

Ignition of aviation kerosene at high temperatures

Anthony J. Dean¹, Oleg G. Penyazkov², Kirill L. Sevruk², Bala Varatharajan¹

¹ General Electric Global Research Center, Niskayuna, One Research Cycle, NY 12309

² Heat and Mass Transfer Institute, 15 P. Brovki str., 220072, Minsk, Belarus

Corresponding author, O.G. Penyazkov: penyaz@dnpi.itmo.by

Introduction

Rapid spontaneous ignition and reaction of the fuel-air mixtures are required for efficient operation of air-breathing scramjets and detonation engines. Usually, liquid hydrocarbons are considered as potential candidate-fuels for these applications because of their high energy density, storage capacity and endothermicity. At the same time, there is scarcity of data on autoignition of heavy fuels at high temperatures and pressure, where the propulsion systems typically operate. Several investigators [1-6] have studied ignition delays of n-heptane in shock tubes. Only limited data have been reported for ignition of aviation kerosene, *Jet-A*, in jet-stirred reactors [9], and for *JP-10* in shock tubes [6, 8]. Thus, there is an obvious paucity of experimental data on autoignition of fuels such as *JP-8* and *Jet-A* at high-temperatures and pressures. The studies presented here apply to experimental and theoretical investigations of ignition of aviation kerosene referred to as *Jet-A*. For correct identification of reaction properties of *Jet-A*/Air mixtures, heated shock tube and optical observations have been used for ignition delay time and autoignition mode measurements. The initial temperature and partial pressures of *Jet A* samples in a shock tube were enough to prevent the condensation of heavy fractions with carbon number up to C_{15} .

Experimental Setup.

A stainless-steel shock tube 76 mm in diameter and 5.5 m length was used in the experiments. The high-pressure valve with a forced start was employed as high-pressure chamber for creating incident shock wave. This device allows controlling the intensity of incident shock wave from shot to shot with an accuracy of ± 0.01 in Mach number. A Nichrome wire was used as the heating element. Four independent current circuits provided an independent heating of four shock tube sections to ensure the uniform temperature distributions along the whole shock tube with accuracy $\pm 1^\circ C$. The initial temperature of the tube was $75 - 100^\circ C$ for all shock tube tests presented in this report. The 18-liter stainless steel mixing cylinder was used for mixture preparations. The independent controlled current circuit was applied for heating the mixing assembly up to the boiling temperature of *Jet-A* ($150^\circ C$). Continuous heating and stirring of the *Jet A*/Air mixture were performed inside cylinder during 3-4 hours.

The chromatographic technique has been applied for characterization of the *Jet-A*. The results of chromatographic analysis are presented in the fig.1. N-alkanes up to *n-Tricosane*, $C_{23}H_{48}$, have been identified during the test. About 50 % of fractional contents were unknown. *Paraffins* and *iso-paraffins* contents are 27.1 % by volume. *Aromatics* are 21.5 % by volume; *Naphthenes* are 2.9 % by volume; *Olefins* are 1.1 % by volume. The averaged formula for studied *Jet-A* deduced from 167 identified compounds was $C_{10.84}H_{19.65}$. Taking into account that a lot of heavier compounds with more than 10 Carbon atoms have not been recognized, we have used an approximate formula of *Jet-A* $C_{11}H_{22}$ from the work [10] for calculations. The thermodynamic properties of *Jet-A* from [11] were used to estimate post-shock conditions behind incident and reflected shock waves.

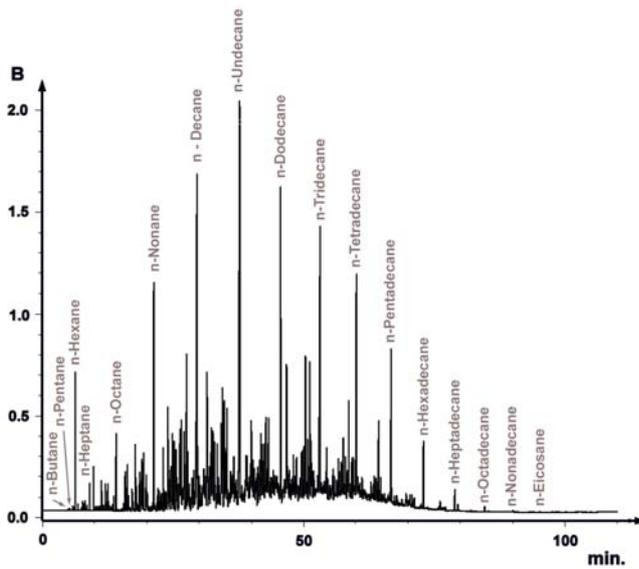


Fig. 1. Chromatogram of investigated *Jet-A* sample. The labeled peaks are n-alkanes.

