SENSITIVITY OF SUPERSONIC COMBUSTION TO COMBUSTOR/FLAMEHOLDER DESIGN

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Abstract

Traditionally, tests of supersonic combustion ramjet engine hardware have been performed using subscale models due to test facility size limitations. The use of small models has been justified on the basis that the combustion was mixing limited and thus correct scaling parameters could be used to predict full scale performance. A series of tests was undertaken at the NASA Langley Research Center to explore the effects of various scale and geometric parameters on direct connect scramjet combustor performance.

Variations in facility stagnation temperature and combustor equivalence ratio were used to assess performance for several combustor configurations. The effects of injector region scale, inlet isolation, constant area combustor length, and combustor divergence on combustion efficiency and upstream pressure propagation were examined.

The results of this study indicate that scale and geometry have an important effect on the performance parameters of interest, and that the beneficial aspects of certain geometric variations can be combined to improve overall performance.

Nomenclature

d	injector diameter, inches
ΔF	change in stream thrust, lb_f
ΔF_ϕ	change in stream thrust, defined in eq. (6), lb_f
G	gap, inches
h	step height, inches
ℓ_o	distance of upstream propagation of pressure
$\ell_{1,2,3,4}$	model length variables, see Fig. 1, inches
$\dot{m}_{fuel}$	fuel mass flow, lb_m/sec
p	pressure, psia
q_r	fuel to freestream dynamic pressure ratio
s	fuel injector spacing, inches
T	temperature, R
x	distance, inches
x_ℓ	distance for complete fuel-air mixing, ϕ=1 , inches
x_ϕ	distance for complete fuel-air mixing, inches
δ	boundary layer thickness, inches
η	efficiency
ϕ	fuel-air equivalence ratio
ϕ_t	total fuel-air equivalence ratio $= \phi_1 + \phi_2$

Subscripts

c	combustion
i	ignitor
l	large scale
m	mixing
max	maximum
r	reacted
s	small scale
t	stagnation value
o	value entering test section
1	value at pilot fuel injector
2	value at primary fuel injector

Introduction

Current interest in high speed endoatmospheric flight utilizing airbreathing propulsion, most notably in the form of the National Aero-Space Plane (NASP), has refocused efforts on supersonic combustion ramjet (scramjet) engine research. Due to test facility size limitations, tests of scramjet hardware (e.g inlets, combustors, and engine modules) have been performed using subscale models. The use of these small models has been justified on the basis that the combustion in the engine will be mixing, rather than kinetically limited, and that if the correct scaling parameters were identified and their relationships preserved in the extrapolation from subscale to full scale hardware, the mixing would be correctly predicted.

In contrast to mixing, which is assumed to scale with the gap between fuel injection struts or walls,[1] ignition and flameholding characteristics have been shown to be strongly affected by model size and boundary layer thickness.[2,3] In general, a thin boundary layer approaching the fuel injection region promotes ignition, and a thick, cooled boundary layer retards ignition. A thick boundary layer promotes flameholding. Flameholding is also enhanced by a larger scale flameholding region, e.g. a step or base, due to increased residence times.[4]

A limited number of tests using unconfined Mach 3.3 combustor flow in order to assess, among other things, scale effects were conducted previously. Since confined flow more realistically simulates scramjet combustor flow than the unconfined flow, a series of direct-connect combustor tests was undertaken at the NASA Langley Research Center to further explore the effects of scale on direct-connect scramjet combustor performance.[2]

Variations in facility total temperature and combustor equivalence ratio were used to determine the sensitivity of combustor performance to these test conditions for several combustor configurations with a factor of two in scale. The configurations included the following parametric model variables (see Fig. 1 for a sketch of the model and nomenclature): the height, h, of the rearward facing step; the distance, ℓ_1, from the end of the facility nozzle to the fuel injector region; the distance, ℓ_4, from the end of the fuel injector region to the end of the constant area section, and the effective half gap, G/2, between the walls containing the fuel injectors and the plane of symmetry. Other model parameters were the distance from the step to the ignitor injector(s), ℓ_2, the distance from the step to the primary fuel injector(s), ℓ_3, the primary fuel injector lateral spacing, s, and the primary fuel injector diameter, d. The parameters ℓ_2/h, ℓ_3/h, s/G, and s/d were held approximately constant in these tests.

The injector configuration used in these tests has provided good ignition and flameholding characteristics with G = 1.8 inches and $\ell_1 = \ell_4 = 0$.[5] The relationships between s, d and G/2 used for the primary fuel injectors were those derived from previous Langley studies intended to optimize fuel mixing.[6-8] These relationships are $s \approx G$ and $d \approx s/15$ and have been shown to promote good fuel/air mixing. The thickness of the approaching boundary layer has been shown to affect ignition and flameholding characteristics, and the variable ℓ_1 allows this sensitivity to be studied. In addition, the variable ℓ_4 allows a determination of the effect of a constant area length downstream of the injectors on mixing and combustor performance.

