A STUDY ON THE UNSTEADY AERODYNAMICS OF PROJECTILES IN OVERTAKING BLAST FLOWFIELDS

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ABSTRACT

A projectile that passes through a shock wave experiences drastic changes in the aerodynamic forces. These sudden changes in the forces are attributed to the wave structures produced by the projectile-shock wave interaction. This sort of unsteady interaction normally takes place in the near filed of ballistic ranges, SILO injections, retro-rocket firings, etc. A computational study using a moving grid method is performed to analyze the effect of the projectile-shock wave interaction. Cylindrical and conical projectiles have been employed to study such interactions. It is found that the projectile configurations hardly affect its total aerodynamic characteristics when it overtakes a blast wave. However, it is noticed that the projectile configurations do affect the unsteady flow structures and hence the drag coefficient for the conical projectile shows considerable variation from that of the cylindrical projectile. The projectile aerodynamic characteristics, when it interacts with the secondary shock wave are analyzed. It is also observed that the change in the characteristics of the secondary shock wave during the interaction is different for different projectile configurations. Viscous simulations were also carried out to investigate the effect of viscosity in the flow field. It is observed that the viscosity hardly affects the projectile aerodynamic characteristics but it alters the shock structures of the unsteady flow fields.

INTRODUCTION

The process of launching of a projectile is associated with many complicated fluid dynamic processes such as the shock wave diffraction at the exit of the launch tube [1], secondary shock wave development [2], generation of contact discontinuities and associated instabilities [3]. When the projectile leaves the launch tube, there are various types of interactions between the projectile and the unsteady flow structures [4]. The shock wave dynamics of a moving projectile in the unsteady flow field is computationally studied previously by Jiang and Takayama [4]. They noticed that the interaction between precursor shock wave and bow shock wave are strongly dependent on the projectile speed. Though the fluid dynamics of the flow field was fairly explained in their work, the aerodynamics associated with the flying projectile in the near field has not been addressed. Watanabe [5] studied the projectile aerodynamics when the projectile overtakes the blast wave using computational methods. They argued that the possible overtaking can be either subsonic or supersonic, depending on an explicitly defined projectile relative Mach number.

A computational study on the projectile overtaking a blast wave was performed by Rajesh et al [6]. Their transient simulations show that the projectile flow field cannot be categorized based on the relative projectile Mach number as the Mach number of the blast wave is continuously changing. It is also shown that the aerodynamic characteristics of the projectile are hardly affected by the overtaking process for smaller blast wave Mach numbers as the blast wave will become weak by the time it is overtaken by the projectile.

There are hardly any works carried out to study the effect of projectile configurations and the effect of viscosity in these types of flow fields. In this paper, a computational study is performed using moving grid method, to analyze the effect of the configuration of the projectile on the overtaking process, its interaction with the secondary shock wave. It is also planned to study the effect of viscosity in the whole overtaking process. Cylindrical and conical projectile configurations are employed to perform this study for various initial blast waves Mach numbers which in turn decide the projectile Mach numbers.

NOMENCLATURE

C_d	[-]	Coefficient of drag
M	[-]	Mach number
Ms	[-]	Shock wave mach number
M_{p1}	[-]	Projectile Mach number relative to still air
M_{p2}	[-]	Projectile Mach number relative to flow behind the moving shock wave
u_p	[m/s]	Projectile velocity
a_1	[m/s]	Speed of sound in still air
u_2	[m/s]	Flow velocity behind primary blast wave
a_2	[m/s]	Speed of sound in the region behind the primary blast wave
D	[N]	Drag force
A_p	[m^2]	Projected frontal area of the projectile
γ	[-]	Specific heat ratio

2. COMPUTATIONAL METHOD:

The computational study has been performed using a commercial software CFD-FASTRAN, which makes use of density-based finite volume method that solves the two-dimensional axi-symmetric Euler equations for the inviscid simulation and compressible N-S equations for the viscous simulations. It employs chimera mesh scheme for the structured grids. For simulating the projectile motion, the chimera mesh scheme allows the overlapping of one zone over the other. The communication between the chimera cells and the overlapping cells is established through a tri-linear interpolation.

