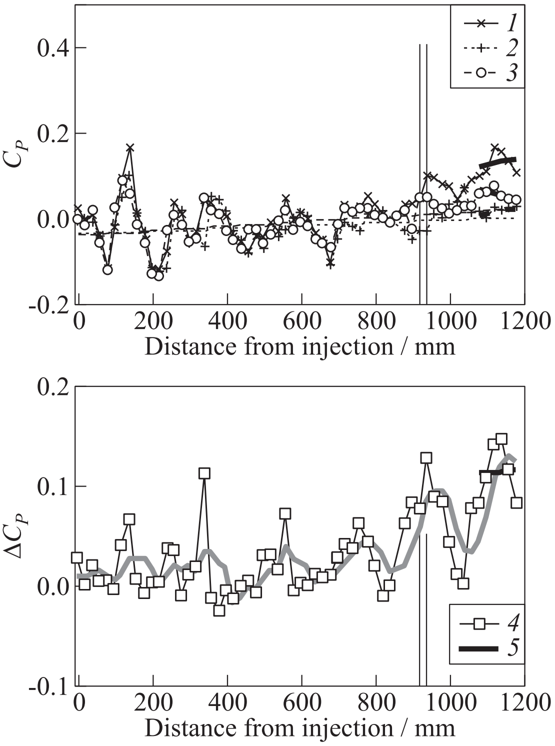

Figure 4 C_P vs. length for JP-8 + 100 ignition at 1320 K: *1* — fuel on, $\overline{C_P} = 0.13$; *2* — fuel off, $\overline{C_P} = 0.01$; *3* — fuel into N_2, $\overline{C_P} = 0.05$; *4* — ΔC_p, $\overline{\Delta C_p} = 0.11$; and *5* — four-point running average

The increase in ΔC_p of 0.15 above the baseline demonstrates that a sustained pressure rise in a supersonic duct was achieved. This result also demonstrates that the fuel supply vaporizer operated satisfactorily and may be used to conduct further research. The ignition length for this particular test occurred between 417 and 437 mm (less than 49-millimeter correction).

At a temperature of 1410 K, it was observed (Fig. 3) that ignition occurred further towards the rear of the duct, as expected, between 497 and 517 mm.

When the temperature was reduced to 1320 K, it was observed (Fig. 4) that ignition occurred further towards the rear of the duct between 917 and 937 mm.

These results were consistent with the anticipated result of Arrhenius-type ignition delay correlations [10–14,16–20] where ignition delay is a strong function of temperature.

Ignition length measurements were made with a duct inlet condition between 1100 and 1550 K at pressures from 85 to 135 kPa, and equivalence ra-

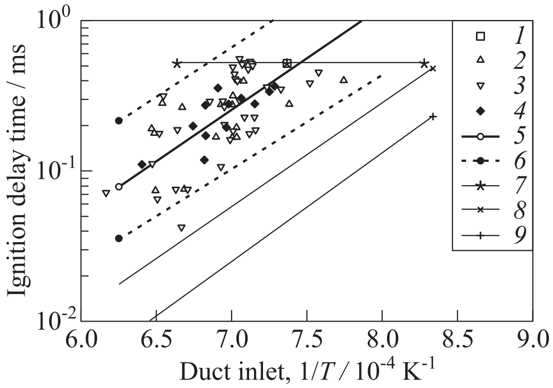

Figure 5 Experimental data for the ignition delay of JP-8 + 100 in a supersonic duct: *1* — $C_{11}H_m$ (90%); *2* — $C_{11.5}H_m$ (94%–96%); *3* — $C_{11.8}H_m$ (97%–99%); *4* — $C_{12}H_m$ (99.8%); *5* — least squares fit to JP8 + 100 data (this work); *6* — 95 percent confidence interval; *7* — temperature uncertainty; *8* — C_2H_4 (ethylene) [18]; and *9* — C_2H_4 [17]. All data are scaled to 1 atm by P^{-1}

