Ignition Length Study in a Supersonic Duct for JP-8+100 with Ethylene Augmentation

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In the scramjet arena, hydrocarbon fuels are being considered for their endothermic potential and for use in flights where compact, volume critical designs are required at flight speeds Mach 6-8. Long-chain hydrocarbon fuels, such as aviation kerosene, have handling and storage advantages over hazardous and volatile fuels, such as hydrogen, that are more aligned with current flight systems. The objective of this research is to investigate the conditions under which kerosene fuel (JP-8+100) can be used in a supersonic duct at a hyper velocity impulse facility. Experimental data on kerosene ignition lengths for temperatures in the range 1100–1550 K, pressure of 1 atm, and equivalence ratios of 0.2–2.5 are compared with ignition delay correlations from literature. The primary aim of the research is an examination of experimental results for the ignition delay times when kerosene is augmented by the addition of ethylene with molar concentrations from 0-86%. It will be demonstrated that ethylene augmentation does not in any significant manner assist ignition of the kerosene. In contrast, it is shown that the ignition times of kerosene dominate that of the ethylene and suppress the ignition of ethylene.

II. Introduction

This paper reports on a study of the ignition length of kerosene- based aviation fuel in a scramjet combustor, and the effects of adding supplementary ethylene. Ethylene combustion in a supersonic flow stream produces a vigorous and rapid combustion onset, much like that of hydrogen [1]. Improving the kerosene ignition length would result in a shorter combustor and reduction in associated skin-friction drag and heat transfer. Kerosene-based fuels are the predominant fuel used in the aviation industry today, and desirous for use in scramjet applications. However they suffer certain drawbacks when applied to a scramjet engine where the airflow through the combustor is of the order 2km/s. Chief amongst these are the time required for ignition to commence and thermal stability of the fuel [2]. The long delay for kerosene fuel ignition results in scramjet combustors of the order of metres long. This is prohibitive for a volume-constrained aircraft. Therefore by augmenting kerosene with the addition of ethylene, it may be expected to react more like ethylene and result in improvements to combustor efficiencies for kerosene-based fuels.

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In order to test kerosene-based fuels, ground-test facilities must be able to deliver fuel at an equivalent condition as experienced in flight. It's reported by Maurice, Edwards and Griffiths in [3] that continuous flow facilities require in the order of 2 MW of power per kg/s of feed fuel to replicate the appropriate fuel injection composition, temperature and pressure. Furthermore, for the quantity of fuel required, the facility requires additional infrastructure to manage fuel pre-heating as well as condensers and containment to deal with possible failures of the system. Impulse facilities have the benefit of extremely short test duration, such that the amount of fuel injected per test is of the order of a few grams for a few milliseconds; thereby avoiding hefty power and infrastructure requirements. The drawback with impulse facilities is the same short test duration - which limits the use of slow- ignition liquid hydrocarbon fuels. There is usually insufficient time for the fuel to be injected, vaporise, mix, and react within the available length of combustor.

This paper presents the design of a fuel vaporiser suitable for use with an impulsive hypervelocity test facility, and the results delivered by it for an ignition length study with JP-8+100 fuel and ethylene augmentation.

II. Experimental Setup

Flow within the supersonic duct is generated by the University of Queensland’s T4 reflected shock-tube impulse facility. The experiments were conducted at a duct inlet condition of Mach 2.7, static pressure of 85-135 kPa and static temperature between 1100K and 1550K. The kerosene is vaporised prior to injection into the supersonic duct, by means of a heated Ludwig tube commissioned for this study. The vaporiser system provides a means of blending gaseous ethylene and liquid kerosene to achieve a desired molar mixture at the final vaporised state. The thermal control of the system moderated the fuel to between 650-700K such that two-phase gaseous-liquid regions are avoided. These are detrimental to the operation of the system, as is the deposition of gum and sooting from kerosene pyrolysis and reformation.

The full paper shall provide detail on pertinent details of the experimental setup including:

- *Experimental model used for the ignition length measurements*
- *Fuel supply system with schematics of the central strut fuel injection*
- *Implementation within the T4 hyper-velocity impulse facility*
- *Experimental Conditions*
- *Accuracy of the measurements*

During each experiment, pressure is measured at 20mm intervals along a 1200mm duct for the cases of fuel-off, suppressed combustion (where fuel is injected into a nitrogen flow) and fuel-on into air. The ignition length is determined as the axial location where the fuel-on coefficient of pressure (Cp) departs from the fuel-off and baseline cases in a sustained pressure rise which exceeds Cp +0.1. It is assumed that ignition occurs centrally within the duct, at the fuel-air interface. Accordingly, an axial correction is applied to the ignition length to account for the delay as the pressure increment propagates across the duct by means of a Mach wave to be measured at the wall. In each of the presented examples, this equates to a 49mm off set.

