Wind and Structures, *Vol. 27, No. 4 (2018) 255-267*
DOI: https://doi.org/10.12989/was.2018.27.4.255

Effect of bogie fairings on the snow reduction of a high-speed train bogie under crosswinds using a discrete phase method

Guangjun Gao[1,2,3a], Yani Zhang[1,2,3b], Jie Zhang[*1,2,3],
Fei Xie[1,2,3c], Yan Zhang[1,2,3d] and Jiabin Wang[1,2,3e]

[1]Key Laboratory of Traffic Safety on Track of Ministry of Education, School of Traffic & Transportation Engineering, Central South University, Changsha 410075, China
[2]Joint International Research Laboratory of Key Technology for Rail Traffic Safety, Central South University, Changsha 410075, China
[3]National & Local Joint Engineering Research Center of Safety Technology for Rail Vehicle, Changsha 410075, China

(Received January 25, 2018, Revised March 21, 2018, Accepted March 23, 2018)

Abstract. This paper investigated the wind-snow flow around the bogie region of a high-speed train under crosswinds using a coupled numerical method of the unsteady Realizable *k*-*ε* turbulence model and discrete phase model (DPM). The flow features around the bogie region were discussed and the influence of bogie fairing height on the snow accumulation on the bogie was also analyzed. Here the high-speed train was running at a speed of 200 km/h in a natural environment with the crosswind speed of 15 m/s. The mesh resolution and methodology for CFD analysis were validated against wind tunnel experiments. The results show that large negative pressure occurs locally on the bottom of wheels, electric motors, gear covers, while the positive pressure occurs locally on those windward surfaces. The airflow travels through the complex bogie and flows towards the rear bogie plate, causing a backflow in the upper space of the bogie region. The snow particles mainly accumulate on the wheels, electric motors, windward sides of gear covers, side fairings and back plate of the bogie. Longer side fairings increase the snow accumulation on the bogie, especially on the back plate, side fairings and brake clamps. However, the fairing height shows little impact on snow accumulation on the upper region of the bogie. Compared to short side fairings, a full length side fairing model contributes to more than two times of snow accumulation on the brake clamps, and more than 20% on the whole bogie.

Keywords: DPM; side fairing; snow accumulation; high-speed train; bogie

1. Introduction

The snow and ice on bogies of a high-speed train can seriously affect the operational safety of the train, and the snow covering on brake clamps even affects the braking performance of the vehicle and the corresponding dynamic characteristics, forcing the train to slow down or stop operation. Therefore, in the past decades many measures have been put forward to solve this problem. For example, Kim *et al.* (2015) studied the influence of an electric heating snow-melting system on the operational safety of light rail vehicles and energy supply. Jemt and Thomas (2009) studied a de-icing solution by using environmentally friendly propylene glycol to clean the snow and ice on the bogie and on the ground. Ross (2009) discussed chemical de-icing solutions implied on the railway vehicle. Kloow (2015) summarized the snowdrift's influences and solutions corresponding to the problems on the journal box, train wheels, axle shaft, spring suspension devices, etc. The results show that the snow mainly drifts in the region of the underframe and the bogie. Fujii *et al.* (2002) investigated the relationship between the density and water content of the snow using a model test to analyze the measures against snow for the extended Hokuriku Shinkansen line. Bettez (2011) summarized the railway de-icing and anti-icing technologies. The work includes the mechanical method, chemical method and electromagnetic technique. Using Propylene glycol to clean snow and ice on the ground is the most effective method.

As to the issue of snow and ice covering on the train, the research above only focuses on how to remove the snow and ice, and contributes less to preventing the snow and ice packing on the bogie from the original source. Besides, there are few studies on the causes and the distributions of the snow on the bogie. Also, no research investigates the influence of bogie structures on the snow and ice accumulation, except of the work on the flow in the bogie region with different configurations (Zhang *et al*. 2018). According to the study of Miao and He (2018), the snow and ice packing on the bogie are mainly caused by the flow underneath the train. Hence, it's a good choice to

∗Corresponding author, Ph.D.
E-mail: jie_csu@csu.edu.cn
[a] Professor
E-mail: gjgao@csu.edu.cn
[b] Master Student
E-mail: yanizhang@csu.edu.cn
[c] Master Student
E-mail: 564094813@qq.com
[d] Master Student
E-mail: zy190033@gmail.com
[e] Ph.D. Student
E-mail: wangjiabin@csu.edu.cn

http://www.techno-press.com/journals/was&subpage=7
ISSN: 1226-6116 (Print), 1598-6225 (Online)

investigate the formation mechanism by studying the snow particles' motion characteristics and their distributions in the bogie flow field.

Some researchers have done studies about the formation of the snowdrift (Sato *et al*. 2008, Gordon and Taylor 2009, Gordon *et al*. 2009). Therefore, some models have been built to predict the snowdrift in the environment and the surrounding buildings. Additionally, these models have been verified and improved by the experiments, of which the RANS model has been widely used (Tominaga *et al.* 2004, Cao *et al*. 2016, Zhou and Li 2010). For example, Beyers and Waechter (2008) using a commercial CFD software based on Euler three-dimensional turbulent flow control equations, simulated the incompressible Newtonian two-phase flow consisting of air and snow. They analyzed the snowdrift and erosion around a cube. Zhou and Li (2010) studied the two-phase air-snow flow near an airport terminal using the standard and Realizable k-ε turbulence models, which confirmed the reliability of the numerical simulation method by comparing the numerical results to the test data of the Beijing international airport terminal 3A. Zhao *et al*. (2016) simulated the snowdrift on flat roofs. Thiis (2000) investigated the snowdrift around different buildings used a CFD method. Moreover, the RNG turbulence model has been widely used in train aerodynamics (Bocciolone *et al.* 2008, Zhang *et al*. 2013, Cross *et al*. 2015, Niu *et al*. 2017). Thus, the RNG turbulence model combined with DPM can be implied to study the snow on the high-speed train bogie.

For the simulation of particles, Morsi and Alexander (1972) investigated the particle trajectories in two-phase flow. They found that particle trajectories are related to the particle density, size and air velocity. Wang and Huang (2016) studied the snowdrift around a complex structure building based on the Lagrange particle model and LES turbulence model. Paz *et al.* (2015) studied the particle impact on the motion of high-speed trains in a sand-laden flow using the Discrete Phase Model (DPM). Generally, the *k-ε* turbulence model coupled with DPM approach is a suitable method to study the snowdrift, for these numerical results show good agreement with the experimental data. Therefore, this method will be applied to simulate the snow packing on the bogie of a high-speed train.

Compared to the architectural structure snowdrift problems, there are two main differences on the train bogie snowdrift problems. Firstly, for the train moves in open air, the slipstream and environmental wind will affect the snowdrift together. Secondly, the bogie structures are so complex that different parts have different influences on the snowdrift distributions on the bogie. Similar to the snowdrift formulation around the building, the snowdrift formulation is related to the flow field. For a vehicle, side fairings have effects on the under-body flow (Hwang *et al.* 2016). Therefore, the side faring will affect the snow covering on the bogie. Xie *et al.* (2017) and Wang *et al.* (2018) investigated the snow and ice on the bogie using DPM, which indicates that the structure in the bogie region could affect the snowdrift on the bogie. However, the crosswind in the open air was not considered. It's necessary to study the effect of bogie fairings on the under-body flow field and snow packing on the bogie for finding a proper side fairing height. This paper will investigate the influence of side fairing's height on the snowdrift on the train bogie. The train is running at a speed of 200 km/h in the open air where the crosswind speed is 15 m/s.

2. Mathematical model

Discrete phase model takes a great advance in numerical simulations as for it can display the particle trajectories directly. In the discrete phase model, the Eulerian approach is used to solve equations of fluid and the Lagrangian approach is used to solve equations of discrete phase. Discrete phase model is appropriate to study the two-phase flow which the second phase volume fraction in the flow field is no more than 10% (ANSYS User Guide 2014). The snow particles volume fraction in the air is far less than 10% according to the Casa *et al.* (2014). Hence, the DPM model is adopted to simulate the discrete phase of snow particles. The air phase of the two-phase flow uses the unsteady Realizable *k-ε* turbulent model. Governing equations of the flow field adopt the classical flow control equations completely and they can be seen in reference (Anderson 1995).

In the discrete phase model (DPM), particle trajectories in the continuous phase are calculated by calculating the forces acting on those particles. The equations of particles are solved by the Eulerian–Lagrangian approach. During the process of particle's motion, besides the gravity and drag, there are additional drags acting on the particle. The additional drags include the virtual mass force, pressure gradient force, Saffman lift force and Basset force. The calculation is done under the Lagrangian coordinates. The particle trajectories are predicted by doing the integration of the particle's force balance equation. For snow particle movement, the aerodynamic force and gravity are important external forces, the effects of other forces are small and they can be neglected. The force balance equation of the discrete phase particle is show as Eq. (1), (ANSYS 16.0. Theory Guide 2014), reflecting the inertial of the particle is equal to its external force.