The projectile is identified as the moving body with six degrees of freedom (6 DOF). The projectile motion is modeled with Euler's equations of motion which is numerically solved at every time step and it requires the physical information of the projectile such as mass, moment of inertia.

The solver uses Van Leer's flux vector splitting scheme with higher order spatial accuracy with Osher-Chakravarthy flux limiter. The time integration is carried out using point Jacobi fully implicit scheme. For viscous simulation, the Navier-Stokes equations with appropriate turbulence modelling are chosen. The k-epsilon model is used to model the turbulence.
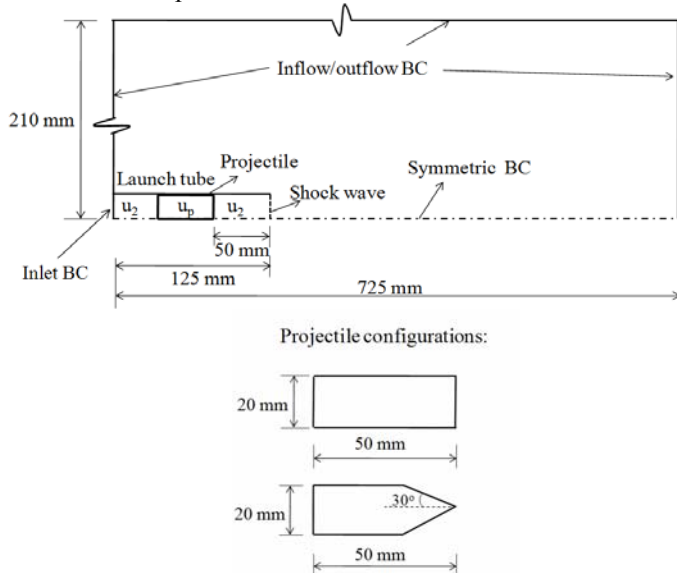

Figure1 Computational domain, boundary conditions and projectile configurations.

2.1 COMPUTATIONAL DOMAIN, GRID SYSTEM AND BOUNDARY CONDITIONS

The computational domain, the boundary condition and the configuration of the projectile for the present study are illustrated in Fig. 1. The projectile has a length of 50 mm, diameter of 20 mm and the half-cone angle for the conical projectile is 30°. The computational domain and the conditions that are used here is same as that used by Rajesh and Kim [6]. Based on a grid independence study performed [6], the number of cells that have been chosen here is 300000 for inviscid simulation and 45000 for the viscous simulation. When the computation starts, the moving shock wave is assumed to be at the exit of the launch tube in which the projectile is kept inside at a distance of 50 mm behind the shock wave. The flows ahead and behind the projectile are assumed to be in the same condition as that of the flow behind the moving shock wave that is at the exit of the launch tube, and the projectile also is moving with the velocity of the flow behind the moving shock wave when the computation starts.

3. RESULTS AND DISCUSSIONS:
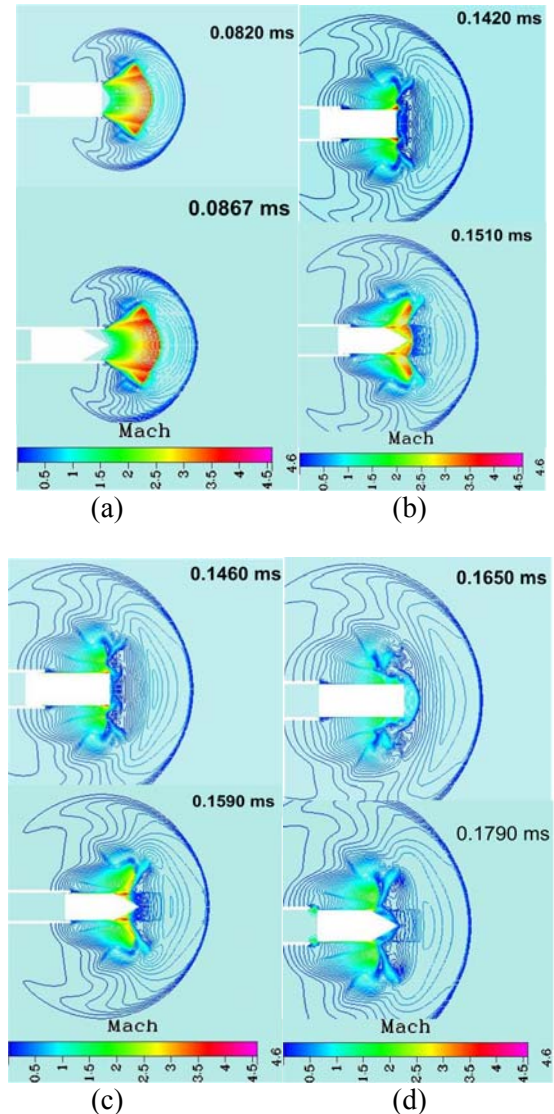
The acceleration histories of the cylindrical and the conical projectiles are compared in Fig. 3a. Various state points are marked in the figure based on the projectile-flow field interactions. The acceleration history of the cylindrical projectile passing through unsteady flow structures is discussed in [6]. Till state b, where the projectile starts interacting with the secondary shock wave, the cylindrical and conical projectiles show similar features in acceleration histories. The absolute and relative projectile Mach numbers are defined as

