Self Ignition of Hydrogen-Air Mixtures with Inclined Porthole Injection in Supersonic Flows

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Abstract
Experiments were performed in the T4 shock tunnel to investigate the self ignition of hydrogen in a supersonic air stream. Hydrogen was injected into the flow over an inclined flat plate for oncoming Mach numbers of 7.9 to 8.0. The nozzle-supply enthalpy was kept between 3.1 and 3.4 MJ/kg and two different pressure levels were used in the tests. Measurements of surface pressures were used to infer the location of ignition but only small pressure increases were obtained when combustion occurred. Therefore multiple tests at nominally the same condition were used so that statistical methods could be used to identify the ignition lengths. The ignition lengths of the hydrogen air mixture directly behind a strong leading edge shock indicate that Pergament's method is able to predict the ignition length to within 35% for the observed autoignition over the range of conditions tested.

NOMENCLATURE

H = enthalpy
L,l = length
M = Mach number
$\dot{m}$ = mass flow rate
p = pressure
T = temperature
t = time
u = velocity
ϕ = equivalence ratio

Subscripts

∞ = free stream condition
f = fuel jet properties at injector throat
i = ignition
m = condition after fuel and test gas are mixed
0 = stagnation condition
s = static condition

1. INTRODUCTION

The ejection of hydrogen from porthole injectors and its ignition in a supersonic air stream is of interest in scramjet propulsion. In the present work, the self ignition of hydrogen injected into air immediately behind a strong shock wave is reported. The model consists of a compression ramp and an expansion surface with sidewalls. There is no cowl, so this is an open combustor configuration. The fuel is injected from the compression ramp and it is of interest to see if it ignites before it reaches the expansion surface for different conditions. The model was designed so that the shock generated by the deflection of the supersonic free stream flow for condition 3 (see below) would produce conditions expected to be suitable for ignition of the injected hydrogen after it mixes with the mainstream air. This paper investigates whether Pergament's method [1-2] of calculating ignition lengths is applicable to such a configuration by comparing results obtained in the T4 Stalker tube at The University of Queensland with calculated ignition lengths.

For the open combustor configuration used in this study, the pressure rises due to heat released from combustion were relatively small. Therefore, a statistical method was employed to enable objective determination of the ignition lengths from the measured surface pressures only.

Pergament [1] correlated the ignition delay times for hydrogen-air mixtures as a function of the pressure and temperature of the mixture. For injection into a moving flow, this can be presented in the form of an ignition delay length, l_i, (Huber et al. [2]) where

$$l_i = \tau_i \cdot u \,, \tag{1}$$

$$\tau_i = \frac{8 \cdot 10^{-9} \cdot e^{\frac{9600}{T_m}}}{p} \tag{2}$$

and

$$T_m \approx T - \frac{0.327\,\phi}{1 + 0.327\,\phi}\left(T - T_f\right) \tag{3}$$

In Eq. (2), p is in atmospheres and temperatures are in Kelvin.

2. MODEL CONFIGURATION

A schematic diagram of the model configuration is given in Figure 1. The compression ramp was 250 mm long and 100 mm wide and was inclined at 27° to the oncoming flow. 25 pressure tappings were used to measure surface pressures using PCB piezoelectric transducers. Figure 1 illustrates that pressure measurements were taken at different spanwise locations for some streamwise locations. For the purpose of this analysis, the average of the spanwise measurements was chosen to represent the measured pressure at this streamwise location. The 95% confidence level uncertainty in an individual pressure measurement, taken as the mean level during the test period, is estimated to be 7% in the current experiments.

