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Research paper

Influence of fuel injection frequency on droplet dispersion in ethanol pulsed spray flames

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HIGHLIGHTS

- Increase in fuel injection frequency (FIF) leads to a decrease in spray density.
- Lower FIF promotes cloud of droplets in group combustion mode.
- Higher FIF induces characteristics of single droplet combustion mode.
- Droplets in the low density spray are highly affected by swirling flow.
- Change in FIF induced a variety of flame behaviors, such as lifted flames.

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ABSTRACT

The optimized use of ethanol in current and new vehicles requires detailed information on atomization, evaporation, mixing and combustion processes of this fuel. In this work, laser diagnostic tools are applied to analyze ethanol combustion in pulsed spray flames. Fuel droplet diameter and velocity distributions are measured by Phase Doppler Interferometry (PDI) across the flame. The evolution of droplets dispersion at early stages of the injection event is visualized in a diametral plane at exit of the injector by high repetition rate Mie scattering. The burner is formed by a swirler mixer and an automotive port fuel injector both positioned at the top exit of a vertical cylinder. Three injection frequencies (100 Hz, 250 Hz, and 400 Hz) are analyzed in depth. The increase in the injection frequency induced a transition from higher to lower density spray patterns impacting the combustion process of the droplets. The higher density spray presented droplet dispersion similar to a cloud in group combustion mode, promoting a mono-modal droplet diameter distribution across the flame centerline and produced an elongated flame with a visible reaction zone down to the injection plane of the burner. The lower density spray suggests droplets in the internal group combustion mode, being highly susceptible to swirling flow structures and promoting a bi-modal diameter distribution at the centerline, mainly produced by residual droplets with high axial velocity and preferential evaporation of small droplets. Furthermore, the lowest density spray led to a shorter flame presenting similarities to a lifted flame.

1. Introduction

The increasing correlation between the degradation of the global environment and the use of fossil fuels makes it necessary to develop new technologies to generate power using alternative sources of energy. In the automotive industry, to reduce costs in the development of new concepts of internal combustion engines (ICE), renewable fuels have been adopted, such as ethanol and biodiesel. In order to improve the use of ethanol-based fuels, several fundamental processes, such as spray formation, evaporation, mixing and combustion must be better understood to provide higher efficiency in current ICEs.

In spray combustion, liquid fuel is atomized into droplets to improve the evaporation and mixing processes with the air flow. In current ICEs, fuel droplets are generated by an electronic actuated injector, based on a high pressure atomizer. This injector consists of a solenoid valve, which allows the active control of both the frequency and the mass of fuel injected into the combustion chamber.

Current ICE generation, based on direct injection of fuel into the combustion chamber, allows the use of different strategies to

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improve efficiency of the combustion process and mitigate harmful emissions. The multiple injection strategy consists of a sequency of injection events that distributes the total amount of fuel over the combustion process. Park, Yoon and Lee [1] compared the single and multiple injection strategies in a Diesel engine using a Bio-diesel. They reported that the multiple injection strategy promoted a decrease in the soot, HC and CO emissions compared to the single injection strategy. Suh [2] tested the multiple injection strategy to a low compression ratio Diesel engine using ultra low sulfur diesel. He found that this strategy decreased the HC and NOx emission but increased the CO emissions, indicating a lower temperature of the mixture during the combustion process. Similar works [5,3,4,17] indicate that multiple injection strategy promotes a decrease in pollutant emission while increasing general combustion efficiency in diesel engines. Nevertheless, those works analyze fuel injection strategies in terms of general engine performance instead of local in-cylinder measurements of droplet dynamics and the mixture process. Furthermore, only diesel-type fuels were tested and the conclusions were not extended to lighter fuels, such as gasoline and ethanol.

This work analyzes fundamental aspects of multiple injection of fuel regarding droplet dispersion and interaction to the airflow. Open ethanol spray flames are used to evaluate the influence of pulsed spray injection onto the mixture and combustion processes. This method avoids complex flow interactions usually found in ICE combustion chambers, such as airflow confinement and condensation of liquid fuel at both cylinder wall and piston head, but maintains general aspects of droplet dispersion and interaction to a swirling airflow [6–9].

In a spray flame, different droplet combustion modes are possible, as described by Chiu et al. [10]. The increase in the number of droplets promotes the decrease of the distance between droplets, changing the combustion behavior from single droplet combustion to group combustion. These combustion modes affect flame characteristics, such as length and stability. Mikami et al. [11] analyzed partially premixed spray flames, verifying the different combustion modes. Results suggested that the external group combustion mode promoted diffusion-like flames and the single droplet combustion mode produced partially premixed flame behavior.

