Experimental Investigation in the Autoignition Behaviour of Aviation Jet Fuel in a Rapid Compression Machine

NYONG, O.E, EBIETO, C.E, AGBRO, E. and BLAKEY, S.

Experimental Investigation in the Autoignition Behaviour of Aviation Jet Fuel in a Rapid Compression Machine.

O. E Nyong[1,4], C.E Ebieto[3,4], E. Agbro[2], S. Blakey[4]

[1] Department of Mechanical Engineering, Cross River University of Technology, Calabar, Nigeria.
[2]Department of Engineering and Mathematics, Sheffield Hallam University, UK.
[3]Department of Mechanical Engineering, University of Port Harcourt, Rivers State, Nigeria
[4]Low Carbon Combustion Centre, Department of Mechanical Engineering, University of Sheffield
Corresponding Author email:nyong.oku@crutech.edu.ng

Abstract

Jet A-1 fuel's autoignition behaviour was examined experimentally in a newly developed rapid compression machine (RCM) at the University of Sheffield. The experiment was conducted at a compressed temperature at compressed temperatures of $697\ K \leq T_c \leq 796\ K$, compressed pressure of 6 and 10 bar, and under lean and stoichiometric conditions ($\varphi = 0.75$ and 1.0). The initial chamber wall temperature was varied from 115°C - 135°C. The effect of the compressed temperature, compressed pressure and equivalence ratio was seen to have influence on the ignition delay time (IDTs) of Jet A-1. In the experimental condition studied, Jet A-1 exhibited an Arrhenius behaviour that is increasing the compressed temperature, compressed pressure and equivalence ratio decreases monotonically with IDTs. Evidence of two-stage ignition delay and absence of Negative Temperature Coefficient (NTC) behaviour was observed within the condition studied.

Key words: Jet A-1; Rapid compression machine; Piston released Mechanism; Ignition delay time.

1. Introduction

The traditional jet fuel precisely comprises different classes of hydrocarbons and has different behaviours due to the refining processes and petroleum feedstocks[1]. It comes mainly from crude oil, which is otherwise known as petroleum jet fuel. It includes a large number of aliphatic and aromatic hydrocarbon compounds with carbon content $C_9 - C_{16}$, consisting mainly of normal alkanes, branched alkanes, cycloalkanes, aromatics, and alkenes. Jet fuels are straight chain such as alkanes with percentage volume of constituent ranging from 35 - 45%, branched chain such as cycloalkanes with constituent range of 30-35% by volume, aromatics one and two rings, 20-25% volume and the alkenes which is less than 5% volume [2]. There are three kinds of conventional jet fuels [3]: (i) the kerosene type (ii) the high flash point kerosene, and (iii) the broad cut. The kerosene type Jet A-1 is mainly used in other parts of the world by international civil aviation companies, and Jet A is most commonly used in the USA. Besides, the U.S. Air Force also uses an aviation kerosene fuel such as the JP8 that has a significant quantity of naphthenes, which enhances thermal stability and storage. This is suitable for use in aviation to run turbine power engines for both military and civilian applications [4]. JP-8 and JP-5 are blends of military fuels which are quite different from the

