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Flame and emissions characteristics of Jet A-1 blended with biodiesel of waste cooking oil using lean pre-vaporized premixed combustion technique

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Abstract: Lean Pre-vaporized Premixed (LPP) combustion concept would be the perfect promising solution for clean liquid fuel combustion aiming to meet the current stringent emission norms. This approach was rarely studied for the combustion of blended fuels having a portion of biodiesel. The current work presents the results of an experimental study about the impact of blending 20 % vol. biodiesel produced from waste cooking oil methyl ester (WCOME) with Jet A-1 (symbolized as B20) on the flame characteristics of LPP combustion. The WCOME was prepared by the transesterification method using ultrasonic to reduce the time of the production process. The flame was stabilized using a high swirl burner with swirl number SN=0.55 configuration characterized by the formation of central recirculation zone. The temperature of the fuel/air mixture entering the combustion chamber was kept constant at 250 °C with equivalence ratio φ = 0.75 for all tested cases. The results of the present study revealed that the local flame temperature distribution of B20 was slightly lower than that of Jet A-1. It can be concluded that, the biodiesel addition to Jet A-1 has a great effect on local and global emission characteristics of LPP combustion where CO and NOx emissions of B20 at the combustor exit were decreased significantly by 70% and 58%, respectively, compared to those of pure Jet A-1 fuel. Thus, the Jet A-1 fuel can be replaced by B20 without any modifications in the combustor design as they have similar temperature distribution and great emission reduction.

Keywords: High swirl burner (HSB), Lean pre-vaporized premixed (LPP), Waste cooking oil methyl ester (WCOME), Flame characteristics, Emissions.

الملخص العربى: تعتبر تقنية الاحتراق مسبق التبخر والخلط الحل الأمثل لاحتراق الوقود السائل بهدف تلبية متطلبات المعايير

الصارمة لحدود الانبعاثات. ويوجد ندرة واضحة في الدراسات لهذه التقنية في احتراق لمخاليط الوقود التي تحتوي على نسبة من الوقود الحيوي. البحث الحالي يعرض نتائج الدراسة المعملية حول تأثير نسبة خلط 20% وقود حيوي منتج من زيوت الطعام المهدرة مع 80% من وقود الطائرات (ويرمز لهذا الخليط ب B20) على خصائص احتراق اللهب مسبق التبخير والخلط. حيث تم إنتاج الوقود الحيوي بإستخدام عملية الهدرجة بواسطة جهاز الخلط بالموجات فوق الصوتية لتقليل زمن عملية الانتاج. تم استخدام حارق عالي الدوامات له معامل دوامات (SN = 0.55) والذي يتميز بوجود منطقة مركزية لإعادة التدوير. حيث تم الحفاظ على درجة حرارة خليط الوقود / الهواء الداخل إلى غرفة الاحتراق عند درجة حرارة 250 درجة مئوية مع نسبة تكافؤ φ = 0.75 لجميع الحالات التي تم اختبارها. أظهرت نتائج الدراسة الحالية أن توزيع درجة حرارة اللهب الموضعية لمخلوط الوقود أقل بقدر بسيط من توزيع درجة الحرارة اللهب الناتج من الوقود الطائرات. ويمكن استنتاج أن إضافة الوقود الحيوي إلى وقود الطائرات له تأثير كبير على خصائص الانبعاثات الموضعية والعامة عند الاحتراق مسبق التبخر والخلط حيث انخفضت انبعاثات أول أكسيد

الكربون وأكاسيد النتروجين عند مخرج غرفة الاحتراق بشكل ملحوظ بنسبة 70 ٪ و58 ٪ على التوالي، مقارنة بقيم انبعاثات حرق وقود الطائرات. لذلك يمكن استبدال وقود الطائرات بمزيج الوقود B20 دون عمل أي تعديلات في تصميم غرفة الاحتراق نظرا لأن له نفس توزيع درجات الحرارة وتحسين كبير للانبعاثات.

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1. Introduction

The emissions exhausted from gas turbine combustors became a critical concern due to their toxic impact on human life and environment. Therefore, the necessity to get clean combustion techniques is an urgent issue. Lean Pre-vaporized Premixed (LPP) concept would be a promising solution to meet the targeted emission norms [1]. In this concept, the liquid fuels are burned via premixed combustion rather than diffusion combustion and so the corresponding complexities in diffusion flames are removed. However, the issues related to combustion instability in LPP flames are major problems ([2] and [3]). The swirling of the incoming reactants to the LPP combustor commonly enhances the LPP flame stability [4]. The emission characteristics of LPP combustion depend on the flow field, fuel properties and the fuel/air mixing quality [5]. Gokulakrishnan et al. [6] performed an experimental study to investigate NOx formation using a high pressure, swirl-stabilized LPP combustion system. The results demonstrated that the fuel oils achieved very low NOx emissions comparable to those of natural gas in LPP combustion system.

