Experimental Investigation and Numerical Simulation of Secondary Combustor Flow in Boron-Based Propellant Ducted Rocket

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This paper establishes a two-phase reacting flow model in the secondary combustor of a ducted rocket. The three-dimensional Favre-averaged compressible turbulent N-S equations are used as the governing equations of the reacting flow, the improved $k/\varepsilon$ two-equation turbulence model is used to simulate the turbulent flow, and the eddy break up model is used to simulate the gas combustion. The particle-phase solution is obtained using a well-established boron particle ignition and combustion model. Boron particles are ejected from the exit of the gas generator into a secondary combustor and their trajectories are traced through the reacting flowfield using discrete phase models. The secondary combustion in a cylindrical combustor for the ducted rocket is investigated preliminarily with tests conducted on a connected-pipe ramjet test bed. During the test, boron-based fuel-rich HTPB propellant is used. The effect of factors, such as air/fuel ratio, velocity of air injection and dome height on the performance of the combustor and the engine is examined. The work described in this paper represents an attempt to direct the design of the secondary chamber in order to increase combustion efficiency. The experimental results show that the reacting flow model established in this paper is correct.

Key Words: Ducted Rocket, Secondary Chamber, Boron-Based Propellant, Numerical Simulation, Connected-Pipe Ramjet Test

Nomenclature

$\phi$: general dependent variable
$\Gamma_\phi$: exchange coefficients
$s_\phi$: source terms
$C_{EBU}$: constant for the eddy break up model
$n$: combustion efficiency of the secondary chamber
$Y_f$: mass fraction of fuel
$Y_o$: mass fraction of oxidant
$Y_p$: mass fraction of product
$c_{th}$: theoretical characteristic exhaust velocity
$c_{ex}$: experimental characteristic exhaust velocity
$A_t$: nozzle throat area
$P_c$, $P_{ram}$: chamber pressure in secondary combustor
$P_g$: chamber pressure in gas generator
$m_{fg}$: total mass flow rate in the secondary combustor

1. Introduction

Replacement of a significant of oxidizer in solid propellant with free stream air, as in the ducted rocket concept, offers a more the five to one increase in missile range capability. The ducted rocket, which combines the advantages of solid propellant rocket and ramjet propulsion, is a kind of new and combinatorial propulsion system. It offer considerable advantages for missile propulsion, such as high specific impulse, high speed, light weight, increased range, mobile performance and simple structure. As the major direction of the propulsion system for supersonic missile, the ducted rocket has good prospects.

Boron has been considered for many years as a prime candidate for use to increase the ducted rocket capabilities based on its high potential energy release coupled with a high energy of combustion, high combustion temperature, and low molecular weight products. These properties make boron an attractive material for use in ducted rocket propellants. In order for these advantages to be realized, however, the boron particles must ignite and burn completely within a very limited residence time. Since boron particles are generally initially coated with an oxide layer to inhibit combustion and since boron has an extremely high boiling point, which necessitates surface burning subsequent to oxide removal, this can become difficult, particularly under adverse operating conditions.

Previous investigations relevant to the ducted rocket secondary combustor have been performed by several research groups. Chuang et al. studied the flowfield in a two-dimensional ducted rocket combustor with glass windows employing laser light-sheet for flow visualization and a laser doppler velocimeter (LDV) for velocity measurement. This work showed that the ducted rocket secondary combustor flowfield pattern depends strongly on the mass flux of the ram air and the momentum ratio of ram air to fuel-rich gas. Lazar et al. conducted a cold flow study on a typical secondary combustor of ramjet to understand the influence of various inlet parameters such as primary nozzle configuration, secondary air injection angle and flow Reynolds numbers on the secondary combustor performance. Brophy and Hawk employed water flow visualization to investigate the mixing and combustion processes inside a four-inlet side dump combustor. It was shown that for inlet angles...
greater than 60 deg, the geometries intrinsically direct a significant portion of the inlet flow towards the dome head region without the need for diverter devices. Vanka et al.\(^7\) solved the three-dimensional reacting flow equations with combustion processes modeled by a one-step chemical reaction scheme. Detailed flow structure, fuel dispersal patterns and temperature fields were calculated for a ducted rocket with two side inlets. Chao et al.\(^8\) numerically studied the turbulent reacting flow in a solid-propellant ducted rocket. This work focused on the feasibility of the turbulence models and combustion models on the ducted rocket.