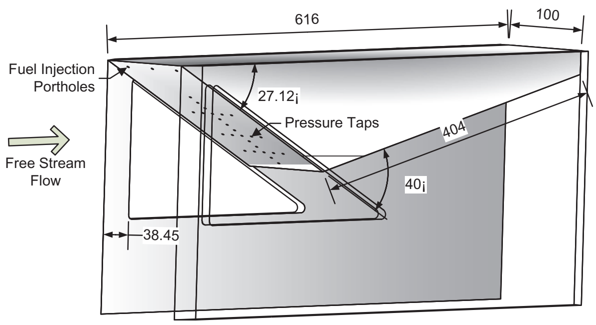

Figure 1. Schematic of model layout

Gaseous Hydrogen was delivered from a Ludwieg tube into the post shock flow via a row of three portholes of 2 mm diameter that were inclined at 45° to the local surface. These injection holes were located 13 mm aft of the leading edge, one on the centreline of the plate and the others 25 mm either side of the centreline. A fast-acting solenoid valve was used to initiate fuel flow. Fuel pressure was measured in the plenum chamber feeding the injection holes. The plenum was of sufficient size that the fuel in it was approximately at stagnation conditions for the duration of the test flow. Full details of the model and instrumentation are given in Kirchhartz [3].

3. EXPERIMENTAL CONDITIONS

Experiments were conducted at four conditions as shown in Table 1. The conditions were chosen to identify the effects of pressure and temperature on the ignition of the fuel. The pressure was varied by a factor of 2.4 and the enthalpy of the flow was varied over a small amount around conditions where ignition is expected to occur within the measurement region. Conditions 1 and 2 are at a relatively low freestream static pressure and conditions 3 and 4 are higher pressure conditions. Conditions 2 and 4 produce freestream temperatures around 230 K and conditions 1 and 3 produce freestream temperatures from 240 to 250 K.

Table 1. Nominal experimental conditions

	p_∞	T_∞	u_∞	H_0	M_∞	Shot Numbers
Condition	Pa	K	m/s	MJ/kg	-	
1	1000	240	2460	3.3	7.9	8512, 8513, 8514, 8515F, 8516F, 8517F
2	1000	230	2400	3.1	8.0	8510, 8518, 8511F, 8519F
3	2400	250	2500	3.4	7.9	8520, 8522, 8531, 8523N, 8529N, 8521F, 8524F, 8528F, 8530F
4	2400	230	2400	3.2	8.0	8526F, 8527N

Up to three types of experiment were conducted for each flow condition. These were

- air test flow with no fuel injection,
- air test flow with fuel injection, and
- nitrogen test flow with fuel injection.

Using nitrogen as the test gas inhibits combustion of the injected hydrogen and the mainstream flow conditions are very similar to those for the air test gas cases. Comparison of the results from these tests with those for the air test gas enables the effects of combustion to be differentiated from the effects of mass injection (of hydrogen). Experiments with fuel injection into air and nitrogen are denoted by “F” and “N” respectively. A comprehensive set of experiments was completed for condition 3 to identify the effects of injection with and without combustion and a reduced set of experiments was completed at each of the other conditions.

The freestream conditions for the measured nozzle-supply pressure and shock speed were calculated from measured parameters using the STN program [4]. This program uses equilibrium chemistry routines for air to compute the conditions at exit of the converging-diverging nozzle. The first step in the calculations uses the fill pressure and temperature in the shock tube, the measured speed of the primary shock wave in the shock tube and the measured pressure in the nozzle supply region after shock reflection to calculate the gas properties in the nozzle supply region. This gas is then expanded through the nozzle, assuming equilibrium chemistry, until the ratio of the Pitot pressure to the nozzle-supply pressure matches that from previous calibration surveys of the Pitot pressure for the nozzle.

For the present experiments, the conditions downstream of the shock wave generated at the leading-edge of the test surface were calculated using oblique shock wave relations. With these post-shock conditions and the conditions of the hydrogen fuel at injection, the ignition length of the hydrogen-air mixture can be calculated using equations 1-3.