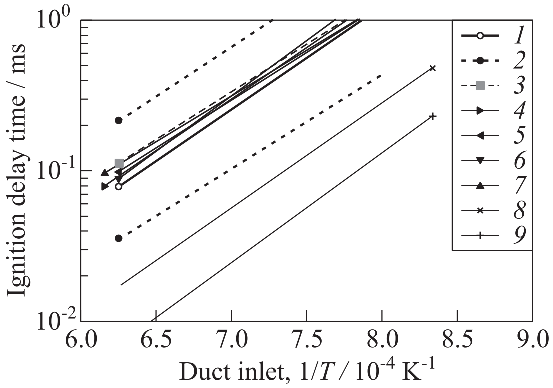

Figure 6 Comparison of the JP-8 + 100 fit with Jet-A and JP-8 correlations: *1* — least squares fit to JP8 + 100 data (this work); *2* — 95 percent confidence interval; *3* — JP-8 [13]; *4* — Jet-A [12]; *5* — Jet-A [11]; *6* — Jet-A [14]; *7* — T-1 (Russian Jet-A) [10]; *8* — C_2H_4 [18]; and *9* — C_2H_4 [17]. All data are scaled to 1 atm by P^{-1}

tios 0.2–3.0. The experimental data are presented in Fig. 5 along with a least squares Arrhenius fit and 95 percent confidence interval. The ignition 'length' has been converted to an ignition 'delay' by the duct inlet velocity and uses an inverse temperature abscissa. The regression fit and confidence interval are compared with correlations for JP-8 [13] and Jet-A [10–12, 14] in Fig. 6.

All experimental data and correlations are scaled to 1 atm for the comparison.

It was observed that there is significant scatter within the data for a given temperature, of the order of 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 nonuniformities and is not a homogenous fuel–air mixture as in shock-tube studies of ignition delay (see, for example, [13]) or with continuous control over flow variables (such as in [16]). Three-dimensional gasdynamic structure of supersonic airflow in these experiments can have a significant impact on the accuracy of the results which is addressed in the aggregated thesis [4]. However, the amount of scatter is consistent with the 42 percent reported in [19] as typical variation in length for shock-tube ignition delay studies. The Arrhenius fit to the data agrees well with the presented correlations. The slope of the Arrhenius fit in Fig. 6 (representing a suggested activation energy of 29.3 ± 8.9 kcal/mol for the fuel) is in keeping with those of JP-8 and Jet-A. This was an anticipated result as the base fuel-stock is from the same family of aviation kerosene. The large uncertainty on activation energy was due to the amount of experimental scatter, suggestive of apparatus-dependent phenomena. Despite the scatter, the apparent activation energy is in agreement with the reported values for JP-8 (29 kcal/mol [13]) and Jet-A (27.8 [11], 29.2 [10], and 32.7 kcal/mol [12]). All of the tabulated activation energies lie within the experimental uncertainty. Units of cal/mol are used for consistency with previously reported works.

The strong similarity between the reported correlations [10–14] and the experimental data demonstrates that the ignition delays observed in the impulse facility correlate with those previously observed in other facilities. The correlations closely predict the ignition delay and activation energy of the fuel at experimental conditions of 1 atm and temperature range 1250–1600 K. The correlations for ethylene [17, 18] are depicted in Figs. 5 and 6 for comparison with the future ethylene augmentation study.

The point of difference in the current study is that the experimental data were obtained from a supersonic duct, with nonuniform flow and nonhomogeneously mixed fuel. This is different from how the ignition delay studies are typically made. They use a reflected shock tube with a homogeneous fuel and oxygen mixture which is subjected to a sudden rise in temperature and pressure from a reflected shock wave [13]. The resulting ignition delay correlations are regarded to be applicable under similar pressure and temperature conditions to those of the experiments from which they were derived. When the correlations were scaled to atmospheric pressure, they matched the experimental data. Therefore, the JP-8 + 100 study justifies the use of ignition delays found from conventional shock tube studies for application in a scramjet duct. This is strong indication that the JP-8 + 100 ignition delay is reaction limited, not mixing limited.