$$M_{p1} = \frac{u_p}{a_1}$$

$$M_{p2} = \frac{u_p - u_2}{a_2}$$

respectively.

At state b, there is a sudden drop in the acceleration of both the projectile configurations. This is the point, where the projectile interacts with the secondary shock wave and enters a flow field, where the relative Mach number becomes supersonic. From the state c to d, there is a fluctuation in the acceleration of the cylindrical projectile. This can be attributed to the formation of the bow shock wave in front of the cylindrical projectile [6]. From the acceleration history of the conical projectile, as shown in Fig. 3a and Fig. 4a, the fluctuation corresponds to the interaction with the secondary shock wave is not observed.
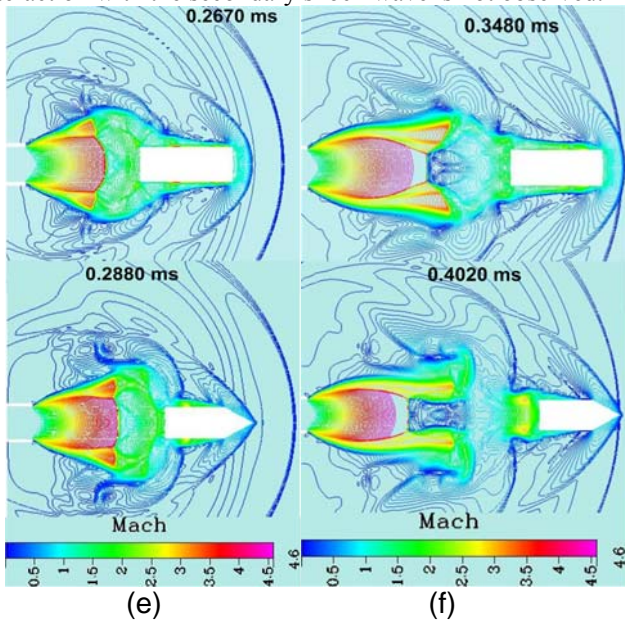

Figure 2 Mach contours of the cylindrical projectile for M_{p1}=1.75 and M_s=2.5.

This shows that the interaction between the projectile and the secondary shock in the case of cylindrical projectile is quite different from that of the conical projectile. This is due to the difference in the configuration and its effect on the flow field. The smooth interaction between the conical projectile and the secondary shock wave reveals that the excursion of waves [4] does not occur during the formation of bow shock wave. To investigate the aerodynamic characteristics of the projectile, the

drag coefficient history of the projectiles are plotted in Fig. 3b and Fig. 4b, where the drag coefficient is defined as [6].