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u}-\vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} \tag{1}$$

$F_D(\vec{u}-\vec{u}_p)$ is the aerodynamic force acting on the unit mass of the particle, $\vec{u}$ is velocity vector of the fluid phase, $\vec{u}_p$ is the velocity vector of the particle phase， r_p is particle density, r is air density， $\vec{g}$ is inertial acceleration vector.

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D \mathrm{Re}}{24} \tag{2}$$

μ is dynamic viscosity, d_p is particle diameter, C_D is drag coefficient.

Re is relative Reynolds number ,the definition as flowing

$$\mathrm{Re} = \frac{\rho d_p \left| \vec{u}_p - \vec{u} \right|}{\mu} \tag{3}$$

It can get the particle velocity on each position of particle track by doing integral of Eq. (1), the equation is showed as Eq. (4)

$$\frac{d\vec{x}}{dt} = \vec{u}_p \tag{4}$$

$\vec{x}$ is the particle displacement vector， t is time.

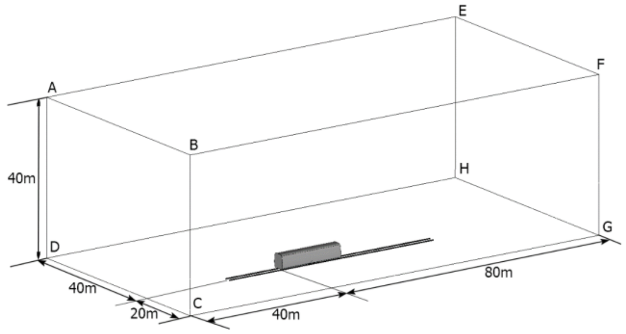


Fig. 3 Computational domain

3. Geometric model, mesh and boundary conditions

To simulate snow particles travelling a complete train model could consume large computer resources, and bogies with cavities are the representative cases in the train underbody regions to study the flow fields around bogie regions (Zhu *et al.* 2016). Therefore, in the first stage we attempt to explore the flow characteristics around a bogie with part of the train body at different fairing heights. The simplification method for the model can refer to Zhu and Hu (2017). Very tiny structures around the bogie are removed from the geometry in order to save computing resources. The simplified geometric model includes two parts: the car body and the bogie, as shown in Fig. 1. There are four cases: one with short side fairings with the height of 0.45 m, the heights of the rest cases are 0.09 m, 0.18 m and 0.31 m, respectively. For the convenience, the four models are named as model-1, model-2, model-3 and model-4, as shown in Fig. 2.

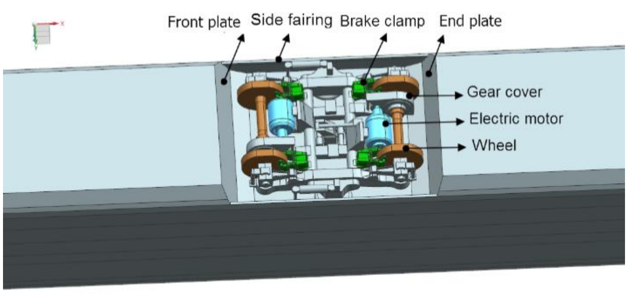


Fig. 1 Schematic of the car body and bogie components

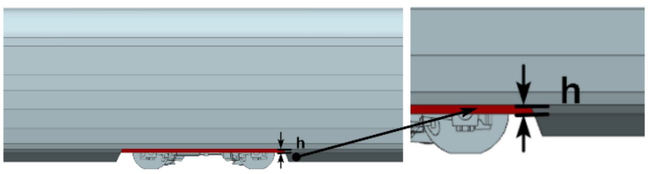


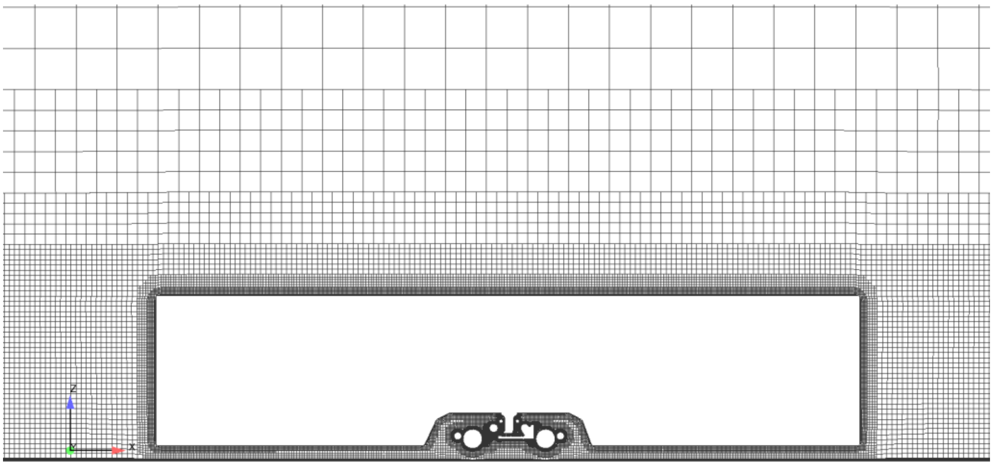
Fig. 2 Different heights of side fairings: h1=0.09 m, h2=0.18 m, h3=0.31 m

The computational domain with dimensions of 120 m×60 m×40 m is illustrated in Fig. 3. The scale of the model is 1:1. Considered the crosswind, the computational domain is set asymmetrically, so the domain in the leeward side is longer than that of the windward side. The computational domain is meshed with hexahedral dominant grids using Open FOAM. The surface grid size of the train body is 31.25 mm, and it is 15.625 mm on the bogie. 6 boundary layers around the car body and bogie and 4 boundary layers around the rail and ground are used to capture the flow features around them. The maximum skewness of the grid is below 4. The inlet velocity is 55.56 m/s, and the corresponding y+ values of the model are roughly in the range of 30-300. The CFL number is roughly 0-9.58.

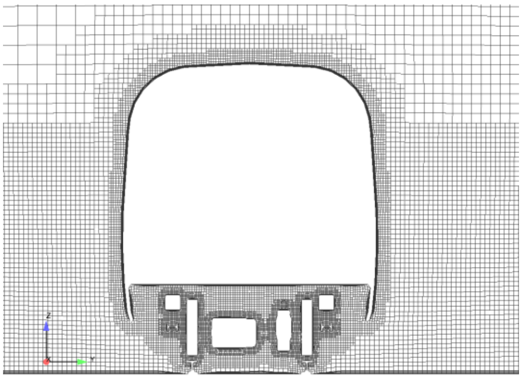
The total number of grids is about 10 million. The mesh distributions are presented in Fig. 4. The model surfaces are treated as no-slip walls. The other boundary conditions of the domain are shown in Table 1. To simulate the train speed, the inlet velocity is 55.56 m/s, corresponding to the train speed of 200 km/h. The rail and the floor are both set as moving walls with the same velocity of the train speed.

The numerical simulation is done in FLUENT 16.0. The SIMPLEC scheme is used to couple the velocity and pressure fields. The total flow rate of particle ejection is 1×10^{-9} kg/(s·m^2) with the particle diameter of 0.0002 m on average (Zhang *et al.* 2013) and the density of 100 kg/m^3 (Tominaga *et al.* 2011). The unsteady case is used to study the transient distributions of snow particles. The time step is 0.001 s, which is determined by the typical cell size and characteristic flow velocity in the bogie. The simulation time is 2 s for the snow particles pass through the domain once, and the previous work (Xie *et al.* 2017, Wang *et al.* 2018) shows that the rate of change on the snow accumulating on the bogie is stable after 1.5 s, therefore, the total simulation time of 2.0 s was used in this paper to save computing resources.

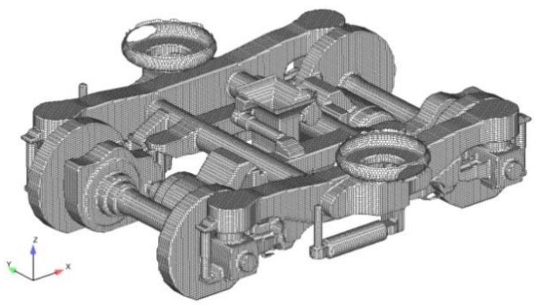
The wheels, electric motors, gear covers, brake clamps are all set as no-slip walls. Considered the worst snow and ice packing on the bogie, the trap boundary conditions are used for the car body, bogie frame, wheels, electric motors, gear covers and brake clamps, which means the particles will be captured when they impact on the structure and the particle tracks will be stopped.



(a) Mesh distribution in the symmetry plane



(b) Mesh distribution in the cross-sectional plane



(c) Surface mesh distribution on the bogie

Fig. 4 Computational mesh

Table1 Boundary conditions

Domain boundary	Boundary conditions	Parameter
ABCD	Velocity-inlet	X=55.56 m/s, y=15 m/s, z=0.
EFGH	Pressure outlet	Static pressure of 0 Pa.
ABFE	Symmetry	No.
CGHD	Moving wall	Velocity of 55.56 m/s.
AEHD	Pressure outlet	Static pressure of 0 Pa.
BFGC	Velocity-inlet	X=55.56 m/s, y=15 m/s, z=0.

