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Technical Notes

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Initiation Mechanism of Thermally Choked Combustion in Ram Accelerators

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Introduction

THE ram accelerator[1] is a propulsion concept based on using shock-induced combustion to accelerate projectiles. In a ram accelerator, a projectile travels at supersonic speeds in a launch tube filled with a premixed combustible mixture. Depending on the projectile velocity and the mixture conditions, the shock-induced combustion that produces high pressure to accelerate projectiles can take different forms. If the projectile velocity is greater than the Chapman–Jouget (C–J) velocity of the mixture, oblique detonations can be stabilized on the projectile body[2,3] to generate the high pressure. If the projectile velocity is lower than the C–J velocity, the energy released in the combustion region behind the projectile can thermally choke the downstream flow to maintain a high-pressure region on the projectile.[4,5] In either case, the high-pressure region follows the projectile and no propellant is carried on the projectile. Therefore, the launch speed and energy-conversion efficiency can be greater than those of conventional launching devices, such as guns and rockets.

The key feature of a ram accelerator operating in the thermally choked regime is the normal shock (Fig. 1) on the rear part of the projectile. This shock is an integral part of the thermally choked combustion. First, it is maintained by the high pressure generated by the thermally choked combustion. Second, the high temperature and pressure behind the shock facilitate the combustion process. Initiation of the normal shock and thermally choked combustion is a crucial issue in the ram-accelerator development. In ram-accelerator experiments, various starting methods have been used to initiate thermally choked combustion. The most common one is using an obturator to temporarily block the flow behind the projectile.[4,6] However, the exact initiation mechanism of the normal shock and thermally choked combustion is not yet fully understood. In this study, we use time-accurate numerical simulations to study the rapid development of the reactive flowfield during the initiation process. Information obtained from these simulations provides a fundamental understanding of the initiation mechanism and crucial knowledge for further improvements of the ram-accelerator starting process.

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Physical Models and Numerical Methods

The conservation equations for mass, momentum, energy, and individual species are solved using the flux-corrected transport algorithm (FCT)[7] in conjunction with a two-step, reduced-chemistry model developed for studying shock combustion.[8] All of the model parameters were obtained from the shock-tube experiments conducted at high-temperature and high-pressure conditions applicable to the ram-accelerator applications, and the details can be found in Ref. 9. The virtual cell embedding (VCE)[10] technique is used to accurately represent the complex shape of the ram-accelerator projectile on an orthogonal mesh. The physical models and numerical methods used here have been validated and extensively used in ram accelerator simulations[5,11] and in studies in other areas involving shock-induced combustion.[12,13]

Results and Discussion

The projectile used in this study is similar to those used in the experiments at the University of Washington[4] (Fig. 1). Different CH_4–O_2–N_2 mixtures were used in the simulations. The mixture ratio ranges from CH_4:O_2:N_2/2.7:2.0:2.0 to CH_4:O_2:N_2/2.7:2.0:15.0. The initial mixture pressure in the tube (fill pressure) is 25, 50, or 100 atm, and the initial mixture temperature (fill temperature) is 300 K. The initial projectile velocity is 1150 m/s. The projectile mass is 75 g and the obturator mass is 16, 32, or 48 g. The size of the computational domain is 75.0 × 1.9 cm^2. The upper and lower boundaries of the computational domain represent the inner wall and the axis of the ram-accelerator launch tube, respectively. Two cell sizes, 0.05 and 0.025 cm, were used and the results showed that the solutions were grid independent. Therefore, the cell size of 0.05 cm was used in all subsequent simulations. In this study, we have simulated the development of the reactive flowfield during a short period (25 ms) after the projectile enters the combustible mixture in the launch tube:

1) To obtain information on the basic initiation mechanism of the thermally choked combustion and the associated normal shock.

2) To demonstrate the strong dependence of the sustainability of thermally choked combustion and the normal shock on the mixture and obturator parameters.

3) To provide guidelines for achieving sustained thermally choked combustion and projectile acceleration.

At the different mixture ratios and fill pressures studied here, basic initiation mechanism of thermally choked combustion remains the same. As an example, the pressure and water concentration from the simulation conducted for the mixture CH_4:

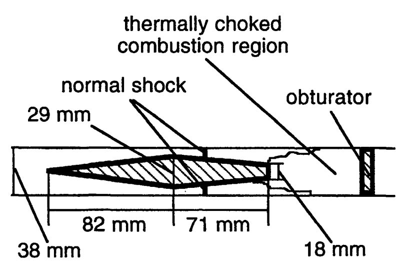

Fig. 1 Schematic of the projectile used in this study and major flow features in the thermally choked ram accelerator.

