J. Appl. Comput. Mech., 5(2) (2019) 311-333
DOI: 10.22055/JACM.2018.25495.1272

ISSN: 2383-4536
jacm.scu.ac.ir

M&MoCS
Shahid Chamran University of Ahvaz

Journal of
Applied and Computational Mechanics

Review Paper

A Review of Recent Studies on Simulations for Flow around High-Speed Trains

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Received April 12 2018; Revised December 12 2018; Accepted for publication December 17 2018.
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Abstract. Fluid flow around bluff bodies occurs in numerous fields of science and engineering, such as flows pass vehicles, cables, towers and bridges. These flows have been studied experimentally and numerically for the last several decades. The investigation of flow around high-speed trains is an important application of bluff bodies. Fluid flow, aerodynamic forces and moments, separation and wake region have been studied for the last several decades. This paper brings together a comprehensive review of the research on air flow around high-speed trains and their impacts.

Keywords: Aerodynamics, Air flow, Turbulence, Bluff body, High-speed train.

1. Introduction

Aerodynamics is a branch of fluid mechanics concerned with studying the movement of air, exclusively when it engages with a solid shape, for example, an airplane wing. Obtaining the motion of air around a body enables computation of moments and forces to act upon it. In most aerodynamics issues, the forces of interest are the drag, lift, weight and thrust. Flow around the bluff bodies is an important example of aerodynamics which plays an important role in our today lives.

One of the most practical applications of bluff body studies is the investigation of the flow around high-speed trains. High-speed trains are generally higher in speed than the old traditional trains. Whereas there is not any unique standard used worldwide, new lines more than 250 km/h (160 mph) and existing lines in excess of 200 kilometers per hour (120 mph) are widely considered as high-speed train [1].

The high-speed trains are one of the most significant types of trains that today play an important role in transportation. Many countries and regions have built high-speed train lines to link metropolitan cities, including Germany, China, Austria, Belgium, France, Poland, Italy, Portugal, Japan, Russia, South Korea, Spain, Sweden, Taiwan, Turkey, United Kingdom, United States and Uzbekistan. China has 20,000 kilometers (12,000 miles) of high-speed rails as calculated in September 2016 [2]. The International Union of Railways (UIC) regards three classes (1-3) of high-speed trains:

Class 1: New models specially constructed for high speeds, allowing a maximum running velocity of at least 250 km/h [1].

Class 2: Existing models specially upgraded for high speeds, allowing a maximum running velocity of at least 200 km/h [1].

Class 3: Existing models specially upgraded for high speeds, allowing a maximum running velocity of at least 200 km/h, but with some sections having a lower allowable velocity (for example due to topographic constraints, or passage through urban areas) [1].

In this article, the recent experimental and numerical findings of the air flow simulation around some high-speed trains have been presented; therefore, because of the numerous studies, it is just tried to concentrate on those which had more acceptable findings.

2. Experimental Studies

In recent years, many investigations and simulations of flow around high-speed trains have been performed by researchers. In this section, a review of experimental simulations of flow around the high-speed trains will be illustrated.

In 1986, Baker [3] investigated the aerodynamic forces and moments on a moving model of a high-speed train using experimental setup. So, a 1:50 model of the Advanced Passenger Train (ATP) was designed and used in the mentioned wind tunnel for the simulation of aerodynamic parameters. First, using an internal strain gauge, the aerodynamic moments and forces were calculated. Then, the atmospheric boundary layer of air flow was simulated. Finally, the aerodynamic forces as moments, drag and lift for moving the train model according to the Reynolds number, Re = 6×10^4, were discussed.

In 1990, Brockie et al. [4] evaluated the resistance and drag force of a high-speed passenger train. They built a small experimental model of the considered high-speed train to define the drag force in a wind tunnel. In this research, two models for closer evaluation have been studied as follows: a 1:76 scale model was applied in an environmental wind tunnel of the Nottingham University of UK (as Fig. 1.) and another model with 1:40 scale in low-velocity wind tunnel of the Southampton University of UK (as Fig. 2.). In the 1:76 scale model, the skin friction drag, Cf0, was obtained as follows:

$$C_{f0} = \frac{F_0}{\frac{1}{2}\rho V^2 pL}, \tag{1}$$

where ρ is the density, p is the perimeter of the train, L is the length of the train and F_0 is the skin friction drag force. They found that the value of C_{f0} was 0.0044 ± 10%. The total aerodynamic drag coefficient can be segregated into a pressure drag, C_{DP0}, and a skin friction drag, C_{f0} as follows:

$$C_D = C_{DP0} + C_{f0}\left(pL/A\right), \tag{2}$$

where $C_{DP0} = D_{P0}/0.5\rho v^2 A$ and D_{P0} is the pressure drag at zero yaws. Based on this equation and experimental data, the results have been presented in Table 1.

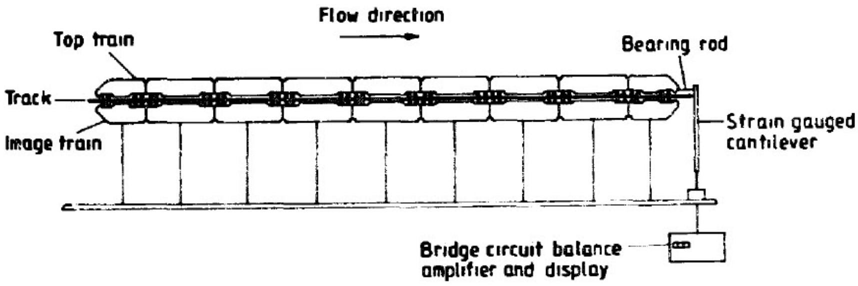

Fig. 1. The scale model of the train (1:76) [4].

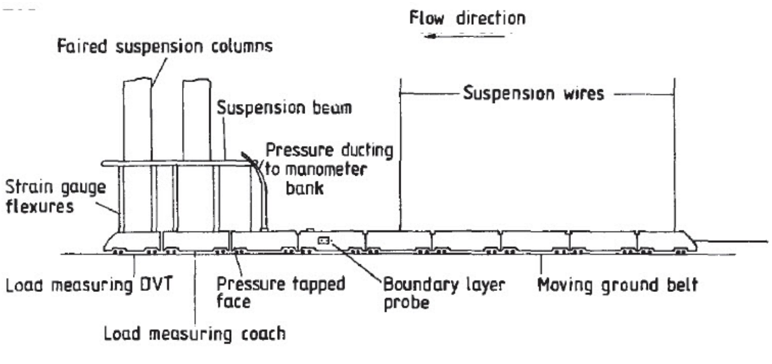

Fig. 2. The scale model of the train (1:40) [4].

Table 1. The significant aerodynamic results of Ref. [4].

IC225 model of British train	1:76th scale	1:40th scale	Full scale
Reynolds number	2.54×10^6	1.08×10^7	1.2×10^8
Total aerodynamic drag coefficient, C_{D0}	1.85 ± 5%	1.84 ± 5%	$1.41< C_{D0} <1.56$
Skin friction drag coefficient, C_{f0}	0.0044 ± 6%	0.0039 ± 10%	$0.002< C_{f0} <0.004$

In 1991, Baker et al. [5] investigated the ground simulation and the Reynolds number influences on the aerodynamic drag forces, experimentally. Thus, a 1:20 scale model of the French (SNCF) TGV001 train and 1:40 and 1:76 scale models of British (BR) HST were made and considered for analysis. According to the results, the ground simulation and Reynolds number changes have affected the drag coefficient up to 10%, approximately.

Watkins et al. [6] in 1992 discussed the reduction of aerodynamic drag force of a freight train. For this goal, a model of the NHJF coal wagon at Wales railways was made for aerodynamic tests in the industrial wind tunnel in the department of manufacturing and process engineering at the Royal Melbourne Institute of Technology (RMIT). Based on the Reynolds number range (0.1×10^6 to 0.7×10^6) and yaw angles, when the train length was decreased, the drag force was reduced, too. Also, optimizing freight wagons and changes in rail operations, the aerodynamic drag coefficient was considerably moderated. Moreover, they discussed the fuel expenditure rate of the train and the effects of drag force on it.

In 1997, Willemsen [7] investigated train using wind tunnel with high Reynolds number. For this work, a 1:10 scale model of a German train was made for experimental tests. The local pressure and temperature and the aerodynamic moments and forces were calculated in this paper. In the following, the influences of drag reduction on the economic advantages were discussed. Moreover, based on the findings, an analysis at the high Reynolds number was necessary to achieve dependable outcomes. Also, the paper indicated that aerodynamic optimization is economically important.

In 2001, Kwon et al. [8] simulated the Korean high-speed train by different moving ground scenarios in three wind tunnels, while the first was KARI (Korea Aerospace Research Institute) with multiple-slot tangential blowing system, the second was Flow Science (with moving belt system) and the third was POSTECH (Pohang University of Science and Technology) (Fig. 3.). They discussed the change of the number of bogies of the train and its nose shape. The characteristics of test models and the wind tunnels are depicted in Table 2.

Table 2. The characteristics of test models and the wind tunnels [8].

Wind tunnel	Test dimension W×H×L (m)	Top speed (m/s)	Ground simulation
Flow Science	2.75 × 2.23 × 5.5	60	Moving ground
KARI	4 × 3 × 10	85	Tangential Blowing
POSTECH	1.8 × 1.5 × 4.3	60	Fixed ground

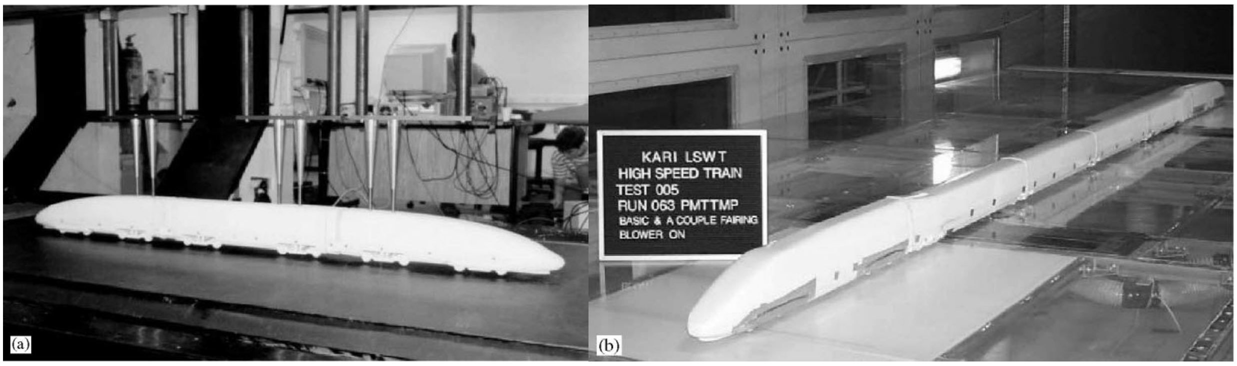

Fig. 3. Train models in the wind tunnel. (a) 1:20 scale of Flow Science wind tunnel. (b) 1:25 scale KARI wind tunnel [8].