Test section for ignition-delay time measurements are mated to the end flanges of shock tubes. Pressure variations at different cross-sections of the tube resulting in distinct *Jet-A* auto-ignition modes [1, 12] were measured by high-frequency pressure sensors. The quartz window has been mounted into reflecting end wall to provide optical observations. The PCB pressure sensor installed near the window measured the reflection time and pressure history behind reflected shock waves. To fix the instant at which the luminosity commences, a thin gas column ($\varnothing 5 \text{ mm}$) along the tube axis was focused onto photomultiplier cathodes. The beam-splitter divides output flame spectrum in two optical paths to ensure the simultaneous observations at two spectral bands. The luminosity from C_2 ($\lambda=516.5 \text{ nm}$; $\Delta \lambda = 5 \text{ nm}$) radicals and integral emission from spectral band of $380 - 480 \text{ nm}$ were employed to measure auto-

ignition of the mixture. The ignition delay time was defined as the time difference between shock arrival at the end wall and the onset of emissions at required intensity levels from the measuring gas column along the tube axis. The flame emission in selected spectral band was registered by means of the photo-multiplier having the maximal sensitivity in the selected spectrum.

Velocities of reflected shock wave (SW) and pressures at different locations from the reflecting wall identified auto-ignition modes of the mixture (strong, transient and weak). The reflected SW velocity in the end part of the tube was defined as $V = V_5 + u$, where V_5 is visible propagation velocity of reflected shock wave, and u is flow velocity of incoming flow behind *ISW* (incident shock wave). Visible velocity was calculated by processing shock-arrival times at pressure sensors along the tube. If experimentally defined velocities are compared with the calculated *C-J* velocity for temperature and pressure behind *ISW*, the direct detonation initiation occurs at post-shock conditions. This regime corresponds to strong ignition of the gas mixture in the vicinity of the reflecting wall. The formed detonation propagates upstream the flow. For transient modes resulting in *DDT*, the flame acceleration behind the reflected shock wave caused the onset of detonation upstream the reflecting surface. For weak ignitions, no visible changes in propagation velocities and sharp pressure spikes have been observed in experiments. The rate of mixture burning did not result in flame acceleration and transmission to detonation.

Ignition times and auto-ignition modes of *Jet-A*/air mixtures

The tests have been done at mean post-shock pressures of $8 \pm 1 \text{ atm}$, and mixture stoichiometries of $\phi = 0.5$, $\phi = 1$, and $\phi = 2$. The autoignition behavior of *Jet-A* within the temperature range of $1000 - 1700 \text{ K}$ has been investigated in details. Not less than 16 ignition data points have been obtained for each ignition delay curve at *Jet-A*/Air mixture initial temperature of $75-80^\circ \text{ C}$.

Figure 2 presents the ignition delays for stoichiometric mixture. As is seen, the ignition delay data measured by different methods and at different initial temperatures correlate well in a studied range of post-shock temperatures. The mean activation energies for lean, stoichiometric, and rich *Jet-A*/Air mixtures are approximately the same and equal to $32.7 \pm 0.2 \text{ kcal/mol}$. This value is less than the one for activation energy for *n-Heptane* (40.2 kcal/mol) and *JP-10* (44.6 kcal/mol) fuels reported in [6,8].

Although generally, the ignition delay times of *Jet-A/Air* mixtures follow the Arrhenius law, the significant decrease of activation energy has been observed in our experiments at high temperatures $T > 1400$ K. Figure 2 indicates this behavior measured for stoichiometric *Jet-A* and a major n-alkane compound, n-Decane, in air. An empirical correlation for ignition delay has been derived based on the experimental data (fig.3).

The critical post-shock temperature required for direct initiation of detonation in rich mixture was $T = 1160$ K. The corresponding value in stoichiometric one was equal to $T = 1205$ K. The *CJ* velocity in rich *Jet-A* mixtures exceeds the detonation velocity of *JP-10* fuel ($V_{CJ} = 1750$ m/s). The appropriate value in stoichiometric *Jet-A* mixture is equal to $V_{CJ} \approx 1670$ m/s. Lean *Jet-A* mixtures ignite and detonate much worse. The measured velocity of *CJ* detonation was less than 1500 m/s.

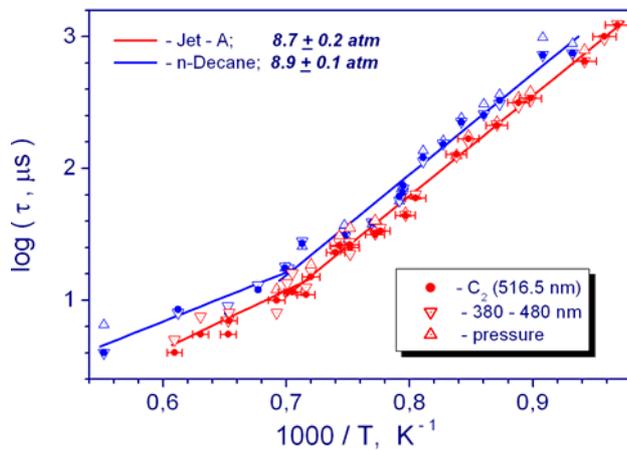


Fig. 2. Ignition times versus reciprocal post-shock temperature behind reflected shock wave in *Jet-A* and *n-Decane* stoichiometric mixtures.