In order to study the effects of scale, the effective size of the fuel injector region was doubled in the following manner: a region equivalent to one quarter of the fuel injector configuration shown in Fig. 1 was scaled up by a factor of two in each direction. This transformation can be seen in Fig. 2, which is a view looking upstream from the fuel injector station. For this transformation to be exact, two no-slip symmetry plane walls are required. Of course, this was not possible, and real walls were used. For this 'large scale' injector block, h and G are twice what they were in the 'small scale' injector block. Similarly, s, d, ℓ_2, and ℓ_3 are also two times what they were in the small scale block. The first series of tests reported in Ref. 3 were conducted with the 48-inch long divergent duct expanding with a 2 degree angle on both the top and bottom walls. An additional series of 'large scale' tests was conducted using a modified diverging duct with 2 degree expansion on the bottom wall only. This latter configuration more nearly simulated the geometric scaling shown in Fig. 2. When the combustor expansion is expressed in terms of gaps, the 'large scale' injector block with the duct with one diverging wall has the same expansion rate as the 'small scale' injector block with the two diverging walls. A sketch of the large scale configurations is shown in Fig. 3.

Background and Discussion

Data from previous Langley cold flow hydrogen-air mixing studies have been correlated to provide a combustor and fuel injector design 'recipe.'[1] The following formulae predict the mixing distribution versus non-dimensional distance downstream of perpendicular or parallel fuel injectors. They are reported to be valid for sonic injection from both walls of a two-dimensional duct with the spacing, s, between fuel injectors being equal to the gap, G, between the walls, and the fuel injector diameter, $d \approx s/15$.

The length required for complete mixing, x_ℓ, when the injected equivalence ratio is unity is

$$x_\ell = 60\ G \tag{1}$$

For an equivalence ratio less than or equal to unity, the length required for complete mixing, x_ϕ, is given by,

$$\frac{x_\phi}{x_\ell} = 0.1791e^{1.72\phi}\ ;\ \phi \leq 1 \tag{2a}$$

while for $\phi > 1$,

$$\frac{x_\phi}{x_\ell} = 3.333e^{-1.204\phi};\ \phi > 1 \tag{2b}$$

The mixing efficiency, η_m, defined by

$$\eta_m = \frac{\phi_m}{\phi};\ \phi \leq 1 \tag{3a}$$

$$\eta_m = \phi_m;\ \phi > 1 \tag{3b}$$

can be expressed as

$$\eta_m = 1.01 + 0.176\ \ell n \frac{x}{x_\phi} \tag{4a}$$

for perpendicular injection, and

$$\eta_m = \frac{x}{x_\phi} \tag{4b}$$

for parallel injection.

If the fuel injection angle is between 0° and 90°, the efficiency can be interpolated linearly between the parallel and perpendicular values.

The mixing of a sonic hydrogen jet injected normal to a supersonic airstream has also been shown to be dependent on the thickness of the boundary layer approaching the injector, but this dependence is not explicitly accounted for by the empirical 'recipe.' In Ref. 9 the penetration of the jet and the decay of the maximum hydrogen mass fraction were correlated with the ratio of boundary layer thickness to injector diameter, δ/d, to the 0.4 and 0.5 powers, respectively. Thus, a thicker boundary layer allowed greater fuel penetration and more rapid mixing than was possible with injection through thin boundary layers.

In a scramjet engine, of course, the combustor would be situated at the end of an inlet, rather than a facility nozzle, as is the case in a direct connect combustor test. Under certain conditions in an engine, the inlet may unstart. Since the sensitivity of the upstream pressure rise to geometry and test conditions will be investigated, a discussion of combustor interaction follows. This unstart is caused by creating too large a pressure rise in the combustor, which separates the incoming boundary layer.[10] In some cases, it is desirable to produce a normal shock pressure rise in the combustor, but in tests of engines with closely coupled inlets conducted at Langley and elsewhere it has not been possible to achieve this level of pressure rise without causing an inlet unstart. In fact, a pressure rise much smaller than that produced by a normal shock will normally unstart the inlet.

It would be desirable if inlet unstart could be predicted from direct-connect combustor tests, since model variations can be accomplished much more readily in this mode, and hence methods of improvement could be found more quickly. There are some important differences between engine inlet/combustor flow and direct-connect facility nozzle/combustor flow which must be realized. A direct comparison between the two cannot be made blindly, or erroneous conclusions may be drawn.

