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Technical Notes

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Inlet Air Temperature Effects on the Performance of the Solid Fuel Ramjet

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Nomenclature

c	=	specific heat
G	=	air mass flux
H	=	heating value of the fuel
M	=	Mach number
m	=	mass flow rate
q	=	heat input rate
T	=	temperature
TR	=	free stream air temperature ratio, $T_0/250$
V	=	velocity
γ	=	specific heat ratio
η	=	efficiency
ϕ	=	equivalence ratio

Subscripts

a	=	air
B	=	burning
e	=	exit (nozzle exit), exhaust
f	=	fuel
p	=	pressure
st	=	stoichiometric
t	=	total, stagnation
th	=	thermal
tot	=	total, performance
0	=	free stream
2	=	combustor inlet

I. 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 understood [8]. 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 combustion efficiency is an important factor for the good energetic performance of the metallized solid fuel, so relatively lots of papers are concerned on the combustion only not on the performance. The objective of the present study is to investigate the effect of the inlet air temperature on the performance efficiency using experimental combustion data. The loss of entry effect and the nozzle flow is not considered.

II. Experimental Apparatus and Procedures

A subscale 63 mm coaxial dump, axisymmetric combustor configuration was tested in the direct connected mode. The fuel grain was bolted between the inlet and the aft mixing chamber. The experimental setup is shown in Fig. 1. The air flows from a high pressure (20 MPa) 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. An ethylene oxygen torch ignited the ignition gas (ethylene gas injected into the recirculation zone) which in turn ignited the ramjet fuel grain. Approximately 1 s ignition time was required for good ignition. Nitrogen gas was used to quench the fuel. Hydrocarboxyl terminated polybutadiene (HTPB) and boron carbide/HTPB were used as 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

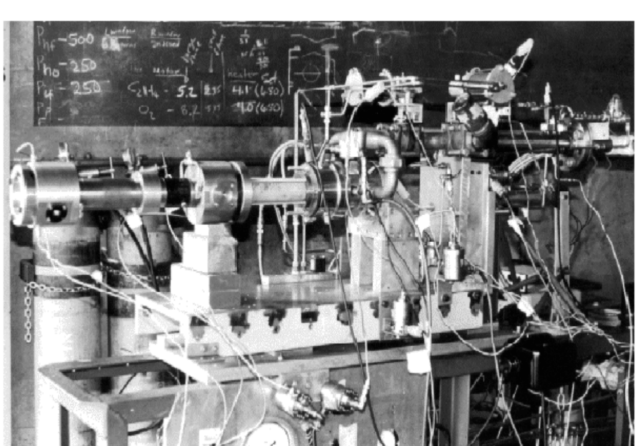

Fig. 1 Experimental setup of solid fuel ramjet.

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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 and 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 between 3 and 4 ms during tests. The nozzle throat diameter was sized to maintain nominal combustion pressure between 550 and 680 kPa. The mixing chamber length was also varied in an attempt to keep the residence time nearly constant for any one set of tests.

III. 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 hydrocarbon fuel.

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

$$\eta_B = 1.1 \times 10^{-7} \phi^{0.5} G^{-0.61} T_2^{2.17} \tag{1}$$

The normalized combustion efficiency for the test series is plotted with respect to the regression equation (1) in Fig. 2.

IV. Performance Efficiency

The performance efficiency was determined based on the Braytin cycle analysis using the previous experimental combustion efficiency. The fuel flow rate is much less than the air mass flow rate ($m_f = 0.03 m_a$) and so we can assume the following heat balance equation:

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

This equation shows that the combustion efficiency η_B will affect q. In the Brayton cycle (which is the 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 Eqs. (3) and (4) [9]:

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

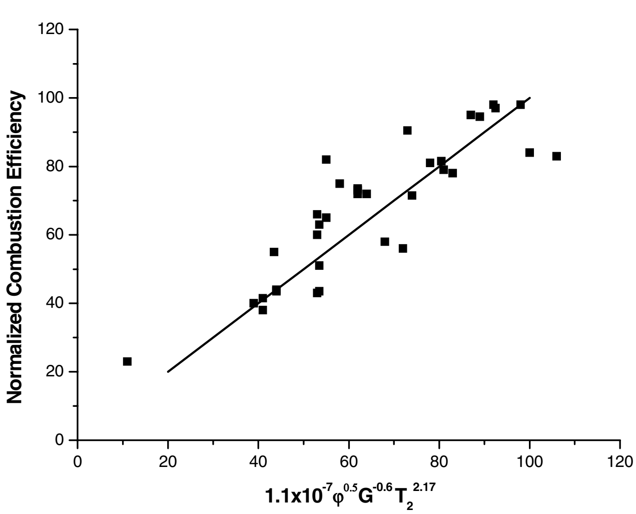

Fig. 2 Normalized combustion efficiency.