The ejecting plane of snow particles is asymmetric in front of the bogie, aiming to ensure the particles can be blown and drifted in both flow fields of the crosswind and the train (Paz *et al.* 2015).

4. Validation

Two wind tunnel experiments have been done to validate the accuracy of the numerical simulation method. The first one used a 1:2 scaled model to validate the simulation of the continuous airflow field, and the streamline directions and velocity values at specified points were compared. The second experiment validated the snow particle distribution on the bogie using a 1:4 scaled model due to the limitation of test conditions. The wind tunnel experiment results were compared with numerical results in the following section.

4.1 Continuous airflow field

The URANS numerical method to predict the flow around the bogie was validated by a wind tunnel experiment in the previous studies (Xie *et al.* 2017, Wang *et al.* 2018), and good agreement was shown for important flow characteristics around the bogie region. The wind tunnel experiment was conducted in the high-speed test section of the wind tunnel at the National Engineering Laboratory for High Speed Railway Construction, and the dimensions of the test section are 15 m×3 m×3 m. The full description of the experimental set-up and results can be found in Wang *et al.* (2018). That study comprehensively evaluated the key numerical settings (including the choice of turbulence model, mesh resolution and time-step) for predicting the flow characteristics and snow accumulation around the bogie region.

4.2 Snow accumulation on the bogie

A 1:4 scaled transparent train body was used to observe the particle flow in the bogie region. The experimental model is shown in Fig. 5. A fixed floor was used with a 1:4 scaled rail model. Sawdust with density of 100 kg/m^3 and diameter about 0.2 mm was used to simulate those snow particles.

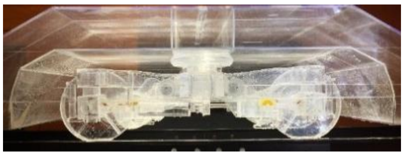


Fig. 5 Wind tunnel test model

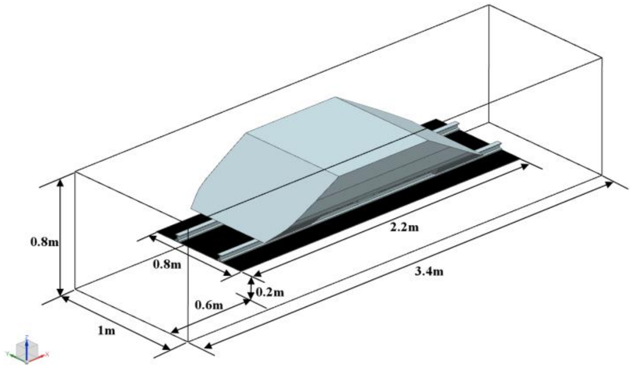
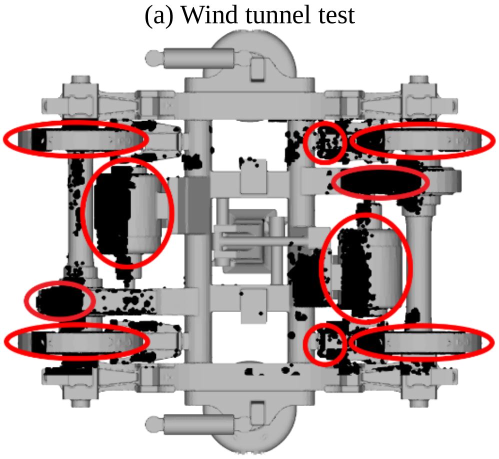


Fig. 6 Computational domain for validation

(a) Wind tunnel test



(b) Numerical simulation

Fig. 7 Comparison of snow accumulation results

Honey was used to increase the stickiness of the sawdust to simulate the snow particles' stickiness when they aggregate together. The wind speed is 35 m/s, and high-speed cameras are used to record the trajectories of the particles. As shown in Fig. 6, the computational domain is presented to obtain the numerical simulation results. The snow distributions on the bogie are shown in Fig. 7.

By comparing the experimental and numerical results, it can be concluded that the snow distribution on the bogie numerical method in the simulations can be used to study the flow field and snow accumulation on the bogie.

5. Results and discussion

Normally the high-speed train runs at a speed of higher than 200 km/h, and it is easy to subject to a crosswind. Thus, in this paper, the train speed is set at 55.56 m/s and the crosswind speed is 15 m/s. The distributions of pressure and velocity fields, snow accumulation on the bogie will be discussed in the following section.

The pressure and velocity field are presented by the dimensionless coefficients C_p and U. The coefficients are defined as

$$C_p = (P - P_\infty) / (0.5 \rho U_{ref}^2) \tag{5}$$

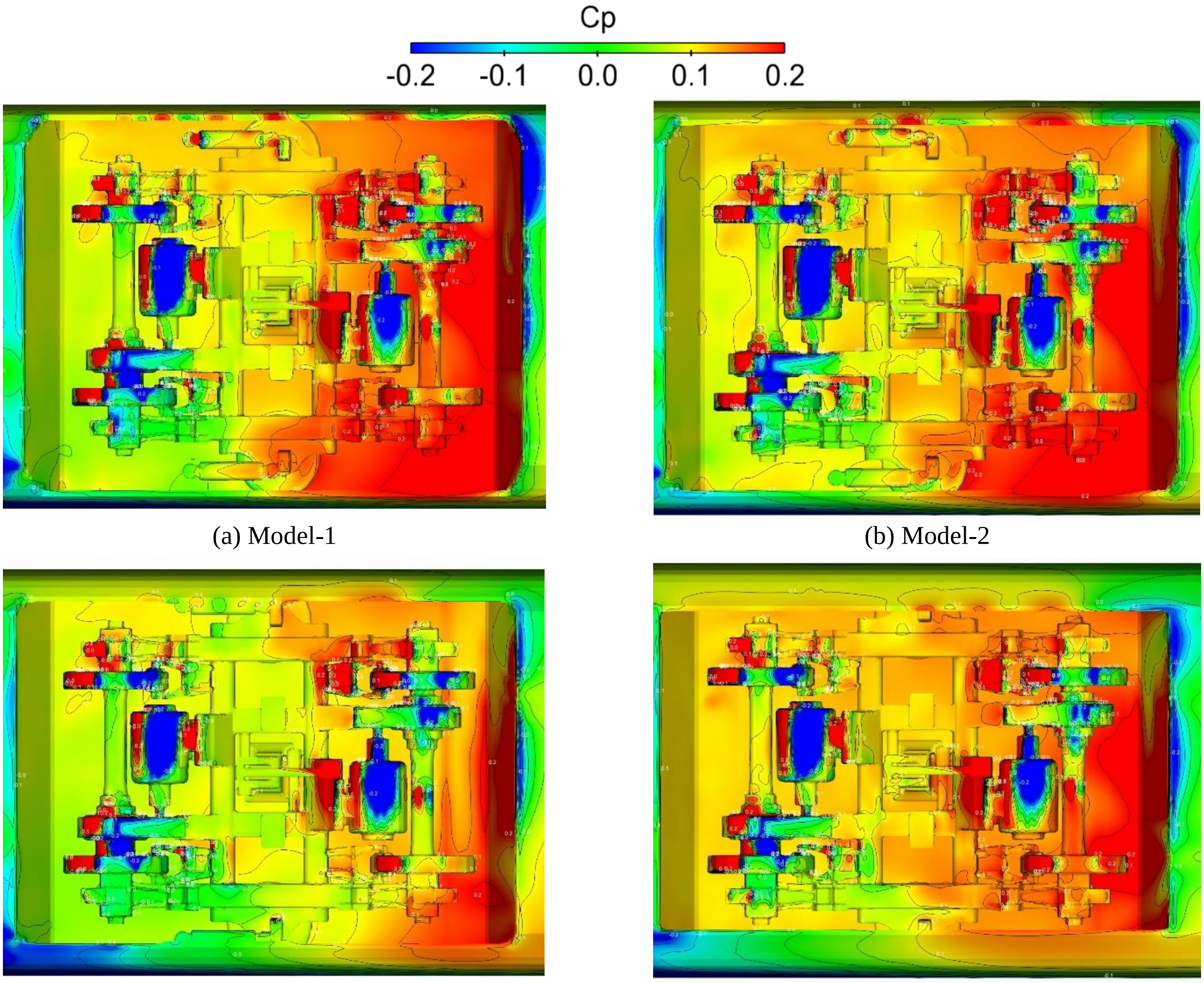
$$U = u / U_{ref} \tag{6}$$

where, $(P - P_\infty)$ is the differential pressure. U_{ref} is the average speed of the income flow. ρ is the density of air, and $\rho = 1.225\ \mathrm{kg/m^3}$. u is the air velocityat the local monitoring point.C_p is the pressure coefficient. U is the non-dimensional velocity.