The first difference between the two flows is that, due to the ingestion, or simulated ingestion of the vehicle forebody boundary layer, the boundary layer entering the engine combustor may be much larger than that entering the direct connect combustor. Pressure feeding forward through the boundary layer is thought to be a primary cause of inlet unstart, and the effect of the thick boundary layer in the engine may be great. Another difference is the direction of the pressure gradient entering the combustor, and the stability of shock waves in these regions. In the engine, an adverse pressure gradient exists in the inlet, making the boundary layer much more susceptible to separation, and if a normal shock should form in this region, it would quickly move out the front of the inlet to a more stable position. In the direct connect test, the flow entering the combustor has been through a negative, or favorable, pressure gradient, and is less susceptible to separation. Converse to the engine situation, a normal shock is stable in this region. A third difference in the two situations is the character of the flow entering the combustor. The facility nozzle in the direct-connect test provides the combustor with a relatively uniform, shock free flow, whereas the engine inlet may have produced a shock train which persists into the combustor, providing sharp gradients in the boundary layer. Although the differences between engine and direct connect tests are great, data from direct-connect tests should be useful if care is taken to use only the information which can reasonably be extended to the engine.

In a fixed or moderately variable geometry scramjet, it is important to achieve, under certain conditions, mixed subsonic-supersonic, or dual-mode combustion. In order to accelerate while at relatively low Mach numbers, it may be necessary to add more heat in the combustor than is consistent with purely supersonic flow. In such a case it is desirable to allow the flow to shock down to subsonic velocities, and reaccelerate to supersonic velocities with continued heat addition in a diverging combustor. In actuality, there will always be regions of subsonic flow in any combustor, e.g. behind steps and near fuel injectors, but the interest here is when the bulk of the flow is participating in the dual mode process.

As with combustor-inlet interaction, it is useful to study this phenomenom in a direct connect environment. In general, the simple combustors used in direct connect tests provide a more uniform flow than that found in a combustor of an engine module, and hence, the flow is more applicable to a simple, one dimensional analysis. The important phenomena involved should be the same in each case, but the analysis and interpretation of the data obtained in the direct-connect test should be much more straightforward.

Apparatus and Procedures

The test hardware used in this study was modelled after that used in Ref. 5, due to the success obtained with that configuration. The injector region consisted of five small (0.050 inches dia.) pilot fuel injector holes, 10 injector diameters apart, located at an axial position 37 injector diameters upstream of a rearward facing step of height h. The purpose of these injectors was to supply a small amount of fuel to the boundary layer approaching the step. By the time the pilot fuel reaches the step, it should be well mixed with the boundary layer flow and in roughly stoichiometric proportions, based on the results of Ref. 11. One or more ignitor fuel injectors were located in the step region (ℓ_2 = 2h). The purpose of the ignitor was to provide ignition of the 'premixed' boundary layer flow. Once this flow was ignited, the ignitor gas flow could be stopped, and the pilot fuel flow continued to burn and provided an ignition source for the primary fuel.

The ignitor fuel used in these tests was a mixture of 20 percent by volume monosilane (SiH_4), 80 percent hydrogen. This mixture has been shown to be an effective ignitor and is relatively simple to use. It does have the undesirable qualities, however, that (1) it is a pyrophoric material, and (2) it tends to leave deposits of silicon oxides on the hardware as it burns. These deposits can and will affect the flow and heat transfer properties of the model, and may influence the results. Other ignitors have been shown to be effective, and may be more desirable, but the silane/hydrogen mixture was chosen for simplicity. Subsequently, this mixture will be referred to as silane.

The primary fuel injector(s) was(were) located at a distance of approximately 10 step heights downstream of the step. (For the small scale, h = 0.15 inches and for the large scale, h = 0.30 inches.) This distance is downstream of the reattachment point of the main flow, and hence the primary fuel should not feed upstream into the recirculation region behind the step. The reason for this positioning of the primary fuel injectors downstream is to prevent cold fuel from entering the recirculation region and quenching the reaction by creating a cool, very fuel rich zone. The purpose of the pilot fuel/step combination is to provide a continuous ignition source for the primary fuel. The distance from the primary fuel injectors to the entrance of the diverging duct was 0.35 inches.

As stated previously, the relationships between the gap, G, distance between the walls from which the primary fuel was injected, the diameter of the primary fuel injector(s), d_2, and the spacing between the primary fuel injectors, s_2, were obtained from previous Langley mixing studies. A fuel injector is expected to fuel an area which is twice as wide as it is high, (height being in the direction of the fuel injection), and the height of this region should be roughly 6-8 injector diameters. Thus, for the small scale apparatus using 4 fuel injectors, with a gap of 1.8 inches, the injector spacing used was 1.8 inches, and the injector diameter was 0.120 inches. The width of the combustor was 3.46 inches, which is close to the 3.6 inches given by the design recipe. Accordingly, for the large scale, G = 3.6 inches and d_2 = 0.240 inches. Placing the injector on the centerline yields s_2 = 3.46 inches, again close to the 3.6 inches given by the recipe. Note that for this large scale, the fuel injection is from one side only.

The reader will note that four fuel injectors of d_2 = .120 inches have the same area as the injector with d_2 = .240 inches. Thus, for a given desired equivalence ratio, ϕ_2, at a given test condition, $q_{r,l} = q_{r,s}$ and hence the parameters which scale with dynamic pressure ratio should also be the same.