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

In Eq. (2), it is noted that q itself depends on the combustion efficiency η_B, which strongly increases with the inlet air temperature more than the power of 2 represented by Eq. (1). From Eq. (2), the heat input parameter $q/c_p T_0$ is represented as the following equation using the equivalence ratio and the stoichiometric fuel air ratio:

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

The stagnation and the static temperature has the following relation:

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

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

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

Now combine Eqs. (1), (5), and (6):

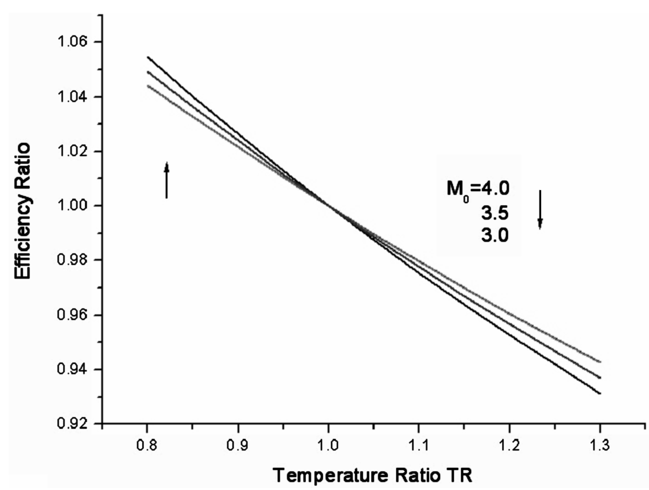

Fig. 3 Normalized performance efficiency $M_2/M_0 = 0.1$.

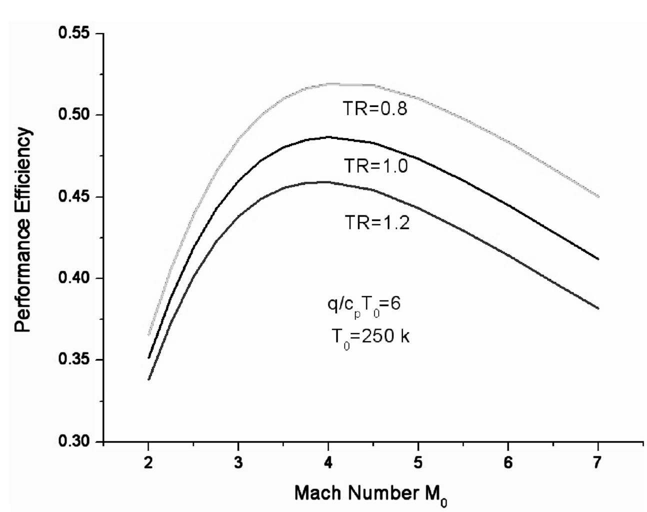

Fig. 4 Performance efficiency vs TR.

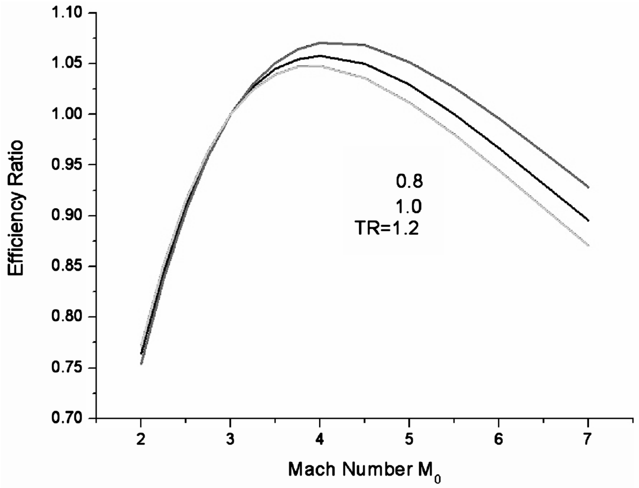

Fig. 5 Normalized performance efficiency.

$$\frac{q}{c_p T_0} = \phi\left(\frac{m_f}{m_a}\right)_{\rm st} \frac{\eta_B H_f}{c_p T_0} = \alpha \frac{1}{T_0} T_2^{2.17}$$
$$= \alpha \frac{1}{T_0}\left[T_0\left(1 + \frac{\gamma - 1}{2} M_0^2\right)\right]^{2.17} \tag{7}$$

We know that the combustion efficiency is affected by the combustor inlet temperature, which depends on the free stream temperature itself and the flight Mach number. Here, one reference point is considered to investigate the performance: $T_0 = 250k$, $q/c_p T_0 = 6$, $M_2/M_0 = 0.1$. These will give the $\eta_{\rm tot}$ using Eq. (4)

In Eq. (7) we know that the heat input parameter $q/c_p T_0$ is affected by the free stream temperature T_0 and the Mach number M_0, respectively. At first for the given Mach number the free stream temperature ratio results in a monotonous decreasing performance efficiency, but the decreasing ratio is slightly different from that shown in Fig. 3.

For the given free stream temperature, the different Mach number also gives the different combustor inlet temperature similar to Eq. (6) and the results represented in Fig. 4. In the figure, TR $= 1$ means $T_0 = 250k$ and TR $= 1.2$ means $T_0 = 250 \times 1.2 = 300k$, and so on. And it shows that the performance efficiency is decreased with the increasing free stream temperature.

If the temperature ratio and the free stream air Mach number are varying simultaneously, then the performance efficiency varies as in Fig. 5. In this, the efficiency was normalized by the value of Mach number 3 for each temperature ratio, respectively. This figure shows the combined results of Figs. 3 and 4 together.

V. Concluding Remarks

Based on the Brayton cycle analysis for the performance and the combustion experimental tests, the following results are concluded:

Higher inlet temperature produces higher combustion efficiency, but lower performance efficiency.

The normalized performance efficiency change rate is lower with a higher Mach number flow for the given free stream temperature ratio.

The performance efficiency is lower with a higher free stream temperature ratio for the given Mach number flow.

The performance efficiency shows the maximum value around Mach number 4.

The difference of the normalized performance efficiencies at the low Mach number among the different temperature ratios is closer than that at the high Mach number.

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