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NUMERICAL STUDY ON THE INFLUENCE OF DEFLECTORS ON THE FLOW FIELD AROUND HEAVY-DUTY TRUCKS

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ABSTRACT

To address the problem that the regulation mechanism of deflectors on the flow field of van-type trucks under a wide range of wind speed operating conditions remains unclear, this paper adopts the standard RNG k–ε turbulence model to perform numerical calculations on the external flow field of van-type trucks with and without deflectors under three typical wind speeds, and systematically analyzes the regulation mechanism of the deflector device on flow field characteristics. The results show that high stagnation pressure exists on the windward surface of the truck without deflectors, which increases sharply with rising wind speed; after the installation of deflectors, the pressure gradient transitions smoothly, thus reducing aerodynamic drag. Without deflectors, the velocity gradient between the low dynamic pressure regions at the cab and the front of the cargo compartment and the high dynamic pressure regions at the cab corners increases significantly with wind speed. The deflectors effectively eliminate the low dynamic pressure region at the cab roof, but have a limited improvement effect on the high dynamic pressure acceleration effect of lateral bypass flow. For the truck without deflectors, the total pressure deficit in the wake region is severe, and the energy dissipation increases non-linearly and sharply. The deflector device reduces part of the irreversible energy dissipation by reducing direct flow impingement.

KEYWORDS: van-type trucks, deflectors, aerodynamic characteristics, numerical calculation.

1. INTRODUCTION

As the core equipment for logistics transportation, trucks are often subjected to a wide wind speed range of 10~50 m/s during actual operation, covering urban low-speed, highway high-speed, and extreme wind speed conditions. The abrupt geometric change at the junction of the cab and cargo compartment easily triggers flow separation and turbulence burst, resulting in severe energy dissipation. As a low-cost aerodynamic optimization device, the cab deflector can mitigate the flow separation effect by guiding the airflow direction.

However, current research on its aerodynamic regulation mechanism across a wide wind speed range is still insufficient, which cannot provide complete theoretical support for the aerodynamic design of trucks under complex working conditions. Therefore, in-depth investigation of the pressure gradient evolution and spatial distribution characteristics of turbulence in the external flow field of trucks with and without deflectors under different wind speeds has become the key to improving their aerodynamic energy efficiency and driving stability.

At present, domestic scholars have carried out a series of studies in the field of truck aerodynamic characteristics. Du et al. **Error! Reference source not found.** investigated the airflow characteristics on the surface of van-type trucks through wind tunnel tests and numerical calculations, and found that the flow separation at the junction of the cab and cargo compartment is the main source of aerodynamic drag. However, the test wind speed was limited to 15~25 m/s, which did not cover ultra-high speed operating conditions. Zhang et al. **Error! Reference source not found.** conducted research on the aerodynamic characteristics of long-head heavy-duty trucks in a wide wind speed range, adopted the SST k–ω model to simulate the flow field evolution at wind speeds of 15~45 m/s, and confirmed that the turbulent kinetic energy dissipation in the cab region increases non-linearly with rising wind speed, but did not discuss the optimization effect of the deflector device on the turbulence field under extreme wind speeds. Zheng et al. **Error! Reference source not found.** simulated the wake characteristics of van-type trucks using the RNG k–ε model, and found that the wake vortex dissipation accounts for more than 35% of the total drag, but did not involve the intervention effect of the cab deflector structure. Cao et al. **Error! Reference source not found.** analyzed the aerodynamic performance of heavy-duty trucks under the special crosswind environment across a wide wind speed range, and verified through numerical simulation that the fluctuation amplitude of the aerodynamic load of the truck increases with the rise of crosswind intensity at crosswind

speeds of 10~35 m/s, and the flow field turbulence in the cab region is significantly higher than that in other parts. In the research on deflector structure optimization and drag reduction effect, Wang Xinyu, Wang Dengfeng et al. **Error! Reference source not found.** systematically elaborated the aerodynamic optimization principle and engineering verification of cab deflectors, and pointed out combined with wind tunnel test data of multiple vehicle models

