Numerical Study on a 2-D Simplified Missile Separation from High Speed Aircrafts

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Abstract. In this paper, 2D numerical simulations are carried out on the symmetric plane of a full size missile separation from high speed aircrafts at the conditions of $Ma=5$ and $AOA=0^\circ$. Aerodynamics and typical flow field characteristics of the missile at different distances away from the cavity bottom are predicted via a steady RANS solver. Results show that the flow of the missile separation from high speed aircrafts with an embedded weapon bay can be divided into four stages, which are dominated separately by the flow around the missile in the deep cavity, compressed incoming flow by the lower surface of the missile, strong interacting flow between the shear flow and the upper surface of the missile and wall effect flow of the missile. For Stage I, the flow field mode of the cavity is determined by the effective length depth ratio of the cavity, however, the effective length depth ratio is decreasing with the fall of the missile. For stage II, the incoming flow will be firstly compressed by the lower surface of the missile since it’s protruding from the embedded weapon bay. After that, i.e. on the stage III, when the axis line of the missile is beyond the surface of the aircraft, the strong shear layer induced by the incoming high speed flow and the non-high speed flow in the cavity will act on the lower incoming flow, which leads to the shock wave interaction at the missile nose. Simultaneously, the strong shear layer will significantly increase the pressure on the upper surface of the missile. For stage IV, i.e. the embedded weapon bay is closed, the reflection times of the shock waves between the missile and the aircraft decrease with the increasing distance between the missile and the aircraft. In addition, the pressure on the upper surface of the missile decreases gradually. The large negative lift of the missile formed due to the extreme wall effect is beneficial to the missile separation from high speed aircrafts in some degree.

1. Introduction
With the breakthrough and maturity of key technologies of scramjet engines and combined cycle engines (RBCC, TBCC, SABRE, PATR, and ATREX), the shape and outline of future fighters have gradually been seen the world. Arguably, high speed cruise will be a fundamental characteristic for future fighters. The high speed unmanned reconnaissance aircraft SR-72 proposed by Lockheed Martin may become the prototype of future fighters.

For high speed fighters, if the external weapon store of traditional subsonic fighters is adopted, the drag and Radar Cross Section (RCS) of the fighters [1] will greatly increase. More importantly, the
thermal environment of airborne weapons, pylons and fighters will definitely be deteriorated, which may lead to the outcome like the pylon structural failure of X-15 (It is probably caused by the type IV shock wave interaction [2]). Obviously, the application of external weapons store to high speed fighter meets great challenges, and the problems to be solved are also very complicated. As for the embedded weapon bay adopted by the current 4th generation fighters, such as F-22, F-35, T50, J20 and other supersonic fighters, further thorough research and adaptable transformations are inevitably required to meet the need of high speed aircraft aerodynamic/thermal and acoustic environments, unless the embedded weapon bay under the aircraft is not adopted.

Recently, external and embedded delivery methods for airborne weapons have been widely studied all around the world. The related researches cover the aerodynamic characteristics of airborne weapons, separation safety and its control [3-6], aerodynamic acoustic and its control [7-11], suspension and delivery mode, airborne weapon type spectrum, and so on.