The current challenges not only include the environmental issues, but also other critical issues related the current limited fuel resources. The use of biodiesel is a promising solution that can simultaneously reduce emitted pollutants and at least partially substitute the conventional fossil fuels. The major features of biofuels include their renewability, biodegradability, non-toxicity, and safety in comparison with conventional fossil fuels [7]. Biodiesel can be prepared from raw or waste vegetable oils (edible and non-edible) and animal’s fats [8]. These oils can’t be used directly in combustion devices because of high viscosity, low volatility, and high molecular [9]. Producing biodiesel from waste cooking oils provides optimal effective disposal process with substantial economic and environmental benefits [8]. The conversion of raw oils into biodiesel can be done via pyrolysis, emulsification, and transesterification [10]. The transesterification is usually used to convert the single/triglyceride molecules of vegetable oils into smaller, straight chain molecules of esters.

The combustion and emission characteristics of biodiesel burned in gas turbines have been studied. Attia et al. [11] investigated the combustion characteristics of Jet A-1 fuel blended with jojoba methyl ester (JME) using LPP combustion setup. In this study, lean mixture of equivalence ratio $\varphi=0.87$ was preheated to 170 ^{o}C and flows through high swirl burner (HSB) of swirl number SN=0.78. it was noticed a decrease in NOx emissions with increasing the JME blending ratio with higher CO emissions. Hashimoto et al [12] used palm methyl ester (PME) as an alternative fuel for gas turbines where air was preheated to 400°C. It was found that, for lean combustion, NOx emissions for PME were lower than those for diesel fuel with comparable CO emissions. Recently, Hashimoto et al [13] investigated the combustion characteristics of Jatropha pure oil (JAPO) and jatropha methyl ester (JAME) as an alternative fuel for gas turbines. They found that, CO emissions for JAPO were higher than those of diesel and JAME with comparable NOx emissions for all tested fuels. Habib et al [14] investigated the performance and emissions characteristics of jet A, soy methyl ester (SME), canola methyl ester (CME), rapeseed methyl ester (RME), and their B50 (i.e. blends containing 50% of jet A and 50% of biodiesel on the volume basis). The results showed that the biodiesel and biodiesel-jet A blends reduced the CO and NOx emissions.

From the previous literature review, even there are few studies conducted to investigate the combustion performance of liquid biofuels using a swirl stabilized LPP technique, the use of biofuel produced from waste cooking oil was rarely studied. To this end, the goal of the present work is to (i) produce biodiesel from waste cooking oil to get waste cooking oil methyl ester (WCOME) following the transesterification process using ultrasonicator, and (ii) experimentally study the combustion characteristics of a mixture of 80% Jet A-1 blended with 20% WCOME on the volume bias (i.e. B20) in comparison with that of the reference fuel (Jet A-1) using swirl stabilized LPP combustion.

2. Material and methods

2.1 Operating fuels

The fuels used in this experimental study are Jet A-1 as the baseline fuel and 20% waste cooking oil methyl ester (WCOME) blended with 80% Jet A-1 on the volume basis (symbolized as B20). Jet A-1 was procured from Misr Petroleum Company, while the tested waste cooking oil was collected from the fast food restaurants and the WCOME was produced in the biofuels laboratory via the transesterification process.

The biodiesel was prepared from raw waste cooking oil using the transesterification process. In this process each liter from waste cooking oil was reacted with 330 mL methanol catalyzed by 1% wt. potassium hydroxide (KOH) for 15 min. using Ultrasonicator (UP200S Hielscher) where the temperature was maintained at 65 °C. The reaction temperature was controlled by (IKA ETS D-5) temperature controller. Once the reaction completed, the oil was transferred to a settling vessel for 2-3 hours to remove glycerol from the biodiesel. Then biodiesel was washed with warm distilled water to remove any residual components within the biodiesel fuel; mainly the excess methanol and the soap contents. Finally, the produced biodiesel was heated to 120 °C for 5 min. to allow the evaporation of any residual water.

2.2. Experimental setup

The combustor used in this study comprised from a cylindrical open-ended steel combustor with internal diameter of 0.15 m and length of 0.5 m as shown in Fig. 1. The air and the tested fuel were introduced to the combustor through an axial swirl burner fixed at the combustor inlet to provide the air-fuel mixture with a swirl motion. The swirler shown in Fig. 2 has eight straight vanes positioned at 35° to the vertical to produce geometrical swirl number SN= 0.55. The combustion air was supplied by air compressor connected with 2 m^3 accumulator tank through a pressure regulator. The air flow rate was measured by Dwyer high flow glass rotameter. Incoming air was heated by two parallel sets of process industrial electrical air heaters (each set has 1.95 kW). The liquid fuel was supplied to the fuel atomizer installed at 1 m below the burner inlet using a fuel pump (having pressure regulator from 1 to 12 bar); this distance would be enough to ensure good homogenous mixture of fuel and air. The temperature of air and fuel mixture at the combustor was fixed to 250°C and the combustor was operated at a constant equivalence ratio of 0.75.