Masri and Gounder [12] applied Laser Induced Fluorescence (LIF) and Phase Doppler Interferometry (PDI) methods to analyze both acetone and ethanol liquid fuels in turbulent piloted spray flames approaching extinction. The OH profiles showed competition between non-premixed and premixed flame behavior, with thin and thick reaction zones.

A double flame structure with an outer region presenting similarities to a diffusion flame and an inner core with partially premixed flame behavior, was visualized by Marley et al. [13] using OH-PLIF analysis of a lifted ethanol spray flame. This dual flame behavior was attributed to the spray pattern and to the mixture of a wide range of droplet diameters with the mixing air.

Bossard and Peck [14] analyzed the influence of droplet diameter distribution on combustion efficiency, using the PDI method in an ethanol spray flame, generated by an air-blast atomizer inside a horizontal combustion chamber. Results showed that narrower droplet diameter distributions led to more complete combustion processes with an increased heat release.

The interaction between the spray formed by a high pressure air-atomizer and the pulsed airflow within a confined burner was analyzed by Dubey et al. [15] using PDI. Results show that forced acoustic waves in air improved the atomization and evaporation processes, resulting in a decrease in the Sauter mean diameter of the ethanol droplets. In addition, Freret et al. [16] analyzed liquid droplets immersed in pulsating airflows by both PIV and Interferometric Particle Imaging techniques. They showed that the interaction between droplets and turbulent vortical structures improved the evaporation rate and mixture with the airflow.

The reviewed literature presents studies of multiple injection strategies focusing only on the overall engine performance using diesel-type fuels, neglecting ethanol or gasoline based fuels. Furthermore, they do not discuss details of local mixture formation and combustion process. The works that present local information of ethanol spray flames do not analyze pulsed fuel supply. Therefore, this work contributes to the understanding of the mixture formation of multiple injection of fuel in an ethanol spray flame.

Multiple injection strategies are selected based on different fuel injection frequencies into the spray flame. Both PDI and Mie scattering techniques are applied to analyze the influence of the spray pattern on the resulting flame by the statistical evaluation of droplet characteristics (diameter and axial velocity distributions) and the visualization of droplet dispersion during the initial stages of the injection event. The atomization mechanism of the injected spray was not analyzed herein.

2. Experimental procedure

In this work, ethanol spray flames (ESF) are produced by a vertical axial burner assembled on a moveable test bench and positioned in an open space with quiescent air. Fig. 1 presents a sketch of the test bench. The burner consists of a swirler mixer and a fuel injector concentrically positioned on the top exit of an 800.0 mm cylindrical tube. An automotive fuel injector is used to produce the pulsed spray.

The swirler configuration was used to provide the stabilization of the flames and is designed based on 10 vanes, inclined at an angle of 65° relative to the axial direction. The axial length of the swirler (L_s) is 15.5 mm and the inner (D_{si}) and outer (D_s) diameters of the vanes are, respectively, 17.5 mm and 40.0 mm. The diameter of the injector exit (D_i) is 10.0 mm. Fig. 2 presents a cross section of the burner. According to Beér and Chigier [18], the calculated geometric Swirl Number was 1.61 which is higher than the lower limit (0.6) to produce strong swirling flows with a central recirculation zone.

The fuel injector (pn: 0280150747 from BOSCH GmbH) is based on the solenoid valve technology and is driven by an electrical Pulse Width Modulated (PWM) signal. The signal generator is developed to allow any combination of injection frequency (f_i) and duty cycle (d_c) parameters of the solenoid valve. The duty cycle in the PWM signal represents the time along which the solenoid valve was kept energized, injecting fuel into the air stream. The injection time per

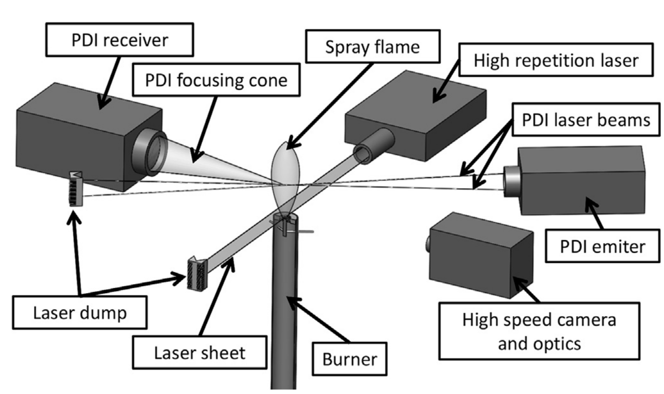

Fig. 1. Layout of the test bench used in this work.