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An IDDES investigation of influence of lower temperature on the underbody flow of a high-speed train

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SUMMARY:
In this study, an improved delayed detached eddy simulation (IDDES) method based on shear-stress transport k-ω turbulence model has been used to investigate the underbody flow characteristics beneath a high-speed train operating at lower temperatures at $Re=1.85\times10^6$. The accuracy of the numerical method has been validated by wind tunnel experiments and full-scale tests. Further, the train's underbody slipstream velocity, pressure distribution in the underbody flow region and on the train's bottom surface, and the aerodynamic drag of lower parts of the high-speed train are compared for four temperature level (＋15°C, 0°C, -15°C and -30°C). The lower operating temperature is found to significantly increase the underbody slipstream velocity level and peak-to-peak pressure values near the cowcatcher of the head car. Additionally, the lower temperature also contributes to stronger underbody impinging flow in the bogie regions, by showing higher positive pressure distribution on the bogies and rear plates of the cavities. These changes of the underbody flow also contribute to higher aerodynamic drag and energy consumption of the high-speed train when running in the cold regions.

Keywords: High-speed train, underbody flow, aerodynamic performance, numerical simulation

1. GENERAL INSTRUCTIONS

In the past decades, high-speed train technology developed rapidly becoming one of the most popular means of transportation thanks to their high capacity and efficiency. More and more railways were built in the snowy areas. Some examples in China are the Qinhuangdao-Shenyang High-speed Railway, Harbin-Dalian High-speed Railway, and Lanzhou-Wulumuqi High-speed Railway, etc. In winter, the operating temperature on there railway lines of high-speed train significantly becomes lower than that in other seasons, which will result in large differences in physical parameters (viscosity and density) of air. Different fluid properties will certainly result in various flow feature around the high-speed train, but, to the knowledge of the authors, this effect has not been investigated in any literature. The first motivation of present study is to provide a supplement to train aerodynamic research concerning how the lower temperature affects the flow characteristics.

When high-speed trains run in the cold and snowy regions (Wang et al., 2018; Gao et al., 2018), a great amount of snow accretion appears in the bogie cavities, which greatly deteriorates the operational quality and even threatens the running safety of the high-speed train. The operational temperature will alter the underbody flow field and thereby influence the movement characteristics of snow particles in the bogie regions. Thus, the second motivation of the present study is to investigate the influence of operational temperature on the underbody flow as well as snow issue beneath the high-speed train, from a point of train aerodynamic view. Furthermore, this study can also provide a guidance to vehicle engineers for the selection of the environmental parameters when conducting the numerical simulations concerning the train's snow issue.

2. SECTION HEADING (12PT BOLD AND ALL CAPS)

A 0.125 scaled three-car grouped CRH2 high-speed train model was adopted in present study, as presented in Fig. 1(a). The model is a combination of three cars (the head car, the middle car and the tail car), consisting of six bogies and two inter-carriage gaps. The train height H, defined as the characteristic dimension, is 0.4625 m. The total length and width of the train are 20.65H and 0.91H, respectively. The high-speed train model is placed in a 65H (length) ×20H (width) ×16H (height) box. To investigate the influence of lower operating temperatures on the underbody flow structures, four operating temperatures＋15 °C (Case 1), 0 °C (Case 2), -15 °C (Case 3) and -30 °C (Case 4) were selected.

