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.

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 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 10-75% 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 750mm, diameter of 152mm, 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 200mm) 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 μ s 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.

2.2 Simulation

The measured ROI profile had significant noise, which needed to be filtered. Filtered ROI signal looked close to a trapezoidal shape as shown in Fig. 1. In the simulation, the injection pressure is closely coupled to the ROI (mass in general), so a noisy ROI will lead to noisy pressure output. Therefore, a trapezoid profile generated from the filtered ROI was utilized to have a stable numerical injection pressure output.

The simulations were conducted using the commercial CFD software package CONVERGETM [11]. The base grid size was limited to 4 mm for all the cases, and a total of 77,293 orthogonal hex volume mesh elements were generated during the simulation. The grid used in the computation was generated internally and automatically. All transported quantities were cell-centered. A Rhie-Chow algorithm was used to interpolate the value of transported quantities at the cell boundaries, which was then used in flux calculations.

An adaptive mesh refinement (AMR) technique and a local mesh embedding technique were used to obtain improved accuracy with acceptable computational cost [11]. AMR was activated when the target flow-field variable (velocity) reached a user-defined critical sub-grid value. Local mesh embedding used in the region of spray was completed with an embedded shape of a frustum of a cylinder with a minimum radius of 0.1 mm, maximum radius of 10 mm, and cylinder length of 0.1 m. The embedding scale was set to an order of 2, thus a minimum element size of 1 mm after mesh refinement (both AMR and local embedding) was generated in the region of fuel spread for all the cases. Ideally, the AMR algorithm adds embedding where the flow field is most under-resolved or where the sub-grid field is the largest within the entire computational domain i.e., the constant volume chamber.

For the CONVERGE simulation, the spray angle was kept at 20°, and the unsteady RNG k- ϵ turbulence model [12] was used for turbulence simulation. Additionally, the No Time Counter (NTC) method [13], which calculates the outcomes of spray droplet collision, and the Frossling correlation [14], which calculates the vaporization rate of liquid droplets, was used to approach real experimental conditions. An optimized break-up time constant and break-up velocity constant were used to closely validate the numerical vapor penetration against the experiment. The *KH-RT* (Kelvin Helmholtz—Rayleigh Taylor) combined break-up mechanism was chosen for simulating spray break-up. This model assumes that only *KH* instabilities are responsible for causing the drop break-up inside of the characteristic break-up distance, whereas both *KH* and *RT* mechanisms are activated beyond the break-up length [11]. The spray parcel count was set as 50,000 per injection, which is sufficient based on the previous study [10]. An ambient gas composition of O₂ (0.0%), N₂ (89.7%), CO₂ (6.5%), and H₂O (3.8%) was chosen to simulate experimental condition of vaporization case.

For combustion simulations, the characteristic time combustion (CTC) model [15] was used for achieving less computational time by simulating the rate of change of the density of species. CTC combustion model does not take into account any detailed combustion chemistry, but it has calculations based on characteristic time to achieve equilibrium [16].

3. Results and Discussion

3.1 Vapor penetration in non-reacting flow

In-house image processing using Matlab® from experimental shadowgraph images provided measurements of vapor penetration shown in Fig. 2 along with simulation results for the mass ratio of 15%/85%. Shorter DT resulted in a faster penetration rate, as main injection provides momentum for the pilot injection to penetrate into the surroundings. Both experimental and numerical results showed similar pilot penetration followed by main injection after corresponding DT. The difference between numerical simulations and experimental data could be due to the test-to-test experimental variability. Vapor penetration in the simulation was determined from the leading spray boundary by setting the threshold to be the location where 0.1% of the fuel mass fraction remains. Additionally, cell size plays an important role in matching numerical results with actual measurements. With reduction in cell size, the vapor penetration decreases slightly and becomes closer to the actual experimental penetration and so is the case with the liquid penetration [17].

