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Numerical simulation of the muzzle flows with base bleed projectile based on dynamic overlapped grids

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A B S T R A C T

Numerical investigations of the launch process of a base bleed projectile from the muzzle to free-flight stage have been performed in this paper. A dynamic overlapped grids approach was applied to deal with the problems of a high-speed moving base bleed projectile. A high-resolution upwind scheme (AUSMPW+) and detailed reaction kinetics model were employed to solve the chemical non-equilibrium Euler equations for dynamic grids. A typical case was calculated for the verification of the dynamic overlapped grids approach and numerical methods solving the chemical non-equilibrium flows. After good agreement was achieved, the development process of muzzle flows with high-speed moving base bleed projectile and the rapid depressurization process in the combustion chamber of base bleed unit are discussed in detail. This present numerical study confirms that complicated transient phenomena exist in the early launch stages after the base bleed projectile moves from the muzzle of cannon to the free-flight stage. The base bleed unit of projectile undergoes a strong non-steady-state rapid depressurization. This paper is a significant investigation for understanding muzzle flows with base bleed projectile and rapid depressurization in the combustion chamber of base bleed unit, which can provide valuable reference data for research on combustion stability of the propellant in the combustion chamber.

1. Introduction

For axial symmetric aerodynamic bodies such as projectiles in supersonic flight, there contains a base recirculation zone which forms as the flow separates suddenly at the base corner. The pressure in the base recirculation zone is typically lower than the pressure in the free stream. This has been recognized as being a major contributor to the drag force in the transonic and supersonic regimes [1]. One of the ways to reduce base drag of projectiles is concept of base bleed. The principle is to append a base bleed unit filled with propellant to the bottom of conventional projectiles, named base bleed projectile, as schematically shown in Fig. 1(a). The base bleed unit injects gas with a low velocity and high temperature into the base recirculation zone, increasing the base pressure and subsequently reducing base drag. The base bleed projectile has been intensively investigated both experimentally and numerically during the past years [2–10]. However, researchers have only considered the steady flow field and drag reduction mechanism of the base bleed projectile.

The muzzle flows induced by a supersonic projectile moving from the muzzle of a cannon to the free-flight stage are a complex blast flow field, which has the characteristics of unsteady flow, strong shock discontinuities and severe chemical reactions. This problem is schematically shown in Fig. 1(b), where several wave phenomena are defined, such as blast wave, incident shock, reflected shock, and Mach disk. It is important to study the mechanism of muzzle flows to improve or increase the efficiency of weapon. There have been many investigations about muzzle flows [11–17] in the past years. For instance, Cler et al. [15] adopted the fluent 6.1 solvers and DG solver to simulate the muzzle flows without projectile. Shock wave dynamics process of the muzzle flows were numerically visualized in detail through special treatment on a moving cylinder projectile in the shock wave tube by Jiang et al. [16]. In previous numerical simulation studies of muzzle flows, the majority of researchers did not consider the muzzle flows affected by the high-speed moving projectile. In the calculation process, it needed not only to deal with the complex shock discontinuity, but also to consider computational grid changes due to the high-speed moving projectile, which led to complicated calculation process. At the same time, they did not consider the real propellant gas and only assumed that the real propellant gas in the cannon tube to be air, which was the same as the external ambient air. They also ignored the chemical reactions between the real propellant gas and the external air. Although the calculation was simplified, the accuracy was insufficient and could only estimate

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the flow field. In order to accurately study the muzzle flows induced by a supersonic projectile moving from the muzzle of a cannon to the free-flight stage, the muzzle flows affected by the real high-speed moving projectile and the propellant gas must be considered.

At the moment when the base bleed projectile leaves the muzzle of a cannon, the propellant gas with high temperature and high pressure exists in the combustion chamber of base bleed unit, which is the same as the interior of cannon tube, because the propellant gas generated by the cannon goes into the combustion chamber of base bleed unit during the launching of the base bleed projectile. Meanwhile, the propellant in the combustion chamber of base bleed unit has been ignited by the propellant gas in the cannon and has begun to deflagrate normally. With the motion of the base bleed projectile, the propellant gas is released rapidly into the external environment, causing the pressure in the combustion chamber to drop sharply. This is a process of strong non-steady-state rapid depressurization in the combustion chamber of base bleed unit, which brings a strong transient disturbance to the propellant and directly affects the combustion stability of the propellant in the combustion chamber. In severe cases, it can cause the propellant to extinguish, or lead to propellant disintegration. This causes the base bleed unit not to function, and then gives rise to the failure of the drag reduction. However, a study of the muzzle flows with high-speed moving base bleed projectile and the rapid depressurization process in combustion chamber of base bleed unit cannot found anywhere in the published literature. After all, it is difficult to study this process and obtain data by experimental methods since the base bleed projectile moves from the muzzle to the surroundings in any extremely short time. On the other hand, due to the rising cost of experimental measurements together with limited experimental facilities and testing technology, it is of great significance to establish a reasonable and accurate calculation method for muzzle flows with a high-speed moving base bleed projectile.

