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# Numerical Study of Hypersonic Wake Flow over Apollo Command Module

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## Abstract

The structural instabilities of base flow in hypersonic wake flow over Apollo reentry capsule are investigated by numerical simulation in this paper. Wakes flow of Apollo reentry capsule at $M\infty = 5$ with AoA of 0 degree and 28 degree are simulated. When it is 0 degree, the evolving process of the structure of flow over Apollo reentry capsule is a periodic behavior at first, but it evolves into a non-periodic behavior after a critical time. When it is 28 degree, there is no periodic behavior anymore. The flow is axisymmetric at first, then evolves to be asymmetric.

## 1. Introduction

The study of hypersonic wake studies may have two main stages, the first one is started since 1950s, and came to a peak at 1960s because of the development and requirement of the retry vehicle. At this stage, most of studies are based on the wind tunnel experiments and ballistic-range experiments. Few works presents the results of theoretical and computational investigations. Then it gained new interest since 1990s, due to the development of a whole new class of space vehicles that exploit aerodynamic force of aero-braking.

William C. Moseley, et al. [1] investigated the Apollo reentry capsule in wind-tunnel experiments, and presented the static and dynamic stability data for a basic configuration of the reentry capsule. An extensive series of investigations was conducted on modifications designed to eliminate an undesirable trim condition of the Apollo reentry capsule. The addition of selected strakes to the reentry capsule was effective in eliminating the undesirable trim condition, but the vehicle proved to be dynamically unstable with such additions. The addition of a plate or plates to the tower structure did result in eliminating the undesirable trim condition, but the configuration was not dynamically stable. So in order to solve the unstable of the capsule, the research of wake flow over a blunt body have been done since then.

In 1991, Venkatapathy et al[2] has implemented grid adaptation to better resolve the complex flow pattern, and reasonable (qualitative) agreement with a ground-based test experiment on an aerobrake configuration (AFE) has been obtained by an adaptive clustering of mesh points in the aft-body where large gradients occur. Two different numerical schemes, an ideal-gas solver and a nonequilibrium solver were used in the present base flow simulations. The time-dependent Navier-Stokes equations are solved by the ideal-gas solver. In the nonequilibrium solver the species conservation equations due to chemical nonequilibrium and the energy conservation equation due to thermal nonequilibrium are solved in addition to the Navier-Stokes equations. Detailed descriptions of these methods can be obtained from appropriate references. The ideal-gas solver is a total variation diminishing (TVD) scheme based on Roe's approximate Riemann solver, and it uses a diagonalized form of ADI time marching to obtain steady solutions. Local time stepping, coupled with approximate diagonalization of the implicit operators, makes the scheme efficient for steady-state solutions only. The ideal-gas solver is spatially second-order accurate with first-order accuracy in the vicinity of shocks, and it solves either the thin-layer or the full Navier-Stokes equations. It is also reports the occurrence of some instability at the wake neck. By assuming a constant Strouhal number of 0.3 and using the wake neck thickness as the characteristic length scale, it is shown that wake instability frequencies can be well predicted, yielding results consistent with experimental data.

In 2007, Sinha[3] computed the flow field around a hypersonic re-entry configuration using the detached eddy simulation (DES) methodology at two different Reynolds numbers. The lower Reynolds number condition corresponds to the 35 km altitude trajectory point of the Fire II re-entry vehicle. The Reynolds number based on

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vehicle diameter is 1.76 $\times 10^6$ and the near wake is predicted to be transitional both by experimental correlations and detached eddy simulation. The computations highlight the limitations of DES in low Re flows. A second computation is performed at a free-stream density that is higher than the earlier value by a factor of 10. The time-averaged flow solutions are compared between the two cases to study the effect of Reynolds number on the DES methodology and predictions. The analysis brings out interesting parallels between the two flow fields. The differences between DES and RANS predictions at the two Reynolds number are also discussed.

In 2011, Brock and Subbareddy[4] presented results from the experiments which were performed by Calspan University of Buffalo Research Center (CUBRC) as well as the previous simulations and compared them to CFD results obtained by US3D using low-dissipation numerics and more refined grids. The flows that were simulated range over three different Reynolds numbers representing low, medium and high Reynolds number wake flows. The results range from laminar, to purely RANS to hybrid RANS-LES. The one equation Spalart-Allmaras turbulence model was used to simulate this flow using both RANS and DES.