III. Results and Discussion

An example of 100% JP-8+100 fuel at an equivalence ratio of 1.5, injected into 1530K airflow at Mach 2.7 is presented in Fig. 1. The increase in Cp of 0.15 demonstrates that a sustained pressure rise in a supersonic duct was achieved. This result also demonstrates that the fuel supply vaporiser operates satisfactorily and may be used to conduct further research. The ignition length for this particular test was determined to occur between 417-437mm (less the 49mm correction). At a temperature of 1320K it is observed in Fig. 2 that ignition occurs further towards the rear of the duct between 917-937mm. This is consistent with the anticipated result of Arrhenius-type ignition delay correlations [4],[5],[6],[7],[8],[9],[10], where ignition delay is a strong function of temperature.

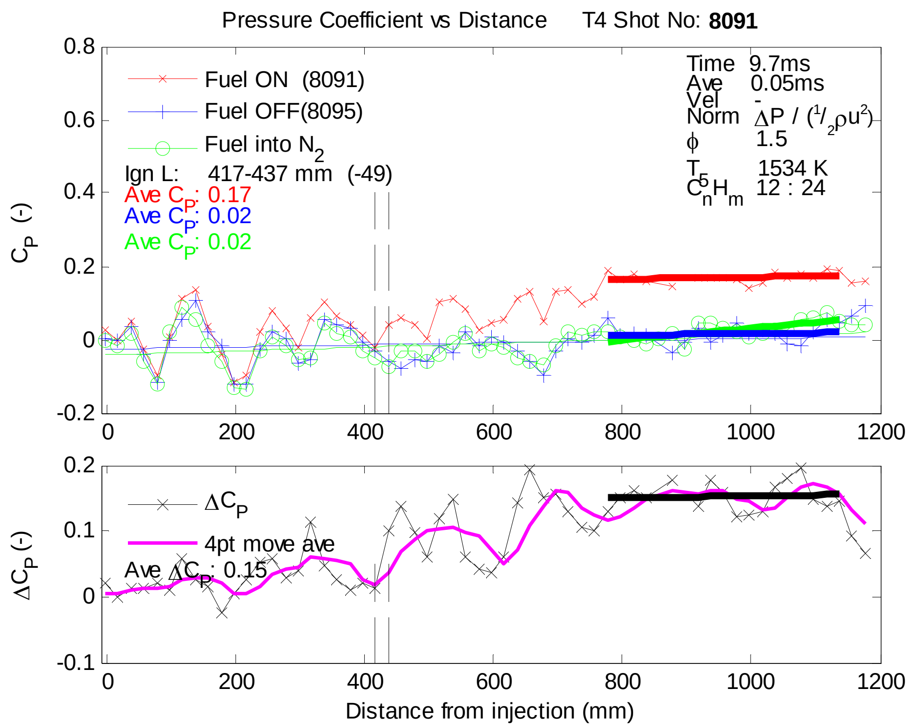

Fig. 1 Cp versus Length for kerosene ignition length at 1530K, showing ignition occurring between 417-437mm