Although the aforementioned work has provided considerable information to aid in the understanding of flow and combustion process in secondary combustors, many fundamental issues regarding the detailed mixing and combustion process, especially in the secondary combustor of the ducted rocket when boron-based fuel-rich HTPB propellant is used, still need to be addressed.\(^9\)–\(^12\) Though the ignition and combustion of boron particles in an oxidizing, temperature-controlled atmosphere have been the subject of interest of numerous studies, there have been only a few publications that provide information on boron particles behavior inside the secondary combustor of a ducted rocket. In view of this, a research program involving both experimental and numerical approaches is initiated. This paper is aimed at providing the complete details of the combustion processes and flow-fields in the secondary combustor and seeking ways to improve the combustion efficiency in order to provide a theoretical basis and direction for the design of the secondary combustor.

2. Theoretical Treatment

The dual-inlet side-dump combustor consists of two rectangular inlet ducts, a chamber, a nozzle and a gas generator. The schematic figure of the secondary combustor is shown in Fig. 1. The four rectangular inlet ducts intersect the combustor at an angle \(\theta\) of 60 deg. The centerline of both inlet ducts intersects the combustor at the same axial station and is located at 90 deg to each other. The gaseous flowfields are treated using an Eulerian approach and determined using Navier-Stokes equations. The motion of the particle is governed by the Lagrangian equation of the motion of a rigid sphere. The particle is under the influence of the local environment produced by the continuous phase.

2.1. Gas flow computation

The computations are performed by numerically solving the fully three-dimensional Navier-Stokes equations, since flow recirculation is expected to be three-dimensional. To simplify the problem, the flow is considered to be steady-state in mean, and the wall boundary is considered to be adiabatic.\(^7\) The turbulent flux (Reynolds) equations of conservation of mass, momentum, stagnation enthalpy and chemical species may all be taken in the common form:

\[
\frac{\partial}{\partial t} \left( \rho \phi \right) + \text{div}(\rho \mathbf{u} \phi - \Gamma_\phi \text{grad} \phi) = s_\phi
\]

where the exchange coefficient assumptions have been invoked. Here, \(\phi\) is a general dependent variable and equations may be solved for \(\phi\) equal to time-mean axial, radial and swirl velocities \(u, v, w\), stagnation enthalpy \(h\), chemical species mass fraction \(Y_{fu}\), turbulent kinetic energy \(k\) and dissipation rate \(\varepsilon\). The equations differ not only in their exchange coefficients \(\Gamma_\phi\) but also in their final source terms \(s_\phi\). Specific details about the equations may be found in Ref. 7).

Even though the fast-chemistry model contains many important aspects of diffusion flames, finite-rate reactions based on multi-step mechanisms must be taken into account if more information is desired concerning detailed flow structures and heat-release distribution. For simplicity, a one-step global reaction scheme is employed to describe the combustion of fuel-rich gases with air in this work, represented as

\[
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}.
\]

The reaction rate is determined by the eddy break up (EBU) model.

\[
R_{fu,EBU} = C_{EBU} \rho^2 \frac{1}{k} \varepsilon
\]

where the constants in the EBU model are taken from Ref. 8) and are summarized as follows: \(C_{EBU} = 0.35-0.4\) and

\[
g = \min \left( \frac{Y_{fu}}{\beta}, \frac{Y_{pr}}{1 + \beta} \right),
\]

and \(\beta\) is the stoichiometric ratio.

The spatial accuracy of numerical schemes for finite difference or finite volume Navier-Stokes solvers applied to
convection dominated flow problems depends strongly on the order of approximation in discretizing the convection fluxes. In recent years, many numerical schemes have been developed for high-speed flows based on the concept of upwind differencing. The splitting schemes, the flux difference schemes and central plus artificial dissipation schemes are the most commonly used. All these schemes approximately follow the characteristics of the flow by an upwinding of the convective terms of the continuity, momentum and energy equations. The convergence criterion is imposed on the gas flowfields calculation. It is superimposed on the gas flowfields calculation.

During the simulations, the stagnation temperature of air is 573 K, stagnation pressure of air is 5.7 atm, the stagnation temperature of fuel-rich gas is 2132 K, and the stagnation pressure of fuel-rich gas is 5.7 atm. The fuel-rich gas consists of CO, CH, and H, the mass fraction of which are 0.1501, 0.6659 and 0.184, respectively.

The combustion efficiency of the fuel-rich gas phase in the secondary combustor, \( \eta_{d,g} \), is defined by

\[
\eta_{d,g} = \frac{m_{CH_4}^{in} - m_{CH_4}^{out}}{m_{CH_4}^{in}} = 1 - \int_\epsilon \rho \mu Y_{d,g} \, dA
\]

where \( Y_{d,g} \) is the mass fraction of CH4, and \( m_{d,g} \) is the mass flow rate of the fuel-rich gas phase. In order to obtain the whole combustion efficiency of the fuel-rich gas phase in the secondary combustor, the integration surface is the exit of the nozzle.

