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Technical Notes

Emissions Reductions in Diesel and Kerosene Flames Using a Novel Fuel Injector

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I. Introduction

A SPRAY serves as the heart of almost every type of liquid-fueled combustion system. Ideally, to promote combustion with maximum efficiency and minimum harmful emissions, an injector should deliver a fuel spray that rapidly disperses and evaporates to yield a homogeneous mixture of gaseous fuel and air. Characteristics of an ideal injector include good atomization over a wide range of either steady or transient fuel flow rates, unaffected by flow instabilities, low power requirements, scalability, resistant to blockages, and delivery of a fine spray [1,2]. Reviews by McDonell and Samuelsen [3], Razdan [4], Mansour [5], and Nakamura et al. [6] deal with fuel sprays optimized for lean combustion. Pressure atomization, air-assist and air-blast atomization, and effervescent atomization [7] are commonly used techniques for a variety of injector applications.

In the current study, we are exploring the so-called flow-blurring injector of Gañán-Calvo [8] in a combustion system. As illustrated in Fig. 1, the flow-blurring (FB) concept consists of a liquid nozzle and an orifice plate situated downstream of the nozzle. The nozzle's wall is tapered at the outlet, and the sharpened edge of the orifice plate is the same diameter as the inner diameter of the nozzle (d). When the axial distance between the nozzle exit and orifice plate (H) is small (i.e., $H/d < 0.25$), some of the gas flowing into the lateral cylindrical passageway between the nozzle exit and orifice plane is forced upstream a short distance into the nozzle carrying the liquid. The backflow of gas causes vigorous combination of turbulent mixing and effervescing, or the so-called flow-blurring, which results in a spray with very fine droplets. Simmons et al. [9] conducted cold-flow visualization experiments for a range of geometric and flow conditions to demonstrate the high efficiency of the FB injector concept.

To the best of our knowledge, the FB injector concept has never been applied to combustion systems. The objective of this study is to experimentally characterize emissions performance of the FB injector in a liquid-fueled combustor operated at atmospheric pressure. Experiments using diesel and kerosene fuels are performed for fixed fuel and total airflow rates, and the atomizing airflow rate is varied. The FB injector performance (NOx and CO emissions) is compared with that of a commercial air-blast (AB) injector.

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II. Experimental Setup

The test apparatus shown schematically in Fig. 2 consists of the combustor assembly and the injector assembly. The combustion air enters the system through a plenum, which is filled with marbles to break down the large vortical structures. The combustion air passes through a swirler into the mixing section, in which the gaseous fuel is supplied during the startup. The combustion air enters the combustor through a swirler with a swirl number of 1.5 to enhance fuel–air mixing. The bulk axial inlet velocity of the primary air is 1.9 to 2.1 m/s, which resulted in the Reynolds number varying from 5960 to 6750. The combustor is a 8.0 cm i.d. and 46-cm-long quartz tube, and it is cooled by natural convection on the back side.

The liquid fuel is supplied to the injector with separate concentric tube inlets for fuel and atomization air. The injector system runs through the plenum and the mixing chamber. An O-ring within a sleeve is located at the bottom of the plenum to prevent any leakage. A commercial AB atomizer (Delavan Siphon type 30609-2 SNA-0.20 nozzle) is used as the comparison injector in the experiments. The commercial version creates swirling flow of atomizing air to break down the fuel jet before it exits the orifice plate. The air swirler within the injector is replaced with a spacer tube to implement the FB concept. In this latter configuration, air and fuel mix together before

