Effect of Spray Bulging on Ignition of High Pressure Diesel Sprays

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Abstract

The early phase of fuel injection and the associated air-entrainment into the spray influences the formation of an ignitable mixture, ignition and flame stabilisation. The present study focuses on the early development of diesel sprays from a 6-hole common rail injector, and how the spray evolution affects the ignition and combustion process. Fuel was injected into an optically accessible constant volume chamber maintained at high temperature and high pressure conditions. The Mie scattering from fuel spray and the natural soot luminosity were acquired at ultra-high frame rate of 135000 frames per second to visualize the transient variations occurring in spray dispersion and ignition process. Analysis of the data reveals that radial spreading or bulging of spray occurs very early in the spray development, near the nozzle. Fuel in these bulges evaporates to form a locally ignitable mixture and ignition starts at these locations. The local flame kernels formed due to bulges subsequently gets entrained into the main spray, which can have significant implications on pollutant formation. Wide variations were observed on the formation of bulges, ignition and subsequent entrainment within an injection event between orifices of a multi-hole diesel injector.

Keywords

Diesel spray ignition, combustion, spray bulging, Ultra high speed imaging, Flame entrainment,

Introduction

Understanding of the in-cylinder processes of sprays, air-entrainment, ignition, combustion and pollutant formation in diesel engines are critical to improve the combustion efficiency and to reduce harmful emissions such as NOx and particulates to achieve ultra-low emissions. Initial spray development and entrainment of surrounding air plays a critical role on ignition and subsequent combustion in diesel engines. Characterisation of the initial stages of spray formation, mixing and combustion are essential for effective modelling of the spray combustion process in diesel engines. Early stages of the fuel spray evolution and dispersion has recently gained attraction to improve the diesel injection process [1-4]. Crua et. al.[1] studied near nozzle structure of the spray during early stages of spray injection both in atmospheric as well as engine like conditions using microscopic images captured at ultra-high imaging speeds of 5 million frames per second . They concluded that fuel trapped in the injector holes from previous injection vaporises and ejects first, followed by a liquid in the form of mushroom head. Pos et al [2] studied spatio-temporal evolution of diesel spray at the early stages of injection from six-hole common rail diesel injectors. They found that local bulging of spray occurs at the early stages of injection especially with used injectors and this affects spray penetration, they also observed variations in bulging from hole-to-hole in multi-hole injectors. Ding et al [3] studied early stages of spray development from a single hole diesel injector at different injection pressure with different fuels and made observations similar to that of Crual et al [1] where residual fuel from the previous injection forms mushroom head like structure. Manin et al [4] studied near nozzle atomization and mixing using high speed microscopic imaging to find evidence of surface tension effects on the formation of ligaments during later phases of injection. The macroscopic structure of diesel sprays, its mixing and combustion have been studied extensively, Payri et al [5] analysed velocity field in the diesel spray using Particle Image Velocimetry (PIV) in a constant volume chamber. Payri et al [6] also explored on the diesel spray tip penetration and radial expansion under reacting and inert conditions. Kondo et al [8] used high speed chemiluminescence imaging to understand late combustion in diesel spray and concluded that the UV emission may be used as a qualitative marker of heat release location and existence of flame during the late stages of combustion. Knox and Genzale [8] studied combustion recession after end of combustion and linked it to unburned hydrocarbon emissions in diesel sprays.

Most of the studies in the literature have been focussed towards the macroscopic spray and combustion characteristics such as spray development angle, liquid penetration and flame lift off length. Fewer studies have

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focussed on near nozzle spray characteristics under non-reacting conditions and few other studies focused on late combustion phases after end of injection [9]. Studies on the effect of anomalies during early development of spray such as bulges near the nozzle under reacting conditions have not been explored much in diesel injection. Hence, the present study is focused on the dynamics of spray bulges formed during early part of the spray near the nozzle under reacting conditions. Spray development, entrainment and ignition in the early part of the diesel spray combustion are studied using ultra-high speed imaging inside a constant volume chamber.

