Effects of Oxygen and Buffer Gas Concentration on Diesel Spray Flame Characteristics

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1 Introduction

Series of nitrogen-free combustion and oxygen-fuel combustion technologies have been put forward. Such as internal combustion Rankine cycle (ICRC) combined oxygen-enriched combustion, carbon capture and storage (CCS), and in-cylinder water injection technology [1]. Pure oxygen mixed with part of the exhaust gas inhales into the cylinder during intake stroke. The combustion products only contain water vaper and CO_2, both of which are easy to be seperated from gas mixture by condensation. Then the liquid water can be used to recycle the thermal energy from the exhaust gas and is directly injected into the cylinder during the combustion process. CO_2 is captured and stored in a tank. As a consequence, an engine system of high effiency and ultralow emissions is achieved. Such closed cycle diesel enging has already been introduced on submarine knowned as closed cycle diesel/air independent propulsion (CCD/AIP) [2]. Due to the addition of carbon dioxide, the specific heat ratio of the intake air changes, which seriously affects the combustion process of the diesel engine and causes low combustion temperature and low ideal engine cycle efficiency. In order to diminish this effect, using argon blending carbon dioxide as buffer gas ensures that air mixture meets the proper requirments for diesel combustion. Oxygen and buffer gas concentration have been shown to have an important impact on combustion and emission [3]. Previous studies have shown that buffer gases mainly have three effects: dilution, chemical, and thermal effects [4]. However, most studies focused on engine performance, such as exploring thermal effiency limits and emission characteristics. The flame characteristics of diesel spray combustion under wide oxygen concentration range have not been fully studied. Therefore, the objective of this work is to explore the effects of oxygen and buffer gas concentration on diesel spray flame characteristics using an optical constant volume vessel

2 Experimental setup

The experimental was carried out in a high-temperature and high-pressure constant volume vessel. A schematic diagram of the experimental apparatus is shown in Fig. 1. One JSG1 quartz block with an effective diameter of 100 mm was mounted to the one window for acquiring images by a camera. The other three windows were obstructed by black metal blocks. An electric heater was installed at the bottom of the vessel,

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heating the ambient gas to a target temperature. The injector was located at the center of the vessel top lid. The temperatures in the visible tested region were measured by thermocouples at different locations (10, 50, 90 mm away from the nozzle tip vertically) and the temperature difference was approximately uniform (less than 20 K). The temperature of the middle thermocouple (50 mm away from the nozzle tip) was adopted as the ambient temperature. The tested gas compositions have been prepared beforehand in the gas cylinder with given ratios. The error of the oxygen volume fraction was less than 0.5%. A common rail injection system (Bosch) was used to supply the fuel to the injector (single-hole type with a diameter of 0.14 mm). The flame natural luminosity was directly recorded by a high-speed camera (FASTCAM SA5, Photron) equipped with a Nikon AF 50 mm, f/1.4 lens. The time to take the images were controlled by a delay pulse generator (DG535, Stanford, USA). The settings of the high-speed camera were as follows: frame rate of 10000 fps, resolution of 768×768 pixels, aperture and exposure time were applied under different oxygen concentrations.

