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Influence of Angle of Attack on Hypersonic Wake Flow Structure of a Sharp Cone

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Abstract

The hypersonic wake flow structure of a sharp cone with different angle of attack was investigated numerically. By comparing with the 0° angle of attack case, the influence of angle of attack on wave and vortex structure was examined. For the non-zero angle of attack cases, the recirculation zone shape is of complex three-dimensional shape and there is a local minimum of recirculation region length at the z=0 plane, while two maximums exist symmetrically about the z=0 plane, in contrast with the axisymmetric shape of non-zero angle of attack case. Two sets of vortex surfaces exist in the near base region and the windward one is smaller than the leeward one because of compression from the windward flow. These vortexes interact with each other and create complex compression and expansion waves in the base region. The length of recirculation region shows a non-linear change of the recirculation region length with the increasing of angle of attack. At small angle of attack, the recirculation region decreases with the increasing angle of attack, but when the angle of attack exceeds the half angle of the cone, the vortexes generated by the forebody interact with wake vortexes and transporting kinetic energy from the forebody region to base region and increase the length of recirculation region.

Keywords: *Hypersonic flow, Wake flow, Flow structure*

Nomenclature

Ma – Mach number
α-Angle of attack

1. Introduction

Hypersonic wake flow is an important research area in hypersonic aerodynamics. Some interest comes from the accurate prediction of base pressure because of its effect on vehicle drag. Other interest come from the far wake properties which is connected to the target identification problem. Despite of 50 years of study, wake flow remains a challenging problem for both experimental and computational research. The reason is that on one hand, wake flow is a typical large separated flow, which is inherent unsteady. And on the other hand, it involves almost every complex phenomenon in fluid dynamics such as shock waves, expansion waves, shear layers and flow recirculations [1]. Due to its complexity, in previous studies, most researchers focused on zero angle of attack case and not much work had been reported on the effect of angle of attack. At supersonic speed regime, Dutton performed detailed experiment measurements on flow structure of wake flow of a cylinder with 10 degrees of angle of attack[2]-[3] and Gaitonde investigated the case numerically[4]. Both found the angle of attack has significant effects on the wake flow structure, especially on the shape of recirculation zone. Lin numerically studied the Reentry-F flight experiment and a wind tunnel experiment with different angle of attack, but the research payed a lot attention on the capability of CFD algorithms in predicting near wake flows but less on the flow structures [5]. In this paper, we performed a series of numerical simulations of a sharp cone at hypersonic speed with different angle of attack to investigate how wave

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and vortex structure evolve with angle of attack. The paper is organized as follows. The numerical method is firstly verified at a trajectory point of Reentry-F flight experiment. Then a sharp cone with the same half angle of attack as the Reentry-F experiment vehicle is used for simulation with the same inflow condition except the angle of attack. The flowfields with 0°, 1°, 2°, 5°, 10° and 15° angle of attack are obtained, and the wave and vortex structure are analyzed.

2. Numerical method and Verification

The code we used is a house made parallel structured Navier-Stokes code aiming at the simulation of large separated flows of complex geometry. The solver includes a hybrid high order flux solver, which is a combination of the 5th order WENO solver and 2^{nd} order Steger-Warming solver. The switching between of two solvers is achieved by a shock/discontinuity detector, which smoothly switches the scheme to Steger-Warming scheme at strong discontinuity and switches back to WENO scheme at relatively smooth region [6]. The 7th order version of the scheme has been used in our previous MILES study of base flow [7]. As for viscous flux, the second order central scheme is adopted.
For the verification of present computation code, a trajectory point from the Reentry-F flight test is chosen for CFD and experiment comparison [8]. The Reentry-F vehicle is a sharp cone with a half cone angle of 5 degree and length of 3.96m, as shown in Fig 1. Because we focus on the flow structure of laminar wake flow, a trajectory point t=450.05s which is much early than the transition trajectory point is chosen. Four heat flux sensors denoted with solid square and two pressure sensors denoted with hollow square are placed on the base surface for the measurement of base surface pressure and heat flux. The freestream flow condition of the trajectory point is shown in Table 1.

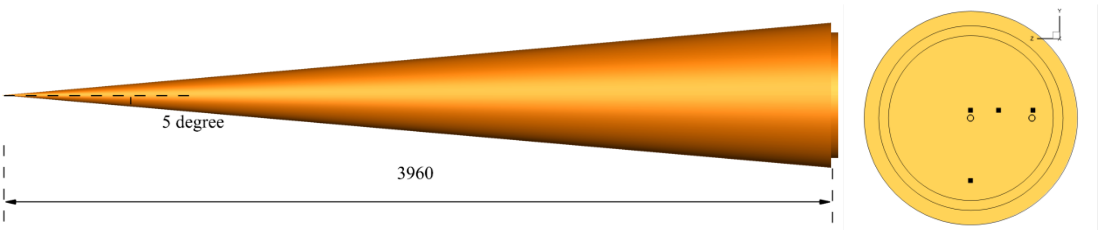
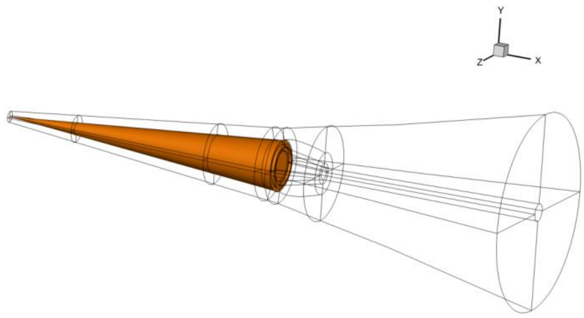


Fig 1. Reentry F flight experiment vehicle

Table 1 Freestream Condition

Trajectory Time(s)	Height(km)	Ma	Angle of attack(°)	Angle of yaw(°)	Effective angle of attack(°)
450.05	37.5	19.13	-0.264	0.305	0.4

Because the flow structure in the wake region is rather complicated, the mesh topology is carefully designed to ensure the good mesh orthogonality and appropriate mesh density. The final mesh used for computation contains 20 million cells. Its topology and the close view of surface mesh are shown in Fig 2.