5.1 Pressure distribution and velocity field

Due to the following feature and inertia of the snow particles in the air, they will whirl around the train when the air velocity is higher than the critic moving speed of the snow particles. However, when the air velocity reduces, the snow particles will drop down onto the bogie surfaces. Additionally, the wheels, electric motors and gear covers are the parts which can generate heat .As a consequence, the snow will melt and freeze on the bogie around these parts. This will influence the train safety.

In order to investigate the snow particles movement and accumulation mechanism around the bogie region, the pressure distributions and velocity field around the bogie region are analyzed in the following section. Firstly, the pressure distributions on the bogie bottom and the whole bogie cabin are analyzed. Secondly, the pressure distributions and streamline on slices of the crucial parts are analyzed to study the specific flow field features. The positions of slices 1, 2, 3, 4, X1 and X2 on the wheels, electric motors, gear covers, the end-plate of bogie cabin and side fairings, are showed in Fig. 8. Fig. 9 shows the pressure distributions on the bogie and the bottom in four cases.



(a) Model-1 (b) Model-2

(c) Model-3 (d) Model-4

Fig. 9 Pressure distributions on the bottom of the bogie and equipment cabin covers in four cases

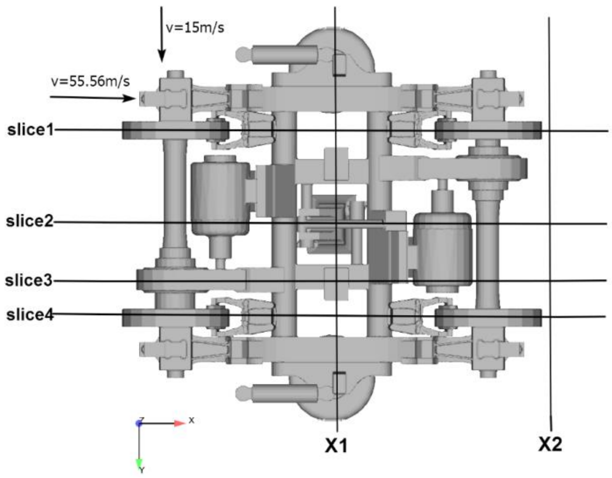
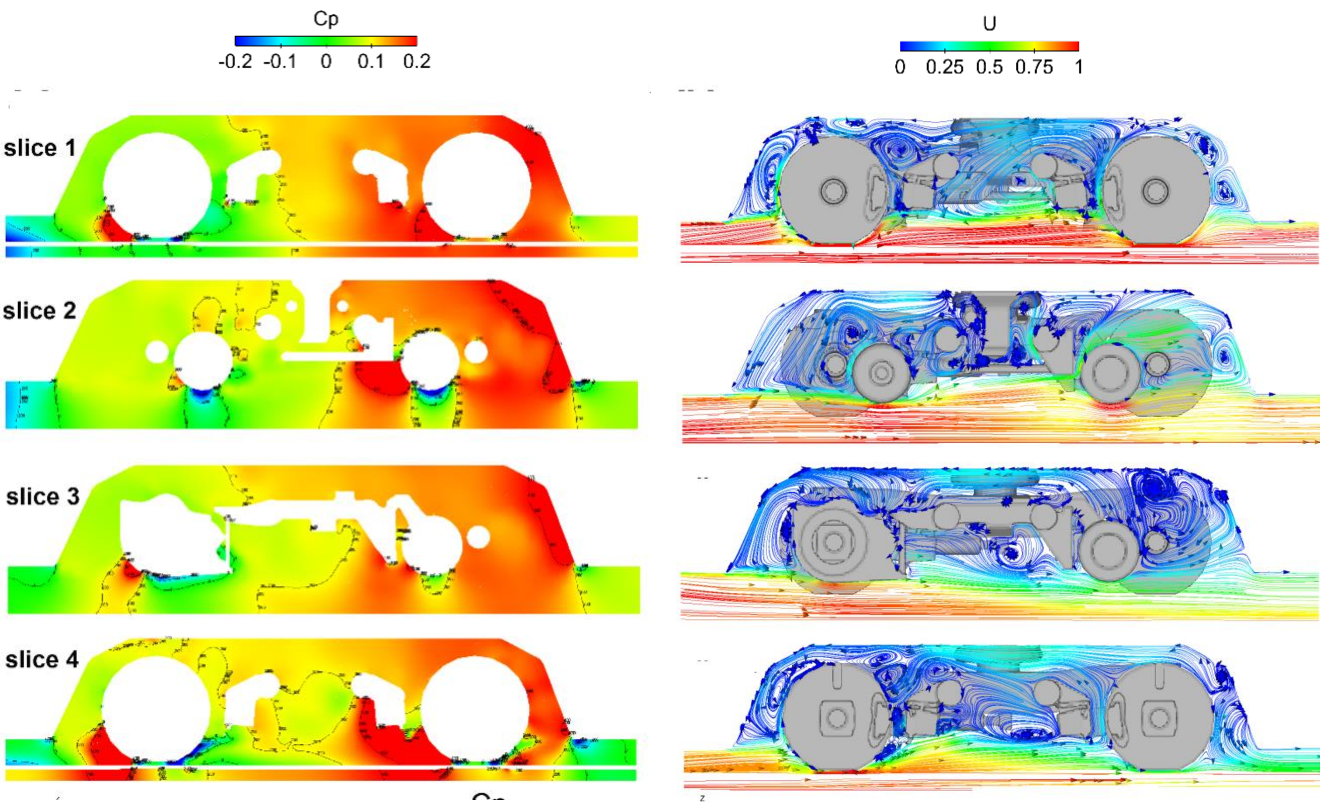


Fig. 8 Positions of slices

As shown in Fig. 9, on the bottom, the pressure mainly presents positive in the rear part of the bogie region and the windward sides of the wheels, electric motors, gear covers, while negative pressure occurs locally on the bottom of those components. The snow will accumulate on the bogie area where the pressure is large, due to the direct impact of the air. As shown in Fig. 10(b), high velocity contributes to negative pressure, and around the stagnation region where the velocity is approximately zero there is positive pressure. The airflow flows fast in the middle of the bogie cavity. Then the velocity slows down when the air impacts on the rear of the bogie. As to the streamlines, they rise up when the air invades into the bogie region. Especially, the directions of the streamlines will change obviously where the air slows down. Due to the large density of snow particles those snow particles do not follow the streamlines, and they will continue to move as the inertia. Then they will impact and accumulate on the bogie.

The pressure of the whole bogie region becomes large with the side fairing height increasing. Compared to model-1, with the height of side fairings increasing, the pressure on other models changes obviously. As to the model-2 and model-3, the positive pressure on the windward sides of wheels decreases while the negative pressure region on the bottom of the wheels becomes higher. The pressure in model-4 changes greatly. The variations of pressure distributions are caused by the air flowing features. High



(a) Pressure distribution (b) Streamlines colored by velocity

Fig.10. Pressure distribution and streamlines colored with velocity in slices 1-4 of model-1

side fairing reduces the crosswind entrance section of the bogie cabin and increases the air velocity. Then, the high speed air carried more snow particles into the bogie and hindered by the side fairing in the leeward side. After that, the airflow direction changes and the speed decreases. Finally, snow particles don't follow by the air and drop off on the bogie components, such as the brake clamps which are close to the side fairing. All these indicate that the side fairing can affect the movement of snow particles around the bogie area.

