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SCALING AND IGNITION EFFECTS IN SCRAMJETS

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ABSTRACT

Some effects that could influence pressure scaling in a scramjet are presented, namely viscous effects, ignition time, and complete reaction time. Results are presented from the first scramjet model which is the largest to be tested in the study. For stagnation pressures from 13 to 40 MPa and stagnation enthalpys from 5.4 to 10.7 MJ/kg ignition was achieved in all combustion runs. As theoretically expected, ignition time decreased with increasing stagnation enthalpy and stagnation pressure. In addition, the ratio of the pressure at the exit of the scramjet to that at the beginning was found to decrease with increasing stagnation enthalpy.

NOTATION

C	species concentration
k_f	forward specific reaction rate constant
l	length
l_{ig}	ignition length
M	Mach number
P	pressure
R	specific gas constant
R_e	Reynolds number
T	temperature
t	time
U	velocity
x	axial distance
ϕ	equivalence ratio
γ	ratio of specific heats
μ	absolute viscosity
ρ	density
τ_{ig}	ignition time

INTRODUCTION

There is at present no facility capable of testing a full size scramjet engine over the full operating range. Scaling laws are therefore needed to relate the data obtained by testing scaled down models to a full size scramjet engine. Ramjet engine data scales with a pressure-length scaling factor, meaning that keeping all other properties (Mach number, velocity, species concentrations, etc.) the same the data would scale the same for twice the pressure and half the length. This may be associated with viscous effects. In a scramjet engine, however, there are a number of factors that can potentially affect the scaling, the most important of which are the viscous effects, the ignition time, the complete reaction time, the mixing process, and the effect of temperature and pressure on equilibrium heat release. With these effects acting simultaneously it will be difficult to determine which effect is dominating the scaling factor. An experiment has therefore been set up to determine how scramjet engines scale with pressure while keeping all other flow properties constant. The experiments cover a range of length scales with similar geometries, maintaining the pressure length product constant. Ignition delay, reynolds number effects and possibly mixing are expected to scale directly with this parameter. Therefore the experiment should give an indication if other effects which do not scale this way have a significant influence on the static pressure which is fundamental for evaluating the performance of a scramjet.

THEORY

Viscous effects scale with Reynolds number. With Mach number, velocity, entropy, and species concentrations held constant, viscous effects will scale by the pressure-length factor.

$$R_e = \frac{\rho U x}{\mu} \tag{1}$$

$$R_e = (Pl)\, T^{-1.2} M \sqrt{\frac{\gamma}{R}} \frac{T_o^{0.7}}{\mu_o} \tag{2}$$

The ignition reaction is a two body reaction. Thus it may be shown that the fractional change in concentration of one of the reactants is directly proportional to the concentration of the other. One may then integrate to find that the relative reaction rate is proportional to the concentration of one of the reactants and thus the pressure. Hence ignition length will scale by the factor pressure-length.

$$A + B \xrightarrow{k_f} C + D \tag{3}$$

$$\frac{dC_A}{C_A} = - k_f C_B \, dt \tag{4}$$

$$\tau_{ig} \propto \frac{1}{C_B} \tag{5}$$

$$\tau_{ig} \propto \frac{1}{P} \tag{6}$$

The final combustion reaction which produces H_2O is a three-body reaction. In an analogous analysis to the two-body ignition reaction it may be shown that the relative reaction rate will be proportional to the concentration squared and thus to pressure squared. Thus the reaction length will scale by the factor pressure squared-length.