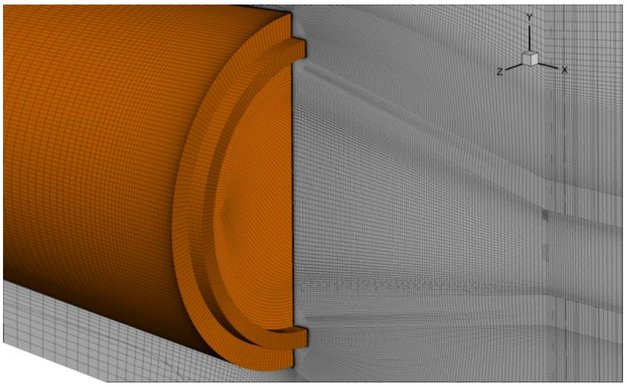


Fig 2. Mesh topology and close view of surface mesh

The heatflux distribution on the forebody centreline is shown in Fig 3. The flight experiment result is denoted with hollow circle and the computation result is denoted with solid line. Good agreement is observed between experiment and numerical simulation.

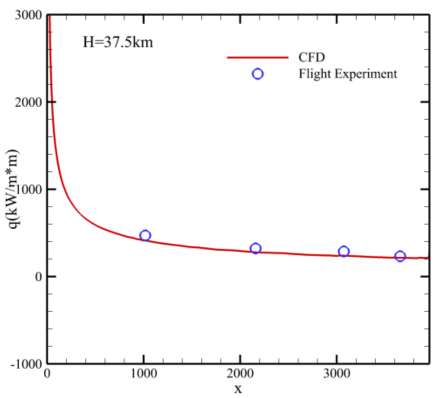


Fig 3. Heatflux on the forebody centreline

Fig 4 is the comparison of base pressure and heatflux at the base surface between flight experiment and computation result. The comparison also proves the reliability of present computation method.

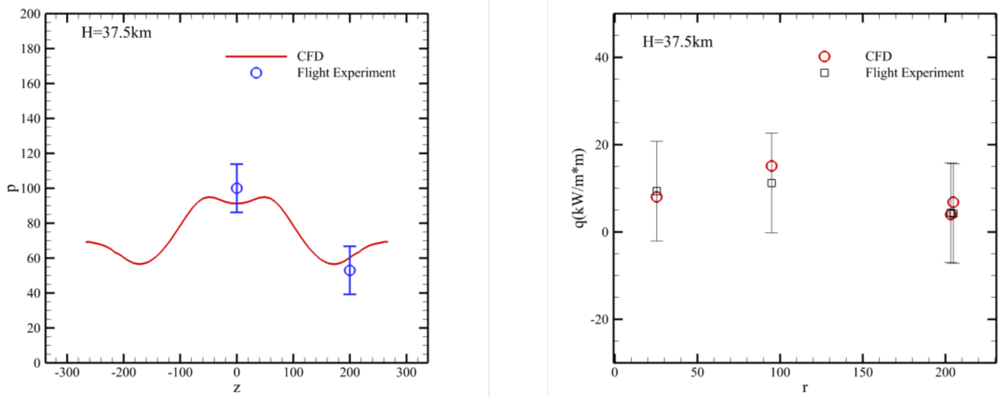


Fig 4. Heatflux and pressure on the base surface

3. Angle of attack effect on wake flow structure

The geometry model for the study of angle of attack effects on wake flow structure is modified from the Reentry-F vehicle. The support ring is removed to further simplify the geometry model and improve the grid orthogonality. The freestream condition is the same as previous verification case and the angle of attack is chosen as 0°, 1°, 2°, 5°, 10° and 15°.

The wake flow is characterized by large separated unsteady flow and involves several phenomenas in fluid dynamics such as shock waves, expansion waves and flow recirculations. To more clearly illustrate the wave structures in the base flow region, we use a nondimensional variable W, as defined in Eq. 1.

$$\mathrm{W} = (\nabla p \cdot \mathbf{u})/(p(|\mathbf{u}| + \varepsilon)/L) \tag{1}$$

The thought is very simple. In compression waves, pressure increases in the flow direction which results in a positive $\nabla p \cdot \mathbf{u}$, while it decreases in expansion waves and result in a negative $\nabla p \cdot \mathbf{u}$. Thus, the sign of $\nabla p \cdot \mathbf{u}$ can be used to distinguish compression waves from expansion waves. Also, because the rapid change of velocity shapeand pressure is a sign of shock wave, W can also be used to distinguish shock waves from expansion waves.
We first used this variable to investigate the flow structure of the case with zero angle of attack. Fig 5 illustrated the streamline and the contour of W variable on the z=0 plane. The freestream flow is compressed by the forebody and two strong oblique shock waves are generated, which are symmetry about y=0 plane. After the flow turning around the base shoulder, it bends to surface center which is of low pressure and generates an expansion wave denoted with blue area in the contour. To prevent vacuum region from presenting, part of flow turns back to refill base region, which forms a recirculation region. When the tuning back flow comes nears to the base surface, the flow velocity decreases, pressure increases and generates a compression wave at the vicinity of the base surface centre. After that, the recirculation flow turns outwards radially and then is compressed by the flow turning around the corner, which forms a small lip shockwave. For flow outside the recirculation region, it needs to turning back to the free stream direction and generates a wake neck shockwave.

