Effect of Alternative Fuels on Emissions and Engine Compatibility

Bhupendra Khandelwal, Charith J. Wijesinghe and Shabarish Sriraman

Abstract Given the increasing focus on climate change and emissions, alongside the motivation to combat these phenomena, it is prudent to consider alternative fuels for gas turbines, a significant source of emissions. Adopting some form of alternative fuels could reduce the carbon footprint as well as the emissions output from gas turbines to manageable levels, provided alternative fuels are coming from overall low life cycle emissions sources. In this chapter, the effects of alternative fuels on the gas turbines performance and their emissions are discussed. With respect to gaseous emissions, it has been found that alternative fuels provide no clear advantage in terms of emissions reduction compared to standard petroleum derived fuels. However, it has been found that the CO_2 emissions of a given fuel is contributed to by the H/C ratio of the fuel. An increase of the H/C ratio could lead to reduction in CO_2 emissions, though energy per unit mass of fuel goes down. The effect of alternative fuels on PM emissions however are more positive if alternative fuels are used, but PM emissions are dependent upon the aromatic content and its species in the fuel. The availability of alternative fuels from F-T processes, as well as bio-derived fuels with very low or no aromatic content, leads to very low PM emissions from alternative fuels. With respect to seal swell in fuel systems, it has been found that some alternative fuels may struggle to maintain good seal swell performance as seal swell has been historically related to aromatic content of the fuel. Therefore, it has been deemed that further research is required to find an alternative. When considering the noise and vibrations from a turbine, there appears to be insufficient data to draw clear correlations between fuel type and amount of noise and vibrations generated, however it has been noted that noise and vibration emitted is a function of the vapour pressure, surface tension and flame velocities used which in turn to a certain extent depend upon the fuel used. In terms of thermal stability, it has been noted that paraffinic fuels are better at absorbing heat and dissipating it without forming carbon deposits on the fuel system components.

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1 Introduction

With growth in the gas turbine industry increasing, demands for a cleaner and more sustainable fuel with lower emissions in needed. One that would also be a suitable replacement for Jet fuel and can satisfy the fuel consumption rate of this industry has increased. Emissions control has taken precedence and has driven the aviation industry to find better alternatives to the existing Jet fuel [1]. This also provides an opportunity to conduct extensive research on new fuel compositions which may provide a solution to the problem of higher emissions and unsustainability. Researchers have been going on a full-scale in the effort to introduce new types of fuels into the industry where there are also known as alternative fuels. To this end intensive research is being carried out to introduce drop-in alternative fuels to replace traditional petroleum-based fuels.

Alternative or advanced fuels can be formulated from a myriad of sources such as biomass, coal, and natural gas. One of the major processes for production of alternative jet fuel is the Fischer-Tropsch (F-T) process. In essence, fuel produced from any feedstock that conforms to strict fuels standard and has been through appropriate fuels approval process could be used as a jet fuel. SASOL of South Africa was the first company to get their 50% synthetic blend approved as a jet fuel. They were also the first company to supply alternative jet fuel commercially. Significant steps have been taken by the alternative fuels industry to make alternative jet fuel a reality (Fig. 1).

Emissions from gas turbines can be divided into two sections, gaseous and particulate emissions. Gaseous emissions are gases in the form of CO_2, NOx (Oxides of Nitrogen), SOx (Oxides of Sulphur) and particulate matter (PM). In western Europe it is estimated that diesel fuel combustion in transportation vehicles contributes 20% of all $PM_{2.5}$ emitted [2].

Whilst PM emissions contribute towards smog and human health risks, gaseous emissions such as CO_2 and NO_x which are detrimental to the environment as well. CO_2 contributes towards climate change as it is a GHG and NO_x is responsible for atmospheric phenomena such as acid rain, smog and ozone layer depletion. Moreover, it has been observed that inhalation of NO_x by human's due to air pollution

Fig. 1 Current and future development Road map of alternative fuels

lead to respiratory illnesses especially among vulnerable sections of the population such as the elderly and the young. Combustion dynamics have been under the scope for over a century, and many aspects of physical process and combustor geometrical arrangement have been researched earlier. With the emergence of new fuels, their varying chemical compositions may help alleviate or even eliminate combustion instabilities without implementing combustion control systems. This would reduce cost, weight and space required in a gas turbine engine. To the authors' knowledge no research other than author's own has been directed towards investigation of combustion instabilities, noise and vibrations through varied fuel compositions.

In this chapter, emissions production and engine performance while using alternative fuels in gas turbines will be discussed with a focus on their gaseous emissions, PM emissions, vibrations, noise and fuel system compatibility. This chapter has been divided into further sub-sections where all the above-mentioned topics have been discussed in detail.

2 Gaseous Emissions

The effects of alternative fuels on gaseous emissions is far less pronounced as opposed to particulate emissions. A study conducted by Cain et al. [3] using an Allison T63-A700 Turboshaft engine burning several alternative fuels and comparing them against JP-8. JP-8 (Jet Propellant-8) is a fuel similar to Jet-A1, but contains several fit-for-purpose (FPP) additives such as a lubricity enhancer, corrosion inhibiting additives and anti-icing additives. The alternative fuels tested were synthetic paraffinic kerosene (SPK) a F-T derived fuel and several other fuel blends whose main component C_{12} n-dodecane mixed with m-xylene (m-X), methylcyclohexane(MCH), iso-octane (i-C_8) or n-heptane (C_7). When these fuels were tested on the turboshaft engine at different power settings, CO_2 and CO was measured at the exhaust plane and the results are shown in Fig. 2.

As expected, for all fuels the EI (Emissions Index, grams of emission per kilogram of fuel burnt) for CO_2 increases with engine power. However, it should be noted that with respect to JP-8 the alternative fuels SPK, MCH and iC_8 consistently emit less CO_2. The study goes on to compare the CO output with respect to engine power as shown in Fig. 2 this shows a trend of CO decreasing with the increase of engine power, this is to be expected as CO is the product of incomplete combustion and as the engine starts to run at full power incomplete combustion is reduced if not entirely eliminated. Cain et al. [3] further goes on to stipulate that as the H/C (Hydrogen atoms to carbon atoms ratio) of the fuels increases the total amount of CO_2 emitted decreases. This is similar to CO_2 emissions trends observed on GTCP85 APU in CLEEN program [4].

Figure 3 shows the results from a study performed by Salvi et al. [5] showing the emissions variations for several bio-derived SPK blends with JP-8. It can be observed from the Fig. 3 that the bio blends lead to a reduction in $NO_{x,}$ especially for blend S8.

