고체 램제트 추진기관에서 보론 카바이드 연료의 연소, 성능 특성

이태호*

Combustion and Performance Efficiency of Boron Carbide Fuel in Solid Fuel Ramjet

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ABSTRACT

An experimental investigation was conducted to investigate the effects of the equivalence ratio and air mass flux on the combustion efficiency in a solid fuel ramjet used fuel grains which were highly loaded with boron carbide. Combustion efficiency increased with increasing equivalence ratio (grain length), and decreasing air mass flux. Higher inlet air temperature produced higher combustion efficiencies, apparently the result of enhanced combustion of the larger boron particles those burn in a diffusion controlled regime. Short grains which considered primarily of the recirculation region produced larger particles and lower combustion efficiencies.
The result of the normalized combustion efficiency increased with inlet air temperatures coincident with the result of the Brayton cycle thermal and the total efficiency relating to the heat input.

초 록

보론 카바이드를 함유한 고체연료 그레인을 사용하여 당량비와 공기 질량 유속에 따라 연소 효율이 어떻게 변하는가를 조사하였다. 연소 효율은 당량비의 증가 방향과 질량유속 감소 방향에 따라서 증가하였다. 높은 흡입온도가 높은 연소 효율을 보이는데 이는 확산 영역에서 큰 보론 입자들의 연소 증진 결과이다. 재순환 영역으로 주로 이루어진 짧은 그레인에서는 큰 보론 입자의 형성으로 연소 효율은 감소하고 있다. 흡입 온도에 따라 증가하는 연소 효율은 흡입온도 증가에 따라 일반적으로 열역학적 사이클의 효율이 감소하는 것과는 상반되는 방향이나 실험적 결과를 해석할 때 합당한 결과로 나타나고 있다.

Key Words: Equivalence Ratio(당량비), Inlet Temperature(흡입온도), Recirculation Region(재순환 영역), Brayton Cycle(브레이톤 사이클)

1. Introduction

The use of metals such as boron or boron-carbide introduced to the polymeric fuel of a

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solid ramjet may theoretically provide a better energetic performance of the motor together with increased fuel loading. However, extracting the energetic potential from boron or boron-carbide is difficult task due to the complicated ignition and combustion process of the boron and boron-carbide particles.

The solid fuel ramjet combustor is divided into three regions;

1. the head-end region behind the inlet step (approximately 6-7 step heights in length), characterized by a separated, recirculating, fuel rich flow that serves as a flame-holder.
2. the boundary layer region, downstream of reattachment and along most of the grain, where a diffusion between the volatile fuel vapor or decomposition products and oxygen is established within the developing turbulent boundary layer, and
3. the rear-end region (the aft-mixing-chamber), where no fuel is placed and extensive chemical reactions take place because of the better mixing and additional residence time.

The latter region is usually of significant length in order to accommodate adequate solid propellant for integral-rocket-ramjet booster.

The fuel regression rate depends on the convective and radiative heat transfer to the fuel surface, and is primarily a function of the air mass flux and inlet air temperature. In the recirculation zone the regression rate is significantly less than the regression rate in the boundary layer region since the flow velocity and temperature in thehead-end region are considerably lower.

The combustion behavior of the solid fuel ramjet is reasonably well understood. In the metallized fuels the particles tend to accumulate and agglomerate on the fuel surface before they are ejected into the gaseous flow. In addition the surface may produce large flakes which are ejected onto the flow. The mechanism of the agglomeration process and the parameters that control it are virtually unknown, nevertheless it seems that the particles produced in the recirculation zone are considerably larger than those in the boundary layer region. The larger metal particles or agglomerates are difficult to ignite and also require a high residence time in the combustion chamber to complete their burning.

The objective of the present study was to investigate experimentally the effect of various parameters, such as inlet flow conditions, air mass flux, geometry and equivalence ratio (grain length) on the combustion efficiency.