commercial one [5]. The JP-5, which is naphtha-typed fuel is made by blending straight-run kerosene streams with lower boiling distillates to fit the ASTM specifications. The main difference of the two fuels is that JP-8 has a lower freezing point (−47 °C) and contains additives such as corrosion inhibitors, icing inhibitors and lubricants and has the capacity to handle high heat. Therefore, the concentration of a crude oil component in the final jet fuel product varies. In literature due to the refining processes and feedstocks, the emergence of new Jet fuels cannot be ignored. A typical example is the RP-3 which differs in composition and combustion characteristics [6]. A pre-knowledge of the chemical kinetics of these fuels are important in the development of aero-combustors. Developing a reliable chemical kinetic model requires kinetic validation objectives such as IDTs. Except when the kinetic mechanisms are tested and validated, it is also possible to use IDTs to assess fuel compatibility with engines with any further modification of the existing architecture. Unwanted autoignition in engines could lead to knock in homogenous compression ignition engine (HCCI) and a considerable amount of emissions. Consequently, the autoignition characteristics of jet fuel are of great importance. To make available experimental data of jet fuel for kinetic validation several researchers have measured the IDTs of Jet fuel with different apparatus such as flow reactor (FR), jet stirred reactor (JSR), well-stirred reactor (WSR), shock tubes (ST) and rapid compression machine (RCM). Previous experimental work carried out showed numerous shock study on real Jet fuels among them are: the first homogenous shock tube IDTs for Jet A measurements reported by Dean et al. [7], at pressures (0.85 MPa) and high temperature conditions (1000–1700 K); Vasu et al. [8, 9] measured IDTs using heated shock tube (ST) for Jet-A and JP-8 at a wide temperature range (715 K–1229 K) and over an elevated pressures (17–51 atm); Davidson et al. [10] reported ST ignition measures for Jet fuels at 700–1250 K and 1.2 MPa: Wang and Oehlschlaeger [11], reported IDTs on Jet-A POSF 4658 using ST at high pressures (8–39 atm) over a range of temperature (651–1381 K) at equivalence ratios from 0.25 to 1.5; the IDTs of Jet A, JP8 and a couple of alternative fuels in both ST and RCM were studied by Sung and Kumar [12, 13]; Recent study on China RP-3 kerosene using both ST and RCM [6]. With these previous reviews on experimental study on IDTs of real jet fuel using both ST and RCM. There is still sparse data on low to intermediate temperature combustion of real jet fuel from RCM facilitates which has necessitated further tests to build an archive of data to deepen our understanding on the oxidation kinetics of real jet fuel.

2.   Experimental Methods

The recently developed RCM [14, 15] a single stroke facility, which imitates a single physical event of an internal combustion engine. The facility consists of five major components namely pneumatic cylinder, hydraulic damper, Piston Release Mechanism (PRM); optimize crevice design and the reaction chamber. The facility is unique in its design, it is pneumatically driven, hydraulically stopped by a ring and groove mechanism and pneumatically releases its reactor piston by triggering the solenoid valve which controls the PRM. The PRM controls the test facility by pneumatically releasing the reactor piston to compress the test mixture ahead of it to a thermodynamic state. A typical compression time for the facility ranges from 23 – 52 ms, while the majority greater than 60% of pressure/temperature rise occurs in the last 4 ms of compression. The roll up vortex is controlled by the effectiveness of piston crevice thus maintaining a homogeneous environment at the end of compression [16]. A mixture of fuel

and air is injected into the reaction chamber and compressed adiabatically to an elevated temperature and pressure at the end of stroke. The end temperature and pressure are characterized by compressed pressure (P_C) and compressed temperature (T_C), by individually varying the initial temperature (T_0), initial pressure (P_0) and the geometric compression ratio. The maximum compression ratio attained by the current facility is 20, thus this can be varied by adjusting the stroke length/shaft lock or changing the end of compression length. The only variable measured from the experiment is the pressure trace data which is recorded from the dynamic pressure signal using a piezoelectric sensor, Kistler 6009 in conjunction with a charge amplifier Kistler type 5007. The data acquisition is recorded with National Instrument (NI cDAQ 9223). Two inlet ports are located at the end of the reaction chamber, one for admitting fuel-air mixtures while the other port allows compressed air into the chamber to retrieve the piston after each run. The port also serves the purpose of evacuating debris and soot particles formed as a result of combustible gases. The initial temperature of the facility is regulated by the PID controller which has a dual-port to accommodate the heating tape and the K-type thermocouple. The reaction chamber is wrapped with a high temperature fiber heat tap (Omegalux) and insulated to minimize the heat loss from the chamber wall to the environment. The initial temperature of the reaction chamber is read with the K-type thermocouple. Fig 1.0 shows the sectional view of the current Shef-RCM.
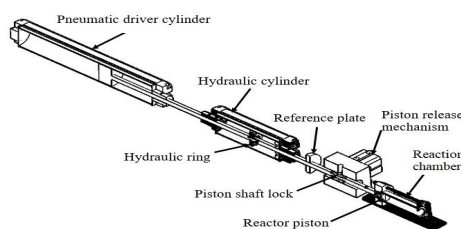

Fig.1 shows the sectional view of the current RCM facility at the University of Sheffield.