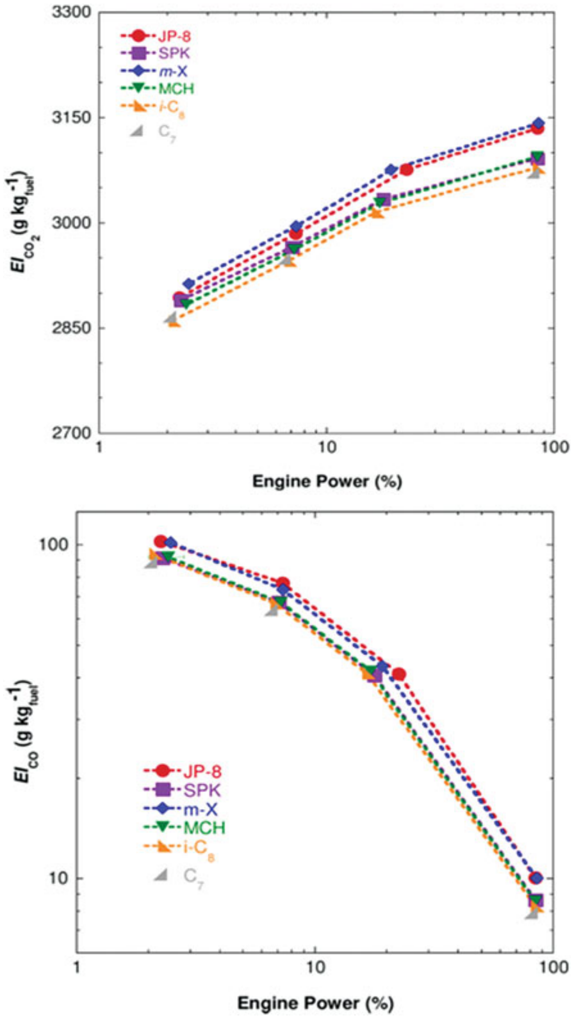

Fig. 2 Engine power setting versus EI of CO_2 for an Allison T63 Turboshaft burning alternative fuels [3]

The study conducted by Lobo et al. [6] measured the gaseous emissions from an Artouste Mk113 APU burning a CTL (F-T) and GTL fuel compared against Jet-A1. It was found that the NO_x emissions for Jet-A1 and the GTL were statistically indistinguishable. However, the CTL fuel showed a 5% decrease in NO_x with respect to Jet-A1 at full engine power. Moreover, a negative correlation between CO emissions and the fuels energy content is observed. As the fuel energy content increases the CO emissions reduced. Furthermore, the CTL fuel did not compare well against Jet A-1 in terms of unburnt hydrocarbon emissions (UHC) with CTL registering a 7%

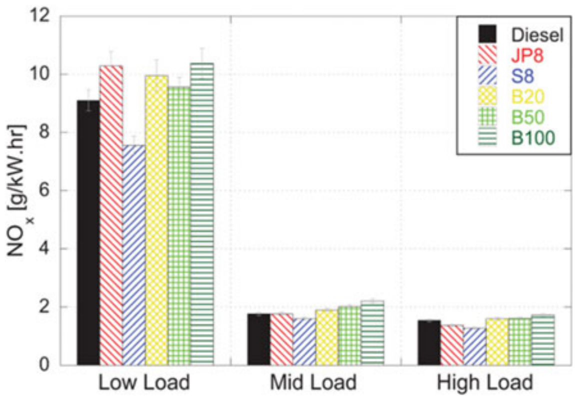

Fig. 3 Comparison bio-synthetic paraffinic kerosene (Bio-SPK) blends compared to reference JP-8 and Diesel [5]

increase in UHC at idle compared to Jet-A1. In testing done at the Low Carbon Combustion Centre (LCCC) under CLEEN program it was also observed that total NOx contents remain similar for all the alternative fuels and blends tested, but NO to NO_2 ratio changes. This observed phenomenon could have implications if only NO_2 or NO is being measured or regulated or used in further combustion research.

A Study conducted by Lee et al. [7] during the Alternative aviation fuel experiment (AAFEX) using a stationary McDonnell Douglas DC-8 fitted with CFM-56 turbines and measuring the emissions form the exhaust plumes 145 m downstream of the engines have observed several phenomenon as illustrated in Fig. 4.

It can be observed from the Fig. 4 that NO_x increases for all the fuels with increased engine power but the individual values of NO_x are all within the error bars indicating no statistically significant reduction in NO_x for the alternative fuels. It was also observed that the minor species of hydrogen peroxide is high at idle engine power and decreases as power is increased while nitrous acid shows the opposite correlation increasing with engine power. There are several other studies in literature which compares gaseous emissions of wide range of alternative jet fuel [3, 4, 8, 9].

It can be observed from Table 1 that the CO_2 emissions for all the fuels tested are within the uncertainty limits yielding no statistically significant trend. However, it can be seen that fuel 4 has significantly higher nitrogen dioxide output with respect to the other fuels and that the commercial alternatives have a slightly less NO_2 output with respect to Jet-A1.

Overall it can be said that CO_2 emissions depends on C/H ratio of fuel, as all the Carbon in fuel should get converted into CO_2, in most advanced engines. Provided the engine is operating on same power condition and its exhaust gas temperature and turbine entry temperatures are same for conventional fuels and alternative fuels then total NOx emissions normally should be similar. This is owing to the fact that NOx production depends on temperature, and fuel bound NOx is very low due to negligible amount of nitrogen being present in aviation fuels. Though in some studies it has been found that NO to NO_2 ratio in gaseous emissions change depending upon the source of the alternative fuel (i.e. If from CTL GTL or bio-derived). UHC and CO

Table 1 Gaseous emissions data for several Alternative fuels and potential drop-in alternatives fuel 1 is Jet-A1 fuels 2-4 are blends of Jet-A1 and SPK and fuels A-D are commercial alternatives [4]

	Uncertainty	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel A	Fuel B	Fuel C	Fuel D
CO_2 (EI)	±10	3169	3171	3172	3172	3170	3171	3170	3171
CO (EI)	±2	14.1	13.4	13.0	12.8	14	13.0	14.0	13.9
NOx (EI)	±0.1	4.1	4.2	4.2	4.2	4.4	4.1	4.0	4.2
NO (EI)	±0.1	2.9	2.9	3.0	2.9	2.8	2.9	2.8	2.9
NO_2 (PPM)	±0.1	34.1	33.4	33.6	47.9	32.4	33.2	32.3	33.3
THC PPM)	±3	0	0	0	0	1	1	0	0
Oxygen (%)	±0.2	14.9	15.1	15.1	15.2	15.1	15.2	15.0	15.1