Reynolds number effect: Based on the results, the Reynolds number (with free stream velocity 40–85 m/s equal to 4×10^5 – 8.5×10^5) has no effect on the drag coefficient. The findings illustrated that the velocity of the air over the train model increased with the increase in the velocity of the blowing jet and the increase in the free stream velocity. It has been shown also that the drag coefficient for fixed ground method 0.06 is smaller than that for Flow Science tunnel.

Drag measurements for different formations: As shown in the results, the drag coefficient of ground simulation with tangential blowing model increases when the number of bogies increases. In addition, it has been shown that the drag coefficient changed by adding bogie fairing on the fixed ground. Finally, the tangential blowing is a useful method to determine the moving belt for wind tunnel simulation.

Auvity et al. [9] in 2001 discussed aerodynamic characteristics using experimental data. For this purpose, a 1:140 scale model of the train for analysis of flow structure and its properties was considered. The paper focused on the influences of the train velocity and the nose influences on the flow structure. The velocity range considered in this research was 5-50 m/s. Also, three various noses were considered: conical with 2.4 m^2 area, elliptical with 3.2 m^2 area and conical with 6.4 m2 area. In the analysis, at first, the impact of the unsteady velocity on the aerodynamic properties was estimated and then, the influences of the three different nose shapes of the train on the key parameters as momentum were discussed.

Matschke et al. [10] in 2002 investigated aerodynamic factors and performance of side wind effect on a full scale German high speed train via experimental data (wind tunnel). In this study, a side wind with range speed of 7 to 13.5 m/s was considered to simulate and evaluate aerodynamic forces around the high speed train. The train used in this test had the following specifications: a train with 200 km/h velocity, the weight of 42 tons and 40 passenger seats (as Fig. 4). Based on the finding results and compared with numerical data, when the cross wind rate or yaw angle increases, the side forces decrease.

In 2002, Baker [11] investigated the moments and cross wind forces on a high speed train and wind fences effects. The Reynolds number range according to the train model height and the wind speed was from 4×10^4 to 6×10^4 . For this purpose, two different models of testing (1:50th) have been used; the first, a moving train model in an environmental wind tunnel with atmospheric boundary layer and the second was a static train model with the wind fences. According to the results, in the moving train model, when the yaw angle is small, the moment, side and lift forces changes are linear. In the case of the effect of wind fences, the situation is more complicated.

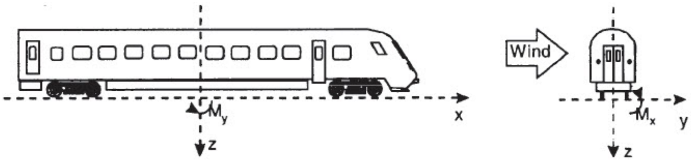

Fig. 4. The schematic view of the high speed train [10].

Suzuki et al. [12] in 2003, investigated the aerodynamic characteristics of a high-speed train against cross wind. In this research, not only the shape of the train but also infrastructure features such as bridges and embankments were considered for aerodynamic analysis. When the thickness of the bridge increases, the aerodynamic side force coefficient also increases. The aerodynamic characteristics of the train, under the influence of the embankment, depends on the distribution of the boundary layer on the ground. Accordingly, on a high embankment, the aerodynamic side force is higher than that on a low one.

Sanquer et al. [13] in 2004 with using a new experimental approach, investigated the cross wind effects on high speed train. A test model of TGV-DUPLEX which is a French high speed train with 300 km/h velocity, as in Fig. 5, was considered in this experimental research. The maximum of wind velocity was 40 m/s and the yaw angle range was 0˚ to 90˚. Using two measurement methods: measurement of aerodynamic coefficients (moments and forces) and mensuration of pressure on the surface of the high speed train, the aerodynamic characteristics of the intended train have been investigated.

Fig. 5. The schematic view of the train [13].

Based on the results, the used method in this research allows the load separation of each section of the train to be investigated separately. Also, this experiment presents the average pressure on the surface of the train. Finally, the obtained results are appropriate for the validation of numerical research.

In 2004, Baker et al. [14] studied crosswind forces on a train using an an experimental method. In the wind tunnel analysis, a 1:30 scale model of the train with three wagons was made for analysis at three yaw angles, 30˚, 60˚ and 90˚. The Reynolds number based on model height, Re = 2×10^5, was considered. The most important parameters discussed in the article were the side and lift forces and moments.

In 2007, the pressure wave nature caused by a high speed train inside a tunnel was considered by Ricco et al. [15]. A 1:87th scale high speed train model consists of two parts; squared and circular (as Fig. 6). The circular model was built in two lengths; 300 and 600 mm; and their diameter was 38 mm. They were made of wood and plastic with a conical nose. The squared models, which in terms of length and diameter were equal to the circular model, were made of aluminum. Also, the maximum velocity of the scale models was 150 m/s.

The first aim of the research was to study the effect of train nose on the separation area. The second aim of the paper was to investigate the process of pressure created by the train. The third goal of the study was to discuss the effect of train length on initial pressure.

An aerodynamic investigation of a high-speed train under crosswind was conducted by Cheli et al. [16] in 2010. A 1:10 scale model of the EMUV250 high-speed train (as Fig. 7) was made to find a more efficient geometry. For this purpose, the two new versions of EMUV250 train were investigated experimentally; the first model with change in the train roof and the second model with change in the train nose. Using the wind tunnel data, the aerodynamic behaviors of the high-speed train as the forces and moments according to the crosswind were investigated. Also, more details were discussed as characteristic wind curves (CWC) to increase safety for the train. In the following, a comparison between the numerical CFD analysis and experimental data will be presented.

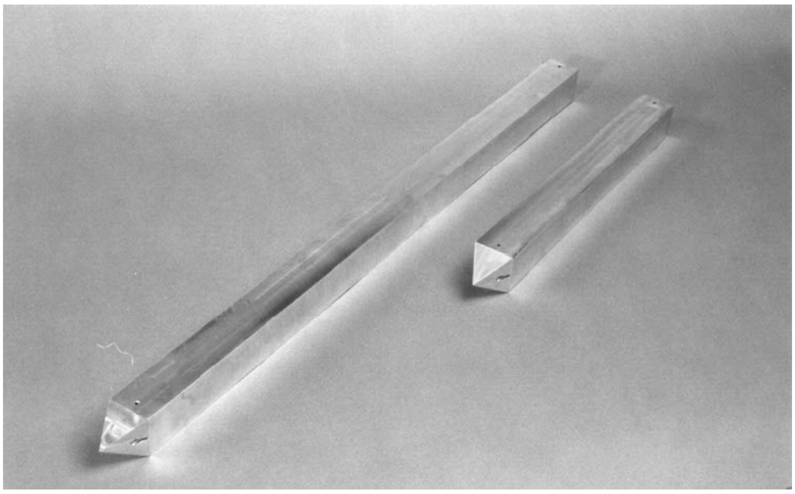

Fig. 6. The 1:87th scale model with a square shape [15].

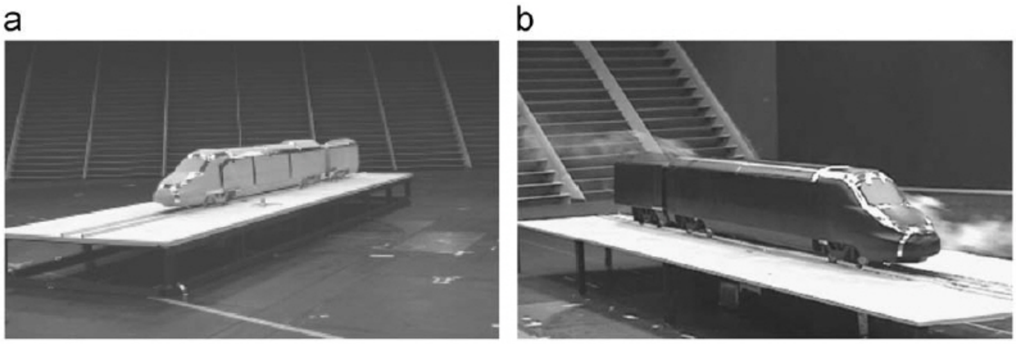

Fig. 7. The 1:10 scale model; a: on flat 1 and b: flat 2 scenario [16].

A simulation of side wind influence on aerodynamic characteristics of a high speed train has been performed by Wang et al. [17]. In this experimental research, a 1: 72nd scale model of German ICE train with 150 km/h velocity was made and used in front of a wind flow with a velocity range of 4 m/s to 25.4 m/s and the yaw angle range of 10˚ to 90˚. Based on the investigation, when the yaw angle increases, the moment and lift forces increase.

In 2012, a new design based on aerodynamic characteristic for two new Chinese high speed trains, CRH380A and CRH380B, via experimental setup was provided by Yang et al. [18]. In this research a 1:8th scale model of high speed train with the maximum velocity of 250 km/h in front of the wind flow at 60 m/h speed was used for the test in a wind tunnel.

Fig. 8. The 1:8th scale model of high speed train [18].

According to wind tunnel data, the drag force was generated mainly at the beginning and end of the train, and in the distance between the wagons. The drag percent of the beginning, end, second and seventh wagons of the train was 31.5%, 31.5%, 33.8% and 33.8%, respectively and for the other wagons was 34.7%.