### 2.2. Particle distribution computation

After the ejection of the boron particles from the gas generator nozzle to the gas flow in the secondary combustor, their motion is dominated by the drag force resulting from the velocity difference between the gas and the particle.13)

\[
\frac{d\vec{X}_p}{dt} = \vec{V}_p
\]

\[
\frac{d\vec{V}_p}{dt} = \vec{F}_p
\]

where

\[
\vec{F}_p = \frac{3}{4} \frac{c_D \rho}{\rho_p d_p} (\vec{V} - \vec{V}_p) |\vec{V} - \vec{V}_p|
\]

\[
c_D = \begin{cases} 
\frac{24}{Re_p} \left( \frac{1}{6} \frac{Re_p^{1/2}}{Re_p < 1000} \right) & Re_p < 1000 \\
0.44 & Re_p \geq 1000.
\end{cases}
\]

Considering King’s model for the ignition stage, the following equations can be written:

\[
\frac{dR}{dt} = -\frac{w_B M_B}{4\pi R^2 \rho_B}
\]

\[
\frac{dX}{dt} = \frac{(w_B/2 - w_B - w_H) M_{B_2} O_3}{4\pi R^2 \rho_{B_2} O_3}
\]

\[
\frac{dT_p}{dt} = \frac{Q_1}{4\pi R^3 \rho_B c_{pB}/3 + 4\pi R^3 X \rho_{B_2} O_3, c_{pB}/3}
\]

\[
\frac{df}{dt} = \frac{Q_1}{4\pi R^3 \rho_B M_H/3}
\]

\[
\frac{dT_p}{dt} = \frac{Q_2}{4\pi R^3 \rho_B c_{pB}/3 + 4\pi R^3 X \rho_{B_2} O_3, c_{pB}/3}
\]

\[
Q_1 = w_B Q_{RX} - w_E \Delta H_{vap} - w_{H} \Delta H_{H_1} + 4\pi (R + X)^2 \left[ h(T_\infty - T_p) + \sigma \varepsilon \alpha R \left( T_{RAD}^d - T_p^d \right) \right]
\]

\[
Q_2 = w_B Q_{RX2} - w_E \Delta H_{vap} - w_{H} \Delta H_{H_1} + 4\pi (R + X)^2 \left[ h(T_\infty - T_p) + \sigma \varepsilon \alpha R \left( T_{RAD}^d - T_p^d \right) \right]
\]

Specific details about the equations may be found in Ref. 10).

Where and if the oxide thickness reaches zero, the particle ignites (or enters the second stage of combustion) and combustion starts. Assuming that the rate of combustion is controlled by oxygen diffusion, the molar consumption rate of boron is given by10)

\[
R_{CB} = 4\pi \rho_p \rho D \ln(1 + 0.667 Y_{O2}) / \rho_B.
\]

A special routine is developed to solve the particle behavior, i.e., motion, temperature and chemical reactions, as a result of the interactions with the surrounding gas. It is superimposed on the gas flowfields calculation.

Boron combustion efficiency is defined by

\[
\eta_B = \frac{\text{reacted boron}}{\text{total boron}}.
\]

There are many kinds of gases and particles in the fuel-rich gas, and the whole combustion efficiency of the fuel-rich gas is defined by
where $\alpha$ is the mass fraction of the boron particle phase in the fuel-rich gas, and $Q_{i,g}$ and $Q_B$ are the reaction heat of CH$_4$ and boron, respectively.

3. Experiment Apparatus

The experiments are conducted on a connected-pipe ramjet test bed. Test apparatus is shown in Fig. 2. The compressed air from the front passes the measuring section, and enters the secondary combustor where the ram air and hot fuel-rich gas from the gas generator carry out mixing and reburning. Then, the secondary combustion products are emitted through a Laval nozzle to the atmosphere.\textsuperscript{14}

During the test, boron-based fuel-rich HTPB propellant is used. The propellant consists of 40% ammonium perchlorate (AP) as an oxidizer, 20% hydroxy terminated polybutadiene (HTPB) as a binder and 40% boron (B). The particle size of B within the propellants are approximately 5 $\mu$m in diameter. The pressure in the gas generator and secondary combustor, and in the airflow channels is measured with pressure transducers (PT301 made by Hefei Zhongya Sensor Limited Company). The combustion efficiency of the secondary combustor, $\eta_{c^*}$, is defined by

$$\eta_{c^*} = c_{ex}^*/c_{th}^*$$

where $c_{th}^*$ is the theoretical characteristic exhaust velocity and $c_{ex}^*$ is the experimental characteristic exhaust velocity. It is shown that $c_{ex}^*$ is given by

$$c_{ex}^* = A_P P_c / m_g$$

where $A_p$ is the nozzle throat area, $P_c$ is the chamber pressure and $m_g$ is the total mass flow rate in the secondary combustor. The theoretical characteristic exhaust velocity is determined by the thermo chemical condition in the secondary combustor.