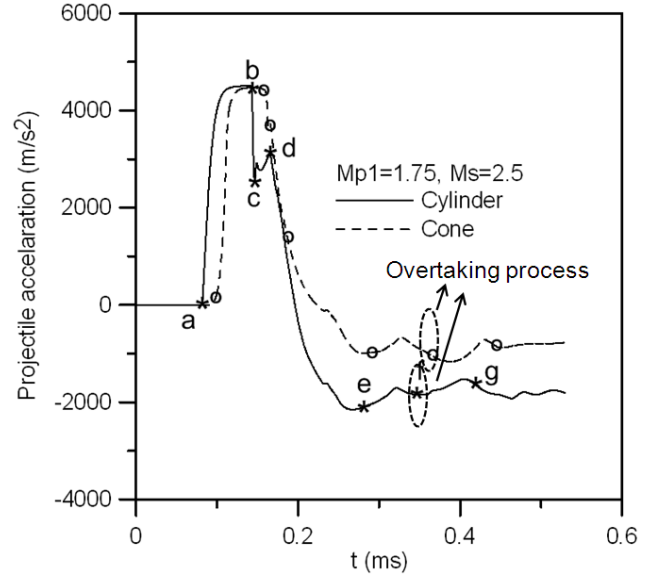$$C_d = \frac{2D}{\gamma P_1 M_{p1}^2 A_p}$$

Figure 3(a) Acceleration history of the projectile for M_{p1}=1.75 and M_s=2.5.
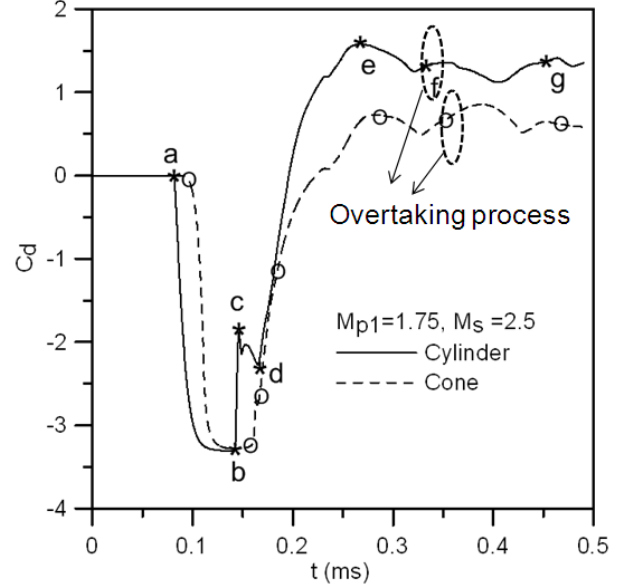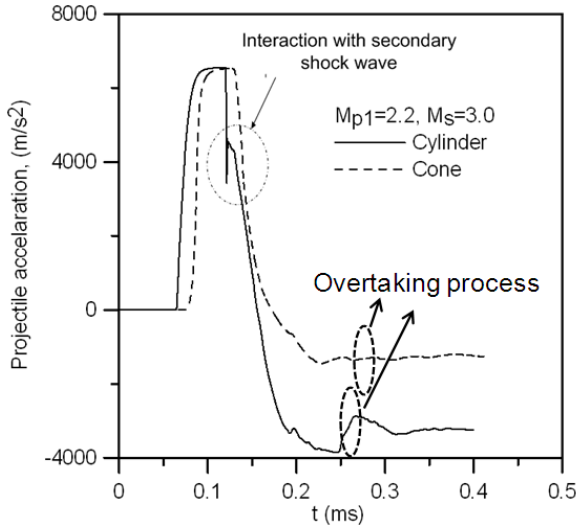

Figure 3(b) Drag coefficient history of the projectile for M_{p1}=1.75 and M_s=2.5.

The same trends as those of the acceleration histories can be seen for the C_d curves of both the cases of M_{p1}. As the projectile passes through the secondary shock wave, the relative projectile Mach number changes to supersonic. The detached bow shock wave develops in front of the conical projectile, as shown in Fig. 2d, because the half cone angle of the projectile becomes more than the θ_{max} at the local relative Projectile Mach number. The relative projectile Mach number increases gradually due to changes in the flow conditions behind the attenuating primary

blast wave. From the state e onwards, the drag coefficient of the conical projectile is significantly less than that of the cylindrical projectile, as shown in the Fig. 3b and Fig. 4b. This verifies the fact that the strength of the bow shock wave being developed in front of the conical projectile is weaker than that of the cylindrical projectile, owing to the aerodynamic shape of the cylindrical projectile. As the projectile overtakes the blast wave, the bow shock wave interacts with the blast wave and forms the familiar triple point on the either side of the projectile.

