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Numerical investigation on combustion in muzzle flows using an inert gas labeling method

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ABSTRACT

The influence of the precursor flow on combustion in muzzle flows is investigated. The fourth-order Runge–Kutta method is employed to solve the classical interior ballistics model, providing velocity for the projectile when it accelerates along the barrel. An inert gas labeling method is proposed. An additional species, helium, is chosen as the label to tracing the precursor gas which fills the barrel before the projectile starts. A high-resolution upwind scheme, AUSM+ (Advection Upstream Splitting Method), and detailed reaction kinetics model are employed to solve the multispecies Navier–Stokes equations with finite rate chemistry. The precursor flow generated by the precursor gas driven out of the barrel ahead of the projectile is simulated. The development of muzzle flow with chemical reaction is simulated. It is demonstrated from the results that the secondary temperature rise in the intermediate region behind the Mach disk is attributed to combustion in this area. It is found that the core of the precursor gas supplies oxygen for combustion at 150 μs after the projectile base leaves the muzzle. Furthermore, despite the disrupted precursor flow, the precursor gas is still united and gradually diffuses into the propellant gas.

1. Introduction

This investigation is motivated by the interest in the combustion phenomenon for a gun-launched supersonic projectile and the interest in how to investigate a certain part which has the same physical and chemical properties with the surroundings. After the projectile base leaves the muzzle, propellant gas of high temperature and high pressure is released into the ambient air, generating an unsteady flow which contains a lot of undesired phenomenon such as blast waves, acoustic waves, pressure waves, electromagnetic radiation, muzzle flash and smoke [1]. In addition, the expulsion of a column of air driven out of the barrel ahead of the projectile generates a precursor flow field, which makes the muzzle flow more complex due to the precursor gas blast shock [2].

Extensive investigations of muzzle flows were carried out in the past decades, both experimentally and numerically [3–8]. Schmidt measured the structure of the flowfields formed about the muzzle of a small caliber rifle during the firing using a time-resolved, spark shadow-graph technique. In his experiment, the coupling and uncoupling between the initial gas blast field and the propellant jet flows were observed [9]. Based on the former experiment, he investigated the flow at the muzzle of a gun during launch of fin-stabilized projectiles both experimentally and analytically. The effect of launch gas dynamic loadings upon projectile motion was calculated and was shown to compare favorably with experiment [10]. Taylor formulated a model to describe the details of the flowfield produced by the firing of a gun or mortar, and numerical results agreed reasonably well with the existing experimental data. Besides, the development of precursor flow was found out in the same manner with propellant gas flow [11]. Subsequently, a lot of research was conducted on the precursor flow and its influence on propellant gas flow. A temporal new computational technique was adopted by Moretti to solve the Navier–Stokes equations which describe the precursor flow. By comparing with experimental results, the results of their numerical tests show that the basic features of their technique, viz. grid definition, integration scheme and shock fitting, do indeed provide very high accuracy [12]. The Arbitrary Lagrangian–Eulerian (ALE) of Euler equations was solved by Jiang using the AUSMDV scheme (a mixture scheme of two forms of the AUSM), and the prominent characteristics including the propagation of first and second blast waves, the generation of bow shock wave and moving of the projectile, etc. were discussed in detail based on the numerical results [13]. Especially, interactions between the precursor flow field and propellant gas exhaust were observed experimentally by Schmidt [14]. The influence of

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Nomenclature

b	burning coefficient of propellant, m s^{-1} pa^{-1}
c	mass fraction
D	diffusion coefficient
e	half of the web-thickness of propellant, m
f	impetus, J kg^{-1}
k	rate constant of reaction
l	displacement, m
L	length, m
m	mass, kg
M	symbol of species
M_w	molecular weight
p	pressure, Pa
q	capacity of heat transmission
R	universal gas constant, 8.314 J mol^{-1} K^{-1}
$\hat{R}$	Arrhenius molar rate of generation
S	area, m^2
t	time, s
T	temperature, K
$\mathbf{u}$	velocity vector, m s^{-1}
u	velocity, m s^{-1}
v	velocity, m s^{-1}
v'	stoichiometric coefficient for reactant
v''	stoichiometric coefficient for product
X	molar fraction
Z	relative thickness of the burnt