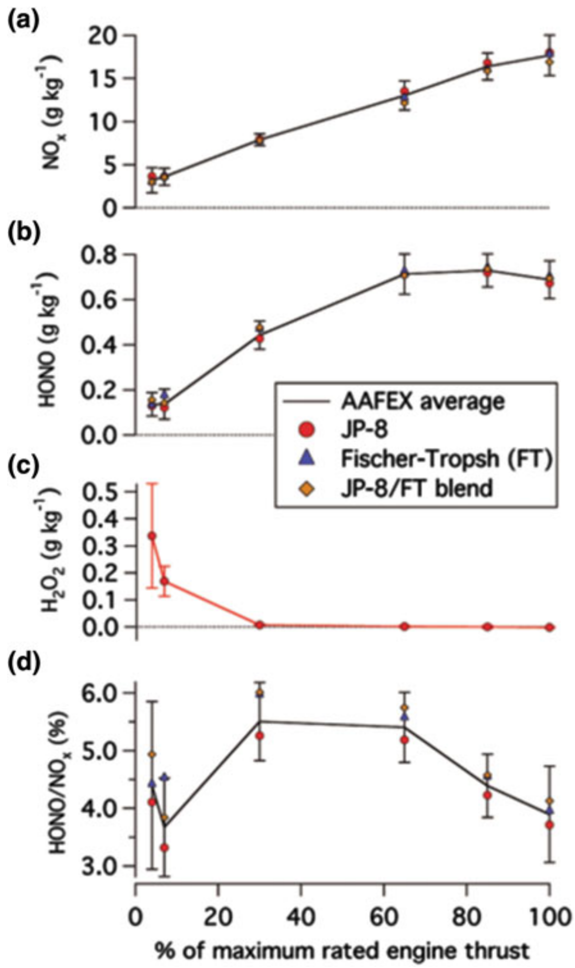

Fig. 4 Emission indices for NO_x HONO (Nitrous Acid), H_2O_2(Hydrogen Peroxide) and HONO/NO_x ratio obtained from the AAFEX experiment for several alternative fuels compared to JP-8 [7]

are products of incomplete combustion which could be due to a multitude of factors such as fuel properties like viscosity, surface tension, aromatic species and several others. Some studies have found that UHC and CO decreases when fuel has been changed to alternative fuels [3], whereas majority of the studies have found there is no significant change when fuel has been replaced with alternative fuels [7].

3 Particulate Emissions

Particulate emissions, when considered in the airborne context, conventionally can be into two subsections, $PM_{2.5}$ used for particles 2.5μm or less in diameter and PM_{10} for particles of diameter 10μm or less. Particle emissions, widely known as particulate matter (PM), refers to solids or liquids present in the exhaust gases after combustion. The particles can include carbonaceous particles, abraded metals, inorganic acids, as well as PM present in the ambient air generated from more mundane sources in the vein of soil and dust particles. Hence the shapes and sizes of the discrete particulates as well as their chemical composition can be irregular. To develop an accurate defection for particulate matter therefore would require clarification of their chemical composition, morphology and the abundance of each particle as a function of particle size. Therefore, some common describers of particulate matters include nvPM and vPM, non-volatile and volatile particulate matter. In general, nvPM are solid particles at the exit plane of the engine exhaust whereas vPM is liable to change state when it encounters the ambient conditions outside the engine, as the exhaust is at extremely elevated temperatures some gaseous emissions may condense into liquid and coat the solid particles when cooled down in the exhaust downstream of the turbine

The rate these gaseous emissions condense is somewhat dependent upon their vapour pressure and other ambient conditions such as temperature and humidity, a classic example of this phenomena are contrails from jet aircraft, which appear sometimes but not others. This is due to water being vapour being condensed due to the prevailing ambient conditions, as well as the exhaust temperature at the time.

Volatile particulate matter (vPM) are formed by the nucleation of gaseous precursors mainly consisting of sulphuric acid and other such organic compounds formed in the cooler exhaust gas downstream of the combustor [10–12]. Furthermore, it has been observed that these gaseous precursors condense to around the nvPM as illustrated in Fig. 6. The volatile PM definition also fits the condensable PM (CPM) terminology mostly used by the Environmental Protection Agency (EPA) (Figs. 5 and 6).

The main reason particulate emissions have garnered attention is due to the fact that it is an air pollutant, which among other things is mainly responsible for the smog that permeate industrial and heavy-traffic oriented cities such as Beijing and Delhi. Furthermore, particulates pose a significant health risk to humans, it is well-established in literature that humans exposed to particulate matter on a regular basis are subject to increased risk of mortality and loss of life expectancy due to respiratory and cardio pulmonary illnesses, such as lung-cancer and cardiac arrest [2, 14–17].

Therefore, it is imperative that particulate emissions be reduced to this end alternative fuels of diverse types have been scrutinized for their particulate emission levels. In one of the studies conducted by Lobo et al. [18] comparison of PM emissions from a commercial gas turbine (CFM-56) while using alternative fuel has been done. Different types of biomass and FT based fuels were used which were then compared with Jet A-1 as a standard. Several blends of FAME (Fatty-Acid-Methyl-Esters) and

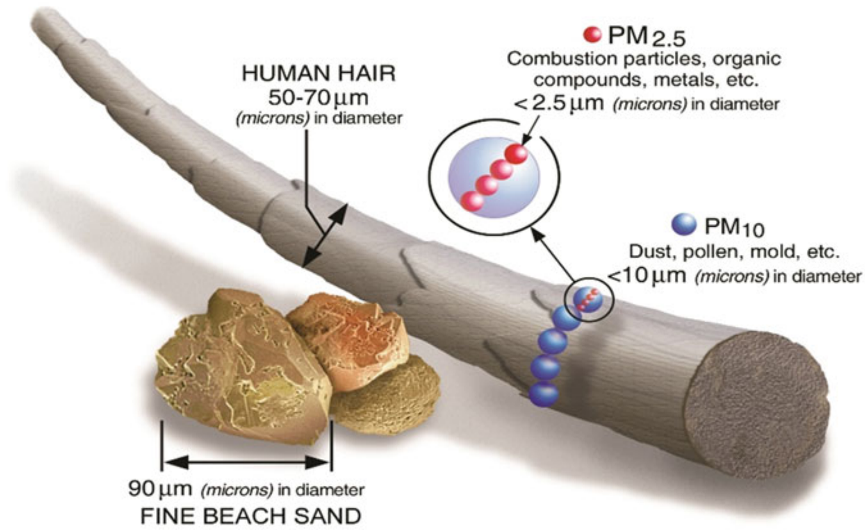

Fig. 5 Differentiation of particulate matter [13]