The temperature distribution and the species concentrations through different axial and radial locations throughout the combustor were measured at eleven horizontal planes with nine radial locations in each plane. The vertical planes are located at longitudinal distances from the burner tip equal to 10, 20, 30, 40, 50, 70, 90, 110, 130, 150 and 500 mm, while the radial locations of the measurements are located at 0, 5, 10, 15, 20, 25, 30, 40 and 50 mm (from the combustor center line) for different fuels using type R (platinum/platinum-13% rhodium) thermocouple (0.6 mm bead diameter, 0.1 mm wire diameter and 3 mm ceramic tube insulation). The temperature readings were corrected against radiation losses. The species concentrations were measured by ECOM-J2KN Pro exhaust gas analyzer. The CO and NOx concentrations were measured in ppm using infrared detectors, while O_2 and CO_2 were measured using electrochemical detectors.

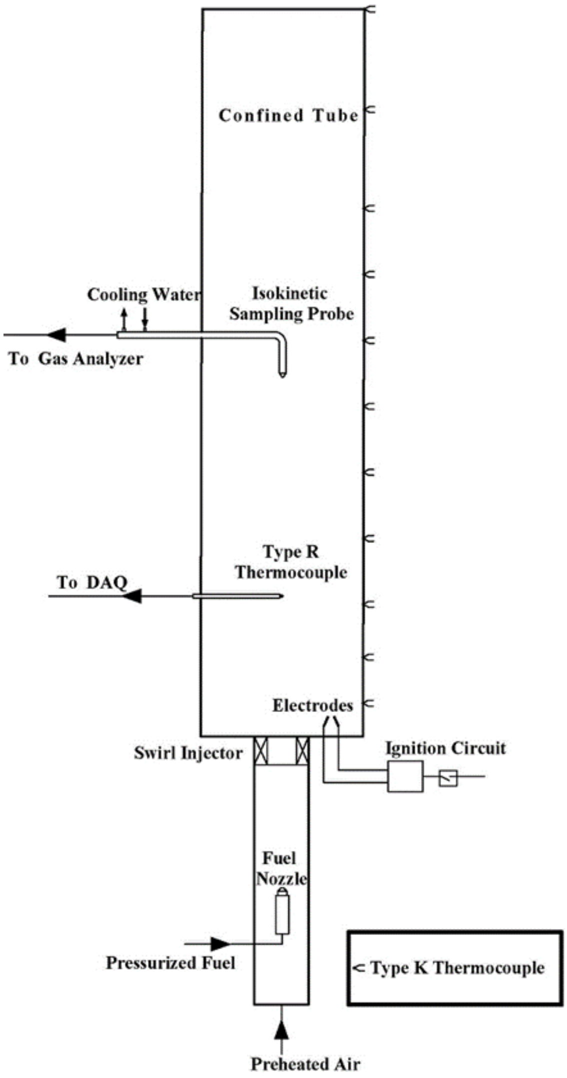


Fig. 1 Schematic drawing for the experimental swirl stabilized LPP test rig

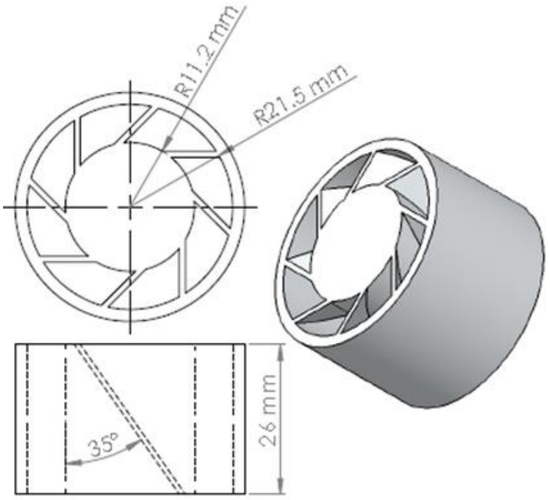


Fig. 2 High swirl burner (HSB) dimensions

2.3 Operating conditions

The current experimental program includes the study of flame characteristics of two fuels; Jet-A1 and B20. The flame was stabilized using HSB of SN=0.55 as described above, while values of other parameters are shown in Table 1.

Table 1 Operating condition in the experiments

Case no.	fuel type	Condition	Air preheated temp (°C)	Air flow (kg/hr)	Fuel flow (kg/hr)	Mixture strength, ϕ	Measured parameters
1	Jet A-1	Reacting flow	250	23.98	1.26	0.75	Temperature and species concentration
2	B20				1.23		

3. Results and discussions

The combustion experiments of the Jet A-1 fuel are performed initially, and then B20 is used according to the experimental program summarized in Table 1.

