Combustion Behavior in a Solid Fuel Ramjet Combustor

T. H. Lee

고체 램제트 추진기관 연소실에서의 연소 현상

이 태 호

초 록

본 연구는 보론 카바이드를 함유한 고체 연료를 사용하여 고체 램제트에서 공기 유속량에 따른 연소 효율과 입자 크기의 분포를 실험적으로 조사하였다.

입자 분포는 그레인 끝 부분과 노즐 입구에서 MALVERN 2600 HSD를 사용하여 측정하였다. 연소 효율은 공기 유속량이 적을수록 연소 효율이 높은 것으로 나타났으며, 일반적으로 입자 분포는 대략적으로 4, 15와 25㎛, 경우에 따라 2㎛ 보다 적은 크기에서 한 곳을 포함하여 3곳의 피크치 또는 4 곳의 피크치를 나타내는 분포를 보였다. 큰 입자는 주로 재순환 영역에서 표면에서의 입자들의 뭉침의 결과이다.

흡입 공기의 온도가 높으면 연소 효율이 좋았는데 이는 확산 영역에서 연소하는 큰 보론 카바이드 입자의 연소 촉진 결과로 보인다.

ABSTRACT

An experimental investigation was conducted to explore the effects of air mass flux on the combustion efficiency and particle size distributions in a solid fuel ramjet using a fuel grain highly loaded with boron carbide. Particle distributions were measured at the grain exit and at the nozzle entrance using a Malvern 2600 HSD. Combustion efficiency increased with decreasing air mass flux. In general, the particle distribution was trimodal or quadrimodal with mode peaks at approximately 4, 15, and 25㎛ and possibly one at less than 2㎛. The larger particles were the result of surface agglomeration, primarily within the recirculation region. Higher inlet air temperature produced higher combustion efficiencies, apparently the result of enhanced combustion of the larger boron carbide particles that burn in a diffusion controlled regime.

1. INTRODUCTION

The SFRJ combustor is divided into three main regions(Fig. 1) :

1. The head-end region behind the inlet step (approximately 6 to 7 step heights in

---

*국방과학연구소 (Agengy for Defense Development)

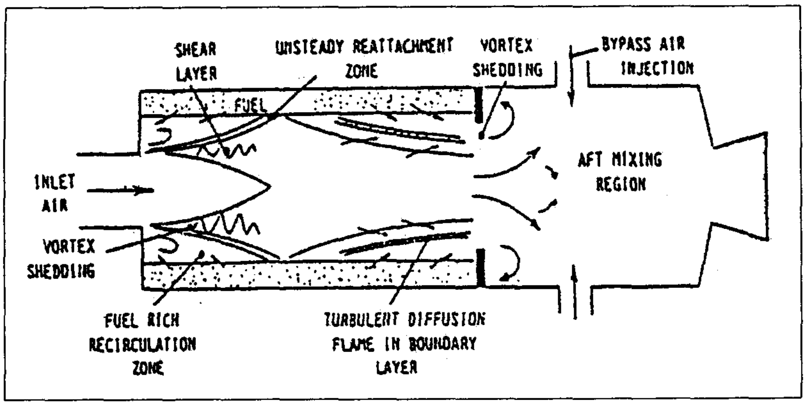

Fig. 1
Solid Fuel Ramjet Combustion Regions.

length), characterized by a separated, recirculating, fuel rich flow that serve as a flameholder

2. The boundary layer region, downstream of the reattachment and along most of the fuel grain, where a diffusion flame between the volatile fuel vapors or decomposition products and oxygen is established within the developing turbulent boundary layer.
3. The rear end region (the aft mixing chamber), where no fuel is located and extensive, chemical reactions take place because of the better mixing and additional residence time.

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

The objective of the present study was to investigate experimentally the effect of various parameters, such as inlet flow conditions, geometry, on the axial variation in particle size distribution and on the combustion efficiency. For this purpose an axisymmetric solid fuel ramjet test motor configuration was employed. The particle size distributions were measured using a Malvern Particle Sizer. Laser light transmittance measurement were also conducted in an attempt to obtain the volume concentration of the particles in the gas flow.

2. TEST MOTOR, INSTRUMENTATION AND MEASUREMENT

A subscale 63mm-diameter, coaxial dump, axisymmetric combustor configuration, as shown in Fig. 2, was tested in the direct-connect mode.

The fuel grain was bolted between the inlet and the aft mixing chamber. To reduce heat loss through the combustor wall, the mixing chamber was insulated with DC 93~104, a Dow Corning ablative material with good high-temperature characteristics. A sonic nozzle with graphite insert was bolted onto the aft mixing chamber.

Air flows from high pressure(3000 psi) storage tanks through a choked nozzle to an air heater. Methane and ethlene were used as fuels for the air heater and oxygen was injected downstream of the heater to ensure that the vitiated air contained 23 % oxygen by mass.