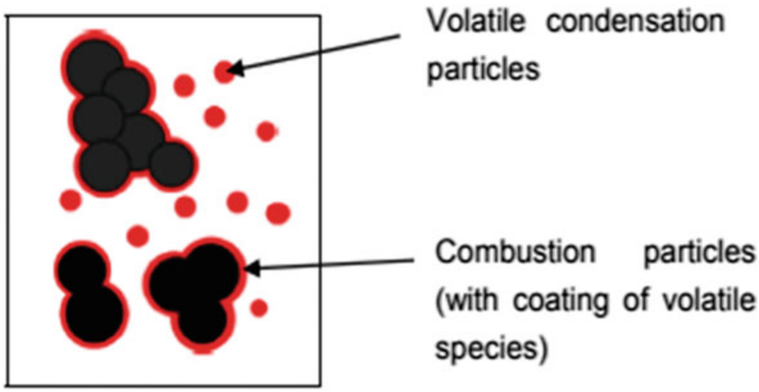

Fig. 6 Volatile particulate matter coating of soot [11]

Jet A-1 and 100% Fischer-Tropsch fuels were tested. The turbine was operated for full LTO (Landing and take-off) cycles for each blend of fuel.

The results of this these test show that PM emissions is reduced significantly when FAME blended fuels and FT fuels are used, as shown in the table below;

Table 2 presents the PM emissions reductions as a percentage when compared to standard Jet A-1, with 100% F-T fuel providing the greatest reduction in particulates matter, however all the alternative fuels tested had lower PM emissions number and size than Jet A-1, this can be attributed to the fact the fuels in this study has been chosen for their low aromatic content and high H/C ratios. Though it is to be noted

Table 2 PM mass and number reductions for alternative fuels with respect to Jet-A1 [18]

Alternative fuel	PM number reduction (%)	PM mass reduction (%)
20% FAME 80%jet-a1	22 ± 7	20 ± 8
40% FAME 60%JET-A1	35 ± 6	52 ± 5
50% F-T 50%JET-a1	34 ± 7	39 ± 7
100% F-T	52 ± 4	62 ± 4

that some the fuels tested by Lobo et al. [8] may not be suitable to be used as jet fuel. There are a substantial number of studies in literature which shows that the increase in aromatic content of a given fuel has a tendency to increase PM emissions in gas turbine exhausts. This effect has also been observed by Brem et al. [19] where an in-production high-bypass turbofan injected with fuel mixed with solvents which alter the aromatic content of the fuel, the results of which have been summarised in Fig. 2 [19].

From Fig. 7 it can be observed that as the aromatic content of the fuel increases the emission indices for nvPM also increases showing a clear causal relationship. Brem et al. [19] goes on to support the view that soot formation is the result of aromatic content in the fuel as opposed to incomplete combustion, as modern day turbines are highly efficient achieving 99.9% combustion efficiency [19]. Moreover a study conducted by DeWitt et al. [20] corroborates the fact that aromatic content of a fuel is proportional to PM emissions. The study measured the number of particles emitted and their size for JP-8 and F-T derived fuels and found that F-T derived fuels emitted particles that were a full order of magnitude smaller than those emitted whilst running JP-8.

Williams et al. [9] has described the effects alternative fuels have on vPM by measuring the organic matter concentrations in the exhaust duct of a Rolls-Royce Artouste Auxiliary Power Unit (APU) during tests conducted in 2009 [9]. During the course of this investigation several coal-to-liquid (CTL), gas-to-liquid (GTL), diesel and biodiesel fuels have been compared with the reference Jet A-1. It has been observed that the organic mass emitted by Jet A-1 is higher than that of the CTL and GTL blends used at the various power levels tested, this lends credence to the view that alternative fuels emit less vPM. Furthermore, the paper goes on to suggest that the vPM content in a given exhaust is sensitive to its measurement location as vPM is gaseous at first and condenses onto the nvPM particles downstream in the exhaust due to temperature drops. The resulting organic mass emissions results from the study are shown in Fig. 8.

In an another study conducted by Liati et al. [21] the size distributions of nvPM produced by a CFM-56 gas turbine with respect to engine power using electron microscopy was studied. It was found that at 100% engine static thrust the nvPM particles are larger and more numerous compared with 65% engine power. With lower engine settings, the amount of nvPM drops dramatically and also the mean size of the particles also drops, however these smaller particles are more oxidative and reactive with respect to larger particles. Reduction in PM emissions therefore

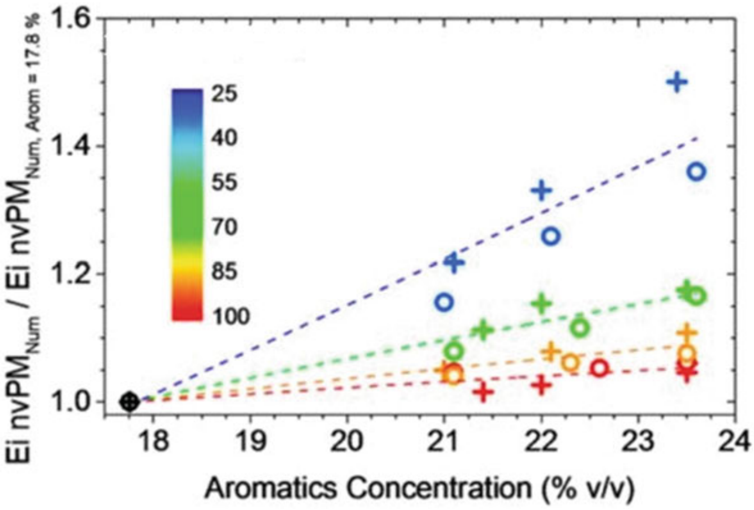

Fig. 7 Aromatic content of a fuel versus emission indices of the non-volatile particulate matter emitted upon the burning of the fuel in a gas turbine coloured lines indicate engine power setting as a percentage. [19]

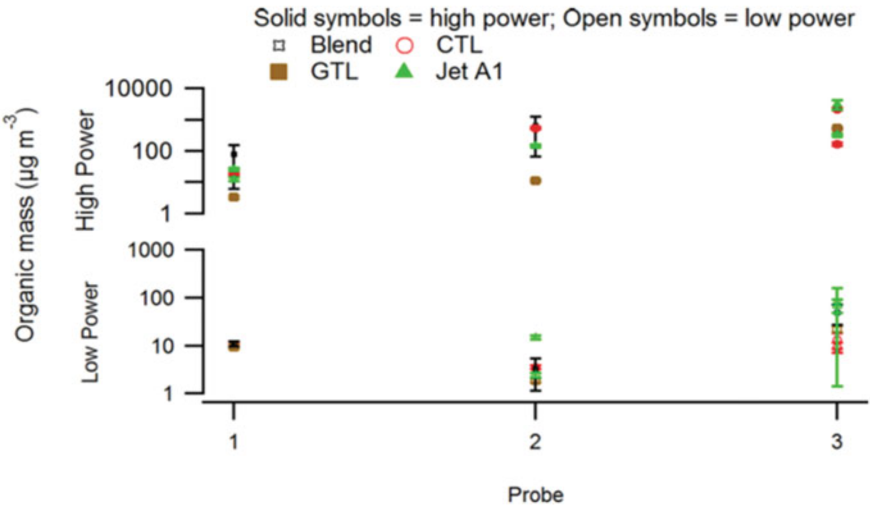

Fig. 8 Organic mass emitted by CTL, GTL and Jet-A1 against measurement locations and power settings [9]

can be achieved in several ways such as, combustor designs that limit the fuel rich areas in the combustion domain and reducing residence times of the fuel in very high temperature zones within the combustor [21].