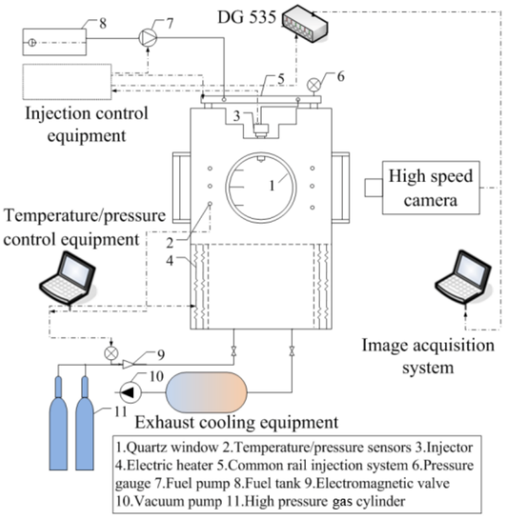

Figure 1. Schematic diagram of the experimental setup

In this test, the effects of gas parameters (component, oxygen fraction) on the combustion process of diesel spray were studied in a constant volume vessel. The ambient temperature and pressure were fixed at 800 K and 4 MPa respectively. The injection pressure was maintained at 1000 bar. The fuel injection duration was kept at 4 ms (fuel quantities were 18.9 mg). The mixtures of O_2-N_2, O_2-CO_2 and O_2-Ar were tested with the oxygen volume fractions ranging from 30%-70%, at the intervals of 10%. In order to avoid CO_2 liquefaction, the charge pressure of gas cylinder was kept only around 3-4 MPa when the oxygen concentration was lower than 30% because of the low saturation vapor pressure of CO_2. Therefore, except the mixture of O_2-CO_2, mixtures of O_2-N_2 and O_2-Ar were tested with the oxygen volume fractions of 10-21%, at the intervals of proximately 5%. The mesurement was conducted 20 times under each condition to obtain repetable results.

3 Results and discussion

Figure 2 shows single shot, true color natural flame luminosity images of diesel spray under wide oxygen concentrations at aperture of f/16. The parameters of the ambition and exposure time were noted at the top of each group of images. The image timing after start of injection (ASOI) was labeled in the top of each image. Exposure time was chosen at 4.1 us under higher oxygen concentrations. When the oxygen concentration was no more than 21%, the exposure times were fixed at 6.94 us (21% and 15% oxygen concentrations) and 20 us (10% oxygen concentration) respectively to obtain unambiguous images as much as possible.

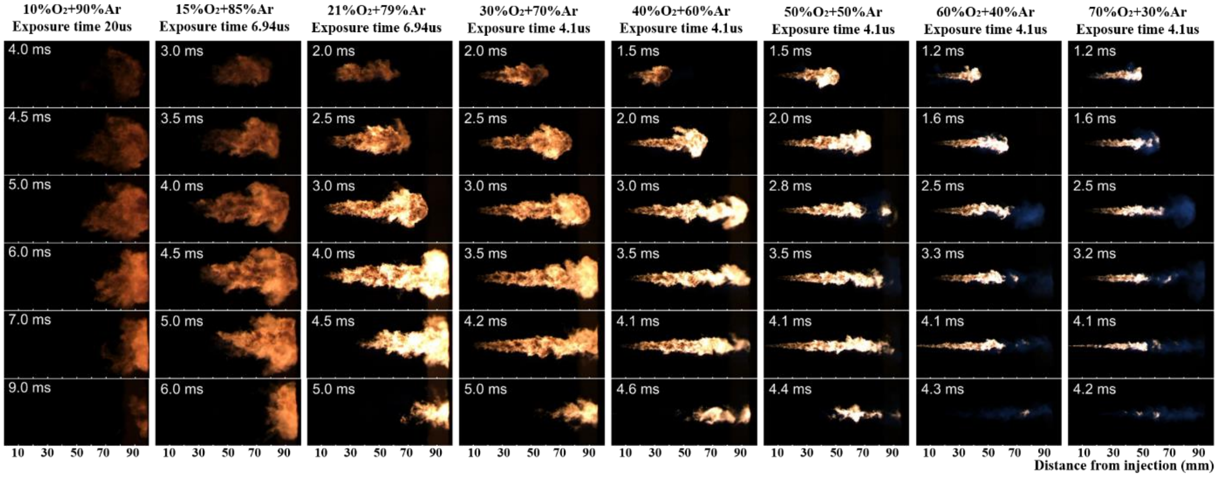

Figure 2. Single shot, true color natural flame luminosity images of diesel spray at different oxygen concentrations of 10%, 15%, 21%, 30%, 40%, 50%, 60% and 70%