O_2:N_2/2.7:2.0:5.7 at 50 atm with the 16-g obturator are shown in Fig. 2 to demonstrate this initiation process. Because the projectile is located near the left end of the computational domain and the most interesting physics occurs around the projectile, only the left 50-cm portion of the computational domain is shown in the figure. Immediately after the projectile enters the ram-accelerator tube filled with the combustible mixture, the obturator is still in contact with the projectile base. The relative velocity between the obturator and the mixture is of the order of the starting velocity of the projectile. About 0.10 ms after the projectile enters the tube, the obturator reaches the combustible mixture and a normal shock is formed on the obturator surface. This shock subsequently moves upstream. Between the shock and obturator, the high temperature and, to a lesser extent, the high pressure, produce enough combustion radicals to ignite the mixture. The energy released in the combustion process further increases the pressure and temperature in this region and also strengthens the normal shock. The combustion-enhanced high pressure in the region provides the thrust for projectile acceleration. It also results in the separation of the obturator from the projectile base at an accelerating rate. There have been several proposed theories on how the thermally choked combustion starts,[13] and the computational results presented here clearly show that the combustion is initiated on the rear part of the projectile when the obturator is still in contact with the projectile base. This initiation mechanism also explains why, under certain conditions, the normal shock overtakes the projectile soon after the projectile enters the mixture, causing launch failures. This phenomenon will be discussed later in greater detail.

On the projectile body, the shape of the normal shock may change slightly as a result of the interaction with the other oblique shocks. Therefore, the term *near-normal shock* is a more appropriate description of this shock and will be used in the following discussion. The near-normal shock also interacts with the boundary layers on the projectile body and the inner wall of the launch tube. However, the effect of the boundary layers on the combustion process and the near-normal shock is very limited under the studied conditions.[14]

Although the basic initiation mechanism is the same in all of the simulations performed in this study, the subsequent behavior of the near-normal shock and the combustion process strongly depends on the conditions of the mixture. In the case of CH_4:O_2:N_2/2.7:2.0:5.7 discussed earlier, as the obturator separates from the projectile, the combustion region also moves downstream behind the projectile and is stabilized there. Even after the obturator is sufficiently away from the projectile, the energy released in the combustion region still thermally chokes the flow immediately behind the projectile and maintains the near-normal shock on the rear part of the projectile, producing continuous projectile acceleration. In the case of CH_4:O_2:N_2/2.7:2.0:15.0, the energy release in the combustion process is too weak to keep the flow behind the projectile thermally choked and to support the near-normal shock on projectile. The shock falls off from the projectile soon after the obturator leaves the projectile base and the projectile acceleration ceases accordingly. On the other hand, in the case of CH_4:O_2:N_2/2.7:2.0:2.0, the energy release is so strong that the near-normal shock is driven upstream through the projectile throat (the widest part of the projectile body). Once the shock overtakes the projectile throat, the high pressure behind the shock rapidly decelerates the projectile. The preceding results clearly show that, at the initiation stage, the energy release rate from the mixture has a strong effect on the thermally choked combustion that supports the near-normal shock.

The initiation process also depends on other parameters such as the fill pressure and obturator mass. A set of simulations was performed for the mixture CH_4:O_2:N_2/2.7:2.0:5.7 at 25 and 100 atm with a 16-g obturator. At 25 atm, thermally choked combustion is successfully established and the near-normal shock is maintained on the rear part of the projectile, resulting in continuous projectile acceleration. At 100 atm, the high fill pressure combined with the energy release from combustion results in a very high pressure on the upstream surface of the obturator, causing the obturator to separate from the projectile base very quickly. This rapid separation generates strong pressure relief behind the near-normal shock. Therefore, the combustion process is significantly weakened and the near-normal shock falls off from the projectile quickly. More information on the obturator separation process is listed in Table 1. Simulations were also conducted using 32- and 48-g obturators in the identical mixture and at the same fill pressures. These simulations further confirm that the obturator separation speed has a strong influence on the thermally choked combustion process. For example, at 25 atm and using the 16-g or 32-g obturators, the near-normal shock is maintained on the rear part of the projectile by the thermally choked combustion at 25 ms, after the projectile enters combustible mixture. On the other hand, with the 48-g obturator, the shock has overtaken the projectile by 25 ms because the obturator does not separate fast enough. At 100 atm, the 16-g obturator separates too fast, resulting in the shock falling off from the projectile at the 25 ms time. However, with the 32-gm obturators, the near-normal shock is still maintained on the rear part of projectile at the 25 ms time. These results are summarized in Table 2. The continuous performance after the initiation stage is beyond the scope of this study and more simulations are needed to analyze further development of the flowfield after the initiation process. Based on the current study, it is evident that parameters such as the fill pressure and the obturator mass have to be considered along with the mixture ratio to achieve successful acceleration. The preceding analysis has demonstrated an effective way to select those parameters for improving the starting process.