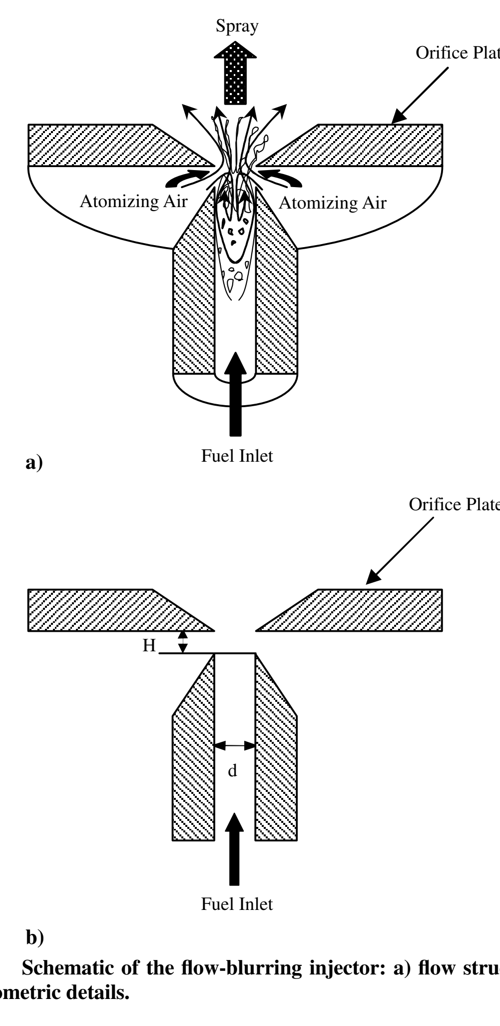


Fig. 1 Schematic of the flow-blurring injector: a) flow structure and b) geometric details.

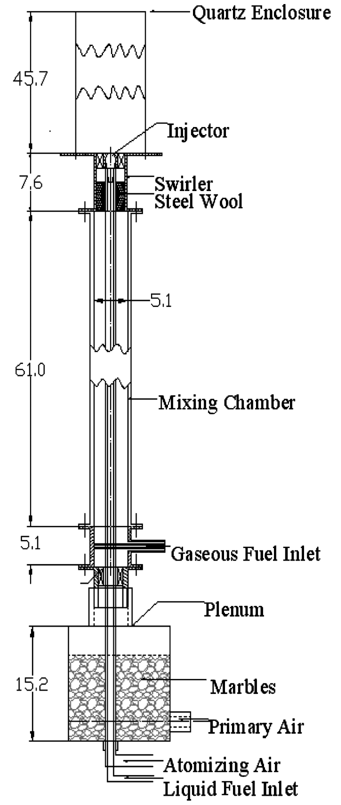


Fig. 2 Schematic diagram of the experimental setup.

exiting through the orifice plate to form the spray downstream. One notable difference between the two injectors is the diameter of the fuel nozzle: 0.5 mm for the AB injector versus 1.5 mm for the FB injector.

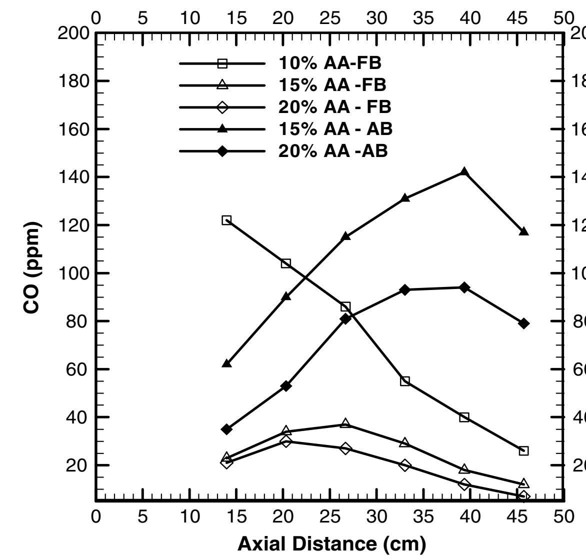
Liquid fuel is supplied by a peristaltic pump with a reported calibration error of $\pm 0.25\%$ of the flow rate reading. Viton tubes are used to prevent any degradation of the fuel lines. A 25 μm filter was used to prevent dirt and other foreign particles from entering into the injector. The air supplied by a compressor passes through a pressure regulator, dehumidifier, and water traps to remove the moisture. The dry air is split into combustion and atomizing air supply lines. The combustion airflow rate is measured by a laminar flow element calibrated for 0 to 1000 lpm of air. The atomizing airflow rate is measured by a calibrated mass flow meter.

The product gas was sampled continuously by a single-tip quartz probe (o.d. of 7.0 mm) attached to a three-way traversing system. The upstream tip of the probe was tapered to a 1 mm i.d. to quench reactions inside the probe. The probe was traversed in the axial direction at the center of the combustor and in the radial direction at the combustor exit plane. The sample passed through an ice bath and water traps to remove moisture upstream of the gas analyzers. The dry sample entered the electrochemical analyzers to measure the concentrations of CO and NOx in parts per million. The analyzer also measured oxygen and carbon dioxide concentrations, which were used to cross-check the equivalence ratio obtained from the measured fuel and airflow rates. The uncorrected emissions data on dry basis are reported with measurement uncertainty of ± 2 ppm.