Since fuel in T4 is stored at ambient temperature, approximately 300 K, and is delivered through sonic injectors, the temperature of the fuel at the exit of the injectors, T_f, is approximately 250 K. For the open combustor configuration of the present experiments, the equivalence ratio, ϕ, cannot be defined. However, Huber et al. [2] suggest that "self-ignition will likely originate at a point in the mixing layer where ϕ is in the order of 0.2". This value has been used in Eq. (3) to calculate the ignition lengths for the present study. The fuel mass flow rates were chosen to keep the ratio of injectant mass flow rate per unit area to the mainstream mass flow rate per unit area, $(\rho_j u_j)/(\rho_\infty u_\infty)$, approximately constant. The values of this parameter and the injection mass flow rate per unit width are given in Table.

Table 2. Fuel mass flow per unit width

Condition	Shot No.	$(\rho_j u_j)/(\rho_\infty u_\infty)$	$\dot{m}/L$, kg/(s·m)
1	8515 F	28	0.082
	8517 F	29	0.088
2	8511 F	29	0.096
3	8521 F	20	0.154
	8523 N	21	0.165
	8524 F	19	0.153
	8528 F	19	0.156
	8529 N	23	0.154
	8530 F	21	0.160
4	8526 F	19	0.152
	8527 N	18	0.151

4. RESULTS

Measured pressures for all the experiments are shown in Figures 2 to 5. Condition 3 was chosen to investigate the influence of injection of fuel without combustion. Tests were done at condition 3 for no injection, injection of fuel into a nitrogen flow and injection of fuel into air. The results are shown in Figure 4. Repeat shots were completed for all types of experiment for this condition and the mean results for each type of experiment are shown in the figure. The static pressures measured on the compression ramp were normalised by the nozzle supply pressure and averaged over the test time of approximately 2 ms. The rise in pressure on the ramp at approximately 135 mm from the leading edge when no fuel was injected is attributed to shock waves that originate from viscous interactions on the side walls and sweep across the ramp. When fuel is injected into a nitrogen test gas, some increase in pressure is expected due to the displacement effect of the injected hydrogen, causing some further compression of the flow behind the leading-edge shock wave. The pressures on the plate when fuel is injected into nitrogen increase by less than 10% from the fuel-off values.

If the hydrogen burns when it is injected into an air flow, additional compression is expected due to an increased displacement effect caused by the heat release. The results show such an increase in pressure on the surface for the fuel injection into air cases, but the changes are again relatively small, with a maximum increase in pressure of less than 30% compared with the fuel-off case.