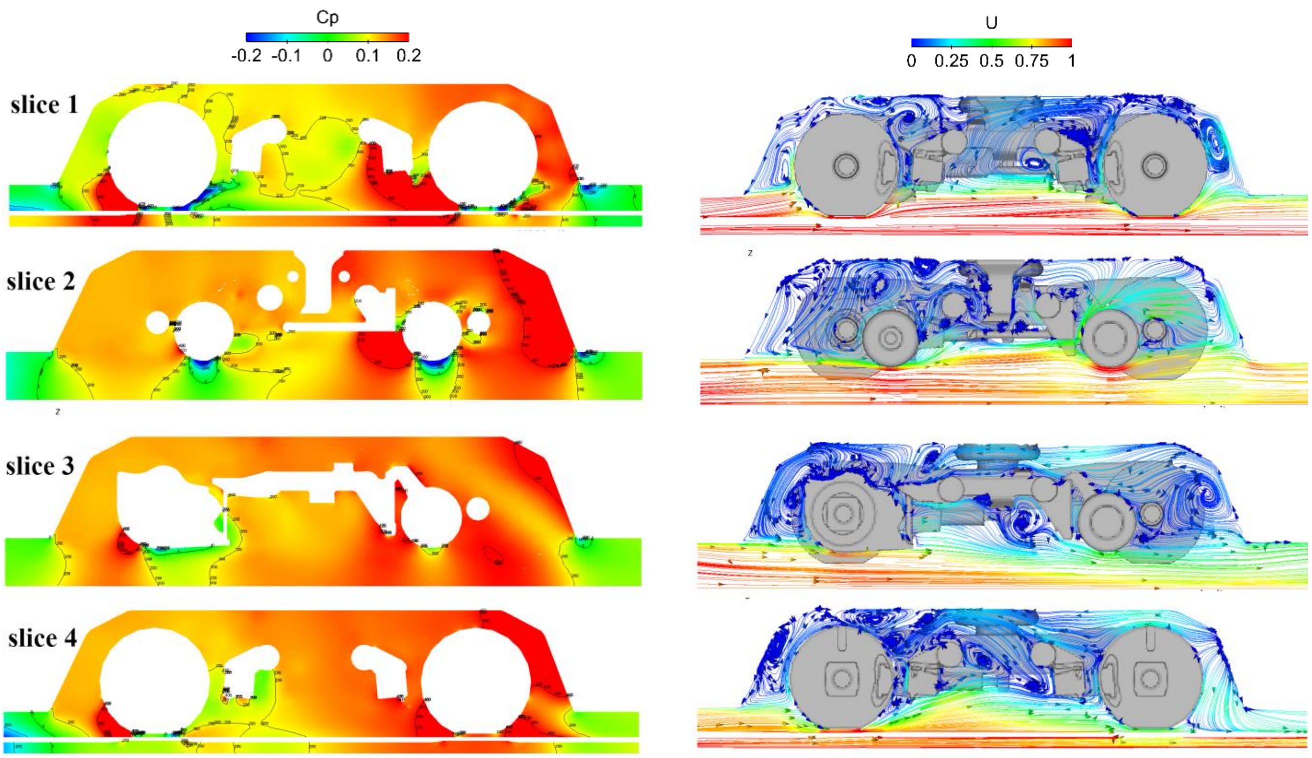
The pressure distributions of the wheels, electric motors, gear covers, end-plate of bogie cabin and side fairings change obviously, which will cause snow changing on these parts. To find the detailed characteristics, the pressure distributions and velocity fields in slices are analyzed.

Fig. 10 shows the pressure distribution and streamlines in slices 1-4 of model-1. In Fig. 10(b), the high velocity airflow entering the bogie is hindered on the wheel surfaces, electric motors, gear covers and brake clamps, etc., which corresponds to the high pressure on the windward side of the wheels in Fig. 10(a). The air flows towards the cavity and forms vortices behind the front plate. Then it travels through the front wheels and is hindered by the rear components of the bogie. More vortices exist around the bogie, corresponding to the negative pressure in Fig. 10(a). As a result, the snow particles flow into the bogie and some impact on the wheels, electric motors, gear covers and brake clamps, etc., and some drop on the bogie surface with the vortices. Slice 4 in Fig. 10(b) shows the streamlines around the wheels and brake clamps. The airflow speed in the bogie top is higher than in slice 1, while it is slower in the bogie bottom. This contributes to more snow particles sticking on the rear end plate and leeward side of the bogie.

Fig. 12 shows the pressure distributions and streamline colored by velocity around electric motor of model-2 and the model-3 in slice 2. Compared with model-1 in Fig. 11(a), the pressure in the rear end region changes obviously with the height increase of the side fairings. The heightened side fairing leads to a change in the pressure gradient of the bogie region, which changes the airflow velocity entering the bogie region and can cause the change of the snow distribution, as shown in Fig. 11(b). The streamlines and velocity in the front region of the bogie don't change obviously, while the velocity in the rear increases with side fairing's height. In general, the side fairings have limited influence on the velocity field of the bogie, but affect the snow accumulation in the rear region.

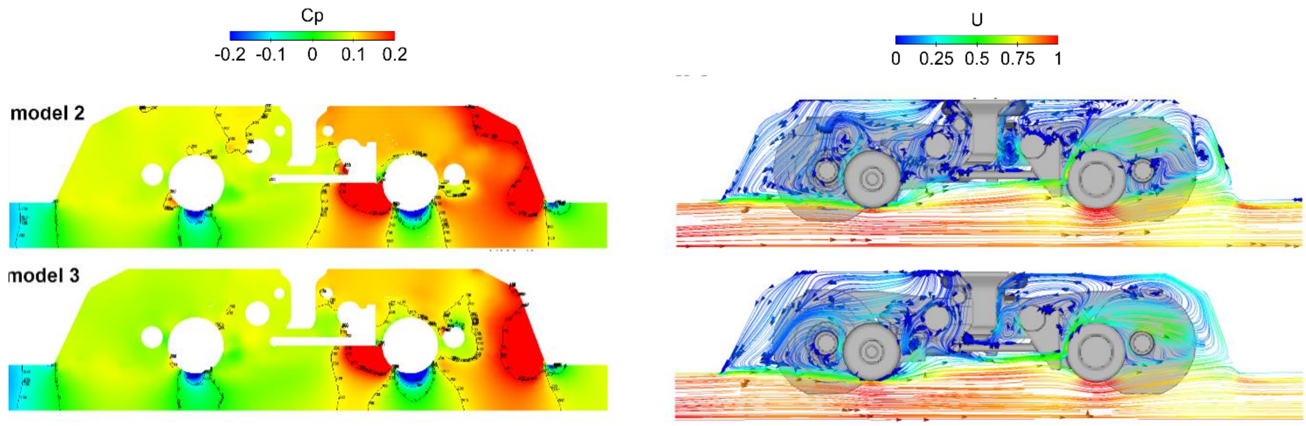
The analysis above indicates that the crosswind has effects on the snow accumulation in the bogie region. To investigate the influence of crosswinds on the flow field in the bogie region, streamlines colored by velocity in slices X1 and X2 are shown in Figs. 13 and 14.

Fig. 13 shows the streamlines colored by velocity in slice X1. The crosswind flows into the bogie from the windward side fairing and is blocked by the bogie structures. The incoming flow velocity becomes slower while the outlet flow velocity becomes faster with the side fairing's height increasing.



(a) Pressure distribution (b) Streamlines colored by velocity

Fig. 11 Pressure distribution and streamlines colored by velocity in slices 1-4 of model-4



(a) Pressure distribution (b) Streamlines colored by velocity

Fig. 12 Pressure distribution and streamlines colored by velocity in slice 2 of model-2 and model-3

This is because the air entrance section of the bogie cabin is smaller and the high side fairing blocks the air flowing out. Vortices occur in the leeward side of the side fairing of model-3 and model-4. The snow particles carried by the high speed airflow will accumulate on the bogie and side fairings when they are blocked by the high side fairings.

Fig. 14 shows that the air flowing into the bogie region from the bottom of the train body is affected greatly by the side fairings. In the rear of bogie cabin, airflow flows out the bogie region from two sides of side fairing, which is different from the streamlines in Fig. 13. The vortices in the leeward side of the fairings become larger with the increase of the side fairing's height, leading to more snow accumulation. Consequently, the snow will accumulate on the whole side fairing. As the fairing is a curved structure and bent towards the inside of the vehicle, the snow covering on the side fairings is difficult to fall off during the operation of the train. Then more snow will pack on the fairings and pose a threat to the train operation safety.