As shown in Figure 2, 10% O_2 concentration has the longest ignition delay since its initial stage of combustion occurs approximately at the end of injection (injection during of 4.0 ms). Limited O_2 molecule availablity affects the buring rate of fuels. Thus combustion occurs downstream of the spray. Flame plume looks broader than that in 15% O_2 concentration. The flame luminosity is composed of chemiluminescence and soot radiation. The latter is generally several orders of magnitude higher than chemiluminescence intensity. Considering the exposure time of 10% O_2 concentration is longer than that of 15%, less soot formation at this condition could be explained by the lower flame temperature and longer premixed combustion duration. When the O_2 concentration increases to 21%, the soot formed in the high equivalence ration region [5] inside the flame is oxidized on the thinner diffusion flame surface compared to lower O_2 concentrations. More oxygen is entrained into spray at the lift-off region with the increase of O_2 concentration, so the initial position of soot formation moves upstream. When oxygen level rises from 21% to 40%, the flame front develops downstream with a decreasing sphere-like head and natural flame luminosity is incresing (Actually 21% O_2 concentration has a weaker natural flame lunimosity than 30% O_2 concentration when the exposure time keeps the same). Signal saturation starts to appear at several locations at 40% O_2 concentration. Moreover, the instabilities of diesel spray flame at the quasi-steady state become stronger with discontinuous flame tips. When the O_2 concentration rises to 50% or more, the sphere-like flame head can only be observed during the flame development phase and the turbulent flame tips are fluctuating and shedding at the quasi-steady state. As the oxygen concentration increases, the amount of oxygen migrating through the diffusion flame region increases, which causes that the large amount of soot is more susceptible to react with adequate oxygen molecules and be oxidized rapidly when moving downstream. Thus, the soot-filled hemispherical head of the diesel spray flame wrinkles and fluctuates drastically. As the oxygen concentration rises, the length of the flame is shorter and the width is narrower. The blue regions shown in the 60% and 70% O_2 concentrations at 2.5 ms ASOI in figure 2 have been demonstrated to be the intense chemiluminescence emitted by chemical reaction of CO and small molecule hydrocarbon in the previous study [6].

Figure 3 shows single shot true color (left) and false color (right) natural flame luminosity images of diesel spray with different buffer gas (Ar, N_2 and CO_2) at 30% O_2 (top) and 50% O_2 (bottom) concentrations. The ambient temperature, pressure and aperture were kept at 800 K, 4 MPa, and f/16 respectively. All cases were maintained same exposure time of 4.1 us.

