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Spray–combustion interaction mechanism of multiple-injection under diesel engine conditions

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Abstract

Multiple-injection has shown significant benefits in the reduction of combustion emissions and soot formation. However, there is a need to understand the secondary flow-induced air–fuel mixture formation and subsequent combustion mechanism under multiple-injection. An experiment was performed by changing the dwell time between the pilot and main injections under the conditions of 23 kg/m^3 ambient density with 0% O_2 (non-combusting) and 15% O_2 (combusting) ambient conditions, at an injection pressure of 120 MPa. The mass ratios of pilot and main injections in the study were 15/85% and 20/80%. A hybrid shadowgraph and Mie scattering imaging technique in a nearly simultaneous mode along the same line of sight was used to visualize the spray and flame luminosity. Pilot-main spray flame properties including ignition delay, ignition location, and lift-off length were characterized from experimental images. CFD simulation of pilot-main spray combustion was performed under the same experimental conditions to provide additional insights into the combustion process. The air–fuel mixing field and ignition process followed by main injection flame structure are significantly altered at different dwells. The spray-to-flame interaction mechanism model has been established for the development of an optimal multiple-injection scheme for, possibly, low soot formation and emissions.

Keywords: Diesel engine; Multiple-injection; Combustion vessel; Spray combustion; CONVERGE

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1. Introduction

Multiple-injection is a common practice in modern compression–ignition engines. The advantages of multiple-injection are relatively well understood through engine dynamometer experiments, including reduced combustion noise, improved engine control, and enhanced soot oxidation [1–3]. Pilot injected fuel enhances the ignition process and improves the soot oxidation

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process, which in turn simultaneously reduces NO_x and soot [4]. However, the detailed spray–combustion interaction in multiple-injection needs to be better understood to refine and further advance fuel injection strategies that lead to higher engine efficiency and lower emissions.

Attempts to reduce emissions and soot formation usually contradict each other; that is, retarding timing will reduce NO_x but increase soot, while higher injection pressure will reduce soot but increase NO_x [4]. Some multiple-injection strategies have been shown to reduce NO_x emission and soot simultaneously [1,5,6]. Advanced injection system technology has made it feasible to study the multiple-injection strategy with precise control over the duration of pilot, dwell, and main injection [7]. Reitz [5] varied the amount of fuel injected in the pilot from 10% to 75% of the total amount of fuel injected and was able to reduce NO_x with minimal increase of soot. Other attempts to decrease the trade-off between NO_x and soot include studies of splitting main injection into two, three, or four parts on HSDI diesel engines [8] as well as double injection [6].

In this work, a pilot injection study is carried out numerically and experimentally to investigate the different phases of spray combustion and their interaction with mixture fields in a multiple-injection event. The importance of dwell is understood by analyzing the experimental results including hybrid shadowgraph and Mie scattering, and flame luminosity imaging for combustion cases. Numerical simulation results provide an understanding of the spray penetration profile and mixing of non-combusting cases, with temperature and velocity vectors characterized in combusting cases.

2. Experimental and numerical approaches

2.1. Experimental setup

A constant volume combustion chamber and optical diagnostics were used to measure spray–combustion interaction phenomena. A high-pressure and high-temperature ambient environment, replicating diesel engine conditions, was obtained by burning a composition of premixed light hydrocarbon gases, ignited by an electrode, which was then continuously mixed via a rotating fan inside the combustion chamber. A detailed description of the combustion chamber can be found in [9].

A simultaneous shadowgraph and Mie scattering imaging technique was used to measure liquid/vapor fuel spray, and flame luminosity with a neutral density filter. A high-intensity pulsed LED was used as a light source to generate the extended parallel beam via a pin-hole aperture, two concave mirrors (focal length of 750 mm, diameter of 152 mm, and f-stop of 5), and a reflector. This beam was used to measure high-speed pulsed shadowgraph and flame luminosity images. During the combustion event, this imaging technique captured flame luminosity, mostly from soot radiation. Another LED was used for Mie scattering imaging. This LED light source was placed in front of the side optical access of the combustion chamber. A negative bi-convex focusing lens (focal length of 200 mm) was used to adjust the field of view on the camera detector. A high-speed camera (Photron Fastcam SA1.1) was used to acquire liquid/vapor fuel spray and flame luminosity images at 40,000 fps, with an exposure time of 8 μs and a spatial resolution 0.14 mm/pixel. The camera lens is a Nikon Nikkor 85 mm lens with f-stop 2.8. In this way, pseudo-simultaneous measurements of shadowgraph and Mie scattering images [10] were taken when the oxygen concentration within the combustion chamber was 0%, while flame luminosity images were taken for an oxygen concentration of 15%.

A single-hole solenoid injector (details in Table 1) was used to generate multiple-injection. An example of two consecutive injections (15/85% mass-base) is shown in Fig. 1, including raw rate of injection (ROI) data, filtered ROI, and input ROI for CFD modeling, overlapped with the driver current profile. The pilot-main injection event was set to keep the same injection pulse width. The ROI was measured using a Bosch type accumulator. The injector had a few test shots before every run to confirm the distinguishable pilot and main injections in time. The pressure variation in the injector high-pressure line is negligible during the injection event as the high-pressure fuel system includes two 100 mL accumulators to store the pressurized fuel for the injection event. The chamber pressure was recorded to calculate the heat release rate. Mass ratio of pilot to main injection quantities were selected at 15/85% and 20/80%. Dwell time (DT), which is the time between the end of the pilot and the start of the main, was set at 0.17, 0.77, and 1.37 ms. The experimental test conditions are summarized in Table 1.

Table 1
Summary of test conditions.

Parameter	Value
Fuel	*n*-Heptane
Nozzle dia	100 μm
Inj. Press	120 MPa
20/80% (mass)	0.26 ms/0.74 ms
15/85% (mass)	0.26 ms/0.95 ms
Dwell	0.17, 0.77, 1.37 ms
Gas density	23 kg/m^3
Oxygen level	0%, 15%
Chamber temp.	453 K
Bulk T at injection	950 K