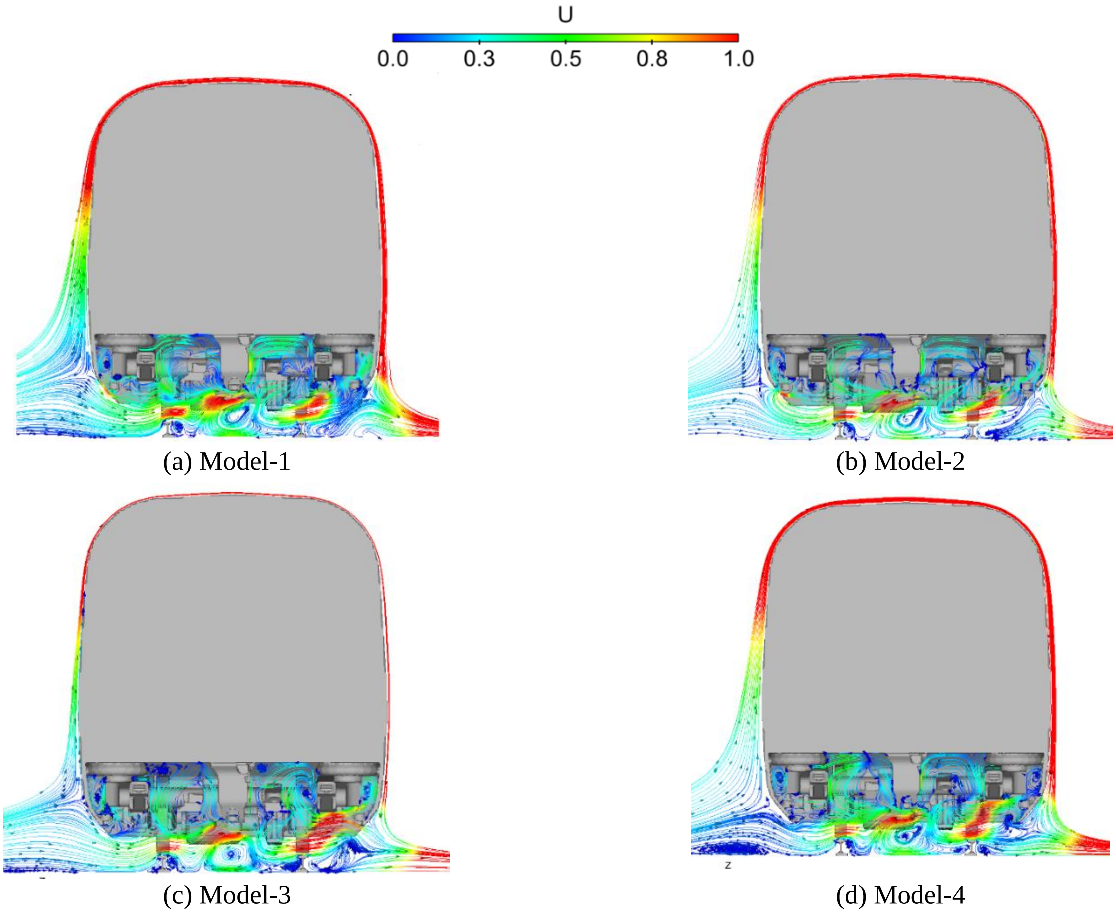


Fig. 13 Streamlines in slice X1

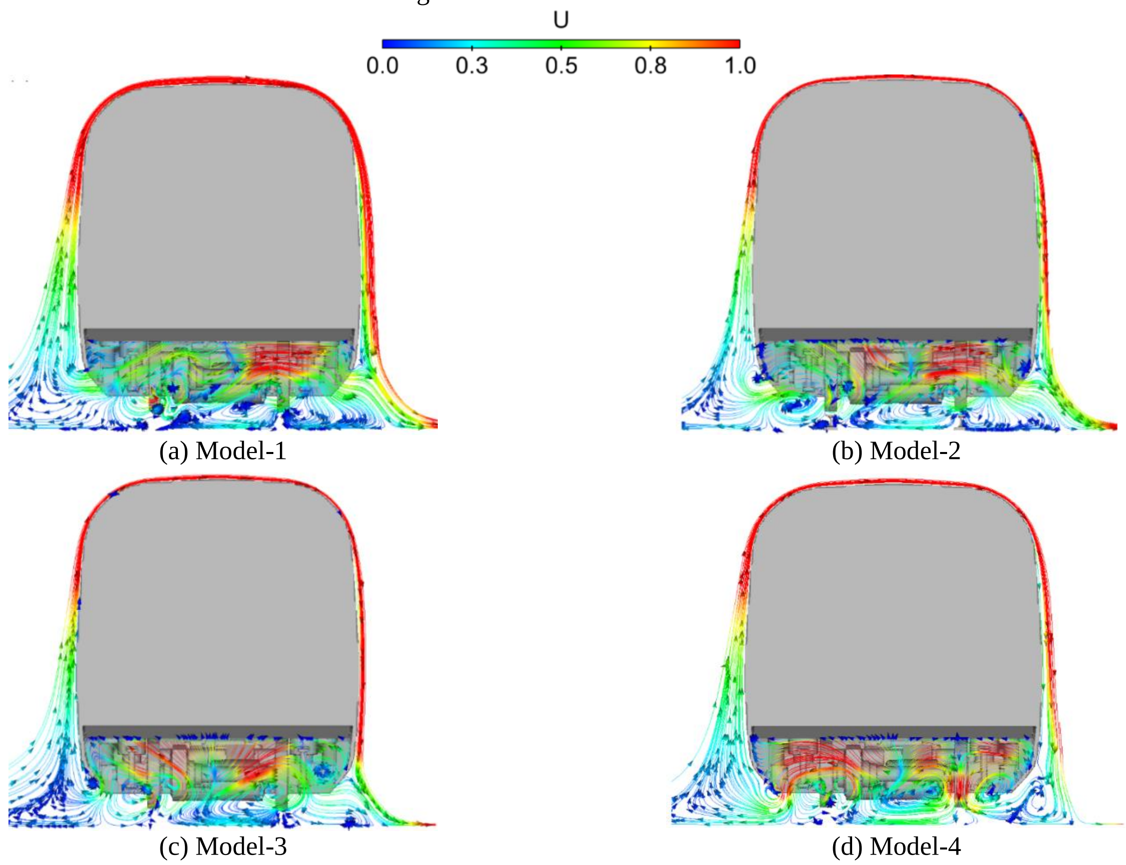


Fig. 14 Streamlines in slice X2

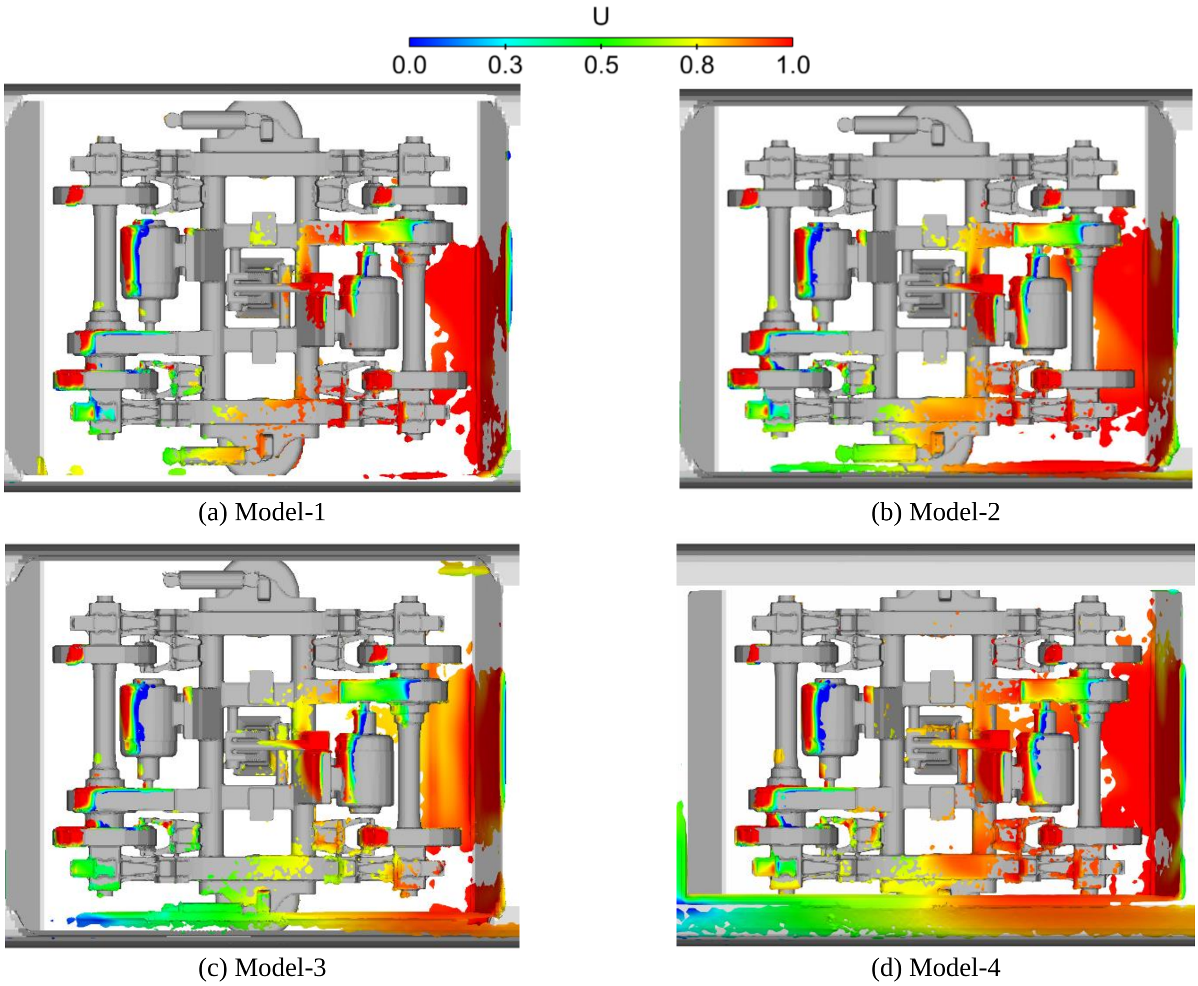


Fig. 16 Snow particles accretion contour on the train bottom and bogie at 3×10^{-12} kg/m^2