Air was bypassed to the atmosphere until the heater temperature had stabilized. At this time, air was switched to the combustor,

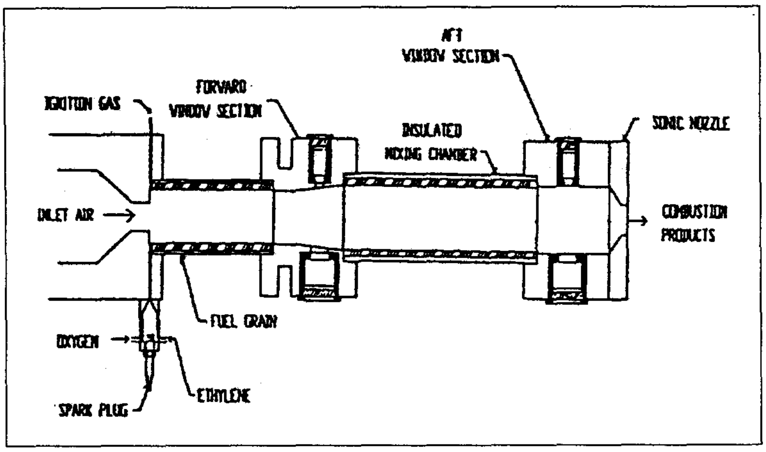

Fig. 2
SFRJ 63mm Direct-Connect
Combustor.

initiating a computer-controlled sequence of events in which the fuel grain was preheated, and the ramjet combustor was ignited, sustained for the desired burn time, and finally quenched, at the end of the test. The air heater was aborted immediately after the 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. Nitrogen was used to quench the HTPB fuel.

HTPB was the baseline fuel for performance comparisons. The B4C particles used in the metallized fuel, which were manufactured by the Norton Company. The Sauter mean diameter(D_{32}) for these particles was about 9㎛.

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

Particle size measurement were taken with a Malvern Particle Sizer, model 2600 HSD.

A 2-mW He-Ne laser produced a collimated, 9-mm-diameter, monochromatic beam of light that illuminated the particles.

The incident light was diffracted by the particles to give a stationary diffraction pattern independent of particle position and velocity.

The background scattered light was measured prior to the combustion test with cold air flowing through the combustor. These voltages were subtracted form those obtained during the combustion test with particles present. In addition, the transmitted light was measured during the cold flow and ramjet combustion tests. These data were used to determine if multiple scattering effects were present and in an attempt to determine the particle concentration according to Beer's Law.

3. RESULTS AND DISCUSSION

The experimental results of test are presented in Table 1 and summaries of the measured particle volume and number distributions are presented in Table 2 and 3.

In general the Malvern measurement indicated a trimodal or quadrimodal distribution with peaks at 4, 15 and 25㎛. A significant number of particles with diameters less than 2㎛ existed, but he Malvern Particle Sizer could not determine if a peak in the

Table Ⅰ. Results From Test.

Test	G, lbm/in^2 · s	Φ	L_G · inches	T_t · R	t_{ree} · ms	P_{43} · sec	η/η_{ref} · %	T_r, %
1	0.302	0.435	5.75	1103	3.1	81	50	41 †
2*	0.250	0.554	5.75	1070	3.0	82	56	-
3	0.250	0.487	5.75	1071	2.9	88	58	47 ‡
4*	0.440	0.442	6.5	1170	3.5	88	44	-
5	0.455	0.423	6.5	1184	3.4	80	43	51 ‡
6*	0.533	0.468	7.5	1106	4.0	95	44	-
7	0.596	0.405	6.5	1102	3.5	83	40	31 †
8	0.597	0.458	7.5	1070	4.1	97	42	54 ‡
9	0.723	0.391	7.5	1279	4.0	79	23	27 †
10	0.740	0.453	7.5	1180	4.0	95	36	50 ‡
11**	0.489	0.377	5.75	1128	3.6	92	45	22 †
12**	0.459	0.398	5.75	1089	4.0	87	54	44 ‡
13**	0.506	0.422	5.75	1235	3.4	102	52	45 ‡
14**	0.387	0.428	5.75	1172	3.5	103	61	24 †
15**	0.459	0.892	13	1053	3.3	121	76	27 †
16**	0.502	0.907	13	1250	2.9	105	79	24 †
17**	0.430	0.908	13	1074	3.4	116	73	31 ‡
18**	0.506	00.949	13	1182	2.9	105	72	43 ‡
19**	0.377	1.03	13	1226	2.9	110	85	-
20**	0.373	1.15	13	1229	2.9	107	83	32 ‡
21	0.318	0.450	5.75	1060	4.5	130	64	24 †

* No particle or transmittance measurements.

** No particle measurements.

† Transmittance measurement at the end of the grain.

‡ Transmittance measurement at the front of the nozzle.

Table 2. Particle Volume Distributions.