In this paper, the researches of airborne weapon separation from aircrafts will be summarized mainly in the point of view of aerodynamic characteristics, and emphasis will be placed on the form of embedded delivery methods. It’s known that the flow characteristics of the embedded weapon bay, i.e. the cavity flow modes are influenced by the length depth ratio, the breadth depth ratio, the wedge angle of bulkheads, Mach number, AOA and so on. Among them, the length depth ratio and Mach number have been considered as the key factors [1, 3, and 12]. Q F Zhang et al. [13] studied the differences between external and embedded delivery methods at subsonic and supersonic speeds. It’s found that the missile separation from the embedded weapon bay is worse than the other one, and it’s recommended to increase the nose-down pitching angular velocity and make the missile pass through the shear layer of the bay with a nose-down profile, which will reduce the negative effects of the shear layer and improve the missile separation safety. S T Zhu et al. [12] studied the missile separation from aircrafts with the embedded weapon bay by six-degree of freedom simulations. It’s shown that the safety of the separation decreases with the increase of Ma in the low supersonic range, and that the missile may stay with no falling down. So they suggested to increase the ejection force and pitching moment to avoid such disadvantages. C Chang and H H Ding [14] exhibits the typical flow field classifications for the separation of embedded delivery methods. Three typical stages are 1) the missile inside the cavity, 2) the missile crossing the shear layer and 3) the missile passed the shear layer, which are classified mainly by the separation process, but not classified precisely by flow characteristics. W Wang [15] pointed out Mach number influences the cavity flow modes. With Ma increasing, the transitional flow mode and the closed flow mode will turn to be the open flow mode and the transitional open flow mode. Y Liu [16] showed the flow fields around the door of the embedded weapon bay with different opening angles, and depicted the flow fields of AIM-120C released from F-22 at different times. Generally, the existed researches focus on the flow field, the aerodynamic characteristics and the trajectories of the missile during the separation. Detailed information of the flow interacting between the cavity and the missile is rare. And the researches mentioned above are all about separation at subsonic, transonic and supersonic speed, the researches on the separation at high speed are also rare.

Based on the similarity of the characteristics of supersonic and high speed flows, it can be deduced that the separation flow field for the embedded delivery methods at high speeds is similar to that at supersonic speeds. However, there also be evident differences and it’s still needs to be studied in detail. For instance, the information of shock wave interactions and shock-boundary layer interactions, which have negligible influence on the missile thermal environment at subsonic, transonic and supersonic speeds, need further research at high speeds; the complicated thermal environment and acoustic environment induced by the complicated flow around the missile, cavity and aircraft (flow mentioned above and the shock/eddy interactions, etc.) at high speeds are different from those at supersonic speeds. There will be a long list of the research on high-speed separation. And these mentioned above are all key research contents in the future.

In this paper, 2D numerical simulations are carried out on the symmetric plane of a full size missile separation from high speed aircrafts at the conditions of Ma=5 and AOA=0. The main purpose of this
paper is to find the main flow characteristic during the missile separation from the high speed aircraft with an embedded weapon bay. Besides, it’s still noted that the missile separation is substantially simplified into a 2-D model and many factors are not considered in this paper. Still, the author believes that it’s meaningful and valuable for such a 2-D simulation. Further 3-D simulations will be carried out later.

2. Problem Description and Numerical Method

2.1. Problem Description

In this paper, the missile separation from the high speed aircraft with an embedded weapon bay is divided into two parts, delivery before and after the bay closure. In the specific designing process, the open door are folded inward the weapon bay to reduce the severity of the thermal environment and improve the feasibility of thermal protection design, which is different from that of F-22, J20, etc. In addition, the door will be closed once the missile leaves the cavity. The separation safety is mainly determined by the parameters of delivery process. Accordingly, 3D effect and the viscous effect of the aircraft are neglected from the perspective of simplification, 2D numerical simulations will be carried out. According to the state of the door, the specific numerical models can be divided into the open (O) model and the closed (C) model, which are shown in Fig. 1 (a) and (b), respectively.

The length of the cavity is $L_c=5.0m$, the depth $D=1.0m$. The length of the missile is $L_d=4.0m$, the maximum diameter $\Phi=0.4m$, and the nose radius $R=0.01m$. AOA = 0° in all simulations, no varying AOs and attitude angles are considered in this paper. The distance between the missile and the bottom of the bay and that between the missile and the aircraft are denoted by $H_o$ and $H_c$, respectively.

2.2. Computational Domain, Boundary Conditions and Grid Topology

An H-O type computational domain around the missile and an H type computational domain with multi-block structured grids are generated by the ANSYS ICEM. The grids are refined above the missile, in the missile wake, in the cavity and in the shear flow region. The non-dimensional normal distance of the first grid layer is about $y^+\sim1$. There are about 150,000 grids for the case of the open model, and 100,000 grids for the case of the closed model. The dimensions of the computational domains for the two cases are basically the same (Fig. 2 (a)), the grid topology are shown in Fig. 2 (b).