3.2 Flame luminosity

Fig. 3 shows the time-dependent flame luminosity images after the start of the main injection (AMI) for the 15%/85% mass ratio case. Images are false color depictions and can be tracked for flame growth and decay, approximately, by following the ROI profile (injection duration and dwell). For a short DT (i.e., 0.17 ms), main combustion started while the pilot combustion was still active (AMI = 0.6 ms). As the DT became longer, main combustion started when the pilot combustion was diminished or extinguished, as in the cases of DT = 0.77 ms and DT = 1.37 ms, respectively. Thus, it is clear that the spray-combustion interaction of two injections is more aggressive as the DT becomes shorter, which results in higher luminosity; that is, soot generation due to a higher local equivalence ratio which results from insufficient mixing time. For the case of DT = 0.17 ms, the main flame appears to be less distorted in its shape when compared to the other cases. The tail structures of each DT are also different, with two tails in the boundary for DT = 0.17 ms, a single, moderately thin tail for DT = 0.77 ms, and a bold, more confined tail shape in DT = 1.37 ms. Further description of the emerging phenomena between pilot and main flame is described in the CFD simulation section later.

Temporal and spatial flame luminosity was calculated by integrating flame luminosity at each axial location of each frame for the 15%/85% mass ratio as shown in Fig. 4 (a-c). This is called *IXT* (Intensity-aXial-Time) plot defined as $IXT(x, t) = \int_{-R}^R I(x, r, t) dr$, where x is the intensity axial direction, r is the radial direction, and R is intensity boundary width. *IXT* contour provides rich information of spray combustion progress including the ignition delay, lift-off length, flame height, and some aspects of internal flame structure. The two islands on the *IXT* contour represent pilot (small) and main (larger) events and the *IXT* contour clearly shows the time and location of the pilot and main combustions. The main injection shapes on the contour are similar for three dwells with differences in start of ignition and the high intensity of the combustion region. The exact mechanism of non-monotonicity of peak luminosity values with dwells on the contour is unclear at the moment. However, the peak luminosity values were repeatable. Three repeats have been performed for each test run and a visual check has been performed to ensure good repeatability. Because of very limited test runs and expensive testing, it is difficult to extract the uncertainty in the present study.

The CV pressure trace is used to determine the heat release rate (HRR) from the combustion event. Before defining the HRR, the pressure data was pre-processed to isolate the region of interest, and then was filtered to remove noise. The pressure differential (change in pressure) for each time step (10 μ s) was determined over the entire filtered pressure region of interest during the combustion event (both pilot and main) and used in the HRR relationship provided by the equation: $\frac{dQ}{dt} = \frac{\gamma}{\gamma-1} P \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dP}{dt} = \frac{1}{\gamma-1} V \frac{dP}{dt}$, where P is chamber pressure, V is the combustion vessel volume, and γ is specific heat ratio. This equation was simplified, since the combustion vessel is constant volume (1.1L), so the volume – time derivative can be neglected. The pressure – time derivative was calculated and γ is a constant representing the ratio of specific heats of the charge-gas environment, approximated as 1.35 for these tests. The cumulative heat release and the total heat released can be determined using this HRR trace. Note that there is some uncertainty in these results from pressure due to noise in the data from signal cross talk, however, this should provide a good indication of the heat release processes under the different dwell conditions.

In Fig. 4(d) there exist two main heat release rate contributions by pilot and main injections, which are separated in time. For the main injection HRR, there exist distinct combustion modes after the main injection ignition delay, the premixed period followed by the mixing controlled period. The peak HRR and total heat released (integrated HRR) during the premixed period show a significant increase with longer dwell while the total heat release during the mixing controlled period changes little. This plot demonstrates the significant influence of the dwell on the main HRR in the premixed period. It should be pointed out that there is some uncertainty to estimate the pilot HRR using the pressure trace, since the magnitude of pressure induced by pilot combustion is low for the analysis, due to the relatively large vessel volume.

The *IXT* contour plot also shows other important parameters including lift-off length (LOL), ignition delay (ID), and the locations of pilot and main injection. Fig. 5 shows that multiple-injection lift-off length varied with dwell time for the case of 15%/85% and 20%/80% mass ratios. This temporal shift of lift-off length was due to the influence of the pilot combustion. Longer lift-off length was observed for shorter DT, which can be explained by the combined momentum of the pilot and main injection pushing the ignition location downstream. However, as the DT becomes longer, the lift-off lengths are stabilized. This is a result of the momentum of the pilot injection decaying as main injection occurs. As explained earlier, in trials with shorter DT, fuel from the main injection started burning as it was injected, resulting in shorter ignition delay. Ignition delay reached an asymptote as DT increased.