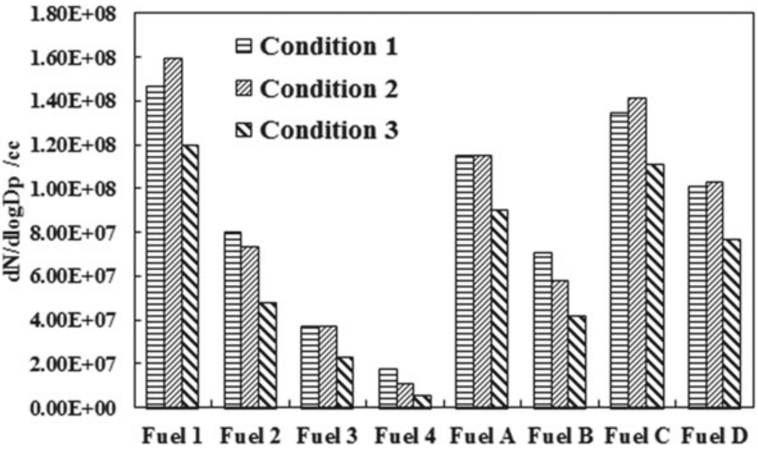

Fig. 9 Particulates measured for fuels at size of ~75 nm. Fuel 1 is Jet-A1 [4]

In another study under Continuous Lower Energy, Emissions and Noise (CLEEN) program at the University of Sheffield's Low Carbon Combustion Centre (LCCC), gaseous and PM emissions from gas turbines were measured for several alternative fuels and then compared to reference Jet-A1 where fuels 1-4 were blends of Jet-A1 and SPK (Synthetic Paraffinic Kerosene) and fuels A through D were potential alternative jet fuels. The turbine in used for the tests was a Honeywell GTCP85 APU [4]. Figure 9 shows the number of particles produced of size ~75 nm particulates for all the fuels tested in the study. Again, it can be observed that the fuels with lower aromatic content show reduced PM density has opposed to fuels with higher aromatic levels. Similar trends were attained for ~27 nm particulates, validating the pivotal role of aromatics in particulate emissions.

Dewitt et al. [20] studied various aromatic solvents, which are consistent with the molecular weight distribution shown by jet fuel used by military users (JP-8). These were then added to F-T fuels as blends and as individual components. The study observed an increased output of soot precursors which in turn indicated higher PM concentrations which was attributed to the increased PM emissions.

In conclusion it has been said from study of Dewitt et al. [20] that aromatic content of a fuel has a very strong impact upon the amount, and size distribution of particulate matter emitted from gas turbines. Furthermore, as the composition of alternative fuels such as those from the F-T process can be altered to reduce their aromatic content, they produce less particulate emissions.

4 Seals Compatibility

Although in the previous sections it has been determined that alternative fuels, on the whole, are beneficial to the aviation industry, as well as the environment, there remains the issue of whether these alternatives are compatible with existing fuel systems and infrastructure. Even though wholly alternative fuels have been approved for use in gas turbines, there exists a possibility of fuel leaks due to the varying composition of the alternative fuels. This happens because the seals in the engine are not compatible with the new fuels. One of the main reasons for the seals not to work is due the absence or reduction of aromatics in the new fuels. Low seal- swell or even seal-swell reduction has been attributed to the lack of Aromatic content in alternative fuels because of the increased particulate matter emissions [22]. The seals shrinking can cause seal failures thus damage in the fuel system and eventually leakages. On the other hand, aromatics are responsible for higher PM emissions.

In essence seal-swell is defined as the increase in volume experienced by a seal when in contact with a liquid and vice versa. This swelling normally means that the inner-diameter as well as the volume of the seal increases due to the absorption of fuel components such as aromatic content. Generally, naphthalene is considered a good hydrogen donor as opposed to alkanes or alkyl benzenes. DeWitt et al. [20] found that fuel component separation and assistance to seal-swell is in the following order:

alkanes < *alkyl benzenes* < *naphthalene's*

As observed by Thomas et al. [23] the swelling of the seal elastomers as a reaction against the fuel, moreover it has been determined by Qamar et al. [24] that seal swelling is caused by the seal absorbing hydrocarbons from the fuel. In the aviation field acceptable seal swell ranges from approximately 18–30% [25, 26] whereas in the automotive industry seal swell is at roughly 12%, this can be attributed to the fact that ground vehicles do not experience the same variation in ambient conditions as aircraft and hence require less seal-swell performance is required. When considered in greater detail it has been observed by Graham et al. [25] that several reaction takes place where intermolecular bonds of the fuel and polymer seal break and form new bonds with each other. Overall these reactions are in equilibrium and are energy balanced. On the contrary seal shrinking ensues in the event that particular molecules of the seals seep into the fuel causing the seal to reduce in volume, the lack of plasticizer in the seals can be a cause for seal shrinkage. This process is shown in the Fig. 10 Baltrus et al. [27] observed that the shrinking process involves the release of fuel components absorbed by the seals.

Figure 11 shows the effect on seal swell different aromatics has on nitrile seal using stress relaxation technique. It can be clearly observed from the figure that tetralin is giving significantly higher seal swell as compared to propyl benzene or P-xylene [22].

A study carried out by Liu and Wilson [28] a stress relaxation technique was utilised to observe the effects of several solvents including n-decane, iso-parrafins and cycloparaffins on seals composed of several materials.