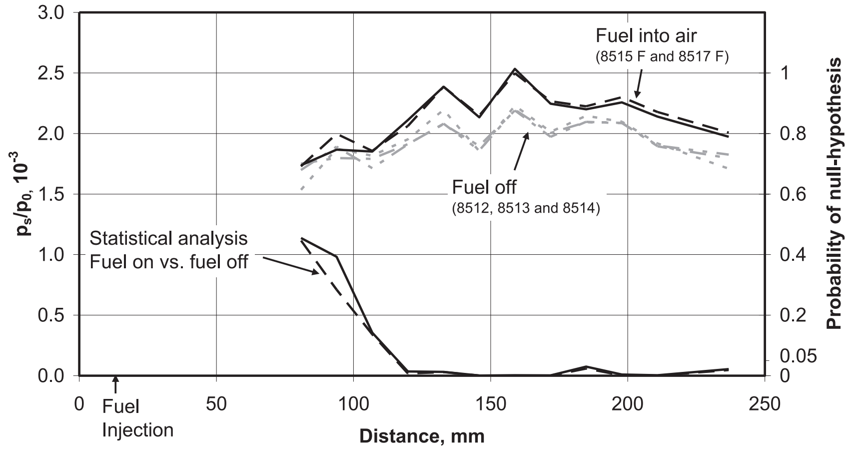

Figure 2. Results of condition 1 experiments

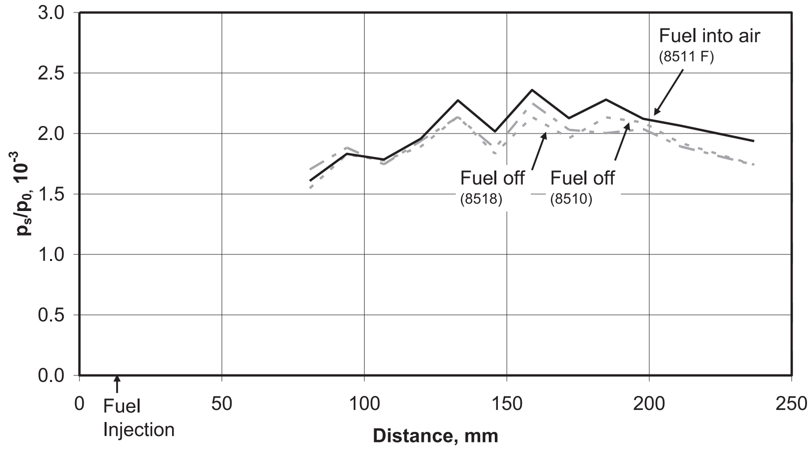

Figure 3. Results of condition 2 experiments

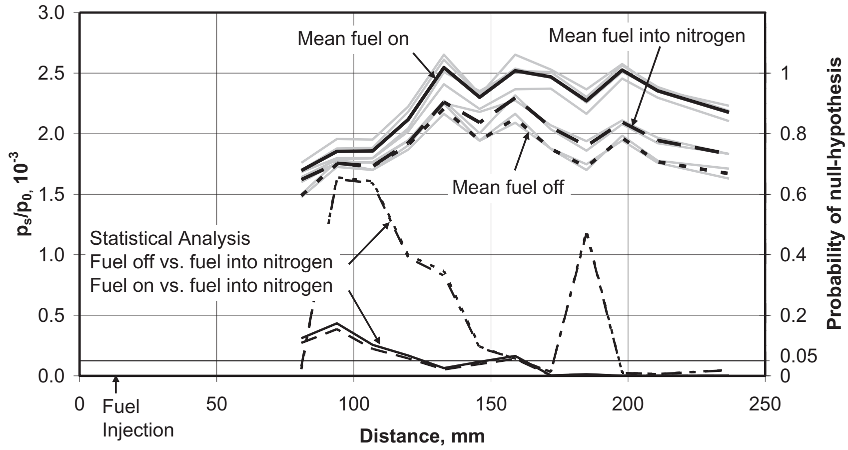

Figure 4. Results of condition 3 experiments

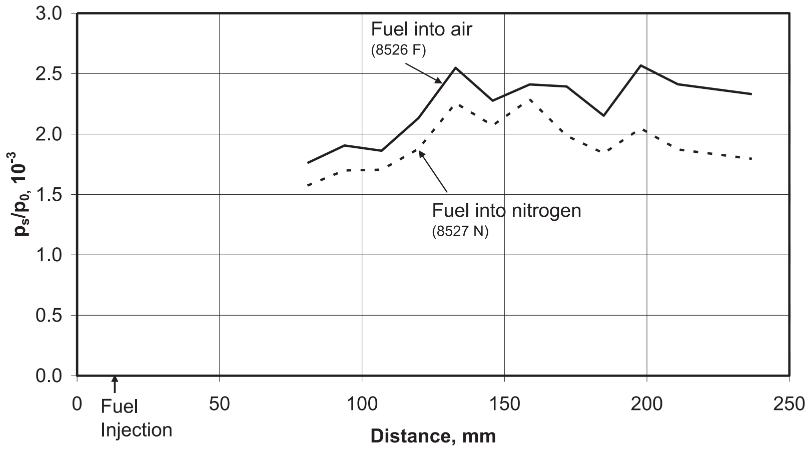

Figure 5. Results of condition 4 experiments

Various experiments were conducted at the same nominal conditions as indicated in Table 1. The different groups have been subdivided into "fuel on", "fuel off" and nitrogen test gas experiments. To justify this subdivision objectively from the collected data, the numerical differences in pressure levels between these groups were tested for statistical significance. Since a theoretical hypothesis for the subdivision exists, a confirmatory multivariate analysis method, as described by, for example, Backhaus et al. [5] and Beichelt [6], is required. For the present data, an analysis of variance (ANOVA) [5] and a Student t-Test [7], both used to test whether or not the collected data originates from one population, have been conducted for each measurement location on the intake plate.