3.1 Fuel properties

The physicochemical properties of the tested fuels are shown in Table 2. The WCOME is denser than Jet A-1 fuel due to its higher molecular weight. The WCOME is more viscous, less volatile and higher flash point as compared to that for Jet A-1. The WCOME also has lower calorific value as opposed to that of Jet A-1 due to its 11% oxygen contents. These different properties would affect the temperature and emission characteristics of blended fuel combustion [15].

Table 2 Properties of the jet -1 and waste cooking oil biodiesel

Property	Test method	Jet A-1	WCOME
Specific gravity at 15°C	ASTM D-1298	0.797	0.877
Viscosity at 40°C, cSt	ASTM D-445	1.08	4.53
Pour Point °C	ASTM D-97	-43	-6
Flash Point °C	ASTM D-93	39	130
Boiling point °C at 1 atm	ASTM D-86	163	350
Lower calorific value, MJ/kg	ASTM D-240	43.465	39.98
Molecular weight, kg/kmol	-	148.025	290.914
Elemental analysis, % by mass:			
Carbon content	Euro Vector EA3000 CHNS/O Elemental Analyzer	86.51	77.22
Hydrogen content		13.48	11.46
Sulfur content		Nil	Nil
Oxygen content		Nil	11.3
Nitrogen content		Nil	Nil

3.2 Flame characteristics

The corrected flame temperature distributions at selected vertical planes for the investigated fuels is shown in Fig. 3. A high similarity between the flame temperature of Jet A-1 and B20 with a slight decrease for case of B20 flame temperature. The HSB existing at the center of the combustor dump plane creates a toroidal reversal flow that recirculates a portion of the hot combustion products into the combustion zone to be mixed with the incoming air-fuel LPP mixture. According to Fig. 4 it seems that, a region of recirculation of hot products with high temperature is formed near the edge of the burner center body (typically at $0.5<r/R<1$). Beyond this region above the burner center body ($0.5<r/R<0.5$), the temperature is still high while away from the burner edge ($1<r/R<2.5$) the temperature decreases gradually especially for $10<Z<70$ mm. With increasing the vertical distance, the flame temperature fluctuation decays until the uniform flame temperature distribution is attained approximately at $Z=130$ mm. The maximum flame temperature for Jet A-1 is equal 2380 K and obtained at $Z= 30$ mm while that for B20 is equal 2360 K and obtained at $Z= 40$ mm. This slight reduction is due to the competitive results of the lower heating value of B20 and the oxygen contents that accelerate the fuel oxidation. Moreover, the retardation in the location of maximum temperature may be owing to the formation of fine WCOME droplets (forming partial premixed combustion) that need more time (translated into larger vertical distance) in the flame to be completely evaporated.