Material and methods

Experiments for this investigation were performed in an optically-accessible constant volume chamber (CVC) capable of reaching peak pressure and temperature of 12MPa and 1500K respectively. Experimental conditions used in the present study were summarized in Table 1. Elevated temperature and pressure conditions inside the constant volume chamber were achieved by pre-combustion of lean acetylene-air mixture. Acetylene and air were fed to the chamber precisely using control values and allowed to mix inside the chamber. Upon ignition with a spark plug, combustion of premixed gas mixture rises temperature and pressure inside the CVC. Pressure inside the CVC increases thereafter decreases due to cooling of combustion products and due to heat loss to chamber walls. Chamber pressure was monitored and the fuel injection was set to occur when the chamber pressure reaches a certain value during the cooling of pre-combustion. Estimated temperature and composition of ambient gas mixture at the time of fuel injection are listed in Table 1. A green LED was used to front illuminate the sprays, light scattered from sprays and the natural soot luminosity from combustion of sprays were recorded using a Photron FASTCAM SA-X2 high speed CMOS camera. Images were recorded at 135 kfps, 256 X 248 pixel^2 with a pixel resolution of 130 µm/pixel. Timing of injection, LED illumination and camera was synchronized; the schematic of the experimental setup used for the present study is shown in Figure 1.

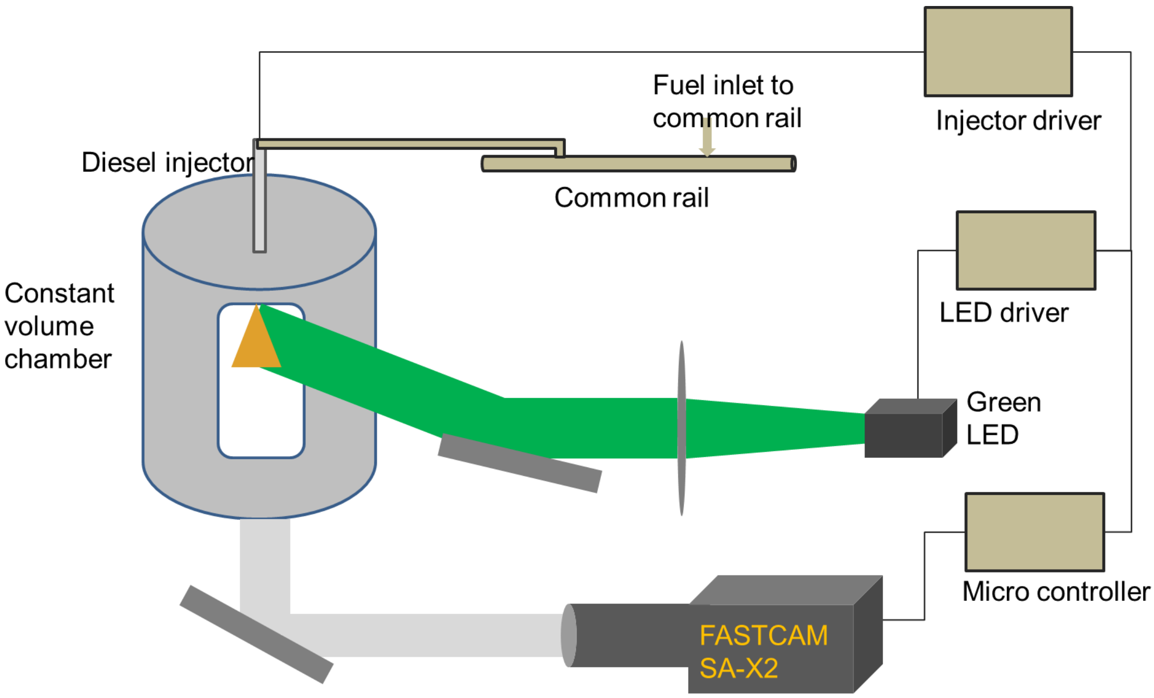

Figure 1: Schematic of experimental setup used in present study. Spray was illuminated using LED and spray combustion images inside constant volume chamber were captured using a high speed camera. Synchronization of injection, LED and camera was done using a controller.