A uniform temperature field as earlier discussed was maintained by employing a creviced piston design based on Mittal and Sung [17] in containing the multidimensional effects such as roll-up vortex while maintaining a uniform temperature core region. The compressed temperature T_c cannot be calculated directly due the poor responsiveness of the thermocouple and the rapid heat loss from the gas to the walls of the reaction chamber since the process of compression is not truly isentropic. However, the heat loss is account for using the adiabatic core hypothesis to the relation where T_c is estimated

$$\ln\left(\frac{P_c}{P_0}\right) = \int_{T_0}^{T_c} \frac{\gamma}{\gamma-1} \frac{dT}{T}$$

Where P_0 is the initial pressure, P_c is the compressed pressure, T_0 is the initial temperature, γ is the specific ratio.

The adiabatic core hypothesis assumes that the effect of heat loss to the wall during the end of compression stroke is limited to the thin boundary layer along the walls and the core chamber region not affected by heat loss. The region of the reaction chamber away from the walls is referred to as the core region, where temperature field uniformity predominates. No mixing occurs between the hot core region and cold boundary layer. The only way heat loss affects the core region is by expansion of the core region caused by boundary layer cooling. Accounting for the heat loss specifically, a non-reactive experiment is conducted under similar

conditions as that of the reactive experiment by replacing O_2 with N_2, and the corresponding heat loss parameters are derived for the compression and post-compression duration from the experimental pressure trace. Then the compressed gas temperature, T_c is numerically estimated by varying the compression ratio to match the experimental pressure trace during the compression and post compression stages. The expected result from an RCM test is the IDTs, which would be defined for clear understanding.

IDTs are defined as the occurrence of an inflexion point in the pressure trace during the pressure rise due to ignition that occurs after the end of compression. The ignition behaviours are shown in a reactive experimental result illustrated in Fig 2; A typical pressure history, *P(t)*, measured from the Shef-RCM for Jet A-1/air mixtures at stoichiometric and *P′(t)* is the time derivative of the measured pressure as a function of time. The IDTs definition appears to have one peak pressure rise signifying a single stage ignition delay of Jet A-1. The time zero corresponds to the end of compression and the first-stage IDTs, τ is the time from the end of compression to the maximum rise in pressure, *P′(t)*.
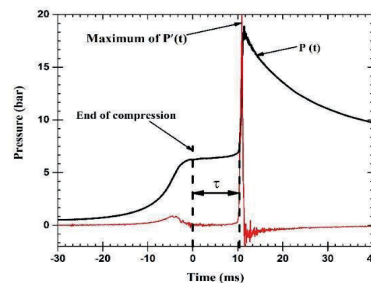

Figure 2: Illustrate the definition of IDTs used in this study. P(t) is the pressure as a function of time, and P′(t) is the time derivative of the pressure as a function of time.

The aviation jet fuel (Jet A-1, labelled as FST- 265638) used in this study was supplied by the Low Carbon Combustion Centre (LCCC). The derived empirical formula for the Jet A-1 is $C_{11.84}H_{22.72}$. The equivalence ratio, however, is calculated based on the derived empirical formula as obtained from the GC*GC analysis. Table 1, summarizes the fuel/oxidizer mixture composition investigated in this work. The initial chamber wall temperatures in the range of $115^{\circ}C$ - $135^{0}C$ were used for all the conductions studied.