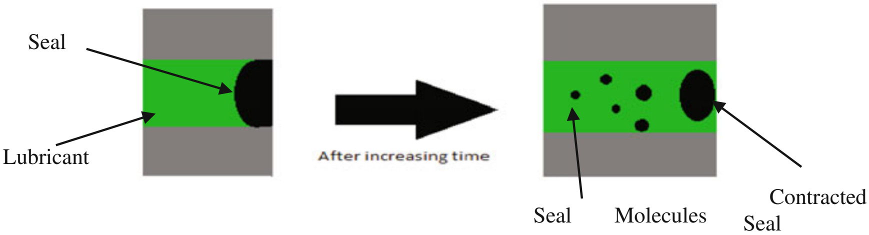

Fig. 10 Contracting process process of seal

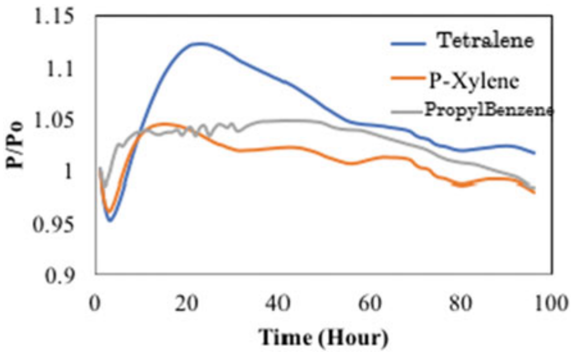

Fig. 11 Swelling effect of nitrile O-rings in mixture of 25% aromatic and SPK [22]

It was observed during this study that O-rings manufactured from fluorosilicone and fluorocarbons performed well in the presence of all the fuel blends tested. Furthermore, it has been found that nitrile O-rings are susceptible to substances other than aromatics and that n-decane causes seals to lose performance.

Figure 12 shows the amount of seal swell achieved while using different compositions of Decalin, Decane and Shellsol T. It can be clearly observed from the figure that there are compounds which leads to seal swell, while others may not take any part in swelling or lead of shrinkages. It is also found from the study that not just aromatics are responsible for swelling of seals. Similar patterns have also been observed by DeWitt et al. [20] and Graham et al. [29]. It was also found that several types of aromatics lead to different amount of seal swell. According to available literature, it can be comfortably said that further optimisation and research is required in alternative fuel industry so that appropriate seal swell can be achieved without compromising on other parameters.

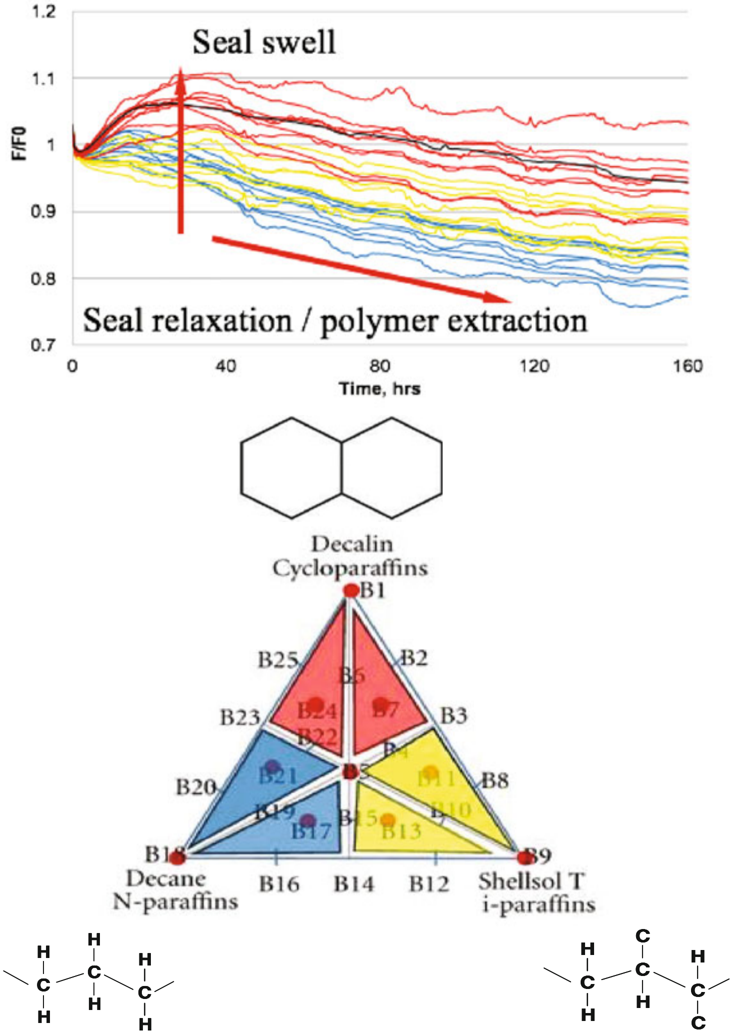

Fig. 12 Relaxation behaviour of nitrile O-rings in the triangle [28]

5 Thermal Stability

In this section, the ability of alternative fuels to withstand thermal stresses is discussed. Fuels must be able to withstand thermal stresses due to the customary practice in aircraft design of using fuel as heat sinks or coolants, moreover as the fuel approaches the engine and combustors through the fuel system its temperature begins to rise, and a range of chemical reactions begin to take place. These reactions may lead rise to particles in the fuel which may or may not be soluble [30, 31].

Particles such as these would have an obvious detrimental effect upon filters and valves in the fuel system which may lead to blockages and disruptions for fuel flow [32]. Increased pressure ratios in gas turbines of the 21st century pose several issues in terms of thermal stability, in that the higher-pressure ratios result in higher thermal loads on the lubrication system. This results in an increased heat sink demand [33]. The increased thermal efficiency of the turbine cycle caused by the increased pressure ratios result in decreased fuel flow rates which while ideal in when considering efficiency puts more strain upon the thermal characteristics of the fuel in that a lower volume of fuel must absorb more heat. This increased heat results in convection transfer into the mechanical components of the fuel system such as the swirlers and burner feed arms [33]. All these phenomenon results in the degradation of the fuel and may cause carbonaceous deposits to form in areas that encounter the fuel, much like atherosclerosis in human blood vessels. The causes for these deposits are multifactorial. Some of these causes are as follows; fuel composition, fuel temperature, duration of thermal exposure, flow characteristics, surface roughness of the fuel wetted areas [30].

In terms of alternative fuels, F-T derived fuels have been observed to perform well with respect to thermal stability whilst contributing far less PM emissions when compared to Jet-A1 [34–36]. When considering SPK fuels which have been derived from Syngas (H_2 CO) thermal stability is considered insignificant because of the reduced amount of impurities contained in syngas which has already been processed. Jet Fuel Thermal Oxidation Tester (JFTOT) is conventionally used to test the thermal stability of the fuels. Due to the JFTOT tubes being aluminium in construction the breakpoint temperature cannot be measured for fuels with high breakpoint temperature. In a recent study by Moses [37] different blends of semi-synthetic fuels were tested for their JFTOT breakpoint. It was observed that semi-synthetic jet fuel blends under study were having very high breakpoint, which indicates very high thermal stability. Moreover, when the depth at the conclusion of the test increased it was found that the tube temperature also increased. Which in turn enables the possibility of using SPK's to improve fuels which are on the verge of thermal stability.

