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ORIGINAL ARTICLE

Development of high intensity low emission combustor for achieving flameless combustion of liquid fuels

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Low emissions

Abstract This paper presents the experimental and numerical results for a two stage combustor capable of achieving flameless combustion with liquid fuels for different thermal heat inputs of 20, 30, 40 and 60 kW and heat release density of 5–15 MW/m^3. Combustion characteristics and pollutant emissions are studied for three different fuels, kerosene, diesel and gasoline. The influence of droplet diameter on pollutant emissions at all conditions is studied. The fuel and oxidizer are supplied at ambient conditions. The concept of high swirl flows has been adopted to achieve high internal recirculation rates, residence time and increased dilution of the fresh reactants in the primary combustion zone, resulting in flameless combustion mode. Air is injected through four tangential injection ports located near the bottom of the combustor and liquid fuel is injected through a centrally mounted pressure swirl injector. Computational analysis of the flow features shows that decrease in the exit port diameter of the primary chamber increases the recirculation rate of combustion products and helps in achieving the flameless combustion mode. Based on preliminary computational studies, a 30 mm primary chamber exit port diameter is chosen for experimental studies. Detailed experimental investigations show that flameless combustion mode was achieved with evenly distributed combustion reaction zone and uniform temperature distribution in the combustor. Pollutant

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emissions of CO, NO_x, C_xH_y are measured and compared for all operating conditions of different fuels and different thermal inputs. The acoustic emission levels are reduced by 6–8 dB as combustion mode shifts from conventional mode to flameless combustion mode.

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1. Introduction

Flameless combustion is a novel combustion mode, with evenly distributed combustion reaction zone results uniform temperature distribution. Flameless combustion is achieved through increased internal recirculation of hot combustion products resulting in the dilution and preheating of fresh reactants. This helps in suppressing the formation of NO_x through thermal route and CO emissions [1–12]. The reaction zone is almost invisible and uniformly distributed throughout the volume of the combustor [13–16]. To achieve flameless combustion mode, the combustion products need to be recirculated in large quantities to ensure that the flame is blown-off from primary combustion zone [1–3,5,16,17]. This reduces the concentration of the reactants to such an extent that combustion is not initiated until mixing process is complete and thereby reducing the reaction rate. Combustion reaction proceeds only when the local temperature is above the auto ignition temperature of the fuel [7]. This helps in avoiding the formation of sharp high temperature zones in the combustion chamber.

Flameless combustion with gaseous fuel has proven that irrespective of fuel quality sustained flameless combustion mode can be achieved in the combustor [7,9,14]. Preheating and dilution of the fuel and oxidizer is an important parameter to achieve the flameless combustion mode. This process is strongly influenced by internal recirculation of combustion products and mixing in the combustor. The mixing process in flameless combustion with gaseous fuel is relatively easy, because both fuel and oxidizer are in the same gaseous phase. Combustion of liquid fuels depends on fuel properties like, surface tension, viscosity, boiling point. The Sauter mean diameter (SMD) of the droplets in a spray is a function of fuel properties [18]. The properties of various liquid fuels considered for present experimental studies are summarized in Table 1. At an injection pressure of $P_{\text{inj}}=9$ bar (900 kPa), SMD of gasoline spray is 14 μm. The SMD of kerosene and diesel sprays is 20 and 26 μm respectively at the same injection pressure. Evaporation rate of droplets is a function of boiling point and surface area to volume ratio (A_s/V) of the droplet size. A_s/V of the gasoline droplets is 4.2×10^5, whereas for kerosene and diesel droplets, the value of this parameter is 3×10^5 and 2.3×10^5 respectively. The evaporation time of these droplets increases with boiling point temperature and SMD of the droplet [19]. Spray cone angle also plays an important role in the entrainment and droplet evaporation rate.

Achieving flameless combustion with liquid fuels involves many complex processes such as fuel injection, droplets distribution, droplet evaporation, mixture formation and subsequent combustion with preheating and dilution of reactants. In case of conventional combustion, flame stabilizes in a narrow zone near the fuel nozzle resulting in the formation of a high temperature zone neat the nozzle exit. Due to this, fuel droplets evaporate quickly in conventional combustion mode and get combusted near the nozzle exit [7]. However, in case of recirculation of hot combustion products, reaction zone is distributed throughout the volume of the chamber [1,2,20]. The peak flame temperature and its fluctuations are relatively lower as compared to conventional combustion mode [1,2,6,9]. The droplet evaporation rate is expected to be lower in this mode as compared with conventional combustion mode due to lower peak temperature. Therefore, to sustain the flameless combustion mode with liquid fuel, large residence time is required as compared with gaseous fuel case.

Although substantial amount of work on flameless/moderate or intense low-oxygen dilution (MILD) combustion with gaseous fuels has been reported in the literature [1–12], very little work with liquid fuels is available in the literature [13,14]. Since most of combustion systems operate with liquid fuels, it is important to develop flameless

Table 1 Characteristics of various fuels.

Property	Kerosene	Diesel	Gasoline
Density/(kg/m^3)	800	860	803
Kinematic viscosity/(m^2/s)	2.71×10^{-6}	3.64×10^{-6}	0.8×10^{-6}
Surface tension/(mN/m)	25	23	21
Flash point/K	334	398	–
Boiling point/K	433	558	364
SMD/μm ($P_{\text{inj}}=9$ bar)	20	26	14
Ratio of surface area to volume/m^{-1} (A_s/V)	3.0×10^5	2.3×10^5	4.2×10^5
Evaporation time/ms τ_{evap} at $T_\infty=1000$ K	8.1	11.6	5.3

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