That the drag reduction rate of streamlined deflector structures can reach 12%~18% under 20~42 m/s working conditions. However, their theoretical analysis did not involve the turbulence regulation mechanism under ultra-high speed conditions above 42 m/s. Wu et al. **Error! Reference source not found.** verified the drag reduction effect of the cab deflector device under 20~30 m/s working conditions through wind tunnel tests, and measured the maximum drag reduction rate of 7.43%, but lacked turbulence characteristic data under ultra-high speeds. Zhou Shaorong **Error! Reference source not found.** earlier focused on the influence of deflectors on the drag of freight trucks, and pointed out through real vehicle road test analysis that a reasonably designed wind deflector can reduce the aerodynamic drag of trucks by 5%~8%, which provided a basic reference for subsequent research on more refined aerodynamic structures such as wind deflectors. However, this study did not involve the influence of wind speed changes on the drag reduction effect. Li et al. **Error! Reference source not found.** carried out optimization research on the windward angle of the front bumper deflector, and confirmed through CFD analysis and wind tunnel tests that the drag coefficient reduction can reach 3.3%~3.9% under the working condition of 80~120 km/h (approximately 22~33 m/s) with a 45° windward angle. However, their research did not involve the analysis of the coupling effect between the deflector and ultra-high wind speed up to 50 m/s. He et al. **Error! Reference source not found.** took a pure electric bus as the research object, established a simulation correction method for deflector structure optimization through the comparison of wind tunnel tests and numerical simulation, and verified that the error of the SST k–ω model under 25~48 m/s working conditions is controlled within 4.2%, but did not focus on the research on the regulation mechanism of truck deflectors.

In view of the above research background, the current research on the effect of deflectors on the external flow field of van-type trucks is still relatively limited, and cannot fully reveal the intrinsic mechanism of energy dissipation induced by flow separation under different wind speeds. In this study, a typical van-type truck is taken as the research object, and the standard RNG k–ε turbulence model is adopted to calculate the external flow field of

the truck under three typical wind speeds. The research results aim to reveal the evolution mechanism of the truck flow field under different driving speeds, and can provide theoretical support for the optimal design of truck deflector devices as well as energy conservation and emission reduction.

2. Computational Model and Method

2.1 Computational Model

Taking a standard 4.2-meter van-type truck as the prototype, simplified three-dimensional (3D) models were established respectively for the truck with two configurations, i.e., with and without a deflector. The core structures of the models include the cab, cargo compartment, wheels, and deflector. The deflector adopts a streamlined design and is mounted on the top of the cab, with its length consistent with the width of the cab and cargo compartment, and its thickness transitioning smoothly from the root to the trailing edge. The key structural parameters are listed in Tab. 1.

Tab. 1: Main Structural Parameters.

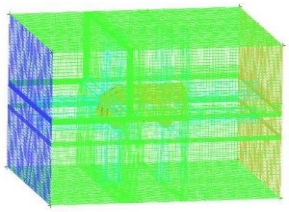
Main Structures	Parameters	Values
	Length /mm	1337.8
Cab	Width /mm	1650
	Height /mm	1300
	Length /mm	4200
Cargo Compartment	Width /mm	1650
	Height /mm	1800
Wheels	Diameter /mm Width /mm	350 325
	Length /mm	1000
Deflector	Maximum Thickness /mm Inclination Angle /（°）	500 26.6

2.2 Computational Domain Setup

To ensure the full development of the incoming flow and complete capture of the wake flow, a cuboid structure is adopted for the computational domain, which extends 4 m upstream of the cab, 4 m downstream of the truck body, 4.5 m in the lateral direction and 1.5 m in the vertical direction. The region occupied by the truck body is removed via Boolean operation to form a fluid-only computational domain, so as to ensure that the airflow bypass around the vehicle and wake diffusion are free from boundary interference.

2.3 Computational Method

The overall meshes of the computational domain for the trucks with and without deflectors are shown in Figures 1 and 2, with the total number of mesh elements of the two configurations being 537312 and 492205 respectively. Unstructured hybrid mesh generation was performed using ANSYS ICEM software: the upstream boundary facing the cab front was defined as the flow inlet boundary, and the downstream boundary facing the truck rear was defined as the flow outlet boundary.



