The recent progress and state-of-art applications of aerodynamics for vehicle

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Abstract. Transportation is an indispensable part of human beings' daily life, thus plenty of scholars have focused on improving the energy efficiency of transportation. The application and development of aerodynamics is of paramount importance. In this article, the effects of three types of locomotives on aerodynamic performance of high-speed trains are investigated. In order to lucubrate this topic, the definition of aerodynamics by different scientists is firstly discussed and showed, they basically classify them by three different kinds of ways. Subsequently, the creation of aerodynamics, historical development, and present situation are briefly introduced. In the main part, mathematical model and calculation formula are carried out to ensure which kinds of aerodynamic model is the most suitable among all the designs. Overall, these results offer a guideline for how to design a more effective and practical train head by applying the aerodynamic knowledge and expanding people's use of aerodynamics.

Keywords: Aerodynamics, train head, modeling.

1. Introduction

Contemporarily, aerodynamics is not only used and applied in design of aircrafts but also for high-speed vehicles [1]. This article introduces the recent progress of aerodynamics for different vehicles, such as airplanes, automobiles, railways, boats and so on. Our main research is the application of this technology in high-speed vehicles, as well as aerospace or flying equipment, the content of the aerodynamic research is the aircraft as well as other features in the flow field of the gas speed, temperature, pressure and density and other parameters of the change law, the aircraft by the lift and resistance and other aerodynamic forces and their change law, the gas medium or gas and the aircraft between the physical and chemical changes and heat transfer and mass transfer law. Automobile aerodynamics and aviation, ships, railway vehicles, in the study of flow field, aerodynamics have many similarities, but the car driving on the ground is a blunt body, the car driving state is extremely complex, different from ordinary aerodynamics. Incompressible aerodynamics is the study of flow all the speeds are less than the speed of sound (subsonic). Compressible aerodynamics is the study of flow that the speeds both below and above the speed of sound (transonic), which possesses plenty of features and characteristics as listed in Ref. [2].

The rest part of the paper is organized as follows. The Sec. 2 will give a basic description of the hydrodynamic models of vehicles. The Sec. 3 will discuss the theoretical models for calculation and CFD simulations. Afterwards, the gaps and limitations for the state-of-art applications will be demonstrated as well as the future outlines will be proposed in the Sec. 4. Eventually, a brief summary is given in Sec. 5.

2. Basic Descriptions

In this section, we briefly introduce the creation of aerodynamics, historical development, and present situation. Bernoulli published Hydrodynamics, which can be considered as the first theorem focusing on aerodynamic and provides a method for calculating aerodynamic lift [3]. The basic equations are given as:

$$\frac{\rho v^2}{2} + \rho g z + p = C \tag{1}$$

where ρ is the density, v is the velocity and p is the pressure. Subsequently, Euler improved and extended the models in Eq. (1) to propose the Euler's equation, which results in the Navier-Stokes equation. The Navier-Stokes equation is the most general control equation for fluid flow, but it is difficult (almost impossible) to solve analytically for most of the cases and configurations. Later, Cayley identified the four core aerodynamic forces of flight (i.e., weight, lift, drag, and thrust), as sketched in Figure 1 [4].

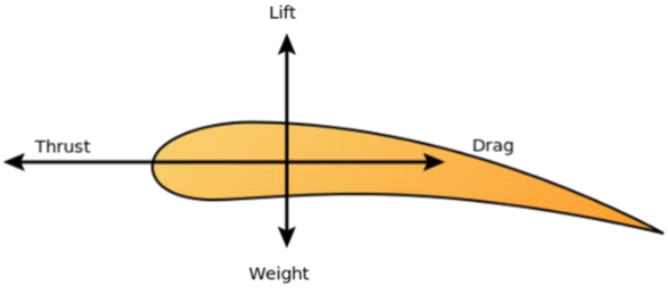

Figure 1. A sketch of the forces on flight.

Subsequently, with the contributions of plenty scholars in the latest hundreds of years, tremendous progress has been achieved. It should be mentioned that some of the important features are given, i.e., the Mach number which corresponds to the ratio of the moving speed to the speed of sound. Rankine and Hugoniot independently proposed the theorem for the hydrodynamic properties in the case of shock wave. Moreover, a specific definition of transonic is given by Kármán and Dryden, which serves as a guideline for break the sound barriers. The broken of the sound barriers can be considered as one of the most important milestones, which offers a path to investigate the supersonic flow.