In 2013, the investigation of pressure around the high-speed train at non-enclosed to enclosed spaces via experimental data (wind tunnel) was conducted by Gilbert et al. [19]. The train model was a 1:25th-scale of the German high- speed ICE2 train as shown in Fig. 9.

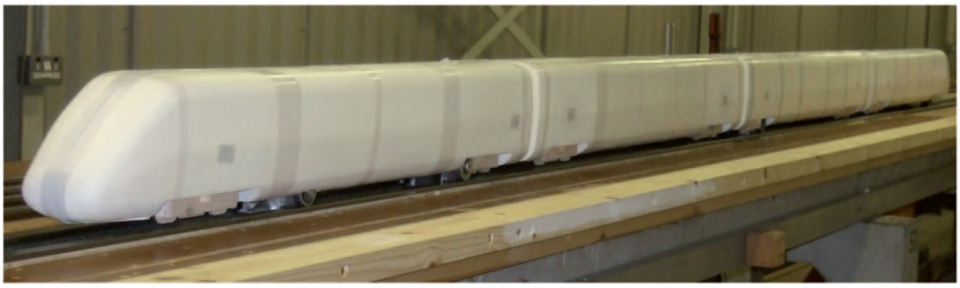

Fig. 9. The 1:25-scale of ICE2 German train (x = 4.216 m, length, y = 0.123 m, width, z = 0.156 m, height) [19].

Based on this work, the following results were presented:

- The aerodynamic surface pressure increases on one wall when the other wall is located on the opposite side of the wagons.
- The superposition of reflected waves from the tunnel outlet decreases the pressure peaks.
- In the open air, the maximum pressure is around the nose of high-speed trains.
- The field of pressure near the entrance of the tunnel is three-dimensional.

Bell et al. [20] in 2014, using a wind tunnel and experimental data (velocity flow mapping) investigated the wake and slipstream over a high-speed train. They built a 1:10 scale model based on the Germany Inter-City Express 2 (ICE2) for investigation, which is shown in Fig. 10.

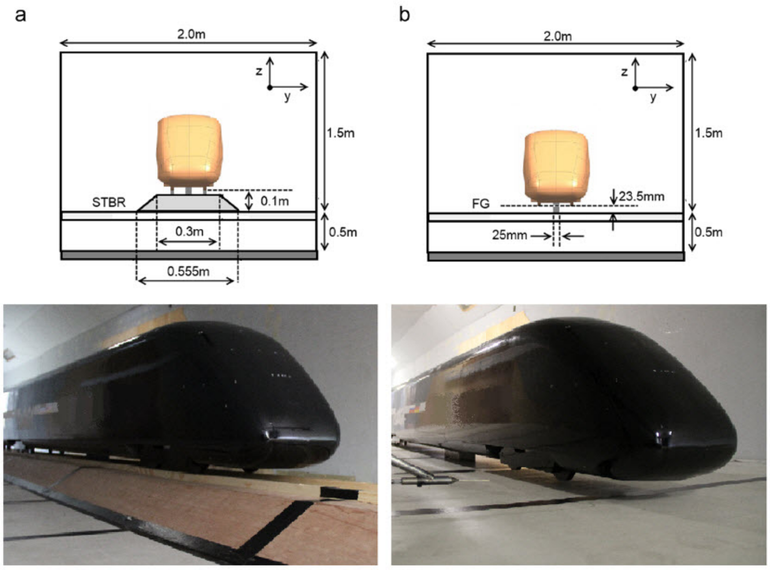

Fig. 10. Ground configurations modeled: the 1:10 scale ICE2 model was mounted on two 25 mm streamlined supports above a 1:10 scale STBR (left) and FG (right) [20].

Bell et al. using dynamic pressure probes measured the profile of slipstream and particularly in the peak of slipstream. One of the benefits of the wind tunnel experiment is that it can be used to determine the key characteristics of wake flow and slipstream. In this experiment, ground configurations were used: flat ground and single rail with ballast (STB). It has been found that the flow characteristics of a slipstream are significantly different for these two configurations. For the flat ground, the wake flow is generated faster and more intense than the STB.

Soper et al. [21] in 2014 did an aerodynamic analysis on a freight train using experimental data. In this research, the slipstream, pressure magnitudes and velocity of flow region over the freight train were studied. Because of unsteady slipstream generated around the moving train has a lot of impacts on train performance and safety, the static pressure and slipstream velocity analysis at the side and roof of the train were done. Also, in this analysis, the influences of the train length and velocity on aerodynamic properties were studied. The Reynolds number as 2.2×10^5 for the 1:25 scale model of the high-speed train was considered.

Xia et al. [22] in 2015 conducted an investigation on the wall interference mechanism on a high-speed train in a large yaw angle. In this research, a simple 1:8th scale model of high-speed train with three wagons was implemented for investigation at a wind tunnel (as shown in Fig. 11). To evaluate the effect of the wall interference, two computational domains were used: the first type was a simple free stream and large enough without wall interference and the second model was a closed wind tunnel with an elaborate design.

The structure of the flow around the train with the 25° inclination angle was studied. In a small deviation angle, the vorticity generated by the surface of the train is transferred on the leeward. With the increasing tendency angle, the impact of the axial advection will be reduced. Also, flow separation at various angles plays a key and pivotal role of vortex shedding on the other side of the train.

Fig. 11. The computational domain. a: closed wind tunnel, b: train in the closed test section, c: mesh around train [22].

In 2015, Bell et al. [23], did an investigation on the wake and slipstream of a high-speed train. In this article, an experimental investigation (wind tunnel) was carried out to evaluate a 1:25 scale model of a German high-speed train (see Fig. 12). The obtained results in this study are as follows:

The slipstream profile is provided for the intended high-speed train in which the maximum of the velocity occurs at the nose of the train and an increase in the boundary layer occurs along the train. And the most deviation occurs near the wake region.

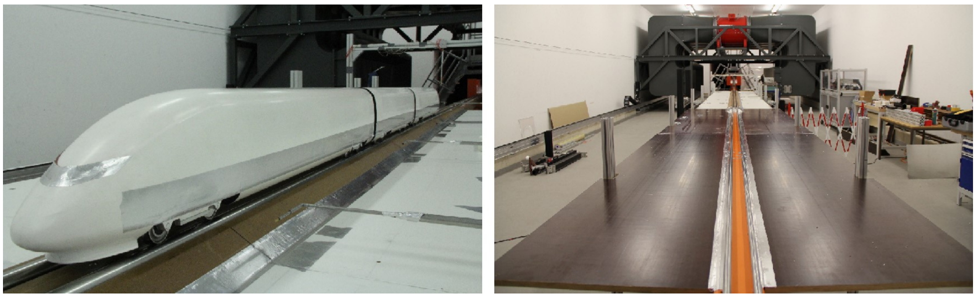

Fig. 12. The scale model of Germany high-speed train [23].

Kikuchi et al. [24] in 2015 evaluated the effects of aerodynamic key parameters on the critical wind velocity using experimental data. Based on the results, when the aerodynamic components changed 10%, the effect of the side force on the critical wind velocity overturning was 5%. The influence of the side force on the critical wind velocity is higher than the effect of the moment and lift forces on it. Moreover, the uniform and atmospheric boundary layer flows were considered for wind tunnel experiments. It should be noted that the considered Reynolds number in the research was 7.7×10^4. Finally, the obtained aerodynamic results by scale model had good agreement with the same one by the full-scale model.

In 2016, Avadiar et al. [25] using experimental investigation did a flow analysis on a high speed train under the crosswind. In this research, a 1:20th scale model of Zhong-Yuan Star train with dimensions 3.5 m × 0.16 m × 0.2 m, was located against an air flow with 32 m/s velocity, 600 Pa dynamic pressure and 3.7×10^5 Reynolds number. Also, three yaw angles of air flow, 0˚, 4˚ and 6˚, were used in this study for comparison. The crosswind effect on the slipstream profile of the high speed train was the main aim of the research. Moreover, the boundary layer length for various yaw angles has been investigated. In yaw angle 6˚, the length of the boundary layer was the maximum.

In 2016, an aerodynamic investigation on a Korean high speed train with 400 km/h velocity was done by Lee et al. [26]. For this purpose, a 1:20th scale model of HEMU-430X train was considered for test in a subsonic wind tunnel. Also, the used Reynolds number range was 3.7×10^5 to 6.2×10^5, the scale dimensions were 3.5 m × 2.45 m × 8.7 m, as in Fig. 12, and the maximum velocity of the wind tunnel was 92 m/s.

For better comparison, three types of pantograph covers (a streamline and two wedge types) were considered. First, the aerodynamic drag force for wagons without any roof was analyzed. Second, the aerodynamic drag for the three types of covers was investigated and third, the obtained results from the first and the second section were compared.

The impacts of Reynolds number on aerodynamic specifications of a high-speed train (Fig. 13) using experimental data were investigated by Niu et al. [27] in 2016. Deviation angle of 0° and 15° and the Reynolds number range from 3.02×10^5 to 2.27×10^6 are the details of this study. The most important findings were:

At yaw angle 0°, with the increasing Reynolds number, the force coefficient of the train is reduced. For yaw angle 15°, with the increasing Reynolds number, the lift coefficient of the high-speed train increases too, but the drag coefficient and lateral force coefficient decrease. The Reynolds number changes also have an impact on the surface pressure of the train.

Fig. 12. The scale model of the Korean high-speed train [26].

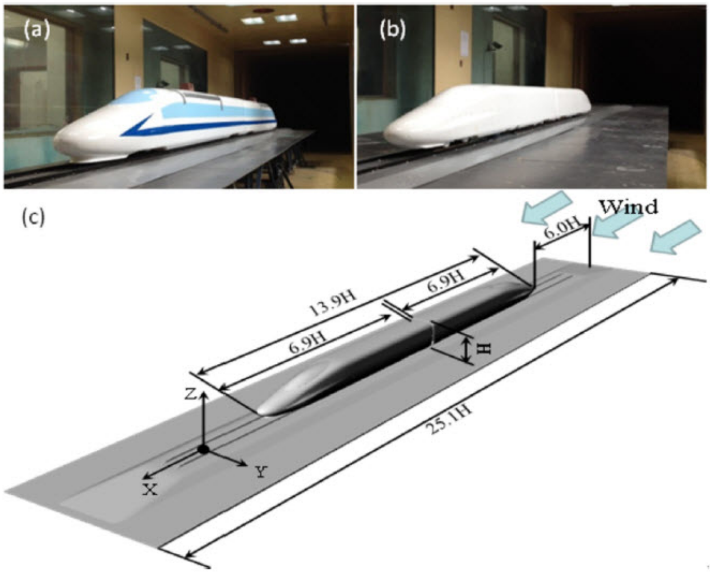

Fig. 13. Schematic of the train scale model [27].