## 2. Governing Equations and Numerical Methods

### 2.1 Governing Equations

The governing equation of flow is three-dimensional unsteady compressible Navier-Stokes equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial f}{\partial x}+\frac{\partial g}{\partial y}+\frac{\partial h}{\partial z}=0 \tag{1}$$

Where $Q$ is the solution vector, the column vector $f$ , $g$ , $h$ is the flux vectors of three-dimensional. They are given by

$$Q=\begin{bmatrix}\rho & \rho \mathrm{u} & \rho v & \rho w & e\end{bmatrix}^T \tag{2}$$

$$f=\begin{bmatrix}\rho u \\ \rho u^2+p-\tau_{xx} \\ \rho uv-\tau_{xy} \\ \rho uw-\tau_{xz} \\ (\rho e+p)u-u\tau_{xx}-v\tau_{xy}-w\tau_{xz}+q_x\end{bmatrix} \tag{3}$$

$$g=\begin{bmatrix}\rho v \\ \rho uv-\tau_{xy} \\ \rho v^2+p-\tau_{yy} \\ \rho uw-\tau_{yz} \\ (\rho e+p)v-u\tau_{xy}-v\tau_{yy}-w\tau_{yz}+q_y\end{bmatrix} \tag{4}$$

$$h=\begin{bmatrix}\rho w \\ \rho uw-\tau_{xz} \\ \rho vw-\tau_{yz} \\ \rho w^2+p-\tau_{zz} \\ (\rho e+p)w-u\tau_{xz}-v\tau_{yz}-w\tau_{zz}+q_z\end{bmatrix} \tag{5}$$

Where $e, u, v, w, \rho, p$ are total energy, velocity of x, y, z, density and pressure, respectively. $\tau_{ij}$ is stress tensor and $q_i$ is heat flux. The formulations for these variables show below:

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$$\begin{cases} \tau_{xx} = \dfrac{2}{3}\mu\left(2\dfrac{\partial u}{\partial x} - \dfrac{\partial v}{\partial y} - \dfrac{\partial w}{\partial z}\right) \\ \tau_{yy} = \dfrac{2}{3}\mu\left(2\dfrac{\partial v}{\partial y} - \dfrac{\partial u}{\partial x} - \dfrac{\partial w}{\partial z}\right) \\ \tau_{zz} = \dfrac{2}{3}\mu\left(2\dfrac{\partial w}{\partial z} - \dfrac{\partial u}{\partial x} - \dfrac{\partial v}{\partial y}\right) \\ \tau_{xy} = \mu\left(\dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x}\right) = \tau_{yx} \\ \tau_{xz} = \mu\left(\dfrac{\partial w}{\partial x} + \dfrac{\partial u}{\partial z}\right) = \tau_{zx} \\ \tau_{yz} = \mu\left(\dfrac{\partial v}{\partial z} + \dfrac{\partial w}{\partial y}\right) = \tau_{zy} \end{cases} \tag{6}$$

$$\begin{cases} q_x = \dfrac{\mu}{(\gamma-1)M_\infty^2 \Pr}\dfrac{\partial T}{\partial x} \\ q_y = \dfrac{\mu}{(\gamma-1)M_\infty^2 \Pr}\dfrac{\partial T}{\partial y} \\ q_z = \dfrac{\mu}{(\gamma-1)M_\infty^2 \Pr}\dfrac{\partial T}{\partial z} \end{cases} \tag{7}$$

$$p = (\gamma-1)[\rho e - \frac{\rho}{2}(u^2 + v^2 + w^2)] \tag{8}$$

### 2.2 Finite Difference Scheme

The NND finite difference scheme which is TVD scheme is used for spatial direction, the third-order accuracy Runge-Kutta method is used in temporal direction. In order to resolve the instability of the wake flow over the Apollo reentry capsule, it needs enough numbers of grid to get a correct result of the wake flow especially in second separation zone.