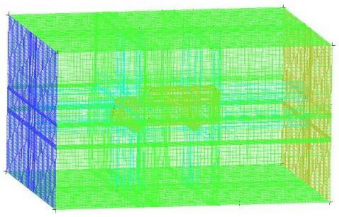
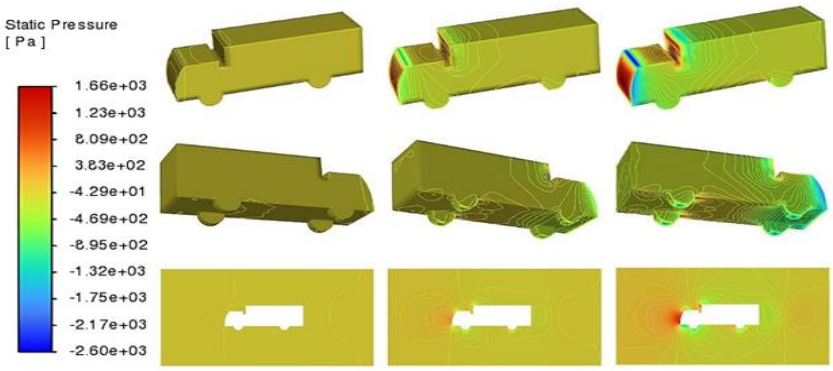


Fig. 1 Full Model Mesh of Truck with Deflector. Fig. 2 Full Model Mesh of Truck with Deflector.

3. RESULTS ANALYSIS

3.1 Static Pressure Distribution

The multi-dimensional and multi-angle static pressure contour plots reflect the static pressure distribution characteristics of the external flow field around the truck under different wind speeds. They can intuitively demonstrate the force conditions of each region and the distribution pattern of the high-pressure stagnation zone, and assist in evaluating the formation mechanism of aerodynamic pressure drag. Fig. 3 shows the static pressure distribution contours of the truck without deflector under different wind speeds.

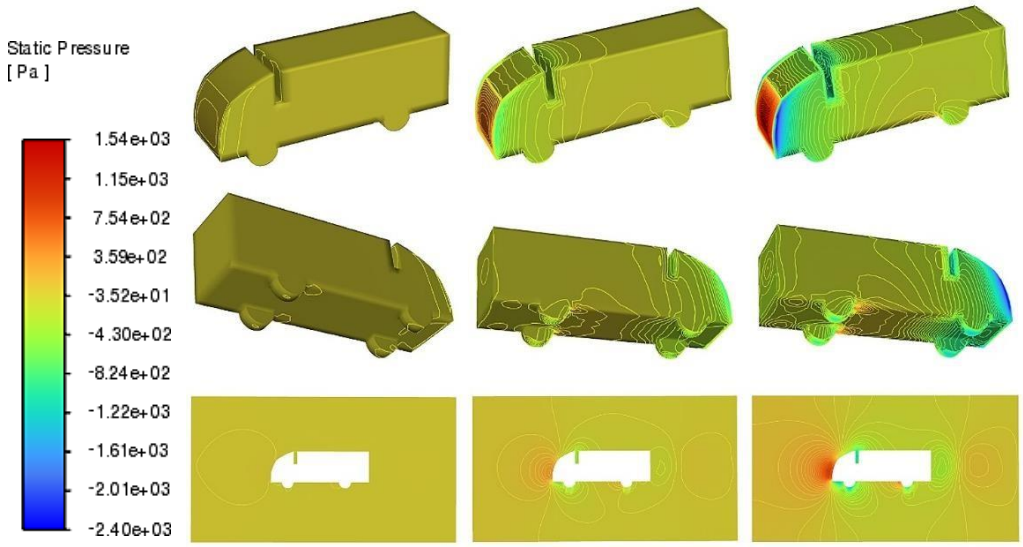


(a) 10m/s (b) 30m/s (c) 50m/s

Fig. 3 Static Pressure Distribution of Truck Without Deflector Under Varying Wind Speeds.

The analysis of the static pressure distribution of the truck without deflector under low, medium and high wind speeds shows that both the windward surface of the cab and the front windward surface of the cargo compartment exhibit significant high-pressure characteristics. This is attributed to the instantaneous stagnation of the airflow upon impacting the nearly vertical wall surface, where the kinetic energy of the airflow is converted into pressure energy or internal energy, forming a high-intensity stagnation high-pressure field. With the continuous increase of wind speed, the positive pressure on the windward surface rises sharply. While the coverage of the high-pressure core region does not expand significantly, its intensity presents a notable non-linear enhancement. These two high-pressure regions, together with the negative pressure zone at the truck rear, constitute a non-negligible source of aerodynamic pressure drag.