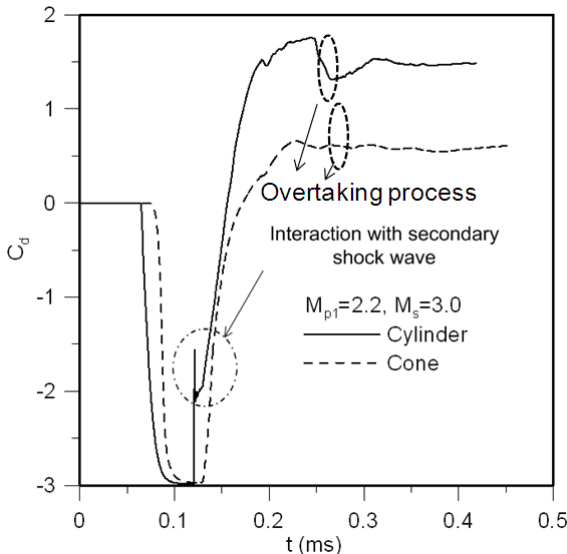**Figure 4(a)** Acceleration history of the projectile for M_{p1}=2.2 and M_s=3.0.

Figure 4(b) Drag coefficient history of the projectile for M_{p1}=2.2 and M_s=3.0.

The formation of triple point corresponds to state g in Fig. 3b, where there is only a slight fluctuation in the drag, and for the lower Mach numbers the overtaking phenomenon hardly affects the unsteady drag of the projectile irrespective of its configurations.
It is also noticed that during the projectile-secondary shock wave interaction, the dynamics of the shock wave depends on the configuration of the projectile. This can be clearly seen

from the Fig. 2b and Fig. 2c, as for the case of cylindrical projectile, the shock wave preserves its shape till the interaction. But for the conical projectile, the characteristics of the secondary shock wave change as it is approached by the conical face of the projectile. This is mainly due to the turning of the flow field in the vicinity of the conical face of the projectile. This causes the normal shock wave to evolve as an oblique shock wave to meet the downstream flow conditions.
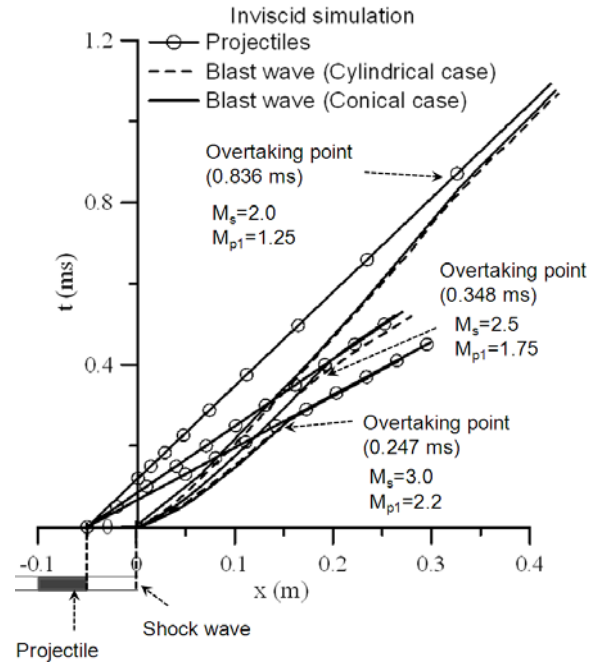

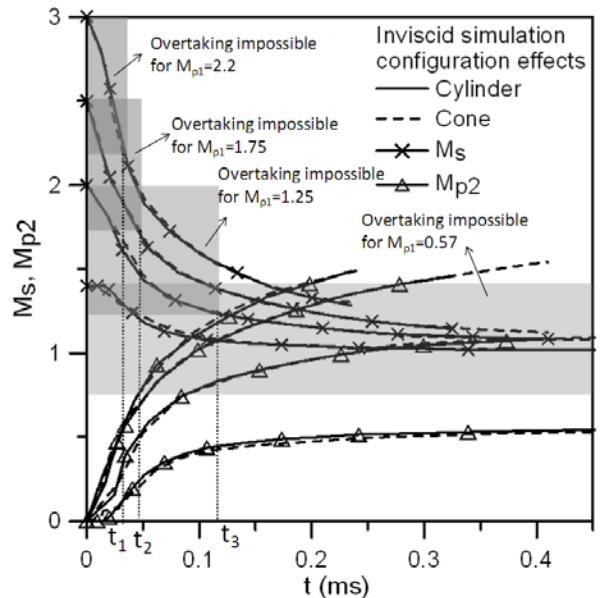**Figure 5(a)** *x-t* diagram of the projectile and the blast wave.