To investigate the effects of upstream length and boundary layer thickness on the parameters of interest, two duct sections were made to fit between the facility nozzle and the fuel injector blocks. These constant area sections had lengths ℓ_1 = 4 inches and 8 inches. These sections created not only a different boundary layer thickness, but also served to slightly increase the pressure and temperature and decrease the Mach number and velocity of the flow entering the fuel injector region. In addition, the thermal boundary layer was also changed, since the facility nozzle was water cooled while the additional sections were uncooled. The distance between the end of this upstream section and the pilot fuel injectors was 0.35 inches.

The effect of constant area combustion on performance could also be studied by the addition of a constant area combustor section downstream of the fuel injector blocks. Each constant area combustor section had $\ell_4/G = 2.22$; thus for each scale, the same amount of mixing should have occurred by the end of this section. The final combustor section consisted of a 48-inch long diverging, 2-dimensional duct, with an expansion half angle of 2°. For the 'small scale' tests and the first series of 'large scale' tests, both the top and bottom walls of the 48-inch long duct were diverging at 2 degrees. During later tests the 'large scale' hardware was fitted with a duct with 2 degree expansion on the bottom wall only. This latter configuration more nearly simulated the geometric scaling shown in Fig. 2. When the combustor expansion is expressed in terms of gaps, the 'large scale' injector block with the duct with one diverging wall has the same expansion rate as the 'small scale' injector block with the two diverging walls. A sketch of the large scale configurations is shown in Fig. 3. For all the large scale tests reported herein using the duct with one diverging wall, both ℓ_1 and ℓ_4 were equal to zero. At an x/G relative to the start of the diverging duct of 13.33 the large scale duct with the two diverging walls has expanded to an area ratio of 3.435, while the small scale has expanded to only 2.318, i.e. the diverging duct for the large scale had an effective expansion which was twice as rapid as the small scale.

The high enthalpy test gas required to simulate scramjet combustor flow for flight Mach numbers ranging from 4 to 7 was produced by a hydrogen-oxygen-air burner. The flow rates of hydrogen, air, and oxygen could be varied in order to achieve the desired stagnation temperature, pressure, and free oxygen content. Of course, it was always desired that the test gas have a free oxygen content of 20.95 percent by volume, the same as air. The stagnation temperatures used ranged from approximately 1800 to 4300 R, while the stagnation pressure was fixed at approximately 115 psia. These conditions yielded a static pressure of roughly 1 atmosphere when expanded through the facility Mach 2 water cooled nozzle. An air ejector was connected to the aft end of the diverging combustor duct to prevent atmospheric back pressure from influencing the test results.

The test procedure used in this study was systematically to vary the burner stagnation temperature and primary fuel equivalence ratio for each configuration, so that a matrix of performance information could be obtained. For a given test point, the test sequence proceeded as follows: after the heater startup transient, the pilot fuel was turned on; 2 seconds later, the silane ignitor was turned on; 2 seconds later, the primary fuel was turned on; 1 second later, the silane ignitor was turned off; 3 seconds later, the pilot fuel was turned off; and 2 seconds after that, the primary fuel and flows to the heater were terminated to complete the test. During some tests, the pilot fuel was ramped up rather than shut off to determine the sensitivity of performance to pilot fuel flow. For some of the higher temperature tests (T_t > 3000 R), the silane was not used as it was not required for ignition.

Typically, several tests were run for each configuration at a given stagnation temperature, with the primary fuel equivalence ratio being varied with each test. The value of ϕ_2 was increased from run to run, until the pressure rise caused by the injection/combustion propagated upstream to the facility nozzle. This value of ϕ_2 was noted as having caused 'upstream interaction.'

Data Reduction

The data taken during each test were both converted to engineering units in near real-time for timely evaluation of a test, and stored on magnetic tape for future use. Typically, data from a test were retrieved from tape, converted to the appropriate engineering units, and analyzed using a one-dimensional, multi-step integration of the governing equations. This one-dimensional iterative analysis uses the experimental pressure distibution, the fuel and test gas flow rates, and the computed static properties entering the combustor, to calculate a fuel reaction distribution which is consistent with the data. The reacted fuel equivalence ratio, ϕ_r, is related to the combustion efficiency, η_c, by

$$\eta_c = \frac{\phi_r}{\phi_t} \tag{5}$$

The unreacted fuel is assumed to be in thermal equilibrium with the combustion products at the local static conditions. This analysis does not account for shock losses which are undoubtedly present, particularly in the region of the fuel injectors, and so the computed values of reacted equivalence ratio, and thus the derived combustion efficiency, will be somewhat higher than is actually the case. Experience with the wall pressure distributions obtained with combustion in these 2-dimensional ducts has shown that, downstream of the fuel injectors, the flow is dominated by combustion and that any shock train present is nearly indiscernable. In Ref. 7, a comparison was made between the combustion efficiency obtained using the method described above and that obtained from gas sample measurements, and these results were shown to be in reasonable agreement. These facts allow this one-dimensional analysis technique to be used for making a comparative assessment of tests in similar hardware.