According to the experimental data, the turbulence intensity has a large effect on the aerodynamic force and pressure coefficient of the high-speed train. When the turbulence intensity increases, the surface pressure and aerodynamic drag coefficient decrease. The aerodynamic drag at the beginning and end of the train decrease by 45% and 53%, respectively. Also, the surface pressure increases by 20%.

Bell et al. [28], [29], [30] and [31] in a series of continuous research, studied wake region of the high-speed train by focusing on the flow specifications using an experimental method. They built a simple 1:10th scale model of a Deutsche Bahn Inter-City-Express 3 (ICE3) high-speed train for the analysis, as shown in Fig. 14. The dimensions and cross-sectional area of the scale model were 5.0m×0.3m×0.4m and 0.12 m^2, respectively. Wake, streamline, velocity mapping, frequency analysis, phase-averaging, etc. [28] were the most important achievements of these two works.

Moreover, the inherent limitations of the wind tunnel have been investigated. Finally, the changes of the roof slip on the key parameters were shown.

Yang et al. [32] in 2017, did an aerodynamic optimization and experimental simulation of two Chinese moving train models in a tunnel. The two 1:8th scale models of a high-speed train with 265 and 106 kg weight and 401 and 507 km/h velocity, respectively, were considered in the investigation.

In 2017, Niu et al. [33] using experimental data conducted a study on aerodynamic properties of a high-speed train under various turbulent flows. In this research, a 1:8th scale model was built (as in Fig. 15). At Reynolds number 7.5×10^5, velocity effect on boundary layer was studied using standard and mean deviation to describe a turbulence properties. As mentioned, in the wind tunnel of the National Engineering Laboratory for High-speed Railway Construction, Central South University, a 1:8th scale model of the train with cross-sectional area 9 m^2, 15 m length and maximum wind speed 94 m/s was used to investigate the turbulence properties of the high-speed train. The findings illustrated that when the turbulence intensity increases, the coefficient of the surface pressure reduces.

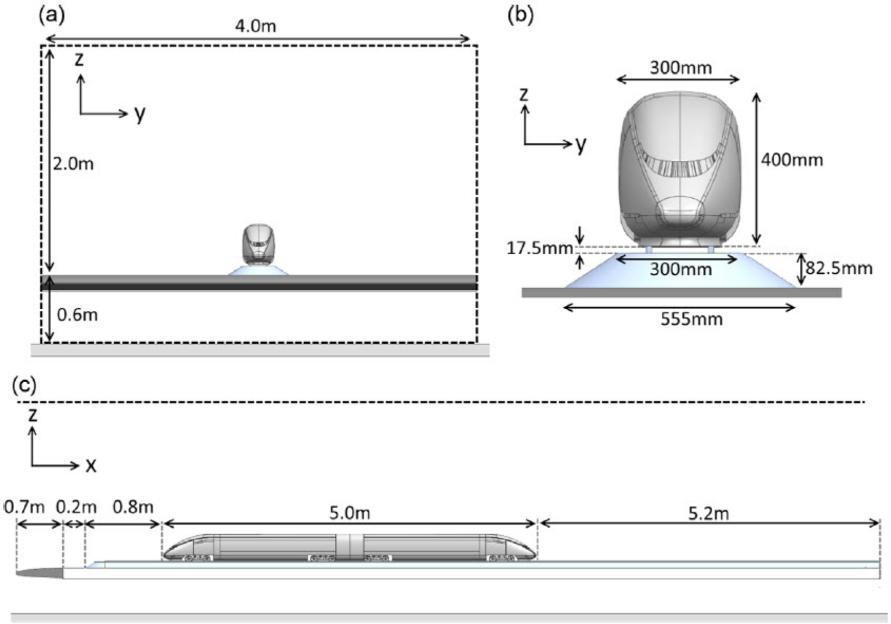

Fig. 14. The 1:10 scale model of the high-speed train [28], [29], [30] and [31].

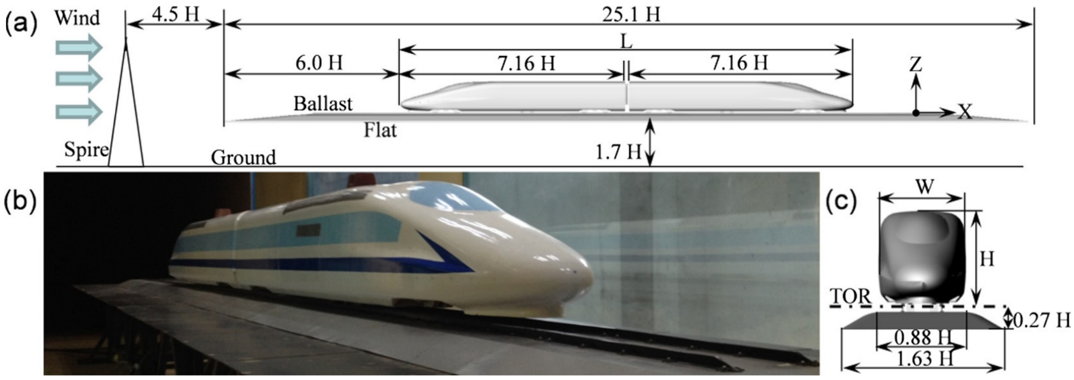

Fig. 15. The 1:8 scale model of the high-speed train [33].

A new approach to calculate the aerodynamic drag force of high-speed trains passing a tunnel was presented by Li et al. [34] in 2017, and a new method was suggested. In this method, a photoelectric sensor was installed at the bottom of the train which calculated the velocity and acceleration of the train. Based on the results of the photoelectric sensor and the Newton's Second Law, the aerodynamic drag before entering the tunnel and inside the tunnel can be calculated. In this research, a 1:16.8th scale model of EMU high-speed train (as Fig. 16) was considered for analysis. According to the findings, the aerodynamic drag coefficient of the train entering into the tunnel can be supposed to be constant; however, its value gradually decreases as the train passing the tunnel. Then, a comparison between the experimental data and the same numerical simulation was done.

Fig. 16. The 1:16.8th scale model of EMU high-speed train [34].

Xiang et al. [35] in 2017, investigated the aerodynamic characteristics of a moving train under crosswind condition using a wind tunnel test. A simple model of the train with a cuboid shape to reduce the effect of Reynolds number on the aerodynamic characteristics was considered. The new moving setup included a vehicle, a bridge and a moving system which can adjust the direction and angle of the wind. In the analysis, at the yaw angles from 45° to 85°, the components of wind coefficient of the moving train under crosswind condition had a good agreement with expected results.

In the experimental studies, the significant and key aerodynamic parameters on high-speed trains were investigated. The finding of experimental data is the best benchmark for checking the accuracy of numerical simulations.

3. Numerical Studies

Although the experimental methods are very accurate and close to practical conditions, construction and testing of the experimental setup are more expensive than numerical methods.

3.1 Reynolds-Averaged Navier-Stokes (RANS)

The RANS are a time-average method of fluid flow. In this method, instantaneous quantities are replaced by average and oscillating ones. Some of the most significant articles on high-speed trains using a RANS are reviewed in the following:

In 2002, a comparison between numerical and experimental simulations of air flow over a high-speed train was investigated by Paradot et al. [36]. A SNCF (French high-speed train) with high Reynolds number (almost 10^9) was used for aerodynamic analysis. Also, a CFD software called Star CD based on the three-dimensional Reynolds-averaged Navier Stokes (RANS) method and RNG k-ε turbulent model for analysis were used. The aerodynamic drag distribution and flow topology were discussed and then a comparison with experimental data obtained by a wind tunnel was done.

In 2002, Khier et al. [37] studied the side wind effect on a high-speed train via numerical investigation. In this research, using Reynolds-averaged Navier-Stokes and k-ε turbulence model, the air flow over the German InterRegio high-speed train, as in Fig. 17, were simulated.

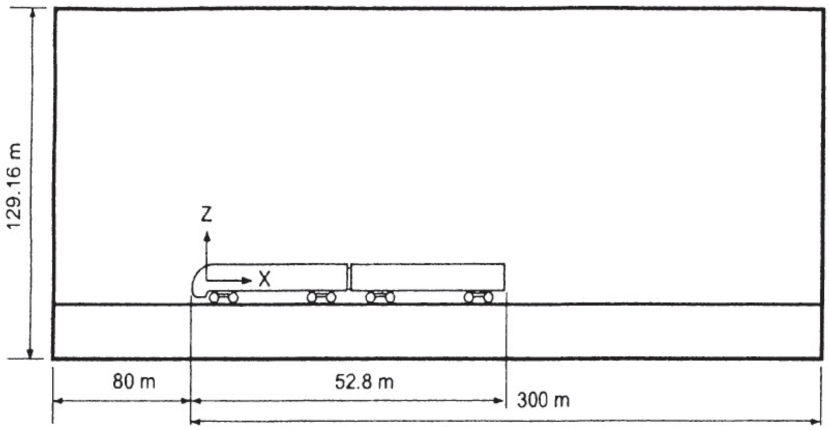

Fig. 17. The 1:8 the computational domain of the high-speed train [37].

The used Reynolds number in the research is based on the height and flow velocity as 1.063×10^8. Based on the simulation; first, the effect of the yaw angle on the flow structure and aerodynamic forces was investigated. The next part discusses the destructive effects of wind on the train. The simulation indicated that the noise barriers are an effective factor in reducing the side wind effect.

Fauchier et al. [38] in 2002, estimated the effects of crosswind on the German InterRegio high-speed train. For this numerical simulation, the RANS approach along with RNG k-ε turbulent model was used. In this analysis, at first, a preliminary study via computational fluid dynamics has been done on a simple geometry of train. Then, a three-dimensional model of the train in three following cases have been investigated; an open embankment, an embankment with a wind fence above and an embankment with a noise barrier above. Finally, a parametric study including the effect of geometry and wind barriers on aerodynamic factors was presented.