The ignition delays of all DT cases were shorter than single injection, where ignition delay was observed to be approximately 0.75 ms. Note that the ignition delay was the elapsed time from the start of the main injection. Therefore, a time (pilot injection duration + dwell time) was subtracted from the start of pilot injection time until the occurrence of luminosity value of the main injection to arrive at the main ignition delay. Such short ignition delay for multiple-injection would reduce the premixed combustion phase and enhance the main injection combustion process, which was observed in Fig. 4(d) for the reduction in the premixed controlled combustion for the shorter DT case. Additionally, the results indicate that longer ignition delay may increase time for fuel-air mixing, which in turns possibly increases the rate of heat release. The trend of the locations of

main ignition was not clear and additional tests are required for a definite conclusion. While main ignition location is longest for a medium DT in cases of 15%/85% mass ratio, it is shortest for the case of 20%/80% mass ratio. However, in both mass ratio cases, shorter lift-off length and longer ignition delay were observed as DT was increased.

3.3 Simulation

Contour plots of temperature and velocity fields at the AMI = 1 ms are shown in Fig. 6 to explore spray-combustion interaction with air entrainment for the 15%/85% mass ratio with different dwells. The main liquid injection is seen in the middle of the temperature fields, and this liquid length varies with different dwells. The flame lift-off is clearly seen from Fig. 6 and Fig. 3. The behavior of the flame at the contact of pilot with main is seen as an outward bulge, which becomes lesser and lesser with increasing dwells. Another observation is the position of the vortex core exhibited by the velocity vectors, which depict the contact region of the pilot with main flame.

The temperature contours reveal an important character of the pilot flame propagation. At $DT = 0.17$ ms, the flame has high temperature regions in the middle section of the flame, due to the location of the freshly burned pilot which is by-passed by the high-momentum less-combusted (air-deficit) main flame. The bulge in the $DT = 0.17$ ms case represents the pilot flame deformation. In longer dwells, the main has more entrained air for its combustion and the pilot products cool down. Thus, pilot leads the flame structure with lesser deformation in the interaction boundary region, since there is reduced effect of the main on the pilot due to increased dwells. Air entrainment in split injection sprays is studied in the diesel engine study of Ref. [19], where there is increased entrainment of main spray under increased dwell time conditions.

At $DT = 1.37$ ms, when the pilot flame extinguishes and products cool down, the main injection will be warmed up gradually by the hot products of pilot flame while simultaneously entrained in air. This results in a confined shape of the main flame similar to the flame image seen in Fig. 3. The agreement between the CFD simulation and experimental images provides a solid foundation to obtain a good fundamental understanding of spray-combustion interaction within a multiple-injection event.

3.4 Spray-combustion interaction model

Fig. 7 shows the visualization of the spray-combustion interaction model for single injection (a) and multiple-injection with different DTs (b-d) conceptually. This concept was conjectured from the liquid/vapor penetration lengths and flame luminosity images through experiments and the CFD model. For shorter DT, vapor penetration lengths became longer and mixing time of pilot and main injections with surrounding air was insufficient. Thus, ignition delay and main ignition location became longer. The result, based on the flame image, provides evidence for agglomerated intense combustion. As the DT became longer, the vapor penetration length, ignition delay, and main ignition location became shorter. Fig. 6 shows that a longer DT increases mixing time, which is presented as more evenly distributed temperature regions.