In another study by Corporan et al. [38] thermal stability of 6 different paraffinic fuels was tested and compared with JP8. This shows that all the paraffinic fuels tested in the study have higher resistance to carbon formation and could be used in elevated temperature environment as a coolant. Figure 13 below shows headspace oxygen profiles and mass accumulation for all the fuels tested in the study. It can be observed from the figure that each fuel shows a different deposition and oxidation characteristic. It was also observed that oxidation profiles are very high in variance.

Alborzi et al. [33] investigated the effect of surface deposition on fuel injector feed arm which was simulated for sudden contraction and expansion. The study was conducted using an Aviation Fuels Thermal Stability Unit (AFTSTU), which can conduct a representative test at full scale 1000 flight hours for surface deposition, to determine how long it takes for surface deposition to start occurring and its associated performance impact upon the turbine. This is a different type of rig for testing ther-

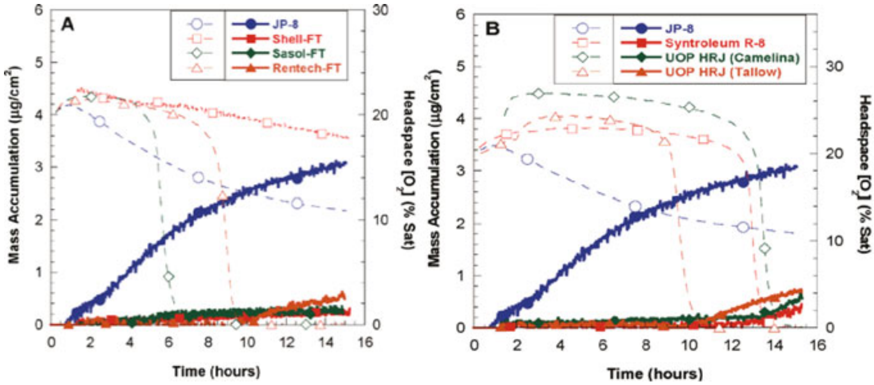

Fig. 13 Mass build-up (solid lines, closed markers) and head-space oxygen (dashed lines, open markers) profiles of alternative fuels. Corporan et al. [38]

mal stability of the fuels. It was observed that deposition in Contraction/expansion tube are significantly higher than straight tube. Balster et al. [39] presented thermal stability data for a novel coal derived fuel. It was observed that surface deposition for novel fuel was significantly lower than other fuels tested in the study which includes JP8. Overall it can be said that novel F-T process based fuels can give better thermal stability, though care needs to be taken while selecting and using these fuels due to other impacts they may have.

6 Combustion Vibration and Noise

In essence, combustion can be defined as a process where chemical energy is converted to heat energy in the company of oxygen [40]. During these reactions, the molecular bonds between the reactants are broken releasing energy, and bonds are formed to create the reaction products, the difference in energy between these reactions is dissipated into the surroundings, increasing the surrounding temperature. This rise in temperature is equivalent to the kinetic energy of the molecules in an object. Hence, according to the second law of thermodynamics these energies must reach equilibrium, generating noise and vibrations in the process. Noise is defined as the unwanted oscillation of air particles whilst vibration is the oscillation of solid material [41].

Combustion instabilities are significant amplitude oscillations that arise in gas turbine combustion. These give rise to thrust oscillations, thermal stresses, and more notably, resonant vibrations in mechanical components. Rayleigh's criterion is useful when understanding this phenomenon, as the namesake described the circumstances in which unsteady heat release oscillations result in acoustic oscillations, which in turn leads to fluctuations in the thermodynamic variables of the system [42, 43].

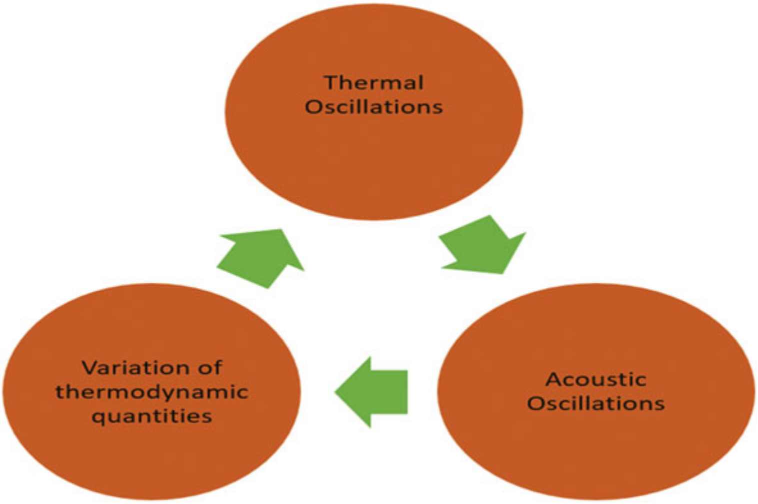

Fig. 14 Combustion instability feedback loop

Figure 14 is useful for visualizing how these factors compound together, thereby helping to rationalize the significant harms foreseeable, if ignored.

Due to the pressures and forces created by these oscillations there exist a possibility for the thrust produced by the turbine to oscillate, furthermore there can be possible interference of the engine control systems leading to malfunctions and premature wear of components due to cyclic fatigue [42]. In addition, if the vibrations caused matches the natural frequencies of the components being vibrated catastrophic failure could occur, however most aviation related components are tested for their natural frequencies and safe ranges of frequencies are specified for each component [44, 45]. Furthermore, if vibrations and instability is not handled correctly then damage to the combustors can happen as shown in Figs. 15 and 16.

The vibrations and noise frequencies generated by combustion are usually divided into 3 categories namely low frequency dynamics (LFD) or Helmholtz modes at less than 50 Hz, Intermediate frequency dynamics (IFD) at between 50 and 1000 Hz and finally high frequency dynamics (HFD) for vibrations above 1000 Hz (Fig. 17).

The extent to which vibration and noise manifest is partially dependent on the different properties of the fuel. Khandelwal et al. [46] investigated the role of different fuel composition and its impact on combustion vibrations [43]. Testing was done on a Honeywell GTCP85 APU using four different fuels. Fuel 1 and Fuel 2 are Jet A-1 sourced from two different sources, whereas fuel 3 and 4 are FT process produced fuel from different sources. It was observed that the FT process fuel which has lowest density from the fuels tested in this study produced higher frequency spectra of vibrations. Though highest amplitude of the vibration was produced by Jet A-1 from source 1. It is to be noted that Jet A-1 sourced from two different sources have similar frequency but significantly different vibrations (Fig. 18).