The boundary conditions are as follows: The left, right and bottom side of the domain use the pressure far-field boundary conditions. The upper side and the cavity wall adopt slipping adiabatic wall boundary conditions. (According to the principle of relative motion, the surface velocity of the aircraft should be zero. If non-slipping wall boundary condition is adopted, a very thick boundary layer will arise above the wall before the cavity, which is inconsistent with the real condition. Further
study will investigate on the impact of the aircraft fore-body boundary layer on the missile separation.)
The surface of the missile uses the non-slip adiabatic wall.

![Figure 2. Computational domain and grid topology around the missile.](image)

2.3. Numerical Method

ANSYS FLUENT 16.0 is used to carry out the numerical simulations with a density based solver. The steady RANS equations grounded on $\kappa$-$\varepsilon$ turbulence model are solved under the assumption of ideal gas. The convection terms are discretized by Roe-FDS scheme, the viscosity coefficient is calculated via Sutherland Law, and the standard wall function is adopted. Specific computational conditions are as follows: Scale Ratio (SR) =1:1, $Ma=5$, $AOA=0^\circ$, $H_0=0.25\Phi$, $0.75\Phi$, $1.5\Phi$, $2.0\Phi$, $2.25\Phi$, $2.5\Phi$, $2.75\Phi$, $H_c=0.25\Phi$ (door closes), $0.5\Phi$, $1.0\Phi$, $P_\infty =5529.31\text{Pa}$, $T_\infty =216.65$. The dimensionless reference length is $4m$.

3. Results and Discussion

3.1. Aerodynamic Characteristics of the Missile

Fig. 3 shows the lift and drag coefficients of the lower surface, upper surface and the whole missile at different $H_0$ and $H_c$. (The lower surface and the upper surface are divided by the axis of the missile).

As shown in Fig. 3 (a), the total lift of the missile increases monotonously when $H_0 \leq 2.0\Phi$. When $H_0 \leq 1.0\Phi$, the positive lift of the lower surface decreases monotonously, while the negative lift (the absolute value in this paper if not mentioned specially) of the upper surface also decreases monotonously; As a result, the little negative total lift gets close to zero gradually. When $1.0\Phi \leq H_0 \leq 2.0\Phi$, the positive lift of the lower surface increases significantly, while the positive lift of the upper surface is near zero and increases slightly; As a result, the missile sees a monotonously increasing positive lift. When $2.0\Phi \leq H_0 \leq 2.75\Phi$, the positive lift of the lower surface increases slightly at first and then increases rapidly, while the negative lift of the upper surface increases monotonously and significantly at first and then decreases rapidly; The total lift shows a similar trend with the upper surface. It can be predicted that if the weapon bay is not closed, the lift of the upper and lower surface will soon offset each other, and the total lift will be zero. When $H_0=2.75\Phi$ (i.e. $H_c=0.25\Phi$), the weapon bay is ordered to be closed in this paper, the negative lift of the upper surface and that of the whole missile will reach a maximum value, while the positive lift of the lower surface will decrease abruptly. With the falling of the missile, the lift of the lower surface stays almost the same, while the negative lift of the upper surface and the whole missile show a greatly monotonic decrease. It’s evident that the lift increment of the whole missile is almost from the upper surface.

As shown in Fig. 3 (b), the total drag coefficient increases monotonously when $H_0 \leq 2.0\Phi$. When $H_0 \leq 1.0\Phi$, the thrust of the lower surface, the upper surface and the whole missile all decrease gradually to zero. When $1.0\Phi \leq H_0 \leq 2.0\Phi$, the drag of the lower surface increase gradually, while that of the upper surface stays almost the same. Thus, the total drag increases gradually. When
2.0Φ≤H_o≤2.75Φ, the drag of the lower and upper surface both increase at first and then decrease, and the total drag reaches the minimum at H_o=2.75Φ. Similarly, it can be predicted that the drag of the lower and upper surface will continue to increase if the weapon bay is not closed. At H_c=0.25Φ with the bay closed, the drag of the lower and upper surface both increase abruptly and the total drag reaches its maximum. With the falling of the missile, the drag of the lower surface slightly increases, while the drag of the upper surface decreases significantly; finally, the total drag decreases rapidly and achieves stability.