In 2003, a research of aerodynamic flow characteristics on a high speed train was done by Shin et al. [39]. In this numerical study, the changes in the aerodynamic forces of the high speed train at the entrance of a tunnel were performed. To achieve the intended goals, the 3D Navier–Stokes equation solver with the compressible and unsteady condition was used for flow field analysis over the high speed train. The results of simulation illustrated that the vortex was formed in the front of the train. Also, when the train was at the tunnel entrance, the pressure was increased significantly, which increased the drag force.

In 2009, Tian [40] did an aerodynamic investigation on a high-speed train (see Fig. 18). As the high speed at modern trains is effective in aerodynamic drag, reducing drag and consequently reducing energy consumption is one of the main issues in the development of the rail industry. According to the numerical results, the most important findings of the paper are as follow:

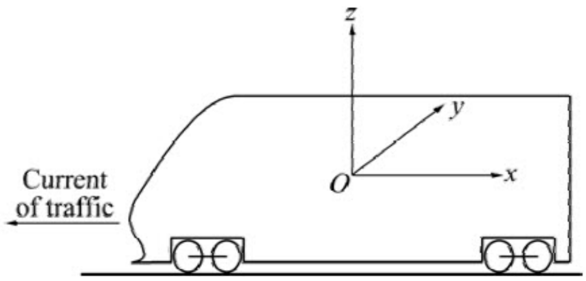

Fig. 18. The schematic domain of the high-speed train [40].

Since the drag force is directly related to the square of the speed, when the train speed increases, the drag increases. Depending on the nature of the pressure and friction drags, a design of the streamline shape head of the trains is an effective way to reduce total aerodynamic drag. Moreover, using the outer wind shields and bottom cover reduces the drag 15% and 50%, respectively.

Zhao et al. [41] in 2009 investigated the aerodynamic characteristic of a Chinese high-speed train using RANS numerical method. In this research, the aerodynamic influences were studied with the train at the entrance and exit of a tunnel. For example, the effect of air pressure on the train body and its window, the relationship between the aerodynamic forces and the size of different sections of the tunnel and the relationship between tunnel input size and air pressure intensity are the most important analysis of the paper. According to the RANS numerical approach and turbulence modelling, the effects of aerodynamic characteristic of the high-speed train at the tunnel for four various speeds at 200, 250, 300 and 350 km/h and for two sizes of the tunnels have been calculated.

An optimization of aerodynamic characteristics of high-speed train using numerical method was investigated by Krajnović [42] in 2009. In this article, using RANS numerical method, the simple polynomial response surfaces instead of complex NS simulations and Genetic Algorithm (GA) an optimization aerodynamic properties of Swedish high-speed train X2000 have been conducted. The optimization has been performed for two purposes; optimization of the train front and vortex generators for the crosswind stability and drag reduction.

Li et al. [43] in 2011 simulated a high-speed train at a tunnel entrance. For this purpose, the RANS numerical method and k-ε turbulent model for a viscous compressible fluid were applied. Based on the simulation of the simple model of electric multiple units (EMU), tunnel wall pressure range, tunnel wall and the microwave were proportional with the square of the train speed filed.

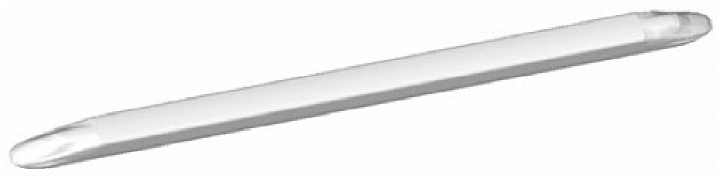

Fig. 19. The simple model of the high-speed train [43].

A numerical simulation of EMU high-speed train using RANS method and RNG k-ε turbulent model was conducted by Wang et al. [44] in 2012. The main reason for this research was the pressure changes and aerodynamic forces with two trains passing alongside each other in a tunnel. Therefore, an EMU high-speed train with 350 km/h velocity and three wagons to move in a 300 m tunnel has been analyzed. Based on the numerical simulation, at first, the extreme pressure fluctuations in the tunnel were investigated when two trains were moving. Then, the same parameters were checked and compared in terms of one train passing. At the movement of the double trains, the pressure range was 177.3% higher than the single one. In the following, the aerodynamic characteristics as lift, drag and lateral forces for the double and single trains movement were investigated, separately.

Asress et al. [45] in 2014 investigated numerical aerodynamic characteristics of a high-speed train against a crosswind using unsteady three-dimensional RANS approach and k-ε turbulent model. The computational area of the high-speed train was illustrated in Fig. 20. In the simulation, two scenarios for ground as static and moving for yaw angles ranges from 30° to 60° were considered. As results, the flow field structure and the streamlines have been shown in the paper based on which the vortex was generated on the upper and lower parts of the train edges. Also, the velocity contours for various angles have been calculated. In the following, the pressure coefficient for over the train for 30° and 60° yaw angles have been computed.

In 2014, a numerical simulation about the wind effect on a high-speed train was done by Peng et al. [46]. For this purpose, a simulation of air flow passing a simple high-speed train via three-dimensional incompressible RANS method and *k-ε* turbulent model has been done. In the simulation, there were two models of the passing train from the tunnel; First model: a train passing from the tunnel and the second one two trains passing from the tunnel side by side. Also, the Reynolds and the Mach numbers were 10^6 and 0.3, respectively. The range of air flow velocity for this analysis was considered between 120 to 350 km/h. According to the findings, the train wind was a complicated flow which changed by time and space, therefore, it created many risks for employees and passengers. So, the basic and proper measures should be considered.

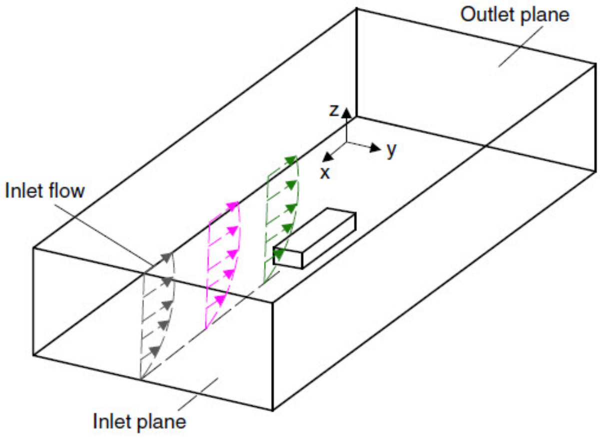

Fig. 20. The computational area of the high-speed train [45].

Shuanbao et al. [47] in 2014, using a numerical method did an optimization of aerodynamic parameters for high-speed trains. The complicated wake flow deeply affects the movement of the trains. In this article, the aerodynamic elements such as lift force using RANS numerical method for CRH380A high-speed train was simulated and using a genetic algorithm (GA), a multi-objective optimization was done. After the optimization and reaching an optimal shape of the train, the lift and the drag forces of optimal shape decreased in the crosswind without crosswind conditions compared to the original one. Moreover, the low fluctuations and more suitable wake flow were the benefits of this optimization.

Chu et al. [48] in 2014, using RANS numerical method and RNG k-ε turbulence model, did an aerodynamic simulation of two high-speed trains in a tunnel. In this paper, a three-dimensional, compressible, turbulence model was applied to find the pressure wave. In the following, the effects of some key parameters as train velocity and length on the interactions of aerodynamic waves produced by the trains. Then, the numerical results were verified compared with experimental data. The simulation findings indicated that the aerodynamic drag and pressure coefficients reached a peak value when the trains were in the middle of the tunnel. Also, when the train velocity and the blockage ratio increased, the drag and pressure coefficients increased, too. Moreover, when the trains were aligned side by side, the aerodynamic side force reached the maximum value.

In 2015, Zhang et al. [49] performed an aerodynamic analysis of a high-speed train (as in Fig. 21) via a numerical method. Effects of the slope angles and cut depth on the flow structure around the train were the most important goals of this article to determine. Also, the surface pressure and aerodynamic forces of the train were analyzed using RANS approach combined with the eddy viscosity hypothesis in the turbulence model. According to the results, when the slope angle improved and cut depth increased, the stability of the train was guaranteed at high speeds and its probability of overthrowing was less. Based on the finding, the suggested optimal angle is 75°.

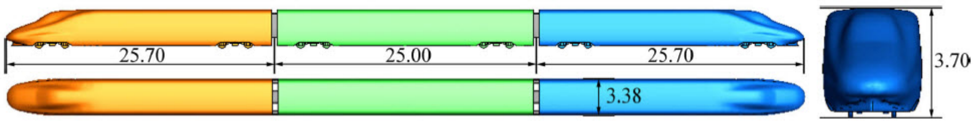

Fig. 21. The model of the high-speed train [49].

In 2016, Catanzaro et al. [50] conducted a CFD simulation using RANS numerical method for a high-speed train under a crosswind for stationary and moving conditions. The effect of each condition was analyzed in details. For the yaw angle lower than 30°, the effect of the aerodynamic moments and forces is less than 10%. Finally, the difference between two stationary and movement scenarios was compared and analyzed.

An aerodynamic design on a high-speed train was done by Ding et al. [51] in 2016. Due to the speed improvements of the high-speed trains and increasing the aerodynamic effect of the mechanical one, the effects and issues of aerodynamics were considered as the main challenge of this paper. For this purpose, the relation between the aerodynamic design of the train, the aerodynamic functional indexes and its numerical simulation have been done. In the following, an optimization for the train was conducted. The considered trains in this research were CRH380A, CRH380AM, CRH6, CRH2G and the standard EMU.

Fig. 22. The geometric model of the high-speed train [51].

In 2016, Liu et al. [52] investigated the aerodynamic performance of a train under crosswinds using RANS numerical method. In this research, via the computational fluid dynamics, the aerodynamic characteristics for the train on a special slope and crosswind conditions was investigated. The used Reynolds number based on the velocity and height of the train was 1.77×10^7. Based on the analysis, the aerodynamic forces and moments increased when the slope was increased. In special circumstances, the aerodynamic forces were at peak value when the yaw angle was 90°. Also, the slope depth on the wind blow had a great impact on the aerodynamic performance of the train.