Table 1: Experimental test conditions

| Jet A-1 (FST 265638) | Molar Composition (%) | | | Equivalence Ratio | Compressed Pressure (bar) |
	O_2	N_2	Ar	φ	P_c
0.86	20.82	78.32		0.75	6,10
1.14	20.76	78.10		1.0	6,10
0.86	20.82	58.74	19.58	0.75	6,10
1.14	20.76	58.58	19.53	1.0	6,10

3.   Results and discussion

Effect of temperature on Jet A-1 ignition

The effect of T_c was studied by injecting Jet-A-1/air mixture into a heated reaction chamber. Fig 3, depicts the pressure traces as a function time for a reactive and non-reactive experiment at φ = 0.75 and 1.0, at P_c = 6 bars and T_c = 697 – 786 K. The non-reactive was performed by running the experiment at the same condition of that of the reactive by replacing the O_2 with N_2 gas. The effect of varying the end gas temperature was seen on the IDTs at different values of φ = 0.75 and 1.0. In Figure 3(a) & (b), as depicted when compressed temperature, T_c was increased, a monotonically decrease in the IDTs was seen. From close observation, the pressure traces showed no evidence of two-stage ignition behaviour and no evidence of strong preignition heat release was found within the test conditions.
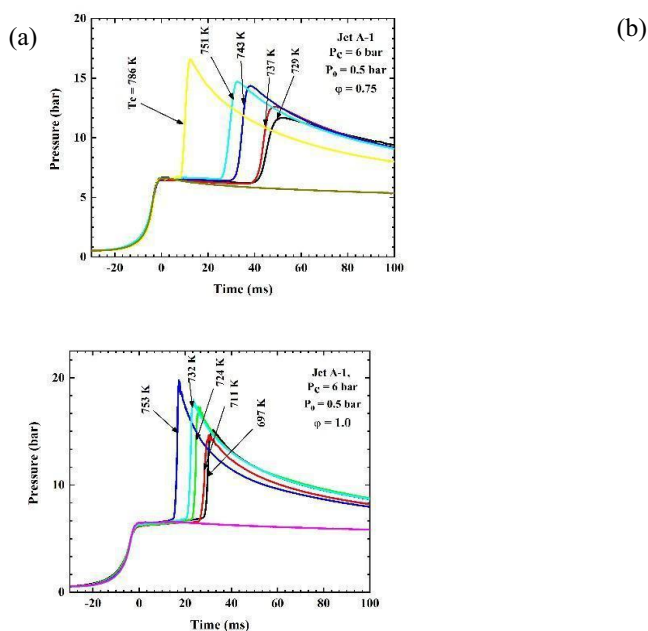

Figure 3, depicts the effect of T_c on IDTs at P_c = 6 bar, (a) φ = 0.75 (b) φ = 1.0.

Effect of pressure   on Jet A-1 ignition delay

Fig 4(a) & (b) shows the Arrhenius plot for Jet A-1/air mixture in a heated RCM at compressed gas temperatures of *697 K ≤ T_c ≤ 796 K*, φ = 0.75 and 1.0, P_C = 6 bar and 10 bar. In Fig 4(a) depicts the IDTs plot against the inverse of 1000/T_c. for Jet A-1at φ = 0.75. The effect of pressure is seen on the IDTs, it is observed that the IDTs get shorter as the compressed pressure Pc increases from 6 bar to 10 bar. In Fig. 4(b) a similar trend is seen at a higher equivalence ratio, φ = 0.75 increasing compressed pressure led to a significant decrease in the IDTs. It was observed that at stoichiometric condition φ = 0.75, the IDTs is about one fold smaller than that at lower pressure. One would expect that at higher pressure means higher concentration for the reactant mixture. Invariably an increase in reactant improves reactivity thereby shortening the IDTs. For both conditions, it can be seen that the

IDTs become smaller as the pressure is increased but objectively a linear variation is seen in this semi-log plot.
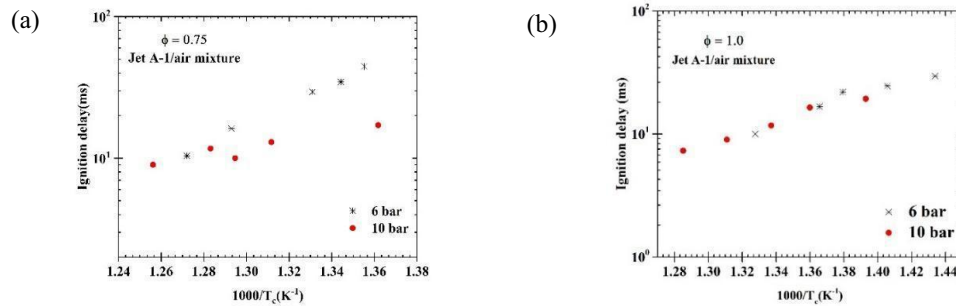

Fig. 4 shows the effect of pressure on IDTs time of Jet A-1/air mixture for (a) $\varphi = 0.75$ and (b)

$\varphi = 1.0$.