$$A + B + C \xrightarrow{k_f} D + E \tag{7}$$

$$\frac{dC_A}{C_A} = - k_f C_B \; C_C \, dt \tag{8}$$

$$\tau_{ig} \propto \frac{1}{C_B \, C_C} \tag{9}$$

$$\tau_{ig} \propto \frac{1}{p^2} \tag{10}$$

EXPERIMENTS

Mixing and combustion experiments have been performed in the University of Queensland's reflected shock tunnel (T4) using a 1.32 metre long scramjet model. This model is the largest of the scramjets to be tested in this study. The model was two-dimensional with a duct height of 48 mm and a width of 100 mm. It was instrumented with thirty PCB pressure transducers to read static pressure and twelve thin film heat flux gauges manufactured at the University. The flow was processed by a contoured mach 8 nozzle, a set of opposing 15 degree wedges and an internal expansion inside the duct. This was done in order to match all the flow conditions (mach number, temperature, density, species concentrations) except pressure which were expected when testing the smallest scramjet using a mach 4.5 contoured nozzle.

Seven test conditions were chosen in order to show the effect of stagnation pressure and stagnation enthalpy on pressure scaling. Figure 1 shows the variation of stagnation pressure and stagnation enthalpy for the seven test conditions used. Holding the stagnation pressure essentially constant, stagnation enthalpy was varied from 5.7 to 10.7 MJ/kg causing variations in static temperature and velocity in the model from 1100 to 2100 K and 2.9 to 3.9 km/s, respectively. Also, while holding stagnation enthalpy constant, stagnation pressure was varied from 13 to 38 MPa causing variations in static pressure in the model from 6.6 to 17 KPa. Table 1 shows the flow properties at the point of fuel injection for the seven test conditions.

DISCUSSION

In all cases ignition was achieved. Figure 2 shows pressure distributions for a combustion, mixing, and tare run at condition 1. (A tare run is a run in which air is the test gas and no fuel is injected through the central injector. A mixing run is when gaseous hydrogen is injected into Nitrogen and a combustion run is when gaseous hydrogen is injected into air.) The pressure rise in a tare run is due to viscous effects at the walls. By comparing the pressure distributions between a tare and a mixing run one can see the extent of the pressure rise due to mixing. The difference in pressure levels between the combustion and mixing runs, therefore, can be attributed to combustion alone. From figure 2 it is quite easy to see that combustion has occurred.

The ignition point, as well, can quite easily be determined from figure 2 as the point where the pressure level of the combustion run rises suddenly above that of the mixing run. Using the duct velocity for each run, ignition times can be determined. Figure 3 shows the variation of ignition times with stagnation enthalpy. Note how the ignition time decreases with increasing stagnation enthalpy. This trend agrees with the theoretical relation for ignition time by Pergament (1963) which follows.

$$\tau_{ig} = \frac{l_{ig}}{U} = \frac{8 \times 10^{-9} \, e^{(9600/T)}}{P} \tag{11}$$

This global model for ignition was developed on the basis of an eight-reaction, six species chemistry system. The pressure and temperature in the relation correspond to the local static pressure and temperature at the point of ignition. Hence the temperature used in the relation is the mixture temperature at the ignition location. Huber et al. (1979) found that for cold Hydrogen injected into a scramjet, self ignition would most likely originate in a mixing layer where the equivalence ratio (ϕ) was 0.2. From an energy balance between the fuel and air, neglecting heat transfer and dissipation effects, the mixture temperature can be determined by the following.

$$T_{mix} = T_{air} - \frac{0.327\phi}{1 + 0.327\phi} (T_{air} - T_{fuel}) \tag{12}$$

The values predicted using the theoretical ignition relation, however, do not match the experimental results very well. Table 2 shows the difference between the experimental values of ignition time obtained in the large model and the theoretical relation. For conditions 2, 3 and 4 the theoretical relation under predicts the ignition time. This could be due to the fact that the theoretical analysis did not take mixing into account in determining the time to achieve five percent of the complete reaction temperature rise (ignition time). The lowest enthalpy condition (condition 1), however, had a lower experimental ignition time than the theoretical value. The theoretical relation has a strong non-linear variation with temperature at lower temperatures due to the required activation energy which must be overcome to start the chain reaction. The experimental results, however, do not show this strong non-linearity at the low temperatures. This could be because the flow may have some free radicals or chain carriers such as atomic oxygen in it due to the fact that the flow was stagnated at the end of the shock tube and then chemically frozen through the nozzle.