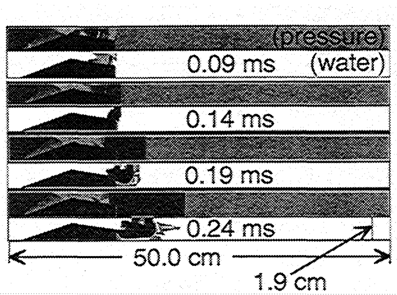

Fig. 2 Pressure and water concentration from the simulation for the CH_4:O_2:N_2/2.7:2.0:5.7 mixture at 50-atm fill pressure at 0.09, 0.14, 0.19, and 0.24 ms after the projectile enters the combustible mixture.

Table 1 Location and separation speed of the 16-g obturator[a]

Fill pressure	25 atm	100 atm
Location from the projectile base	2.45 cm	4.33 cm
Separation speed	240 m/s	593 m/s

Table 2 Location of the near-normal shock[a]

Projectile mass	16 g	32 g	48 g
Fill pressure, atm			
25	On projectile rear part	On projectile rear part	Overtaken projectile throat
100	Fallen of from projectile	On projectile rear part	On projectile rear part

[a]At 25 ms after the projectile enters the combustible mixture with different obturators.

Conclusions

In wide ranges of the mixture ratios, fill pressures, and obturator mass, thermally choked combustion is initiated by the shock generated on the upstream surface of the obturator when the obturator reaches the combustible mixture in the ram-accelerator tube. This occurs as long as the shock generated on the obturator surface is strong enough to ignite the mixture. However, sustainability of the thermally choked combustion and the near-normal shock on the projectile strongly depends on the following two key factors: 1) the energy release rate in combustion process and 2) the separation speed between the obturator and projectile. If energy release in the combustion process is too strong or the obturator does not separate fast enough from the projectile, the shock overtakes the projectile. If energy release is too weak or the obturator separates too fast from the projectile, the shock falls off the projectile. The basic understanding of the initiation mechanism and the additional analyses based on the different simulations discussed in this study provide important guidelines on how to select the different parameters to achieve a sustained near-normal shock and projectile acceleration.

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Noise-Suppressing Nozzle Calculation with Turbulent Viscosity

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Nomenclature

NPR = nozzle pressure ratio, $p_{t,n}/p_a$
p_a = ambient pressure
$p_{t,j}$ = jet total pressure
$p_{t,n}$ = average total pressure at the nozzle entry
x_k, x, y, z = Cartesian coordinates, k = 1, 2, 3

Introduction

THE development of exhaust system for future supersonic transport aircraft is closely connected with jet noise reduction. One of the ways to solve this problem assumes the use of an ejector nozzle, where a noise suppression effect is partly achieved by mixing a high-speed jet with ambient air. Experimental investigation of thrust and acoustic characteristics of a noise-suppressing nozzle (NSN) is a rather difficult task; therefore, it's necessary to combine wind-tunnel tests with numerical simulations. First-stage calculations based on a three-dimensional Euler equation system (EUL) for inviscid compressible perfect gas are published.[1] This Note presents second-stage calculations that use a three-dimensional Favre-averaged Euler equation system describing turbulent flows of inviscid compressible perfect gas, i.e., only free turbulence is considered, boundary layers are not simulated. This equation system is closed using a $(q - \omega)$ model of turbulence.[2] The effects of turbulence compressibility are described by a simple TRB approach.[3] A new version of the computational fluid dynamics (CFD) code has been prepared by Yatskevich. The objective of this publication is to compare results using the same geometry and grid, but different physical models of the flow. It allows one to evaluate the turbulence contribution to NSN integral characteristics.

Basic equations and the CFD method are described in Ref. 1. A mathematical model of the nozzle was created in accordance with the plots for the real experimental model manufacturing.[1] It consists of several parts: duct, lobes, ejector, central body, flaps, etc. The computational grid in the nozzle was constructed with the use of a multiblock approach. The total grid consists of 137 blocks (650,000 cells).[1] The size of the computational cells in the region of mixing is about 1/16 the distance between neighboring lobes. The outer boundaries of the computational domain are distanced from the NSN surface to remove the influence of boundary conditions on the flow inside the nozzle. This distance is equal to the characteristic length of the task, the full length of the NSN model (~0.5 m). The largest computational cells (near the outer boundaries) are approximately 65 times larger than the cells in the region of mixing.

Results of Calculations and Experiments

Calculations were made at different values of nozzle pressure ratio (NPR), and different Mach numbers, M_a, for the ambient flow. The most interesting case for comparison in this

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