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Injection parameters	
-Injector	6-Orifice Nozzle, Solenoid activated common rail injector
-Injection pressure	50 MPa
-Injection duration	1.5 ms
Ambient conditions at the time of Injection	
-Composition	Approximate: 11% O_2 , 77% N_2 , 8% CO_2 and 4% H_2O
-Pressure	2.55 MPa (±0.04)
-Temperature	930K (±30)
Imaging and illumination parameters	
-Frame rate	135,000 fps
-Image resolution	130 μm/pixel @ 256 X 248 pixel^2
-Camera shutter opening	3.75 μs

Table 1: Experimental conditions used for the present study.

Results and discussion

Spray combustion images of diesel from a six-hole common rail injector were recorded using the experimental setup described in the previous section. For the present study ambient conditions inside CVC at the time of injection were set at temperature of about 930 K and a pressure of about 2.55 MPa. Six orifices of the injector are numbered from 1 to 6 starting from top orifice and moving clock-wise as shown in Figure 2. The frame at which fuel spray appears at the injector tip is taken as the start of injection (SOI) and the time elapse with reference to SOI is represented on each image. Scattering of green light from spray was used as a marker to detect liquid portion of the spray and the broadband natural soot luminosity was used as a marker to identify regions of ignition and combustion. Sequence of images showing early development of spray is shown in Figure 2. Local bulging of the spray for orifice 2 is clearly visible at 66.6 μs after start of injection and where as it was visible at 96.3 μs ASOI for orifice 2 and at 185 μs for orifice 6. These images shows that occurrence of spray bulging differs between different orifices of injector both in terms of spatial as well as temporal coordinates. It was also observed that bulged part of the spray losses momentum very quickly and evaporates at that location creating a favorable mixture for ignition compared to the other parts of the spray which is clearly visible through ignition on spray from orifice 1 at 185 μs and 214.6 μs on spray from orifice 2 marked using an orange arrow.

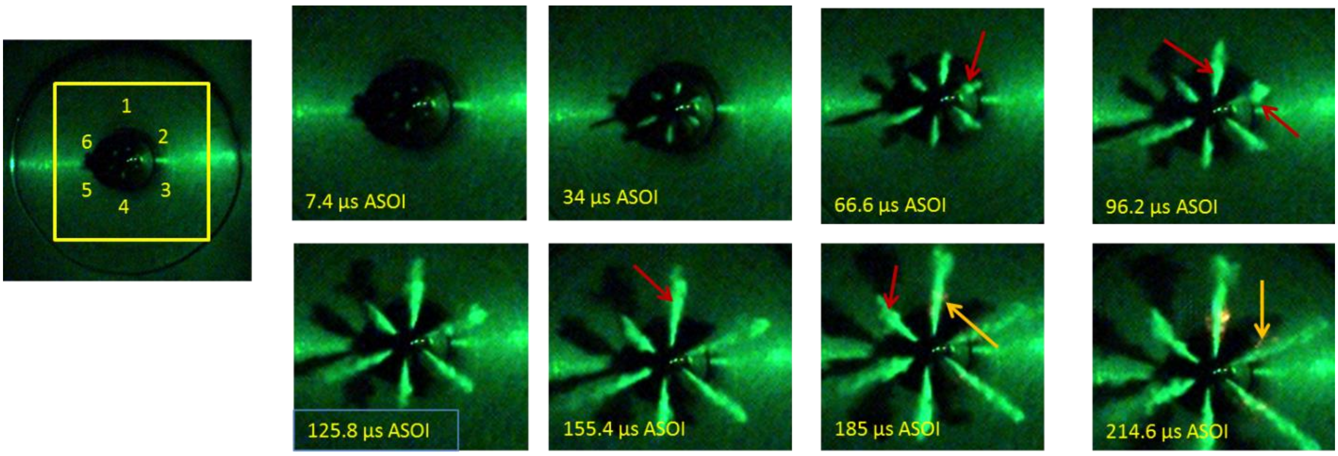

Figure 2: Local bulging in sprays during the early stages of injection.