With the development of the computation ability, computers with high-performances are available, which gives the possibility to numerical solve hydrodynamic equations to derive the properties and features instead of analytically. Since then, the so-called computational fluid dynamics (CFD) served as an effective tool to address the hydrodynamic issues for flight tests as well as other relevant subjects and disciplines. On this occasion, the Navier-Stokes equations (pretty tough equation to analytical solve as mentioned above) is available to be analysed, where a theorem named flow turbulence is also established [5]. Obviously aerodynamic design relies extensively on computational methods more and more. In now days, which also plays an important role in vehicle design [6, 7] and this is what these paper focuses on.

3. Computational model

The vehicles are acted by two different kinds of aerodynamic force, drag and lift without side wind effect normally. As a matter of fact, the main focus on this stage is to make reliable evaluations about the driving stability of vehicles. Recent progress and state-of-art applications are given in Ref. [8-12], which will be detailly discussed below.

3.1. Governing equations of flow

In general, the continuity equation can be described mathematically as following expression

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

and impulse equation

$$\rho\left(\frac{\partial u_i}{\partial t}+\frac{\partial(u_j u_i)}{\partial x_j}\right)=\frac{\rho v\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{\partial p}{\partial x_i} \quad (3)$$

where ρ there is a streaming fluid density; Turbulent viscosity, ρv, depends on the flow and is calculated from a certain model of turbulence.

3.2. Flow area of the train head and boundary conditions

Based on the characteristics of the longitudinal profile of the train nose of high-speed train, a 2D analytical equations and CFD simulations are carried out to investigate the impact of the longitudinal profile on the aerodynamic behaviour of high-speed trains. Height of the train head is 3.8 m. The length is 60 m, the height is 15 m, and the inlet is at a distance of 24 m from the draft head, the outlet is at a distance of 24 m from the rear of the train, the upper limit distance is 7.6 m, the lower limit distance is 3.6 m. The size of the flow field guarantees sufficient calculation accuracy. The boundary conditions are detailly listed and summarized in Ref. [8], which will not be mentioned repeatedly in this paper.

3.3. Numerical solutions

The main discussion in this paper is: assuming a certain width and height of the train head and with a constant project area on the upwind side, the designed configurations are schematically illustrated in Fig.2. Group A shows the double arch shape of the locomotive, group B shows the single arch shape of the locomotive and group C shows the spindle shape of the locomotive. Each group has three types of shapes, depending on the length of the locomotive and the variation of the streamline profile. The length of the streamline in each group is 8 m, 6 m and 4 m, respectively. The simulations were used to determine features of the fields the correlation of the distribution of the turbulence regions.

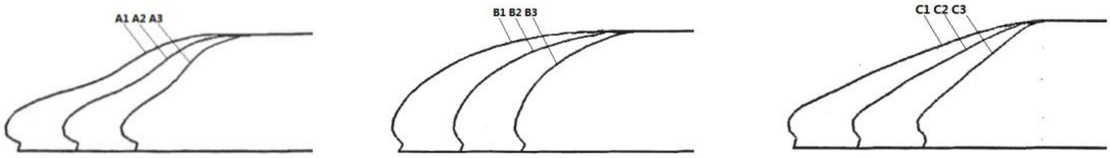

Figure 2. Profile sketch map of longitudinal streamline of train head [8].

3.4. Double-curved heads

The double arch allows the aerodynamic shape of the wagon to be maintained while ensuring the safety of the locomotive. It also ensures that the space in the driver's cab is high enough to have a sufficient angle of inclination to the windscreen [9-12]. The windscreen has a sufficient angle of inclination. This design does not affect the driver's field of vision and does not limit the space in the driver's cab. However, it does impede airflow between the first and second arches of the vehicle, resulting in considerable air resistance in front of the windows. Figures 3 show the pressure distribution and airflow profile for the double arch models.

The comparison shows that the highest over pressure is concentrated in the front part of the rising side. The progressive color changes in the image reflect the variation in pressure and airflow velocity from top to bottom. As the length of a pull point increases from 4 m to 8 m, the variation in the surface pressure of a pull point gradually decreases. The maximum over pressure on the upstream side gradually decreases from 4800Pa to 3400Pa, while the flow velocity decreases from 140m/s to 134m/s. This decrease is due to the fact that the air flow sticks to the surface of the head outside the flow field, which flattens out with the shape of the streamline. In addition, the change in slope in the head area is small. Furthermore, for models A1~A3, the isotope distribution rules are very similar: the central area of greatest over pressure is located firstly in the nose area of the vehicle and secondly in the arc interface area. The intersection between the nose of the vehicle and the deflector generates two obvious air flows. This similarity indicates that the flow field is greatest in the area of the nose of the train.