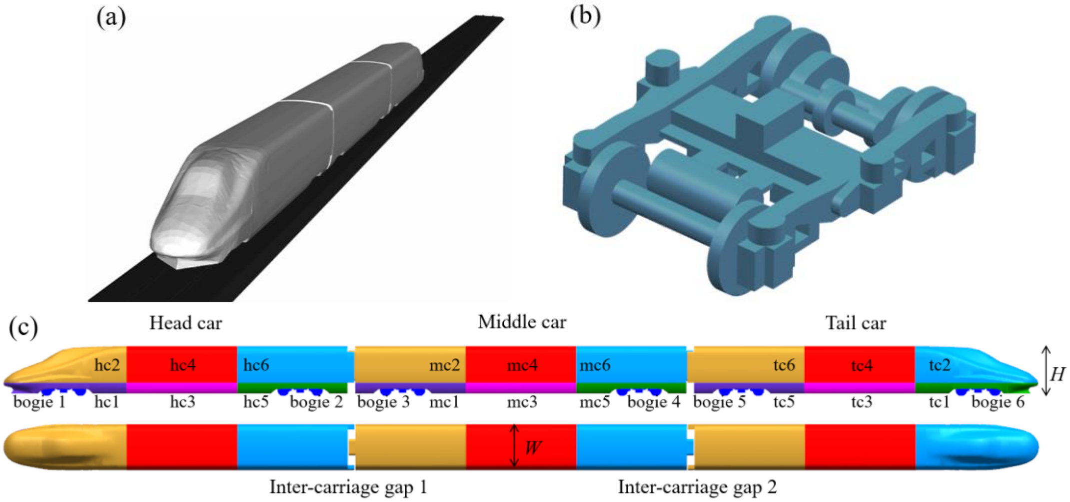

Fig. 1 The selected high-speed train model in the numerical simulation.

A hexahedral dominated mesh is designed for the numerical simulations. This type of mesh has been widely used for the numerical predictions of the flow characteristics around the high-speed trains. The normalised resolutions of the train-surface in the wall-normal (y^+), streamwise (Δs^+) and spanwise directions (Δl^+) are 1.0, 250 and 250, respectively. The definitions of y^+, Δs^+ and Δl^+ have been provided in previous studies (Wang et al., 2020). In this study, the IDDES with Shear-Stress Transport k-ω turbulence model has been used to investigate temperature effect on the underbody flow characteristics beneath the high-speed train. The introduction of IDDES method has been given in the previous publications (Shur et al., 2008; Menter, 2012). The governing equations were solved using the commercial finite-volume CFD software ANSYS FLUENT. Simulations were performed using a pressure-based solver. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used to update the pressure and velocity fields. The bounded central differencing scheme and the second-order upwind scheme were used to solve the momentum equation and the k-ω equations, respectively. The second-order implicit scheme was used for the temporal advancement. The physical time step $\Delta t = 5\times10^{-5}$ s. The

CFL number was less than 1.0 in more than 99% of the computational cells during the entire simulations, with the maximum value of 3.0.

3. RESULTS AND DISCUSSION

Figure 2 presents the time-averaged pressure coefficients (C_p)along the streamwise sampling lines beneath the HST. Generally, the time-averaged pressure coefficient increases sharply as the cowcatcher of head car passes by. After that, it decreases rapidly due to the acceleration effect brought by the cowcatcher of the head car on the local airflow. Then, the second sharp peak of time-averaged pressure occurs near the tail car and the peak-to-peak values beneath the head car are far larger than that beneath the tail car. The strong suction effect caused by negative pressure near the head cowcatcher will roll up the accumulated snow particles from the subgrade. The higher negative pressure in the cases with lower temperature will result in more snow particles suspending in the underbody flow region (Zhu and Hu., 2017), when compared to that in Case 1, especially for Case 4 having the lowest temperature. Therefore, the lower operating temperature will cause a stronger pressure fluctuation and thereby result in a more serious situation for the formation of snow accumulation in the bogie regions.