So for the case of Apollo reentry capsule numerical simulation, the numbers of grid points are $61\times73\times81$, and the sketch of the computational grids shows below:

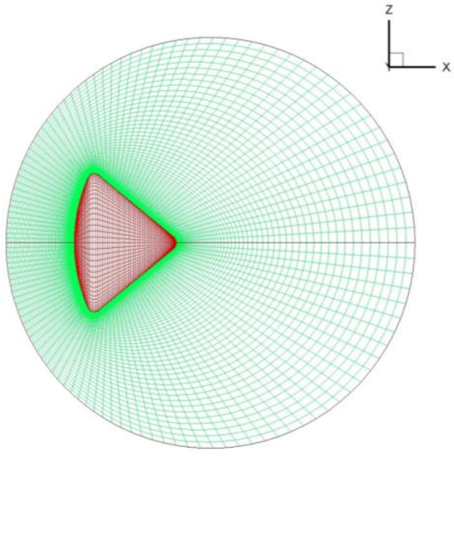

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Figure 1 Sketch of computational grids for Apollo reentry capsule

## 3. Results and Discussion

### 3.1 Wake flow over Apollo reentry capsule at $M_{\infty} = 5$ with AoA=0°

In the first case, the freestream Mach number is 5 and the Reynolds number is 1×106 based on the head's radius of the Apollo reentry capsule. The time step is 0.0005 while the Courant Number is 0.79.
When the AoA is 0 degree, the numerical results indicate that there are two stages in the evolving process of the wake flow.
Here gives the steady result of the wake flow first, the numerical schlieren result, the instantaneous streamlines of the symmetrical plane and the base limit streamlines shows below. In figure 4, the separation point at the shoulder forms a separation shock wave, the separation shock wave extend downtream and meet at the point which is called the back stagnation point. Between the separation point and the back stagnation point, the near wake flow form a main separation zone and a secondary separation zone. It can obviously to see that the wake flow is almost axisymmetric in space at this moment.

Figure 2 Numerical schlieren of the wake flow over the Apollo reentry capsule

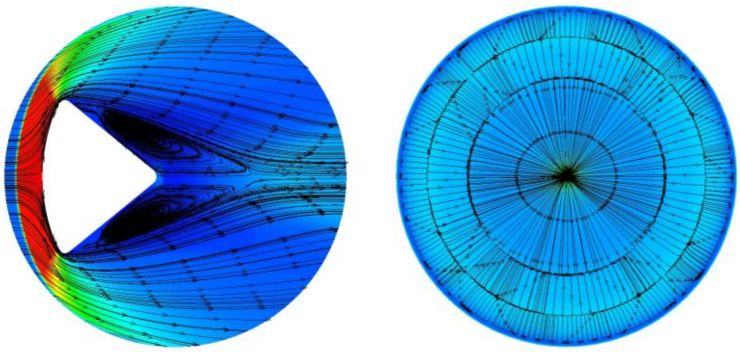

Figure 3 Instantaneous streamlines in the symmetric plane and base limit streamline near the wall

The flow evolves into the first stage as the wake flow is still axisymmetric. The evolving process is shown in Figure 4. In the second stage, the secondary separation zone starts to expand and contract periodicity, which makes the periodic changes of the second separation line. Firstly in Figure 4(a) and (b), there is a saddle point on the axis after the primary separation zone and semi-saddle points of sepaparation-type on the leeward surface, the system structure is unstable. In the further step, the saddle point structure has been evolved into a node structure as shown in Figure 4(c). This phenomenon is more remarkable from Figure 4(d) to Figure 4(g), where the unstable crunodes structure evolves into SNS structure (Saddle-Node-Saddle point structure).
Furthermore, the SNS structure can also turn back as saddle point structure as shown in Figure 4(h) and Figure 4(i) with the flow comes back into the topology shown in the Figure 4(a). So there is a period of the above evolving process and its period is about 40.

