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A study of snow accumulating on the bogie and the effects of deflectors on the de-icing performance in the bogie region of a high-speed train

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ABSTRACT

The operation of high-speed trains in ice and snow weather results in a large amount of snow accumulation with ice on the bogies, which will pose a risk to the safety of high-speed trains. In this paper, the snow accumulating on the bogie has been investigated using a numerical simulation method based on the Realizable k - ε turbulence model and Discrete Phase Model (DPM). The accuracy of mesh resolution and methodology of CFD was validated by the experimental results of wind tunnel tests. The DPM was used to investigate the mechanism of snow accumulation on the bogie by analysing the characteristics of movement of snow particles. Based on this analysis, two deflectors with the angles of 2.58° and 5.14° were designed, and the anti-snow effect of deflectors for the bogies was compared with numerical results. The results show that lots of snow particles underneath the bogie have direct impacts on the equipment of the bogie, causing massive snow accumulation on the bottom surface. A small amount of snow particles turn back to the region above the bogie from the rear cabin cover, which leads to little snow accumulation on the upper surface of the bogie. The number of particles accumulating on the bottom surface of the bogie is much more than that on the top. Application of deflectors with different angles can improve the anti-snow performance in the bogie region of high-speed trains. The deflector with an angle of 5.14° has the better anti-snow performance. It can reduce the snow accumulation on the whole bogie surfaces by 49.34%, while on the primary heat-producing devices, such as calipers and motors, by 42.47% and 47.40%, respectively.

1. Introduction

During snowy weather, trackside snow tends to be stirred up by the slipstream of high-speed trains, leading to massive snow and ice accumulation on the surfaces of bogies (Allain et al., 2014). The snow and ice accumulating on the bogies would cause series of problems. For example, the snow and ice packing on the elastic suspension will restrain the displacement of springs which seriously intensify the vibration of the train (Giappino et al., 2016). The heat radiated by the motors and gear covers of high-speed trains will melt the snow particles into liquid water which can be turned into heavy ice in a low temperature, increasing the axle load significantly (Cao et al., 2016). Additionally, the moving parts of brake calipers may be hindered by the ice, which results in being a more dangerous operation of high-speed trains (Kosinski and Hoffmann, 2007). Therefore, it is necessary to have a further study on the snow accumulation on the bogies to ensure the operational safety of high-speed trains and improve the comfort of passengers.

To solve this issue, a large number of studies have been undertaken in the past decades. Some European railway institutions have investigated several methods to remove the snow and ice covering on the bogies. Scottish railway institution used hot air to melt the ice on the equipment of the bogie (Scott, 2010). In Sweden, the environmental propylene glycol was heated circularly to eliminate the snow and ice (Bettez, 2011). Finnish railway institution thawed the ice by spraying hot water above the bogie (Paulukuhn, 2012). A propylene aqueous solution was adopted for removing the ice on the bogie in Russia (Paradot et al., 2014). Moreover, some other countries alleviated the snow and icing problem of the bogies by reducing the amount of snow accumulating on the railway lines. For instance, new viaducts were built on the Tohoku Shinkansen Line to mitigate the ice problem of the bogie (Fujii et al., 2002). The spraying devices were installed beside the Joetsu Shinkansen Line and Tokaido Shinkansen Line to reduce the amount of snow accumulation on the railway (Thomas, 2009). The Swedish railway institution used snowbrushes to prevent the snow particles accumulating beside lines rolling back into the track. To avoid massive snow particles flowing into the track, the snow fences were built along the Bergen railways (Bettez, 2011). However, the de-icing

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and snow removal devices mentioned above are fixed at certain locations to deal with the icing and snow problems. In addition, the method about how to prevent the issue of snow and ice accumulating on the bogies is rarely mentioned in literatures. On the other hand, China has the longest operating high-speed railway lines in the northern vast cold areas where the high-speed train travels across in several hours. Therefore, the snow-accumulating problem of bogies, imposing a threat to the safety of high-speed trains, is becoming a difficult and complicated event for the China High-speed Rail, and it is urgent to be solved.

The slipstream induced by the motion of high-speed trains blows up the snow particles along the track (Paulukuhn, 2012), then the phase change of snow particles on the surface of the bogie leads to a serious problem. Okaze et al. (2012), Smedley et al. (1993), Uematsu et al. (2010), Beyers and Waechter (2008) and Tsuchiya et al. (2002) studied the snow-drifting phenomenon by a wind-snow two-phase flow method. Therefore, in this paper a wind-snow two phase flow method was selected to simulate the snow particles' movement and accumulation effects in order to explore the reasons of snow packing on the bogie. At present, the research methods that are used to solve this wind-snow two phase flow include Euler-Euler (*E*-E) and Euler-Lagrange (E-L) methods. Ansari et al. (2014), Kosinski and Hoffmann (2007), Pankajakshan et al. (2011) and Zhou et al. (2011) simulated the movement characteristic of particles in the air flow field using the Euler-Lagrange (E-L) method, which shows a good prediction. Meanwhile, the volume fraction of snow particles in the bogie regions is much lower than 10% (Casa et al., 2014), and the DPM based on Euler-Lagrange (E-L) method has enough resolution on simulating the movement state (velocity and displacement etc.) of the solid particle phase in a continuous gaseous flow field whose volume fraction is less than 10% (Paz et al., 2015). Zhou et al. (2004), Wan et al. (2013), Ma et al. (2015) and Lai and Chen (2007) also used DPM to simulate the movement of particles in airflow, and the simulation results showed good resemblance to these experimental results. What's more, Xie et al. (2017) have investigated the snow accumulation on the single bogie surface utilizing the DPM method. Thus, it is reasonable to use the DPM based on the Euler-Lagrange method to study the effect of snow accumulation on the bogie.