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Figure 3 shows few of the selected sequences of images indicating the spatio-temporal location of local ignition sites observed in the sprays from different orifices within an injection event. The images also confirm that the location of the local ignition sites coinciding well with the location of bulges formed in the sprays, which further supports the observation of formation of locally favourable mixture formation for ignition due to evaporation of bulges. Once the ignition starts locally, it further progresses into other locations and engulfs entire spray and then develops into a steady part of spray flame. This observation indicates that formation of bulges affect the start of ignition as well as flame lift of length in diesel sprays.

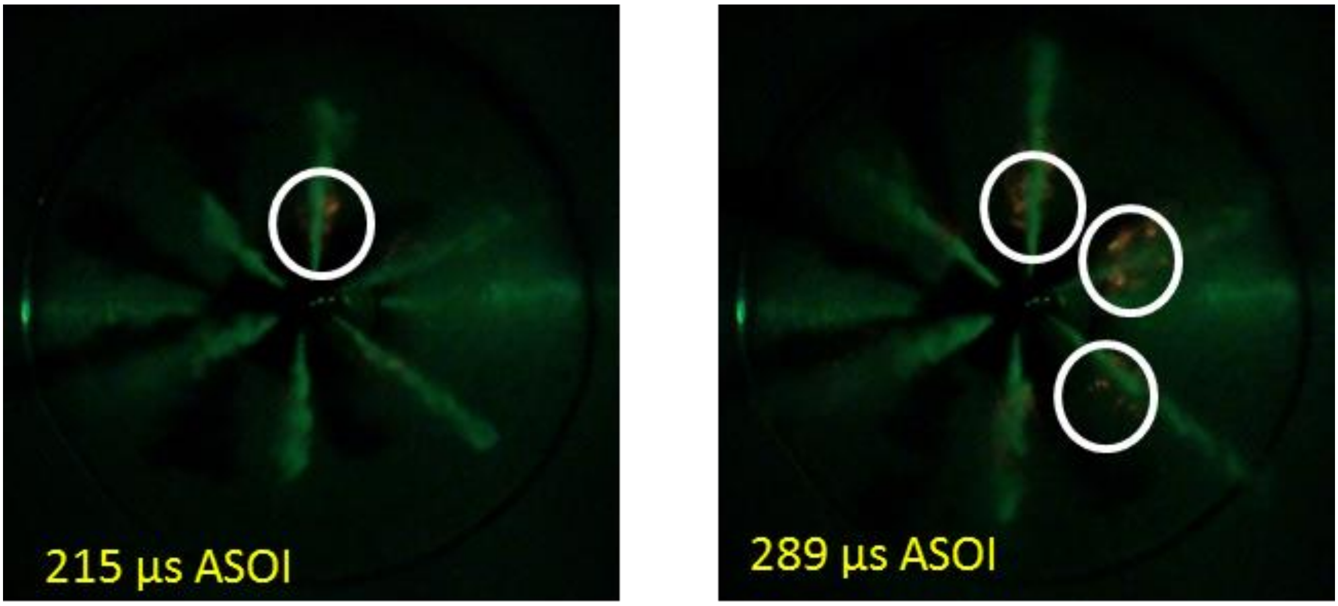

Figure 3: Location of ignition for different spray plumes from six-hole injector. Location of ignition correlates well with the location of spray bulging indicating that spray bulges create local air fuel mixture favourable for ignition.

Evolution of the local ignition sites formed within the bulges during the steady part of the spray have been indicated in white circle on the images as shown in Figure 4. It can be clearly seen that as the time progress the local ignition sites develop into flame pockets and they get entrained into the core of the spray.