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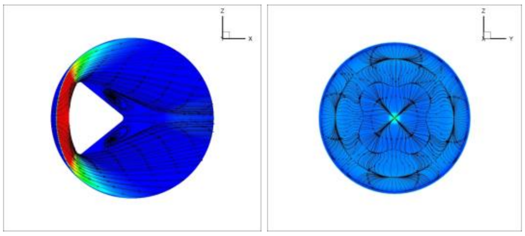
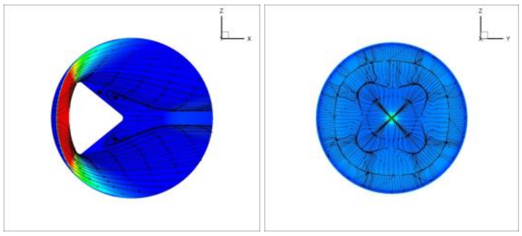
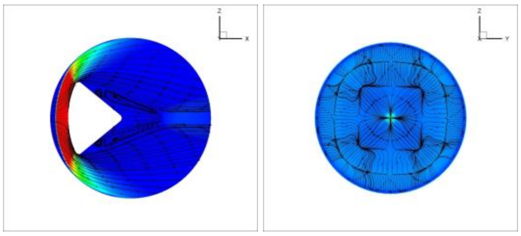


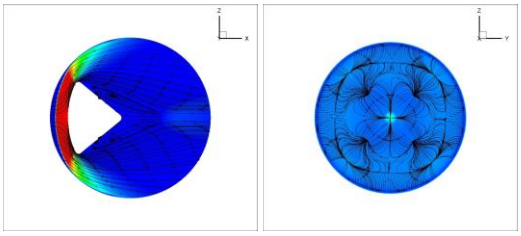
a) t=105



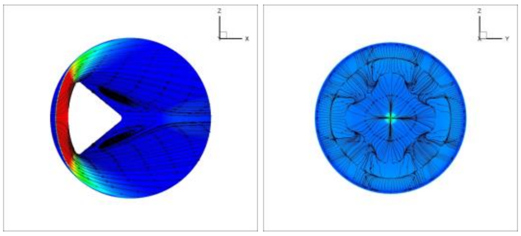
b) t=110



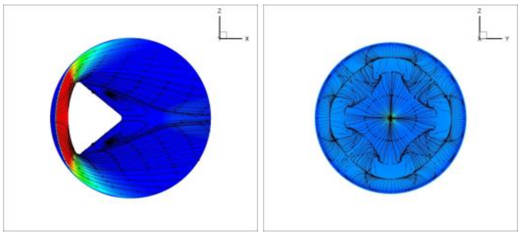
c) t=115



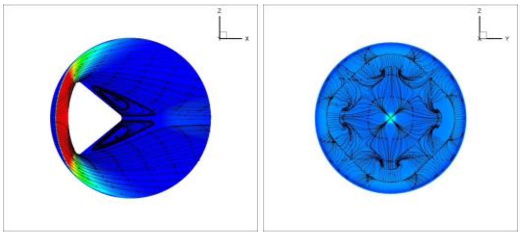
d) t=120



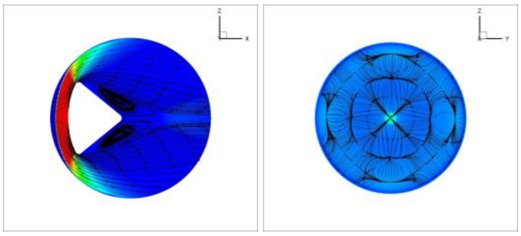
e) t=125



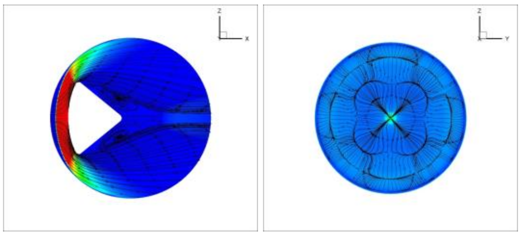
f) t=130



g) t=135



h) t=140



i) t=145

Figure 4 Evolving process of wake flow over Apollo reentry capsule for t=105 to t=145

As streamline between the stagnation point on the base wall and the secondary separation line are curves, the first stage of the evolving process will disappear soon and the flow turns into the third stage, which is shown in Figure 5. In the second stage, the wake flow is asymmetric but the periodicity disappear.

