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An Experimental Comparison of the Emissions Characteristics of Standard Jet A-1 and Synthetic Fuels

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Abstract Emissions characteristics of lean, turbulent, partially premixed swirled flames of synthetic fuels along with a standard Jet A-1 fuel are studied. The investigated synthetic fuels are (a) Fully synthetic jet fuel (FSJF), (b) Fischer Tropsch synthetic paraffinic kerosene (FT-SPK), (c) FT-SPK+20 % hexanol, and (d) FT-SPK+50 % naphthenic cut. The measurements are performed in a tubular combustor equipped with a burner based on the principle of air-blast atomization. The exhaust gas compositions are measured using a non-dispersive infrared gas analyzer for carbon dioxide (CO_2) and carbon monoxide (CO), a flame ionization detector for unburned hydrocarbons (UHC), and a chemical luminescence detector for nitric oxides (NO and NO_2). The emissions indices (EI) of CO and NO_X of the investigated fuels are calculated using guidelines provided by the Society of Automotive Engineers (SAE). Measurements are performed at several combustor pressure levels, i.e., 0.3, 0.54 and 0.8 MPa, to compare the emissions behavior of the investigated fuels at varied operating conditions. At 0.3 MPa of combustor pressure, the order of fuels with their increasing formation of NO_X are FSJF, FT-SPK+20 % hexanol, Jet A-1, FT-SPK+50 % naphthenic cut and neat FT-SPK. Differences in the observed NO_X formation behavior of the investigated fuels are attributed to their probable different degrees of mixing with air in the combustor. At 0.8 MPa, no significant differences in their emissions characteristics are observed due to very low absolute values; hence we report that at higher pressure conditions which prevail in the aero-engine combustion systems, the emissions characteristics of tested synthetic fuels are very close to that of standard Jet A-1 fuel.

Keywords Emissions · Air-blast atomization · Synthetic fuels · Gas turbine combustion

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1 Introduction

Today, the ever-increasing demand for and cost of crude oil required for the production of aviation fuel motivates researchers to develop synthetic fuels based on biomass, coal and other possible resources. The consistent policy issues with oil producing nations have forced industrialized and developing countries to explore their own resources for fuel and energy. In the EU, many projects such as SWAFEA (Sustainable Way for Alternative Fuels and Energy for Aviation), AlfaBird (Alternative Fuels and Biofuels for Aircraft Development) and ECATS (Environmentally Compatible Air Transport System), etc. have been initiated, involving the collaboration of industries, research labs and academia [1–4]. The major challenge with the new fuels is that they need to be compatible with the existing methods of fuel production, blending, transportation, delivery onto aircraft and consumption. Otherwise, proposing any significant change in the characteristics of aviation fuel asks for altogether new regulatory procedures and infrastructure starting from production, transport, storage and the consumption units. The expense of this makes the option too difficult to implement in a running system.

Any synthetic fuel capable of being used with the existent infrastructure that the standard Jet A-1 currently uses, is termed as a `"drop in"` fuel. The `"drop in"` synthetic fuels must possess similar characteristics to those of current jet fuels. Specifically, they must be similar enough that they can be used without any changes to the delivery processes from place of manufacture to the aircraft tanks, and then not require any on-board operations or equipment to be altered. They must be approved via the ASTM D4054 process into the ASTM D7566 standard, from where, once in the distribution system, they are technically equivalent to international specifications such as ASTM D1655 (mainly applied to Jet A in USA) or DEF STAN 91-91 for Jet A-1. In 2008, SASOL got the approval via DEF STAN 91-91 for a fully synthetic jet fuel (FSJF), which is a material blended from light distillate, heavy naphtha and iso-paraffinic kerosene streams [5]. Royal Dutch Shell, also using the Fischer Tropsch process, produced an aviation fuel component from natural gas, which fits the approved class of jet fuel components known as Fischer Tropsch synthetic paraffinic kerosene (FT-SPK) [6].

In the first stage of the AlfaBird project, a reference fuel, base fuel and about 12 blends of candidate synthetic components were tested and the most interesting four fuels were taken forward for larger scale testing. These four fuels were FT-SPK, FT-SPK+20 % hexanol, FT-SPK+50 % naphthenic cut and FSJF (fully synthetic jet fuel). These four fuels were analyzed in detail by Pidol et al. [7] for their physical and chemical characteristics. They concluded that the neat FT-SPK does not meet the final Jet A/Jet A-1 aspects of ASTM D7566 standard due to its low density and low aromatic content; it does, however, meet the criteria for a blending component. Therefore to enhance the properties of FT-SPK, 20 % hexanol and 50 % naphthenic cut were separately added in it. Within a work package named ‘Towards real conditions’ in Alfabird project, Karlsruhe Institute of Technology (KIT) in Germany was responsible for evaluating the emissions related performance of a burner based on air-blast atomization running with these synthetic fuels under varied combustor conditions. The fuels used in this work were procured and blended by Institut Français du Pétrole (IFP). This paper reports the emissions related performances of the following synthetic fuels burned under highly turbulent conditions (Reynolds number >20,000):

1. FSJF, fully synthetic jet fuel.
2. FT-SPK, which mainly consists of paraffins. Naphthenes and aromatics are present in very small quantities.

3. Blend of 20 % 1-hexanol and 80 % FT-SPK by volume.
4. Blend of 50 % naphthenic cut and 50 % FT-SPK by volume. The naphthenic cut mainly consists of naphthenes (also called cycloparaffins or cycloalkanes); whereas paraffin (iso and normal) and aromatics together constitute up to maximum of 10 % by volume.

For detailed information about the reasoning behind the selection of these fuels and their blends, reader is referred to a recently published article by Braun-Unkhoff et al. [8], in which authors have also reported the burning velocities of these fuels. Zabeti [9], involved in the AlfaBird project, measured the gaseous species at the centreline of laminar co-flow diffusion flames of these fuels. No differences in CO concentrations were observed for the tested fuels; however, FSJF had the highest CO_2 concentration and FT-SPK+20 % hexanol had the lowest among all tested fuels. Thomson et al. [10] compared the sooting behavior of laminar co-flow diffusion flames of above mentioned synthetic fuels with Jet A-1. The highest soot concentration was observed for the Jet A-1 whereas the FT-SPK+20 % hexanol blend had the lowest. Using a jet stirred reactor, Dagaut et al. [11] have studied the oxidation kinetics of a reformulated jet fuel. Their results imply that switching from jet A-1 to the reformulated jet fuel will marginally modify the kinetics of oxidation and the formation of unburned species, besides hexanol. D' Herbigny et al. [12] measured evaporation behaviors of these fuels using an InfraRed Extinction method (IRE) at combustor pressure and temperature of 0.3 MPa and 553 K, respectively.

