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A STUDY OF THE FLAMMABILITY LIMIT OF THE BACKWARD FACING STEP FLOW COMBUSTION

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ABSTRACT

An experimental investigation was conducted in order to determine the flammability limit of the solid fuel ramjet using the backward facing step flow combustion of the plexiglass grain. In order to get the different step height ratio, the grain was drilled straight forward or stepwise. The Phoenics computer code was adopted in order to compare the flow patterns of the some sample tests using a non-reacting cold turbulent flow model. The stepwise grain give some loading advantage; specially thin and long shape grain design.

NOMENCLATURE

Ai	Inlet section area
Ag	Void grain area in the boundary layer region
Ap	Grain port area
Ath	Nozzle cross section area
Di	Inlet diamenter
Dg	Grain diameter in the boundary layer region
Dh	Step height : (Dp - Di)/2
Dp	Grain port diameter
Dth	Nozzle throat diameter
f	Fuel air ratio
G	Air mass flux
M	Mass flow rate
Pc	Chamber pressure
Tair	Air temperature
Ti	Air temperature during the ignition time
V	Volume
VL	Loade volume
η	Temperature - Rising combustion efficiency
$\varnothing$	Equivalence ratio

Subscripts

gr	grain
mas	total mass

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INTRODUCTION

Solid fuel ramjets normally operate at low chamber pressures(2-7 atm) and high air mass fluxes, resulting in relatively high port velocities. Except for high inlet air temperatures the solid fuel ramjet (SFRJ) is required to use some means of flame stabilization other than boundary layer stabilization. Bluff body and/or sudden expansion flame stabilization has been used successfully in both turbojet and ramjet combustor designs. In the

SFRJ a dump or sudden expansion inlet is generally employed. After flow reattachment a turbulent boundary layer developes.

For a given inlet air temperature flammability limits for a solid fuel ramjet fuel is generally expressed in a plot of Ap/Ai vs Ap/Ath. Large values of Ap/Ai result in large inlet steps and, therefore, large high energy recirculation zone, which can sustain the downstream combustion at higher flow velocities. Higher values of Ap/Ath result in lower port March number and, therefore, in a more readily sustained boundary layer combustion begin.

It is, of course, desirable to employ as small a port diameter as possible, since this permits the higher fuel loading efficiency and increase ramjet range.

In liquid-fueled combustor, swirl can be used to enhance mixing and increase residence time, thus improving flammability limits and combustion efficiency. In the SFRJ small amounts of increased mixing near the wall may enhance combustion. However, if the mixing is too severe the diffusion flame within the developing boundary layer can be broadened to the point where combustion is deterred.

Earlier investigation[1,2,3] had shown in a 2-D motor that small steps in the fuel surface downstream of flow reattachment could improve flammability caharacteristics. However it was not determined if combustion characteristics could also be improved.

The objective of this study was to investigate alternatives to single-step sudden enlargement flame stabilization technique which could permit increased fuel loading and/or improved combustion efficiency.

METHOD OF INVESTIGATION

Experimental firings were conducted using polymethylemthacrylate(PMM) grains with various geometries. Initially, go, no-go tests were conducted to determine the Ap/Ai ignition limits for a sudden step inlet and particular values of Ap/Ath, Tair, G, Pc and Ø . Then Ap/Ai in the recirculation zone was decreased and small steps were added in the fuel surface to determine if combustion could be sustained with higher loadings. Conversely, increased Ap values of Ap/Ai were employed in the reattachment zone together with decreased Ag/Ai were employed in the reattachment zone together with decreased Ag/Ai in the boundary layer region.

The Phoenics computer code was used to visualize the non-reacting flows and provide guidance on the best locations for the geometric modification.

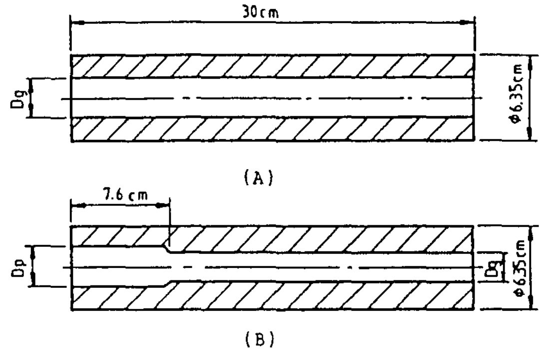
Instrumentation for determining combustion performance or flame stabilization consisted of combustor static pressure, inlet air temperature, air flow rate.