Figure 4 shows the variation of ignition time with stagnation pressure. The predicted trend of decreasing ignition time with increasing stagnation pressure is observed for all four conditions. Table 3 shows the difference between the experimental values of ignition time obtained in the large model and the theoretical relation. The theoretical values over predicted the ignition time in all four cases. This again can be due to the fact that my flow did not exhibit a strong non-linearity of ignition at low temperatures. The most surprising result was the fact that ignition was achieved for condition 5 and 6 where it was thought that for such low pressures ignition should take four and six model lengths, respectively, to ignite.

The ratio of the final pressure at the exit of the duct to the initial pressure in the duct before injection is shown as a function of stagnation enthalpy in figure 5. From this figure one can see that the pressure rise due to combustion decreased with increasing stagnation enthalpy. This is a result expected from theory since at the higher temperatures the dissociation process will work against the final combustion reaction.

CONCLUSIONS

Ignition was achieved for stagnation enthalpys from 5.4 to 10.7 MJ/kg and stagnation pressure from 13 to 40 MPa. Trends of decreasing ignition time with increasing stagnation enthalpy and increasing stagnation pressure were observed. These trends match theoretical trends, however, the ignition time predicted by theory was less than the experimental ignition time for stagnation enthalpys greater than 7.6 MJ/kg. This was most probably due to the fact that the theoretical model did not take mixing times into account. For enthalpys less than 5.9 MJ/kg the experimental ignition times under predicted the theoretical values which may be due to the presence of chain carriers in the flow wavier the need for activation energy to initiate the reaction.The ratios of final to initial pressures in the duct were found to decrease with increasing stagnation enthalpy as was expected from theory due to the higher levels of dissociation at the higher enthalpys.

Further work includes the design and testing of the smallest scramjet in this study. This scramjet will be one fifth the size of the large scramjet with a 2 mm central injector. Experiments are scheduled for early 1993.

ACKNOWLEDGEMENTS

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PERGAMENT, H (1963) A theoretical analysis of non-equilibrium Hydrogen-air reactions in flow systems. [Preprint] 63113, American Inst. of Aeronaut & Astronaut.

Table 1 : Test Conditions in Large Scramjet

	cond. 1	cond. 2	cond. 3	cond. 4	cond. 5	cond. 6	cond. 7
M_{air}	4.42	4.36	4.38	4.26	4.38	4.47	4.45
$P_{T_{air}}$ (MPa)	38	40	34	36	13	19	32
$H_{T_{air}}$ (MJ/kg)	5.7	7.6	8.5	10.7	5.5	5.4	5.9
P_{air} (kPa)	17	19	14	21	6.6	7.8	13
T_{air} (K)	1100	1500	1600	2100	1100	1000	1100
U_{air} (km/s)	2.9	3.4	3.5	3.9	2.9	2.8	3.0
ϕ	1.23	1.36	1.26	1.32	1.23	1.53	1.29

M_{fuel}=3.41

$T_{T_{fuel}}$=296 K

Table 2. Experimentally and Theoretically Obtained Ignition Time for Various Stagnation Enthalpys

Condition	H_{stag} (MJ/kg)	τ_{ig} (μs) (experiment)	τ_{ig} (μs) (theory)
1	5.7	183	487
2	7.6	171	36
3	8.5	129	29
4	10.7	25	5

Table 3. Experimentally and Theoretically Obtained Ignition Times for Various Stagnation Pressures

Condition	P_{stag} (MPa)	τ_{ig} (μs) (experiment)	τ_{ig} (μs) (theory)
5	13	243	1780
6	19	231	2500
7	32	219	493
1	38	183	487