Prior to the AlfaBird project, some earlier independent studies were performed involving FSJF and Fischer Tropsch (FT) fuels and their comparisons to the existing Jet fuel were made. In 2009, Moses and Roets [13] reported that the FSJF emits lower CO levels than standard Jet A-1 fuel. Such observed behavior was attributed to the lower viscosity of the FSJF fuel. Dewitt et al. [14] have evaluated the effect of aromatic molecular weight on emissions performance of a FT fuel. In their work, it was concluded that CO and UHC emissions increased significantly with increasing concentrations of aromatic compounds in the fuel. Corporan et al. [15] evaluated emissions performances of FT fuel, JP-8 fuel (a petroleum based commercial Jet A-1 fuel with some additional enhanced properties suitable for military applications) and blends of these two fuels in a turbine engine and in a research combustor. In both combustion systems, no significant changes were observed in the CO, CO_2 and NO_X formations due to addition of the FT fuel in the JP-8 fuel. Bulzan et al. [16] examined the effect of addition of FT fuels on gaseous emissions and particulate matter emissions of the JP-8 fuel. A slight reduction in CO formation was observed in their measurements with addition of FT fuels at low power conditions. IATA [17] provided important information about the detailed emissions performances of different types of synthetic fuels. In its report, the effects of blending of Bio-SPK on the emissions performance of Jet A fuel have been discussed. Wilson et al. [18] have written an excellent review about the emissions performances of different types of aviation alternative fuels. The two of their many important conclusions of their review are, a) understanding the effect of paraffins and aromatics in a fuel on its combustion performance. b) to pay special attention to the emission characteristics of any new proposed alternative fuel under varied operating conditions. For better readability, Table 1 summarizes the aforementioned information about the available data about synthetic fuels in order of the year of their publication.

Because of so many diverse opinions and contradictory statements regarding the emissions formation behavior of new synthetic fuels / FT fuels, it can be concluded that the emissions behavior of a fuel under investigation is strongly dependent on the testing conditions. Hence; it is always important to evaluate the impact of combustor operating conditions on emissions behavior of these fuels and preferably near to those operating conditions that

Table 1 Literature summary in order of the year of their publication

Author(s)	Fuel tested	Measured parameter	Year
Corporan et al. [15]	FT fuel and JP-8	CO, SO_2, CO_2 and NO_X	2007
Dewit et al. [14]	FT fuel along with aromatics as blending material	PM, Soot, NO_X, CO, CO_2 and UHC	2008
Pidol et al. [7]	FT-SPK, FSJF, FT-SPK+20 % hexanol and FT-SPK+50 % naphthenic cut	Physical and chemical properties	2008
IATA report [17]	FSJF, FT-SPK, Hydrotreated Renewable Jet fuel (HRJ), Hydrodeoxygenated Oil (HDO), Bio-SPK, Jet A-1, etc.	UHC, CO, CO_2 and smoke	2009
Moses and Roets [13]	Jet A-1 and FSJF	Viscosity, density, specific heat, bulk modulus, SMD, CO, Smoke number, boiling points, extinction limits and ignition characteristics	2009
Bulzan et al. [17]	FT fuel and JP-8	NO_X, UHC, SO_2, CO and black carbon mass	2010
Zabeti P. [9]	Jet A-1, FT-SPK, FSJF and FT-SPK+20 % hexanol,	CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and C_3H_6	2010
D' Herbigny et al. [12]	FT-SPK, FSJF, FT-SPK+20 % hexanol and FT-SPK+50 % naphthenic cut	Evaporation behavior	2011
Thomson et al. [10]	Jet A-1, FT-SPK, FSJF, FT-SPK+20 % hexanol and FT-SPK+50 % naphthenic cut	Soot	2011
Wilson et al. [18]	A review paper, hence covered many alternative fuels	–	2011
Braun Un-khoff et al. [8]	FT-SPK, FSJF, FT-SPK+20 % hexanol and FT-SPK+50 % naphthenic cut	Burning velocity	2012
Dagaut et al. [11]	Jet A-1 and Jet A-1/1-hexanol	Oxidation kinetics	2012

actually prevail in an aero-engine combustion system. In this work, an attempt has been made to evaluate the emissions performances of the fuels at several combustor operating conditions.

2 Experimental Setup

The experiments were performed at the Pressurized EXhaust gas (PEX) rig located at the Engler Bunte Institute, KIT (Karlsuhe Institute of Technology). Figure 1 shows the ceramic combustor, the burner, the gas probe and other important components. A thick ceramic cylinder made of compound alumina (Al_2O_3) was used as the combustor. Choosing a ceramic combustor reduced the heat losses to the surroundings and resulted in near adiabatic conditions inside the combustor. Ignition was performed by an electric spark generator, which was withdrawn from the combustor after establishment of a stable flame in the combustor. A regulating valve (not shown) was used to control the pressure inside the combustor. The exhaust gases produced in the combustor exited through a cylindrical cooling tower equipped with water spraying nozzles to cool the hot gases. To visually inspect the presence of a flame during the ignition and measurements, a glass window of 0.02 m diameter was used. The measurements of air and fuel flowrates were done with Krohne OPTISWRIL 4070 and Krohne OPTIMASS 3300c, respectively. The uncertainty associated with the calculation of equivalence ratio based on these flowrates is around 0.14 %. The combustor pressure was measured by using a Keller pressure transducer (PR 33X) with an accuracy of 0.1 % of full scale. The measurement of pressure drop across the burner was done with Halstrup-Walcher differential pressure transmitter (P82R) with an accuracy of

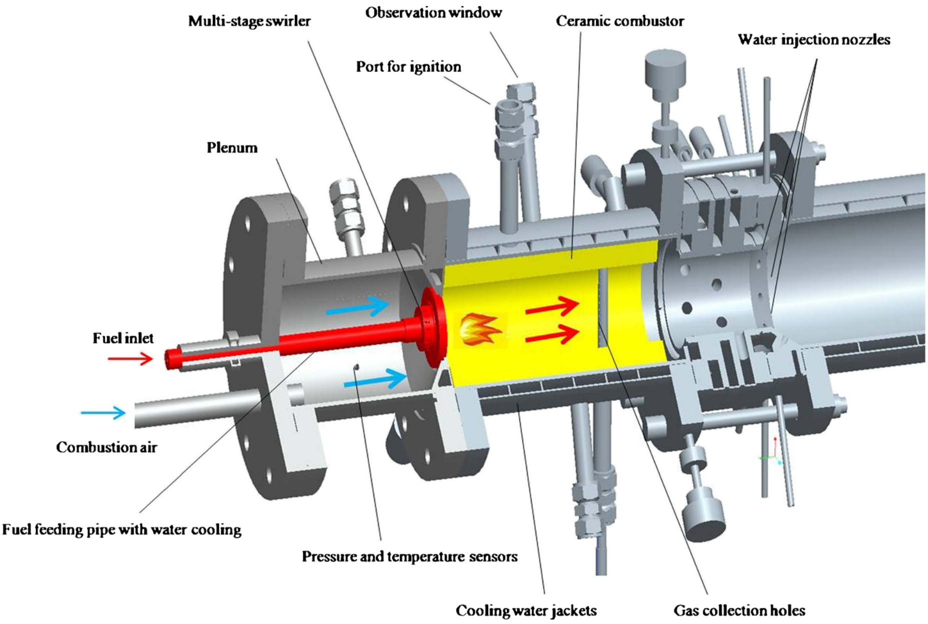

Fig. 1 A cut view of 3D computer aided drawing of the pressurized exhaust gas rig

1 % of full scale. For other details about the PEX rig, the reader is referred to our previous publication [19].