For a moving body flow problem, the computational grids must move with the body. The most straightforward approach is to deform the computational grid locally using a spring-analogy type algorithm to follow the motion of the moving body [18]. This approach is very efficient because it does not require solution interpolation, but it has the disadvantage that the grid integrity can be destroyed by large motions of moving body or boundary. The dynamic overlapped grids approach seems to be the state-of-the-art in handling moving boundary problems, and has been used successfully for a variety of applications [19–22]. The dynamic grids are generated first near the moving body and the static grids are generated for background overlapped with the dynamic grids. With the motion of moving bodies, the dynamic grids move with the moving body on the static background grids. It is demonstrated that this approach of dealing with moving bodies is accurate and efficient.

The present study aims at establishing a reasonable and accurate calculation method for muzzle flows with a high-speed moving base bleed projectile in conjunction with the chemical reactions. A dynamic overlapped grids approach is applied to deal with the problems of a high-speed moving base bleed projectile. A high-resolution upwind scheme (AUSMPW+) and detailed reaction kinetics model are adopted to solve the ALE Euler equations with chemical reactions. A special case is chosen for the verification of the numerical algorithms. After checking the accuracy of the numerical algorithms, the case of the muzzle flows with a high-speed moving base bleed projectile is simulated. Using the numerical results, the development process of muzzle flows, the interaction between a base bleed projectile and the muzzle flows, and the rapid depressurization process in the combustion chamber of the base bleed unit are discussed in detail.

2. Mathematical method

2.1. Governing equations

Assuming that the muzzle flows in this present study are two-dimensional axisymmetric during the short time duration while the base bleed projectile moves from muzzle of the cannon to the free-flight stage and the viscosity effects of the wave dynamic process are negligible. The time-dependent Arbitrary Lagrangian Eulerian (ALE) of Euler equations with chemical non-equilibrium are expressed in the integral form as:

$$\frac{\partial}{\partial t}\int\int_V \boldsymbol{Q}dV + \oint_S (\boldsymbol{F}(\boldsymbol{Q})n_x + \boldsymbol{G}(\boldsymbol{Q})n_y)dS = \int\int_V (\boldsymbol{H}_1 + \boldsymbol{H}_2)dV \qquad (1)$$

where S is the surface surrounding the control volume V, $\boldsymbol{n} = n_x\boldsymbol{i} + n_y\boldsymbol{j}$ is the out-going unit normal of S, $\boldsymbol{Q}$ is the vector of the conservative variables, $\boldsymbol{F}$, $\boldsymbol{G}$ are the vectors of the convective fluxes, $\boldsymbol{H}_1$ is the vector of source term caused by chemical reactions, $\boldsymbol{H}_2$ is the vector of source term caused by axial symmetry. Here, $\boldsymbol{Q}$, $\boldsymbol{F}$, $\boldsymbol{G}$, $\boldsymbol{H}_1$, $\boldsymbol{H}_2$ are given by

$$\begin{aligned}
&\boldsymbol{Q} = [\rho\ \ \rho u\ \ \rho v\ \ E\ \ \rho f_i]^T \\
&\boldsymbol{F} = [\rho(u-u_w)\ \rho u(u-u_w)+p\ \rho v(u-u_w)\ (E+p)(u-u_w)\ \rho f_i(u-u_w)]^T \\
&\boldsymbol{G} = [\rho(v-v_w)\ \rho u(v-v_w)\ \rho v(v-v_w) \\
&\qquad +p\ (E+p)(v-v_w)\ \rho f_i(v-v_w)] \\
&\boldsymbol{H}_1 = [0\ \ 0\ \ 0\ \ 0\ \ \omega_i]^T \\
&\boldsymbol{H}_2 = -\frac{v}{y}[\rho\ \ \rho u\ \ \rho v\ \ E+p\ \ \rho f_i]^T
\end{aligned} \qquad (2)$$

In Eq. (2), ρ is the density, p is the pressure, u, v are the velocity components of fluids, u_w, v_w are the moving velocity components of the surface S, f_i is the mass fraction of species i. The subscripts $i = 1,\ldots,N-1$, where N is the total number of species. ω_i given by

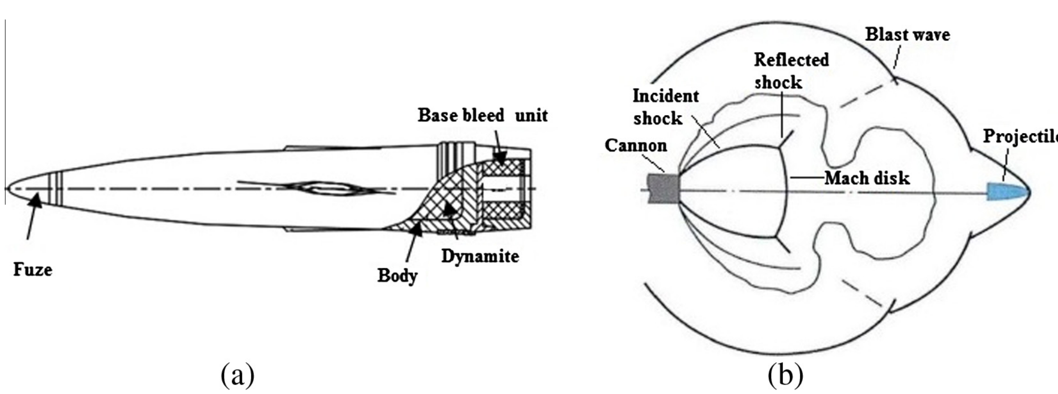

Fig. 1. (a) Schematic of base bleed projectile and (b) schematic of muzzle flows with moving projectile.