![Diagram](image)

(a) Lift coefficients (Down denotes to the lower surface of missile, up the upper surface of the missile)

(b) Drag coefficients

**Figure 3.** Lift and drag coefficients of the lower surface, upper surface and the whole missile.

According to the aerodynamic characteristics of the missile and the flow fields discussed in the following sections, the flow of the missile separation from high speed aircrafts with an embedded weapon bay can be divided into four stages, which are dominated separately by the flow around the missile in the deep cavity, compressed incoming flow by the lower surface of the missile, strong
interacting flow between the shear flow and the upper surface of the missile and wall effect flow of the missile, as shown in Fig. 3 (a).

3.2. Flow around the Missile in the Deep Cavity

The length depth ratio of the cavity in this paper is $L_c/D=5$, the flow of the cavity without missile is of a typical open flow mode, as shown in Fig. 4. The incoming flow firstly goes through a wide weak expansion area in the middle and posterior area below the cavity, and then a local shock wave and weak expansion wake in the rear area below the cavity. In the cavity, there is a large separation circulation. Based on the flow structure mentioned above, the open flow mode of the cavity is beneficial to thermal protection structure design under high speed conditions.

![Figure 4. Flow field of the cavity at $H_0=0.25\Phi$.](image)

Fig. 5 and Fig. 6 show the pressure coefficient contour & streamlines and Ma contour of the flow field at $H_0=0.25$ and 0.75, respectively. Fig. 7 presents the pressure coefficient curves of the upper and lower surfaces of the missile. In Fig. 5, there is a strong expansion area at the front of the cavity, while there are shock waves and expansion waves in the middle and posterior area below the cavity. There is a typical circulation area in the cavity, and the velocity magnitude is relatively small in the circulation area. An obvious separation bubble generates below the rear of the missile due to the high pressure at the rear of the cavity and the strong shear induced by the external high speed flow. Simultaneously, a smaller separation bubble is forced to generate below the missile nose. From the back to the forward, the flow between the upper surface of the missile and the wall of the cavity is similar to the flow of the nozzles. Despite the flow around the missile nose is complicated, the thermal environment around the nose is not that severe since the Ma is relatively low in this region. In general, the pressure on the upper surface is larger than that on the lower surface, thus, the missile lift is negative. Owing to the high pressure at the rear of the cavity, the missile gains thrust. Since the missile is very close to upper wall of the cavity, the effective length depth ratio of the cavity greatly increases, and the flow is characterized as the transitional open flow mode[16], which can be seen from the monotonously increasing pressure on the lower surface of the missile at $H_0=0.25\Phi$ in Fig. 7.

In Fig. 6, there are weak compression and expansion areas at the front below the cavity. The weak expansion area covers the middle area below the cavity, at the same time, there are relatively strong compression and expansion area at the rear below the cavity. The circulation area in the cavity is relatively simple, the flow between the upper surface of the missile and the wall of the cavity is similar to that at $H_0=0.25\Phi$; Below the missile, the flow velocity magnitude gradually increases front to back due to the ejection effect of the external high speed flow, and the pressure at the rear of the missile decreases significantly when compared to that at $H_0=0.25\Phi$. According to the Fig. 6 and Fig. 7, because of the relatively low pressure at the rear of the cavity, the total drag coefficient of the missile increases gradually from negative to positive. The circulation area of the in the cavity is such smooth due to the sufficient space between the missile and upper wall of the cavity, the flow mode of the cavity with the missile at $H_0=0.75\Phi$ is similar to that in Fig. 4, only slight differences exist at the front below the cavity.
Based on the flow fields, flow characteristics around the missile in the deep cavity when $H_0 \leq 1.0\Phi$ can be summarized as follows: When the missile is very close to the upper wall of the cavity, the effective length depth ratio of the cavity increases, and it develops from the open flow mode to the transitional open flow mode; the missile gains thrust due to the high pressure area at the rear of the cavity. When the missile is in the middle of the cavity, the impact of the presence of the missile on the open flow mode is weak, and the missile lift and drag are close to zero.