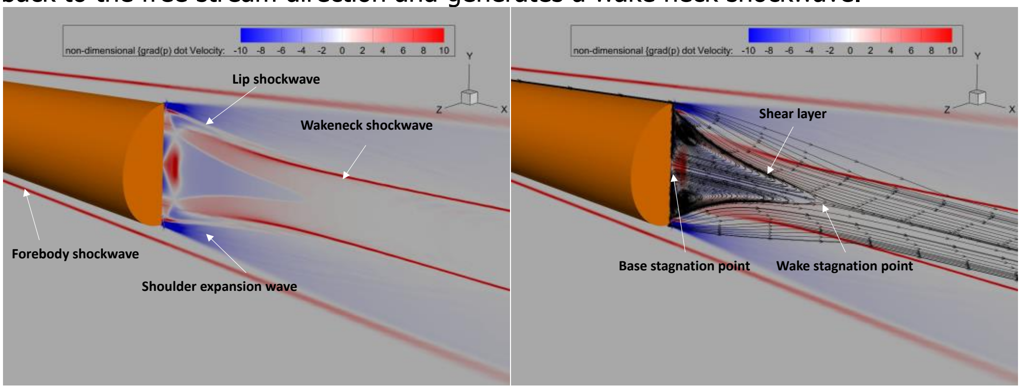


Fig 5. Wave structure and streamlines on z=0 plane with zero angle of attack

Recirculation region shape and its length are important features for base flows. In two-dimensional base flows, we use the streamlines to illustrate the recirculation region shape and to identify its length. But for three-dimensional flows, the streamlines pattern is too complicated for the identification of recirculation region shape. In the present study we propose to use the zero iso-surface of streamwise velocity $\mathrm{U}_{\|\infty}$ to identify the recirculation region and wake stagnation point. $\mathrm{U}_{\|\infty}$ is defined in Eq. 2.

$$\mathrm{U}_{\|\infty} = ucos(\alpha) + vsin(\alpha) \tag{2}$$

This idea comes from the thought that in the process the flow leaving the recirculation zone, its streamwise velocity must be positive. And zero iso-surface of this variable is a division surface which flow particles will leave the recirculation zone and which flow particles will return to the recirculation zone. Fig 6 exhibited the zero iso-surface of streamwise velocity at zero angle of attack. The recirculation zone is of axisymmetric shape and is consistent with that indicates by the streamlines in Fig 5.

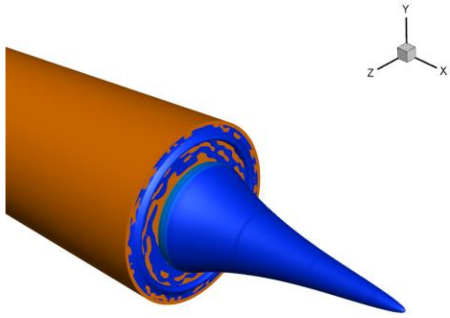
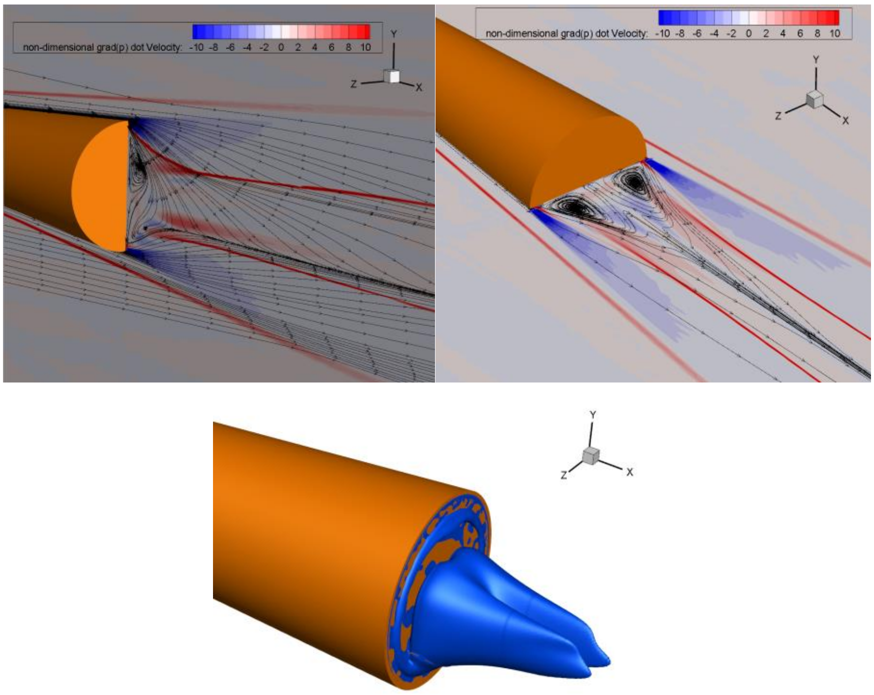
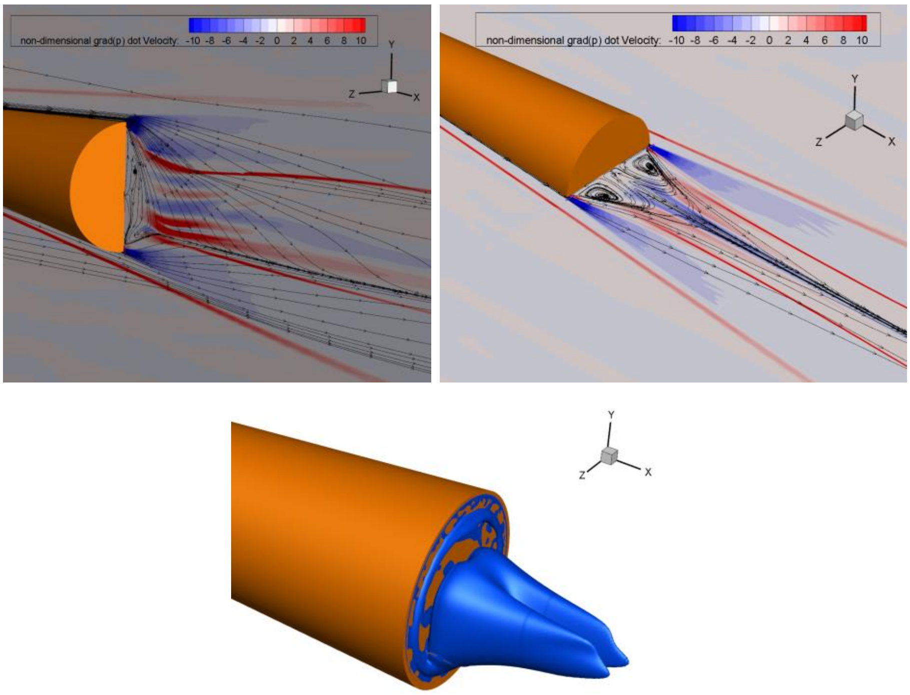