Figure 5(b) Variation of M_s and M_{p2} of the cylindrical and conical projectile with respect to time.

To identify the overtaking process, the *x-t* relation of the projectile and blast wave is shown in Fig. 5a. It can be seen that the speed of the projectile in the near field region is constant

due to its high inertia. But the blast wave attenuates spatially and temporally. The overtaking process is identified as the point, where the x-t curves of the projectile and the blast wave meet. The overtaking times and distances are same for both the projectile configurations.

The variations of M_s and M_{p2} of the conical projectile with time are shown in Fig. 5b. It clarifies the effect of the attenuating blast wave on the overtaking process. It can be seen that during the whole overtaking process, the blast wave Mach number is varying from an impossible overtaking ($M_{p1}<M_s$) condition to possible one ($M_{p1}>M_s$). The overtaking is impossible until time t_1 for the case of M_{p1}=3 and time t_2 for the case of M_{p1}=2.5, since the blast wave travels faster than the projectile, and after this time the overtaking becomes possible due to the blast wave attenuation.

4. EFFECT OF VISCOSITY:

So far, the aerodynamics of the projectile is considered without the effect of viscosity. It is well known from the steady simulations [7] that the formation of the boundary layer and the diffusion of the slip lines can alter the flow field as well as the projectile aerodynamic characteristics. To analyze the effect of viscosity, the viscous simulations have been performed. It can be seen clearly from Fig. 6 that the viscosity has the negligible effect on the aerodynamics of the projectile and there is hardly any variation between the Inviscid and viscous cases.

The pressure drag is the dominating factor in determining the overall drag of the projectile for compressible flows. There is a thin boundary layer over the wall of the moving projectile due to the viscosity and it has the negligible effect on the drag of the projectile.
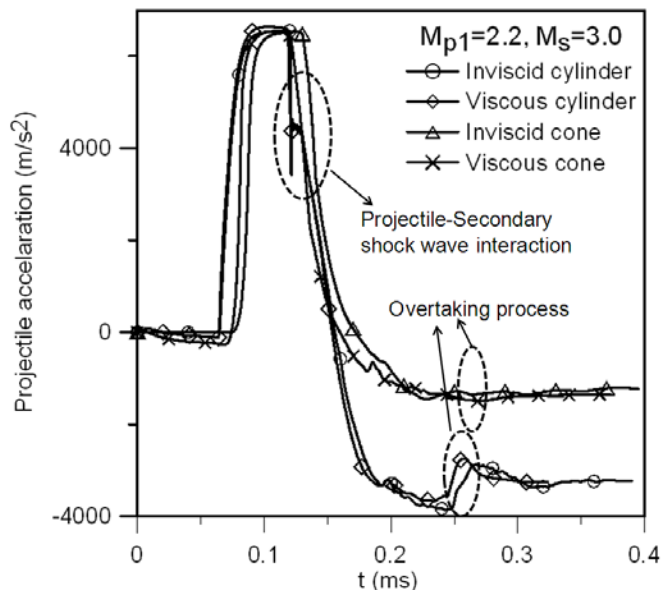

Figure 6(a) Acceleration history of the projectile for M_{p1}=2.2 and M_s=3.0.

Although viscosity does not affect the unsteady aerodynamics of the projectile, it does affect the shock wave structures of the flow field around the projectile. In the initial stage of the projectile coming out of the launch tube, the flow fields of the