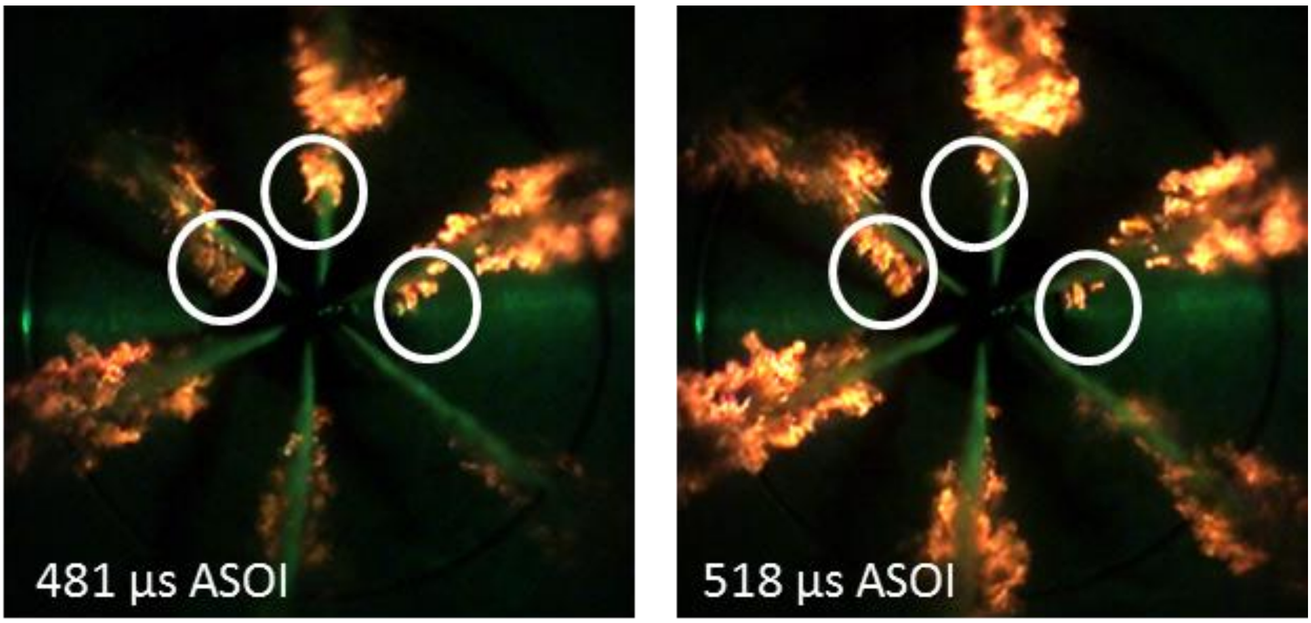

Figure 4: Images showing annihilation of flame kernels formed due to spray bulges.

Flame kernel images are processed and its entrainment into the flame core has been shown in figure 5. The ignited portion seen closer to the nozzle of spray 6 that has been encircled in white was subtracted from the rest of the main spray. This ignition zone was then converted to a binary image to capture only the soot luminosity,

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which indicates the flame in the ignition zone. Flame area was then counted as the number of bright pixels and plotted with time. The sooting regions observed in the ignition zone closer to the nozzle of spray 6 initially increased due to continuous ignition of reactive mixtures formed in the bulge. Once the entire vapour mixture formed in the bulge gets ignited at about 550 µs ASOI and this is indicated by the peak of the flame kernel area in figure 6. The soot and various species formed in the ignition region gets entrained into the main core of the spray and the flame area started to reduce, indicating a reduction in the flame area. Entrainment of hot gasses, soot and other soot precursors from the flame kernels into spray core can affect the combustion dynamics, thereby leads to the formation of pollutants. Depending on the size of the bulges, hot gasses entrained from the bulges can affect the pollutant formation significantly which require further detailed study.

A close-up view of flame kernel formed on spray 6 is sequenced showed dynamics during the entrainment process. Top portion of the flame kernel gets entrained very rapidly leaving pockets small pockets of flame. As the time progresses rate of entrainment seem to be reduced which could be due to the volume of flame kernel. Nearly half of the visible kernel was entrained in about 200 µs while the other half has taken approximately 400 µs which can also be observed from the change in area of the flame kernel in figure 5. This could be due to reduction in the interface between the flame kernel and the main spray. As the flame kernel formed due to bulges gets entrained, interface area between the kernel and the main spray jet keeps reducing and results in continuous decrease the rate of entrainment.