Premoli et al. [53] in 2016 did an aerodynamic comparison between two cases, a stationary and a moving train. In this research, using the numerical RANS method the simulation results of the relative movements of the trains between the vehicle and its infrastructure that was effective on the aerodynamic coefficients were compared. Firstly, a validation done by experimental wind tunnel and then using the numerical simulation, the effects of the relative motion was obtained. It should be noted to achieve this purpose, a 1:15 scale model of an ETR500 high-speed train was considered for the simulation. The results of the aerodynamic coefficients derived from static and moving models of the train were illustrated that the lateral force and moment for the stationary case was lower than the another one about 5%. Also, the difference of the vertical force between two models was 12%.

In the above researches which used the numerical RANS models, some of the important aerodynamic parameters as lift and drag forces, pressure field, slipstream velocity, crosswind, yaw angle effect and some design optimization were investigated. Finally a comparison with experimental data was conducted which represented a good agreement between the results.

3.2 Large Eddy Simulation (LES)

The LES is a computational approach for turbulence modelling applied in CFD provided by Joseph Smagorinsky in 1962 [54]. LES is currently used in a variety of engineering applications, including acoustics, combustion, and simulations of boundary layers. Some of the most important articles on high-speed trains using a LES are proposed in the following:

Krajnović et al. [55] in 2012 did a simulation of flow over a simple train under crosswind. In this study, with using LES numerical method, a comparison between a stationary and moving train model for aerodynamic forces and moments according to the Reynolds number as 22615 was done. In the following, a comparison between the numerical findings and the corresponding experimental results was conducted. These comparisons showed a good agreement.

In 2015, Zhuang et al. [56] by using the numerical method and LES turbulence modelling, performed aerodynamic investigation on a simple model of high-speed train under crosswind. In this study, the effects of flow diversion with two angles of φ = 30° and 60° using LES were investigated. The considered train in this paper, as Fig. 23, is a 1:25th scale CRH3 high-speed train without any wagons. According to the results, when the angles decrease, the mean value of the side effects and lift force increases, respectively. The side effects at φ = 60° is 2.5 times larger than φ = 30˚. Also, the 3D vertical structures were performed for the flow over the considered high-speed train. At φ = 60° and φ = 30°, vortex shedding usually happens in the half front and back half of the train, respectively.

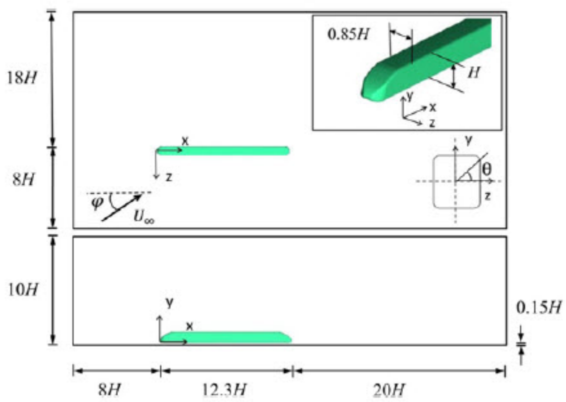

Fig. 23. The computational domain and schematic view of the considered train model [56].

Khayrullina et al. [57] in 2015 using LES numerical approach, did an aerodynamic simulation of German passenger and freight trains under crosswind condition. When the passenger and freight trains move at 140 km/h and 100 km/h, respectively, the people who stand on the platform can experience extreme wind effects. To calculate the wind danger and damage potential, a wind with 5 m/s velocity was considered for simulation. The wind velocity at the platform due to the passenger train was higher than freight one which increased the velocity of the passenger train. Also, the velocities of the slipstream near the wake region for the freight train was higher than the passenger one. Finally, for validation, a comparison was done with experimental data by wind tunnel.

In 2017, García et al. [58] investigated the aerodynamic characteristics of a high-speed train under synthetic turbulent wind conditions using LES turbulence model. For this purpose, a 1:10 German ICE 2 Aerodynamic Train Model (ATM) with two smooth and rough surface models was simulated for analysis. Because of this way, there was no need to solve turbulent eddies. In this simulation, the time-averaged aerodynamic parameters as forces and moments were illustrated. Also, with a comparison by experimental data, a good agreement was obtained.

3.3 Detached Eddy Simulation (DES)

The DES improved the RANS model used in more complex problems. A numerical investigation about flow structure over a high-speed train via proper orthogonal decomposition (POD), dynamic mode decomposition (DMD) and DES was conducted by Muld et al. [59] in 2012. In this research, numerical simulation for wake flow behind the high-speed train was done. In the following, a comparison among the numerical methods and their precision has been performed. To achieve this, a 1:50th scale model of train with Reynolds number based on the velocity and length Re = 60,000, as in Fig. 24, was considered. The flow near wake was studied in this research because of the most significant region is wake region for slipstream.

Fig. 24. The geometry of high-speed train [59].

Zheng et al. [60] in 2012 by using numerical DES method analyzed aerodynamic performance of a high-speed train. In this article, a simple model of high-speed train with 500 km/h velocity, as in Fig. 25, and Reynolds number as $Re = 2.29\times10^7$ were considered (see Fig. 28). In this velocity range, the aerodynamic drag plays an important role in total air resistance; therefore, the aerodynamic design of trains is very important. To achieve this opinion, a complicated problem was the great separation of wake region. To solve this problem, the train was simplified. In the results, the drag coefficient for various parts of train was extracted and these results were compared with the same one by other numerical methods.

Fig. 25. The simple model of high-speed train [60].

A numerical study of wake for a high-speed train was studied by Yao et al. [61] in 2013. In this research, combining DES and Unsteady Reynolds-averaged Navier–Stokes (URANS) method, the vortex formation of CRH2 model of high-speed train have been done. The simulation was divided into two parts; flow analysis with and without cross wind. Based on the results, in the without -crosswind condition, there were two helical vortices in the wake region which had great interaction with the ground. In crosswind condition, there were three types of vortices around the train with the optimization of the aerodynamic performance leading to reduce the effects of these vortices. Finally, the DES method compared to URANS one had better response for small eddies.

Miao et al. [62] in 2015, did an investigation on the effect of ribs on a train aerodynamic performance using DES turbulence model. In this article, three types of the roof ribs of the train were compared, aerodynamically; a train without roof ribs, with convex ribs and with cutting ribs. Based on the findings and the considered Reynolds number ($Re = 6.37\times10^6$), the side forces for different types of trains were different. The side forces for the convex and cutting ribs were increased 110% and 88%, respectively compared with train without ribs. Compared with the train without ribs, the contraction moment factor for the train with convex ribs and for the train with cutting ribs was increased 140% and 106%, respectively. Also, there were no resistances when passing air flow on the train with the roof without ribs. Moreover, it was illustrated that the flow structure changed with the ribs changes.

Muld et al. [63] conducted a flow structure analysis of a high-speed train in a wake flow in 2016. So, using the DES method, a numerical simulation of air flow around a high-speed train was done. The simulated train in this article was a 1:50th of aerodynamic train model (ATM), a train with 4 wagons as shown in Fig. 26. By simulation, the wake flow and its region, the velocity profile and structure were investigated and a comparison between the numerical results and experimental ones (which obtained by German Aerospace Centre (DLR)) was done.

Fig. 26. The view of the train model [63].

An aerodynamic operation of a high-speed train by computational fluid dynamics (CFD), Fluent, was performed by Zhang et al. [64] in 2016. The moving ground and rotating wheels were the main characteristics of this study. After the numerical simulation, a comparison between the CFD results and the experimental results of the wind tunnel is done. The air flow around the high-speed train is considered unsteady. The main objective of this study is to investigate the impacts of moving ground and wheel conditions on numerical modelling. A 1:8th scale model of CRH2 high-speed train was built in the wind tunnel as Fig. 27. The most important results of this paper are:

The total aerodynamic drag for the moving ground is greater than the stationary ground case. In the moving ground, the drag of each wagon increases and in the moving ground and rotating wheels it increases substantially. The velocity of air flow behind and around the wheel increases at the region of the wagon making the wheel drag increase and change the pressure distribution; as a result, in moving ground with rotating wheel condition and condition with the moving ground, the total drag of the train is equal approximately.

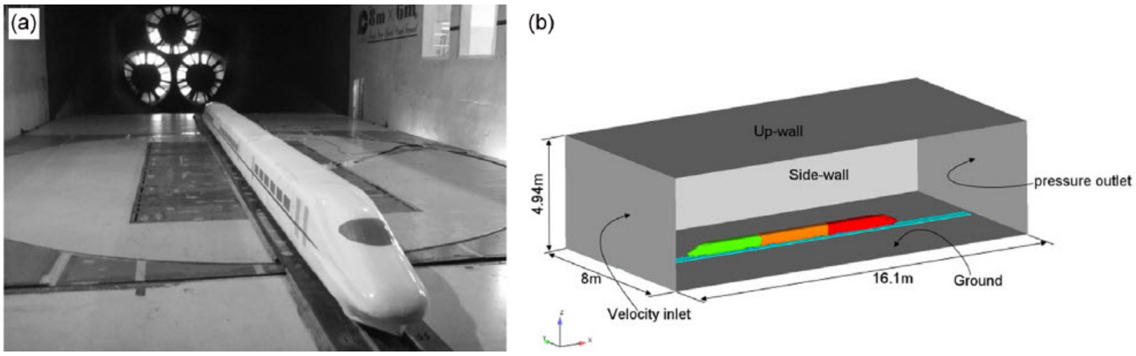

Fig. 27. a: the wind tunnel and **b:** CFD simulation of this article [64].

Simulation of air flow around a high-speed train on a bridge under cross wind was performed by Chen et al. [65] in 2016. In this research, a 1:8th scale model of a high-speed train and a common bridge using numerical simulation with DES was investigated. Also, the Reynolds number of the air flow according to the train geometry was considered as Re = 1.9×10^6. In this research, the effects of the side force and moment on the different parts of the train as head, middle and tail of the train are investigated and compared. In the following, the influence of the train movement on the bridge on the velocity profile and pressure distribution are analyzed. Moreover, the paper illustrated many vortices on the leeward edge of roofs. Finally, these vortices leading to a significant degree of turbulent flow around the train.

