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Combustion characteristics of biodiesel fuel in high recirculation conditions

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ABSTRACT

The potential of biodiesel as an alternative fuel for various applications leads to an investigation to understand the combustion characteristics of pure and blended biodiesel. The concept of internal recirculation of combustion products is employed in a high swirl and low emission burner to reduce emissions. Due to high boiling point (613 K) and SMD (37 μm) of biodiesel, air preheating with minimum temperature above the boiling point of biodiesel is considered. Air at different temperatures of 623, 673 and 703 K is injected tangentially. Swirl flow pattern in the combustor creates the central low pressure zone due to vortex breakdown and improves the recirculation of combustion products. Results in improved mixing and high residence time of reactants. Biodiesel is blended with diesel to reduce the surface tension and viscosity and improve the combustion characteristics. Literature has little consensus on NOx emissions from the combustion system operating with biodiesel. Therefore, the present study aims to reduce the thermal NO formation through the concept of exhaust gas recirculation. The CO, HC, NOx emissions and soot-volume fraction from biodiesel (100B0D), 50% blending (50B50D), diesel and kerosene are compared at different air preheating temperatures. A drastic reduction in emissions is observed in 50B50D as compared with pure biodiesel.

1. Introduction

The increased demand for energy is putting additional pressure on fossil fuel resources leading to early depletion of these resources [1–3]. Therefore, there is a great need to develop alternate resources and methods to fill the increasing energy demand of human civilization. Various bio-fuel energy resources such as biomass, biogas, vegetable oils, biodiesel, etc. are being explored as alternate sources of energy. These alternate energy resources are considered as environment-friendly [4,5]. Biodiesel has immense potential for being used as an alternate fuel to the conventional or fossil diesel for industrial heating applications, transportation, power generation and internal combustion engines. These biofuels are renewable, biodegradable, oxygenated and expected to help in reducing green-house gas (GHG) emissions [6–14]. There is little consensus on the effects of biodiesel on NOx emissions. However, as extensive literature indicates, a slight increase in emissions of nitrogen oxides (NOx) has been observed [9–14]. Blending of biodiesel reduces the NOx formation [10,15]. Biodiesel and its blends with diesel can be used in diesel engines without modifications because of similarities with diesel properties [1,6,8,10]. Espadafor et al. [10] have conducted experimental investigation to reduce the emissions of NOx on a 4-strock single-cylinder engine with the method of EGR (exhaust gas recirculation), however internal recirculation has little viability in IC engines due to various constraints. Extensive literature is available for high pressure conditions in IC engines [3–14]. However, very little work has been reported in the field of continuous combustion systems, such as gas turbine combustors and industrial heating applications. Recently, Chong and Hochgreb [16], and Bolszo and McDonnell [17] have experimentally studied the combustion characteristics of biodiesel in an open can-type gas turbine combustor configuration. Chong and Hochgreb [16] have investigated the combustion characteristics of palm biodiesel in swirl flow type cylindrical quartz combustor. A plain-jet air-blast atomizer is used for fuel injection. The main air flow is heated by two in-line air heaters (750 W) arranged in a series to simulate the high temperature conditions similar to that of a gas turbine combustor. The burner plenum and body are additionally heated by three Omega rope heaters (500 W) and insulated with high temperature heat-resisting materials to reduce heat loss. The heating facility allows the main air to be preheated to a temperature of 623 K. More investigations are required to study the evaporation and combustion characteristics of these biodiesel based fuels in order to understand the emissions characteristics from the combustion of these fuels. Therefore, in the present work, detailed combustion studies have been carried out in a high swirl combustor with air preheating to assess the emissions from the combustion of such fuels at conditions similar to those existing in gas turbine and industrial heating applications [17]. Internal recirculation of combustion products due to high swirl results in the dilution and preheating of fresh reactants that helps in suppressing the formation

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of thermal NO and CO emissions [18–26]. This motivated the authors to study the combustion and emission characteristics of biodiesel with the concept of recirculation of hot combustion products for reducing the emissions.

The process of combustion of liquid fuels is very complex due to the involvement of many processes such as atomization, droplet evaporation, mixture formation and subsequent combustion reaction. A brief summary of various liquid fuels having different properties is given in Table 1. The Sauter mean diameter (SMD) of the droplets in the spray is a function of surface tension (σ) and viscosity (μ) of the fuel [17,27]. At an injection pressure of ΔP = 9 bar, the SMD of biodiesel spray is 37 μm. At the same injection pressure, the SMD of kerosene and diesel sprays are 20 and 26 μm respectively. Evaporation rate of droplets is a function of surface area to volume ratio (A_s/V) of droplet [28]. The A_s/V ratio of the biodiesel droplets is 1.62×10^5, whereas for kerosene droplets it is 3×10^5. The time required for droplet evaporation increases with an increase in the droplet diameter (SMD) [29]. With an increase in the evaporation time, species mixing and flame stabilization become more difficult. Evaporation rate of biodiesel droplets is relatively very small because of high boiling point of biodiesel. In the case of conventional combustion, flame stabilizes in a narrow zone near the fuel nozzle resulting in the formation of a high temperature zone near the nozzle exit. Due to this, fuel droplets evaporate quickly in the conventional combustion mode and get combusted near the nozzle exit [30]. However, in the case of recirculation of hot combustion products, reaction zone is distributed throughout the volume of the chamber [18,22]. The peak flame temperature and its fluctuations are relatively lower compared to those in the conventional combustion mode [18–22,25]. The droplet evaporation rate is expected to be higher in this mode compared to that in the conventional combustion mode due to the higher average temperature in the combustor [30].