2. Experimental Apparatus

A sub-scale 63 mm coaxial dump, axi-symmetric combustor configuration wastested in the direct connected mode. The fuel grain was bolted between the inlet and aft mixing chamber. In order to reduce heat loss through the combustor wall, the mixing chamber was insulated with DC93-104 a Dow Corning ablative material with good high temperature characteristics. A sonic nozzle with graphite insert was bolted onto the aft mixing chamber (Fig. 1).

In the NPS (Naval Postgraduate School) facility air flows from high pressure, 2.07×10^4 kPa storage tank through a choked nozzle to an air heater. Methane and ethylene were used as fuels for the air heater

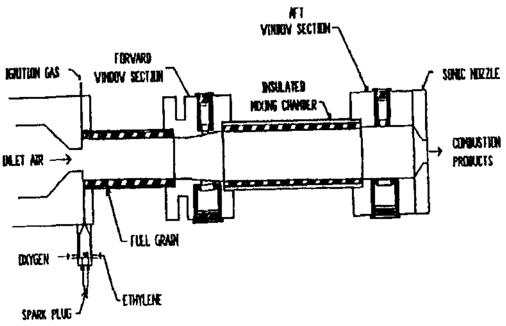

Fig. 1 Schematic of SFRJ combust

and oxygen was injected downstream of the heater to ensure that vitiated air contained 23% oxygen by mass(Fig. 2).

The heater was acoustically isolated from the ramjet combustor with a sonically choked orifice. Air was bypassed to the atmosphere until the heater temperature had stabilized. At this time air was switched to the combustor, initiating a computer controlled sequence of events in which the fuel grain was preheated for approximately 4 seconds, the ramjet combustor was ignited and sustained for the desired burn time, and finally quenched at the end of the test. The air heater was aborted immediately after burn ended. The ethylene oxygen torch ignited the ignition gas (ethylene gas injected into the recirculation zone) which in turn ignited the ramjet fuel grain. Approximately 1 second ignition time was required for good ignition. Nitrogen gas was used to quench the fuel (Fig. 3).

HTPB and boron carbide/HTPB were used as a solid fuel ramjet fuels. Both fuels were supplied by the Naval Weapons Center, China Lake, CA. HTPB was baseline fuel for the performance comparisons.

Instrumentation for determining combustor performance consisted of combustor static pressure, inlet air temperature, flow rates and

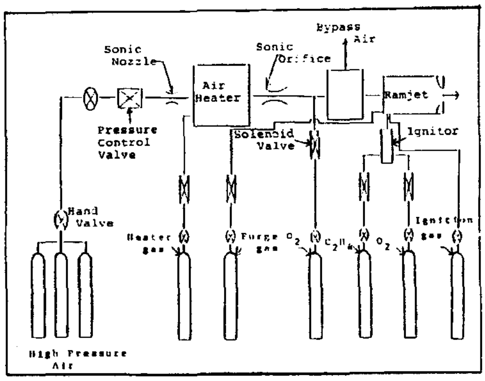

Fig. 2 Schematic diagram of the test facilities

thrust measurements.

3. Procedures

Two series of tests were conducted to investigate the effects of the equivalence ratio and air mass flux on combustion efficiency. The first series (18 tests) emphasized the effect the equivalence ratio (or grain length) while air mass flux was kept constants. The second test series (21 tests) investigate the effect of inlet air mass flux at equivalence ratio approximately 0.4.

An effort was made to keep other parameters, such as combustion pressure and particle residence time, constant. Inlet air

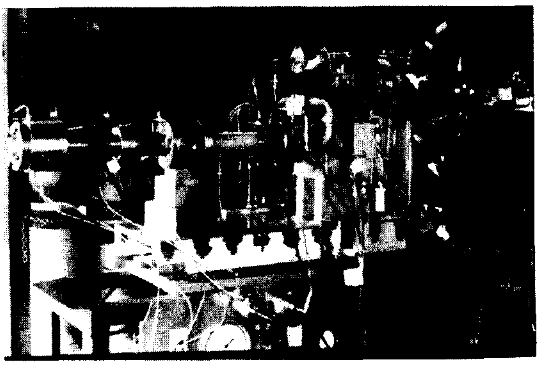

Fig. 3 Experimental set-up of SFRJ

temperature varied between 560-780'K. The approximate combustor residence time was determined from mean combustor length, the theoretical adiabatic combustion temperature and measured pressure at the entrance to the nozzle. This residence time is lower than the actual residence time of the particle in the combustor. Nevertheless, it can be used for comparison purposes. The residence time varies 3 and 4 seconds during tests. The nozzle throat diameter was sized to maintain nominal combustion pressure between 550 and 690 kPa.