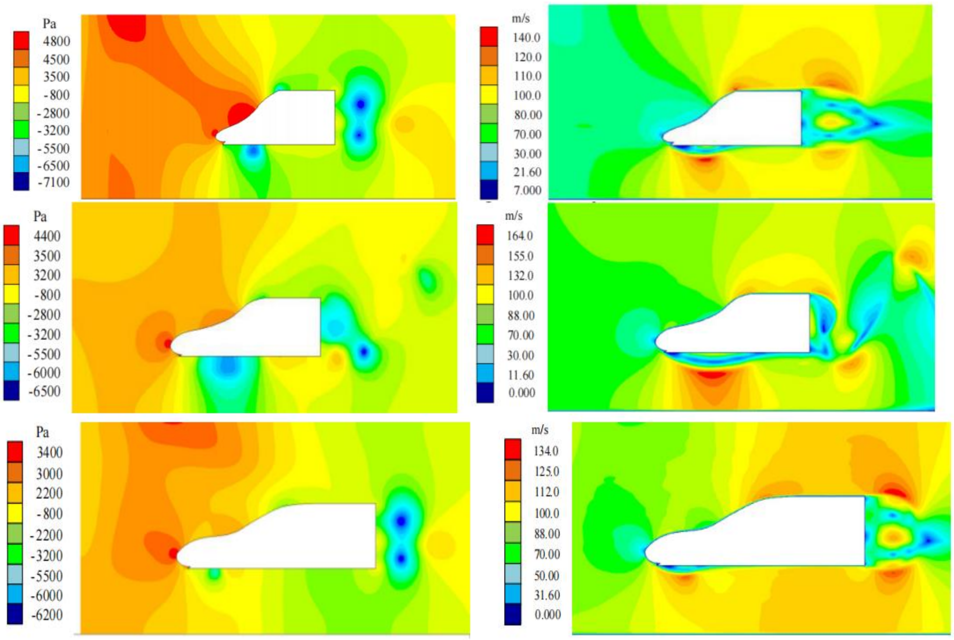

Figure 3. The pressure (left panel) and velocity (right panel) distributions for 4m (upper panel), 6m (middle panel) and 8m (lower panel) in Group A, respectively [8].

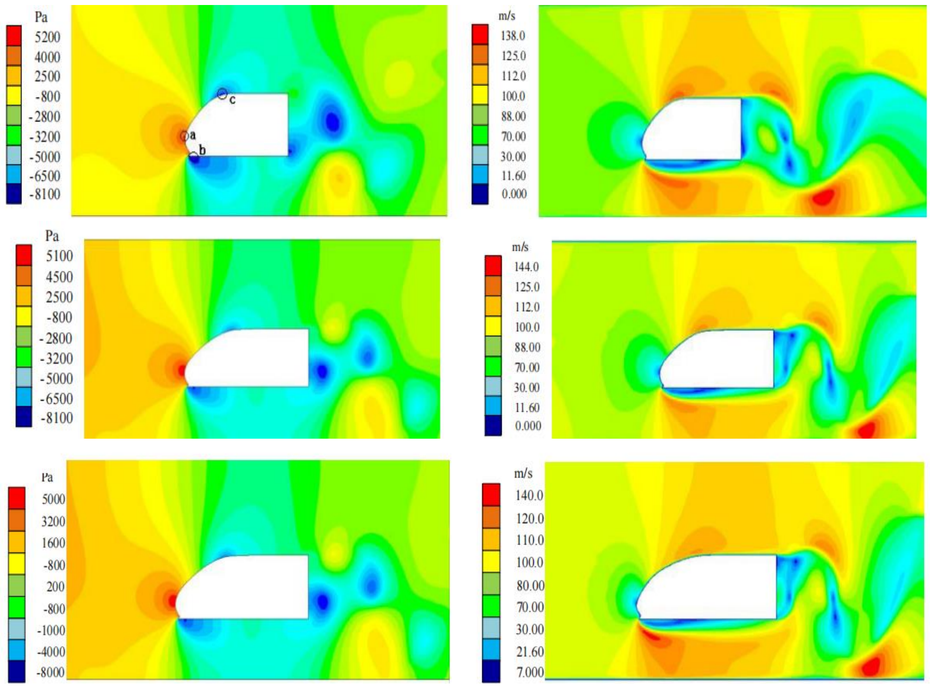

Figure 4. The pressure (left panel) and velocity (right panel) distributions for 4m (upper panel), 6m (middle panel) and 8m (lower panel) in Group B, respectively [8].