inviscid and viscous simulation are similar and the effect of the viscosity on the flow field is not observable. This is due to the fact that the rate at which the vorticity diffusion takes place in unsteady flow field due to the viscous effects are smaller compared to the process of launching the projectile itself. This can be seen clearly in Mach contours of Fig. 7a, Fig.7b and Fig 7c. However, as the time progresses, the diffusion of the vorticity occurs and it alters the flow field and finally the shock wave structure of the flow field. This difference between the viscous and the inviscid case is seen clearly in Fig.7c and Fig 8.
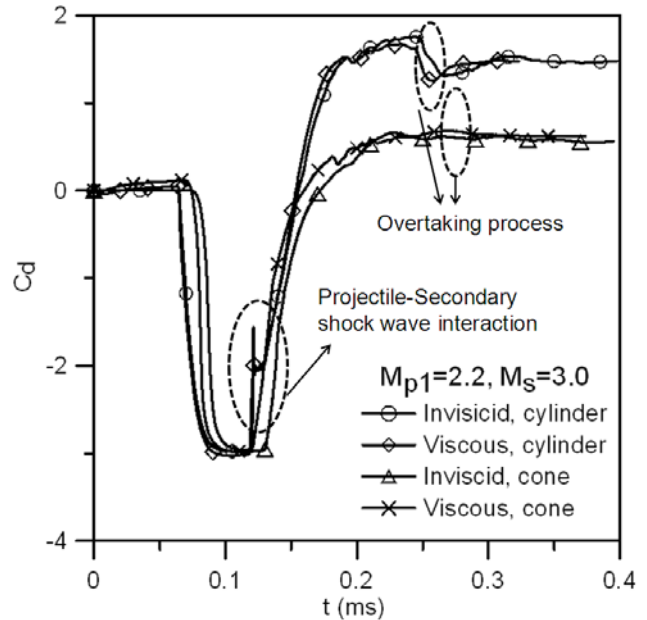

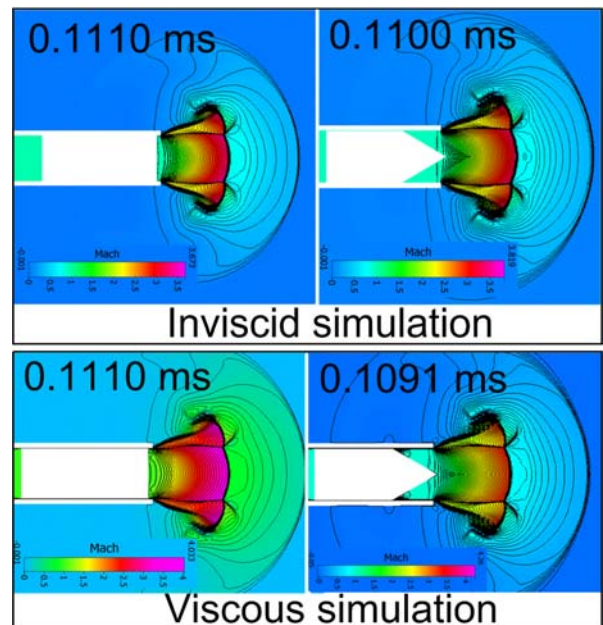**Figure 6(b)** Drag coefficient history of the projectile for M_{p1}=2.2 and M_s=3.0.

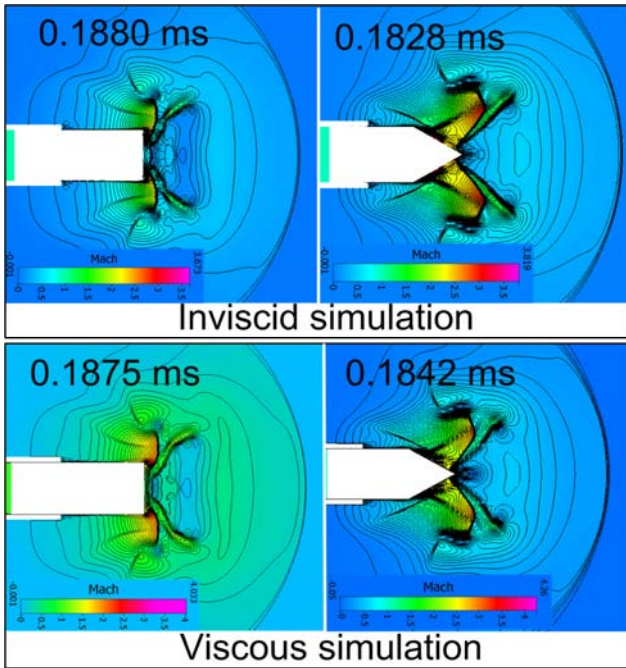**Figure 7(a)** Unsteady flow field before the projectile launch for M_{p1}=1.25 and M_s=2.