In the present study, detailed combustion and emission characteristics of biodiesel and its blends have been studied in a swirl flow combustor configuration with the concept of internal recirculation of combustion products. A two stage combustor configuration with 19 kW thermal input and heat release density of ~4.8 MW/m^3 is used as shown in Fig. 1a. Tangential air injection scheme is used to achieve swirl flow pattern in the combustor. The concept of swirl stabilized flame is commonly used [31–34] to achieve high mixing levels and high residence time. The details of design methodology of the present combustor have been discussed in Reddy et al. [33]. Initial experiments showed that it was not possible to achieve low emission combustion mode with biodiesel for ambient conditions (300 K) due to the high boiling point of biodiesel. This necessitated air-preheat to a temperature close to the boiling point of biodiesel (~613 K). Therefore, the initial air-preheat temperature is maintained at 623 K. The capacity of the present air preheater is sufficient to preheat the air supply up to 710 K at all equivalence ratios (Φ = 1 to 0.45). Therefore three preheat temperature conditions of 623, 673 and 703 K are considered in this study. Air preheating improves the evaporation rate of biodiesel droplets as the rate of evaporation of biodiesel is less than half that of kerosene fuel. An electrical air preheater with a variable heating capacity of 3 to 8 kW is installed on the primary line before the combustor inlet; the location of the air preheater is shown in Fig. 1b. Biodiesel is blended with diesel for certain studies to understand the effect of blending on the combustion process and emissions [35–37]. Three different fuel combinations are tested in this study, 100% biodiesel, 50% blending with diesel (50B50D), and pure diesel. Temperature distribution in the combustor, exhaust gas temperature and emissions are compared for different operating conditions and different fuels.

Table 1
Characteristic details of different fuels.

Property	Kerosene	Diesel	Biodiesel
Density (kg/m^3)	800	860	890
Kinematic viscosity, ν (m^2/s)	2.71×10^{-6}	3.64×10^{-6}	5.27×10^{-6}
Surface tension, σ (mN/m)	25	23	30.55
Flash point (K)	334	398	429
Boiling point (K)	433	558	613
SMD (μm) (ΔP = 9 bar)	20	26	37
Ratio of surface area to volume (m^{-1}) (A_s/V)	300,000	230,769	162,162
Evaporation time (ms) (τ_{evap})at T_∞ = 1000 K	8.1	11.6	18.9

2. Experimental setup

Fig. 1 shows a schematic diagram of the experimental setup and dimensional details of a typical two-stage combustor. The combustor is placed vertically on a test stand as shown in the figure. Biodiesel is stored in a pressurized steel tank. A ball valve is inserted in the line between fuel tank and fuel nozzle. The fuel flow is controlled through a ball valve during the combustor operation. A pressure swirl injector with a mass flow rate of 1.78 kg/h at ΔP = 9 bar is mounted centrally at the bottom of the combustor. The spray cone angle of the injector is 45°, and the SMD at ΔP = 9 bar is in the range of 36–39 μm (measured with Malvern Mastersizer). The spray characteristics are measured at a retraction position of 120 mm from the orifice of the nozzle. The air is drawn from a high pressure storage tank and controlled through electric mass-flow controllers (500 and 1000 SLPM). Preheating in the secondary chamber is not considered because partially combusted species and evaporated fuel from the primary chamber achieve a sufficiently high temperature to ensure the continuation of the combustion reaction in the secondary chamber. Clockwise air injection and counterclockwise fuel swirl scheme is used for quick evaporation and increased mixing of fuel droplets with the incoming fresh air [27]. For all operating conditions, the air inlet diameter (5 mm) of tangential ports is maintained constant. An electrical air preheater with a variable heating capacity of 3 to 8 kW is installed on the primary air line near the combustor inlet. The location of the air preheater is shown in Fig. 1b. Air preheating temperature is controlled through an auto temperature controller circuit. Preheated air is supplied to the primary chamber and air at ambient conditions is supplied to the secondary chamber. For stoichiometric combustion, 95% of the air is injected in the primary chamber and the remaining 5% is injected in the secondary chamber. For lean combustion cases, 50% of the excess air along with the stoichiometric air is injected into the primary chamber. The remaining 50% of excess air is injected into the secondary chamber. The combustor is initially ignited with spark-plug and run with premixed liquefied petroleum gas (LPG)–air mixture. To ensure initial flame stabilization, the stoichiometric flow rates of biodiesel and air are maintained. The exhaust gas composition is measured with QuintoxKM-9106 gas analyzer and normalized to 15% O_2 level in the exhaust. The accuracy of the sensors in the gas analyzer with an O_2 analyzer(0–25% range, 0.1% accuracy), CO analyzer (0–10,000 ppm range, accuracy ±5% of reading),NO analyzer (0–5000 ppm, ±5 ppm accuracy), a HC (hydrocarbon) analyzer (0–50,000 ppm), and a CO_2 analyzer. Continuous online measurement of the sample gas has been carried out. Temperature measurements are carried out with Omega KMTXL-040 (diameter = 1 mm) type thermocouple, with a maximum measured temperature range of 1600 K. The measured temperature is corrected for conduction and radiation losses from the thermocouple junction [38]. A photograph of the soot volume fraction measurement system is shown in Fig. 1c. The soot volume fraction has been measured using the technique of carbon balance method of Choi et al. [39], the accuracy of the instrument is ±1%. The sampling tube is placed at the outlet of the combustor and is connected to the filter paper assembly through flexible piping which is subsequently connected to vacuum pump with rotameter (0–30 SLPM). The flow rate of 12–14 LPM is maintained during the experiment based on limiting flow rates provided by the manufacturer of the micro glass fiber filter paper (99% collection efficiency and 0.1 μm retention size). The time of soot collection is also