3.5. Single arched head

When the airflow hits the front end of the head, the wind resistance can be effectively reduced. According to the Fig. 4, it can be seen that the maximum pressure arrives at the wind side at 5220Pa, while the pressure intensity is remains continuously transient from point a to point b. Furthermore, as the length of the draft head increases, the curvature of the profile gradually changes and the pressure intensity increases. Furthermore, as the length of the draft head increases, the curvature of the profile changes gradually and the zone of positive pressure on the wind side decreases accordingly.

3.6. Spindle head

The spindle-shaped head profile has a straight sloping line on the windward side. This design reduces the side facing the rising wind to decrease significantly. When the airflow reaches the front of the train, it overflows both the top of the vehicle and both sides. The airflow will overflow and avoid the obstacles that the arched head creates due to the large surface area of the windward side.

As depicted in Fig. 5, maximum pressure on the windward side is reduced from 5100Pa to 4700Pa, and the largest depression area is reduced. The largest area of low pressure is reduced. In addition, the longer the train head length, the larger the area of low-pressure propagation on the windward side. The longer the length of train head, the more the area of depression propagation on the updraft side increases gradually. If the length of the traction point is increased to 8 m, a wide band of depression will appear on the updraft side.

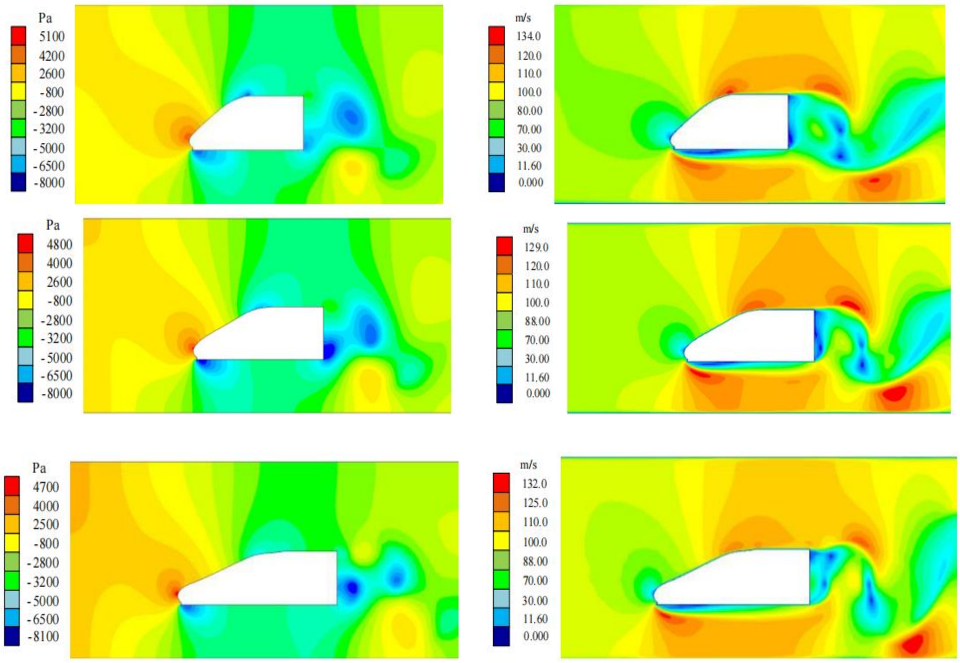

Fig. 5. The pressure (left panel) and velocity (right panel) distributions for 4m (upper panel), 6m (middle panel) and 8m (lower panel) in Group C, respectively [8].

3.7. Results of the calculation of the program in three groups

According to the analysis above, the aerodynamic performance of the head of model C1 is the best among all three designs, which is exhibited in Fig. 6.

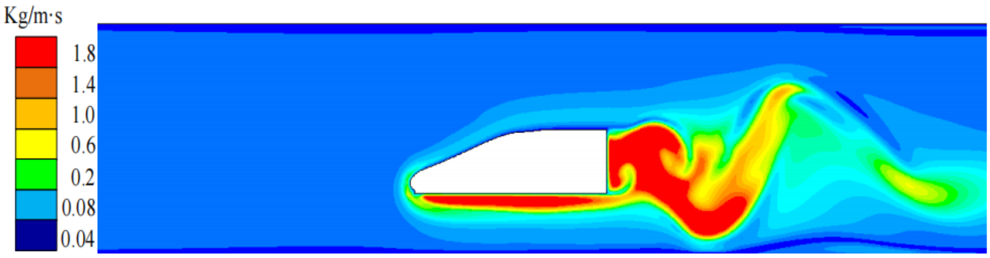

Fig. 6. CFD simulations results of C1 [8].