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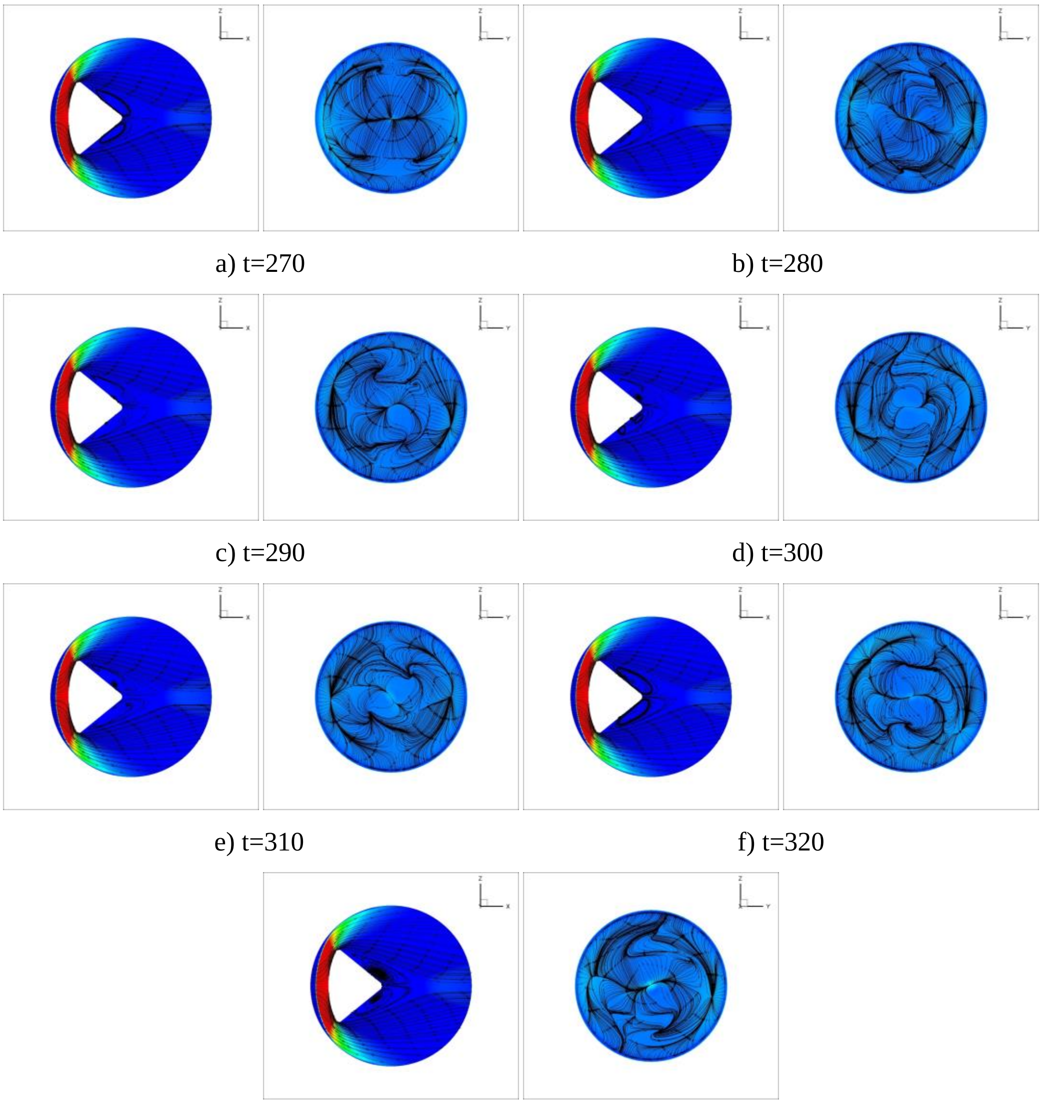

a) t=270 b) t=280

c) t=290 d) t=300

e) t=310 f) t=320

g) t=330

Figure 5 Evolving process of wake flow over Apollo reentry capsule for t=270 to t=330

### 3.2 Wake flow over Apollo reentry capsule at $M_\infty = 5$ with AoA=28°

In the second case, the freestream Mach number and the Reynolds number remain the same with the first case, but the AoA change from 0 degree to 28 degree. The steady result of the wake flow in 28 degree AoA is shown in Figure 6 and Figure 7.

In Figure 6, there are two separation points, one at the shoulder and another at the back stagnation point, which form a separation shock wave and a expand wave. A bigger separation zone and two smaller symmetric separation zones show between the two separation points. In Figure 7, the separation zone on the down leeward side flow through the symmetric plane of the Apollo reentry capsule, and the two separation vortex are rotor opposite.