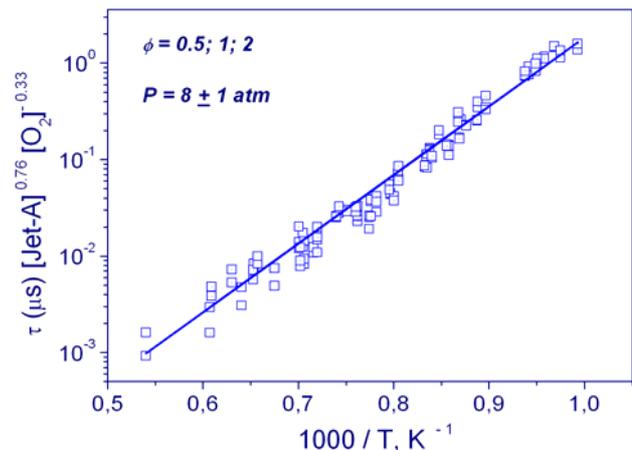


Fig. 3. Correlation equation for *Jet A/Air* mixture deduced from the experimental data

Conclusions

Ignition delay times were measured in reflected shock waves at post-shock pressure of 10 atm for lean, stoichiometric, and rich *Jet-A/Air* mixtures ($\phi = 0.5, 1, 2$) within the temperature range of 1000 -1700 K. An empirical correlation for ignition delay has been derived based on the experimental data.

For *Jet-A* ignition, significant decrease of activation energy has been observed at high post-shock temperatures of $T > 1400$ K.

The critical post-shock temperatures required for direct initiation of detonation in *Jet-A/Air* mixture were $T = 1160$ K ($\phi = 2$), 1205 K ($\phi = 1$) and 1248 K ($\phi = 0.5$). The corresponding *CJ* detonation velocities were equal to $V_{CJ} = 1780$ m/s, 1670 m/s, and 1480 m/s correspondingly.

The obtained data can be used directly for propulsion applications, verifications of kinetic mechanisms, and for analysis of detonability limits and explosion hazards of *Jet-A* fuel.

Acknowledgements

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References

1. Vermeer, D.J, Meyer, J.W., and Oppenheim, A.K., Auto-ignition of hydrocarbons behind reflected shock waves, *Combustion and Flame*, Vol.18, pp. 327-336, 1972.
2. Coats, C.M., and Williams, A., Investigation of ignition and combustion of n-heptane-oxygen mixtures, 17th Symp. (Int.) on Combustion, The Combustion Institute, pp.611-621, 1979.
3. Burcat, A., Farmer, R.C., Espinoza, R.L., and Matula, R.A., Comparative ignition delay times for selected ring-structured hydrocarbons, *Combustion and Flame*, Vol. 36, pp. 313-316, 1979.
4. Ciezki, H. K., and Adomeit, G., Shock tube investigation of self-ignition of n-heptane –air mixtures under engine relevant conditions, *Combustion and Flame*, Vol. 93, pp. 421-433, 1993.
5. Davidson, D.F., Hitch, B., Horning, D.C., and Hanson, R.C., Shock tube ignition time measurements for n-heptane/oxygen/argon mixtures with and without additives, 1st Joint Meeting of the U.S. Sections of the Combustion Institute, Washington DC, 1999.
6. Colket, M.B., and Spadaccini, L.J., Scramjet fuels autoignition study, 14th Int. Symp. on Airbreathing Engines, Florence, Italy, September 5-10, 1999.
7. Fieweger, K., Blumenthal, R., and Adomeit, G., Self-ignition of S.I. engine model fuels: a shock tube investigation at high pressure, *Combustion and Flame*, Vol.109, pp.599–619 (1997).
8. Davidson, D.F., Horning, D.C., Herbon, J.T., and Hanson, R.K., Shock Tube Measurements of JP-10 Ignition, 28th Symp. (Int.) International on Combustion, The Combustion Institute, pp. 1687-1692, 1999.
9. Gueret, C., Cathonnet, M., Boettner, J-C, and Gaillard, F., Experimental study and modeling of kerosene oxidation in a jet-stirred flow reactor, 23rd Symp. (Int.) on Combustion, The Combustion Institute, pp. 211-216, 1990.
10. Lindstedt, R. P., and Maurice, L. Q., Surrogate mixtures to represent complex aviation and rocket fuels, *Journal of Propulsion and Power*, Vol. 17, No. 2, pp. 461-466, 2001.
11. Burcat, A., Third Millenium Ideal Gas and Condensed Phase Thermochemical Database for Combustion. Technion Aerospace Engineering (TAE) Report # 867 January 2001.
12. Voevodsky V.V., Soloukhin R.I.. On the mechanism and explosion limits of hydrogen-oxygen chain self-ignition in shock waves. *Proc. Combust. Inst.* 10 (1965) 279-283.
13. Penyazkov O.G., Ragotner K.A., Dean A.J., Varatharajan B. Auto-Ignition of Propane behind Reflected Shock Waves // *Proceedings of 30th Int. Symp. on Combustion*, The Combustion Institute, 2004. In press.