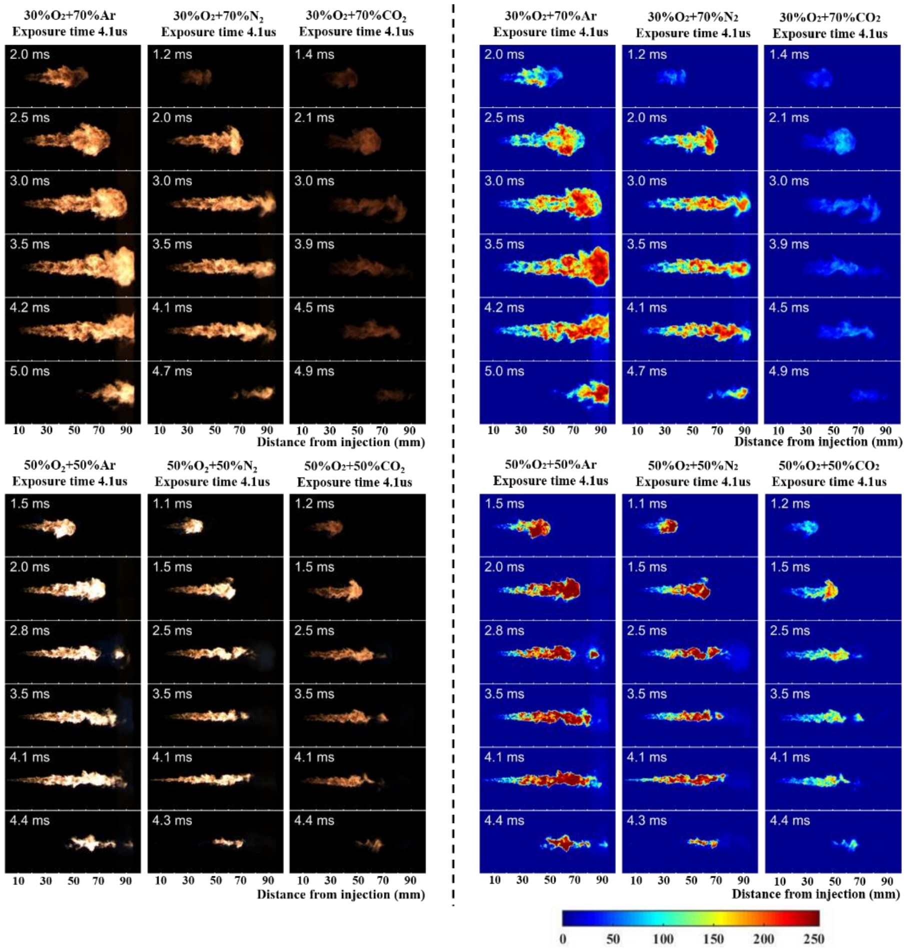

Figure 3. Left: Single shot, true color natural flame luminosity images of diesel spray with different buffer gas: Ar, N_2, CO_2 at 30% O_2 concentration (top) and 50% O_2 concentration (bottom); Right: Single shot, false color natural flame luminosity images of diesel spray with different buffer gas: Ar, N_2, CO_2 at 30% O_2 concentration (top) and 50% concentration (bottom)

As the oxygen concentration increases, all three buffer gases have the same diesel spray flame development regularity: the length of the flame is shorter and the width is narrower, the flame luminosity of center region is stronger. The natural flame luminosity of O_2-N_2 is lower than that of O_2-Ar under the same O_2 concentration, saturation pixel begins to occur at 50% O_2 concentration while it appears at 40% O_2 concentration of O_2-Ar mixture gas. The O_2-CO_2 mixtures have the weakest natural flame luminosity, indicating that it is more difficult to meet appropriate conditions for soot generation due to the thermal effects of CO_2 as the buffer gas [4]. The thermal effect due to the change in specific heat capacities affects the temperature decrease during the initial fuel decomposition step and the temperature increase during the ignition period. Because of the differences among specific heat capacities (CO_2>N_2>Ar), the thermal effects of CO_2, N_2 and Ar influence the natural flame luminosity in a decreasing order. The difference of natural flame luminosity between Ar and CO_2 is much lower than that between Ar and N_2, it could mainly be explained by the thermal effect, which is also the reason why O_2-CO_2 mixtures have the shortest flame length and soot formation zone is closer to the downstream under same oxygen concentration conditions. The severer fluctuation of O_2-CO_2 mixture in the flame head is observed at 30% oxygen condition. Under relatively lower oxygen concentration, the process that fuel molecule migrating through the flame front reacts with more oxygen atoms supplied by ambient gas prolongs due to the higher specific heat capacity of CO_2. Thus, the flame is more susceptible to violent interaction of turbulent motion. The cause of fluctuation of O_2-CO_2 mixture in the flame head at lower oxygen concentration is different from that of O_2-Ar at higher oxygen concentrations. The latter is mainly due to the increasing chemical heat release with discontinuous flame tips as mentioned before.

Figure 4 shows single shot true color natural flame luminosity images of diesel spray using Ar (left) and N_2 (right) as the buffer gas at low oxygen concentrations (10%, 15%, 21%). In order to obtain unambiguous images as much as possible, the camera parameters were set as follows (noted at the top of each group of images): the exposure times of 21%O_2+79%N_2, 10%O_2+90N_2, 21%O_2+79%Ar and 15%O_2+85%Ar were consistently set to 6.94 us; 15%O_2+85%N_2 and 10%O_2+90%Ar were consistently set to 20 us. All these cases except 10%O_2+90N_2 were kept the same aperture of f/16. Since the case of 10%O_2+90N_2 was barely ignited, the aperture was set to the biggest value of f/1.4 to observe the flame ignition process.