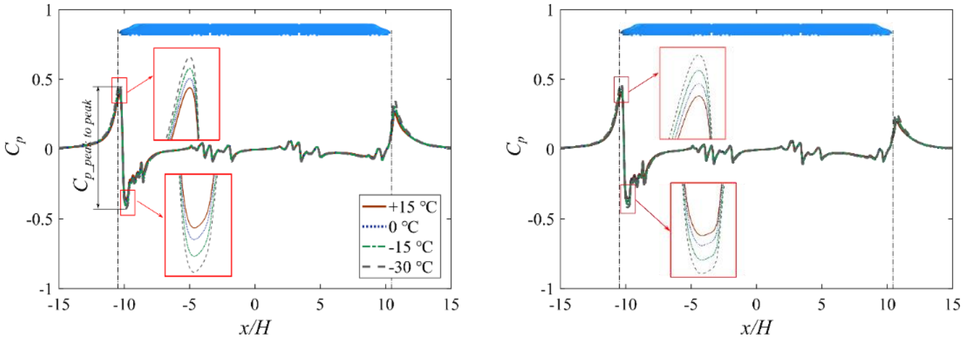

Fig. 2 Comparison of time-averaged C_p distribution between four cases along the sampling lines.

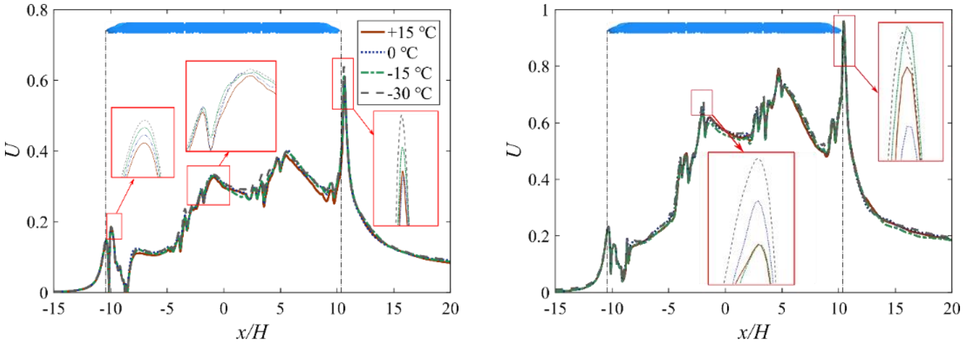

Fig. 3 Comparison of time-averaged U distribution between four cases along the sampling lines.

Previous study have found that the trajectories of snow particles show strong correlation with the shear velocity between the accumulated snow particles and the underbody airflow speed induced by train's motion (Fujii et al., 2002). Thus, the slipstream velocity (U) distribution along the streamwise sampling lines are compared in Fig. 3. The definition of the slipstream velocity in the present study is the same as that defined in (Guo et al., 2018). Generally, the underbody slipstream velocity increase along the streamwise direction, owing to the increasing the boundary layer thickness, and the maximum underbody slipstream velocity appears in the vicinity of the cowcatcher of the tail car. As zoomed by the red box in Fig. 6, the slipstream velocity in Case 2, Case 3 and Case 4 increase obviously, compared to that in Case 1, indicating a dominant effect of operating temperature on the underbody flow beneath the high-speed train, and lower temperature will contribute to higher shear speed between the underbody flow and accumulated snow particles and thereby increase the possibility of snow particles moving with the air flow.

4. CONCLUSIONS: FINAL CHECKS AND SUBMISSION

In this study, an improved delayed detached eddy simulation (IDDES) method based on shear-stress transport k-ω turbulence model has been used to investigate the underbody flow characteristics beneath a high-speed train operating at lower temperatures at $Re=1.85\times10^6$. The accuracy of the numerical method has been validated by wind tunnel experiments and full-scale tests. The results are summarized as follows. The lower operating temperature is found to significantly increase the shear velocity between the underbody airflow and accumulated snow particles, and thereby increase the possibility of snow particles to start moving with the airflow. The lower temperature significantly increase the negative pressure level near the cowcatcher of the head car, and stronger suction effect results in more snow particles suspending in the underbody flow region. The lower temperature also contribute to higher positive pressure distribution on the bogies and rear plates of the bogie cavities, and thus significantly increase the aerodynamic drag of the lower parts of the high-speed train. Comparing with the aerodynamic drag of high-speed train running at +15 ℃ (in Case 1), it increase by 5.3% in Case 2 at 0 ℃, 11.0% in Case 3 (-15 ℃) and 17.4% in Case 4 (-30 ℃), respectively.

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