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Visualization study for the effects of oxygen concentration on combustion characteristics of water-emulsified diesel

Zhaowen Wang [a,b,*], Xiong Chen [a,c], Sheng Huang [a], Yulin Chen [b], J. Hunter Mack [d], Jie Tang [a], Lei Li [a], Ronghua Huang [a,*]

[a] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China
[b] Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720, USA
[c] Dongfeng Commercial Vehicle Co., Ltd., Technical Center, Wuhan, Hubei 430056, China
[d] Department of Mechanical Engineering, University of Massachusetts Lowell, Lowell, MA 01854, USA

HIGHLIGHTS

- The combustion characteristics of water-emulsified diesel were investigated.
- Soot emissions of water-emulsified diesel were reduced by 30% compared to diesel.
- Ignition occurred first near the maximum liquid core penetration zone.
- Water-emulsified diesel decrease oxygen dilution demand by 10% for a fixed NO_x emission level.
- The flame structure was mainly determined by spray structure, not ambient O_2 level.

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ABSTRACT

Although exhaust gas recirculation (EGR) is widely implemented to suppress the NO_x, it can increase soot emissions and decrease the thermal efficiency in internal combustion engines. Water-emulsified diesel is a promising alternative approach, as it decreases soot emissions, suppresses NO_x formation, and promotes thermal efficiency through improved mixing between the fuel and air. Based on the inhibiting functions of oxygen dilution and emulsified diesel on engine emissions, a visualization study on the spray combustion of water-emulsified diesel was experimentally explored in a constant volume combustion chamber at various ambient oxygen concentrations. This study firstly examined the different combustion characteristics of water-emulsified diesel and pure diesel. Secondly, the effects of ambient oxygen concentration on combustion characteristics of water-emulsified diesel and pure diesel were investigated. Furthermore, the characteristics of soot formation and oxidation during the combustion process were revealed by flame features observed using optical techniques. Experimental results showed that a micro-explosion arose in the emulsified diesel spray which promoted mixing between the fuel and air. Local temperatures were reduced due to water's high specific heat and latent heat of vaporization, which also played important roles in ignition. The high specific heat and latent heat of vaporization had stronger effects than micro-explosions in the combustion process. The combined functions of the micro-explosion event, specific heat and latent heat of vaporization significantly decreased the soot emissions in water-emulsified diesel. Additionally, the ambient oxygen concentration affected the integrated flame luminosity and soot formation of the water-emulsified diesel. However, there were no obvious effects of the explored ambient oxygen concentrations on the ignition limit, flame boundary and flame area. The results showed that when the requirement of NO_x emissions was held constant, the use of water-emulsified diesel could decrease the need for oxygen dilution by 10%.

1. Introduction

Emissions from internal combustion (IC) engines are one of the world's main pollution sources due to the rapid rise in the number of automobiles globally [1]. The increased pollution from IC

* Corresponding authors at: State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China.
E-mail addresses: wangzhaowen@hust.edu.cn, wangzhaowen1978@gmail.com (Z. Wang).

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engines has greatly influenced the atmospheric environment [2], resulting in more stringent regulations of engine emissions and new requirements for combustion and emissions control technology.

The main emissions of diesel engines are NO_x, soot, CO and unburned HC [1,3]. A method inhibiting both the emissions of NO_x and soot is necessary to solve the emission problem of diesel engines, due to their inherent trade-off relationship [4]. According to the equivalence ratio-temperature (Φ–T) map [5,6] for locating NO_x and soot generation, the proper approach to simultaneously reduce both emissions is to concurrently control the Φ and T of the combustion process.

Exhaust gas recirculation (EGR) has been widely adopted as a common method to suppress NO_x emissions [7,8]. The reasons are due to (1) reduced in-cylinder temperature by the high specific heat of CO_2 and (2) the lower oxygen concentration diluted by CO_2 [9,10]. However, EGR also promote soot generation since they often inhibit reactions of soot consumption. The formation of soot is not reduced using EGR unless a large ratio (more than 60% by volume) is used to lower the peak in-cylinder temperature below 1600 K [11,12]. However, the use of heavy EGR can significantly drop the thermal efficiency [13,14].