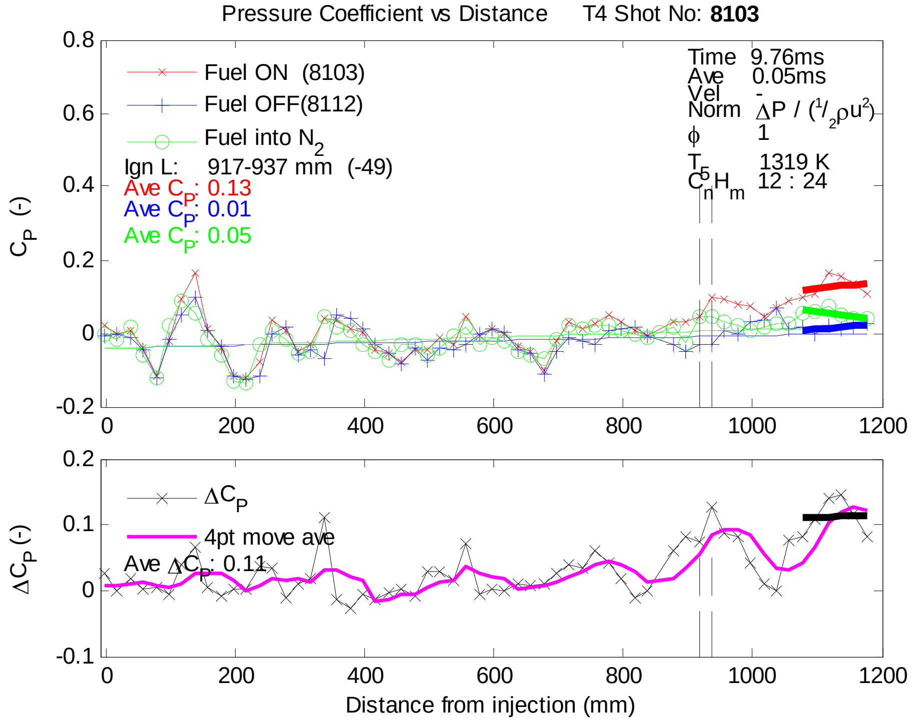

Fig. 2 Cp versus Length for kerosene ignition length at 1320K, showing ignition occurring between 917-937mm

Tests were carried out on 90-100% molar blends of JP-8+100 with ethylene, and ignition delay measurements were made with a duct inlet condition between 1100 – 1550K at pressures from 85-135kPa and equivalence ratios 0.2-3.0. The experimental data is presented in Fig. 3 along with an Arrhenius fit and 95% confidence interval plus correlations for JP-8 [5] and Jet-A [6],[7],[8],[9],[10]. All experimental data and correlations are scaled to 1 atmosphere for the comparison.

It is observed that there is significant scatter within the data for a given temperature, of the order 45%, which represents the variation due to the experimental apparatus for measuring ignition length in a scramjet duct, as well as the inherent repeatability of ignition delay studies. Flow within the duct has inherent non-uniformities and is not a homogenous fuel-air mixture as in shock-tube studies of ignition delay (for example [5]) or with continuous control over flow variables (such as in [4]). However, the amount of scatter is consistent with the 42% reported in [11] as typical variation in length for shock-tube ignition delay studies, and the Arrhenius fit to the data agrees well with the presented correlations. The slope of the Arrhenius fit in Fig. 3 (representing a suggested activation energy of 29.3kcal/mol for the fuel) is in keeping with those of JP-8 and Jet-A This is an anticipated result as the base fuel-stock is from the same family of aviation kerosene.

The strong similarity between the reported correlations [5],[6],[7],[8],[9],[10] and the experimental data demonstrates that the ignition delays observed in the impulse facility correlate with those previously observed in other facilities. The correlations for ethylene [12],[13]] are depicted in Fig. 3 for comparison with the augmentation study.

Ignition length tests with 100% ethylene were carried out which were consistent with the data of [12],[13] and [14]. The full paper will present the ethylene experimental data as well as correlations for other long-chain hydrocarbons such as kerosene, JP-10 and several n-alkanes.