Fig 6. Zero Iso-surface of streamwise velocity with α=0°

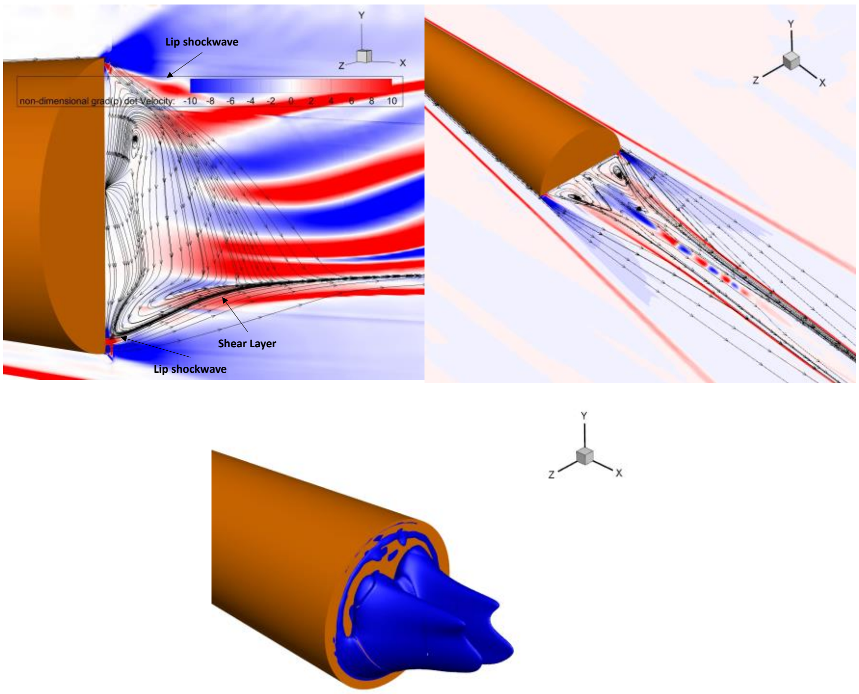
Fig 7 exhibits the wave structure, streamlines on y=0/z=0 planes and zero iso-surface of streamwise velocity with α=1°, α=2° and α=5°. The most significant difference between zero and non-zero case is the size and shape of recirculation region. For α=0° case, the recirculation zone is axisymmetric and the cross section of recirculation region is of triangular shape. But for non-zero angle of attack case, the recirculation zone shape is of complex three-dimensional shape and there is a local minimum of recirculation region length at the z=0 plane, while two maximums exist symmetrically about the z=0 plane. As a result, the streamlines on z=0 plane and y=0 are also quite different, which is also indication of nontrivial recirculation region shape. With the increase of angle of attack, the recirculation zone shows a stretch in the freestream direction. The position of wake-neck shock waves shows different trend for z=0 and y=0 plane. The distance between two wake-neck shock waves on y=0 plane decreases with the increasing of angle of attack and the wake-neck shock waves on z=0 inclines to align with the inflow condition. It is also noted that with the increase of angle of attack, several blue/red bands emerge on the z=0 plane, which indicates the existence of multiple compression and expansion waves.



α=1°



α=2°



α=5°

Fig 7. Wave structure, streamlines on y=0/z=0 planes and zero iso-surface of streamwise velocity with α=1°, α=2° and α=5°

To understand the mechanism of the observed wave structure. The three-dimensional streamline in the base region for case α=5° is shown in Fig 8. Two typical streamlines are displayed individually in (a) and (b). The streamlines shape in recirculation region are shown in (c) and (d). Streamlines far from recirculation region are shown in (e). The streamlines illustrate the vortex structure in base region. Two vortexes surfaces with curved axis originated in circumferential direction lies in the near base region and the windward one is larger than the leeward one. Then lateral flow rolls inward to the x-axis and several vortexes with axis originated in x-axis are observed in the region far from recirculation zone.