The basis of these tests is the assumption that the difference between the two data sets is zero. The so-called "null-hypothesis" thus postulates that the two tested datasets originate from the same population. Based on this assumption, the probability of measuring the observed values can be determined. If this probability is below 5%, the initial assumption that the two datasets are contained in one population is regarded to be false. Conversely, if the probability of obtaining the measured or larger values is above 5%, a statistically relevant difference between the datasets cannot be assumed with sufficient certainty.

The background of both of these statistical tests is the theoretical distribution of measurements taken of the same quantity. In case identical quantities are measured multiple times, the measured values are scattered around the true value with a normal distribution. The spreading of this normal distribution of the datasets that are considered separate samples is then compared with the overall spreading of an assumed normal distribution of all collected measurements. If the normal distributions overlap too much, it cannot be proven that the measurements were taken from different quantities.

The statistical analysis must be carried out separately for each nominal condition. However, to be able to conduct such an analysis, a minimum of two measurements for each "fuel condition" within these nominal conditions must be provided. As a result, statistical analysis cannot be conducted for conditions 2 and 4.

The analysis of variance relates the sample's variances to the variance between the sample means. If the variance between the sample means is sufficiently larger than that within the samples, it is concluded that the samples originate from separate populations.

The statistical assessment is carried out by calculating a weighted mean of the sample variances and dividing this mean by the total variance of all collected data points. The resulting value is called the "empirical F-value" and is calculated from

$$F_{emp} = \frac{\sum_{g=1}^{G} K_g \cdot \left(\bar{y}_g - \bar{y}\right)^2}{G-1} \cdot \frac{n-G}{\sum_{g=1}^{G}\sum_{k=1}^{K_g}\left(y_{gk} - \bar{y}_g\right)^2} \qquad (4)[5]$$

where F_{emp} is the empirical F-value, n is the number of data points, G is the number of samples, K_g is the sample size, y_{gk} is the data point, $\bar{y}_g$ is the sample mean and $\bar{y}$ is the mean of all data points.

This empirical F-value follows an F-distribution (from: R. A. Fisher [8]) that is the quotient of two Chi-distributed variates. This distribution is applicable to experimental data that is distributed around the expected value in a normal distribution [9].

The criterion for evaluation of this empirical F-value is a theoretical F-distribution, a function of the degrees of freedom of all data points (n-G) and the degrees of freedom of the number of samples (G-1). Quantiles (or the area enclosed under a certain portion of the F-distribution's probability density function, representing the probability of the tested problem) of the F-distribution can be found in tables [5] and represent theoretical F-values for comparison with empirical F-values. If the empirical value exceeds the theoretical value, the null-hypothesis (assuming identical means for the different samples) can be discarded with a probability equal to the quantile rank.

As an example, the calculation of the null-hypothesis probability is shown for the condition 3 experiments. Pressures measured for shots 8523 N and 8529 N to 8521 F, 8524 F, 8528 F and 8530 F are compared at the measurement point located 133 mm from the leading edge of the plate. In this case, the number of data points is $n = 6$ and the number of samples is $G = 2$. The mean values of the total data points and the separate samples are given in Table 3. Eq. (4) results in $F_{emp} = 13.56$. This F-value is compared with tabulated F-Values as provided in Kaiser et al. [10] to determine the likelihood that the assumptions of the null-hypothesis are true. The probability curve is shown in Figure 6. In this case the probability of obtaining the observed or a larger value of F_{emp} if the "null-hypothesis" was true is 2.1%. Hence it is very unlikely that the assumptions made under the "null-hypothesis" are true and it can be concluded that, at this location, the differences in the measured pressures of "fuel on" and nitrogen test gas shots are not random. Therefore, the differences are attributed to the effects of combustion.