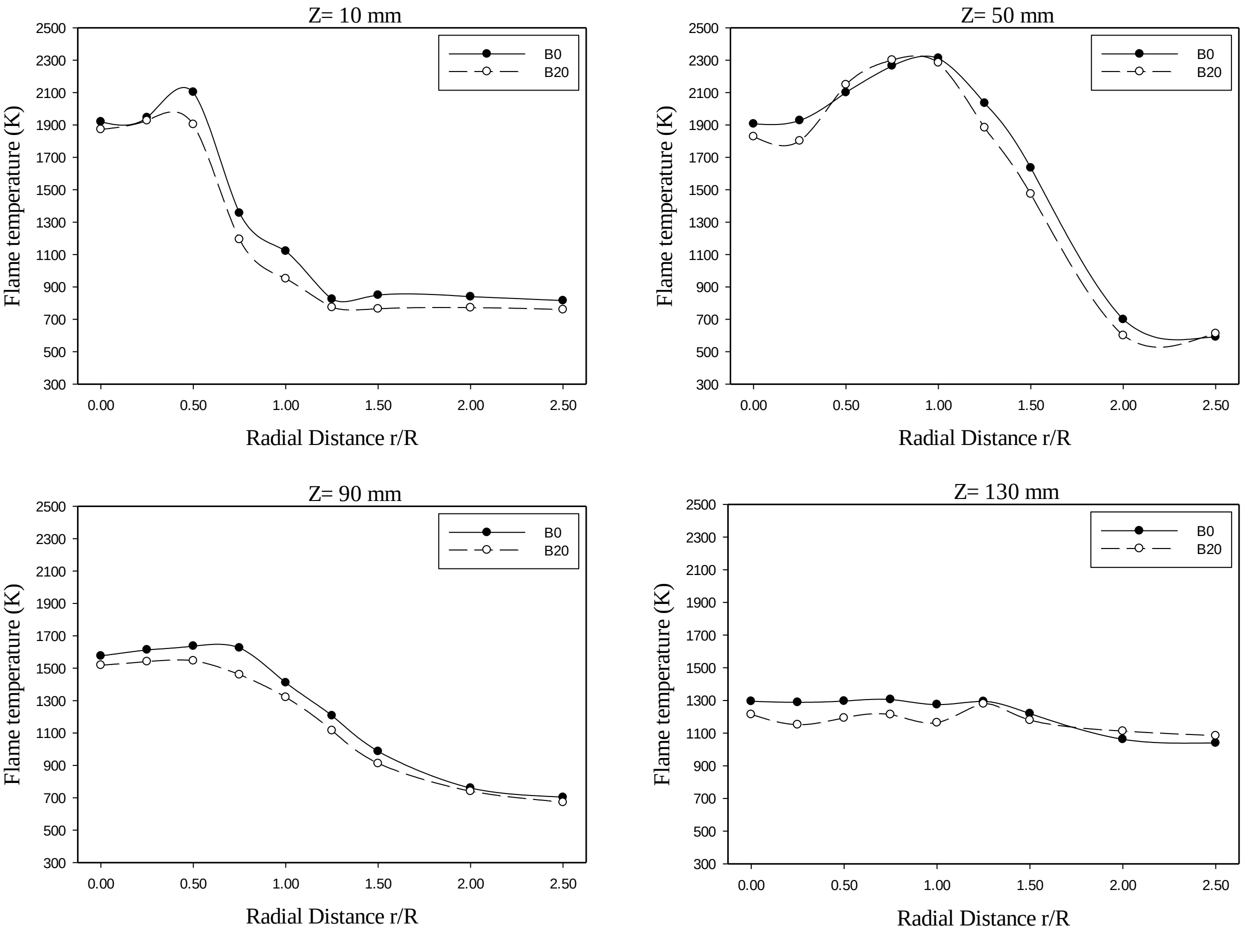
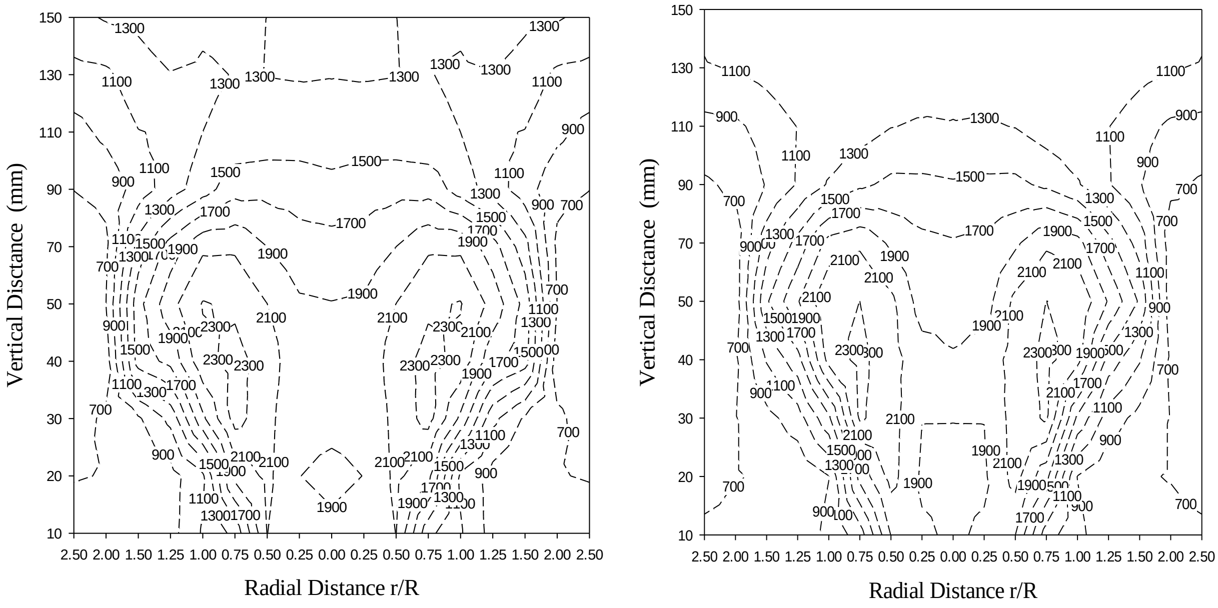


Fig. 3 Flame temperature radial distribution at different axial locations



(a)

(b)

Fig. 4 The basic features of the temperature contour; (a) for B0, (b) for B20

The thermal uniformity through the combustor can be represented by pattern factor (PF) as one of the major parameters that shall be considered in gas turbine combustion [1]. The more the pattern factor decreases the more the thermal uniformity. As shown in Fig. 5, for Jet A-1 the PF decreases with increasing the vertical distance and so thermal uniformity of the combustor is increased. For B20 the PF value at Z=10 mm is 0.77 and at Z=20 mm is 0.95 then the PF decreases with increasing the vertical distance. The high values of PF may be due to the existing of partial premixed combustion of WCOME droplets combustion occurred at the lower zone in the combustor. At the higher zone in the combustor (Z>150 mm) the PF of the B20 is lower than that of the Jet A-1.