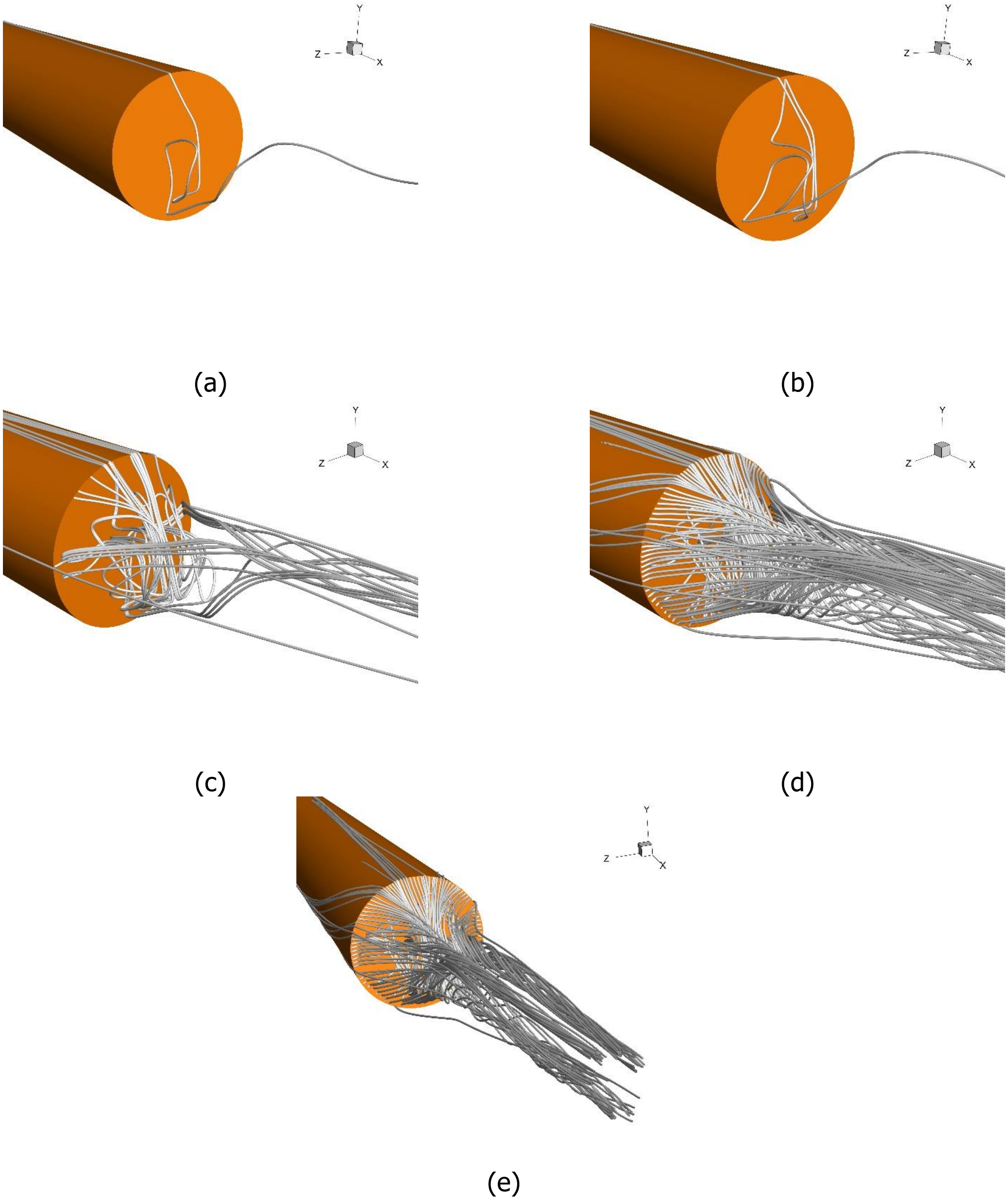


Fig 8. Three dimensional streamlines in the base region

To visualize the vortex structure of the base region, the iso-surface of second invariant of velocity gradient (Q2) is shown in Fig 9. As the half angle of the cone is also 5°, the leeward centerline is parallel with the inflow direction and small vortexes are generated in the forebody leeward region. Two vortex surfaces with curved axis originated in circumferential direction in the near base region are also observed. These vortex surfaces are then elongated in the x-axis to form vortex surfaces outside the recirculation region. These vortex surfaces interact with each other and create the compress/expansion waves observed on the z=0 plane. Viewing in the direction of z-axis, it is also noted that the vortex surfaces are stretched to align with the freestream direction.