Fig. 4 shows the static pressure distribution characteristics of the truck with deflector under different wind speeds.



(a) 10m/s **(b) 30m/s** **(c) 50m/s**

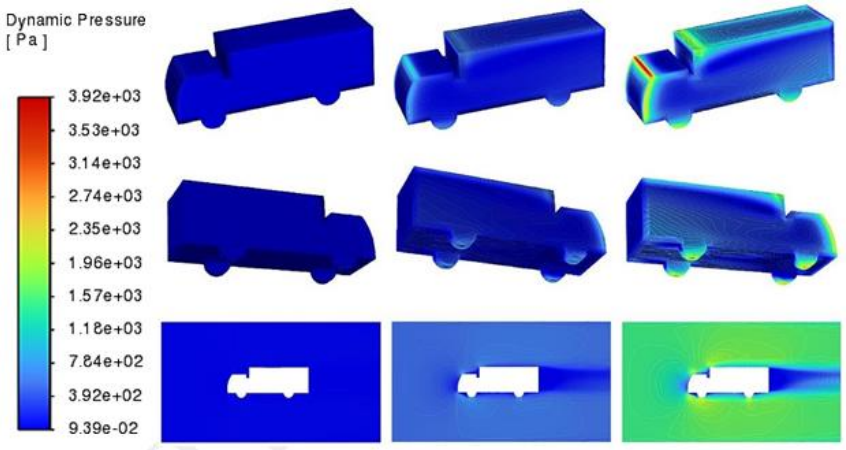
Fig. 4 Static Pressure Distribution of Truck With Deflector Under Varying Wind Speeds.

After the installation of the streamlined deflector, the static pressure structure of the flow field changes significantly. The airflow smoothly transitions along the slope of the deflector to the top of the cargo compartment, completely eliminating the high-pressure stagnation zone on the front windward surface of the original cargo compartment, and making the static pressure distribution along the slope at this position tend to be uniform. With the continuous increase of wind speed, although the overall static pressure rises and the pressure gradient on the

windward surface of the deflector increases continuously, the peak value of the high-pressure region is lower than that of the configuration without deflector. This indicates that the deflector device can effectively improve the static pressure distribution on the vehicle body surface and reduce aerodynamic drag within a wide wind speed range.

3.2 Dynamic Pressure Distribution

The dynamic pressure contours can be used to analyze the distribution pattern of the fluid kinetic energy in the external flow field around the truck under different wind speeds, and assist in evaluating the acceleration and stagnation characteristics of the flow field. The dynamic pressure distribution contours of the truck without deflector under different wind speeds are shown in Fig. 5.



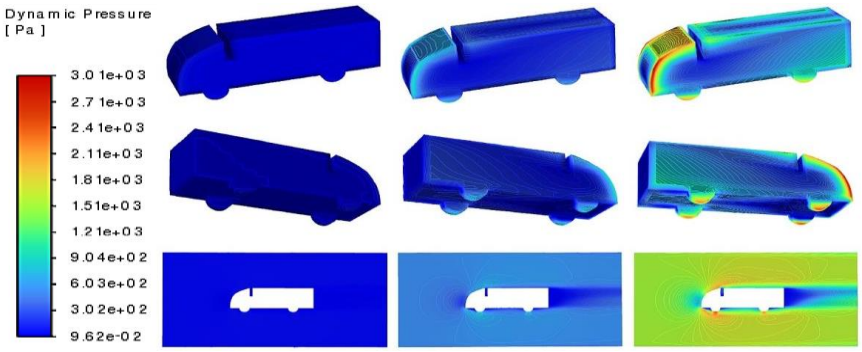
(a) 10m/s (b) 30m/s (c) 50m/s

Fig. 5 Dynamic Pressure Distribution of Truck Without Deflector Under Varying Wind Speeds.

The investigation of the dynamic pressure distribution of the truck without deflector under low, medium and high wind speeds shows that significant low dynamic pressure zones exist directly in front of the cab and in the front area of the cargo compartment above the cab height. The fluid flow in these zones presents obvious stagnation and recirculation characteristics, and the airflow cannot pass through smoothly, resulting in a large dissipation of kinetic energy. In contrast, high dynamic pressure concentration zones appear at the front side corners and side edges of the cab. This is attributed to the sharp shrinkage of the flow passage cross-section when the airflow flows around the bluff body structure, where the fluid is forced to accelerate drastically to pass through the corner area, leading to a dramatic increase in local flow velocity and a significant rise in kinetic energy. With the continuous

increase of wind speed, the high dynamic pressure zone at the cab gradually extends around, and the velocity gradient formed between the high and low dynamic pressure zones increases synchronously, which causes the inhomogeneity of the aerodynamic load on the vehicle body surface to present a significant increasing trend.