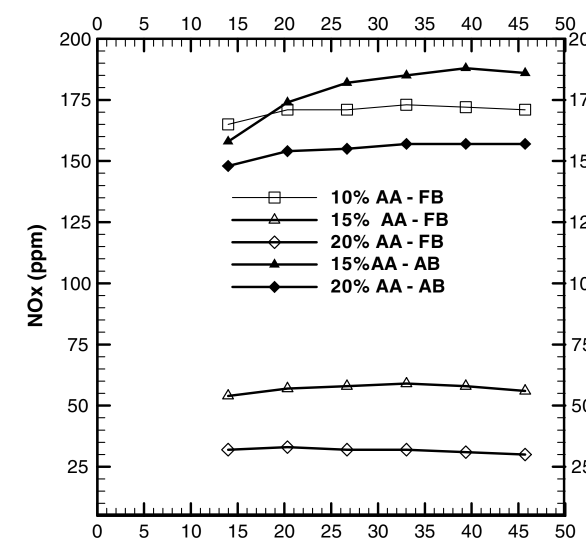
In this study, the fuel flow rates and total (combustion plus atomizing) air were kept constant, respectively, at 12 ml/min and 150 standard lpm. Experiments were conducted using diesel and kerosene fuels acquired from local supply stores. Combustion performance is strongly dependent upon the spray quality determined by the atomizing airflow rate. Thus, experiments were conducted by varying the percentage of the atomizing air (AA) in the range of 10 to 25% of the total air, depending upon the fuel and injector type. Because the total-air-to-fuel mass ratio is constant for all experiments, the effects of atomizing airflow rate, injector type, and fuel can be distinguished from emissions measurements.

III. Experimental Results

Figure 3 presents the NOx and CO emissions profiles along the axis of the combustor in diesel flames for both injectors. The axial distance z in these profiles is measured from the injector exit plane; thus, $z = 45$ cm refers to the combustor exit plane. Figure 3a shows that the CO concentrations tend to increase and then decrease in the axial direction. Initially, the CO is produced in the flame during the fuel breakdown process and it is subsequently oxidized in the reaction and postreaction zones. An increase in the atomizing airflow rate decreases the CO emissions because the premixed mode of combustion becomes more prevalent. Figure 3a shows a remarkable difference in the CO emissions of the two injectors for a given atomizing airflow rate; the FB injector results in significantly lower CO emissions than the AB injector. CO emissions of the AB injector



a)



b)

Fig. 3 Axial profiles of emissions in diesel flames: a) CO concentration and b) NOx concentration (open symbols represent the FB injector and closed symbols represent the AB injector).

for AA = 10% are not shown in Fig. 3a because they exceeded the 2000 ppm range of the gas analyzer.

NOx concentrations presented in Fig. 3b are nearly constant in the axial direction. Evidently, most of the NOx is formed in the reaction zone within $z = 12$ cm. Figure 3b shows a significant decrease in the NOx concentrations for the FB injector as AA increases from 10 to 20%. The decrease is greater between AA = 10 and 15% compared with that between AA = 15 and 20%. Again, for a fixed atomizing airflow rate, the NOx produced in AB injector flames is 3 to 5 times higher than that in the FB injector flame.

Emissions measurements were also taken at the combustor exit plane to characterize variations in the transverse flow direction. Figure 4 shows that the NOx and CO concentrations are nearly independent of the radial coordinate at the combustor exit plane, although flow asymmetry is evident at low atomizing airflow rates because of the high turbulent fluctuations in the resulting diffusion flame. Results show that higher atomizing flow rates result in a homogeneous product gas mixture at the combustor exit. Figure 4 shows that the CO and NOx emissions decrease with increasing atomizing airflow rate, and they are always 3 to 5 times lower for the FB injector as compared with the AB injector.

Emissions profiles in the axial and radial directions for the kerosene flames are presented, respectively, in Figs. 5 and 6. Results show the same trends as those observed previously in diesel flames:

1) The CO emissions initially increase and then decrease in the axial direction.