Results

The various configurations described previously and illustrated in Fig. 1 were assembled and tested. A summary of the configurations tested is given in Table I. Combustion/mixing efficiency and upstream interaction sensitivity to scale and combustor geometry are presented. Typical calculated combustion efficiencies, pressure and area distributions are shown to illustrate the effects of the test variables.

Mixing/Combustion

A primary objective of this study was to determine the applicability of the mixing 'recipe,' previously described, to the two different scales involved, and to the situation where the degree of flow confinement varied, i.e. in a constant area or divergent channel, and to situations where the boundary layer approaching the combustor varied in thickness and character. Accordingly, the reaction distribution was calculated for each test by the one-dimensional procedure described previously, and this was compared to the mixing distribution calculated using equations (1-4). Figure 4 shows the calculated combustion and mixing efficiency profiles for the pressure distribution shown, for the small scale, at a stagnation temperature of 2070 R and a total equivalence ratio of 0.45. As indicated by the area distribution, both the upstream length and the downstream constant area length are zero. In this and subsequent figures, the x axis is scaled by G due to the x/G dependence of η_m, and the point x/G = 0 is located at the station of the primary fuel injector(s). The reader will notice that the calculated reaction efficiency is slightly lower than the predicted mixing efficiency given by the recipe, which is shown for comparison. This result is typical for this configuration (6) and test conditions, although not for all configurations. It should be noted once again that the computed combustion efficiency may be too high since shock losses are not accounted for.

Figure 5 shows typical test results for a test when the large scale injector block was used with the duct with only one divergent sidewall. This configuration (number 9 in Table I) closely simulates a factor of two in geometric scale of the combustor. The divergent combustor length was not increased to maintain the 26.6 gaps due to length restrictions in the test cell. Since the axial distance is normalized and plotted in terms of gap heights, the large scale combustor results can be compared directly with the first half of the small scale results. Figure 5 is plotted in the same format as Fig. 4. Again the calculated η_c was lower than the η_m, but at the 13.3 x/G axial station of the large scale combustor the calculated η_c was about the same (80 percent) as for the small scale test at this same location. In fact, when the figures were overlayed, the calculated combustion efficiency distributions for these tests were almost coincident except in the near field of the fuel injector. From this comparison and similar tests at other conditions, it appears that within the limits tested here, i.e. a factor of two in scale, geometric scaling was verified, and the mixing distributions calculated from equations (1-4) appear to predict a reasonable mixing profile. These results also suggest that the scramjet combustor length should be about 30 gaps if high combustion efficiencies are to be realized.

The effect of combustor divergence on performance is illustrated in Fig. 6. The geometry is the large scale configuration 4 with both diverging walls at a T_t of 2000 R and ϕ_t of 0.46. (Similar condition to Fig. 5.) Notice the moderate pressure rise as compared to results from Fig. 5 for the large scale with one diverging wall. Although the combustion efficiency is continuing to rise, the calculated efficiency is lagging the predicted mixing considerably. Of course, the mixing model does not account for the rapid duct divergence. The η_c at the end of the duct was just over 65 percent as compared to about 80 percent for the same scale with the reduced divergence. Regarding the poor performance of the large scale high expansion rate tests (configuration 4) compared to its small scale counterpart (configuration 6), the following cause is proposed: If mixing can be assumed, for the moment, to scale with x/G, the large scale hardware experiences an expansion in area which is twice that of the small scale for a given degree of mixing. Hence, the temperature and pressure are correspondingly lower and the reaction is inhibited to a greater degree.

Scale and geometry effects are illustrated in Fig. 7. Figure 7 shows the effect of scale when 2.22 G of constant area combustor was added downstream of the injector block. Both scales used the duct with both walls diverging at 2 degrees. Note that, in terms of gaps, the large scale (configuration 3) sees a more rapid expansion. Figure 7 provides a comparison at a stagnation temperature of approximately 2000 R and a total equivalence ratio of 0.30. The ratio of the maximum pressure to the nozzle exit static pressure, p_o, is approximately the same for each scale and is approximately equal to 2.8 times the nozzle exit static pressure. The sharp pressure dropoff in the large scale distribution is misleading, since the area is increasing more rapidly. The reacted equivalence ratio distribution exhibited by the small scale test shows a rapid initial rise (due in part to shock pressure rise) followed by a very gradual rise; the large scale distribution similarly rises sharply at x/G = 0, and then continues to rise, to a somewhat higher level than that achieved in the small scale case after an equivalent number of gaps downstream. The dip in η_c at the end of each distribution is believed to be an error caused by the proximity of the pressure taps in this region to the air ejector. The comparison of Figs. 7 and 6 reveals that although the large scale, high expansion configuration performance was poor as compared to the small scale for the configuration with no constant area combustion, when a constant area section was added the large scale performance improved, and the small scale performance deteriorated somewhat. A statement that the benefit of constant area is due to improved mixing is a bit strong. It must be noted that one would expect combustion to be improved with the addition of a constant area combustor section, since this would tend to keep both pressure and temperature higher. However, the important point to note here is that it is not correct to assume that the combustion will track the mixing prediction regardless of geometric variations. It is evident that only with careful selection of combustor geometry can the combustion be caused to follow the predicted mixing.