Subscript

i	species
j	species
r	reactions
x	in x-direction
y	in y-direction

Superscript

n	burning exponent

Greeks

ψ	mass fraction of the burnt
χ	form characteristic quantity
ξ	form characteristic quantity
η	form characteristic quantity
φ	minor work coefficient
ω	charge weight, kg
α	covolume, m^3 kg^{-1}
τ	viscous stress, N m^{-2}
ρ	density, kg m^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}
μ	molecular viscosity coefficient, N s m^{-2}
Δ	charge density, kg m^{-3}

the precursor flow field was analyzed by comparing data taken at fully ambient conditions with that acquired in firings from an evacuated gun tube, and it was concluded that precursor flow must be taken into consideration when muzzle flow is studied.

In terms of combustion in muzzle flow, Klingenberg conducted experiments of combustion phenomenon associated with the flow of hot propellant gases [15–17]. In these experiments, spatial and temporal distributions of temperature, velocity and pressure of a rifle of a caliber 7.62 mm were measured, and the muzzle flash is separated into three main luminous regions in space and time, i.e., the primary flash, intermediate flash and secondary flash. Schmidt examined the influence of both transient and three-dimensional flow on the probability of ignition in gun plumes [18]. Klingenberg investigated the influence of turbulent mixing on combustion of muzzle flows. Conclusions were drawn that oxygen from the entrained air is transported to the core of the flow in the vicinity of the Mach disk, i.e., the so-called "intermediate" flash, or "intermediate" flow region and combustion reactions take place there. A more vital conclusion was drawn that the ignition sequence leading to secondary muzzle flash is governed by an ignition temperature whose value is determined by two energy sources: the well-known shock heating and the combustion reactions in the intermediate flash [19]. Zhuo simulated the muzzle flows with base bleed projectile based on dynamic overlapping grids. In this simulation, a chemical reaction kinetic model was adopted to describe the chemical non-equilibrium flow [20].

As concluded by Schmidt, precursor flow must be taken into consideration when muzzle flow is studied [14]. Previous studies analyzed the influence of the precursor flow based on comparing data acquired from cases with and without a precursor flow field [14], or directly simulating the muzzle flow coupled with the precursor flow [12,13]. But, to date, there is no published research describing the detailed process of the precursor flow interacting with the propellant gas flow, especially the oxygen contribution of the precursor gas to the intermediate flash which directly affects the ignition of secondary combustion [19]. From Fig. 1 [14], it is obvious that it is hard to locate the precursor gas, which makes it impossible to analyze the motion of the precursor gas and the entrainment of oxygen.

To investigate the influence of the precursor flow on combustion in muzzle flow, especially, the oxygen contribution of the precursor gas, the entire process from the start of the projectile in the barrel to the complete development of the muzzle flow, shown in Fig. 2, is simulated. In order to distinguish the precursor gas from the surrounding environment, and to investigate the oxygen contribution of the precursor gas as well as the interaction between the precursor flow and the propellant gas flow, an inert gas labeling method inspired by the research of Grynkiewicz [21] is proposed. In his research, fluorescent indicators were used for biochemical studies of the physiological role of cytosolic free Ca^{2+}. In this investigation, helium is chosen as the inert gas label because of its chemical inertness to trace the motion of precursor gas, which is similar to that of the fluorescent indicators tracing Ca^{2+}. With the help of helium, it is easy to directly trace the motion of precursor gas, interaction between the precursor flow and the propellant gas flow, as well as the entrainment of oxygen. To take

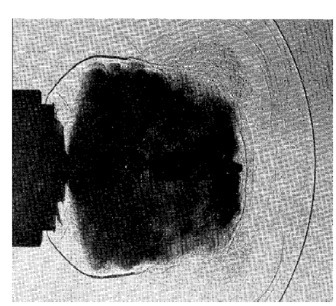

Fig. 1. Experimental shadowgraph of muzzle flow with precursor flow.