The burner used in the present work is a product of the AVIO low NO_X PERM (Partial Evaporation Rapid Mixing) technology [20]. Figure 2 shows a line sketch of the burner, which consists of two radial swirl generators (primary and secondary) and a pressure fuel atomizer. At low pressure conditions, $p_c \leq 0.3$ MPa, only pressure atomizer is active. For high power conditions, the principle of air-blast atomization is used to operate the burner. In air-blast atomization, a liquid fuel film is formed at the inner wall of the burner (shown with red colored dotted arrows in Fig. 2). This fuel film is shear driven by the air flow to the atomization lip where it first disintegrates into ligaments and then into droplets. The fuel droplets are further subjected to shear forces between the primary and secondary air flows. Generally air-blast atomizers have many advantages over pressure atomizers [21], especially in high pressure combustion systems. They require lower pumping pressures in the fuel line and also produce a homogenous spray. Thorough mixing of air and fuel is achieved, ensuing a low flame radiation with lower emissions formation. Because of relatively larger fuel passage in air-blast atomizers, the clogging of fuel passage is also some avoided due to undesired fuel coking process.

3 Temperature Measurements

A K-type thermocouple (Nickel+Chromium) with a bead diameter of 0.001 m was positioned in the plenum to measure inlet temperature of combustion air. Four S-type thermocouples (Platinum +10 % Rhodium) were positioned circumstantially in the combustor to measure the temperature inside the combustor. The bead of S-type thermocouple was

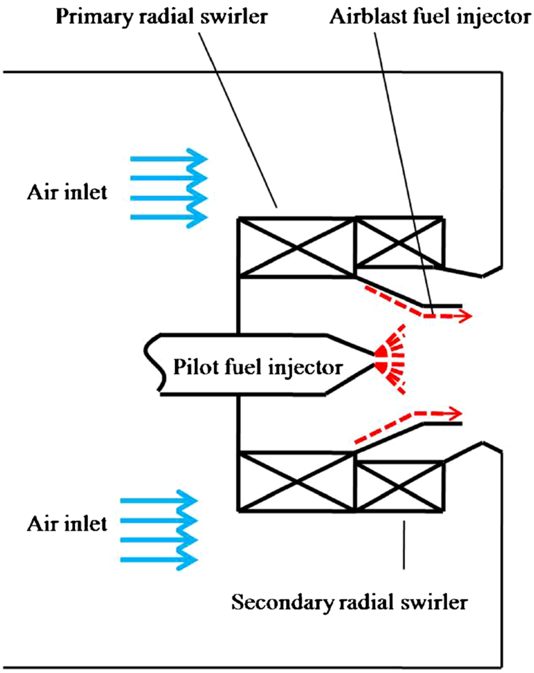

Fig. 2 Schematic layout of PERM burner used in the present measurements

uncoated and had a diameter of 300 μm. A mean temperature calculated from these four measured temperatures has been used in the present work to compare emissions performances of the candidate fuels at varied operating conditions. The uncertainties associated with the S-type thermocouple and K-type thermocouple are 0.25 % and 0.75 %, respectively.

4 Measurements of Gaseous Species

Exhaust gas samples were collected using an oil cooled suction probe, which was placed at a distance of $x/D_0 = 4.2$ away from burner exit (Fig. 1) where x is the axial distance from the burner exit in the combustor and D_0 is the combustor diameter. In a gas sampling process, the fundamental problem is to obtain a gas sample, representative of the actual composition of the mixture at the sampling point, and then to quench it to avoid any reaction occurring inside the probe. The suction probe was maintained at a temperature of 433 K to quench the reactions after the gas sample entered into the probe. The collected gas sample flowed to the exhaust gas analyzers through electrically heated hoses to avoid any condensation of water during the passage of gas through the sampling probe. Unlike many other measurements reported in the literature, the sample lines used in the present work were undiluted and had multi-collection ports spread over the full diameter of the combustor. The material used to make the sample lines was chosen to be stainless steel. Any sharp bends were avoided in the gas sampling line. During sampling process, the difference between the velocity of the gas sample that enters the probe and the stream velocity at the sampling point plays an important role. In the presence of large fluctuations in density of the mixture, the lighter constituent is preferentially drawn in provided the sample probe entry velocity is higher as compared to stream velocity, whereas in the case of stream velocity higher than the sample probe entry velocity, the heavier component is preferentially drawn in. The optimum situation is to have the sample probe velocity higher than the stream velocity at the sampling point, therefore in the present experiments, the sample probe velocity was always maintained higher than the stream velocity.

To measure the mole fractions of CO, O_2, CO_2 and NO_X in the exhaust gas sample, water was removed from the gas sample with the help of a drier and then the gas sample was fed to the measurement devices. CO_2 and CO were detected with a continuous non-dispersive infrared (NDIR) gas photometer (ABB, URAS 26) having CO measurement range of 0–2500 ppm and CO_2 measurement range of 0–15 %. NO_X were detected with a chemical luminescence detector (Eco Physics, CLD 700 EL ht) with a measurement range of 0–1000 ppm. It is a known fact that the humidity of air affects the NO_X formation due to the ability of water vapor to absorb heat and consequently to lower the flame temperature and thermal NO_X formation. Therefore, the humidity levels in the compressed air were controlled by using an absorption dryer. The dryer delivered compressed air at a constant temperature with a fixed dew point, hence the relative humidity of the compressed air was maintained the same throughout all experiments performed in the present work. Using a wet exhaust gas sample (without removal of water), the UHC was detected with a flame ionization detector (FID) analyzer (ABB, AO2000 MultiFID14) with a measurement range of 0–2000 ppm. To ensure proper functioning of the instruments, they were calibrated with the reference gases of known composition before and after the measurements.

Concentrations of CO and NO_X produced by the investigated fuels are compared in terms of the emissions indices. EI_q unambiguously expresses the ratio of mass of pollutant (q) formed to the mass of fuel burned. The unit of g gas/kg fuel is used to avoid usage of small numbers. Calculations of emissions indices have been done by following the guidelines provided by the Society of Automotive Engineers (SAE) [22]. Equations 1 and 2 have been used for the calculations of emissions indices. The overall uncertainties associated with the calculation of the Emission Index of CO and NO_X in the present work are 2 % and 2.2 %, respectively. The uncertainties values have been displayed in the form of error bars in the figures. To avoid redundancy error bar are shown only in some figures, though.

$$EI_{\mathrm{CO}} = \frac{[CO]}{[CO]+[CO_2]+[C_{\mathrm{m}}H_{\mathrm{n}}]} * \frac{M_{\mathrm{CO}}}{M_{\mathrm{C}}+\alpha * M_{\mathrm{H}}} * \left[1+F\left(\frac{X}{m}\right)\right] \tag{1}$$

$$EI_{\mathrm{NO_X}} = \frac{[NO_{\mathrm{X}}]}{[CO]+[CO_2]+[C_{\mathrm{m}}H_{\mathrm{n}}]} * \frac{M_{\mathrm{NO_2}}}{M_{\mathrm{C}}+\alpha * M_{\mathrm{H}}} * \left[1+F\left(\frac{X}{m}\right)\right] \tag{2}$$

where [q] is the measured concentration of constituent q, M_q is the molar mass of the constituent q, symbol X is the ratio of the moles of the air to the moles of the fuel, m and n are the number of moles of carbon and hydrogen present in the fuel, respectively i.e., C_mH_n. Symbol F is a function of mole fraction of CO_2 and humidity present in the inlet air and α is the molar hydrogen to carbon ratio (n/m) present in the fuel.