Fig. 6 shows the dynamic pressure distribution characteristics of the truck with deflector under different wind speeds. After the installation of the deflector, the dynamic pressure distribution structure of the flow field is significantly optimized. Compared with the truck without deflector, the original stagnant low dynamic pressure zone in the front windward area of the cargo compartment is effectively eliminated. The airflow accelerates along the slope of the deflector and then smoothly transitions to the top of the cargo compartment, avoiding the sharp kinetic energy dissipation caused by abrupt geometric changes. This is because the deflector acts as an attachment surface for the airflow, suppressing the premature separation of the boundary layer, and enabling the high-speed airflow to continuously transfer kinetic energy along the deflector surface. At high wind speeds, the high dynamic pressure concentration at the side edges of the cab is still significant, but the value of the high dynamic pressure is significantly lower than that of the configuration without deflector. This indicates that although the deflector device can significantly improve the kinetic energy transfer in the longitudinal flow field, it has a limited inhibitory effect on the local acceleration effect caused by lateral bypass flow.



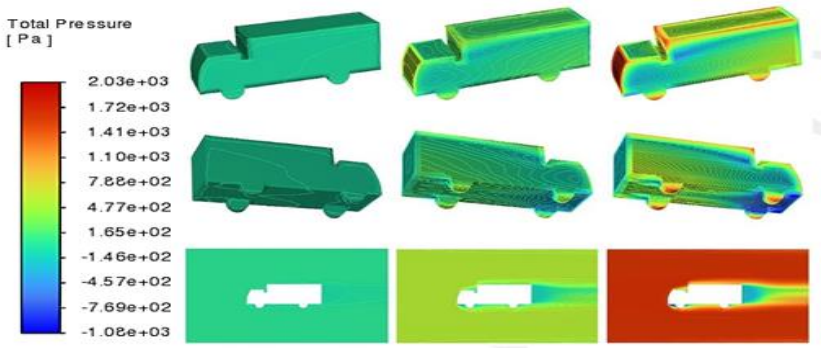
(a) 10m/s (b) 30m/s (c) 50m/s

Fig. 6 Dynamic Pressure Distribution of Truck With Deflector Under Varying Wind Speeds.

3.3 Total Pressure Distribution

The total pressure contours can comprehensively reflect the sum of the static pressure potential energy and kinetic energy of the fluid, and the gradient of its decrease along the

flow path directly characterizes the intensity of irreversible energy dissipation. The total pressure distribution of the truck without deflector under different working conditions is shown in Fig. 7.



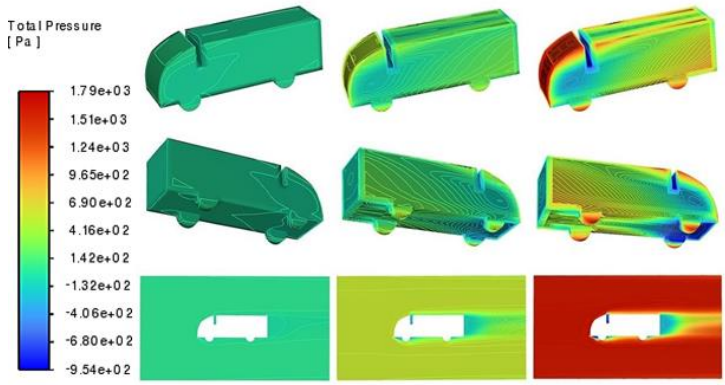
(a) 10m/s **(b) 30m/s** **(c) 50m/s**

Fig. 7 Total Pressure Distribution of Truck Without Deflector Under Varying Wind Speeds.