In this paper, the DPM was used to simulate the motion state of the snow particles in the flow fields of bogies. In order to find out the reason of snow accumulation on the bogie, the motion of snow particles and the characteristics of flow fields in the bogie regions were discussed. On this basis, two kinds of deflectors were designed, and their anti-snow performances were also analysed using the numerical simulation method. This paper is organized as follows: In Section 2, the setup of wind tunnel tests, the mathematic model, the geometric model, the computational grid, the boundary conditions and the related parameter settings in numerical simulations are given together. The numerical results of a single continuous air phase (flow fields in the bogie region) are compared with wind tunnel tests results to validate the accuracy of the method and the resolution of the mesh. In Section 3, the mechanism of snow accumulation on the bogie is analysed. In Section 4, two deflectors are introduced, and the anti-snow performance of deflectors is analysed using numerical simulations. Finally, conclusions are drawn in Section 5.

2. CFD analyses

2.1. Mathematical model and geometric model

Based on Reynolds averaged motion equations, the Realizable k-ε turbulence model with wall function treatment was selected to simulate the continuous phase (flow fields in the bogie region). The Reynolds average method which not only ensures the accuracy of calculation, but also saves the computing resources, has been widely used in engineering (Cheli et al., 2010). The details of the continuity equation, momentum equation, energy equation and related parameters were given by John and Anderson (1995). The details of k equation and ε equation are discussed by Shih et al. (1995).

To simulate the discrete phase (snow particles), the DPM model implemented in Fluent was used. The movement parameters (velocity and displacement etc.) can be obtained by integrating the differential equations that describe the forces acting on the snow particles. The external forces acting on the particles include the aerodynamic force, gravity, false mass force, Basset force, Magnus force, Saffman force and pressure gradient force, but no additional forces are included in the force balance equation except the gravity and aerodynamic force (Spalding, 1981; Ni and Li, 2006). Thus, the differential equations describing the forces acting on the snow particles are presented as follows:

$$\frac{du_p}{dt} = \frac{18\mu}{\rho_\mathrm{p} d_\mathrm{p}^2}\frac{C_D \mathrm{Re}_\mathrm{p}}{24}(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} \tag{1}$$

where u is the velocity of continuous phase; u_p is the snow particle velocity; μ is the dynamic viscosity; d_p is the snow particle diameter; ρ_p is the density of snow particle; ρ is the density of air; g is the gravity acceleration; C_D is the drag coefficient of the snow particle. Re_p is the relative Reynolds number, and the relative Reynolds number is defined as follows.

$$\mathrm{Re}_\mathrm{p} = \frac{\rho d_p \, |\vec{u}_p - \vec{u}\,|}{\mu} \tag{2}$$

The trajectories of the particles in the flow fields can be obtained by integrating formula (1).

To validate the accuracy of the CFD method, the flow field in the bogie region has been investigated by wind tunnel tests that were conducted in the National Engineering Laboratory for High Speed Railway Construction. The aim of this paper is to study the phenomenon of snow accumulation on the bogie through analysing the flow characteristics in the bogie regions. Thus, this paper focuses on studying the airflow field in the bogie region rather than the whole aerodynamic performance of high-speed trains. The tuft visualisation was used to measure the airflow trend in the bogie region in the wind tunnel tests. To ensure the reliability of measurement, a simplified 1:2 scaled bogie with a half high-speed train body model was adopted in the wind tunnel tests. And the geometric model in numerical simulation and the wind tunnel model are basically the same (Zhang et al., 2016), as shown in Fig. 1.The vertical surfaces of the vehicle body were simplified to the inclined faces with 30° to avoid causing disturbance to the flow fields in the bogie region. The height of the train, 0.7 m, is chosen as the characteristic length and is denoted by H, the length is $L = 3.6$m and the width is $W = 1.3$m. The wheels, brake calipers, motors, gear covers and bogie frame were both preserved in the numerical simulations and wind tunnel tests, as shown in Fig. 1. The pipes and wires of the bogie were omitted, the gap between the wheels and rails were adjusted to facilitate meshing and calculating.

2.2. Computational grid and boundary conditions

The OpenFOAM mesh generator package was applied to build the hexahedral dominant mesh around the train and bogie, as shown in Fig. 2. The refining grids are applied to the region close to the surfaces of the train and the bogie. In addition, a uniform transition mode with a constant growth factor between the fine grid and the sparse grid was adopted, which not only ensures the accuracy requirements, but also saves the computing resources. The quality of meshes is verified by using OpenFOAM's inbuilt mesh metrics to make sure that the maximum skewness of every cell was below 4. The definition of skewness was given by Flynn et al. (2016). Ten prism layers in the boundary layer were applied from the train and bogie surface in order to catch the flow characteristics in the boundary layer. The thickness of the first boundary layer is 0.39 mm. The y^+ over the high-speed train's surface and bogie surface is between 30 and 70, which ensures the use of wall function in the Realizable k-ε turbulence model (Veersteg and