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Figure 6 Numerical schlieren of the wake flow over the Apollo reentry capsule

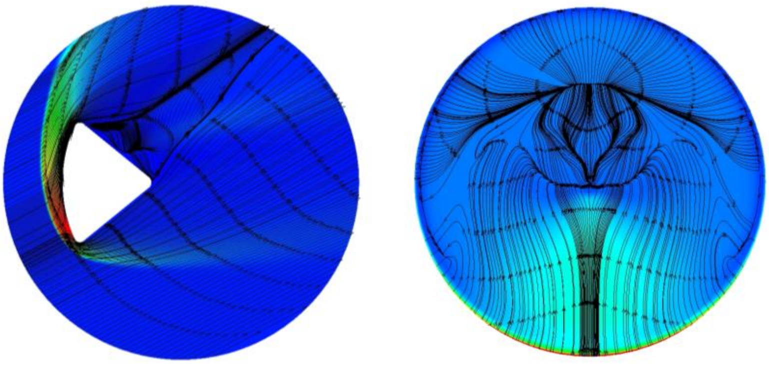
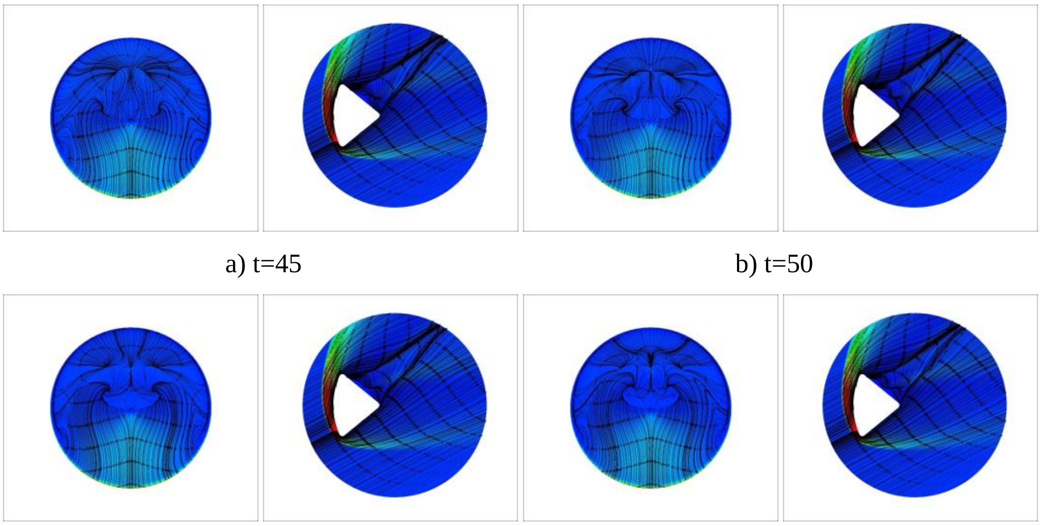


Figure 7 Instantaneous streamlines in the symmetric plane and base limit streamline near the wall

When the AoA is 28 degree, the wake flow will also evolves two stages. In the first stage, the two endpoints of the separation line move close to the symmetric plane of the Apollo reentry capsule. The two separation vortex move close to each other and then induce two small secondary separation vortex.



a) t=45 b) t=50

c) t=55 d) t=60

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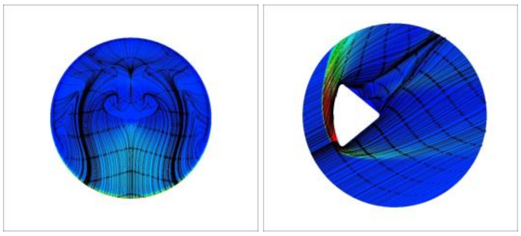
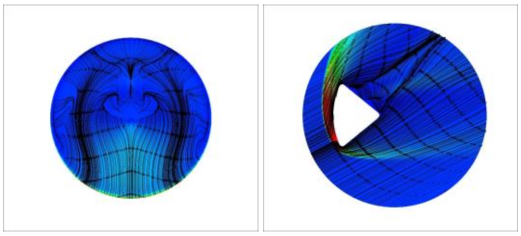