Fig. 15 Damaged Injectors [48]

Fig. 16 Damaged rocket motor injector shear [48]

Furthermore, the relationship between fuel density and vibration is more explicitly considered in the work done by How et al. [46], where a higher density, coconut oil blend, biodiesel was compared with conventional diesel [46]. In this study, the higher density fuel blend displayed a significant reduction in vibrational acceleration.

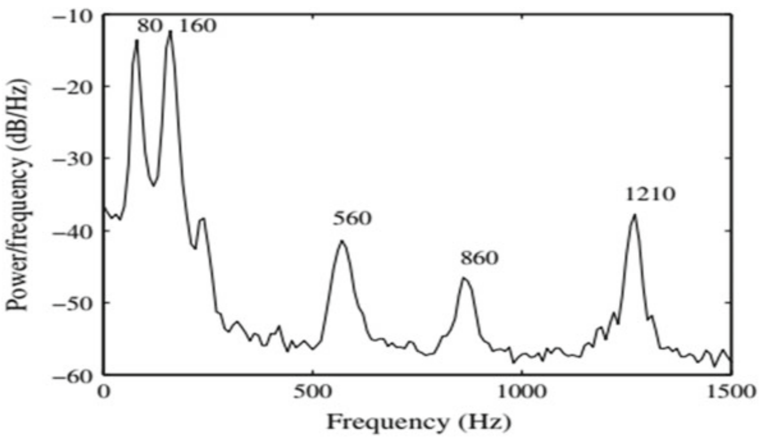

Fig. 17 Instabilities for combustors according to their frequency range [49]

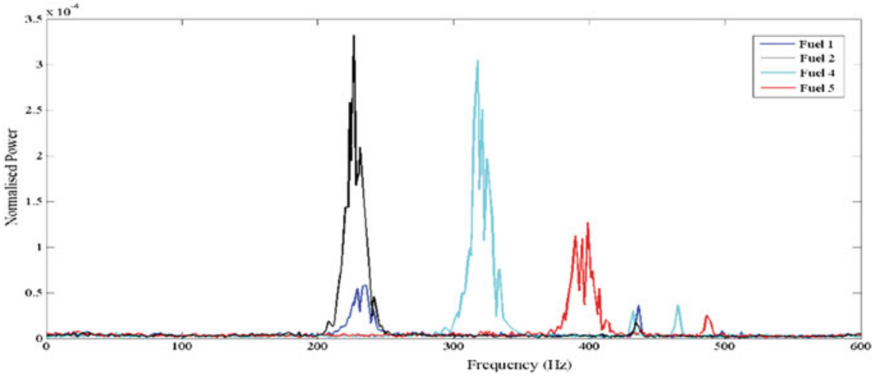

Fig. 18 Vibration amplitude and frequency with 4 different fuels [46]

Overall it is observed that there has been little research on the combustion instability, noise and variations caused by combustion induced vibration with alternative fuels. This pattern is reflected across all of the major public domain journals under current situations. Stricter emissions legislations demand the use of lean premixed combustion, but combustion instability is more likely in these types of lean combustors compared to current rich burn systems. It was observed that the instabilities may be due to oscillations in pressure, velocity, temperature or equivalence ratio of fuel. Among these variables, Rayleigh's criterion was made to be one of the primary conditions to be met for a self-excited combustion oscillation to occur. Equivalence ratio oscillations are a possible cause of combustion instabilities.

The underlying reason for change in combustion instability could be due to change in fuel's boiling point, viscosity, vapour pressure, flame speed, stoichiometric equivalence ratio, cetane rating, density, energy density and/or composition. So far, these

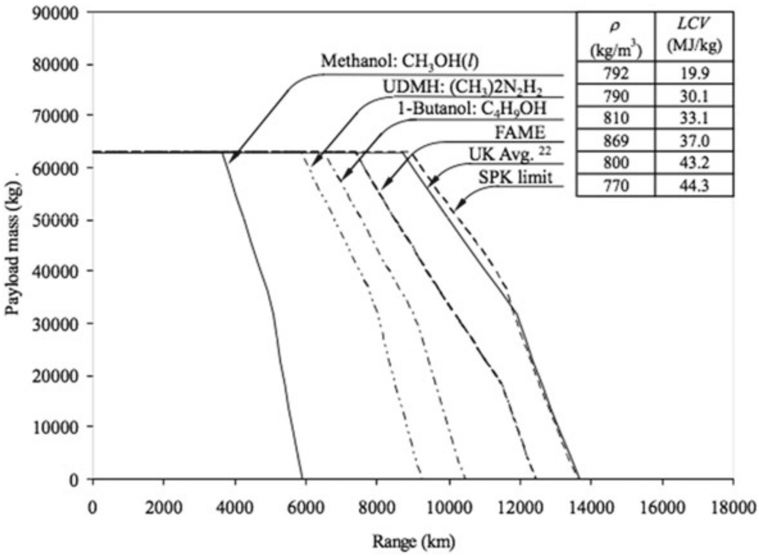

Fig. 19 Range versus Payload for B747-200B using alternative fuels [47]

instabilities are suppressed in existing engines by using Helmholtz resonators, Active combustion Control (ACC), noise suppressers, controlling the droplet size, changing the flame speed and length and varying the flame injector geometry and location. But with the arrival of new alternatives, if the instabilities can be understood better and designed out by fuel selection and combustion design optimisation.

7 Aircraft Range and Payload

Due to different properties of alternative fuels, not just emissions and engine performance change, but aircraft range can also change significantly. Blakey et al. [47] studied the effects on payload and range while using wide range of candidate fuels for aviation. This also includes variations in the blends of conventional hydrocarbon fuels. Short haul commercial flights tend to use low density fuels as range per volume of fuel is not relevant as for long haul or military aviation where the maximum range is required for a given volume of fuel. Figure 15 below shows the changes to range of a Boeing 747-200B can have while using a range of different fuels investigated under study (Fig. 19).

It was also observed that hydrocarbon blends could be suggested for each aircraft type, which could be designed for a maximum range while allowing maximum payload. It was also said that specific flight plans lower than the maximum range of the aircraft may be supplied with a fuel of lower specific energy.

8 Concluding Remarks

In this chapter, the effects of alternative fuels on the gas turbines performance and their emissions have been discussed. It has been found that alternative fuels provide no clear advantage in terms of emissions reduction compared to standard petroleum derived fuels though benefits in PM have been observed. Effect on seal performance, vibrations, noise and engine life still needs further work. Impact on range of an aircraft can be easily calculated by change in energy density. Overall further work is required to say which option is good and how to move ahead in this area.

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