4. Gaps and Future outlook

Aerodynamics can be used in all aspects of life, not just in the head of a train, aerodynamics research content in the plane, missile and other machinery in motion conditions of fluid field, (e.g., gas velocity, pressure and density of parameters), the change rule of mechanical lift force and resistance of air power and its change law of gas medium or gas of physical and chemical changes that take place between mechanical, heat and mass transfer laws, etc. The main stream of aerodynamic research is still on aircraft and automobiles. One can clearly deduced that aerodynamic can be used more in the filed like aviation industry and jet propulsion technology etc.

However, there are still a lot of limitations. First of all, most models have oversimplified lines and surfaces, resulting in the differences for the flow field around the model from that of a sporting tool, making drag, lift, lateral forces, pitch and yaw moments, etc., impossible to use directly in the development of a sporting tool, and most standard models use smooth surfaces, ignoring the effect of components on air flow that exist on the surface of a real sporting tool. Secondly, most of the standard models were proposed earlier, and there are significant differences in model size and scale from those of current or future developments in transport machinery. As a result, we usually need to develop a new model for each new machine, which is often time consuming and expensive. Thirdly, it is difficult to obtain accurate data, and it cannot be recorded in the database because each model is different even when it is available. It is also very difficult to have a cross-reference between two different machines using the same aerodynamics.

It is hopeful for the development of a common database allows for cross-referencing in the design of models, even on different machine types in the future. Besides, we hope to be able to demonstrate experiments through virtual technology in order to save costs and improve efficiency, and in some difficult or costly experiments, to record experimental data accurately for subsequent development. It will be possible to combine more theoretical techniques such as stealth fighters, etc.

5. Conclusions

In summary, this paper mainly discussed the way to use aerodynamics to make the train head more effective. As a result, after using continuity equation, impulse equation, turbulence models, calculations and comparisons, the best performances case is found (i.e., the C1 case), which means this kind of head can play better in real-life situations. In the future, it is hopeful to use database and virtual simulation to reduce the cost of labor, material, model building and experimentation so that much more low energy cost but high efficiency vehicles can be produced. Overall, these results shed light on the advantages of the further researches for aerodynamics.

References

[1] J. D. Anderson, Fundamentals of Aerodynamics (6th edition.). McGraw-Hill, 2017. ISBN 978-1-259-12991-9.

[2] John David Anderson, A History of Aerodynamics and its Impact on Flying Machines. New York, NY: Cambridge University Press, 1997. ISBN 0-521-45435-2.

[3] L. J. Clancy. Aerodynamics. Wiley, 1975. ISBN 978-0-470-15837-1.

[4] G. K. Batchelor. An Introduction to Fluid Dynamics. Cambridge: Cambridge University Press, 2000, ISBN 978-0-521-66396-0.

[5] L. M. Milne-Thomson. Theoretical aerodynamics. Courier Corporation, 1973.

[6] J. Katz, Low-speed aerodynamics: From wing theory to panel methods. McGraw-Hill series in aeronautical and aerospace engineering. New York: McGraw-Hill, 1991. ISBN 0-07-050446-6.

[7] W. Hucho, G. Sovran, Aerodynamics of road vehicles. Annu. Rev. Fluid Mech. (1993), 25:485-537.

[8] R. S. Raghunathan, H. D. Kim, T. Setoguchi, Aerodynamics of high-speed railway train. Progress in Aerospace Sciences, 38, (2002), 469-514

[9] H. Tian, Train aerodynamics. Beijing: China Railway Press, 2007.

[10] X. Chen, Appearance and development trend of high-speed train. Electric Locomotive Technology, 3, (1997), 1-4.

[11] D. Wang, W. Zhao, S. MA, Application of CFD Numerical Simulation in High Speed Train Design. Journal of the China Railway Society, 29 (5), (2007), 55-59.

[12] C. Xu, H. Zhu, H. Qi, Conformal mapping-based analytical modeling on head shape of high-speed train. Journal of the China Railway Society, 24 (4), (2002), 38-41.