Altitude Effects on the Combustion of the Solid Fuel Ramjet

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Abstract

The combustion efficiency of the solid fuel ramjet is affected by the inlet air temperature. And this inlet air temperature is dependent on the flight Mach number and the environment air temperature. If the flight altitude is changeable, the inlet air temperature and the air density also vary. The performance efficiency is investigated with this variables related to the combustion efficiency.

1. Introduction

The use of metals such as boron[1] or boron carbide[2] introduced to the polymeric fuel of a solid ramjet may theoretically provide a better energetic performance of the motor together with increased fuel loading. Also various methods are studied for increasing the loading[3] itself and fuel properties[4,5]. These metal particles in the fuel matrix are covered with a thin boron oxide layer that serves as a barrier. Ignition of the particles is obtained when the oxide layer is removed[6,7].

The combustion behavior of the solid fuel ramjet is reasonably well understood8. 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 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. The inlet air temperature effects on the solid fuel ramjet using the boron-carbide fuel combustion are studied recently9.

It is necessary to burned well for the good energetic performance of the metallized solid fuel,
so relatively lots papers are concerned on the combustion not on the performance.

The objective of the present study is to investigate the effects of the altitude on the performance efficiency using experimental combustion data. The loss of entry effect and the nozzle flow is not considered. Also the thrust change because of the nozzle expansion ratio with the environment is not considered in this study.

2. Experimental Apparatus and Procedures

A sub-scale 63 mm coaxial dump, axi-symmetric combustor configuration was tested in the direct connected mode. The fuel grain was bolted between the inlet and aft mixing chamber. The air flows from high pressure (20MPa) 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. 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.
Instrumentation for determining combustor performance consisted of combustor static pressure, inlet air temperature, flow rates and thrust measurements. Two series of tests were conducted, the first series (18 tests) emphasized on keeping the air mass flux constants. The second test series (21 tests) were investigated with the equivalence ratio approximately 0.4. An effort was made to keep other parameters, such as combustion pressure and particle residence time, constant. Inlet air 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. The residence time varies 3 and 4 mili-seconds during tests. The nozzle throat diameter was sized to maintain nominal combustion pressure between 550 and 680 kPa. Mixing chamber length was also varied in an attempt to keep the residence time nearly constant for any one set of tests.

3. Combustion Efficiency

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.

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Assuming the equivalence ratio constant, the combustion efficiency is decreased with the increasing air mass flux. A regression analysis was employed for the combustion efficiency and the following correlation expression is represented all the data.

$$\eta_B = 3.94 \times 10^{-9} G^{-1} T_2^{\,2.54} \qquad (1)$$

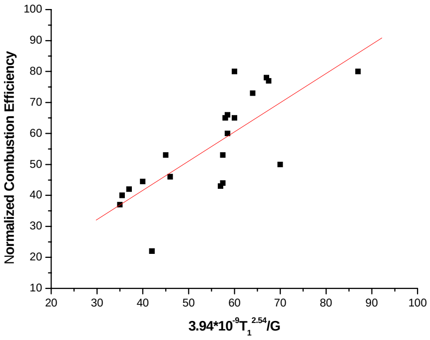

Fig. 1 Normalized Combustion Efficiency

The normalized combustion efficiency for the test series are plotted with respect to regression equation (1) in Fig. 1.

4. Performance Efficiency

The performance efficiency was determined based on the Braytin cycle analysis using the above experimental combustion efficiency.

The fuel flow rate is much less than the air mass flow rate, ($m_f = 0.03 m_a$) so, we can assume the following heat balance equation

$$m_a q = \eta_B m_f H_f , \ (m_f \square \ m_a) \qquad (2)$$

This equation shows that the combustion efficiency ‘ η_B ’ will affect the heat input rate ‘ q ’.

In the Brayton cycle (which is simplified ramjet cycle) the thermal efficiency is increased and the total efficiency of the ramjet is decreased respectively with the heat input parameter $q/c_p T_0$ through the equation (3) and (4)[9].

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

$$\eta_{tot} = \frac{(\gamma - 1) M_0^2}{q/c_p T_0}\left[\sqrt{1 + \frac{q}{c_p T_0}\frac{1 - \left(\frac{M_2}{M_0}\right)^2}{1 + \frac{\gamma - 1}{2} M_0^2}} - 1\right] \qquad (4)$$

Seeing on the equation (2), 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 and inversely proportional to the air mass flux which is directly related to the air density. These relations are represented by the equation (1).

From the equation (2), the heat input parameter $q/c_p T_0$, is represented as following equation using the equivalence ratio and the stoichiometric fuel air ratio.

$$\frac{q}{c_p T_0} = \phi \left(\frac{m_f}{m_a}\right)_{st} \frac{\eta_B H_f}{c_p T_0} \qquad (5)$$

The stagnation and the static temperature has a following relation.

$$T_{t0} = T_0 \left(1 + \frac{\gamma - 1}{2} M_0^2\right) \qquad (6)$$

For the conventional ramjet combustor inflow Mach number M_2 is very low, therefore

$$T_2 \square \ T_{t2} = T_{t0}$$

Now combine the equations (5), (1) and (6), then

$$\frac{q}{c_p T_0} = \phi \left(\frac{m_f}{m_a}\right)_{st} \frac{\eta_B H_f}{c_p T_0} = \alpha \frac{1}{T_0} T_2^{2.54} G^{-1} \qquad (7)$$
$$= \alpha \frac{1}{T_0} [T_0 \left(1 + \frac{\gamma - 1}{2} M_0^2\right)]^{2.54} G^{-1}$$

Fig. 2 shows the air properties with the altitude, the pressure and the density are monotonously decreased with the altitude.