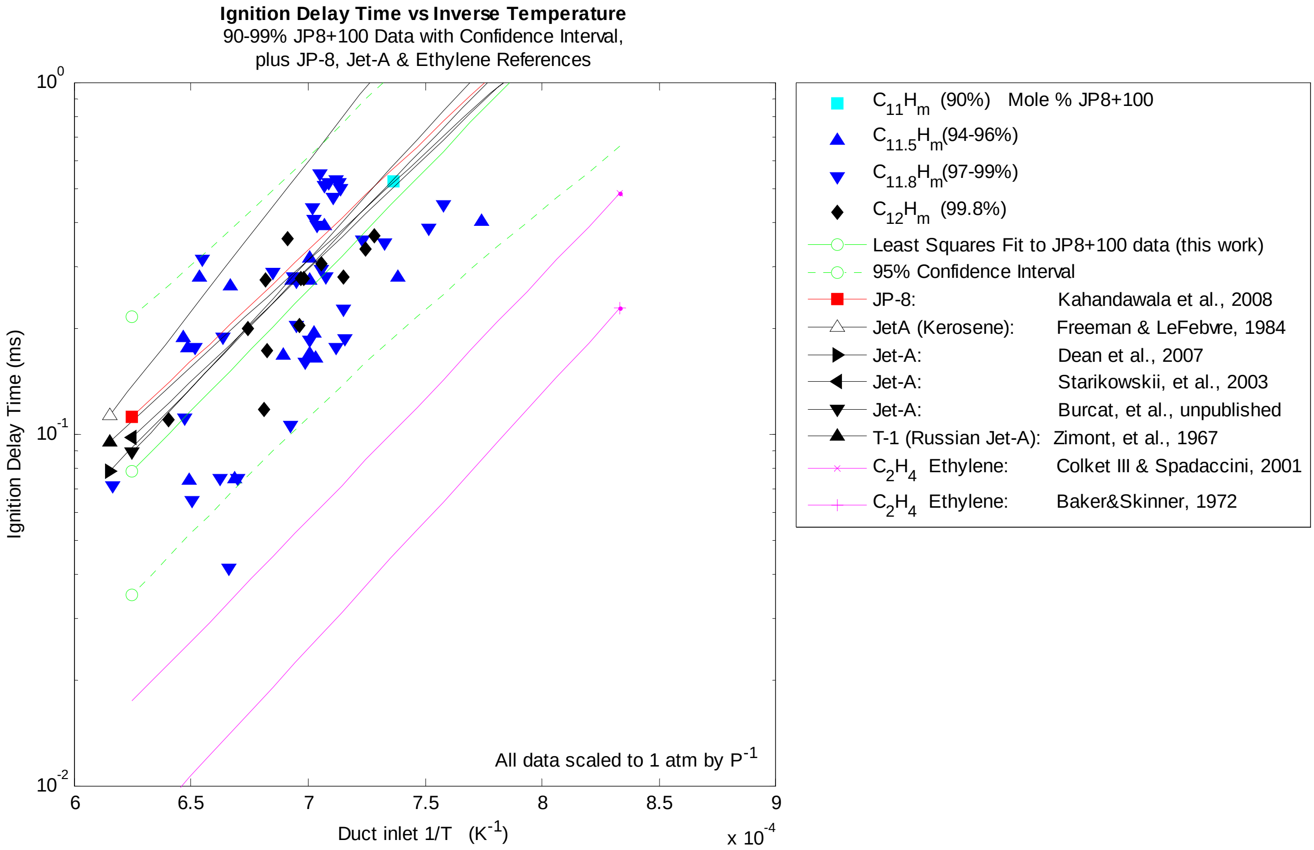

Fig. 3 Experimental data for ignition delay of JP-8+100 in a supersonic duct compared with correlations.

Having demonstrated that the experimental setup delivers results consistent with published correlations; the amount of ethylene within the fuel was varied in an augmentation study. For any given temperature, ethylene ignition delays are an order of magnitude shorter than Jet-A (refer Fig. 3). It may be anticipated that the addition of ethylene to the kerosene would alter the ignition characteristic towards the pure ethylene correlation. Ethylene augmentation is of interest as the products of endothermic fuel reformation consist of between 15-30% ethylene depending on the conditions during pyrolysis ([2], [15], [16]). Proponents of endothermic fuels seek to utilise the capacity of kerosene-type fuels to absorb the thermal loads in hypersonic applications, and deliver some benefit within the combustion chamber by utilising the cracked shorter-chain hydrocarbon fuels and their associated reduced ignition delays. In this way, it is anticipated to reduce combustion chamber lengths and associated high skin friction loads [1].