On the aspect of thermal protection, there is no severe problem in the cavity when $\text{AOA}=0^\circ$. However, when the incoming flow comes into the cavity when $\text{AOA}\neq 0^\circ$, the middle and the rear of the missile, the rear of the cavity are all the key areas that should be considered. This problem will be studied later.

![Figure 5. Flow around the missile in the deep cavity at $H_0=0.25\Phi$.](image)

![Figure 6. Flow around the missile in the deep cavity at $H_0=0.75\Phi$.](image)

![Figure 7. Pressure coefficients of the upper and lower surface of the missile at $H_0=0.25\Phi$ and $H_0=0.75\Phi$.](image)
3.3. Compressed Incoming Flow by the Lower Surface of the Missile

Fig. 8 and Fig. 9 show the pressure coefficient contour & streamlines and Ma contour of the flow field at $H_0=1.5$ and $2.0$, respectively. Fig. 10 presents the pressure coefficient curves of the upper and lower surfaces of the missile. With the falling of the missile, the interaction between the lower surface of the missile and the shear flow at the front below the cavity increases gradually. At $H_0=1.5\Phi$, the incoming flow is slightly deflected inward the cavity region, thus there is a narrow and weak expansion area at the front edge of the cavity. But, the change of the incoming flow is negligible. With the flow developing downward, a weak shock wave generates at the shoulder of the missile nose, and a wide expansion area arises after the arc shoulder. At the rear below the cavity, the flow changes little. The compression effect on the incoming flow due to the lower surface of the missile just appears at $H_0=1.5\Phi$. As for the flow in the cavity, since the lower surface of the missile is right parallel to the surface of the aircraft, the cavity is considered to be closed. A relatively large separation bubble generate above the rear of the missile, and the circulation flow around the missile is still preserved. The pressure increase at $X=0.5\text{m}$ on the lower surface of the missile is due to the pressure increase behind the shock wave.

At $H_0=2.0\Phi$, the incoming flow passing the front edge of the cavity is also slightly deflected inward and goes through an expansion area. The deflected flow passes through the lower and upper surfaces of the missile and forms a stagnation point at the nose of the missile. The flow below the lower surface of the missile experiences a strong compression due to the cambered surface at the nose and an expansion when passing the shoulder. At the same time, the kinetic energy of the flow above the upper surface of the missile decreases rapidly due to the recirculation, and the flow is expelled from the rear of the missile.

Based on the flow mentioned above, the lift increment from $H_0=1.5\Phi$ to $H_0=2.0\Phi$ is mainly due to increasing compression strength and region of the flow below the nose of the missile, which can also be reflected in the partial enlarged picture in Fig. 10.

In this region, the flow covers the missile changes from the recirculation flow in the cavity to the incoming flow. It can be speculated that the thermal environment of the missile is deteriorating rapidly, especially that of the lower cambered surface of the missile.

Figure 8. Flow around the missile at $H_0=1.5\Phi$.

Figure 9. Flow around the missile at $H_0=2.0\Phi$. 
Figure 10. Pressure coefficients of the upper and bottom surface of the missile at $H_0=1.5\Phi$ and $H_0=2.0\Phi$.

3.4. Strong Interacting Flow between the Shear Flow and the Upper Surface of the Missile

Fig. 11, Fig. 12 and Fig. 13 present the pressure coefficient contour & streamlines and $Ma$ contour of the flow field at $H_0=2.25\Phi$, $2.5\Phi$ and $2.75\Phi$, respectively. Fig. 14 presents the $Ma$ contour & streamlines around the missile nose at $H_0=2.0\Phi$, $2.25\Phi$, $2.5\Phi$ and $2.75\Phi$. Fig. 15 presents the pressure coefficient curves of the upper and lower surfaces of the missile. As shown in the contours, the flow field below the missile changes little before $H_0=2.5\Phi$, while the flow field above the missile changes significantly. At $H_0=2.75\Phi$, both of them change greatly. It’s noted that the change of the flow field above the upper surface is closely related to the shear layer formed at the front edge of the cavity. Besides, the complicated flow phenomena such as shock wave interaction at the nose of the missile should also be concerned.