5 Validation of the Experimental Setup

Validation of the adopted methodology and the measurement technique used must be the foremost step in any research activity. In the present work, it is achieved by performing a mass balance of the reactants and the products, which is simply a comparison of calculated equivalence ratios Φ_{cal} from the composition of the exhaust gases with Φ_{meas}, the equivalence ratios obtained from the measured mass flow rates of the fuel and the air. The comparison shown in Fig. 3 indicates an excellent concordance between both parameters and thus it ensured the proper functioning of the used instrumentation and confirmed the accuracy of the results reported in this work.

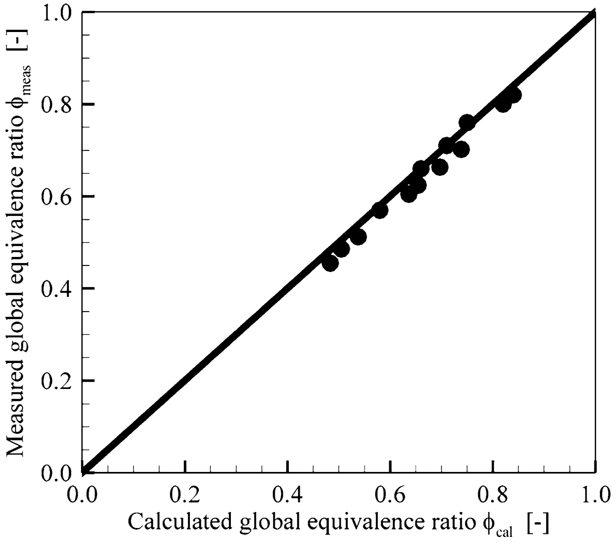

Fig. 3 Validation of the present measurements for Jet A-1

6 Operating Conditions

Table 2 shows the operating conditions used in the present work to perform the measurements. During the measurements, the air pressure drop across the burner was kept constant so that the combustion air passing through the burner would have nearly the same residence time, which is one of the important characteristics of an aero-engine combustion system. The performed measurements were limited to lean regime only. The inlet temperature of the combustion air was kept constant at 578 K. Three combustor pressures levels (0.3, 0.54 and 0.8 MPa) were used to evaluate the emissions behavior of these fuels. Already available emission data at these combustor pressure levels was the reason for the selection of these combustor pressure levels. Available emission data was obtained with the same burner operating with Jet A-1 from earlier performed measurements during the NEWAC (NEW Aero Engine Core concepts) project [23]. It also helped in cross-checking and ensuring the repeatability of the results obtained in the present work.

7 Results and Discussion

Variation in the measured combustor temperature profiles with changes in the equivalence ratios for all investigated fuels is shown in Fig. 4. It is worthwhile to mention here again that T_c is a mean temperature calculated from four thermocouples placed circumstantially in the combustor. The measurements performed in this work were limited to a maximum temperature value of 1950 K (due to the upper measurement limit of the S-type thermocouples) while the minimum temperature value was constrained by the occurrence of lean extinction limits. Assuming equilibrium conditions, the theoretical adiabatic flame temperatures at different equivalence ratios for Jet A-1 were calculated with a commercial software EQUIL [24] whereas for synthetic fuels, the adiabatic flame temperature values were provided by DLR (project partner in AlfaBird project). It is noticed in Fig. 4 that the adiabatic temperature values of the investigated fuels (symbol T_{ad}) overlap with each other. Due to nearly similar values of net heat of combustion of all fuels (Table 3), it is expected that at the same equivalence ratio and the same inlet condition of reactants, the combustion of all investigated fuels should result in the nearly similar combustor temperature. However, the experimental results suggest otherwise. The measurements reveal that by keeping the same combustor operating conditions and by just changing the fuel, significant deviation occurs in the measured combustor temperature profiles. Due to the observed lower extinction limit of FT-SPK at 0.3 MPa, the measurement of neat FT-SPK was limited to a narrower range of equivalence ratios as compared to other tested fuels; the reasoning for such observed behavior is discussed later in the document. The differences between measured values and theoretical adiabatic temperature values is due to the thermocouples being positioned far

Table 2 Operating conditions used in the present work

Parameter	Value
Equivalence ratio [−]	0.5–0.85
Inlet air temperature [K]	578
Air pressure drop across the burner [%]	3.5
Combustor pressure [MPa]	0.3, 0.54, 0.8

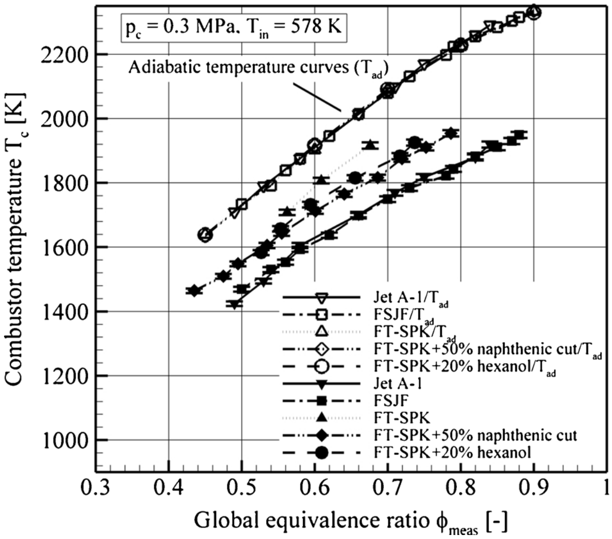

Fig. 4 Comparison of the measured combustor temperatures with adiabatic temperatures for all investigated fuels at combustor pressure level of 0.3 MPa

away from the main reaction zone in the combustor (Fig. 1). The deviations in the measured temperature values of FT-SPK from calculated equilibrium temperature values are the smallest, while Jet A-1 and the blend of FT-SPK+50 % naphthenic cut have the largest deviations. Thomson et al. [10] also have reported significant differences in the measured flame temperatures of these fuels. Despite the ranges of equivalence ratios studied in the present work were limited to the lean regime for all the fuels, the mixture of fuel droplets and air ahead of the combustion process was mostly partially premixed. Such partially premixing of fuel droplets with air generally results in the localized stoichiometric rich zones in combustor and consequently soot formation occurs. Different sooting tendencies of the different fuels can be mainly due to their different atomization behaviors. If a fuel does not get good atomized and results in a bigger Sauter mean diameter (SMD) than another fuel than it will have higher tendency to form soot. The soot formation during the experiments was not measured; hence the argument related to the different sooting tendencies of fuels is justified in the following few paragraphs by discussing an observed relation between the predicted atomization characteristics of investigated fuels with their thermo-physical properties.

