperature of piston wind in tunnel is hotter than the inner environment temperature. The simulation shows the back area in a train is colder than the front. The abundant results and discussion in this paper are helpful to optimize the Environment Control Systems (ECS) in every single cabin and improve the comfort level for commuters.

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