The specific impulse of the ducted rocket, $I_{sp}$, is defined by

$$I_{sp} = I_{sp,g} - rV_{air}$$

where $r$ is the air/fuel ratio, $V_{air}$ is the air flow velocity (the flight speed) and $I_{sp,g}$ is the ground experimental specific impulse given by

$$I_{sp,g} = F/m_g$$

where $m_g$ is the mass flow rate in the gas generator and $F$ is the ground experimental thrust of the ducted rocket. Thrust measuring components include leaf springs, a flexible universal joint and a thrust meter.\textsuperscript{15} Through a flexible universal joint, the movable frame is connected to a thrust meter (model BLR-12 made by Hefei Zhongya Sensor Limited Company) with a maximum range of 1000 N.

4. Results and Discussion

The effect of factors, such as air/fuel ratio, Mach number of air injection and dome height on the performance of the combustor and the engine is examined. With computations and analysis, the comprehension on the mixing and combustion process is increased, and some significant results are listed below.

4.1. Effect of air/fuel ratio

Efforts are made to study the effect of the air/fuel ratio on the ducted rocket secondary combustor while keeping other operating conditions constant. The maximum combustion efficiency occurs under conditions that tend to completely burn the fuel-rich gas injected from the gas generator prior to the ducted rocket secondary combustor.

Figure 3 shows the experimental scene of a connected-pipe ramjet test facility. Figure 4 shows a SEM photo of a sample of condensed combustion products in the exhaust plume. It may be seen that the diameter of B$_2$O$_3$ is less 5 $\mu$m.

Table 1 shows the experimental case for the effect of the air/fuel ratio. It is shown that increasing the air/fuel ratio increases combustion efficiency. But if the ratio is too big, too much cold air is injected into the ducted rocket secondary combustor, and it will tend to reduce the temperature and worsen the combustion efficiency. Figure 5 shows the effect of the air/fuel ratio on the distribution of particle diameter in the secondary combustor. The ignition event of the boron particles, characterized by the complete removal of the oxide layer, is affected by thermal and chemical factors influencing this process. High air/fuel ratio results in particle trajectories close to relatively low surrounding gas temperature. Further increase the air/fuel ratio above a certain value may result in a failure of the boron particles to ignite. In general, larger boron particles exhibit longer
ignition delay. At high air/fuel ratio, it may be seen that increasing the air/fuel ratio decreases combustion efficiency.

4.2. Effect of the dome height

The dome height influences the mixing process through changes to the recirculation flow in the dome region. Table 2 shows experimental case for the effect of the dome height. Figure 6 shows the effect of the dome height on the distribution of the particle diameter in the secondary combustor. Figure 7 shows the effect of the dome height on the temperature and oxygen mass fraction along the axis. It may be seen that decreasing the dome height increases combustion efficiency. Apparently, the increased length of the dome region does not increase the bifurcating flow but also decreases overall mixing because of the smaller combustor length available downstream of the air inlet. But the dome height influences the mixing process through changes to the recirculation flow in the dome region. At 0-m dome height (i.e., the side arms are flush with the dome plate), the recirculation flow in the dome region is markedly decreased and most of air flows directly to the exit nozzle. The mixing is therefore reduced, and combustion efficiency is small. It shows that there is an optimum dome height.