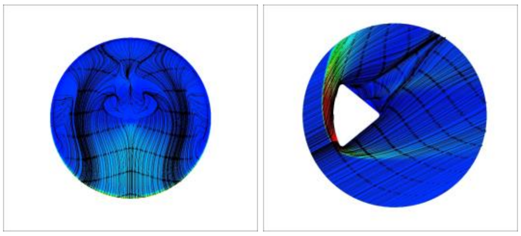
e) t=65



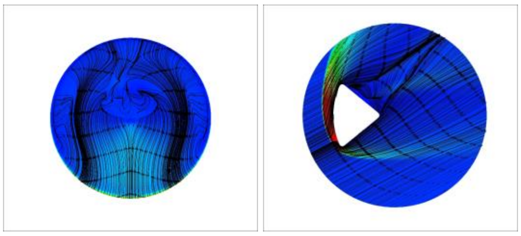
f) t=70

Figure 8 Evolving process of wake flow over Apollo reentry capsule for t=45 to t=70

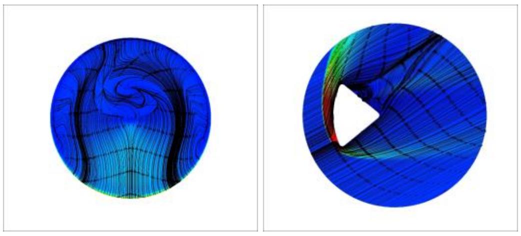
In the second stage, the wake flow start to be asymmetric, the two separation vortex on the up leeward side deviate from the centre symmetric plane, one of the separation vortex flow through the centre symmetric plane. The two secondary separation vortex induce by the two main separation vortex in the first stage merge into one secondary separation vortex. Another new secondary separation vortex generate at the top of the Apollo reentry capsule. At last, the wake flow will be a steady asymmetric flow.



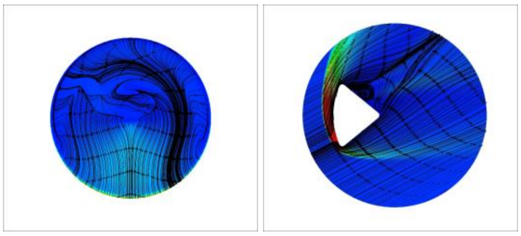
a) t=75



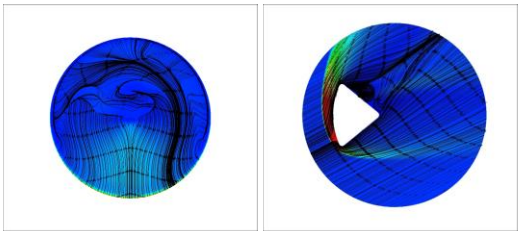
b) t=80



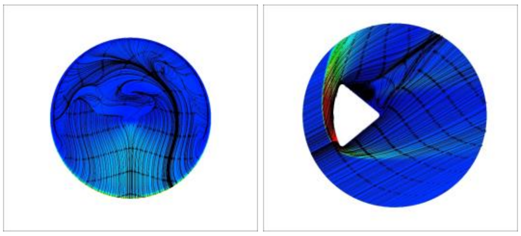
c) t=90



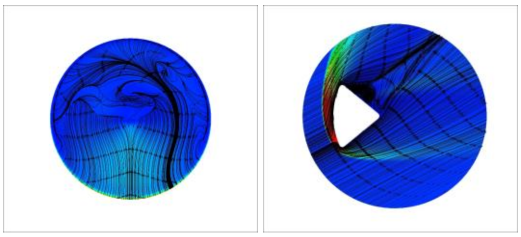
d) t=100



e) t=120



f) t=140



g) t=150

Figure 9 Evolving process of wake flow over Apollo reentry capsule for t=75 to t=150

## 4 Conclusion

The wake flow over Apollo reentry capsule with AoA of 0 degree and 28 degree are investigated by numerical simulaiton. The results indicate that:

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(1)When the angle of attack is 0 deg, the near-wake flow will experiences periodic stage and aperiodic stage because of the deformation of the secondary separation line. And the wake flow is still symmetry at last.
(2)When the angle of attack is 28 deg, the near-wake flow will experiences a stage of symmetry evolution and a stage of asymmetry evolution. The unsteady node on the leeside of the capsule base will immediately lead to the asymmetric instability of the main separation vortex. At last the near-wake flow will be asymmetry.

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