International Journal of Heat and Mass Transfer 127 (2018) 188–199

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical analysis of aerodynamic characteristics of high-speed train with different train nose lengths

Jiqiang Niu [a], Yueming Wang [a], Lei Zhang [b,*], Yanping Yuan [a]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, Sichuan, China
[b] Key Laboratory of Traffic Safety on Track, Ministry of Education, School of Traffic and Transportation Engineering, Central South University, Changsha 410075, Hunan, China

ARTICLE INFO

Article history:
Received 16 March 2018
Received in revised form 21 June 2018
Accepted 13 August 2018

Keywords:
High-speed train
Train nose length
Aerodynamic performance
Flow structure
Boundary layer

ABSTRACT

In this study, based on the SST κ-ω turbulent model, the IDDES method is used to simulate the unsteady aerodynamic performance of trains with respect to different lengths of the tapered nose of the train (8 m and 12 m). The numerical simulation used in this study is verified through wind tunnel tests. The effects of the length of the tapered nose of the train on the aerodynamic performance, such as the train forces, boundary layer, velocity distribution, pressure distribution, and flow structure around the train, are elucidated via comparing and analyzing the obtained results. The results indicate that the effect of the length of the tapered nose of the train on the drag force of the tail car and lift force of the head car is stronger than the effect on other cars, and the C_d value of the tail car decreases by 30.53% and the C_l value of the head car increases by 87.98%. Increase in the length of the tapered nose of the train decreases the fluctuation of the drag and lift forces of the train, especially the head car. It is also observed that the boundary layer thickness around the train is decreased with the increase in the length of the tapered nose of the train. Moreover, it is observed that vortex drag is the primary factor in the aerodynamic drag of the tail car and that vortex drag primarily depends on the length of the tapered nose of the train.

1. Introduction

With the increase in train speed, train aerodynamic problems become very obvious; for example, the train aerodynamic drag increases significantly, which will not only cut the efficiency of railway transportation, increase energy consumption, and waste resources but also produce more noise, influencing the surrounding environment. Previous research shows that the shape of a high-speed train is closely related to the train's aerodynamic performance, that the characteristics of train drag and lift force are significantly related to the shape of the train head, and that the train nose length has a great effect on improving the train aerodynamic performance [1–3].

To date, some scholars have studied the effect of the train nose length on the train aerodynamic performance. Choi and Kim [4] studied the effects of the train nose length on the aerodynamic drag of trains traveling in tunnels with the speed increasing from 100 to 200 km/h and found that the aerodynamic drag is reduced by up to approximately 50% by changing the nose from a blunt to a streamlined shape. Hemida and Krajnović [5] investigated the influence of the nose shape on the train flow structures under a crosswind and found that highly unsteady three-dimensional flow around the nose yielded more vortex structures in the wake in the short-nose simulation, which resulted in a surface flow that differed from that in the case of a long-nose train and influenced the dominant frequencies that arose due to the shear layer instabilities. Chen et al. [6] found that the influence of different nose lengths on the surface pressure on the train body was mainly concentrated at the front and rear of the train, and the amplitudes of the lateral force and overturning moment were also influenced by the nose length, with the strongest effect on the head car and a stronger effect on the middle car than on the tail car by simulating the flow and pressure waves caused by two trains with different nose lengths passing each other in a tunnel. Chen et al. [7] compared and discussed the pressure distribution on the train surface, vortex development around the train, and variation of the velocity field around the train with different nose lengths under a strong crosswind and analyzed the variations in the aerodynamic force coefficients with different nose lengths. Chen et al. [8] studied the influence of the train nose length on the aerodynamic properties using the detached-eddy simulation (DES) method and found that the total drag coefficient, strength of vortex shedding, and strength of the wake flow decreased with increases in the train

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* Corresponding author.
E-mail address: gszxzhanglei@126.com (L. Zhang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.041
0017-9310/

nose length and a minor positive pressure area was generated in the nose cone compared to a shorter train nose. Ku et al. [9] studied the optimization of the cross-sectional area distribution of a high-speed train nose of various lengths in order to minimize the micro-pressure-wave intensity at the tunnel exit and found that some optimal shapes divide one large compression wave into two small waves by causing a strong expansion effect between the front and rear ends. Tian [10] analyzed the formation mechanism of aerodynamic drag of high-speed trains, put forward some reduction measures, and found that adopting a streamlined train shape is the most effective measure to reduce the aerodynamic drag. Tian [11] studied the influence of a streamlined head shape on the air pressure pulse from two trains passing each other and found that as the length of the streamlined train head increases, the amplitude of the air pressure pulse decreases logarithmically while the absolute value of the aerodynamic drag and lift of head-car decrease linearly and the aerodynamic drag of the tail-car decrease by quadratic. Chen et al. [12] studied the aerodynamic drag of maglev trains of different shapes in an evacuated tube with different vacuum pressures and blockage ratios and found that there were no obvious differences in the aerodynamic drag reduction among different streamlined head shapes. Some other scholars also studied the effect of train length on the train aerodynamic characteristics [13–16].

