Numerical analysis on aerodynamic performance of different automobile body shape

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Abstract. Aerodynamic characteristics directly affect the dynamics, economy, control stability and ride comfort of automobiles. In this paper, the FLUENT software is applied to analyse the automobile aerodynamic performance considering the influence of different tire width and ground clearance in order to enhance the automobile fuel economy so as to provide reference for the design of the automobile body shape.

1. Introduction
With the development of automobile technology and the shortage of energy resources, how to improve the body shape to improve the fuel economy of automobile has been the research focus of the automobile industry [1]. Among all the influence factors, the body shape takes the major role because it determines the automotive aerodynamic parameters [2]. It is a traditional and effective method to improve the body shape through wind tunnel test, but there are many problems such as large investment in wind tunnel construction and long test period [3-5]. With the development of computing technology, a new way-CFD simulation which is first applied in the automotive design in America provides a new analysis method for the research of automobile aerodynamics [6, 7]. In this paper, CFD simulation was applied to analyse the aerodynamic performance of simple automobile models with different body shapes, so as to provide reference for the design of the automobile body shape.

2. Model Development

2.1 Mathematical model
Usually, the maximum speed of automobile is less than 400km/h, or less than 1/3 sound. The body surface flow can be considered incompressible flow. The physical parameters of air dielectric are constant. Considering the separation phenomenon caused by automobile complex shape, we treat it as turbulence. The control equations are as follows.

Mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = S_m
\]

In the formula: \( t \) means time; \( \rho \) means density; \( u_i \) means the direction of velocity; \( S_m \) means the quality of continuous phase. In incompressible flow, it is 0.

Momentum conservation equation:
\[
\frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i
\]

(2)

In the formula, \( \rho g_i \) means direction of gravity. When the effect of gravity is not considered, the term can be ignored; \( F_i \) means the external volume force in the \( i \) direction. An example the external volume force would be an applied electric field force. In this paper it is 0, with the assumption that there is no external volume force.

\[
\tau_{ij} = \mu_{\text{eff}} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right]
\]

(3)

In the formula, \( \mu_{\text{eff}} \) means effective turbulent viscosity coefficient, \( \mu_{\text{eff}} = \mu + \mu_t \). \( \mu \) means the viscosity coefficient of laminar flow. \( \mu_t \) means the viscosity coefficient of air turbulence, which varies with the different turbulence models; \( \delta_{ij} \) means three order identity tensor.

2.2 Automobile body model

Figure 1 as the automobile body of GAMBIT model with dimensions: length 4800mm, width 1800 mm, height 1500 mm.

![GAMBIT automobile body model](image1)

2.3 The body mesh

The flow field near the body is the main research object. In this paper, hybrid grid technology is used for space division of the wind tunnel. A structured grid represents the air around the automobile, an unstructured grid represents the body surface, and a non-structured grid is used for the body. Figure 2 is the schematic diagram of the automobile body distribution grid.

![Schematic diagram of body mesh distribution](image2)

2.4 The wind tunnel model

The wind tunnel’s dimensions should meet the following specifications: three times the automobile length allotted for space in front of the automobile, five times the length of the automobile allotted for rear space, five times the height of the automobile between the ceiling and automobile roof, five times the automobile width allotted for each side. Only in this way, the blocking effect does not appear. Figure 3 shows a wind tunnel cross sectional shape.
2.5 Boundary conditions

The entrance boundary for the velocity boundary condition is the automobile's speed with its surface perpendicular to the direction of import. The export is the pressure outlet boundary condition, equal to the standard atmospheric pressure. Specific boundary conditions are set as follows:

1) Simulating the wind tunnel entrance boundary condition, the entrance boundary for the velocity boundary condition speed is the automobile's speed of 100km/h, its surface being perpendicular to the direction of import;

2) Simulating a wind tunnel outlet boundary condition, the pressure outlet boundary condition is equal to standard atmospheric pressure;

3) The automobile's body wall boundary condition, assuming the surface is under a no slip boundary condition.