| Table 1. Experimental case for the effect of the air/fuel ratio. |
|---------------------------------------------------------------|
| No. 1 No. 2 No. 3 No. 4                                      |
| Grain regression rate (mm/s)                                    |
| Fuel mass flow rate (kg/s)                                     |
| Air mass flow rate (kg/s)                                      |
| Air/fuel ratio                                                |
| Pressure in gas generator (MPa)                               |
| Pressure in secondary combustor (MPa)                         |
| Characteristic exhaust velocity (m/s, experiment)             |
| Characteristic exhaust velocity (m/s, theory)                 |
| Combustion efficiency (%)                                     |
| 3.8198 4.0685 1.5985 0.9287                                   |
| 0.0251 0.0221 0.0055 0.0054                                   |
| 0.2544 0.3301 0.1616 0.1905                                   |
| 10 15 29 35                                                   |
| 0.7126 0.8621 0.2631 0.2785                                   |
| 0.7043 0.8240 0.2647 0.2811                                   |
| 872.7698 810.2191 746.7557 676.2435                           |
| 1111.400 998.4020 838.1097 804.6686                           |
| 78.53 81.15 89.10 84.04                                       |

| Table 2. Experimental case for the effect of the dome height. |
|---------------------------------------------------------------|
| L1 0.8 Dc 1.6 Dc 2.4 Dc                                       |
| L2 1.6 Dc 2.4 Dc 3.2 Dc                                       |
| A1 60° 60° 60°                                             |
| A2 60° 60° 60°                                             |
| Pressure in gas generator (MPa)                              |
| Pressure in secondary chamber (MPa)                          |
| Characteristic exhaust velocity (m/s, experiment)            |
| Characteristic exhaust velocity (m/s, theory)                |
| Burning rate of propellant (mm/s)                            |
| Air/fuel ratio                                               |
| Expulsion efficiency (%)                                     |
| Combustion efficiency (%)                                    |
| 0.46 0.44 0.43                                              |
| 0.45 0.43 0.42                                              |
| 915.74 857.86 853.58                                         |
| 968.20 936.90 949.38                                         |
| 1.77 1.62 1.62                                              |
| 20.11 22.21 21.34                                           |
| 95.66 93.19 92.47                                           |
| 94.58 91.56 89.91                                           |
4.3. Effect of the air and fuel gas injection Mach number

Table 3 shows the computational case for the effect of the air and fuel gas injection Mach number. In each case, the air and fuel mass flow rate are essentially the same. The first case has a small air/fuel momentum ratio, and the other three have the same high air/fuel momentum ratio. Figures 8 and 9 show the distribution of CH$_4$ species and temperature (K) in the secondary combustor at some different cross-sections. It is observed that the fuel jet would partially penetrate the inlet flow column when the momentum ratio is small. The fuel jet is seen to “bend back” and follow the governing “inlet flow” for the high momentum ratio. This has the effect of increasing the air/fuel momentum ratio as compared to case 1, so the air jets are much more intense and abruptly cut off the fuel jet. Thus, the combustion efficiency of the first case is much smaller than that of the other three cases having high momentum ratio. Comparing with case 2, a combination of smaller air and fuel injectors is therefore modeled (case 3). High turbulent levels, which are associated with high flow velocities, along with well-chosen air/fuel momentum ratio, are necessary...
for good mixing. The results indicate that high injection velocities promote better mixing as long as the air/fuel momentum ratio is high enough to prevent the fuel jet from passing through the air inlet section. But high injection velocities mean the residence time is so small that the fuel cannot burn out and the combustion efficiency is still small. Good mixing of air and fuel in the secondary combustor is a prerequisite for efficient combustor performance. Since mixing occurs on the interface between the air and the fuel, maximizing this interface is desirable. Increasing the gas generator nozzle number means maximizing this interface, in which case the combustion efficiency of case 4 is higher than that of case 3.

Table 4 shows the experimental case for the effect of air injection Mach number. It is observed that the combustion efficiency is small when the air injection velocity is high, which corresponds quite well with the computational fluid dynamic (CFD) modeling result. The unchoked ducted rockets use the unchoked gas-generator design to ensure the self-regulation of the fuel-rich gas flow.
5. Conclusions

The work presented in this paper further characterized the internal flowfields of two-inlet ducted rocket engine geometries. Important conclusions are as follows:

1) The air/fuel momentum ratio is a critical parameter for describing the flowfield in the secondary combustor.
2) Increasing gas generator nozzle number can improve combustion characteristics in the dome region and produce good conditions for combustion progress.
3) When the speed of fuel streams increased, the intensity and temperature of the recirculation region improved. While the speed is very large, the fuel-air mixing behind the airstream is decreased and the span of the fuel flow in the second combustor is reduced, so the combustion efficiency is decreased.
4) Increasing the air/fuel ratio within a proper range can increase the combustion efficiency.
5) The dome height influences the mixing process through changes to the recirculation flow in the dome region.

Information gained from CFD modeling and the direct-connect combustion tests will provide future engine designers with valuable information regarding the design of two-inlet ducted rocket engine systems and a methodology that may be used to investigate these and other new air-breathing propulsion systems.

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