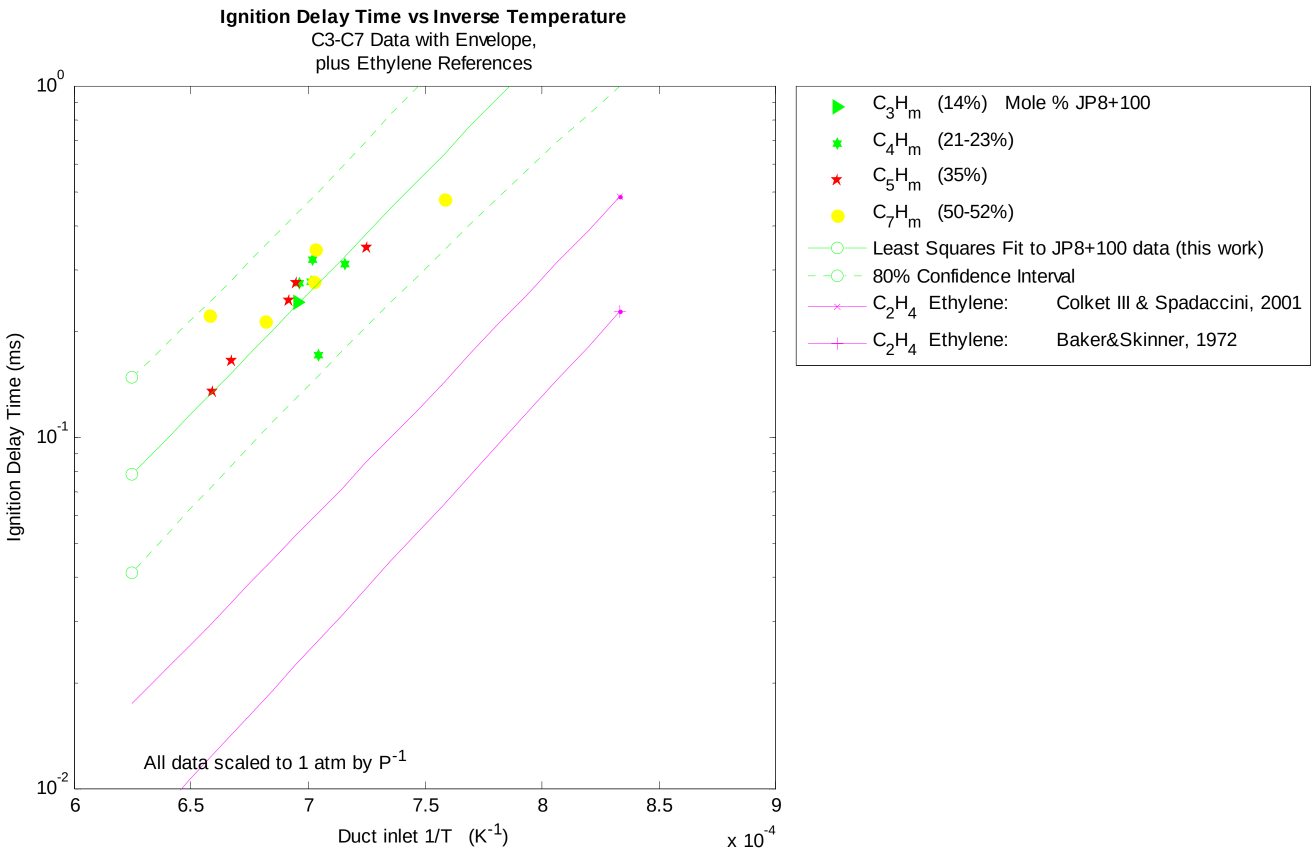

Fig. 4 Ethylene augmentation of JP-8+100

The amount of JP-8+100 was reduced across the range 90%-molar, 50%, 35%, 22% and 14% (with the compliment consisting of ethylene). The results, presented in Fig. 4, clearly show that across all ranges, the ignition delay of the ethylene-enhanced fuel blends matched the trend for the neat JP-8+100. On a mass-basis, the range for the augmentation study is 98%-mass, 86%, 76%, 63% and 49%. The effect of a high kerosene mass-fraction would suggest that the mixing of ethylene and oxygen molecules is suppressed compared to the pure ethylene tests. There are simply fewer ethylene molecules coming into contact with the oxygen under combustible circumstances. Therefore it may not be able to follow the ignition- delay correlations for pure ethylene. However, even for 14% molar tests, which is equivalent to 50% by mass, the effect of ethylene augmentation is not apparent. The kerosene appears to dominate the ignition reaction mechanism at each fuel blend tested.

The data suggests that the products from pyrolised and cracked aviation kerosene, when present in typical concentrations, are not likely to improve ignition length in a scramjet combustor if any of the parent-hydrocarbon remains in the mixture. This is an important conclusion for endothermic fuel concepts as it appears to refute some of the benefits of such processes if reformation is incomplete.

The full paper will present comparisons of experimental data against other augmentation studies such as the hydrogen enrichment ignition delay tests from [12].

IV. Conclusions

The ethylene augmentation experiments deliver the conclusion that the addition of ethylene at up to 86% molar (51% by mass) has no measurable effect on reducing the ignition length of JP-8+100 fuel in a supersonic flow stream at pressures of one atmosphere and 1100-1550K. A similar result was seen by other researchers [12] for hydrogen addition. The proportion of ethylene expected in the pyrolysis and reformation of aviation kerosene is of the order 25-40% molar [2],[15],[16]. The ethylene augmentation experiments span this range, yet the ignition delay matched that of pure JP-8+100.

These results suggest that the proposed benefits of endothermic cooling by regeneratively transforming kerosene-based fuels prior to injection in the combustor would have negligible benefit on improving the combustion on-set and reducing the length of the scramjet engine if as little as 14% (molar) of the parent fuel remained. To deliver the proposed benefits, the reformation process would have to reach completion prior to injection into the combustion chamber. Endothermic fuels may still have benefit in absorbing excess heat and could be used as part of a regeneratively cooled vehicle system; but the results of the current study show that any benefit in reducing combustor length and combustor-related drag would be minimal as remnant kerosene dominates the ignition reaction mechanism.

Acknowledgment

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