Combustion Efficiency of Boron Carbide Fuel Solid Fuel Ramjet

Tae-Ho Lee
Propulsion Department Agency for Defence Development
Daejeon, Korea

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 temperature, is coincident with the result of the Brayton cycle thermal and the total efficiency relating to the heat input.

Introduction

The use of metals such as boron or boron-carbide introduced to the polymeric fuel of a solid ramjet may theoretically provide a better energetic performance of the motor together with increased fuel loading. However, extracring 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 intergral-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 the head-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.

Experimental Apparatus

A sub-scale 75 mm coaxial dump, axisymmetric combustor configuration was tested 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. In the NPS facility air flows from high pressure (3000 psi) storage tank through a choked nozzle to an air heater. Methane and ethylene were used as fuels for the air heater and oxygen was injected downstream of the heater to ensure that vitiated air contained 23% oxygen by mass.

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 computor 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.

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.

Instrumentaion for determining combustor performance consisted of combustor static pressure, inlet air temperature, flow rates and thrust measurement.

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 inlet air temperature, combustion pressure and particle residence time, constant. Inlet air temperature varied between 1080-1400'R. 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 2.9 and 4 seconds during tests. The nozzle throat diameter was sized to maintain nominal combustion pressure between 80 and 100 psia.

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 0.5lbm/in s ranged from 3 inches to 13 inches. The fuel grains had nominal initial port diameter of 1.7 inches. Mixing chamber length was also varied in an attempt to keep the residence time nearly constant for any one set of test.

Results and Discussions

The experimental results of test series 1 and 2 are presented in tables 1 and 2 respectively. The data for normalizes combustion efficiency for two test series are plotted against the equivalence ratio in figure. 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 a 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. 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.

It is notified very interesting result if we consider the following equation;

$$m_a q = \eta_B m_f H_f \qquad (1)$$

$$\eta_B = {m_f H_f}/{m_a q} \propto {\phi H_f}/{q}$$

This equation gives us that the combustion efficiency is inversely proportional to the air mass flow rate, which is expressed in the equivalence ratio implicitly and that is proportional to the equivalence ratio. The experimental results show same trend like as the combustion efficiency increases with the equivalence ratio and that means decreases with the air mass flux.

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.

A regression analysis was employed and the results did in fact show strong effect of the inlet air temperature. 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.

Here we have very interesting result which shows in references 11, 12 that the BRAYTON cycle thermal efficiency is increased and total efficiency of the ramjet is decreases respectively with heat input q/c_pT_0.

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

$$\eta_{tot} = \frac{(\gamma-1)M_0^2}{{q}/{c_pT_0}}\left[\sqrt{1 + \frac{q}{c_pT_0}\frac{1-\left(\frac{M_2}{M_0}\right)^2}{1+\frac{\gamma-1}{2}M_0^2}} - 1\right] \qquad (3)$$

It is noted that 'q' itself depends on the combustion efficiency η_B, which increases with the inlet air temperature strongly more than power 2.

Therefore, the heat input parameter will increase like as following equation.

$$\frac{q}{c_p T_0} = \phi\left(\frac{m_f}{m_a}\right)_{st} \frac{\eta_B H_f}{c_p T_0} \qquad (4)$$

It means that the dependence of the total efficiency is much large because the heat input parameter value increases with the increasing inlet air temperature with together combustion efficiency itself.

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 experimental results show that the combustion efficiency trend is same as the results of the thermodynamic cycle analysis, which decreases with the air mass flux.

The total and thermal efficiency of the ramjet based on thermodynamic cycle analysis decreases with the heat input parameter which is reversely proportional to the inlet air temperature for the given heating value fuel. Therefore the ramjet efficiency will be increases with the inlet air temperature which will decrease the heat input parameter.

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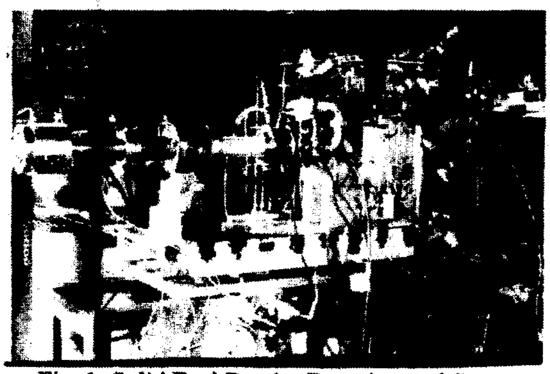

Fig. 1. Solid Fuel Ramjet Experimental Setup

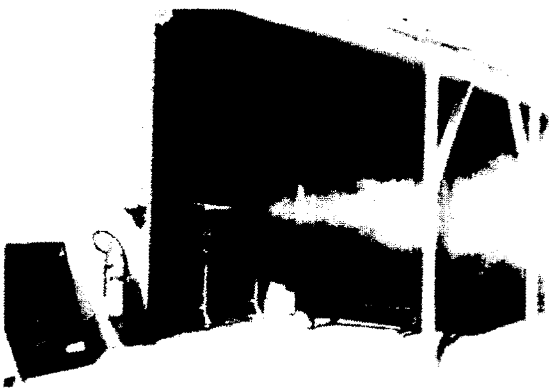

Fig. 2. Static Test Fire

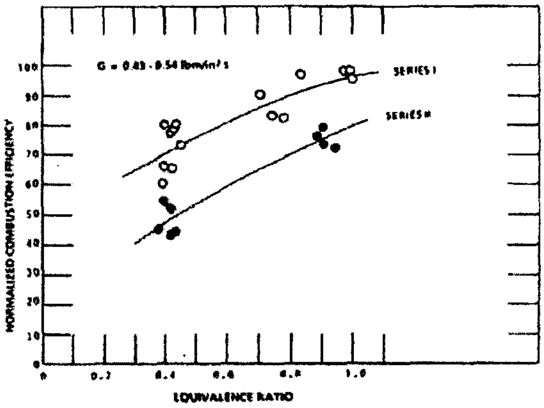

Fig. 3. Normalized Combustion Efficiency

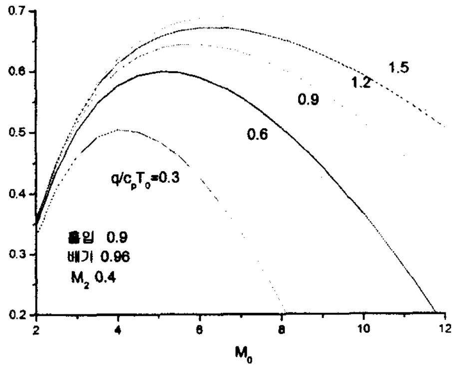

Fig. 4. Thermal Efficiency