Upstream Interaction

Upstream interaction was defined in the current study as a pressure rise at the exit of the facility nozzle. Figures 8 and 9 summarize the data relating upstream interaction to ϕ_t, T_t, ℓ_1, ℓ_4, and scale. In Fig. 8, the effects of ℓ_4 are presented. A comparison between $\ell_4 = 0$ and $\ell_4 = 2.22$ G is shown. Again as expected, the limiting ϕ_t is higher for the case of no constant area combustion. Thus, the addition of a constant area combustor reduces the amount of fuel which can be injected at a given condition, and this effect appears to be relatively independent of scale.

The effect of ℓ_1 on upstream interaction is summarized in Fig. 9. Figure 9 shows upstream interaction data for $\ell_1 = 0$, 4, and 8 inches, respectively. The figures indicate that the addition of upstream length can allow additional fuel to be injected without incurring upstream interaction. It is postulated, based on Figs. 8 and 9, although tests of such a configuration have not been made, that the addition of upstream length could be used to offset the denigrating effect of constant area combustion on the maximum amount of fuel that could be injected, ϕ_{max}.

The configurations with more upstream length can withstand a higher pressure ratio. It should be noted that a pressure ratio of 4 is nearly the normal shock pressure ratio for M = 2, and thus little further increase would be expected with $\ell_1 > 8$ inches.

The pressure ratios achieved without upstream interaction in these direct connect combustor tests are significantly higher than those achieved in engine tests at similar conditions, and the reasons for this may be those discussed previously regarding the differences between engine and direct-connect combustor tests. This does not mean, though, that these results are invalid; it indicates that additional length between the inlet and combustor may be helpful in achieving higher pressures in the combustor without unstarting the inlet.

Summary and Conclusions

A series of tests was conducted to determine the effects of various scale and geometric parameters on the combustion and pressure rise limit in a direct connect supersonic combustor. The tests were conducted in a Mach 2 flow with stagnation temperature ranging from 1800 to 4300 R, at a static pressure of 1 atmosphere, using hydrogen fuel. An injector configuration similar to that developed by Wagner, et.al.[5] was used, as it had previously demonstrated good performance characteristics.

The effects of upstream length, ℓ_1, fuel injection gap, G, and constant area combustor length, ℓ_4, as well as those of equivalence ratios, ϕ, and stagnation temperature, T_t, were studied, and the following conclusions were drawn:

(1) The calculated combustion efficiency appears to be independent of scale for the same geometry.

(2) Combustion can be strongly dependent on geometry, i.e. some constant area combustion versus immediate expansion, for the same scale. The rapid expansion in the large scale model quenched the reaction when no constant area combustor was provided. The constant area keeps pressure and temperature high to promote combustion.

(3) The calculated combustion efficiency is independent of upstream length between the nozzle exit and the injector block.

(4) The addition of upstream length allows a larger total equivalence ratio to be injected without incurring upstream interaction, and the addition of a constant area combustor decreases maximum equivalence ratio.

(5) The maximum pressure rise sustainable without incurring upstream interaction increases with upstream length but is independent of constant area combustor length and scale. Near normal shock pressure rise was exhibited without upstream interaction for upstream length of 8 inches.

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Table 1. Test Configurations

Configuration	Scale	ℓ_1 (inches)	ℓ_4 (inches)	G/2	No. 2° Diverging walls
3	1*	0	8	1.8	2
4	1	0	0	1.8	2
5	s*	0	4	0.9	2
6	s	0	0	0.9	2
7	s	4	0	0.9	2
8	s	8	0	0.9	2
9	1	0	0	1.8	1

* s = small; l = large

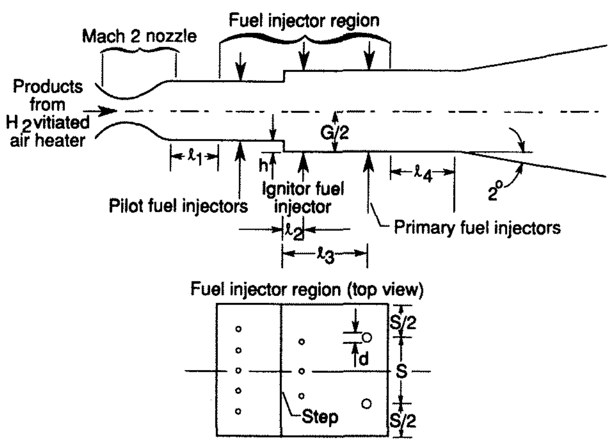

Fig. 1 - Schematic of test apparatus, small scale.