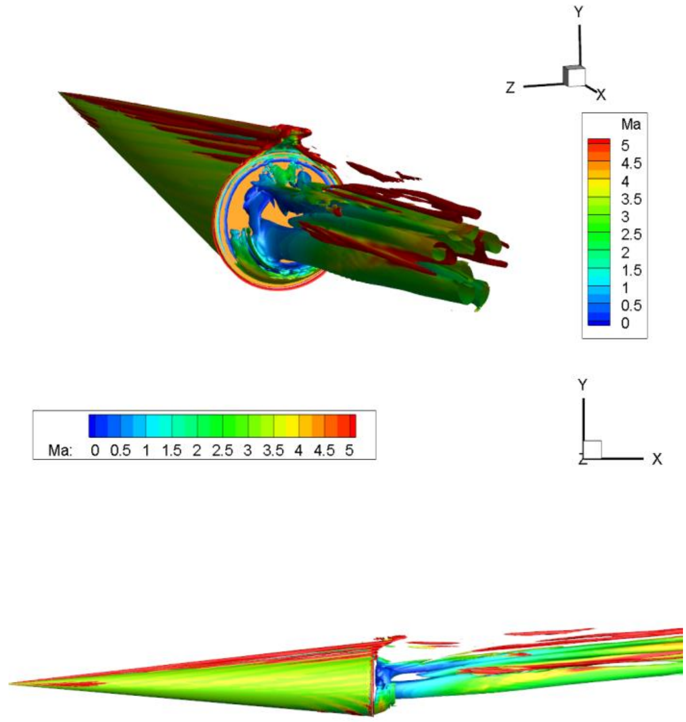
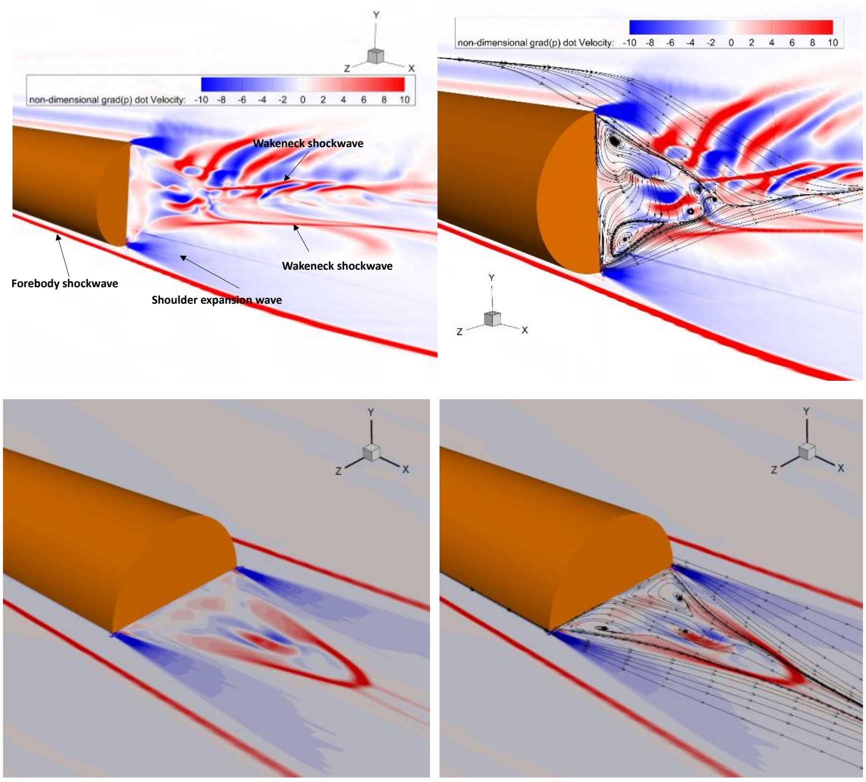
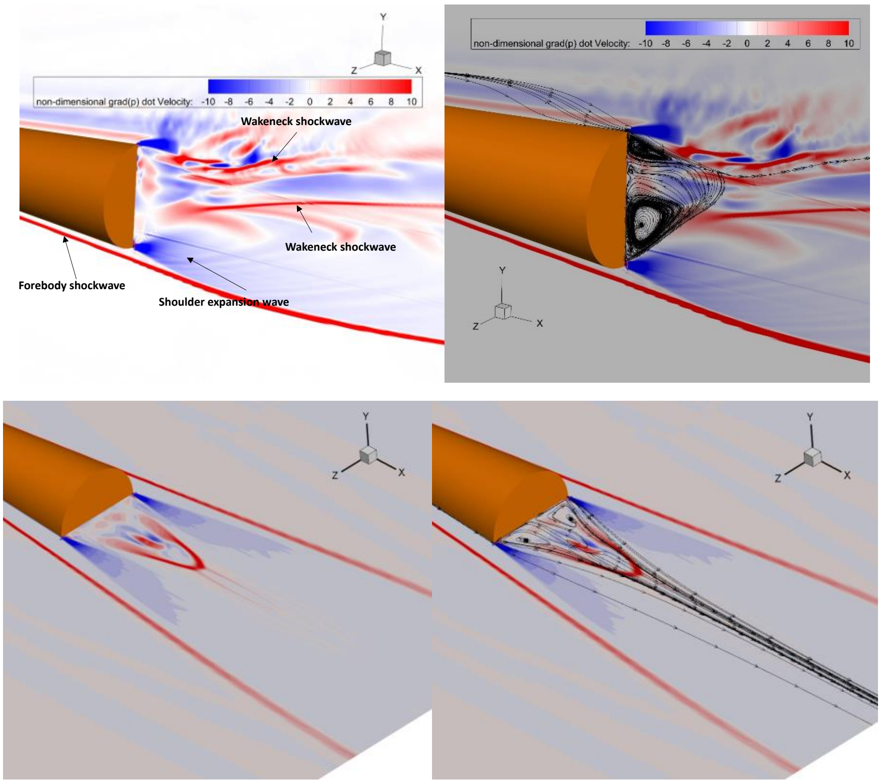


Fig 9. Iso-surface of Q2 in base region with α=5°

Fig 10 illustrates the wave structures and streamlines on z=0/y=0 plane at the angle of attack α=10° and α=15°. Because the half angle of the cone is 5°, the expansion wave is also observed in the leeward side of forebody. Besides that, the most significant difference with small angle of attack cases is that the compression/expansion waves extend outwards of the wake-neck shockwave and present with large scales.