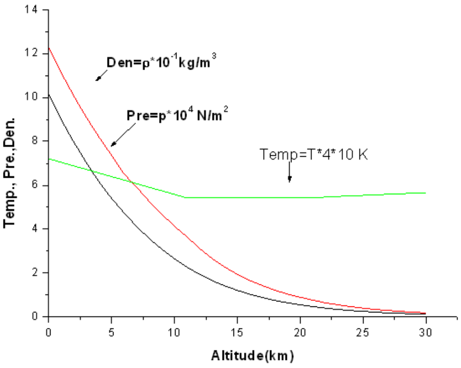

Fig. 2 Air Properties with the Altitude

The air density varies with the altitude and using the “Origin” program analysis, the following polynomial shows the relation.

$$\rho = 0.99792 - 0.09381h + 0.00305h^2 - 3.38868E - 5h^3$$

The density at the 10km is only 30% to the ground level and even more at the 30 km is only 2%. In the troposphere it is decreased to the one quarter from 10 to 20 km. but the air temperature becomes constant.

On set of the stratosphere, the temperature starts to increase very slowly (5 % increase in the range 20 to 30), but the density is decreased very much to 25%. The air density is decreased dramatically comparing the temperature variation. Therefore the air mass flux has to be considered as a dependent variable on the altitude even if the flight speed is constant. Also we can expect that the change of heat input parameter $q/c_p T_0$ by seeing equation (7).

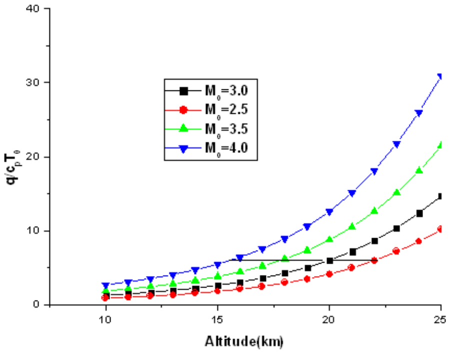

Fig. 3 q/c_pT_0 vs Altitude

Fig. 3 shows the variation of the heat input parameter q/c_pT_0 with altitude. For the reference given conditions at the 20 km $M_0 = 3.0$, $T_0 = 216.65k$, and $q/c_pT_0 = 6$. For the fixed Mach number (for example $M_0 = 3.0$) the only variable is mass flux which is related to the air density, because of the negligible temperature variation. But for the different Mach number case, The Mach number effect has to be considered and we know that the index of this is quite high order. Therefore at the high altitude, the heat input parameter values are bigger than those of the low altitude.

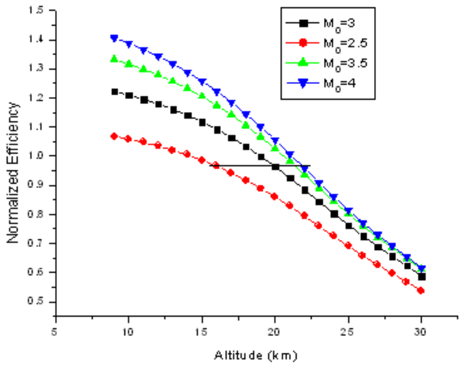

Fig. 4 Normalized Efficiency vs Altitude

Finally Fig.4 represents the normalized performance efficiency with the altitude to the reference point value. This figure shows that the performance efficiency is decreased with the altitudes, but the decreasing rate is less than that of the air density itself. At the same altitude, the normalized performance value is large for the high Mach number flight. These results are based on the assuming constant equivalence ratio around 0.4 and also air mass flux ratio is less than 2. by the experimental data. Therefore the air density value variation has to be limited in 50%.

5. Concluding Remarks

Based on the Brayton cycle analysis for the different altitude performance using the static combustion experimental tests, the following results are concluded;

For the fixed Mach number, the heat input parameter q/c_pT_0 is increased with the altitude, the performance efficiency is decreased.

At the same altitude the heat input parameter q/c_pT_0 is bigger for the high Mach number than that of the low Mach number flight.

The normalized performance efficiency is also bigger for the high Mach number than that of the low Mach number flight. Because the Mach number affects more than the air mass flux does.

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Nomenclature

c specific heat

G	air mass flux
H	heating value of the fuel
HC	hydro- carbon
HTPB	hydrocarboxyl terminated poly-butadiene
M	Mach number
m	mass flow rate
q	heat input rate

Subscripts

e	exit (nozzle exit), exhaust
f	fuel
p	pressure
tot	total, performance
th	thermal
0	free stream
2	combustor inlet

T	temperature
TR	free stream air temperature ratio, $T_0 / 250$
V	velocity
γ	specific heat ratio
η	efficiency
ϕ	equivalence ratio

a	air
B	burning
st	stoichiometric
t	total, stagnation