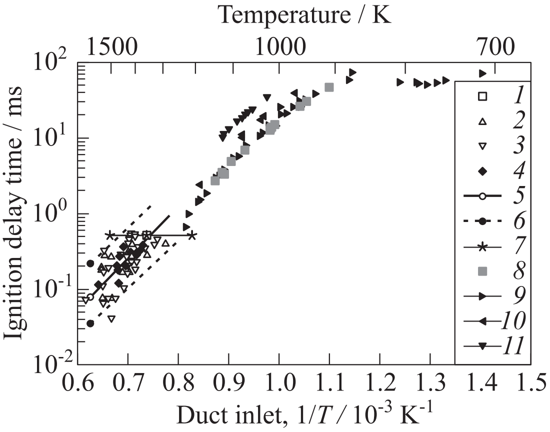

Figure 7 Comparison of JP-8 + 100 data with JP-8 and Jet-A data from [20]: *1* — $C_{11}H_m$ (90%); *2* — $C_{11.5}H_m$ (94%–96%); *3* — $C_{11.8}H_m$ (97%–99%); *4* — $C_{12}H_m$ (99.8%); *5* — least squares fit to JP8 + 100 data (this work); *6* — 95 percent confidence interval; *7* — temperature uncertainty; *8* — JP-8 [20]; *9* — Jet-A [20]; *10* — Jet-A ($\phi = 0.5$) [20]; and *11* — Jet-A (10% O_2) [20]. All data are scaled to 1 atm by P^{-1}

The experimental data are compared with ignition delay data for JP-8 and Jet A from a heated shock tube across the range 715–1229 K [20] in Fig. 7. Both sets of data display a consistent activation energy in the region above 900 K. Below 900 K, there is evidence of the negative temperature coefficient region, where the slope of the Arrhenius-like exponential temperature dependency is reversed [12, 20–22]. While the regression fit to the JP-8 + 100 data should not be extrapolated beyond the range of the experimental data (1100 to 1600 K), it is shown to be consistent with JP-8 data between 1000 and 1229 K.

The data [20] show the difference in ignition delay at equivalence ratio of $\phi = 1$ and 0.5. This reduction in ϕ had the effect of increasing the ignition delay by 40% at 1080 K. The same influence of ϕ on ignition delay is reported for Jet A and JP-8 from shock tube studies [11, 12, 23, 24]. Equivalence ratio variation may explain the scatter observed in the experimental results for JP-8 + 100. Differences in induction times between stoichiometric, fuel-lean, and fuel-rich mixtures also have an effect on ignition delay [11, 12].

4 CONCLUDING REMARKS

The JP-8 + 100 experimental study shows that traditional correlations can be used to effectively predict the ignition delay times of LCHC fuels in a scramjet combustor, provided pressure effects are taken into account. This is an important finding which allows the correlations to be used with confidence in scramjet combustor design and computational fluid dynamics simulations of LCHC combustion in supersonic ducts. The fact that multiple Jet-A and JP-8 correlations are closely aligned to the regression fit gives confidence that the calculated duct inlet temperatures are near the middle of the measurement uncertainty for temperature and not at the ±11 percent limit. The correlations are a validation of the regression and the temperature calculations.

The data presented for JP-8 + 100 conclusively show that the pressure rise occurred can be attributed to the heat release from combustion. The examples represented 0.94 to 1.0 mole fraction JP-8 + 100 mixtures. This demonstrates that the fuel injection system can be used to study combustion of JP-8 + 100 in a supersonic flow stream in an impulse facility. For the current experimental configuration, the earliest possible point of ignition was limited by the presence of a strong expansion and shock system extending 100 mm downstream of the strut injector.

Combustion of JP-8 + 100 was found to have an apparent activation energy of the order of 29 kcal/mol. The comparison with ignition correlations from premixed homogenous tests provides good evidence that JP-8 + 100 combustion in a supersonic flow stream is reaction-limited.

The ignition delay and ignition temperature is not an absolute property of a substance. Therefore, empirical relations will have an inherent degree of uncertainty related to the nature of the test apparatus and methods used for their determination [25]. Yet, despite the scatter in the data, the results of the present study correlate well with the published correlations for JP-8 and Jet-A from a broad range of fuel-stocks and researchers.

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