In a single injection event seen in Fig. 7(a), fuel is injected into ambient and air entrainment follows from the spray boundary to spray core. Fuel is vaporized by hot gas and the fuel rich region is formed. Fuel and air are subsequently well-mixed to an ignitable mixture. The fuel oxidation process takes place in the fuel-rich mixture region near the downstream of liquid penetration and is continued to the boundary of the diffusion flame [20,21]. The conceptual model of multiple-injection is introduced by selecting three different DTs, i.e., short, medium and long dwell times, where the effect of pilot on the main flame is expected to differ for each individual DT. This is because combustion of the pilot has a significant effect on the main combustion, in terms of temperature and the composition of the region it leaves behind. Note that the reference time is when the pilot is injected. For the case of a short DT, the short separation time of pilot and main would leave a relatively hot region behind for the main injection, which will likely yield a shorter ignition delay compared to longer DT cases. However, the lack of oxidizer in the region that the pilot leaves behind under short DT would give the frontal area of the main injection less of a chance to combust compared to the outer boundary area of its spray. In this case, the main injection is moving toward a “circle of flame” left by the pilot. This will likely leave the main flame to have a flame on the boundary, instead of being hot in the spray core.

In the case of a medium DT, the pilot flame is well formed. Main injection is pushed into a hot “ball of flame,” and the result is that the main flame has a large heat transferring region, which causes the front region

of the main flame to burn aggressively along with the nearby spray boundary. In long DTs, pilot combustion is complete, and the remaining cooled products gradually warm the frontal region of the main injection. This results in a well-shaped confining main flame in which temperatures are, to some extent, evenly distributed along the spray. Note that the pilot has a different shape and temperature mode with varying dwells, due to the increased availability of oxidizer owing to the late occurrence of the main flame on increased dwells. These three different DTs are likely yielding different tail shapes for the main combustion as described earlier.

Soot formation can also be reduced by optimizing the split injection scheme. This is evident from the studies of Ref [22] investigating various effects related to split injection in diesel engines including the effect of mass ratio on the NO_x and soot. It shows reduction of NO_x and soot as the mass of the pilot is reduced and the main increased, however this reduction occurs in small amounts. In their study the increased NO_x from a single injection to a split injection scenario is observed while showing a reduction in the soot amounts.

4. Conclusions

Interaction of spray and flame were investigated through experimental and numerical work. For non-reacting cases, vapor penetration was accelerated with a shorter dwell time, as main injection provides higher momentum to the pilot injection compared to longer dwell cases in both experimental and numerical results. Flame luminosity imaging of main combustion enabled characterization of the ignition processes and flame structure for each case of dwell time. It is possible to conceptually categorize the shape of the main flame depending on when it is injected. As dwell time increases, ignition delay of main flame increases, but the trends of LOL and ignition location are not well defined. Agreement in CFD simulation with experimental result provides a useful tool to further investigate the interaction of spray-to-flame or flame-to-flame in a multiple-injection scheme, especially to fully understand the characteristic of main flame. Future work will focus on detailed CFD models, such as large eddy simulation (LES) to characterize flame boundary interaction with air entrainment, extracting soot formation from experimental data, and identifying optimal schematics including duration of pilot injection, dwell, and main injection.

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Figure Captions

Fig. 1. Profiles of rate of injection and injector current command (0.26ms/0.95ms with DT=0.77ms).

Fig. 2. Vapor penetration length for 15%/85% case.

Fig. 3. Pilot and main flame luminosities (false color) after main injection (AMI) for DT = 0.17 ms (left), DT = 0.77 ms (middle), and DT = 1.37 ms (right) for 15%/85% case.

Fig. 4. Instantaneous axial integration of flame luminosity for (a) DT = 0.17 ms, (b) DT = 0.77 ms, (c) DT = 1.37 ms, and (d) corresponding relative heat release rates for 15%/85% case.

Fig. 5. Ignition location, ignition delay, and average lift-off length of main flame (top) 15%/85% and (bottom) 20%/80% cases.

Fig. 6. Simulated temperature and velocity vector at AMI = 1 ms for 15%/85% case.

Fig. 7. Spray combustion interaction model for single and multiple-injection by varying dwell time; (a) single injection: (b) short DT: (c) medium DT: and (d) long DT.

Fig. 1.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Table Caption

Table 1: Summary of test conditions

Parameter	Value
Fuel	n-heptane
Nozzle Dia.	100 μm
Inj. Press.	120 MPa
20%/80% (mass)	0.26ms/0.74ms
15%/85% (mass)	0.26ms/0.95ms
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