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고체램제트 추진기관 성능에 미치는 고도의 영향

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Altitude Effects on the Performance of the Solid Fuel Ramjet

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ABSTRACT

고체 램제트 추진기관의 연소효율은 연소실 흡입공기 온도에 따라서 영향을 받고 있다. 이 흡입공기의 온도는 비행 마하수와 비행 대기의 온도에 따라 다르게 마련이다. 비행 고도가 변하는 상황이라면 흡입 공기의 온도뿐만 아니라 대기의 밀도 또한 변하게 되어 이들 성능에 미치는 영향을 연소 효율과 연관하여 조사하였다.

초 록

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 also the air density vary. The performance efficiency is investigated with this variables related to the combustion efficiency.

Key Words: Altitude (고도), Combustion Efficiency(연소 효율), Brayton Cycle(브레이튼 사이클)

1. INTRODUCTION

The use of metals such as boron[1] or boron carbide[2] introduced to the polymeric fuel of a solid ramjet. 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]. The inlet air temperature effects on the solid fuel ramjet using the boron-carbide fuel combustion are studied recently[9].

The objective of the present study is to investigate the effects of the altitude on the

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performance efficiency using experimental combustion data. The loss of entry effect and the nozzle flow is not considered.

2. Experimental Apparatus and Procedures

A sub-scale 63 mm coaxial dump, axi-symmetric combustor configuration was tested in the direct connected mode. The air flows from high pressure (20MPa) storage tank through a choked nozzle to an air heater. Oxygen was injected downstream of the heater to ensure that vitiated air contained 23% oxygen by mass. Approximately 1 second ignition time was required for good ignition. Instrumentation for determining combustor performance consisted of combustor static pressure, inlet air temperature, flow rates and thrust measurements. 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.

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.

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

$$\eta_B = 3.94\times10^{-9} G^{-1} T_2^{\,2.54} \qquad (1)$$

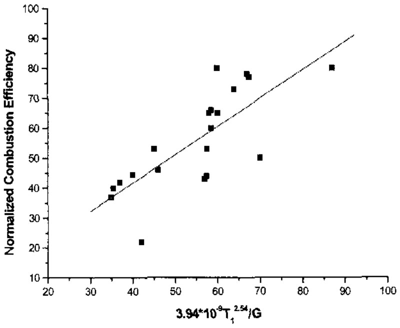

Fig. 1 Normalized Combustion Efficiency

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 Brayton 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

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

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

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

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 2and 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_pT_0, is represented as following equation using the equivalence ratio and the stoichiometric fuel air ratio.

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

The stagnation and the static temperature has a following relation.

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

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

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

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

$$\frac{q}{c_pT_0}=\phi\left(\frac{m_f}{m_a}\right)_{st}\frac{\eta_BH_f}{c_pT_0}=\alpha\frac{1}{T_0}T_2^{2.54}G^{-1}$$
$$=\alpha\frac{1}{T_0}[T_0\left(1+\frac{\gamma-1}{2}M_0^2\right)]^{2.54}G^{-1} \tag{7}$$

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

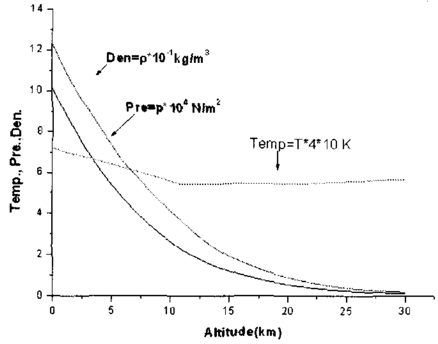

Fig. 2. Air Properties with the Altitude

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_pT_0 by seeing equation (7).

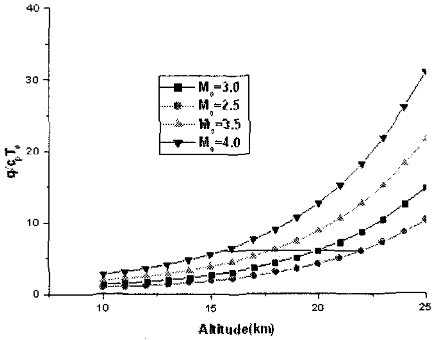

Fig. 3 q/c_pT_0 vs Altitude

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.

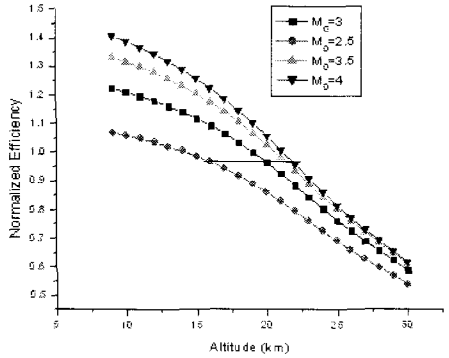

Fig. 4 Normalized Efficiency vs Altitude

Finally Fig.4represents 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. Therefore the air density value has to be limited 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.

References

1. G. M .Faeth,"Status of Boron Combustion Research", AFOSR Specialists Meeting on Boron Combustion, 1984.
2. Gany, A and Netzer, D. W., "Fuel Performance Evaluation for the Solid Fueled Ramjet", *International Journal of Turbo and Jet Engines*, Vol.2 No. 2 1985, pp157-168
3. Tae-Ho Lee, "A Study of the Flammability Limit of the Backward Facing Step Flow Combustion", *AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference*, AIAA 92-3846, Nashville, TN. 1992. 7
4. Tae-Ho Lee, D. W. Netzer, "Temperature Effects on Solid Fuel Ramjet Fuel Properties and Combustion", *Journal of Propulsion and Power*, Vol. 8, No. 3 1992. May-June, pp721-723
5. Tae-Ho Lee, "Multi-Run Effects on the Solid Fuel Ramjet Combustion", *AIAA/SAE/ASME/ASEE 31st Joint Propulsion Conference*, AIAA 95-2416, San Diego, CA. 1995. 7
6. M. K. King, "Boron Particle Ignition in Hot Gas Stream", *Combustion Science and Technology*, Vol. 8, 1974, pp.255-273
7. M. K. King, "Ignition and Combustion of Boron Particles and Clouds", *Journal of Spacecraft and Rockets*, Vol. 19, 1982, pp.294-306
8. J. A. Nabity, Tae-Ho Lee, B. Natan and D. W. Netzer, "Combustion Behavior of Boron Carbide Fuel in Solid Fuel Ramjet", *Combustion of Boron-Based Solid Propellants and Solid Fuels*, edited by K.K. Kuo and R Pein, CRC Press, 1993, pp.287-302
9. Tae-Ho Lee, "Inlet Air Temperature Effects on the Performance of the solid Ramjet", *Journal of the Thermophysics and Heat Transfer*, Vol. 20, No. 4, Oct-Dec 2006, pp.937-939