It is a well known fact that the burners with air-blast atomizers are relatively more sensitive to the properties of the liquid fuel compared to commonly used pressure atomizers and

Table 3 The thermo-physical properties of the investigated fuels [7, 26]

Fuel	ΔH [MJ/kg]	ρ [kg/m^3]	η [m^2/s] * 10^{-6}	σ [m^2/s]
Jet A-1	42.8	800.0	5.5	0.025
FSJF	43.18	815.7	5.4	0.027
FT-SPK	44.06	737.7	2.6	0.024
FT-SPK+50 % naphthenic cut	43.41	800.3	5.8	0.027
FT-SPK+ 20 % hexanol	42.05	754.2	3.6	0.026

any small difference in fuel properties may lead to significant differences in their atomization characteristics. For a pre-filming type of air-blast atomizer, El-Shanawany and Lefebvre [25] had proposed a correlation (3) to predict the SMD of liquid fuel droplets from its thermo-physical properties and inlet conditions of the air and fuel.

$$\frac{SMD}{d_0}=\left(1+\frac{1}{ALR}\right)\left(0.33\left(\frac{\sigma_{\mathrm{L}}}{\rho_{\mathrm{A}}\cdot U_{\mathrm{A}}\cdot{}^2\cdot d_{\mathrm{p}}}\right)^{0.6}\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{A}}}\right)^{0.1}+0.068\left(\frac{\mu_{\mathrm{L}}{}^2}{\rho_{\mathrm{L}}\cdot d_{\mathrm{p}}\cdot\sigma_{\mathrm{L}}}\right)^{0.5}\right) \tag{3}$$

where d_p and d_0 are the characteristics dimensions of the burner used and the subscripts L and A refer to the properties of liquid fuel and air, respectively.

Using the thermo-physical properties of the fuels listed in Table 3, the SMD values at the investigated operating pressures and at the temperature of 300 K have been predicted. The relative changes in the SMD values of tested fuels with respect to Jet A-1 are shown in Fig. 5. FT-SPK has the smallest SMD and Jet A-1 has the largest SMD among the tested fuels. D' Herbigny et al. [12] measured evaporation behaviors of these fuels using an InfraRed Extinction method (IRE) at combustor pressure and temperature of 0.3 MPa and 553 K, respectively. They reported that the evaporation behaviors of all investigated fuels are identical under these operating conditions. This means that, at identical combustor operating conditions, with better atomization of FT-SPK fuel and similar evaporation behavior, a more homogenous mixture existed in the combustor for FT-SPK as compared to all other fuels. This supports the hypothesis that the combustor temperatures are higher for FT-SPK because of its probable lower production of soot compared to the other investigated fuels. This trend is also visible in the case of FT-SPK+20 % hexanol and FT-SPK+50 % naphthenic cut, where calculated SMD of both these fuels are higher than that of neat FT-SPK but both possessed lower measured flame temperatures than FT-SPK. It is reasonable to conclude here that all investigated fuels tend to indicate a link between their atomization qualities and the measured combustor temperatures, that is, a better atomization of fuel should result into good mixing of fuel with air, hence reduced localized rich stoichiometric

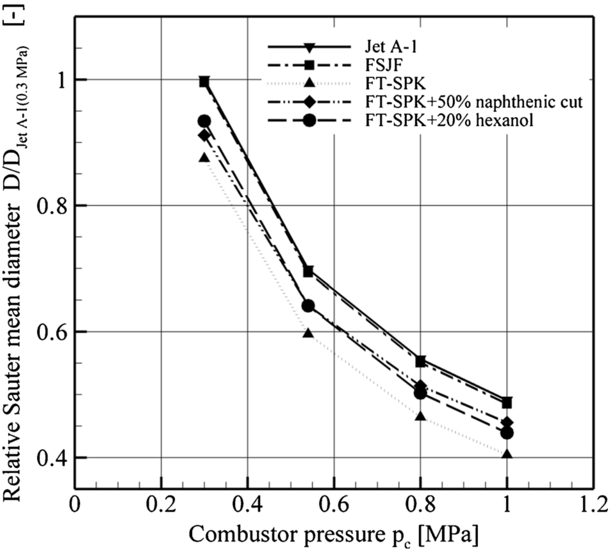

Fig. 5 Comparison of the predicted SMD of the investigated fuels at different pressure levels

regions and lower soot formation and consequently higher combustor temperature during its combustion.

8 Measurement of CO concentration

Figure 6 shows the variation in the measured volumetric fractions of the CO_2 in the gas sample with the equivalence ratios. It is noticed that the CO_2 formation behaviors of the investigated fuels except hexanol blend are almost identical. Such identical behavior is attributable to the fact that the number of of carbon atoms are same on the both, reactants side and as well as on the products side. The peculiar behavior of the hexanol blend with lower CO_2 production as compared to other fuels was also reported to some extent by Thomson et al. [10] and has been attributed to the replacement of carbon atoms with oxygen atoms when 1-hexanol is added to the neat FT-SPK.

Figure 7 shows the variation in the CO emission indices with the change in the equivalence ratios at the combustor pressure of 0.3 MPa. Experiments results suggested that the level of CO concentration increased with increase in equivalence ratio due to the acceleration of dissociation process of CO_2 to CO. In the present work, for all the fuels, there occurred a specific range of equivalence ratio, in which the CO concentration was very low, with a minimum value of EI lesser than 1 g/kg. Any further reduction in the equivalence ratio beyond this range caused the CO emissions to rise again. High levels of CO at lower equivalence ratios (lower combustor temperatures) in Fig. 7 were due to slow oxidation rates of CO to CO_2. Any further reduction in the equivalence ratio led to an unstable condition, where the flame fluctuated and lean extinction of the flame occurred. At such unstable conditions, it was too difficult to accurately measure the operating parameters. Hence, the CO emissions results are reported only down to those equivalence ratios at which CO formation began to increase sharply. It is noticed in Fig. 7 that the naphthenic blend emits the highest

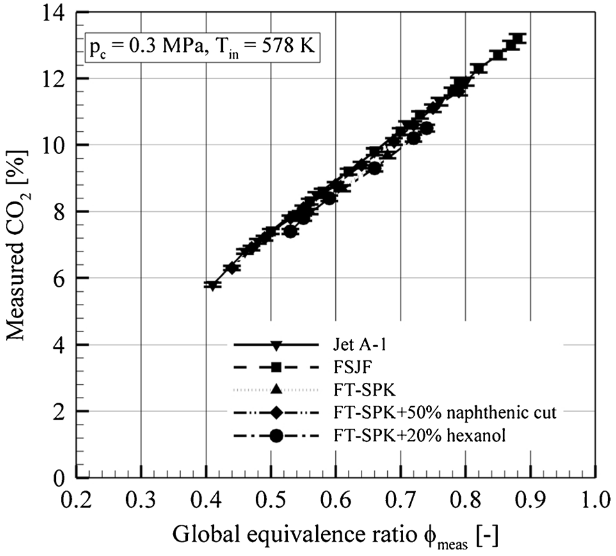

Fig. 6 Comparison of the variation in the measured CO_2 concentrations of the investigated fuels at combustor pressure level of 0.3 MPa and $T_{in} = 540$ K