EXPERIMENTAL PROCEDURES

Experimental firing tests were performed at the Naval Postgraduate School Combustion Laboratory. A subscale 63.5mm O.D. axisymmetric combustor configuration was used in the direct connect mode. The fuel grain was bolted between the inlet and the mixing chamber The mixing chamber was insulated with C93-104 to reduce heat loss through the combustor wall. A sonic nozzle with graphite insert was bolted onto the aft mixing chamber[4,5].

Air at a rate of approximately from 0.17 to 0.36 kg/sec, depending on the grain port diameter, was bypassed to the atmosphere until the heater temperature had stabilized. Then the air was switched to the combustor, initiating a computer controlled sequence of events in which the fuel grain was preheated about 4 seconds, the ramjet combustor was ignited 2 seconds and sustained 1 second, and finally quenched for the go, no-go ignition limit tests. If this test resulted in no sustained ignition (after ignitor termination) the grain was permitted to cool to atmospheric temperature and test was repeated. This procedure was continued each time using slightly larger values of AP until one or both of the tests sustained. At this limit value of AP/Ai a larger duration test (15 seconds) was conducted to measure the obtainable temperature-rising combustion efficiency.

Tests were repeated for various inlet and nozzle throat diameters in order to obtain a broader range of ignition limit data.



(A) : Straight
(B) : Step-wise

Figure 1. Tested Grain Shape

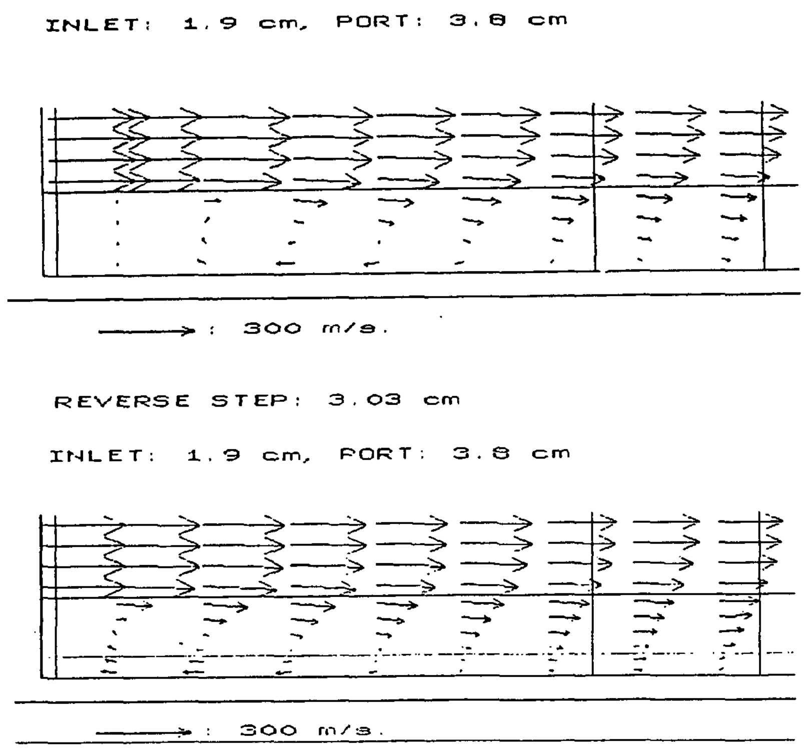


Figure 2. Cold Flow Pattern (By Phoenics)