The analysis of the total pressure contours of the truck without deflector under three wind speed conditions (low, medium and high) shows that the total pressure is the highest on the windward surface of the cab, but decreases significantly when the airflow flows through the rear of the cab and the front edge of the cargo compartment. Especially in the rear area of the vehicle body, a large-scale low total pressure wake zone is formed. This means that when the fluid flows through the vehicle body, a large amount of mechanical energy is converted into internal energy or turbulent kinetic energy and dissipated, as the fluid does work to overcome friction drag and pressure drag. The root cause of this phenomenon is the flow separation without the deflector: the airflow undergoes large-scale flow separation at the corner between the cab and the front edge of the cargo compartment, forming a high-intensity shear layer and wake vortices. These large-scale vortex structures are continuously broken up and dissipated during their downstream evolution, resulting in a sharp drop in total pressure. With the continuous increase of the incoming wind speed, the core negative value of the rear low total pressure zone decreases continuously, and the degree of energy loss presents a non-linear growth with the wind speed.

Fig. 8 shows the total pressure distribution law of the truck with deflector under different wind speeds. Comparative analysis shows that under the three wind speed conditions of low, medium and high, after the installation of the deflector, the total pressure of the flow field on the upper and side areas of the cargo compartment is well maintained,

and the energy attenuation is slowed down. Especially at high wind speeds, the deflector guides the airflow over the front edge of the cargo compartment, avoiding the energy loss caused by the direct impact of the fluid on the front surface of the cargo compartment. The total pressure recovery rate of the rear flow field shows a slight acceleration trend, indicating that the deflector device reduces the irreversible energy loss of the whole vehicle to a certain extent and improves its aerodynamic energy-saving performance.

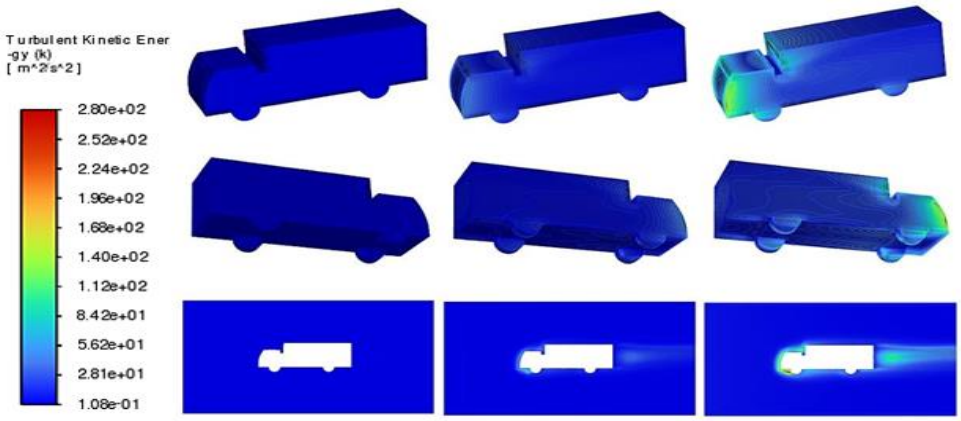


(a) 10m/s **(b) 30m/s** **(c) 50m/s**

Fig. 8 Total Pressure Distribution of Truck Without Deflector Under Varying Wind Speeds.

3.4 Turbulent Kinetic Energy Distribution

Turbulent Kinetic Energy is a key indicator for evaluating the intensity of turbulent fluctuation of the fluid, which is directly correlated with the flow stability of the fluid and the intensity of energy dissipation in the external flow field around the truck. The turbulent kinetic energy contours of the truck without deflector are shown in Fig. 9.

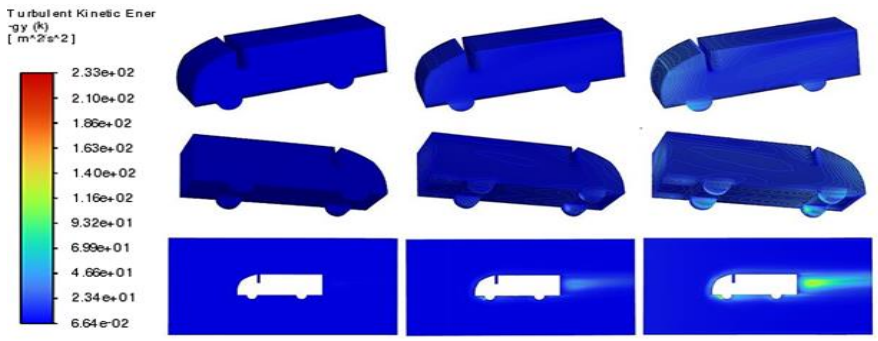


(a) 10m/s **(b) 30m/s** **(c) 50m/s**

Fig. 9 TKE Distribution of Non-deflector Truck Under Varying Wind Speeds.