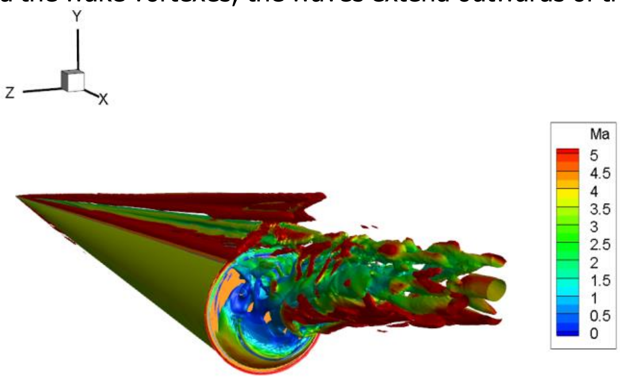
α=10°



α=15°

Fig 10. Flow structures at angle of attack of 10° and 15°

To understand the origin of these compression/expansion wavs. Fig 11 shows the Iso-surface of Q2 in base region with α=10° and α=15°. Because the angle of attack of these two cases is large than half cone angle, vortexes are generated in the leeward surface of cone's forebody. These vortexes interact with those in the wake region, which feed kinetic energy to the recirculation region and produce the large-scale compression/expansion structures in Fig 10. Because the compression/expansion is between the forebody vortexes and the wake vortexes, the waves extend outwards of the wake-neck shockwave.



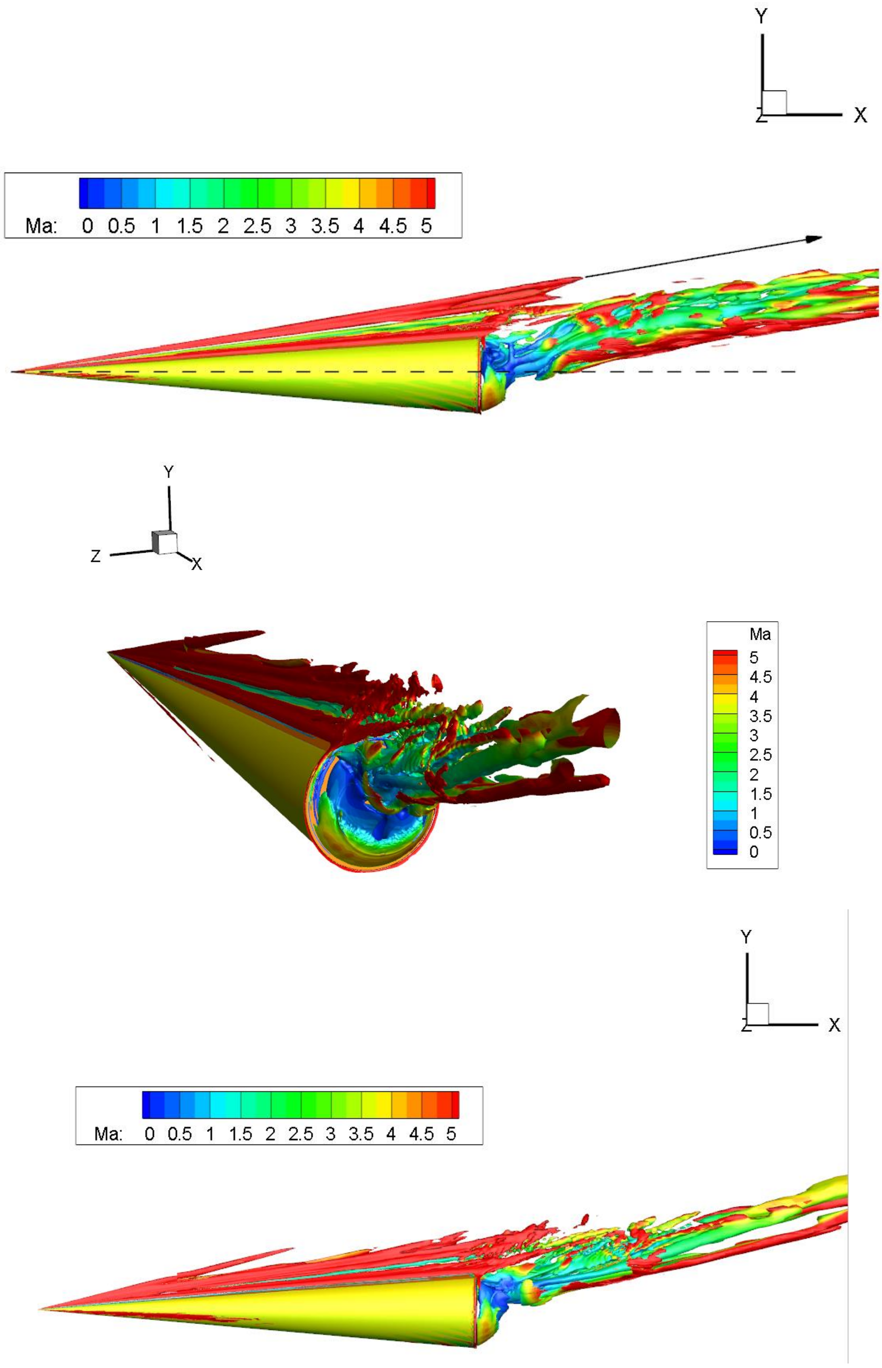


Fig 11. Iso-surface of Q2 in base region with α=10° and α=15°

Fig 12 illustrates the zero iso-surface of streamwise velocity for the comparison of recirculation zone length. For zero angle of attack case, the wake flow stagnation is at about x=1000mm. For 1° angle of attack, the recirculation zone shrinks as mentioned previously and the wake flow stagnation goes back to x=650mm. For 2° angle of attack, the wake flow stagnation goes back to x=550mm. For 5° angle of attack, the recirculation zone stretches, and the wake flow stagnation goes to x=600mm. For 10° and 15° angle of attack, the recirculation zone further stretches, and wake flow stagnation goes further to x=800mm. The stretch is considered to be caused by the interaction between forebody vortexes and wake vortexes, which feeding kinetic energy to base region from the forebody flows. The recirculation zone size shows a non-linear change with the increase of angle of attack.