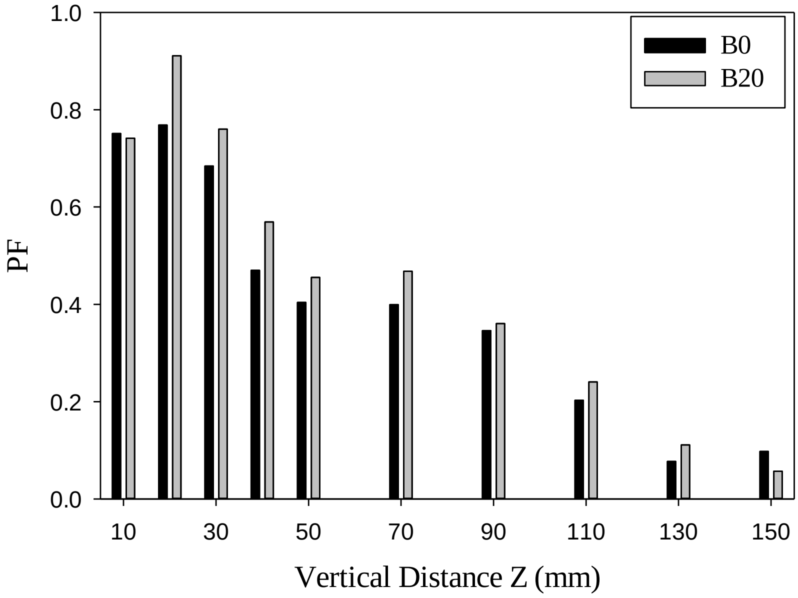


Fig. 5 Combustor pattern factor for tested fuels

3.3 Species concentration

The basic factors influencing the emissions formation in the swirl stabilized LPP combustion, mainly CO and NOx, are the combustor inlet temperature, the local flame temperature, the combustion pressure, the equivalence ratio, the turbulence intensity, and the residence time of flue gas in the high-temperature zone [1]. To conduct the effect of fuel type on the species concentration all the factors are kept constant through the experiments except fuel type. Fig. 6 shows the CO concentrations at selected radial planes throughout the combustor including Jet A-1 fuel and B20.

In the core of Jet A-1 flame, where the temperature is relatively lower, the CO concentration is decreased as a result of the reduced dissociations of CO_2 into CO with low temperature. Near the edge of the burner center body, the maximum CO concentrations are achieved where the dissociation rate of CO_2 is high at high flame temperature (>1900 K). Near the combustor wall, the CO concentration is decreased again to be lower than that in the flame core. As the vertical distance is increased, the mixture become more homogeneous and the CO concentration decreases to reach the minimum value at the combustor exit. By the comparison, the CO concentration of B20 has a comparable value with that of Jet A-1 at the lower levels in the combustor (Z= 10 mm) and it is started to increase at high vertical distance reaching its maximum value at Z= 30 mm. The peak of CO concentration for Jet A-1 was approximately twice that for B20 and this gap was getting smaller with increasing the vertical distance. This reduction of CO concentration for B20 is mainly due to the oxygen content in biodiesel which promotes fuel oxidation and so complete combustion.