The comparative analysis of the Turbulent Kinetic Energy distribution of the truck without deflector under low, medium and high wind speed conditions can be summarized into several core laws. At low and medium wind speeds, local high Turbulent Kinetic Energy zones begin to appear on the windward surface and top of the cab, as well as at the front edge of the cargo compartment, and a high Turbulent Kinetic Energy concentration zone is also generated at the bottom of the cab. As the wind speed increases to 50 m/s, the peak value of the high Turbulent Kinetic Energy zone rises sharply and its scope expands continuously around, indicating that the intensity of fluid turbulent fluctuation is significantly enhanced. The cause of this phenomenon is as follows: after flowing through the cab, the airflow undergoes flow separation at the front edge of the cargo compartment, and directly impacts the front windward surface of the cargo compartment to form a shear layer. Meanwhile, the airflow under the cab is affected by the wheels, resulting in strong vortex system interference, which leads to a sharp increase in flow field instability, thus continuous energy dissipation occurs and the aerodynamic efficiency of the whole vehicle is reduced.

Fig. 10 shows the turbulent kinetic energy distribution of the truck with deflector. With the increase of working intensity, i.e., the rise of wind speed, although the overall Turbulent Kinetic Energy of the truck with deflector still shows an upward trend, its growth amplitude is significantly reduced. Under the action of the deflector, the original local high Turbulent Kinetic Energy zones are effectively suppressed, the fluid flows smoothly along the streamlined surface, and the Turbulent Kinetic Energy presents a monotonic decreasing trend along the streamwise direction. However, there is still a certain high Turbulent Kinetic Energy wake zone in the rear flow field, indicating that the deflector has a relatively weak inhibitory effect on the far-field wake vortices.



(a) 10m/s **(b) 30m/s** **(c) 50m/s**

Fig. 10 Turbulent Kinetic Energy Distribution of Non-deflector Truck Under Varying Wind Speeds.

Especially at the extreme wind speed of 50 m/s, the Turbulent Kinetic Energy level on the windward surface of the cab, the deflector surface and the front edge of the cargo compartment is significantly lower than that of the non-deflector configuration. This indicates that the deflector device significantly weakens the turbulent dissipation caused by impingement separation by optimizing the cab profile of the truck, and maintains the flow field at a relatively low disturbance level.

4. CONCLUSION

For the truck without deflector, high stagnation pressure presents on the windward surface of the cab and the front windward surface of the cargo compartment, which rises sharply with the increase of wind speed. After the installation of the deflector, the pressure gradient achieves a smooth transition, the original high-pressure stagnation zone on the front windward surface of the cargo compartment is completely eliminated, and the aerodynamic drag is effectively reduced; for the truck without deflector, a prominent low dynamic pressure concentration zone exists at the front of the vehicle, and a high dynamic pressure concentration band is formed at the cab corner due to the shrinkage of the flow passage, with the velocity gradient and kinetic energy consumption increasing significantly as wind speed grows. The installation of the deflector effectively eliminates the low dynamic pressure zone at the top of the cab and improves the continuity of longitudinal kinetic energy transfer, but has a limited improvement effect on the high dynamic pressure acceleration effect induced by lateral bypass flow; for the truck without deflector, severe total pressure deficit occurs at the vehicle tail, and the energy dissipation caused by large-scale flow separation increases non-linearly and sharply with wind speed. The deflector device mainly reduces partial irreversible energy dissipation by avoiding the direct impingement of airflow on the front edge of the cargo compartment, thus improving the overall aerodynamic performance of the vehicle; for the truck without deflector, multiple local high Turbulent Kinetic Energy zones appear at low and medium wind speeds. At high wind speeds, the airflow impingement on the front edge of the cargo compartment and the interference from wheels lead to a sharp rise in fluid turbulent fluctuation and a large expansion of its affected range. The deflector significantly weakens the local turbulent burst caused by abrupt geometric changes and maintains the flow field disturbance at a relatively low level, but has a relatively weak inhibitory effect on the far-field wake vortices in the tail flow field.

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