Table 3. Data points and mean values

Shot No.	Normalised Pressure	Mean		Standard Deviation
8523 N	0.002270	0.002260	0.002450	1.36E-05
8529 N	0.002251			
8521 F	0.002652	0.002545		0.000109
8524 F	0.002612			
8528 F	0.0024082			
8530 F	0.0025092			

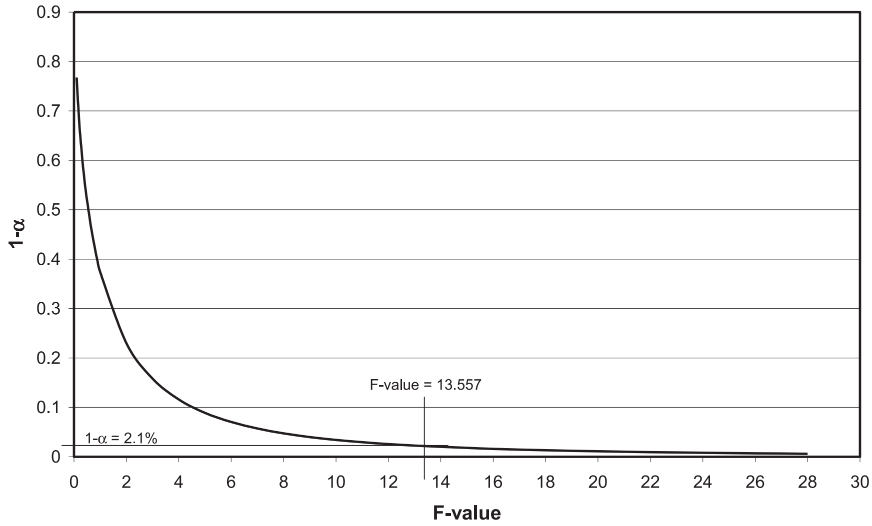

Figure 6. F-distribution probability function for two samples and six data points

The Student t-Test tests for the true difference between the two mean values and determines whether the two can be pooled [10]. The basis for this test is the t-distribution developed by Gosset [7]. The t-distribution is a special form of the normal distribution with a bell-shaped curve that is dependent on the degrees of freedom ($f = n_1 + n_2 - 2$). Using a similar procedure to that used for the variance analysis, an empirical value is calculated from the experimental data that is subsequently compared to the theoretical t-distribution values. Provided that the variances of two samples are similar, an empirical value t can be computed according to

$$\tau = \left| \frac{\bar{x}_1 - \bar{x}_2}{s_d} \right| \cdot \sqrt{\frac{n_1 \cdot n_2}{n_1 + n_2}} \tag{5}$$

with the pooled standard deviation:

$$s_d = \sqrt{\frac{(n_1 - 1) \cdot s_1^2 + (n_2 - 1) \cdot s_2^2}{n_1 + n_2 - 2}}$$

Here $\bar{x}$ is the sample mean, n is the number of elements in the sample and s is the standard deviation.

The assessment of this calculated value is again carried out with tabulated values as provided by Kaiser et al. [10]. From Eq. (5), $t = 3.47$ and $s_d = 9.48 \times 10^{-5}$ with $n_1 = 2$ and $n_2 = 4$ and the means and standard deviations as given in Table 3. This t-test results in a probability of 2.5% for obtaining the stated or a larger value of t if the null hypothesis was true.

The two analysis methods agree well and the conclusions are identical for all cases presented here.