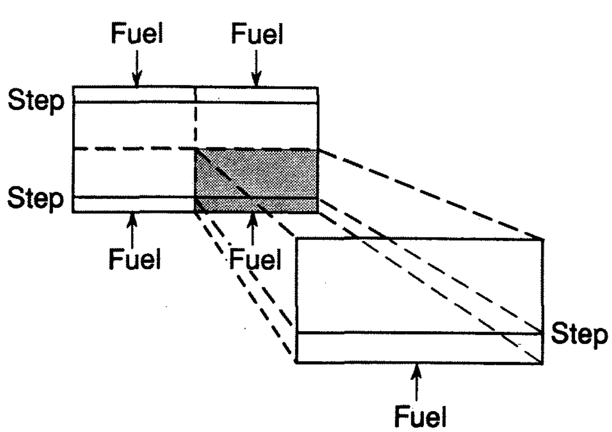

Fig. 2 - Small to large scale transition.

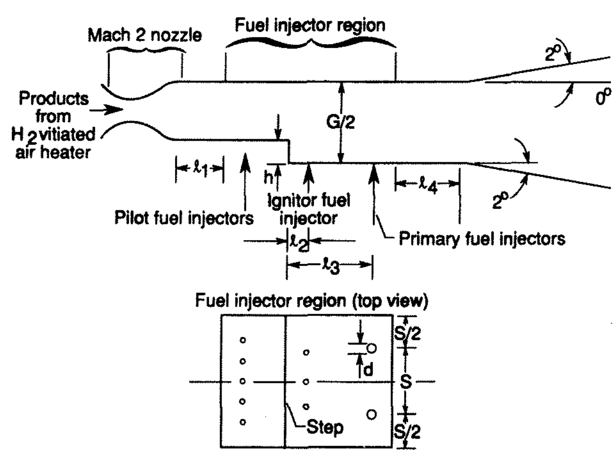

Fig. 3 - Schematic of test apparatus, large scale.

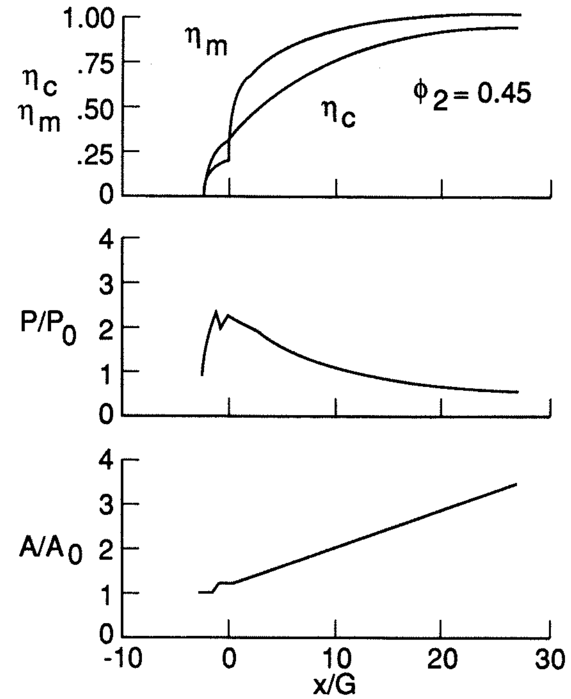

Fig. 4 - Area, pressure, and efficiency distributions; configuration 6, T_t = 2070R.

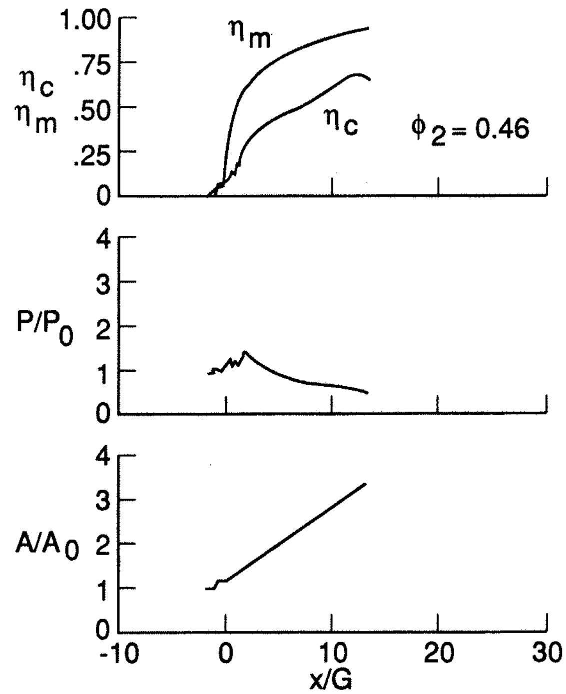

Fig. 6 - Area, pressure, and efficiency distributions, configuration 4, T_t = 2000R.