The purpose of the investigation reported in this paper was to analyze the flow field around a high-speed train with different lengths of train nose and also to study the effect of the train nose length on the aerodynamic characteristics of the train. This paper is organized as follows: the train model, numerical method, grid description, size and boundary conditions of the computational region, and data process are introduced in Section 2. The validation of the algorithm is described in Section 3. The aerodynamic characteristics of the train and the effect of the train nose length on the aerodynamic performance of trains as well as the flow structure around trains are described in Section 4. Finally, Section 5 presents the conclusions drawn based on the results.

2. Numerical model

2.1. Train model

In this study, trains with two different lengths of the train nose were used as models for the numerical simulations (see Fig. 1a). The models, including the streamlined area, windshield, and bogie, used for the numerical simulation were simplified in accordance with the CEN standard (2009, 2010) [17,18], and the subgrade was also modelled. The dimensions of the train with a short train nose are shown in Fig. 1b, and the length (L_{tr}) and height (H, distance from the upper surface of the train to the top surface of the rail, TOR) of a full-scale model of the train were 77 and 3.7 m, respectively. The streamlined length of the primary type of high speed train is approximately within the range of 5–15 m, such as the Shinkansen train in Japan, TGV in French, ICE in Germany, and CRH in China. The main difference in the dimensions of the two types of trains is the length of the train nose: 8 and 12 m, respectively, as shown in Fig. 1c. Fig. 1c also shows that the two trains with different lengths of train nose both have a width of 3.4 m.

2.2. Numerical method

In this simulation, the unsteady flow field around trains with different lengths of the train nose was simulated by IDDES based on the Shear Stress Transport (SST) κ-ω turbulence model. This method has been widely used to simulate train aerodynamic performance and is very effective [19–22]. The IDDES method is a combination of the delayed detached eddy simulation (DDES) method and wall-modelling in the large eddy simulation (LES) method and considers the characteristics of the turbulent incoming flow. The DDES method is derived from the DES method by introducing a delay function to prevent the LES method from being used in the boundary layer and to ensure that the Reynolds-averaged Navier–Stokes equations are used in the boundary layer; this can cause modelled-stress depletion and grid-induced separation. Compared to the case for the DDES grid scale, the IDDES grid scale further reduces the sub-grid viscosity in the log layer. Other advantages of using IDDES to simulate train unsteady aerodynamic performance have been described in detail in previous studies in Refs. [16,21]. More information about IDDES and a description of it can be found in studies in Refs. [23–25].

In this study, a pressure-based solver selected in Fluent was used for the numerical simulation. The gradients were computed for the control volumes around the cells using the least-squares method. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used to solve the pressure and velocity coupling equations. The bounded central differencing scheme and the second-order upwind scheme were used to solve the momentum equation and the κ-ω equations, respectively. The unsteady calculation method of the dual-time-step format was used for time discretization, with the physical time step being 1×10^{-4} s, in keeping with studies in Refs. [8,16,26,27], and the second-order implicit scheme was used for the transient formulation. For each time step, the number of iterations was 30, and the residual of each turbulent equation was at least 10^{-6}.

2.3. Grid generation

In this study, a hexahedral-dominated mesh was generated around the train using the open-source CFD toolbox OpenFOAM

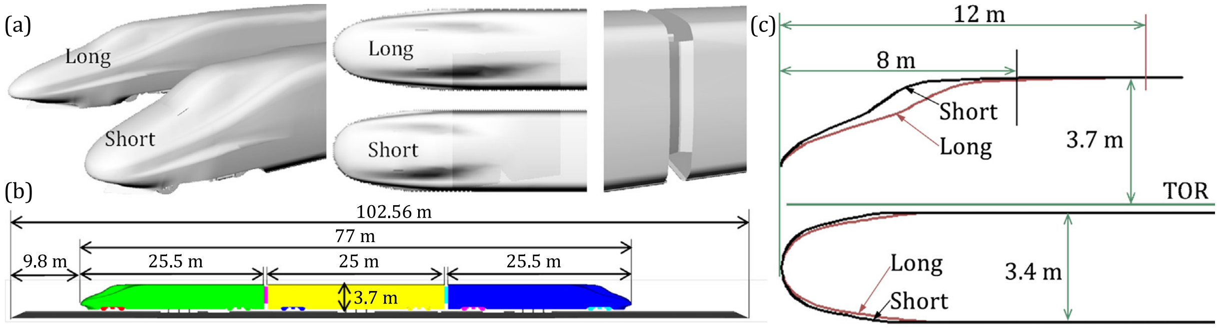

Fig. 1. Dimensions of the full-scale train: (a) 3D train model including streamlined train head, windshield, and bogie; (b) size and position of the train relative to the subgrade; (c) size of the train streamlined area.