In 2017, the ground configurations effect on the slipstream and near wake of a high-speed train was investigated by Improved Delayed Detached Eddy Simulation (IDDES) by Xia et al. [66]. For this simulation, a 1:8th scale model of CRH3 high-speed train with Reynolds number Re = 1.65×10^6 and cross section 0.172 m^2, was used. The IDDES method which is a hybrid RANS-LES model (consisting of a combination of different new approaches) creates a comfortable and more flexible scale-resolving simulation model for high Reynolds number flows, with SST *k-ω* turbulent model used for the simulation. Based on the findings; the validity of the IDDES approach was investigated for predicting flow over the high-speed train, based on aerodynamic forces, pressure distribution and velocity profiles. Also, the effect of a ground configuration near the wake region on the slipstream was collected. Moreover, the large scale longitudinal vortices in the near wake region corresponding to high slipstream velocity were analyzed.

In 2017, Wang et al. [67] compared three numerical models, DES, URANS and Scale-Adaptive Simulation (SAS), for predicting high-speed train slipstream. In this research, a Deutsche Bahn Inter-City-Express 3 (ICE3) high-speed train (widely using in Asia and Europe) was considered for the simulation (see Fig. 28). Based on the results, the prediction about the drag coefficient for three numerical models was almost identical. About the cross-stream, the accuracy of the URANS method was low, but the IDDES and SAS method had good agreement with experimental data with the difference that the cost of the SAS method was lower.

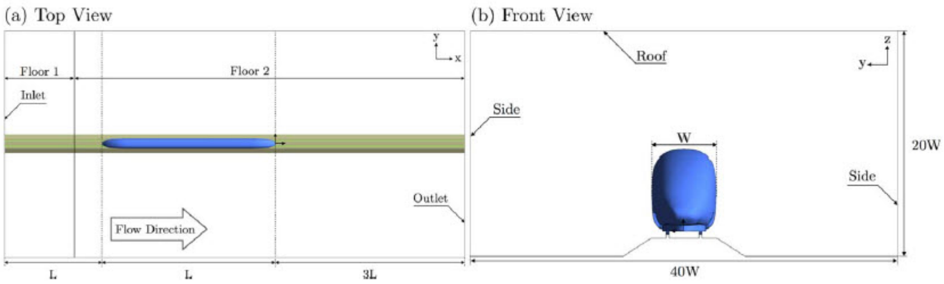

Fig. 28. The top view and the front view of the train model [67].

In 2017, Zhang et al. [68] focused on the analysis of a high-speed train under crosswind. In this numerical investigation, a DES approach with the SST k-ω turbulence model was applied to simulate a high-Reynolds number air flow around the high-speed train. A 1:15th scale model of a high-speed train with 60 m/s velocity and consequently Reynolds number, Re = 3×10^5, was considered. Also, the effects of crosswind at 20˚ yaw angle on aerodynamic characteristic as pressure distribution were indicated. Moreover, in this research, a comparison between the finding results and experimental data and between results and numerical RANS model were done.

Eventually, influences of train cut-outs' angles on aerodynamic characteristic of a high-speed train were performed by Zhang et al. [69] in 2018. In this research, there was a special look at reducing aerodynamic drag force, in order to reduce energy consumption. To achieve this, a numerical DES approach with the Realizable *k-ε* turbulence model was applied to analyse the underbody flow characteristics of high-speed trains with different Re = 1.85×10^6. The influences on the aerodynamic drag force with various angles of the bogie cutouts and the changes in the velocity profile, pressure distribution, time-averaged flow structure and the boundary layers around the train were analyzed and illustrated and then were compared with the experimental data.

The paper in this part, simulates air flow around high-speed trains by DES method. The most important parameters of flow over high-speed trains have been calculated and in order to validate, a comparison with experimental data was performed.

3.4 Other Numerical Methods

In 1965, Hara [70] discussed the aerodynamic drag of a Japanese train using a numerical approach. The resistance to train movement is divided into two parts; the mechanical and aerodynamic resistances. Since the aerodynamic resistance has a significant effect on the train velocity, therefore, in designing and planning for high-speed trains, it is crucial to consider aerodynamic drag. In this paper, the aerodynamic drag of a high-speed train when entering into a tunnel can be found. Vernikov et al. [71] in 1971 did an investigation on aerodynamic pressure of a wall due to the train movement using a numerical method. The thin wing theory applied for an incompressible and ideal fluid in this research.

In 1993, Zakharov et al. [72] investigated the numerical analysis of air flow over an electrical high-speed train at the turbulent condition. Using viscous-inviscid interaction a three-dimensional flow over a high-speed train consisting of the turbulent boundary layer separation was considered for analysis. Also, the Reynolds number was considered as $Re = 5.6\times10^6$. The findings illustrated that the benefit of the separationless flow over the train front and less separation after the train. Moreover, in this research, a local separation area on the train front was studied.

The aerodynamic analysis of two high-speed trains crossing each other according to the three-dimensional compressible Euler/Navier-Stokes method and Fortified Solution Algorithm (FSA) were done by Fuji et al. [73] in 1995. The calculated findings illustrated that the flow pattern is complex. Also, a powerful side force which has several negative and positive maximum points was effected on the trains. For the other forces and moments, severe fluctuations were visible.

Chiu [74] in 1995 predicted the aerodynamic loads on a train in crosswind condition and at high yaw angles. Using the source/vortex panel approach, the aerodynamic characteristics of a three-dimensional flow over a high-speed train at crosswind condition and with up to 90˚ yaw angles were presented. The moment distribution was satisfactory when the vortex shedding had a large distance from train nose at 60˚ and 70˚ yaw angles. In this analysis, the side and lift forces were underestimated and overestimated, respectively. To do a more accurate prediction of the standard deviation factor, the exact prediction of the pressure distribution around the corners was done.

In 1996, the simulation of the turbulent flow over a high-speed train was done by Devheat et al. [75]. The mean velocity and turbulent field were analyzed on a French train using a numerical method based on the complete Navier-Stokes calculation. After the numerical calculation, a comparison between the numerical data and experimental ones was conducted which represented a good agreement between them. The main demands of this research were the reducing aerodynamic drag and noise in high-speed Trains.

Baron et al. [76] in 2001 studied the reducing methods of aerodynamic drag and waves on high-speed trains inside very long tunnels using a numerical method. An aerodynamic simulation of air flow over a high-speed train using Lattice Boltzmann Method (LBM) was conducted by Wang et al. [77] in 2008. In this study, a non-simplified high-speed train was applied for aerodynamic analysis. The LBM method compared with the traditional CFD methods has very benefits such as the high performance of a parallel calculation, easy and fast in complicated geometry and saving memory. There is only one commercial software based on the LBM called PowerFLOW which used in this paper. The aerodynamic lift, drag and lateral forces were investigated under crosswind conditions. In this condition, the mentioned aerodynamic forces increased and had a great impact on the stability of the high-speed train. Also, the air flow at the end side of the train generated a great vortex.

In 2008, an aerodynamic optimization of a freight train was investigated by Lai et al. [78]. In this article using the ALAM numerical method, the following goals were pursued:

Firstly an optimization method was implemented to enhance the aerodynamics and energy efficiency of the train. Secondly, the developed model used in this research can also be applied for other freight train models. Also, the cost and fuel saving was the other significant goal of this study.

The flow specifications of a high-speed train was investigated by Baker [79] in 2010. An experimental and computational work is used to analyze the wake behind the high-speed train, the boundary layer through the length of train and flow around the nose and front side of the train. This research has been carried out in two states; the flow around the high-speed train without cross wind and with cross wind.

An optimization method for nose shape of a high-speed train using numerical method was suggested by Sun et al. [80] in 2010. The CFD analysis by Navier-Stokes solving with Genetic Algorithm optimization was applied for designing a more efficient head shape of the Chinese CRH3 high-speed train against an air flow field were discussed in this research. Based on the optimization results, the forward, height, thickness and top channel of the train nose were redesigned and optimized and thus the aerodynamic drag force decreased as 1.85%.

In 2010, Baker [81] investigated the influence of the crosswind on aerodynamic characteristics of a high-speed train. Using weight function, the simulation of the aerodynamic forces on the train and influence of the wind velocity in generating a yaw angle were conducted. The side force, lift, yaw angles and train geometry parameters were the most important variables which were analyzed.

Shao et al. [82] in 2011 investigated the aerodynamic stability of a high-speed train against rain and crosswind. In this research, a simplified model of Chinese CRH2 train under the rain rate of 60 mm/h and against crosswind with 40 m/s velocity was used. In this position, the destructive effects of the rainfall and crosswind and after that increasing the lift and side forces and moment were discussed. In the following, a semi-static stability investigation for the train has been done.

The effect of aerodynamic resistance on the pressure wave of a CRH high-speed train was investigated by Wu et al. [83] in 2011. The aerodynamic resistance and braking have a significant effect on the flow field around the trains and also on the comfort and safety of them. In this research, the pressure wave of the train at three points of it for the aerodynamic braking condition and without braking one was analyzed and discussed. The numerical results showed that the maximum value of the pressure happened when two trains cross by each other with braking and that maximum value was 2 kPa. In trains with aerodynamic braking, the pressure pulse is visible in the nose, end and the middle part of the trains but in train without aerodynamic braking, the pulse only can be seen at the head and tail of train. Generally, the finding of this simulation illustrated that the aerodynamic braking has significant influences on the movement of high-speed trains and their performances.

In 2012, a new design of high-speed train cabin according to the aerodynamic load was conducted by Goa et al. [84]. Since the velocity increase of the train leads to the increasing aerodynamic interaction, an optimized design of the train cabin seems necessary. To do so, at first a topology optimization for reducing aerodynamic effects was conducted and then 8% minimization of the train weight for the mentioned purpose was applied.

Yao et al. [85] in 2012 with focusing on aerodynamic parameters of simplified CRH380A high-speed train, extracted some design parameters for streamline optimization to reduce drag force. Using Local Shape Function (LSF) parameterization approach and Response Surface Method (RSM) of GA-GRNN, the following results were obtained:

The total aerodynamic drag of train model was decreased by 8.7%. The viscous drag and the inviscid drag were reduced by about 1.18% and 53.85%, respectively. Also, the aerodynamic drag reduction of the head section was 12.86% and the value of the tail section was 12.59%.