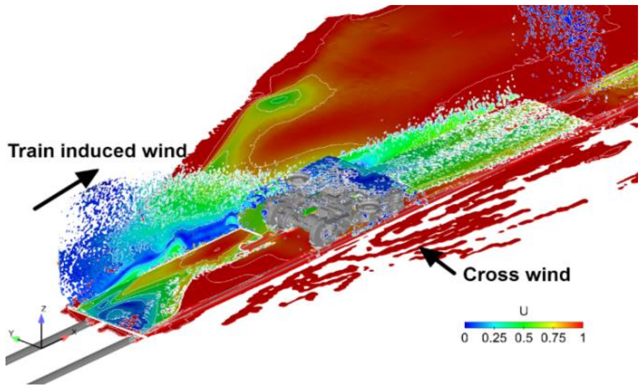


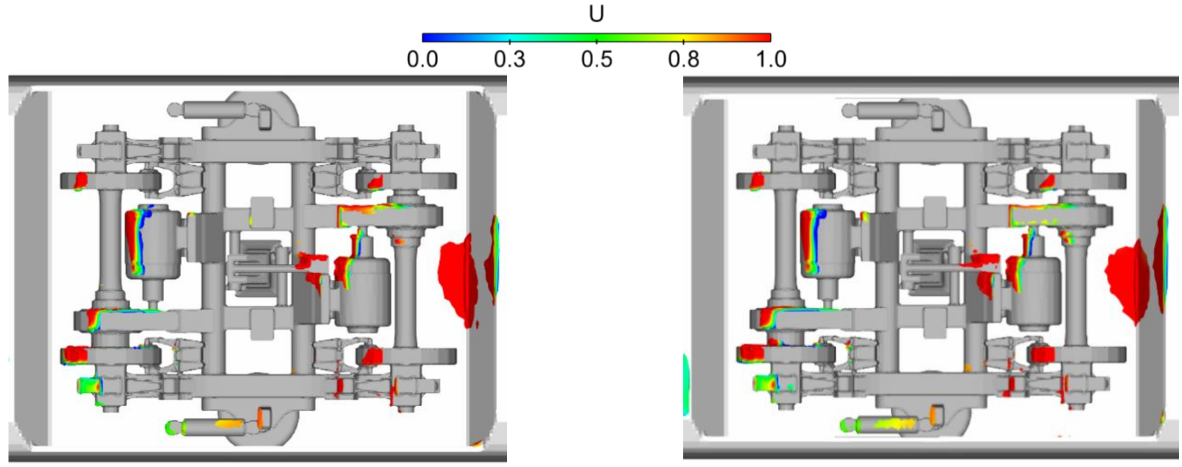
Fig. 15 Isometric view of snow particles whirling around the train body at 5×10^{-13} kg/m^2

5.2 Snow on the surface of the train body and bogie

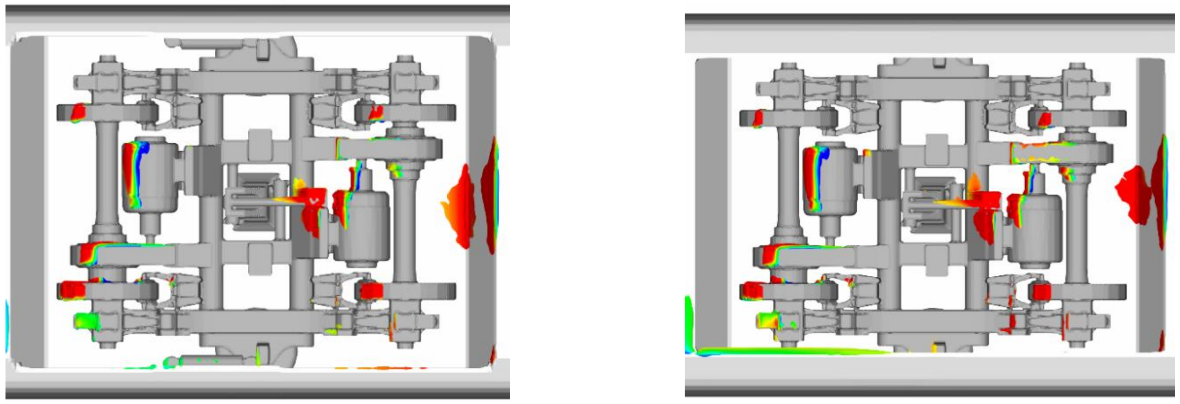
The pressure distributions and velocity fields indicate that the snow particles probably accumulate on the wheels, electric motors, gear covers' windward side and bottom where the positive pressure, backflow and vortex exist. The snow particles accretion rate contour of 5×10^{-13} kg/m^2, 3×10^{-12} kg/m^2, 3×10^{-11} kg/m^2 are presented in Figs. 15-17, respectively, to show the snow accumulation regions.

Fig. 15 shows snow particles whirl around the whole train body in an isometric view. Most of particles are blown out from the bottom of the train body with the high speed air. The snow particles accumulate seriously on the bogie region, e.g., the bogie cabin rear plate and the leeward side of the side fairings.

Figs. 16 and 17 show the snow particles accumulating on the train bottom and bogie. Note that the snow covering on the bogie mainly accumulates on the wheels, electric motors, gear covers' windward sides, bogie cabin back plate and side fairings. Among these parts, the bogie cabin end plate is the part which is the worst region covered by snow particles. Also, the windward sides of the electric motor and wheels are easier to be packed by the snow particles. As to the side fairings, although a few snow particles can be found, the covering region is much larger. Additionally, with the increase of side fairing's height, the snow accumulation regions on the end plate and side fairings increase.

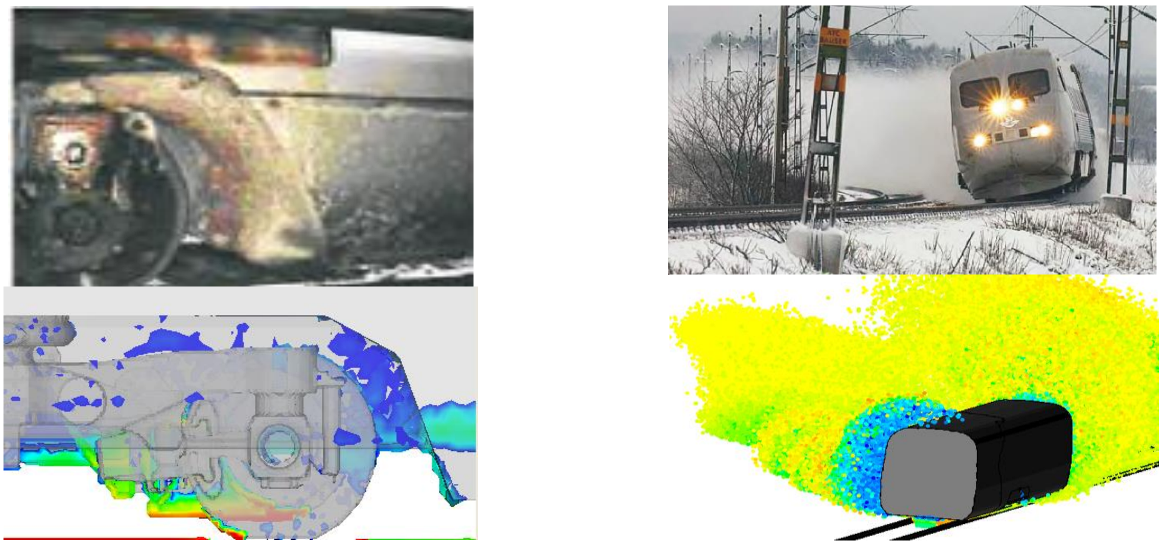


(a) Model-1 (b) Model-2



(c) Model-3 (d) Model-4

Fig. 17 Snow accretion on the train bottom and bogie at 3×10^{-11} kg/m^2



(a) The snow packing on the rear plate (b) The snow whirls around the train.

Fig. 18 Comparison of snow around the train

Table 2 Number of snow particles covering on the bogie at $t = 2$ s

Part name	Train body	Bogie frame	Wheels	Electric motors	Brake clamps	Particle Number	Variation
Model-1	786389	90502	84147	93755	2677	1057470	-
Model-2	1038175	101723	87643	93095	8166	1328802	25.66%
Model-3	1042338	92079	84095	88659	6351	1313522	24.21%
Model-4	1090749	105905	87016	91944	8024	1383638	30.84%

Note that the results obtained above are consistent with a real operation situation around the train, as shown in Fig. 18 (Ross 2009). Fig. 18(a) shows the snow packing on the rear plate, and Fig. 18(b) shows the snow whirling around the train.

In order to quantitatively analyze the influence of side fairing's height on the snow accumulation on the bogie, the numbers of particles accumulating on the main parts of the bogie and vehicle body are calculated at the end of those simulations. Here, the fairings and bogie cabin belong to the train body. The results are showed in Table 2.

Table 2 shows the amount of snow particles packing on the train body takes up 70% of the total, particularly on the side fairings and bogie cabin end plate, as shown in Figs. 15-17. As the height of the side fairings increases, more snow accumulates on the bogie, especially on the rear plate and brake clamps. The full side fairing model contributes to more than two times of snow accumulation on the brake clamps, and more than 20% on the whole bogie as compared to the short side fairing model. Table 2 also shows the height of the side fairing mainly influences the snow accumulation on the side fairings, end plate and bake clamps.