Table 1. SFRJ Flammability Limit Test Results

	Di cm	Dg cm	Mair g/s	G(DP) g/s,cm2	Ap/Ai	Dth cm	Ti k	Pc atm	Ap/Ath	Re
1	1.29	2.54	233	45.9	3.88	2.18	611	4.0	1.35	
2	1.29	2.54	250	49.4	3.88	2.18	594	4.3	1.35	
3	1.29	2.83	246	39.0	4.81	2.18	572	4.2	1.68	
4*	1.29	3.06	251	34.2	5.62	2.18	600	8.9	1.96	
5	1.29	2.79	168	27.3	4.67	2.18	528	2.9	1.64	
6	1.29	2.79	167	27.2	4.67	2.18	518	2.9	1.64	
7	1.29	3.06	166	22.6	5.62	2.18	519	2.7	1.96	
8*	1.29	3.06	208	28.3	5.62	2.18	544	7.4	1.96	
9	1.90	4.16	261	19.3	4.80	3.07	616	2.2	1.83	
10	1.90	4.16	251	18.6	4.80	3.07	611	2.1	1.83	
11	1.90	4.31	286	19.6	5.15	3.07	606	2.5	1.97	
12*	1.90	4.31	284	19.4	5.15	3.07	611	5.0	1.97	
13*	1.90	4.31	284	19.4	5.15	3.07	611	5.0	1.97	
$\overline{14}$	1.90	4.05	252	22.1	4.00	3.07	583	2.1	1.54	3.8p7.6
$\overline{15}$	1.90	4.05	261	22.9	4.00	3.07	578	2.2	1.54	3.8p7.6
$\overline{16}$	1.90	4.05	251	17.2	5.12	3.07	583	2.2	1.97	4.3p7.6
$\overline{17}$	1.90	4.05	248	16.9	5.12	3.07	583	2.2	1.97	4.3p7.6
$\overline{18}$	1.90	4.05	251	17.1	5.12	3.07	600	2.2	1.97	4.3p10
$\overline{19}$	1.90	4.05	264	18.1	5.12	3.43	600	1.8	1.26	4.3p10
$\overline{20}$	1.90	4.05	278	19.0	5.12	3.43	578	1.8	1.26	4.3p10
21	1.90	4.38	293	19.5	5.31	3.43	567	1.9	1.63	
22	1.90	4.38	293	19.5	5.31	3.43	578	1.9	1.63	
23	1.90	4.57	329	20.0	5.78	3.43	556	2.1	1.77	
24	1.90	4.57	335	20.2	5.78	3.43	556	2.2	1.77	
25*	1.90	4.83	363	19.8	6.46	3.43	544	4.4	1.98	
26	1.90	4.83	363	19.8	6.46	3.43	578	2.2	1.98	
27	1.90	4.83	363	19.8	6.46	3.43	575	2.2	1.98	
28	1.90	4.83	356	19.5	6.46	3.43	572	2.2	1.98	
29*	1.90	3.81	245	21.5	4.02	2.64	511	5.4	2.08	
30*	1.90	3.81	244	21.5	4.02	2.64	494	5.4	2.08	
31*	1.90	3.81	247	21.7	4.02	2.64	511	5.6	2.08	
32*	1.90	3.03	219	25.6	2.54	2.64	528	2.3	1.56	
33	1.90	3.03	209	24.4	2.54	2.64	5172	2.2	1.56	
34*	1.90	3.56	221	22.3	3.51	2.64	578	5.0	1.81	
35*	1.90	3.56	223	22.4	3.51	2.64	544	5.1	1.81	
$\overline{36}$	1.90	3.03	229	20.0	4.00	2.64	539	5.2	2.08	3.8p7.6
$\overline{37}$*	1.90	3.03	231	20.3	4.00	2.64	556	5.2	2.08	3.8p7.6
$\overline{38}$*	1.90	3.03	229	20.1	4.00	2.64	550	5.2	2.08	3.8p7.6
$\overline{39}$$	1.90	2.79	224	19.6	4.00	2.64	544	5.3	2.08	3.8p7.6
$\overline{40}$$	1.90	2.82	226	19.8	4.00	2.64	556	5.3	2.08	3.8p7.6
$\overline{41}$$	1.90	3.00	227	19.9	4.00	2.64	539	5.3	2.08	3.8p8.9
$\overline{42}$*	1.90	3.35	230	20.1	4.00	2.64	533	5.3	2.08	3.8p7.6
43$	2.30	3.66	220	20.9	2.53	2.64	561	4.8	1.92	
44$	2.30	3.81	228	20.0	2.74	2.64	556	4.8	2.08	
45$	2.30	4.06	245	18.8	3.11	2.64	561	5.1	2.37	
46$	2.30	4.27	274	19.2	3.45	2.64	550	5.9	2.61	
47*	2.30	4.27	255	17.9	3.45	2.64	556	5.7	2.61	

* ; Ignited and sustained well

$; Ignited but not sustained

Others are no ignition

Ti and Pc are measured during the ignition time(even if there was no ignition)

- ; This test was conducted with the step grain which was described by port grain dia and length in Re column. For example the test No. 14, the grain had a step which was represented by '3.8p7.6' ; 3.8cm port grain dia with 7.6cm long, then grain dia was changed to Dg ; 4.05 cm.

Table 2. Combustion Efficiency

Test No.	Di cm	Mgr g/s	Mmas g/s	G g/s,cm2	Tair k	Pc atm	f %	η
8	1.29	20.6	212	28.3	584	7.1	.097	.872
13	1.90	22.4	290	19.4	650	4.6	.079	.874
31	1.90	18.3	254	21.7	526	4.9	.072	.857
35	1.90	14.3	230	22.4	585	4.4	.062	.859
38	1.90	15.9 (3.8p7.6 & 3.03)	237	20.1	584	4.5	.067	.846
42	1.90	15.3 (3.8p7.6 & 3.35)	237	20.1	572	4.5	.065	.870
47	2.30	15.4	265	17.9	607	4.8	.58	.913

Tair, Pc are measured and averaged during combustion time.
3.8p7.6 & 3.03 represents that the grain had 3.8cm port grain dia with 7.6cm and then the grain dia was changed to 3.03 cm.