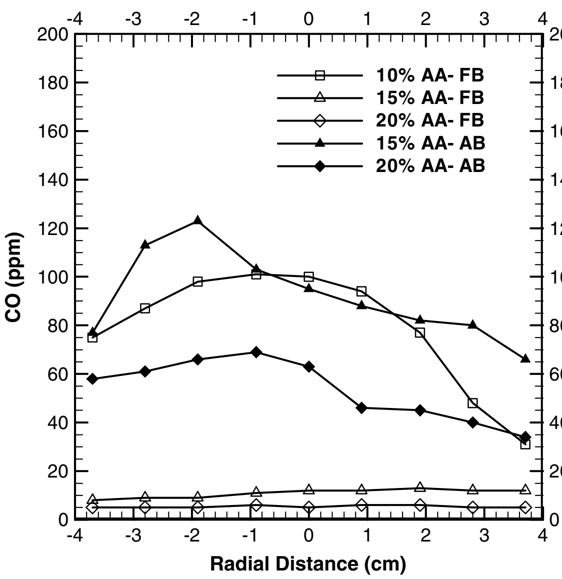
2) Much of the NOx is formed in a short reaction zone near the injector exit.

3) The CO profiles at the combustor exit display asymmetry for low atomizing airflow rates, but they are uniform at higher atomizing airflow rates when combustion occurs in the premixed mode.

4) The NOx emission profiles are nearly uniform at the combustor exit plane.

5) Both CO and NOx emissions decrease with increase in the atomizing airflow rate.

6) For a given atomizing airflow rate, the CO and NOx emissions for the FB injector are always lower (3 to 5 times) than those for the AB injector.



a)

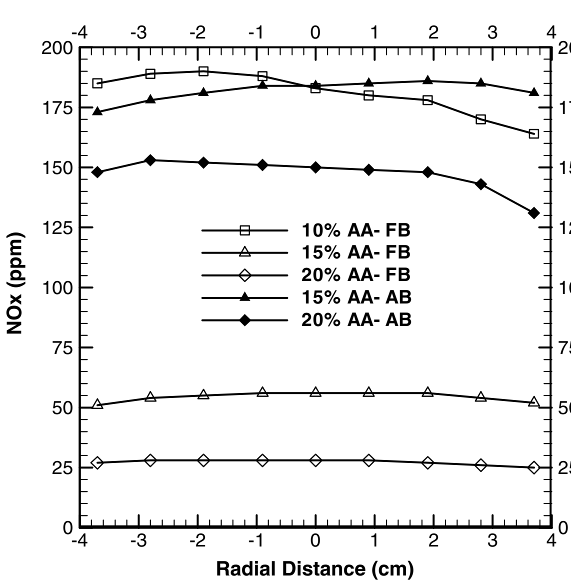


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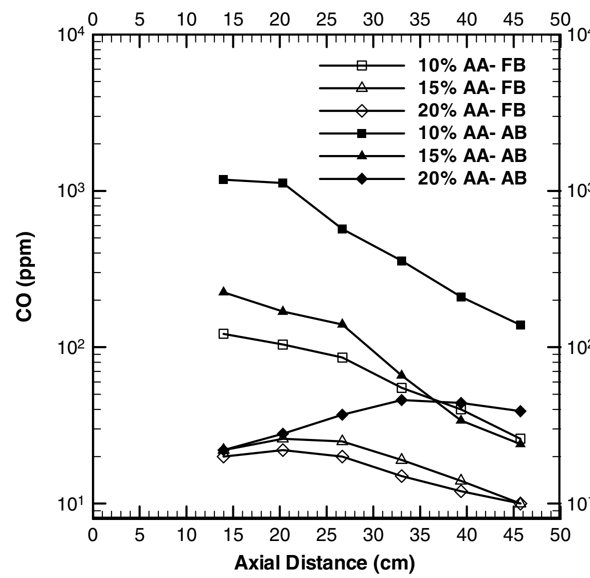
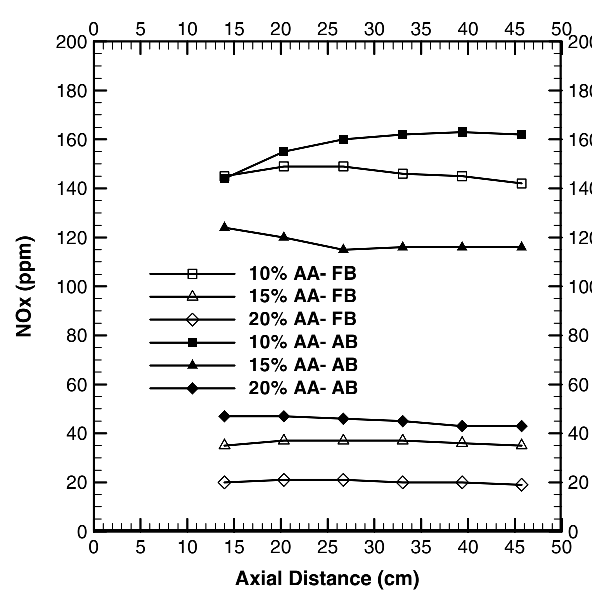
Fig. 4 Radial profiles of emissions in diesel flames: a) CO concentration and b) NOx concentration (open symbols represent the FB injector and closed symbols represent the AB injector).