Effect of equivalent ratio on Jet A-1 ignition delay.

Figure 5, depicts the effect of equivalence ratio on the IDTs for Jet A-1/air mixture in heated RCM at $P_c = 6$ and 10 bar, T_c in the range of 717K – 796 K. Fig 5(a) display the Arrhenius plot at $P_C = 6$ bar.

The ignition delays shown in Figure 5(a) are seen to decrease monotonically with increasing temperature. Fig 5(b) depicts the Arrhenius plot for $P_c = 10$ bar. The influence is seen as the equivalence ratio is increased from $\varphi = 0.75$ to $\varphi = 1.0$, the IDTs gets shorter indicating a more reactive mixture. Additionally, at $P_c = 6$ bar the change in ignition delays is larger when the equivalence ratio is increased from $\varphi = 0.75$ to $\varphi = 1.0$ at $P_c = 6$ bar as compared to the change when the equivalence ratio is increased from $\varphi = 0.75$ to $\varphi = 1.0$ at $P_c = 10$ bar. It was observed that the IDTs at $P_c = 10$ bar is approximately about 1.3 fold smaller than the IDTs at lower pressure $P_c = 6$ bar. At both conditions studied, it was established that increasing the equivalence ratio decreases monotonically with the IDTs. At both compressed gas pressures no evidence of two-stage ignition and NTC behaviour was observed.
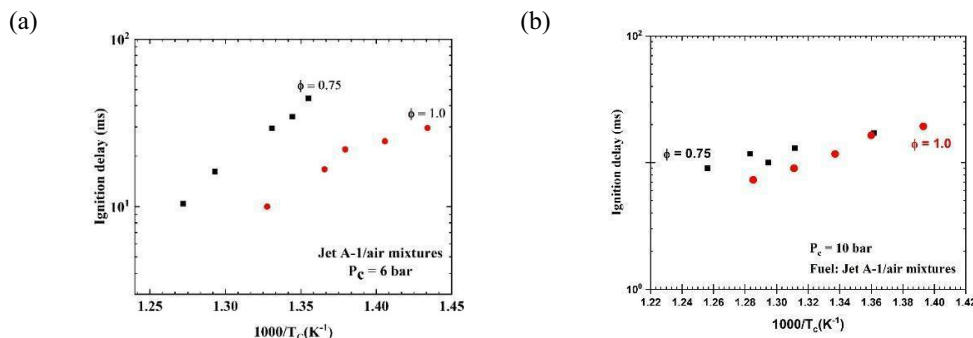

Fig. 5: shows the effect of equivalence ratio on the IDTs of Jet A-1/air mixture. Conditions: $\varphi = 0.75$ and 1.0 for (a) 6 bar and (b).10 bar.

4.   Conclusions

An experimental investigation Jet A-1/air mixture in a heated recently developed RCM was conducted at low to intermediate temperatures regime *(697 ≤ T_c ≤ 796),* compressed pressure, P_c = 6 and 10 bar and equivalent ratio ratios, φ = 0.75 and 1.0. At both compressed pressures the effect of pressure is seen as the IDTs decrease monotonically with increase as the pressure. The difference in IDTs is greater when the equivalence ratio is increased from φ = 0.75 to φ = 1.0 at P_c= 6 bar compared to the change when the equivalence ratio is increased from φ = 0.75 to φ = 1.0 at P_c= 10 bar. The reason could be that the fuel concentration has increased by a factor making the mixture become more reactive thereby decreasing monotonically with IDTs. Increasing the compressed temperature, compressed pressure and equivalence ratio have considerable effect on the IDTs. It was observed that the effect of increasing the temperature, pressure and equivalence ratio has shown to decrease monotonically with IDTs. Within the conditions studied Jet A-1 displays a single stage ignition and no NTC behaviour displayed. The results presented here would tend to complement the existing data on Jet A-1 with a view to validating the chemical kinetic models of Jet fuels.