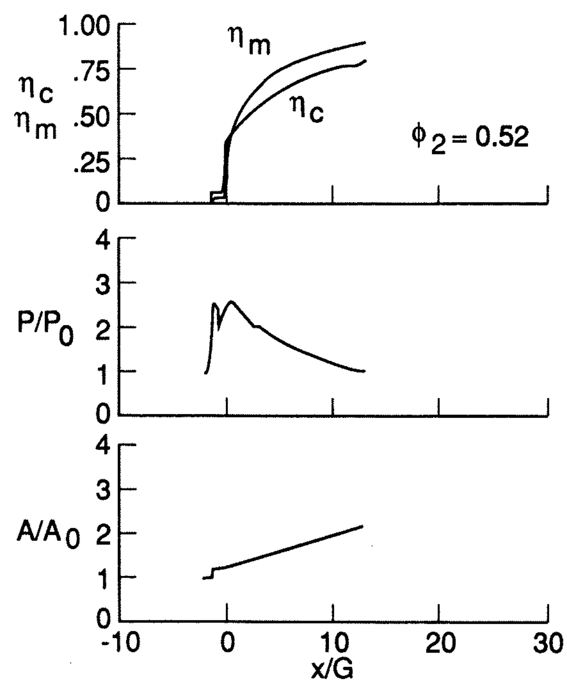

Fig. 5 - Area, pressure, and efficiency distributions, configuration 9, T_t = 2170R.

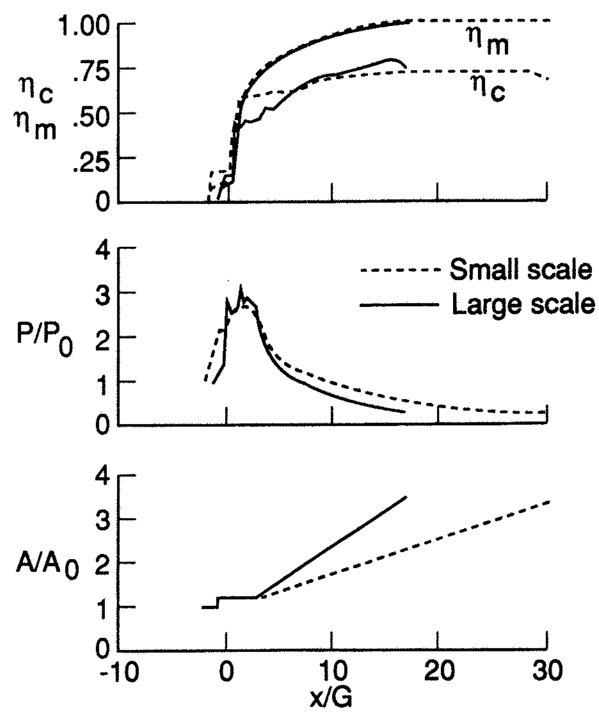

Fig. 7 - Comparison between large and small scales; ℓ_4 = 2.22 G, T_t = 2000R, ϕ_t = 0.30.

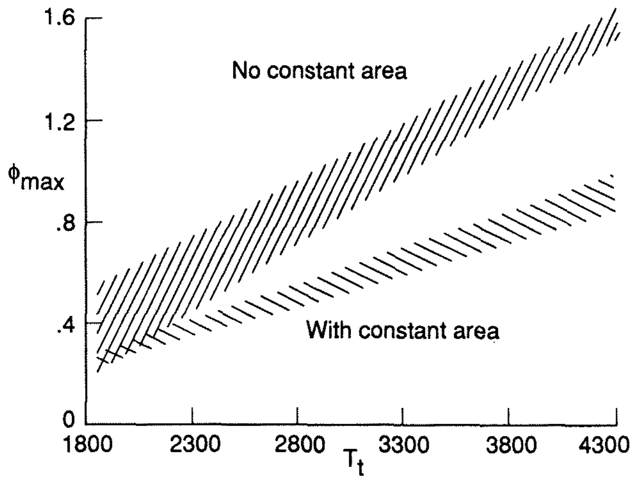

Fig. 8 - Upstream interaction limit, small and large scales.

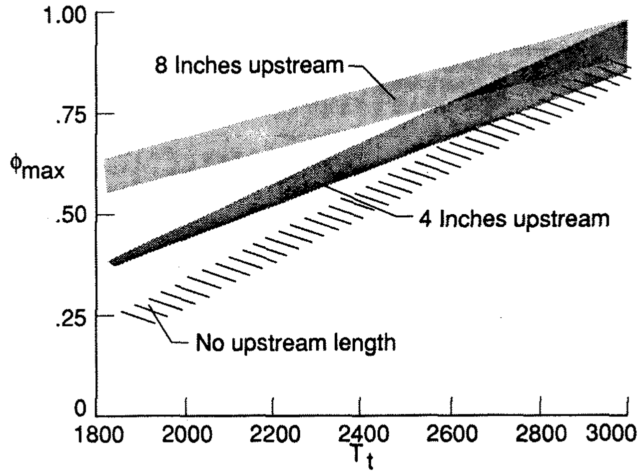

Fig. 9 - Effect of isolator length on upstream interaction for small scale.