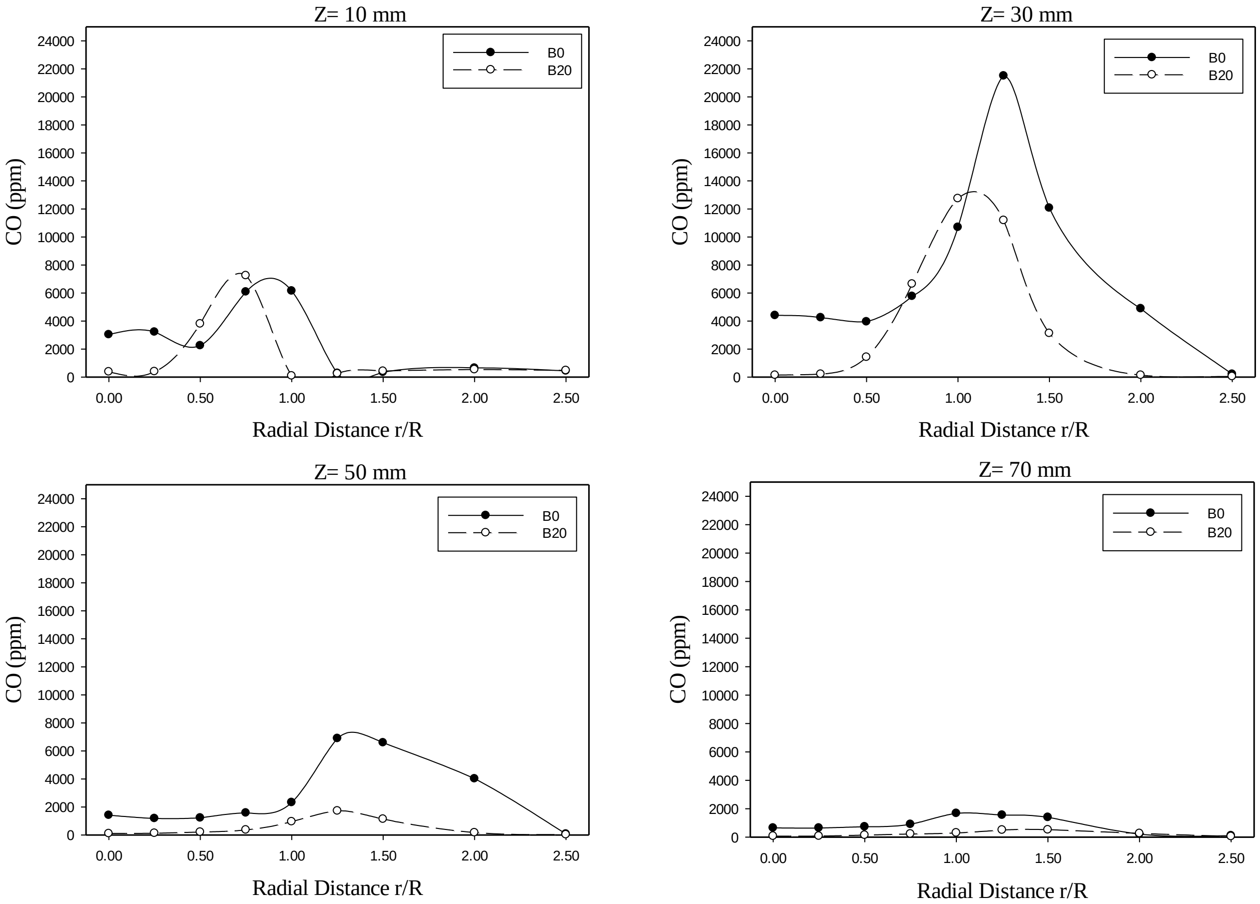


Fig. 6 In flame CO concentrations radial distribution at different axial locations

NOx is the term comprise both gases, nitric oxide (NO) and nitrogen dioxide (NO_2). NO is mainly formed in a combustion process due to high temperature (>1850 K) [1]. NO_2 is formed by oxidation of NO in the lean combustion conditions at low temperature. Generally, the concentration of NO_2 is lower than that of NO because the rate of the oxidation of NO is too slow to give significant conversion in short residence time. The NOx concentrations of the LPP swirl stabilized combustion at selected radial planes throughout the combustor including Jet A-1 fuel and B20 are shown in Fig. 7. The NOx concentrations of Jet A-1 increase with increasing the vertical distance towards the combustor exit. The maximum NOx concentration appears after getting the maximum temperature at Z = 50 mm then NOx concentrations are decreased rapidly with increasing the vertical distance towards the combustor exit as a result of temperature decrease. The NOx concentrations for B20 are remarkably lower than those for Jet A-1 even there is slight decrease in temperature. The high oxygen content existed in the WCOME enhances the combustion process also increase the formation of some active radicals such as OH [1]. This plays a significant role in Zeldovich mechanism of thermal NOx formation and may be one of the major reasons for this different NOx concentration behavior.