The desired equivalence ratio was obtained by cutting the fuel grain to the approximate length. The required fuel grain length at an initial port mass flux of 35 g/㎠ · s ranged from 76 mm to 330 mm. The fuel grains had nominal initial port diameter of 43 mm. Mixing chamber length was also varied in an attempt to keep the residence time nearly constant for any one set of tests

4. Results and Discussion

The data for normalizes combustion efficiency for two test series are plotted against the equivalence ratio in Fig. 4.
This combustion efficiency was determined from the calculated temperature rise based on the static pressure at the end of the mixing chamber and normalized by the reference combustion efficiency.

In general, inefficiencies were assumed to be only due to metal because the mixing length was long enough for complete burning of the HC fuel.

The combustion efficiency increased with equivalence ratio (Fig. 4). In order to change the equivalence ratio from test to test the grain length was changed. In short grains the recirculation zone covers a great part of the grain, while in long grains the combustion occurs mainly in the boundary layer region.

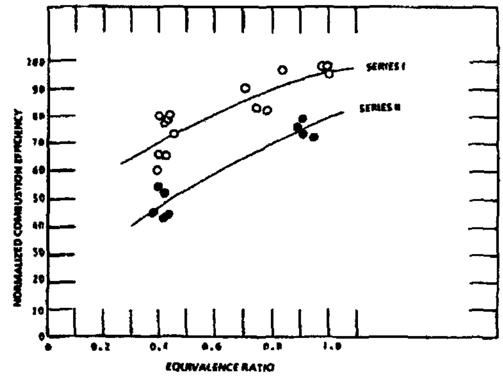

Fig. 4 Normalized combustion efficiency vs equivalence ratio

The normalized combustion efficiency decreased with increasing air mass flux. Again the different results for tests series 1 and 2 appeared to be due to the different inlet air temperatures.

The air mass flux was changed by changing the air mass flow rate. In order to keep a constant equivalence ratio the fuel grain length was changed accordingly. Also the mixing length was changed in order to keep an approximately constant particle residence time.

The recirculation zone for all tests series 2 was approximately the same, however the thickness of boundary layer and the position of the flame zone relative to the fuel surface varied with the air mass flux.

A regression analysis was employed for the combustion efficiency and following correlation expression is represented all the data.

$$\eta_B = 1.1\times10^{-7}\phi^{0.5}G^{-0.61}T_2^{2.17} \quad (1)$$

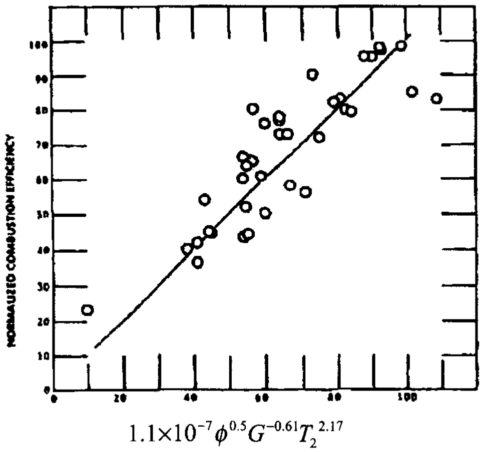

Fig. 5 Normalized combustion efficiency

T_2 is the combustor inlet temperature. The normalized combustion efficiency for the test series are plotted with respect to regression Eqs. (1) in Fig. 5.