Oxygen dilution also has a strong influence on controlling the development paths to mitigate emissions in Φ–T map [15,16]. There are many diluents [10] such as N_2, Ar and water that are used to dilute the in-cylinder oxygen concentration, thus decreasing engine-out emissions. This approach has been shown to be effective in spark-ignition (SI) [17], homogenous charge compression ignition (HCCI) [18], and diesel engines [19]. Water-emulsified diesel [20,21], a fuel created by mixing a certain proportion of pure diesel and water, has gained research interest to enable large pollution reduction in IC engines [22,23]. Studies performed in diesel engines have indicated these emissions reductions [24,25] are due to the large latent heat of vaporization [26,27] and specific heat [28,29] of water. The inclusion of water significantly lowers the in-cylinder temperature, which is primarily responsible for the reduction of NO_x emissions in internal combustion engines. Some research has shown that soot emissions were suppressed by the presence of water–gas reaction during the combustion event [30,31]. Additionally, a micro-explosion [32,33] is shown to exist in the spray of emulsified diesel, which improved the fuel–air mixing and resulted in decreased soot emissions.

Another benefit of using water-emulsified diesel, in comparison to EGR, for emissions mitigation in diesel engines is that water also promotes the thermal efficiency and decreases the soot emission by micro-explosions and water–gas interactions. Thus, using a combination of oxygen dilution and water-emulsified diesel is a promising route to improve engine performances and emissions.

In this study, a visualization study on the spray combustion of water-emulsified diesel was explored experimentally in a constant volume combustion chamber (CVCC) at various ambient oxygen concentrations. The difference in combustion characteristics between the water-emulsified diesel and pure diesel was firstly studied at ambient oxygen concentration of 21%. The effect of the water addition was analyzed to assess how the attributes of water (i.e. latent heat of vaporization, specific heat and micro-explosions) affected the combustion characteristics and emissions formation. Furthermore, the influence of ambient oxygen concentration on the combustion characteristics, such as ignition delay, flame luminosity, flame area, lift-off length, lift-off position and the spread velocity of the flame surface, was investigated for water-emulsified diesel. These studies expanded the understanding of water-emulsified diesel combustion at various ambient oxygen concentrations and provide a fundamental framework for subsequent studies on the emission characteristics of water-emulsified diesel in IC engines.

2. Experimental setup and procedure

2.1. Constant volume combustion chamber system

The constant volume combustion chamber system used in the experiments can reproduce the high ambient temperature and pressure found at top dead center (TDC) in the cylinder of a real IC engine. The spray and combustion characteristics in a constant volume combustion chamber (CVCC) are easier to be observed than in an engine, so the approach is widely adopted as a convenient method of characterizing the injection and combustion processes. The spray, ignition and combustion processes under high ambient temperatures and ambient pressures can be observed using optical techniques and analyzed to deduce in-cylinder properties and behaviors [34].

A schematic of the CVCC used in this study is shown in Fig. 1, which includes a constant volume chamber, a gas supply system, a fuel supply system, an injection control system, a high-speed optical system and a data acquisition system [34]. The high-speed optical system includes schlieren optical components, a high-speed charge-coupled device (CCD) camera, and a data acquisition module. In schlieren photography, the collimated light is focused with a lens and a knife-edge is placed at the focal point, positioned to block almost half of the light. The first derivative of the density in the direction of the knife-edge is measured. In the spray experiments, the light from a single collimated source shines on the spray zone in the CVCC. Variations in the refractive index caused by density gradients in the spray zone distort the collimated light beam. The different densities found in the spray are shown using the high-speed camera.

The studies conducted by Pickett et al. [35] and Nakamura et al. [36] showed that cold-flame, high-temperature chemical luminescence and soot incandescence emerged successively during combustion. The camera used in this study was a CCD camera with two ND8 dimmer lenses, which could reduce the photosensitive strength. The high temperature chemical luminescence was eliminated so that the light signal captured by the camera was merely the incandescence radiated from the high-temperature soot particles [37,38]. Using this approach, the ignition and combustion processes could be studied in addition to the rate and distribution of soot generation. The maximum recording speed of the high-speed camera was 20,000 frames-per-second (fps). The initiation of recording in the CCD camera was synchronized with the injection timing signal.

2.2. Experimental procedure

The high ambient temperature and pressure conditions similar to real engines near TDC were achieved using a pre-burn of acetylene in the CVCC. Acetylene, nitrogen and oxygen were introduced into the CVCC successively during the pre-burn event. The mixture was then ignited to achieve a high ambient temperature and pressure. Next, the burnt mixture slowly cooled down until the target temperature was reached. The fuel was subsequently injected into the chamber and ignited. The images of spray, ignition and combustion of fuels were recorded for analysis.

The target ambient temperature and density for diesel injection were 900 K and 15.0 kg/m^3 respectively. The ambient oxygen concentrations varied from 21%, 19%, 17% and 15% (by volume). The injection pressure was 150 MPa and injection duration was 2.5 ms. In order to achieve the target ambient conditions, the mass of acetylene, nitrogen and oxygen in the chamber were controlled accurately.

Before and after the pre-burn of acetylene, the constant volume chamber was well-sealed to keep the mass, and therefore the