In 2012, Mei et al. [86] predicted the generated pressure waves by a high-speed train passing a tunnel. Based on the unsteady, compressible, one-dimensional, non-homentropic air flow and using characteristics of generalized Riemann variables method, the generated pressure waves were predicted.

Cui et al. [87] in 2012 conducted an aerodynamic optimization of a high-speed train using numerical methods (Fig. 29). In this paper, with the aim of reducing aerodynamic drag force, via Response Surface Method (RSM), Genetic Algorithm (GA) approach and *k-ε* turbulence model, a method based on a grid for optimization of train head and relation between the drag force and optimized design have been investigated. All these analyses were done for 500 km/h.

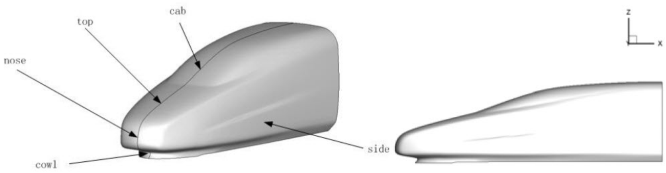

Fig. 29. The head shape of the train model [87].

In 2012, Liu et al. [88] investigated the effects of cross-section difference of a high-speed train on aerodynamic performance. In this paper using a numerical method and SST *k-ω* turbulence model, based on the CFD analysis, when the train was run under crosswind condition, the aerodynamic drag and moment forces were increased. When the width-to-height ratio of the cross-section was increased, the aerodynamic forces were decreased. Also, when the train arrived at the tunnel, the air pressure was proportional with the cross section.

Zhang [89] conducted a numerical simulation of aerodynamic drag on a subsonic train in 2012. In this research, a two-dimensional incompressible viscous flow at steady state with lubricity wall conditions was assumed. The Navier-Stokes equations with the k-ε turbulent model were applied to estimate the aerodynamic drag of train in an Evacuated Tube Transportation (ETT). According to the simulation results, the aerodynamic drag of the train was located in subsonic range in ETT, when the air pressure was 10 Pa and also, when the air pressure was less than 10 Pa, the train which located at subsonic range, experienced a nonresistance area. Moreover, in this analysis, the acceptable diameter and the air pressure of the subsonic ETT were specified.

A numerical evaluation of aerodynamic characteristics of air flow over a high-speed train under the crosswind condition was investigated by Li et al. [90] in 2013. The aerodynamic forces and train movement have deep interactions on the performances of each other. Also, when moving under the influence of air flow under crosswind conditions, the train safety was discussed and analyzed. In the following, the zones which had the most impacts on the aerodynamic performances were illustrated.

Muñoz-Paniagua et al. [91] in 2014 performed an optimization of shape and nose of a high-speed train (Fig. 30) by CFD numerical method and Genetic algorithm (GA). In this numerical research, three-dimensional, turbulent, compressible and unsteady air flow was considered in CFD simulation to reduce pressure and aerodynamic drag.

The simulation results showed the following:

The maximum of pressure gradient increases when the nose length or slenderness ratio decreases. The aerodynamic drag and the slenderness ratio decreased when the nose length increased. The best and worst nose of the train is presented using the pressure contour of the train surface at tunnel. Then, the impact of decreasing the bluntness of the nose is lower than that of the cross-sectional area to minimize the drag coefficient. Since the nose length plays a significant role, the effect of the cross-sectional is more significant than the peak pressure gradient for aerodynamic drag.

The considered diameter and density of the particles are 0.1-0.5 mm and 0.001-0.1 kg/m^3, respectively. In one of the results of this paper, the impact of distribution for three different sizes of particles is provided with two important features; first, around the cape of train and second between nose and wind shield in the flat region. Based on the results, the maximum speed of the train occurs between the forehead and end of it. Moreover, according to the tests, the larger and/or heavier sand particles produce a greater drag force. More than 10% of the aerodynamic drag force results in sand particles with diameter and density of 0.5 mm and 100 g/m^3, respectively. The impact of the smaller and lighter sand particles is about 1% of the aerodynamic drag force.

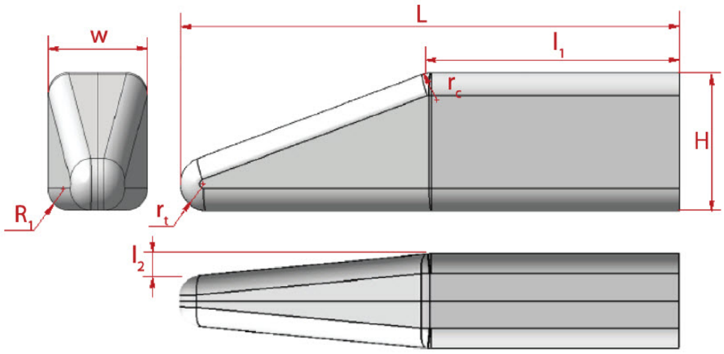

Fig. 30. Schematic geometry of the research [91].

In 2015, an investigation to specify the interaction between high-speed train and accidental crosswind was performed by Li et al. [92]. In this research, a high-speed train with 350 km/h as Fig. 31 and a crosswind with 13.8 m/s are considered. Using a numerical method, the researchers have conducted a study on aerodynamic specifications of the air flow around the high-speed train.

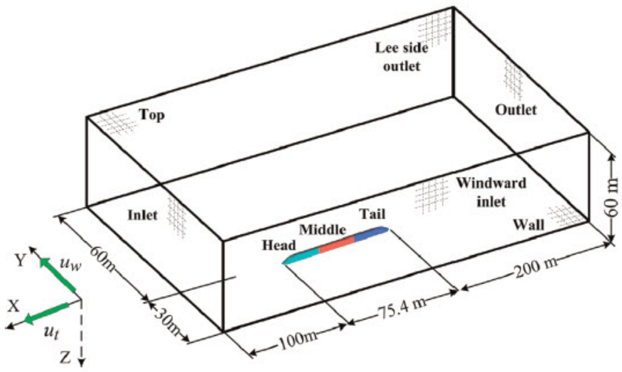

Fig. 31. The computational domain of the considered train model [92].

The flow structure around a high-speed train in the open air was investigated by Tian et al. [93] in 2015. The turbulent intensity ranges from 0.2 to 0.5 was related to high turbulence flow. In this research, the flow around the train was divided into 8 categories; high pressure with air stagnant region, pressure reducing with air accelerating region, low pressure in high air flow velocity, turbulent region, steady flow region, low pressure in high air flow velocity region, pressure increasing with air decelerating region and wake region. The results explained the flow over the high-speed train is turbulent and complicated. Moreover, the main sources of the vortex generation are the head and end of the train, under the structure, the wagons connections and the wake region. Decreasing wake and improvement wake structure are the most effective ways to reduce drag.

In 2015, a numerical investigation of air flow characteristics over a passenger train into a tunnel was investigated by Rabani et al. [94]. For this purpose, a three-dimensional train model which simulated by a RNG k-ε turbulence model was applied for analysis. The influences of the train velocity on the aerodynamic parameters as drag and side forces and pressure waves were studied. Also, the nose shape of the train has a notable effect on the pressure waves and experience a peak value. When the train was inside the tunnel, the drag coefficient increased as five times more than other conditions which had a deep effect on the safety of the train and passengers. Moreover, there was a destructive side force which pushing the train to the tunnel wall. The maximum value of the side force was 900 N. Also, the simulation illustrated that if an air vent and hood to be used on the tunnel roof and entrance, the pressure waves decrease as 28% and 36%, respectively.

Li et al. [95] in 2016 did optimization on a high-speed train using the Free-Form Deformation (FFD). In this research, the performance of aerodynamic specifications of the CRH2 high-speed train via multi-objective optimization for the purpose of drag reduction and lift force are analyzed. Also, the air flow over the high-speed train is considered three-dimensional, incompressible, steady and viscous. The results of this study included the following three steps: First, the relation between the design parameters and the external factors; second, an optimization using Genetic Algorithm (GA) and the last a comparison of the aerodynamic operation between the original and optimal models. Based on the carried out simulations by the CFD method; the aerodynamic drag force of the end of the train is greater than the beginning of it, and the aerodynamic lift force is positive at the beginning of the train and negative at the end of it.

In 2016, Yu et al. [96] investigated the aerodynamic effects on a high-speed train exposed to longitudinal and lateral wind.

In this article, a dynamic simulation for unsteady wind load on the high-speed train was done using the numerical approach. In 2017, the influence of the peripheral wind on the aerodynamic performance of two moving high-speed trains in a tunnel was done numerically by Chen et al. [97]. A model of the CHR6 high-speed train was applied for numerical investigation of aerodynamic parameters. After the numerical simulation, a comparison between the finding results and the full-scale test was done. According to the numerical findings, the pressure waves effects at different times and points in the tunnel were measured in that when the wind velocity increased, the maximum pressure increases, too. Furthermore, the maximum values of the aerodynamic drag and side forces for two trains were calculated and compared with each other.

4. Conclusion

In the present review paper, it has just been tried to introduce the most important and latest experimental and numerical studies on flow over high-speed trains. This paper brings together a comprehensive review of research on air flow around high-speed trains. The first section of the paper included the review of flow around the HST by experimental tools generally with their properties and the second section of the paper included a review of the high-speed train, flow around it and its factors and specifications via different numerical approaches, such as RANS, LES and DES.

In the above research papers, most of the parameters and critical issues of high-speed trains have been investigated. However, for future research on high-speed trains, the following subjects are suggested to be considered:

- For better simulation, more details of trains' geometry are to be considered.
- For realistic analysis, the geographic and topographic conditions such as weather, area elevation and related local pressure and railroads mazes can be considered.
- Aerodynamic geometry design especially for train’s nose, as one of the most significant issues, needs be studied more.
- Applicatiion of wall-based methods to achieve more accurate results near the body and reduce the need for supercomputers for large meshes will be of interest.

Acknowledgments

This work is sponsored by the EU commission Marie Curie Scheme.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author(s) received no financial support for the research, authorship and publication of this article.

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