If the fuel flow rate is much less than the air mass flow rate, we can assume the following heat balance equation

$$m_a q = \eta_B m_f H_f \quad (m_f \ll m_a) \tag{2}$$

This equation gives us that the combustion efficiency will affect the heat input q.

In general it is well known analysis that the

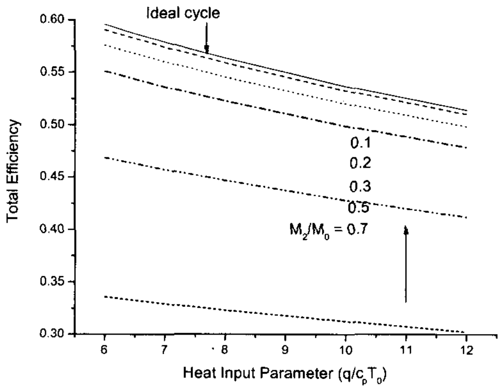

Fig. 6 Total efficiency vs heat input parameter

cycle engine performance efficiency decreases with increasing inlet temperature. But in this experimental tests, the combustion efficiency increases with increasing inlet air temperature. If combustion efficiency increases, does total (performance) efficiency increase also or not ?

In the Brayton cycle (which is simplified ramjet cycle) thermal efficiency is increased and total efficiency of the ramjet is decreased respectively with heat input parameter q/c_pT_0 [10].

$$\eta_{th} = \frac{V_e^2 - V_0^2}{2q} = 1 - \frac{1}{q/c_pT_0}\left(\frac{T_e}{T_0} - 1\right) \tag{3}$$

$$\eta_{tot} = \frac{(\gamma-1)M_0^2}{q/c_pT_0}\left[\sqrt{1 + \frac{q}{c_pT_0}\frac{1-\left(\frac{M_2}{M_0}\right)^2}{1+\frac{\gamma-1}{2}M_0^2}} - 1\right] \tag{4}$$

Above Eqs. (3) and (4) are Brayton cycle thermal and total efficiency ones through thermodynamic analysis. We can see that the thermal efficiency will increase if heat input 'q' increases for fixed T_0, which is increasing heat input parameter q/c_pT_0 by seeing Eqs. (3) directly but performance efficiency is decreased with this heat input parameter like as shown in Fig. 6.

It is noted that 'q' itself depends on the combustion efficiency, η_B (Eqs. (5)) which is increased with the combustor inlet temperature strongly more than power 2 from the experimental results.(Eqs. (1))

$$\frac{q}{c_pT_0} = \phi\left(\frac{m_f}{m_a}\right)_{st}\frac{\eta_B H_f}{c_pT_0} \tag{5}$$

If we assume the adiabatic flow from free stream to the combustor inlet and low mach number then,

$$T_2 \; ; \; T_{st} = T_0(1+\frac{\gamma-1}{2}M_0^2) \tag{6}$$

Now we can see the performance efficiency through semi-experimental result by using Eqs. (1), (5), and (6). From these equations

$$q/_{c_pT_0} = \alpha\frac{T_0^{2.17}}{T_0} = \alpha T_0^{1.17} \tag{7}$$

Where α is length equation including the other parameters for the fixed given condition.

It means that the combustion efficiency is increased with increasing (combustor) inlet air temperature but performance efficiency is decreased, because high inlet air temperature results in high heat parameter Eqs. 7, which is same trend as the general thermodynamic cycle engine performance.

5. Concluding Remarks

Combustion efficiency increased with increasing equivalence ratio (grain length), and with decreasing air mass flux. The larger particles were the result of surface agglomeration, primarily within the recirculation zone. Short grains that consisted mainly of the recirculation region produced larger particles and lower combustion efficiencies.

Higher inlet air temperature produced higher combustion efficiencies, apparently the result of enhanced combustion of the larger boron particles that burn in a diffusion controlled regime.

The total efficiency is decreased with increasing air inlet temperature.

Therefore the higher inlet air temperature gives higher combustion efficiency and this results in higher heat input parameter but this higher heat input parameter gives lower performance efficiency for this metallized solid fuel ramjet.

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