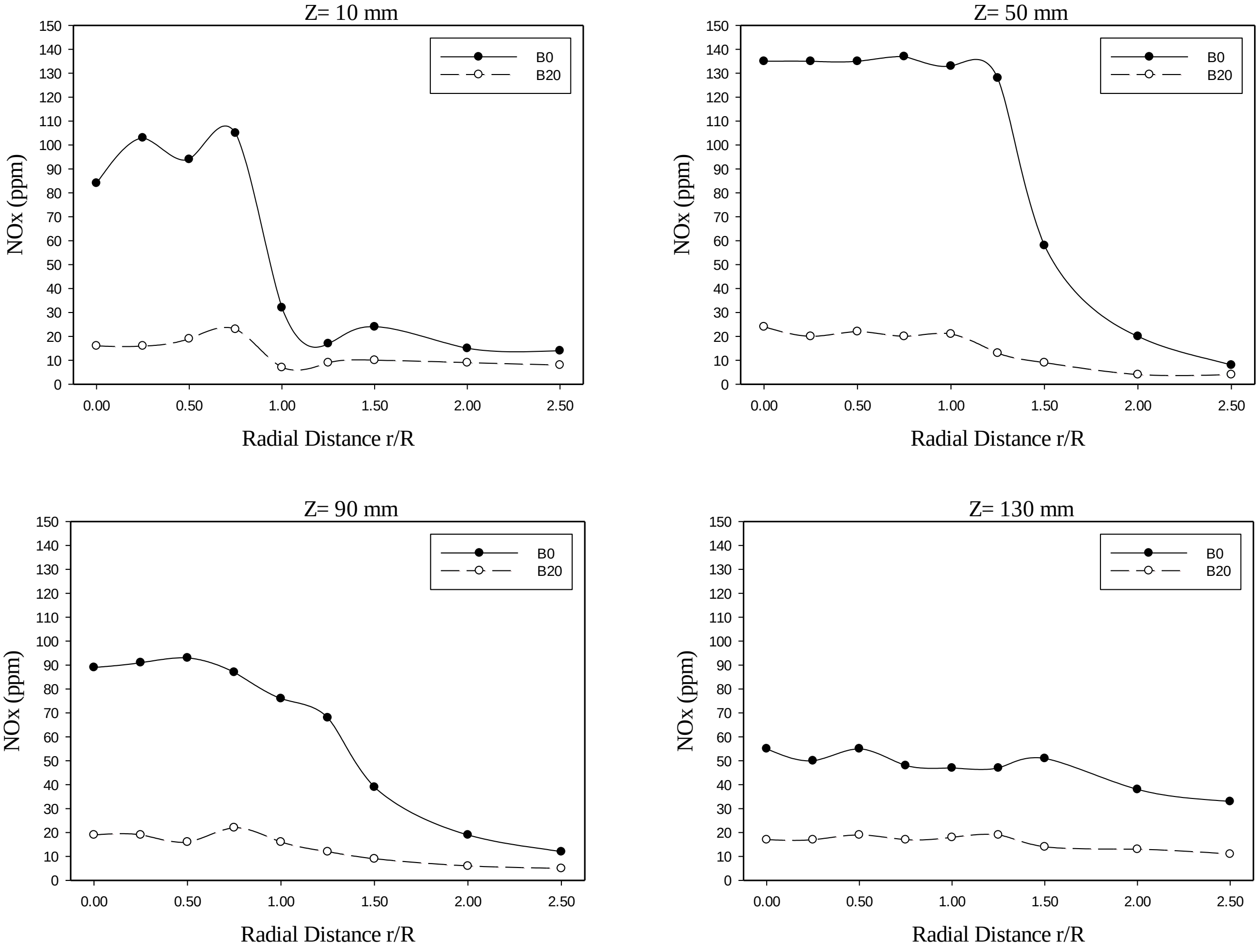


Fig. 7 In flame NOx concentrations radial distribution at different axial locations

In order to compare the environmental impact of Jet A-1 and B20, the average emission index at the combustor exit is calculated for different species. Emission index (EI_i) is a generic way to quantify the level of emissions. The EI for a certain species is defined as the ratio of the mass of the species emitted (i) to the mass of fuel burned and can be calculated according to Eq. 1 [16].

$$EI_i = \frac{m_{i,emitted}}{m_{F,burned}} \tag{1}$$

The EI_i is a dimensionless quantity represented in g/kg fuel to make the species concentration measurement independent of any dilution by air. The level of pollution is also expressed as g/MJ to eliminate the effect of the heating values of different fuels according to Eq. 2 [16].

$$\frac{mass\ of\ pollutant}{heat\ of\ combustion} = \frac{EI_i}{LHV\ or\ HHV} \tag{2}$$

The average NO emission index (EI_{NO}) and CO emission indices (EI_{CO}) obtained from the combustion of the tested fuels are listed in Table 3. The results demonstrated that the blending of 20% of WCOME with Jet A-1 would be able to make a great reduction impact on local and global CO and NOx concentration, mainly as a result of oxygen content in the biodiesel.

Table 3 Jet A-1 and B20 average EI_{NO} and EI_{CO}

FUEL	EI_{NO} (g/kg)	EI_{CO} (g/kg)	EI_{NO} (mg/MJ)	EI_{CO} (mg/MJ)
Jet A-1	1.87	0.126	42.9	2.9
B20	1.08	0.088	25.2	2.05

4. Conclusions

In the current study, biodiesel was produced from waste cooking oil by the transesterification process using the ultrasonic system. The 20% of biodiesel was blended with 80% Jet A-1 fuel to form B20. The effect of B20 on the combustion characteristics of swirl stabilized lean pre-vaporized premixed (LPP) combustion system was investigated. The flame is stabilized by the use of HSB having SN=0.55. The combustor inlet temperature and the equivalence ratio were kept constant through the experiments. The following conclusions were raised:

- The local flame temperature distribution of B20 was slightly lower than that of Jet A-1.
- Biodiesel (oxygenated fuel) addition to Jet A-1 has a great effect on local and global emission characteristics of LPP combustion.
- The CO and NOx emissions of B20 at the combustor exit were decreased significantly by 70% and 58%, respectively, compared those for neat Jet A-1 fuel.
- The Jet A-1 fuel can be replaced by B20 without any modifications in the combustor design as they have similar temperature distribution and great emission reduction.

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