3. The effect of tire width on the aerodynamic performance

With the reference of real automobile proportion, we combined with the size of basic automobile model and selected the tire diameter 240mm and the tire width 100mm as showed in Figure 4. Table 1 is aerodynamic parameters of different tire width. Drag coefficient: the tire width is 100mm, and the drag coefficient of the model is the smallest; Lift coefficient: the tire width is 100mm and 140mm, and the drag coefficient of these models is small, and both the lift coefficient is basically close. Synthesis of drag coefficient and lift coefficient, the aerodynamic performance of the automobile model is superior with the tire width 100mm.

| L (mm) | Drag (N) | Drag coefficient | Lift(N) | Lift coefficient |
|-------|----------|------------------|---------|-----------------|
| 0     | 94.88    | 0.5375           | -3.51   | -0.0066         |
| 100   | 108.77   | 0.5770           | -1.54   | -0.0029         |
| 110   | 110.72   | 0.5833           | -4.1    | -0.0078         |
| 120   | 111.41   | 0.5831           | -4.05   | -0.0077         |
| 130   | 112.59   | 0.5855           | -5.25   | -0.0010         |
Figure 5 is the distribution of pressure field (a), velocity field (b) and vector field (c) on the surface of automobile when the tire width is $L=100mm$. From the pressure field distribution diagram, the front pressure of the head and the windowpane is large. The negative pressure is formed at the front end of the automobile top and head, the front side and the rear of the automobile. From the velocity field distribution, we can see that the wind speed at the front end and the rear of the automobile is low, and there is a large velocity variation at the top front end and the sides of the body. From the vector field distribution, we can see that the flow direction of the front end is changed, and there is eddy current at the front part of the rear and the both sides of the body. When the wheel is added, the aerodynamic performance of the bottom is greatly changed. The pressure of the windward side is larger, the rear of the wheel has a negative pressure, and there is a vortex in the combination of the wheel and the bottom of the wheel, and the eddy current in the front wheel is larger than the rear wheel. In the further design, the guide plate can be set at the combination of the wheel and the bottom to improve the pressure difference and reduce the eddy current, and the guide plate can improve the aerodynamic performance of the front wheel.

| 140 | 113.76 | 0.5879 | -1.45 | -0.0028 |

Figure 5. Flow field distribution of the tire width of $L=100m$.

4. The effect of automobile passability on the aerodynamic performance

The influence of automobile passability geometric parameters on aerodynamic performance is closely related to the improvement of body styling design. By changing some parameters of the body, we apply the orthogonal test to analyse the change law of the aerodynamic drag of the automobile, and seek a reasonable body model with lower aerodynamic drag coefficient on this basis. In this section, the minimum ground clearance is chosen as the influencing factor to observe vehicle passing ability.

The diameter of the selected tire is 240mm, the wheel width is 100mm, and the initial ground clearance is 120mm. Figure 6 is the schematic diagram of different minimum ground clearance. $L$ is the minimum ground clearance of the automobile body. Table 2 is aerodynamic parameters of different minimum ground clearance. From the calculation results, we can see that the drag coefficient reduces with the decrease of the minimum ground clearance. When the minimum clearance is $L=90$, the drag coefficient is the lowest, which is about 1.9% lower than the initial minimum clearance. The
lift coefficient increases first and then decreases with the decrease of the minimum ground clearance. Considering that the change of the minimum clearance of the automobile is not obvious to the decrease of the drag coefficient, but the increase of the lift coefficient is obvious, so the automobile model of \( L=120 \) is chosen as the optimal model.

It can be seen that in the clearance range of a certain body, reducing the clearance of the body to the ground can reduce the resistance coefficient at the same time, and the reduction of the clearance of the ground will reduce the passing ability. Therefore, in vehicle design, if the minimum ground clearance decreases, the drag coefficient will not decrease obviously, so we should ensure that the vehicle has good continuity.

| L (mm) | Drag (N) | Drag coefficient | Lift (N) | Lift coefficient |
|--------|----------|------------------|----------|-----------------|
| 120    | 108.77   | 0.5770           | -1.54    | -0.0029         |
| 110    | 108.57   | 0.5759           | -4.07    | -0.0077         |
| 100    | 108.12   | 0.5735           | -6.12    | -0.0116         |
| 90     | 106.70   | 0.5660           | -4.45    | -0.0084         |
| 80     | 107.07   | 0.5679           | -3.27    | -0.0062         |

Figure 7 is the distribution of pressure field (a), velocity field (b) and vector field (c) on the surface of automobile when the minimum clearance is 120mm, which is basically the same as that of the optimal automobile model with 100mm tire width.
Figure 7. Flow field distribution of the minimum ground clearance of 120mm.

5. Conclusion
FLUNET software was used to analysis the effects of automobile tire width and ground clearance on aerodynamic performance. It provides relevant guidance for model making and wind tunnel experiment. From the results, it can be concluded that drag coefficient and lift coefficient increase with the increase of tire width; drag coefficient decreases and lift coefficient increases firstly and then decreases with the decrease of ground clearance.

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