6. Conclusions

This paper simulated an air-snow two-phase flow in the high-speed train bogie region based on the unsteady Realizable k-ε turbulence model and discrete phase model (DPM). Four geometry models with different height side fairings are studied at the train speed of 200 km/h and the crosswind speed of 15 m/s. The numerical simulation method is validated by wind tunnel experiments, which shows good agreement. To understand the effect of side fairings on the snow accumulation in the bogie region, the pressure and velocity fields, snow accumulation distributions are analyzed.

- The height of the side fairings has significant effects on the pressure, velocity and snow distributions in the bogie region. High side fairings lead to low pressure in the upper part of the bogie region due to the blockage effect of the fairings, which will contribute to the snow accumulation on the upper part of the bogie.
- The snow packing on the bogie mainly accumulates on the wheels, electric motors, gear covers' windward sides, bogie cabin end plate and side fairings. The full side fairing model leads to more than two times of snow accumulation on the brake clamps as compared to the short side fairing model, while more than 20% on the train body.
- The side fairing's height mainly influences the snow accumulation the side fairings, bogie cabin end plate and bake clamps, which has little influence on the snow accumulation in the upper part of the bogie region.

In this paper, although the simulation of snow packing on the bogie region under the influence of the side fairing's height has been investigated and some differences have been found, a certain length of cross section with a bogie was used due to the limitation of the computational resources. A realistic train model will be used in the future study. Additionally, the next research should consider the crosswind speed and the validation of the snow distribution on the bogie under the crosswind should be carried out.

Acknowledgments

The authors acknowledge the computing resources provided by the High-speed Train Research Center of Central South University, China.

This work was accomplished by the supports of the National Key Research and Development Program of China [Grant No. 2016YFB1200404-04] the Strategic Leading Science and Technology Project of Central South University [ZLXD2017002], the National Natural Science Foundation of China [Grant Nos. 51605044 and U1534210] and the Science Foundation of Hunan Province [Grant No. 2016jj3004].

References

Anderson, J.D. (1995), *Computational fluid dynamics: the basics with applications.* McGraw-Hill, New York, US.

ANSYS.16.0 Theory Guide (2014), ANSYS inc.

Bettez, M. (2011). "Winter technologies for high speed rail", *Sweden: Norwegian University of Science and Technology.*

Beyers, J.H.M., Sundsbo, P.A. and Harms, T.M. (2004), "Numerical simulation of three-dimensional, transient snow drifting around a cube", *J. Wind Eng. Ind. Aerod*., **92**(9), 725-747.

Beyers, M. and Waechter, B. (2008), "Modeling transient snowdrift development around complex three-dimensional structures", *J. Wind Eng. Ind. Aerod*., **96**(10-11), 1603-1615.

Bocciolone, M., Cheli, F., Corradi, R., Muggiasca, S. and Tomasini, G. (2008), "Crosswind action on rail vehicles: Wind tunnel experimental analyses", *J. Wind Eng. Ind. Aerod*., **96**(5), 584-610.

Cao, Y., Huang, J. and Yin, J. (2016), "Numerical simulation of three-dimensional ice accretion on an aircraft wing", *Int. J. Heat Mass Tran*., **92** 34-54.

Casa, X.D.L., Paradot, N., Allain, E., Pauline, J., Delpech, P. and Bouchet, J.P. (2014), "A numerical modelling of the snow accumulation on a high-speed train", *Proceedings of the International Conference in Numerical and Experimental Aerodynamics of Road Vehicles and Trains*, Bordeaux, France, June.

CEN European Standard (2013), "Railway Applications-Aerodynamics. Part 4: Requirements and Test Procedures for Aerodynamics on open track ", CEN EN 14067-4.

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", *J. Wind Eng. Ind. Aerod*., **146** 195-206.

Fujii, T., Kawashima, K., Iikura, S., Endo, T. and Izunami, R. (2002), "Preventive measures against snow for high-speed train operation in Japan", *Proceedings of the 11th International Conference on Cold Regions Engineering*, Anchorage, Alaska, United States, May.

Hwang, B.G., Lee, S., Lee, E.J., Kim, J.J., Kim, M., You, D. and Lee, S.J. (2016), "Reduction of drag in heavy vehicles with two different types of advanced side fairings", *J. Wind Eng. Ind. Aerod.*, **155**, 36-46.

Mao, X.J. and He, K. (2016), "Cause analysis of snow packing in high-speed train's bogie regions and the anti-snow packing design", *J. Cent. South Univ. (Science and Technology),* (Accepted).

Gordon, M., Savelyev, S. and Taylor, P.A. (2009), "Measurements of blowing snow, part II: Mass and number density profiles and saltation height at Franklin Bay, NWT, Canada", *Cold Reg. Sci. Tech*., **55**(1), 75-85.

Gordon, M. and Taylor, P.A. (2009), "Measurements of blowing snow, Part I: Particle shape, size distribution, velocity, and number flux at Churchill, Manitoba, Canada", *Cold Reg. Sci. Tech*., **55**(1), 63-74.

Jemt, T. (2009), "De-icing solution". *International Railway Journal*, January.

Ross, F. (2009), "Beating the chill", *International Railway Journal*, January.

Kim, M.S., Jang, D.U., Hong, J.S. and Kim, T. (2015), "Thermal modeling of railroad with installed snow melting system", *Cold Reg. Sci. Tech*., **109** 18-27.

Kloow, L. (2015), "High-speed train operation in winter climate (To Be Continued)", *Foreign Rolling Stock*, **52**(1),1-10.

Morsi, S.A. and Alexander, A.J. (1972), "An investigation of particle trajectories in two-phase flow systems", *J. Fluid Mech*., **55**(2), 193-208.

Ni, J.R. and Li, Z.S. (2006), *Wind blowing sand two-phase flow theory and its application*., Science Press, Beijing.

Niu, J.Q., Zhou, D., Liu, T.H. and Liang, X.F. (2017), "Numerical simulation of aerodynamic performance of a couple multiple units high-speed train", *Veh. Syst. Dyn*., **55**(5), 681-703.

Paz, C., Suarez, E., Gil, C. and Concheiro, M. (2015), "Numerical study of the impact of windblown sand particles on a high-speed train", *J. Wind Eng. Ind. Aerod*., **145**, 87-93.

Sato, T., Kosugi, K., Mochizuki, S. and Nemoto, M. (2008), "Wind speed dependences of fracture and accumulation of snowflakes on snow surface", *Cold Reg. Sci. Tech.*, **51**(2-3), 229-239.

Thiis, T.K. (2000), "A comparison of numerical simulations and full-scale measurements of snowdrifts around buildings", *Wind Struct*., **3**(2), 73-81.

Tominaga, Y., Mochida, A., Okaze, T., Sato, T., Nemoto, M., Motoyoshi, H., Nakai, S., Tsutsumi, T., Otsuki, M., Uamatsu, T. and Yoshino, H. (2011), "Development of a system for predicting snow distribution in built-up environments: Combining a mesoscale meteorological model and a CFD model", *J. Wind Eng. Ind. Aerod*., **99**(4), 460-468.

Wang, J., Zhang, J., Xie, F., Zhang, Y. and Gao, G. (2018), "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", *Cold Reg. Sci. Tech*., **148,** 121-130.

Xie, F., Zhang, J., Gao, G., He, K., Zhang, Y. and Wang, J. (2017), "Study of snow accumulation on a high-speed train's bogies based on the discrete phase model", *J. Appl. Fluid Mech*., **10**(6), 1729-1745.

Zhang, J., Wang, J.B., Wang, Q.X., Xiong, X.H. and Gao, G.J. (2018), "A study of the influence of bogie cut outs' angles on the aerodynamic performance of a high-speed train", *J. Wind Eng. Ind. Aerodyn.***175**, 153-168.

Zhang, T., Xia, H. and Guo, W.W. (2013), "Analysis on running safety of train on bridge with wind barriers subjected to cross wind", *Wind Struct.*,**17**(2), 203-225.

Zhao, L., Yu, Z.X., Zhu, F., Qi, X. and Zhao, S.C. (2016), "CFD-DEM modeling of snowdrifts on stepped flat roofs", *Wind Struct*., **23**(6), 523-542.

Zhou, X. and Li, X. (2010), "Simulation of snow drifting on roof surface of terminal building of an airport", *Disaster Adv*., **3**(1), 42-50.

Zhu, J.Y. and Hu, Z.W. (2017), "Flow between the train underbody and trackbed around the bogie area and its impact on ballast flight", *J. Wind Eng. Ind. Aerod*., **166**, 20-28.

Zhu, J.Y., Hu, Z.W. and Thompson, D.J. (2016), "Flow behaviour and aeroacoustic characteristics of a simplified high-speed train bogie", *Proc. Inst. Mech. Eng. Part F-J. Rail Rapid Transit.*, **230**(7), 1642-1658.

CC