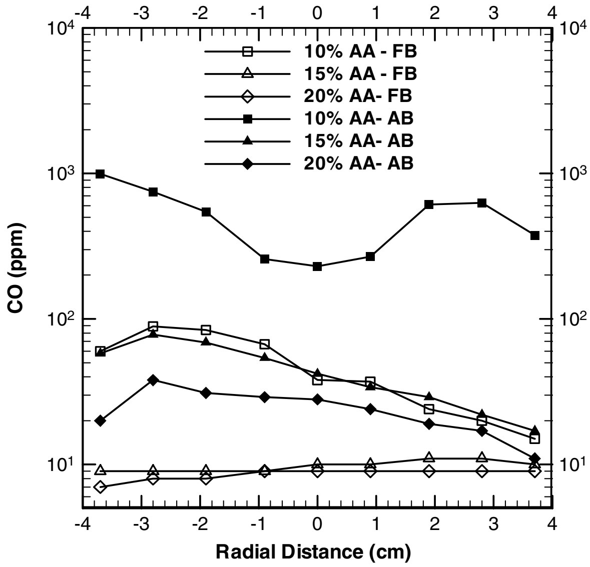


a)

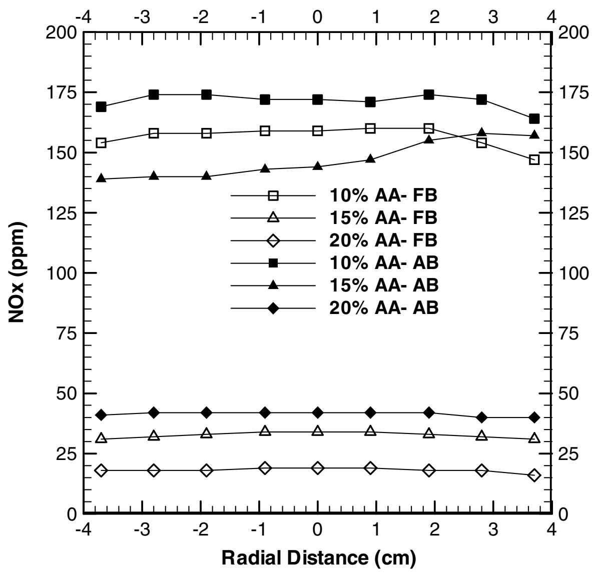


b)

Fig. 5 Axial profiles of emissions in kerosene flames: a) CO concentration and b) NOx concentration (open symbols represent the FB injector and closed symbols represent the AB injector).



a)



b)

Fig. 6 Radial profiles of emissions in kerosene flames: a) CO concentration and b) NOx concentration (open symbols represent the FB injector and closed symbols represent the AB injector).

In general, NOx and CO emissions in kerosene flames are lower than those in the diesel flames; thus, we were able to measure kerosene flame emissions for the AB injector with AA = 10%.

IV. Conclusions

A liquid fuel injector concept previously unproven in combustion systems was tested in a swirl-stabilized combustor operated at atmospheric pressure. In this so-called flow-blurring injector, the atomizing air backflows into the fuel nozzle to create vigorous fuel–air mixing, resulting in a spray with fine droplets. The emissions performance of the FB injector was compared experimentally with that of a commercial air-blast injector using diesel and kerosene fuels burning in air. For given fuel and atomizing airflow rates, the FB injector produced 3 to 5 times lower NOx and CO emissions as compared with the AB injector. Emissions in kerosene flames were slightly lower than those in diesel flames, and the FB injector was found to be consistently superior to the AB injector. Reduction in emissions can be attributed to the smaller droplets produced by the FB injector creating an effervescent effect at the nozzle exit. However, detailed measurements of drop sizes in the reacting spray similar to those reported recently by Simmons et al. [9] in water sprays are necessary to fully explain the observed results.

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