Given the relatively small pressure increases due to injection and combustion and some shot-to-shot variations in the results, both these statistical analyses have been used to assist in locating the point of ignition. The results of these analyses indicate that there is a statistically significant difference at some location downstream of injection for most of the cases where fuel was injected into a nitrogen test flow.

However, the pressure rises for such cases were always less than 10%.

Huber et al. [2] suggest that “Ignition is considered accomplished when the temperature rise reaches 5 percent of the complete reaction temperature rise”. For the conditions of the test gas behind the initial shock in the present experiments, this corresponds to a pressure rise of 5% to 15%. Thus, the location of ignition for the fuel injection into air tests was taken to be the location where the pressure increase over the fuel-off case was greater than 10% and the Student t and ANOVA tests indicated that the differences were statistically significant.

This analysis is carried out for each pressure transducer location and can be used for test conditions where two or more experiments were conducted for each nominal fuel condition. The resulting probabilities for each transducer station are plotted along with the experimental data in Figure 2 to Figure 5. The results for the Student’s t-test and the ANOVA test are nearly identical and the differences cannot be seen in the figures.

Pergament’s method indicates that ignition is not expected on the compression ramp for the low pressure cases, conditions 1 and 2. The experimental data support this expectation; there was a small increase in pressure for experiments where fuel was injected, but not a sufficient amount to indicate ignition or combustion. Pergament’s method does predict ignition on the ramp for condition 3 and the results support this. The statistical analysis indicates the ignition point to be about 130 mm downstream of the leading edge. The pressure increased by approximately 15 to 20% above the pressure level for fuel into nitrogen pressure. The data shown in Figure 4 also allows comparison of results from the nitrogen test gas experiments with those from the fuel off experiments. The statistical analysis indicates a significant difference in pressure levels between the two groups at a downstream distance of approximately 160 mm. The high probability for the null-hypothesis at 185 mm is solely caused by the exceptionally high pressure value measured at this location during one experiment - shot 8520. It is concluded that the pressure rise due to injection of hydrogen is significant and is sufficient in magnitude to indicate combustion.

Similar results were found for the experiments at condition 4. Although the post-shock temperature for these shots is considerably lower than for condition 3, combustion is still evident by a pressure rise of the same order of magnitude as found in the high temperature experiments. It is noted that ignition takes place at a point further downstream on the intake compared to the experiments with a higher temperature. This is consistent with estimates obtained using Pergament’s method.

A summary of the calculated and experimental ignition lengths is given in Figure 7. Ignition is only detected on the compression ramp at conditions 3 and 4. For these conditions, the measured ignition distances agree with the distance calculated from the method of Pergament to within 35%. There was insufficient data to perform statistical analysis for condition 4.

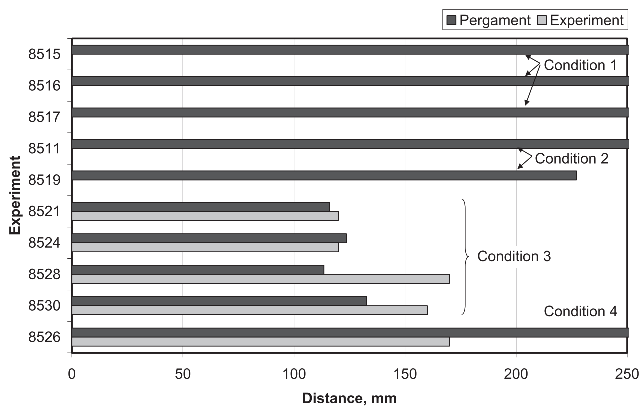

Figure 7. Comparison of estimated and experimental ignition lengths

5. CONCLUSION

Established statistical methods are found to be useful for analysis of small differences in pressure distributions to assist in identifying ignition lengths in shock tunnel experiments. The ignition lengths of the hydrogen air mixture directly behind a strong leading edge shock indicate that Pergament's method is able to predict the ignition length to within 35% for the experimental conditions tested.

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