Acknowledgements

Reference

[1]   Maurice, L. Q., Lander, H., Edwards, T., et al., Advanced aviation fuels: a look ahead via a historical perspective, *Fuel,* vol. 80, pp. 747-56, 2001.

[2]   Edwards, T. and Maurice, L. Q., Surrogate mixtures to represent complex aviation and rocket fuels, *Journal of Propulsion and Power,* vol. 17, pp. 461-66, 2001.

[3]   Guibet, J. C. and Faure-Birchem, E., Fuels and engines: Technology, *Energy, Environment,* vol. 1, pp. 1-385, 1999.

[4]   Dagaut, P. and Cathonnet, M., The ignition, oxidation, and combustion of kerosene: A review of experimental and kinetic modeling, *Progress in Energy and Combustion Science,* vol. 32, pp. 48-92, 2006.

[5]   Bacha, J., Barnes, F., Franklin, M., et al., Aviation fuels technical review Chevron Products Company, 2000.

[6]   Mao, Y., Yu, L., Wu, Z., et al., Experimental and kinetic modelling study of ignition characteristics of RP-3 kerosene over low-to-high temperature ranges in a heated rapid compression machine and a heated shock tube, Combustion and Flame, vol. 203, pp. 157-69, 2019/05/01/ 2019.

[7]   Dean, A. J., Penyazkov, O. G., Sevruk, K. L., et al., Autoignition of surrogate fuels at elevated temperatures and pressures, Proceedings of the Combustion Institute, vol. 31, pp. 2481-88, 2007/01/01/ 2007.

[8]   Vasu, S., Davidson, D., and Hanson, R., "Jet Fuel IDTs Times and Modelling: Studies at High Pressures and Low Temperatures in a Shock Tube," in 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, ed.

[9]   Vasu, S., Davidson, D., and Hanson, R., "Shock Tube IDTs Times and Modelling of Jet Fuel Mixtures," in 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, ed.

[10]   Davidson, D. F., Zhu, Y., Wang, S., et al., "Shock Tube Measurements of Jet and Rocket Fuels," in 54th AIAA Aerospace Sciences Meeting, ed.

[11]   Wang, H. and Oehlschlaeger, M. A., Autoignition studies of conventional and Fischer–Tropsch jet fuels, Fuel, vol. 98, pp. 249-58, 2012.

[12]   Kumar, K. and Sung, C.-J., An experimental study of the autoignition characteristics of conventional jet fuel/oxidizer mixtures: Jet-A and JP-8, Combustion and Flame, vol. 157, pp. 676-85, 2010.

[13]   Kumar, K. and Sung, C.-j., Autoignition of Jet Fuels under High Pressure and Low-to-intermediate Temperatures, in 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 2009, p. 1527.

[14]   Nyong, O., Ebieto, C., Woolley, R., et al., A Single Stroke Cylinder Rapid Compression Machine for Chemical Kinetic Study at Elevated Pressure and Temperatures, in Journal of Physics: Conference Series, 2019, p. 032013.

[15]   Nyong, O., Development of a Rapid Compression Machine for Screening Alternative Fuel for Gas Turbines, University of Sheffield, 2017.

[16]   Nyong, O., Woolley, R., Blakey, S., et al., Optimal piston crevice study in a rapid compression machine, in IOP Conference Series: Materials Science and Engineering, 2017.

[17]   Mittal, G., Raju, M. P., and Sung, C.-J., Vortex formation in a rapid compression machine: Influence of physical and operating parameters, Fuel, vol. 94, pp. 409-17, 2012.

[18]   Allen, C., Advanced rapid compression machine test methods and surrogate fuel modelling for bio-derived jet and diesel fuel autoignition, vol. 73, 2012, p. 2012.