RESULTS AND DISCUSSION

In order to investigate the effect of the step flow, straight and stepwise grain shapes as shown in Figure 1 were tested. The Phoenics computer code was used to predict the flow patterns for non-reacting flow. This showed as expected that the reattachment point is generally located at 6 to 7 inlet step heights down from the air inlet, when a second small step was located in the grain surface downstream of flow reattachment, the second reattachment point also was located approximately 6 to 7 new step heights further downstream. This predicted behavior was used to select the initial location and size of the second (fuel surface) step.

Figure 2. shows that cold turbulent flow pattern used the Phoenics computer code for the grain shape of test No. 31.

It was found that the reattachment point (largest regression point) of the tests grains were shown similar trend to the computer models : Test No. 38 grain, the reattachment point was located at less distance from the inlet than that of the Test No. 31. But the locations of the largest regression point are further down than those of the computer result, probably due to the hot reacting flow effect.

Total forty seven experimental firing tests (including combustion performance tests) were conducted and the steady state data are tabulated in Table 1. Because of the different grain port diameter or grain step (Figure 1.) air flow rate was varied from 166 g/sec to 362 g/sec in order to fix the air mass flux approximately 17 g/sec,cm^2 range except initial 4 tests. The vitiated inlet air temperature was range from 495 K to 610 K during ignition time.

The combustion efficiency resulted in Table 2 indicated that the grain port diameter variation or grain step had no effects on the combustion.

In Table 3, the flame stabilized tests are listed. By considering Table 1 and Table 3, it can be seen that the port area ratio to the inlet area is required larger than 3.4 (Figure 3). And Table 1 shows that Test No. 25 was sustained, but followed tests (Test No. 26, 27, 28) were not sustained even though same grain and same test

Table 3. Flame Stabilized Condition and Loaded Volume

Test No.	Ap/Ai	Ap/Ath(Ag/Ath)	VL/V
4	5.62	1.96	.77
8	5.62	1.96	.77
12	5.15	1.97	.54
25	6.46	1.98	.42
29	4.02	2.08	.64
34	3.51	1.81	.68
47	3.45	2.61	.55
37	4.00	2.08(1.56)	.71
42	4.00	2.08(1.61)	.70

conditions were applied probably because of the critical limit. By using the step grain, we can improve the flammability limit (arrow direction in the Figure 3).

Therefore in the view point of flammability limit, backward-facing grain step does not give any advantage (Test No. 4,15), but forward-facing grain step might be useful for increasing the loading capacity, specially for the thin thickness grain or long grain shape design cases. From Table 3 it can be seen easily that the loaded volume of the step grain (Test No. 37,41) is increased by at least 3% than the orresponding straight grain (Test No. 34,29) for the 30cm long and 6.35cm O.D. grain. Also the flammability limit of the grain is a function of step height and port diameter ratio and throat and port diameter ratio together.

CONCLUSIONS

Based on this investigation it might be concluded as follows :

1. The Phoenics Computer output showed that the reattachment point is located 6 to 7 inlet step heights down from the air inlet for the cold flow including the 2nd backward facing grain step. But the experimental results showed that the reattachment points are located more that 10nlet step heights down for this hot combustion flow.
2. The port area ratio to the inlet area is required larger than 3.4 and larger than 1.98 value of port area ratio to the throat for this specific model in order to sustain the combustion.
3. In the view point of flammability limit, the backward facing grain step does not give any advantages to the loading copacity.
4. By using the forward facing grain step grain the loaded volume can be increased by 3 to 6% than the of the plain straight grain.

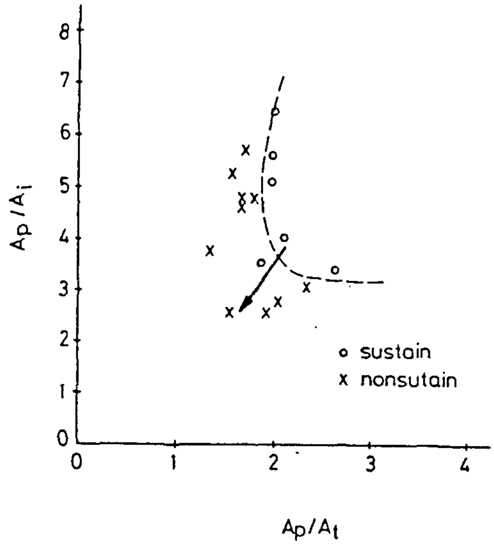


Figure 3. Flame Sustain vs Area Ratio

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