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Development process of muzzle flows including a gun-launched missile

Zhuo Changfei, Feng Feng *, Wu Xiaosong

School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

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Abstract Numerical investigations on the launch process of a gun-launched missile from the muzzle of a cannon to the free-flight stage have been performed in this paper. The dynamic overlapped grids approach are applied to dealing with the problems of a moving gun-launched missile. The high-resolution upwind scheme (AUSMPW+) and the detailed reaction kinetics model are adopted to solve the chemical non-equilibrium Euler equations for dynamic grids. The development process and flow field structure of muzzle flows including a gun-launched missile are discussed in detail. This present numerical study confirms that complicated transient phenomena exist in the shortly launching stages when the gun-launched missile moves from the muzzle of a cannon to the free-flight stage. The propellant gas flows, the initial environmental ambient air flows and the moving missile mutually couple and interact. A complete structure of flow field is formed at the launching stages, including the blast wave, base shock, reflected shock, incident shock, shear layer, primary vortex ring and triple point.

1. Introduction

The gun-launched missile[1–3] is a special missile launched by tank or cannon. It can obtain a high initial velocity by cannon and then use rocket engine to further accelerate. Compared with the general projectile and missile, the gun-launched missile has many advantages such as reducing launch cost, improving hitting accuracy and extending firing range, which is a rapid developing guided weapon in recent years.

The muzzle flows induced by a general projectile moving from the muzzle of a cannon to the free-flight stage are a complex blast flow field, which have the characteristics of unsteady flow, strong shock discontinuity and severe chemical reactions. 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 flow[4–10] in the past years. For instance, Cler[8] adopted the Fluent 6.1 solvers and discontinuous Galerkin (DG) solver to simulate the muzzle flows without a projectile. Shock waves' dynamics process of the muzzle flows was numerically visualized in detail through special treatment on the moving cylinder projectile in the shock wave tube by Jiang and Takayama.[9] In the 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

* Corresponding author. Tel.: +86 25 84303185.
E-mail address: nust203@aliyun.cn (F. Feng).

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the calculation process, it is 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 just assumed that the real propellant gas in the cannon tube to be air, which was the same as 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 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.

However, according to the published literature, a study of the muzzle flows including a gun-launched missile is not nearly performed. After all, it is difficult to study this process and obtain data by experimental methods since the gun-launched missile 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 including a gun-launched missile.

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.[11] This approach is very efficient because it does not require solution interpolation, but a disadvantage of the approach is that the grid integrity can be destroyed by large motions or shear-type of boundary motions. 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.[12–14] 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 body, the dynamic grids move with the moving body on the static background grids. It is demonstrated that this approach dealing with moving body is accurate and efficient.

The present study aims at establishing a reasonable and accurate calculation method for muzzle flows including a gun-launched missile in conjunction with the chemical reactions. The dynamic overlapped grids' approach are applied to dealing with the problems of a gun-launched missile. The high-resolution upwind scheme (AUSMPW+) and the detailed reaction kinetics model are adopted to solve the ALE (Arbitrary Lagrangian Eulerian) Euler equations with chemical reactions. A special case is chosen for the validation of the numerical algorithms. After checking the accuracy of the numerical algorithms, the case of the muzzle flows including a gun-launched missile is simulated. Using the numerical results, the development process of muzzle flows including a gun-launched missile is visualized numerically and discussed in detail.

2. Mathematical method

2.1. Governing equations

Assuming that the muzzle flows in the present study are two-dimensional axisymmetric during the short time duration while the gun-launched missile moves from the muzzle of a cannon to the free-flight stage, the time-dependent ALE Euler equations with chemical non-equilibrium are expressed in the integral form as

$$\frac{\partial}{\partial t}\int\int_V \boldsymbol{Q}dV + \oint_S (\boldsymbol{F}(\boldsymbol{Q})n_x + \boldsymbol{G}(\boldsymbol{Q})n_y)\mathrm{d}S = \int\int_V (\boldsymbol{H}_1 + \boldsymbol{H}_2)\mathrm{d}V \tag{1}$$

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

$$\begin{cases} \boldsymbol{Q} = [\rho \;\; \rho u \;\; \rho v \;\; E \;\; \rho f_i]^{\mathrm{T}} \\ \boldsymbol{F} = [\rho(u-u_{\mathrm{w}}) \;\; \rho u(u-u_{\mathrm{w}})+p \;\; \rho v(u-u_{\mathrm{w}}) \;\; (E+p)(u-u_{\mathrm{w}}) \;\; \rho f_i(u-u_{\mathrm{w}})]^{\mathrm{T}} \\ \boldsymbol{G} = [\rho(v-v_{\mathrm{w}}) \;\; \rho u(v-v_{\mathrm{w}}) \;\; \rho v(v-v_{\mathrm{w}})+p \;\; (E+p)(v-v_{\mathrm{w}}) \;\; \rho f_i(v-v_{\mathrm{w}})]^{\mathrm{T}} \\ \boldsymbol{H}_1 = [0 \;\; 0 \;\; 0 \;\; 0 \;\; \omega_i]^{\mathrm{T}} \\ \boldsymbol{H}_2 = -\frac{v}{y}[\rho \;\; \rho u \;\; \rho v \;\; E+p \;\; \rho f_i]^{\mathrm{T}} \end{cases} \tag{2}$$

where ρ is the density, p the pressure, and f_i the mass fraction of species i; u, v are the velocity components of fluids, u_{w}, v_{w} the moving velocity components of the surface S. The subscripts $i = 1, 2, \cdots, N-1$, where N is the total number of species. ω_i given by the chemical reaction kinetic model is the mass production rate of species i:

$$\omega_i = M_i \sum_{j=1}^{N} (\beta_{ij} - \alpha_{ij})(R_{\mathrm{f}j} - R_{\mathrm{b}j}) \tag{3}$$

where M_i is the molar mass of species i; $R_{\mathrm{f}j}$ and $R_{\mathrm{b}f}$ are the positive reaction rate and the reverse reaction rate of elementary reaction, respectively, α_{ij} and β_{ij} the stoichiometric coefficients of species i in the jth elementary reaction; N is the total number of elementary reaction.

The total energy E is defined as

$$E = \rho h - p + \frac{1}{2}\rho(u^2 + v^2) \tag{4}$$

where h is the specific enthalpy of the gas mixture.

2.2. Numerical methods

In order to improve the accuracy of spatial discretization, we should reconstruct the primitive variables before computing the convection flux quantities of the governing equation using upwind scheme.

In the computational domain of structured grid, the non-oscillatory and non-free-parameter dissipation (NND) scheme[15] is used. In the computational domain of unstructured grid, the reconstruction method in Ref. [16] presented by Barth and Jespersen is used in this study.

Convection flux quantities are computed by using the AUSMPW+ scheme[17] with reconstructed state primitive variables on both sides of a face, after completing the reconstruction in the cell interface. AUSMPW+ scheme has higher resolution in capturing oblique shocks than any other AUSM-type scheme. Furthermore, the AUSMPW+ scheme is more efficient to implement than AUSMPW while maintaining the same level of the robustness and accuracy.