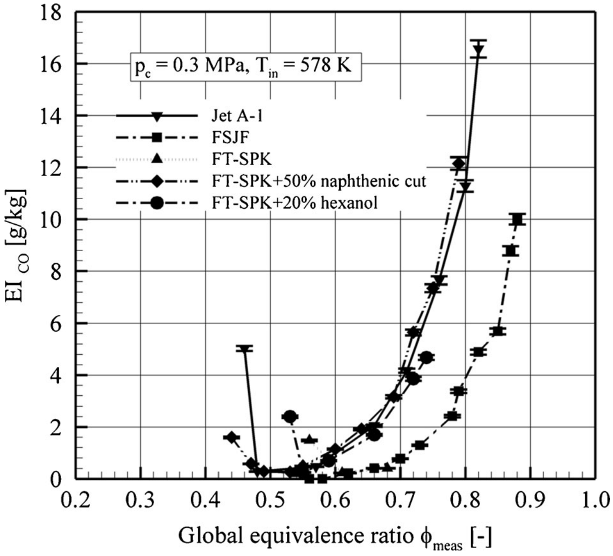

Fig. 7 Comparison of the variation in the measured CO concentrations of the investigated fuels at combustor pressure of 0.3 MPa and $T_{in} = 540$ K

levels of CO while FSJF emits the lowest CO emissions among all the tested fuels. Blending of either naphthenic cut or hexanol in FT-SPK increases the CO formation compared with neat FT-SPK. A possible explanation for the observed behavior follows.

In Fig. 4, for an approximate combustor temperature of 1800 K, neat FT-SPK fuel corresponds to an equivalence ratio of $\Phi = 0.6$ whereas for all other investigated fuels it is $\Phi > 0.7$. At such fixed combustor temperature condition (1800 K), the global reaction kinetics should be almost of the same order for all the fuels. An identical air flow field for all the fuels was also ensured by keeping same pressure drop of air across the burner. Mixing capability of burner (mixing between air and fuel droplets) remains unchanged if air pressure drop across the burner (air exit velocity) is kept constant. Now if the equivalence ratio is increased at same air pressure drop across the burner, the amount of fuel, that needed to mixed with the same amount of combustion air, increases. It means that for higher equivalence ratios, poorer mixing between air and fuel in the combustor should be expected. The level of homogeneity of the mixture in the combustor is very critical as better mixing of fuel and air avoids localized rich mixture zones in the combustor and thus leads to more of premixed type of combustion with lower CO production. Hence neat FT-SPK with a lower equivalence ratio as compared to all other fuels might have resulted in a relatively better mixing with air in the combustor as compared to other fuels. Such probable differences in the homogeneity levels in the combustor to some extent justify the observed CO formation behavior of the investigated fuels except FSJF. No specific reasoning about the disagreement of the atomization behavior of FSJF with its peculiar lowest CO formation can be suggested in this work. Moses and Roets [13] also reported lower CO formation of FSJF than Jet A-1. They concluded in their work that the lower viscosity of FSJF compared to the Jet A-1 led to its better atomization and consequently lower CO formation than Jet A-1. Present results do not support their findings concerning atomization behavior of FSJF and Jet A-1 though.

9 Measurement of NO_X Concentration

Figure 8 shows the NO_X formation of investigated fuels at different equivalence ratios at combustor pressure of 0.3 MPa. Generally for the lean mixtures, the well known thermal mechanism is active above flame temperatures of 1600 K and is mainly responsible for NO_X formation; hence the tendency to form NO_X in the investigated regime can said to be solely dependent on the combustor temperature. The differences in the observed NO_X formations among investigated fuels correlate well with their different measured combustor temperatures at same inlet conditions of reactants. It is noticed in Fig. 4 that FT-SPK has the highest temperature in the combustor and thus also the highest NO_X formation in Fig. 8. Blending of either hexanol or naphthenic cut into FT-SPK decreased the combustor temperature and subsequently lowered the NO_X formation. FSJF on the other hand, despite having same combustor temperature as Jet A-1 (Figs. 4 and 8) exhibits lower NO_X formation than that of Jet A-1 which is not understandable.

10 Measurement of Unburned Hydrocarbons Concentration

Figure 9 shows the variation in the measured gaseous unburned hydrocarbons profiles of investigated fuels with the variation in the equivalence ratios at combustor pressure level of 0.3 MPa. Unburned hydrocarbons (UHC) values, being a minor species in exhaust gas sample as compared to the other measured quantities, are shown in terms of ppm by volume. The measured UHC values for all tested fuels are lower than 10 ppm, hence it is reasonable to assume that no significant differences occur in their UHC formation behavior.

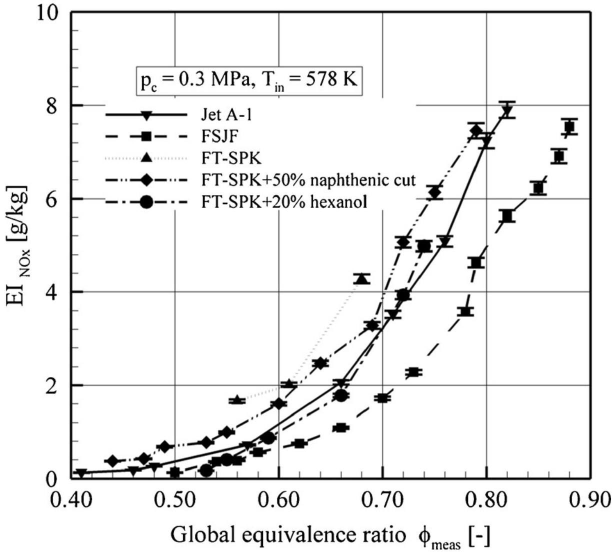

Fig. 8 Comparison of the variation in the measured NO_X concentrations of the investigated fuels at combustor pressure level of 0.3 MPa and T_{in} = 540 K

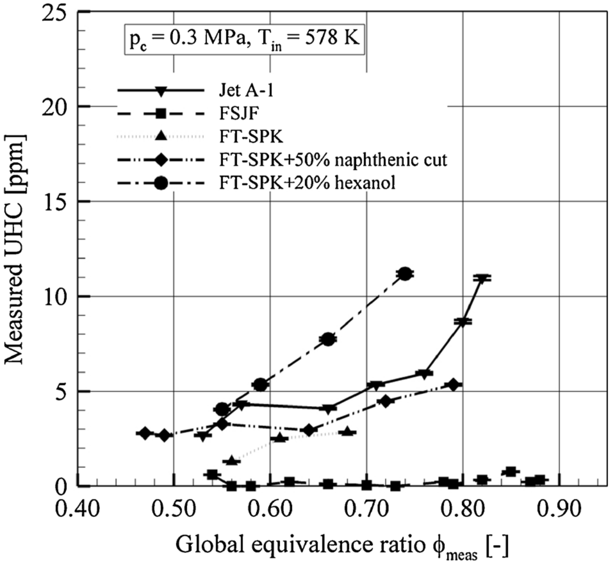

Fig. 9 Comparison of the variation in the measured UHC concentrations of the investigated fuels at combustor pressure level of 0.3 MPa