As shown in Fig. 14, with the falling of the missile from $H_0=2.0\Phi$ to $H_0=2.75\Phi$ (before the weapon bay closed), the shear layer formed at the front edge of the cavity gradually changes from a slight inward deflection to an outward deflection. The shear layer is like a protruding wedge. The oblique shock wave hits on the bow shock wave right before the missile nose, as a result, the shock wave interaction happens. The type of the shock wave interaction is related to the position of the missile. It’s deduced from Fig. 14 that there should be six types of shock wave interaction around the missile nose from $H_0=2.25\Phi$ to $H_0=2.75\Phi$ (The position interval in this paper is relatively large). Since the shock wave interaction has a great impact on the thermal environment of the missile nose, it needs further study and the type IV shock wave interaction requires special attention.

During the falling of the missile, the strong shear flow formed at the front edge of the cavity right passes over the upper surface of the missile. The complicated circulation in the cavity will interact with the strong shear flow, leading to a more complicated flow channel between the upper surface of the missile and the circulation. In Fig. 15, the pressure on the upper surface of the missile increases gradually from $H_0=2.0\Phi$ to $H_0=2.5\Phi$, which is consistent with the increase of the negative lift on the upper surface. At $H_0=2.75\Phi$, the strong shear flow over the missile cannot withstand the adverse pressure gradient at the shoulder of the missile, which leads to a relatively large separation region after the shoulder of the missile. The separation shock wave generates at the front of the separation, thus the high pressure region appears at the middle and rear of the missile. However, the pressure is much lower than that at $H_0=2.5\Phi$. Meanwhile, the complicated flow field downstream the missile also induces a separation region at the rear below the missile, and, the shock wave before the separation and the resulting high pressure region after the shock wave generate. Therefore, the lift of the missile is just slightly larger than zero.
Figure 11. Flow around the missile at $H_0=2.25\Phi$.

Figure 12. Flow around the missile at $H_0=2.5\Phi$.

Figure 13. Flow around the missile at $H_0=2.75\Phi$. 

(a) Pressure coefficient contour and streamlines

(b) Ma contour
3.5. Wall Effect Flow of the Missile

After the missile separates from the cavity, whether the embedded weapon bay should be closed quickly may be a problem to be discussed. From the perspective of safety, there are disadvantages for closing the bay quickly. However, it can reduce the thermal and acoustic environment severity and increase the negative lift (In Fig. 3 (a)) if the bay closes quickly. In this paper, the weapon bay is ordered to be closed quickly when the missile is at \( \text{HC}=0.25 \Phi \).

Fig. 16, Fig. 17 and Fig. 18 present the pressure coefficient contour & streamlines and Ma contour of the flow field at \( \text{HC}=0.25\Phi, 0.5\Phi \) and \( 1.0\Phi \), respectively. Fig. 19 and Fig. 20 present the streamwise density gradient contour and the pressure coefficient curves of the upper and lower surfaces of the missile, respectively. According to these figures, the pressure on the lower surface and the flow field below the missile vary slightly. The variation of the aerodynamic characteristics of the missile is mainly determined by the flow between the upper surface of the missile and the door of the bay. The flow mentioned above is denoted as the wall effect flow.