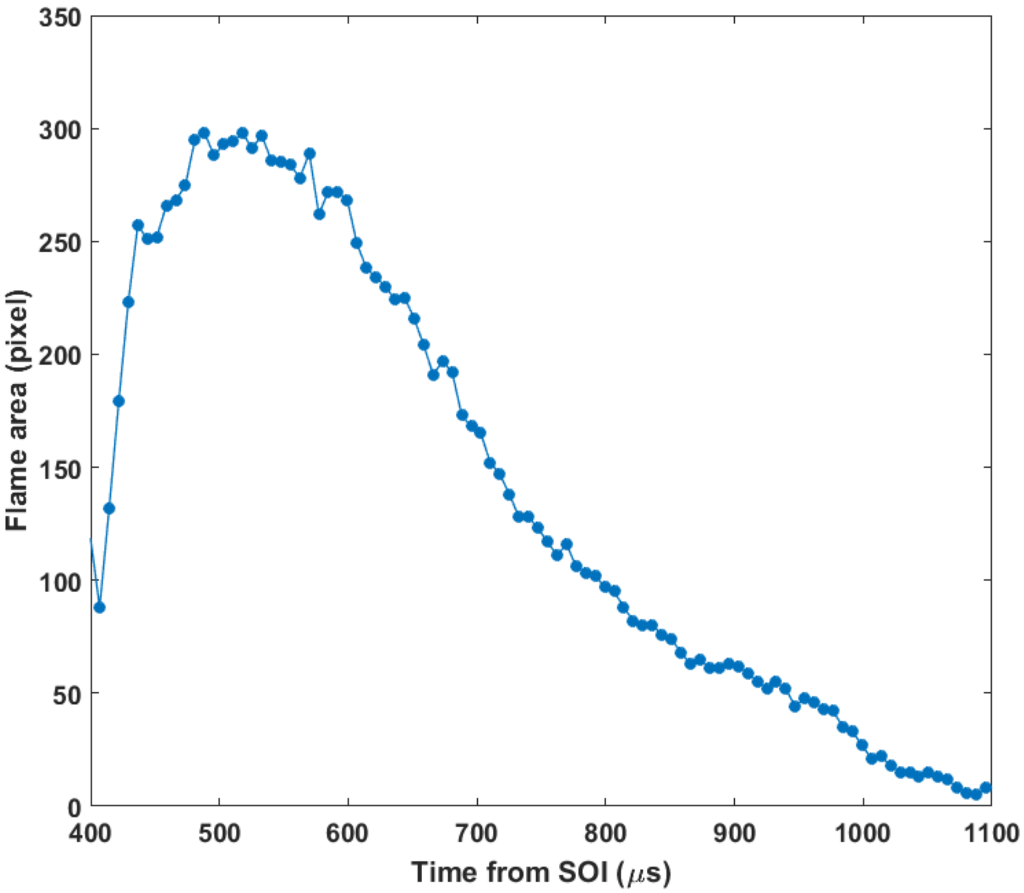

Figure 5: Variation of the flame area with time in the vicinity closer to nozzle of spray 6. Graph shows entrainment of flame pocket into the spray and complete annihilation at the end.

Conclusions

Early part of spray combustion of diesel under high temperature and high pressure conditions were studied using high speed optical diagnostics in a constant volume chamber. Spray bulges formed during the early part of the spray were tracked and it was observed that the fuel in the bulges losses momentum and they evaporate quickly forming a locally favorable conditions for ignition. Once the ignition occurs, it propagates to the remaining portion of the spray creating a sustained spray flame. Hence, the bulges developing the spray can alter the designed

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ignition characteristics of fuel sprays and may even reduce the ignition delay. Also, it was observed that the flame pockets formed due to bulges gets entrained into the core of the spray flame with time and this alters the lift-off length. Disparity in terms of ignition location as well as time was observed between sprays from different orifices of the multi-hole injector for a given injection, and this was mainly associated with the anomalies of early spray development due to complexities of flow within the nozzle sac.

Acknowledgements

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Nomenclature

CI	compression ignition
CVC	constant volume chamber
SOI	start of injection
ASOI	after start of injection

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