11 Effect of the Combustor Pressure

To explain the influence of the combustor pressure on the emissions behaviors of the investigated fuels, Fig. 10 compares the CO formation behaviors of tested fuels at the two highest of the three combustor pressure levels studied in this work. In Fig. 10, the measured combustor temperature have been used to compare the emissions formation behavior of the tested fuels. The changes in the combustor temperatures in Fig. 10 were achieved by changing the equivalence ratio while keeping all other operating parameters (inlet temperature of air, the air pressure drop across the burner) constant. In the present work, increase in the combustor pressure decreases CO formation, which seems to be mainly due to two different phenomena. The first effect is the better atomization of droplets occur at higher combustor pressures (Fig. 5), and the second effect is due to the dissociation of CO_2 which is explained with the help of the following reversible reaction:

$$CO_2 \Longleftrightarrow CO + O \tag{4}$$

Due to fewer moles on the left hand side of the reaction, any increase in the combustor pressure shifts the chemical equilibrium towards the left (formation of CO_2); hence at combustor pressures of 0.54 and 0.8 MPa, CO formation is lower than at 0.3 MPa. In the temperature range of 1573-1923 K and with combustor pressure levels of 0.54 MPa and 0.8 MPa, all tested fuels possess CO emissions indices lesser than 3 g/kg and 2 g/kg, respectively. With such low CO formation and considering the experimental uncertainties, the behavior of the investigated fuels in terms of CO production cannot be differentiated at combustor pressure of 0.54 and 0.8 MPa.

NO_X formation behaviors of investigated fuels at combustor pressure levels of 0.54 and 0.8 MPa have been compared in Fig. 11. All investigated fuels show EI lesser than 9 g/kg. At combustor temperatures lower than 1700 K, the NO_X formation behaviors are almost identical for all the fuels whereas at high temperatures, the blend of hexanol and Jet A-1 have

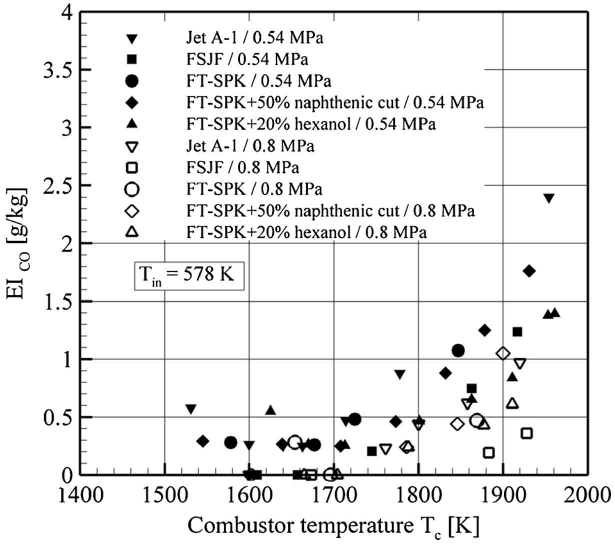

Fig. 10 Effect of combustor pressure on CO formation for all investigated fuels at fixed $T_{in} = 540$ K and at different combustor temperatures

the lowest and the highest NO_X formation, respectively. Nevertheless the results presented in Figs. 10 and 11 suggest that all investigated fuels performed well in terms of their low CO and NO_X formation at higher combustor pressure levels (0.54 MPa and 0.8 MPa).

By combining Figs. 8 and 11, the variation in NO_X formation behaviors of some of the tested fuels with increase in the combustor pressure is shown in the Fig. 12. As the NO_X

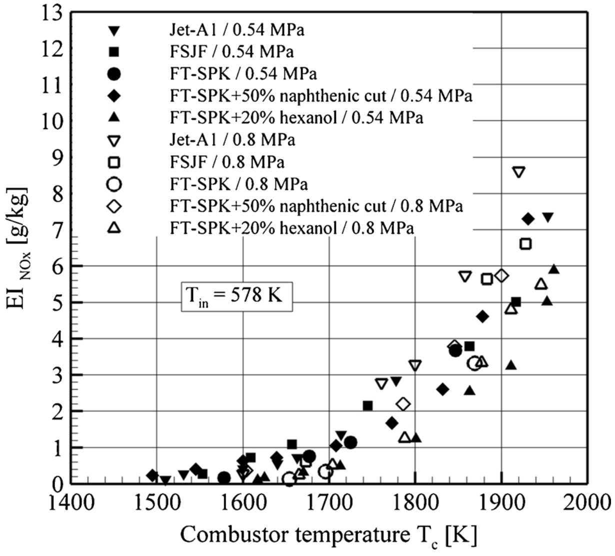

Fig. 11 Effect of combustor pressure on NO_X for all investigated fuels at fixed $T_{in} = 540$ K and at different combustor temperatures

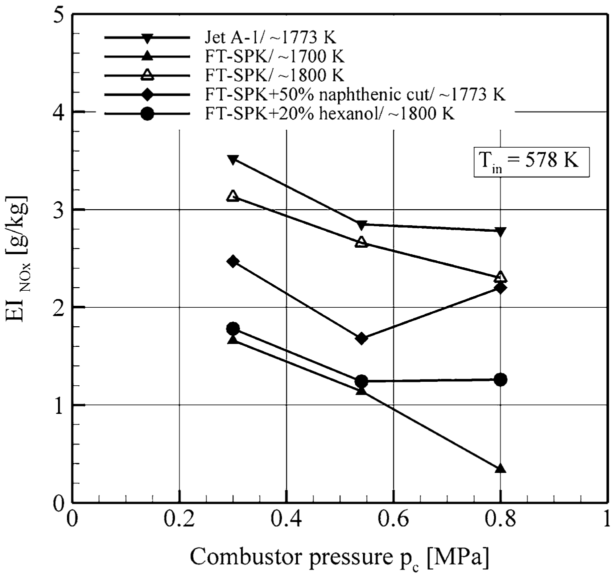

Fig. 12 Effect of combustor pressure on NO_X formation for all investigated fuels at fixed $T_{in} = 540$ K

formation tendencies of different fuels are shown at different combustor temperatures in the Fig. 12; hence their performance should not be compared with each other. Nevertheless it is noticed in Fig. 12 that an increase in the combustor pressure from 0.3 MPa to 0.54 MPa decreased the NO_X formation, whereas further increase in the combustor pressure beyond 0.54 MPa led to an increase in the NO_X formation for all fuels except FT-SPK. Any increase in the operating pressure affects the combustion process involving liquid fuels in many ways, such as, improved atomization and faster reaction kinetics of NO formation. Improved atomization of droplets results in a good mixing of fuel with air ahead of combustion, which further leads to a premixed type of combustion with lower NO_X formation. In Fig. 12, the initial decline of NO_X formation from 0.3 MPa to 0.54 MPa is probably due to the improved atomization process, which reduced the localized temperature hotspots at the higher combustor pressure due to the better mixing of fuel and air. Further an increase of combustor pressure beyond 0.54 MPa led to an increase in NO_X formation for all fuels except FT-SPK. Such increase in NO_X formation with combustor pressure can be attributed to the faster reaction kinetics of NO formation at higher combustor pressures.