In the wall effect region, the main flow characteristics are shock wave reflections and shock-boundary layer interactions (Because the shear on the aircraft is neglected, the viscosity effect only embodies on the surface of the missile). When the missile is very close to the wall (\( \text{HC}=0.25\Phi \)), the incident shock wave from the missile nose is reflected by the aircraft wall, the reflected shock wave then strongly interacts with the boundary layer at the shoulder of the missile. Consequently, a local small separation is forced by the strong adverse pressure gradient induced by the high pressure after the shock wave. The small separation makes the posterior flow channel invariant, and the pressure gains its balance gradually along the flow through weak shock waves and expansion waves. Later, a
weak adverse pressure gradient in the flow channel keeps and develops to the rear of the missile. With $H_c$ increasing, the incident point of the oblique shock wave on the bay door moves downstream, the interaction strength between the reflected shock wave and the boundary layer on the missile declines gradually, and the reflection times also decrease gradually. Finally, the influence of the wall completely disappears. The pressure on the upper surface is dominated by the reflection times. With the reflection times decreasing, the pressure on the upper surface decreases gradually (as shown in Fig. 20), and the negative lift decreases, too.

In Fig. 20, the high pressure on the rear of the missile is likely to induce a nose-up pitching moment, which is harmful to the separation safety. Accordingly, it is necessary to balance the influence of the negative lift and the nose-up pitching moment on the separation safety. If we can increase the negative lift and decrease the nose-up pitching moment simultaneously, it will be more favorable for the separation safety.

![Figure 16. Flow around the missile in wall effect at $H_c=0.25\Phi$.](image)

![Figure 17. Flow around the missile in wall effect at $H_c=0.5\Phi$.](image)

![Figure 18. Flow around the missile in wall effect at $H_c=1.0\Phi$.](image)
Figure 19. Stream-wise density gradient contour at $H_C=0.25\Phi$, $0.5\Phi$ and $1.0\Phi$.

Figure 20. Pressure coefficients of the upper and lower surface of the missile at $H_C=0.25\Phi$, $0.5\Phi$ and $1.0\Phi$.

4. Conclusion
In this paper, 2D numerical simulations are carried out on the symmetric plane of a full size missile separation from high speed aircrafts at the conditions of $Ma=5$ and $AOA=0^\circ$. Aerodynamics and
typical flow field characteristics of the missile at different distances away from the cavity bottom are predicted via a steady RANS solver. The main conclusions are summarized as follows:

1) The flow of the missile separation from high speed aircrafts with an embedded weapon bay can be divided into four stages, which are dominated separately by the flow around the missile in the deep cavity, compressed incoming flow by the lower surface of the missile, strong interacting flow between the shear flow and the upper surface of the missile and wall effect flow of the missile.

2) For stage I, when the missile is very close to the cavity wall, the effective length depth ratio of the cavity increases and the flow around the cavity develops from the open-type flow to the transitional open-type flow. When the missile is in the middle of the cavity, the impact due to the presence of the missile on the open-type flow is weak.

3) For stage II, the incoming flow will be firstly compressed by the lower surface of the missile since it’s protruding from the embedded weapon bay. After that, i.e. on the stage III, when the axis line of the missile is beyond the surface of the aircraft, the strong shear layer induced by the incoming high speed flow and the non-high speed flow in the cavity will act on the lower incoming flow, which leads to the shock wave interaction at the missile nose. Simultaneously, the strong shear layer will significantly increase the pressure on the upper surface of the missile.

4) For stage IV, i.e. the embedded weapon bay is closed, the reflection times of the shock waves between the missile and the aircraft decrease with the increasing distance between the missile and the aircraft. In addition, the pressure on the upper surface of the missile decreases gradually. The large negative lift of the missile formed due to the extreme wall effect is beneficial to the missile separation from high speed aircrafts in some degree. In addition, the closed weapon bay is also favorable to improve the thermal and acoustic environments.

The missile separation from high speed aircrafts is a key problem for airborne weapons in the future. It involves the aerodynamic characteristics, thermal environment, thermal protection structure design, acoustic environment, instruments, materials, and many other aspects. Whether the traditional embedded weapon bay of supersonic aircrafts can be adapted to the high speed one should be considered with caution.

The traditional embedded weapon bay with great simplification has been studied in this paper. There are many aspects that need to be improved based on the preliminary results. Besides, considering the predicting accuracy of complex flows such as cavity flow, shock-boundary layer interaction, and so on, there are lots of issues to be further studied.

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