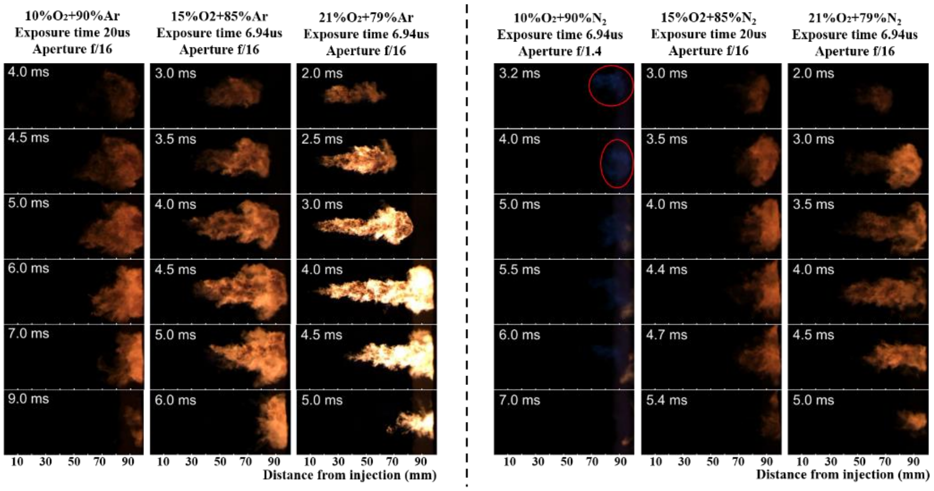

Figure 4. Left: Single shot, true color natural flame luminosity images of diesel spray using Ar as the buffer gas at different oxygen concentrations of 10%, 15%, 21%; Right: Single shot, true color natural flame luminosity images of diesel spray using N_2 as the buffer gas at different oxygen concentrations of 10%, 15%, 21%

The ignition location of O_2-N_2 cases are closer to the downstream of the spray (almost beyond the optical window under 10% and 15% oxygen concentrations) compared to that of O_2-Ar under the same oxygen concentration. Higher heat capacity of N_2 composed as the buffer gas causes lower heat release and slower temperature rise during ignition stage, which significantly affects the ignition delay and ignition location. The natural flame luminosity of 15%O_2+85%N_2 case is still slightly weaker than that of 15%O_2+85%Ar despite the higher exposure time. Natural flame luminosities using N_2 as the buffer gas are much weaker than that of Ar, which is mainly because of the less soot formation in the flame center due to the thermal effect of N_2. The general regularity of different buffer gas (N_2 and Ar) under low oxygen conditions remain the same except 10% oxygen concentration of O_2-N_2. As the oxygen concentration rises, the flame head area reduces and the flame moves upstream after initial stage. An extremely weak combustion process occurs at 10%O_2+90%N_2 case which can only be captured at the biggest aperture (f/1.4) while a stronger and more distinct flame development is observed at O_2-Ar. A faint blue chemiluminescence of small molecule hydrocarbon is captured at 3.2 ms and 4.0 ms after start of fuel injection (circled in red), which can be mainly explained by the excessive time for fuel-gas mixing due to a higher specific heat capacity of N_2. Thus, a low equivalence ratio and low temperature region was formed where soot is barely exists. When ASOI was 5 ms, the soot radiation blended with blue chemiluminescence can be observed in figure 4. A small part of local rich region meets a increasing temperature leading to the soot formation.

4 Conclusions

Effects of oxygen and buffer gas concentration on diesel spray flame ignition and development process were investigated by high-speed imaging techniques in a constant volume vessel under wide oxygen concentrations ranging from 10% to 70% with different buffer gases (Ar, N_2 and CO_2). The findings can be summarized as follows: 1. As the oxygen concentration increases, the natural flame luminosity of diesel spray flame becomes stronger, the width and length of soot flame reduce in size, a stronger fluctuation of soot head vortex occurs in the flame tips. 2. Comparing three different buffer gases, the thermal effects of CO_2, N_2 and Ar influence natural flame luminosity in a decreasing order. The severer fluctuation of O_2-CO_2 mixture is observed at 30% oxygen concentration. 3. Under low oxygen concentrations (less than 21%), natural flame luminosities using N_2 as the buffer gas are much weaker than that of Ar. An extremely weak combustion process occurs at $10\%O_2+90\%N_2$ case which can only be captured at the biggest aperture (f/1.4). A faint blue chemiluminescence is observed at initial stage of combustion.

Acknowledgment

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