12 Operational Range/Emission Window (EW)

It was also noticed during experiments that these fuels differ significantly with each other in terms of the operational ranges which have been determined in the current experimental setup. Such operational range (also called an emissions window) is generally a narrow range of equivalence ratios, where low levels for both CO and NO_X emissions can be achieved. Near lean extinction limits, higher levels of CO formation are observed due to its slower rate of oxidation to CO_2, whereas near stoichiometric equivalence ratios, due to high flame temperatures, higher formations of both, NO_X (thermal NO_X mechanism) and CO (dissociation of CO_2) are observed. The measurement of an upper limit of the EW was not possible in present work due to the measurement limit of combustor temperature in the used experimental setup; hence the emissions window is defined only in the terms of the the lowest combustor temperature beyond which any further decrease in the combustor temperature, the CO level in the gas sample increased abruptly. The lowest combustion temperature in the present work is termed as lean boundary of Emission Window. It is noticed in the Fig. 13 that the investigated fuels exhibit significant differences in terms of their lean boundaries of the emission windows.

In the case of Jet A-1 in Fig. 13, lean boundary of EW is 1490 K, whereas in the case of FT-SPK, it was around 1710 K. Among all investigated fuels, the operational range/ emission window is narrowest and broadest with FT-SPK and Jet A-1, respectively. Such observed behavior of FT-SPK supports the aforementioned conjecture that it possessed better mixing with air in the combustor as compared to the other tested fuels. As already earlier discussed that better mixing of fuel with air leads to more of a premixed type of combustion which suffers from poor lean extinction limits as compared to the partially premixed or diffusion combustion systems and subsequently premixed combustion have narrower emissions windows [27]. An increase in the combustor pressure increases the mixing between fuel and air due to improved atomization of the liquid fuel, therefore the lean boundary of emission window (EW) should narrow down with increase in the combustor pressure. This is seen in the Fig. 13, where an increase in the combustor pressure from 0.3 MPa to 0.8 MPa led to an increase in the value of lean boundary of the emissions windows of all the investigated fuels except neat FT-SPK. Exception of EW behavior of FT-SPK is justified with the fact that it already possessed very good mixing with air as compared to all other fuels at 0.3 MPa, hence the effect of any improved atomization on lean extinction must have been weaken by the increase in the turbulent burning velocity which increases with combustor pressure, as reported by Kasabov et al. [19].

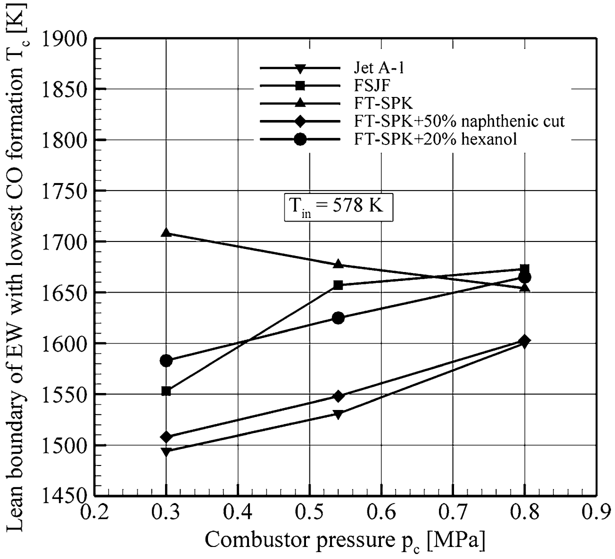

Fig. 13 Effect of combustor pressure on the lean boundary of Emission Window (lb-EW) for the investigated fuels

13 Conclusions and Future Work

Evaluation and comparison of the emissions behaviors of four synthetic fuels and a standard Jet A-1 fuel were the main objectives of this experimental work done within AlfaBird project. Based on the aforementioned analysis, the main conclusions of the present work follows:

- Higher temperature in the combustor are observed for FT-SPK as compared to the other fuels at same inlet conditions of reactants.. Such behavior is attributed to the assumption that combustion with FT-SPK has smaller heat losses to the surroundings due to its lower soot formation tendency (better mixing with air in the combustor). The results were also supported by their predicted atomization behavior i.e., lower values of predicted SMD for FT-SPK as compared to other fuels.
- At 0.3 MPa of combustor pressure, blending of either hexanol or a naphthenic cut in FT-SPK led to increase in both, CO and NO_X formations due to the probable decrease in their atomization qualities. FT-SPK had the highest NO_X and Jet A-1 had the lowest NO_X owing to the differences in their combustor temperatures (due to difference in their sooting tendencies) at same inlet conditions of reactants.
- All investigated fuels in the present work, except the blend of hexanol with FT-SPK have almost similar characteristics concerning the CO_2 production.
- At a combustor pressure of 0.8 MPa, lower formation of both CO and NO_X were observed for all investigated fuels. With an increase in the combustor pressure from 0.3 MPa to 0.8 MPa, maximum values of EI_{CO} for the all tested fuels were reduced by approximately 70 %. The emissions characteristics of the investigated synthetic fuels with the burner are very close to that of standard Jet A-1 fuel at higher pressure conditions (0.54 MPa and 0.8 MPa).
- Results indicate a relation between atomization characteristics of an air-blast burner with the thermo-physical properties of the investigated fuels. Different properties of fuels (density, surface tension and viscosity) have considerable effects on the atomization characteristics and consequently on their emissions behaviors. Neat FT-SPK and its blends have narrower emissions windows than that of Jet A-1.

With experimental data at variety of combustor operating conditions coupled with an in-depth analysis, present work throws some light on emission behaviors of the investigated fuels, however there is still scope for the future studies involving these fuels, in which blending of either 1-hexanol or naphthenic cut into FT-SPK can be done in the systematic proportions e.g., 5 %, 10 %, 15 %, 20 %....50 %. Such an exercise will just not only allow us to understand the impact of these components on emissions characteristics, additionally it will also help in finding an appropriate proportion of either of these components required to be blended in FT-SPK, so that the requirements of "drop in" fuel are also satisfied. In present work it was possible to link the combustion behavior of the tested fuels with their predicted atomization characteristics; however a detailed study should be performed to evaluate the atomization behaviors of these new synthetic fuels in reactive conditions with different types of atomizers (air-assist, pressure swirl, air-blast, etc.).

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