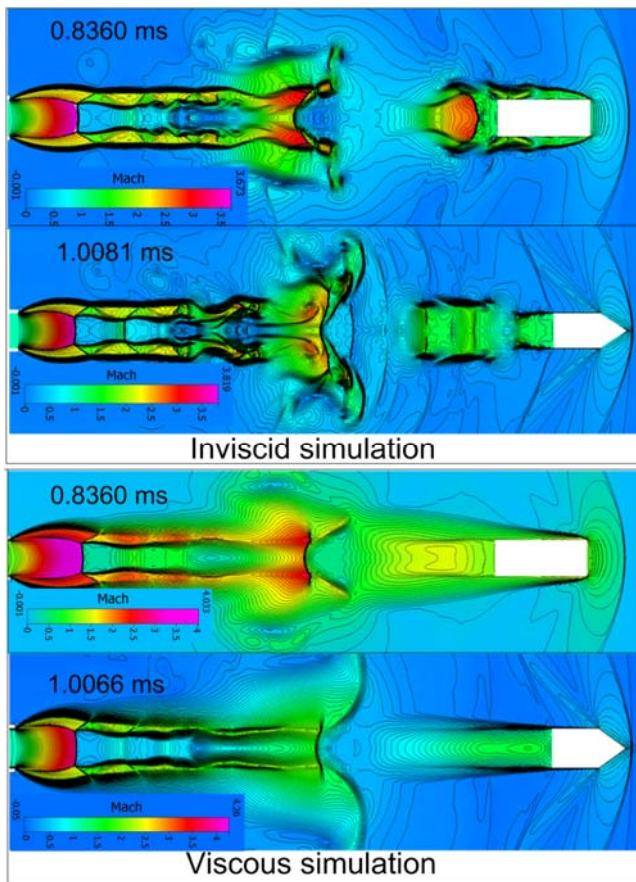**Figure 7(b)** Interaction between projectile and secondary shock wave for M_{p1}=1.25 and M_s=2.

Figure 7(c) Unsteady flow field during the projectile overtaking the primary blast wave for M_{p1}=1.25 and M_s=2.
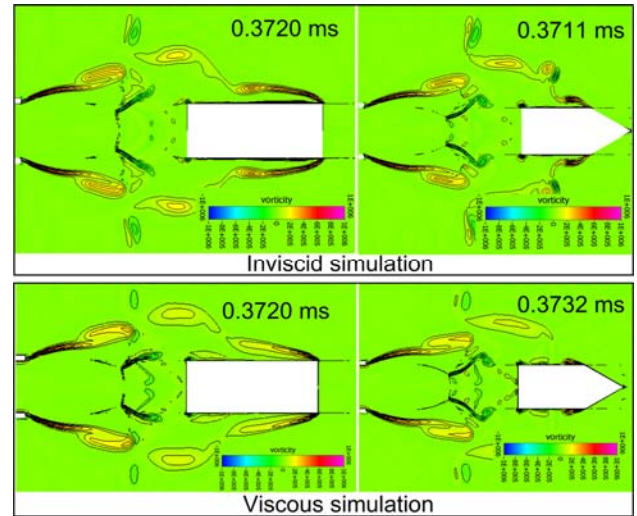

Figure 8 Vorticity contours for M_{p1}=1.25 and M_s=2.

5. CONCLUSION:

A computational study has been performed to analyze the effect of the projectile configuration on overtaking blast flow field as well as its interaction with the unsteady flow field. The study shows that the aerodynamic characteristics of both the projectile configurations are unaffected during the overtaking process as they undergo only supersonic overtaking in low blast wave Mach number conditions. This happens due to the blast wave attenuation in the transient flow field. However, the projectile configurations determine the aerodynamic characteristics due to its interaction with the secondary shockwave in the unsteady flow field. This interaction between the projectile and the secondary shock wave is highly transient, and the wave structures in the flow field are determined by the projectile configuration. It is observed from the viscous simulations that the viscosity has negligible effect on the projectile aerodynamics but it alters the flow structures in the unsteady flow field.

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