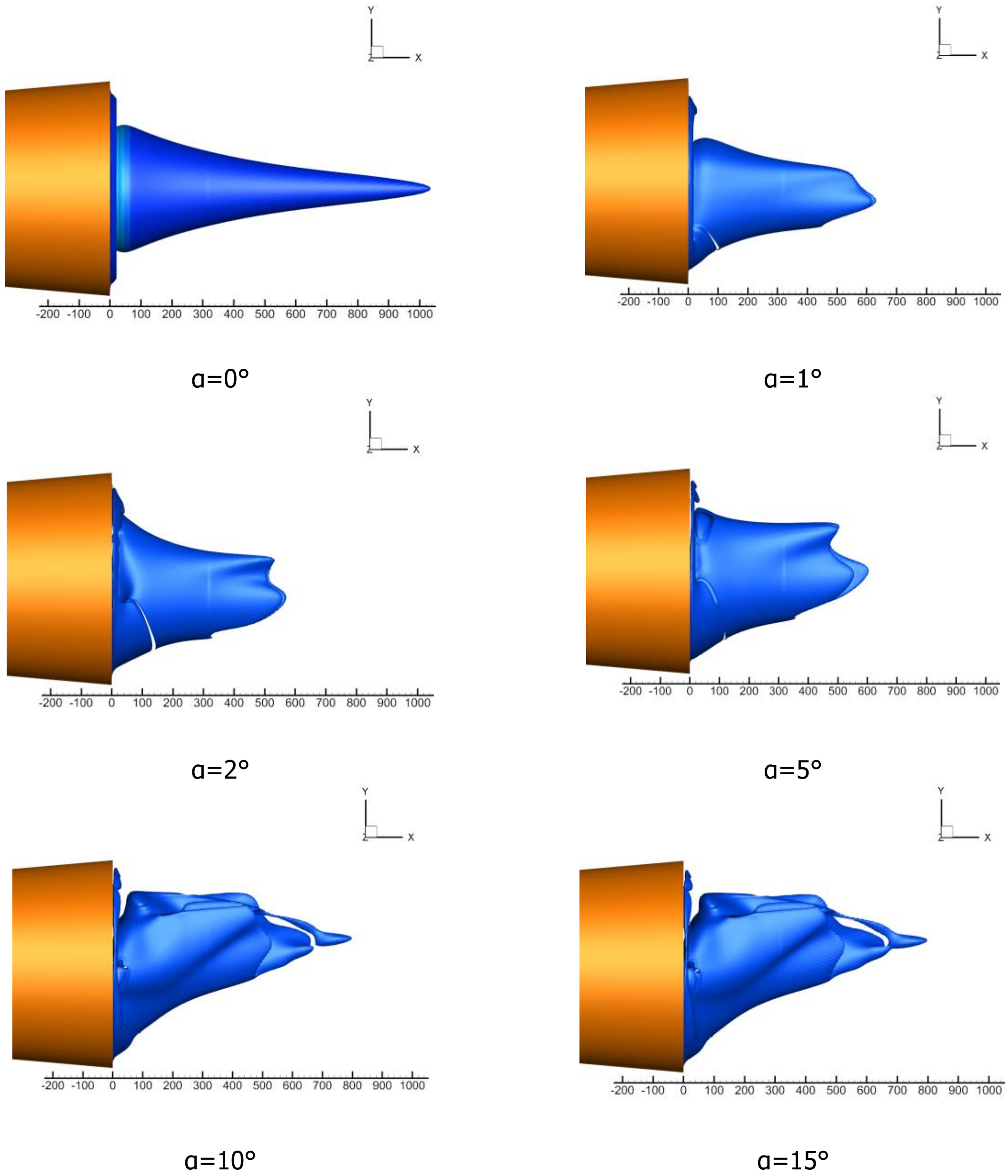


Fig 12. Zero iso-surface of streamwise velocity at each angle of attack

4. Conclusions

The influence of angle of attack on wave structure and vortex structure of hypersonic base flow is studied with numerical method. Several conclusions can be made:

(1) By comparing with the measurement result of the Reentry-F flight experiment, the reliability of present numerical method and code is verified.

(2) The recirculation zone shape of zero angle of attack case shows a non-regular geometry, which is of very small cross section on the z=0 plane, in contrast to the axisymmetric shape of non-zero angle of attack case.

(3) The vortexes structure shows a transform of two sets of vortexes surface originated in two directions. In the near base region, two vortexes surface originated in circumferential direction are formed. The windward one is smaller than leeward one because of compression from windward flow. Then the vortex surface tuning towards to the z=0 plane and transforms to vortexes surface originated in the freestream direction. These vortexes interact with each other and creates compression and expansion waves in the wake region outside the recirculation zone.

(4) When the angle of attack exceeds the half angle of the cone, the vortexes generated by the forebody interact with wake vortexes and transporting kinetic energy from the forebody flows to base region. This phenomenon causes the recirculation zone size shows a non-linear change with the increase of angle of attack.

Acknowledgments

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