Test	W_{air}, lbm/s	Station 4.0					Station 4.2				
		D_{32}, μm	Distribution peaks, μm				D_{32}, μm	Distribution peaks, μm			
			1	2	3	4		1	2	3	4
21	0.747	11	$<2_2$	4_{15}	9_{21}	25_{62}					
3	0.719						13	$<2_2$	4_9	9_{23}	25_{66}
1	0.711	15	$<2_0$	4_{10}	9_{18}	25_{72}					
7	1.40	13	$<2_0$	5_{15}	11_{16}	25_{69}					
5	1.41						12	$<2_0$	5_{17}	12_{34}	25_{49}
9	1.70	8	$<2_5$	4_{22}	10_{26}	25_{47}					
8	1.84						16	$<2_0$	5_8	12_{27}	26_{65}

Note : the numbers for the distribution peaks may be described by example: the number 4_{15}, for example, means that approximately 15% of the volume of particles were contained in the mode with a mean diameter at 4μm.

Table 3. Particle Number Distributions.

Test	W_{air}, lbm/s	Station 4.0					Station 4.2				
		D_{32}, ㎛	Distribution peaks, ㎛				D_{32}, ㎛	Distribution peaks, ㎛			
			1	2	3	4		1	2	3	4
21	0.747	11	$<2_{85}$	4_{14}	9_1	25_0					
3	0.719						13	$<2_{94}$	4_5	9_1	25_0
1	0.711	15	$<2_{74}$	4_{22}	9_3	25_1					
7	1.40	13	$<2_0$	5_{91}	11_7	25_2					
5	1.41						12	$<2_0$	5_{79}	12_{19}	25_2
9	1.70	8	$<2_{90}$	4_9	10_1	25_0					
8	1.84						16	$<2_{84}$	5_{11}	12_4	26_1

Note : the numbers for the distribution peaks may be described by example : the number 4_{15}, for example, means that approximately 15% of the volume of particles were contained in the mode with a mean diameter at 4㎛.

distribution was present for these small particles. Since there were no 25㎛ particles in the original distribution, these are expected to be agglomerates that originated primarily in the recirculation zone. There was a shift to a lower Sauter mean diameter with an increase in equivalence ratio.

The normalized combustion efficiency decreased with increasing air mass flux. A regression analysis was employed, and the results did in fact show the 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 chamber length was changed in order to keep an approximately constant particle residence time. The recirculation zone length for all tests was approximately the same; however, the thickness of the boundary layer and the position of the flame zone relative to the fuel surface varied with the air mass flux. Many of the particles and agglomerates that originate in the recirculation zone probably ignite when they cross the flame zone in the downstream boundary layer region.

At high air mass flux, the flame zone is closer to the fuel surface and these particles might never penetrate it. On the other hand, at low air mass flux, the grain is short and the, residence time of the particles within the flame zone might not be sufficient for ignition. Another factor that should be taken into account is the solid fuel regression rate that varies with the air mass flux. Low air mass flux results in low surface regression rate ; but then, large-size agglomerates tend to form on the surface in the boundary layer region.

The number of particle size measurements made in the tests(see Tables 2 and 3) were insufficient to indicate any particular trends with increasing air mass flux. Thus, it was difficult to determine which parameter dominated the particle agglomeration and the ignition at the combustion processes when the air mass flux was varied.

It should be noted that the values of the transmittance at the back of the motor were significantly higher than those at the front; this phenomenon was due to the combustion of the particles.

4. CONCLUDING REMARKS

Combustion efficiency increased with decreasing air mass flux. In general, the particle distribution was trimodal or quadrimodal with mode peaks at approximately 4, 15, and 25 ㎛ and possible one at less than 2 ㎛. The larger particles were the result of surface agglomeration, primarily within the recirculation region. Short grains that consisted primarily of the recirculation region produced larger particles and lower combustion efficiencies.

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

NOMENATURE

D_{32}	Sauter mean diameter
G	initial air mass flux(G_o=500kg/m^{2}s)
L_G	grain length
P	pressure
SFRJ	solid fuel ramjet
T_i	temperature(T_i = 800 °K)
T_r	transmittance
t_{res}	mixing section residence time
W	mass flow rate
η/η_{ref}	normalized combustion efficiency
ϕ	equivalence ratio(ϕ_o=1.0)

REFERENCES

1. Gany A., and Netzer, D.W. "Fuel Performance Evaluation for the Solid-Fueled Ramjet," : Int. J. of Turbo and Jet Engines, Vol.2, No.2, 1985, pp.175~168.
2. Karadimitris, A., Scott I , C., Netzer, D.W.,, and Gany, A., "Regression and Combustion Characteristics of boron Containing Fuels for Solid Fuel Ramjet" J. of Propulsion and Power, 1990.
3. Nabity J.A., Lee Tea-Ho, Netzer, D.W., and Natan, B., "Mass Concentration and Particle Size Distributions in a Solid Fuel Ramjet Combustion Utilizing a Boron-Based Fuel," 2nd International Symposium on Special Topics in Chemical Propulsion, Lampoldhausem, Germany, March 4~6, 1991.
4. Nabity J.A. "Metallized Fuel Particle Size Study in a Solid Fuel Ramjet." M. Sc. Thesis, Naval Postgraduate School, September 1989.