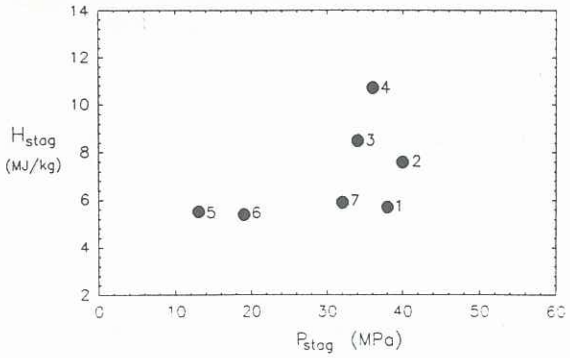

Figure 1. Variation of stagnation enthalpy and stagnation pressure for the seven test conditions in the large scramjet

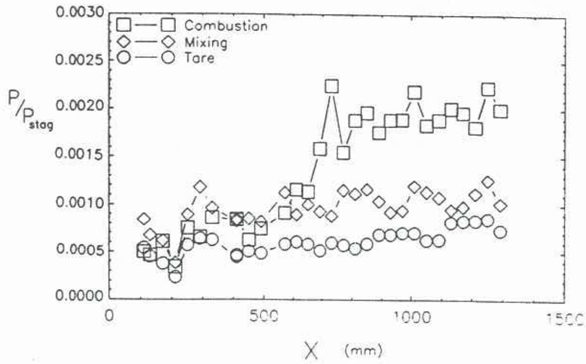

Figure 2. Pressure Distributions for a Combustion, Mixing, and Tare Run at Condition 1

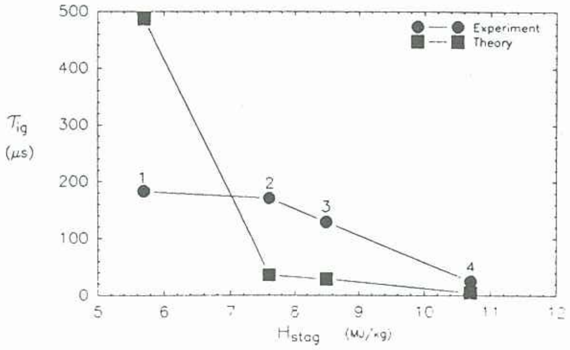

Figure 3. Variation of Ignition Time with Stagnation Enthalpy

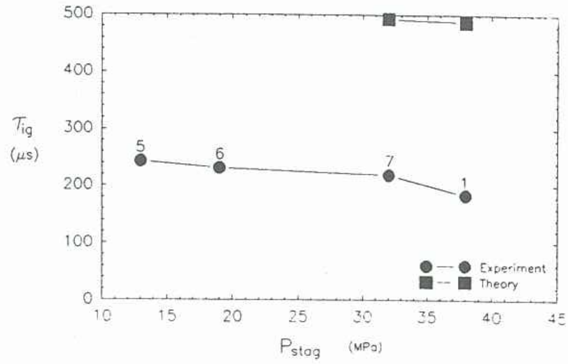

Figure 4. Variation of Ignition Time with Stagnation Pressure

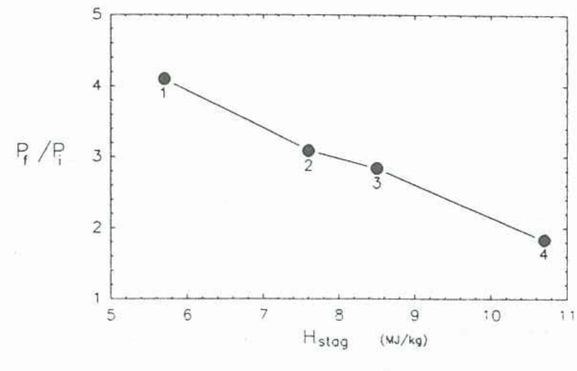

Figure 5. Ratio of Final to Initial Pressure in the Duct as a Function of Stagnation Enthalpy