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Insights into near nozzle spray evolution, ignition and air/flame entrainment in high pressure spray flames

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ABSTRACT

Experimental investigations were performed to study the dynamic processes related to early development of high pressure sprays and their effects on ignition, local soot formation and its entrainment as well as spray to spray interactions in a six-hole common rail diesel injector. These spray-flame measurements were performed using ultra-high speed imaging technique in an optically accessible constant volume chamber maintained under reactive high pressure environment. The acquired back scattered light from fuel droplets and the broadband natural soot luminosity images and their analysis have revealed new insights on how the radial dispersions of fuel sprays during its early development at high injection pressures affect the ignition, flame stabilisation and soot formation in diesel spray flames.

Analysis of the high speed data have shown that radial spreading also called as bulge in this paper occurs during the very early stages of fuel spray development closer to nozzle. The cloud of finely dispersed fuel droplets trapped within these bulges loses its moment and evaporates quickly relative to liquid core of the spray to form a locally ignitable mixture and this initiates ignition from these locations. Local flame kernels formed from these local ignition sites tend to develop into small pockets of sooting flame, which subsequently moves counter to the main spray towards the nozzle and gets entrained into the liquid core of spray. At times, these sooting pockets are also transported to into the next spray when the bulges are large. The sooting flames that are transported towards the nozzle and into the liquid spray core are quenched upon its interaction with the core of liquid spray. Quenched flames are rich in unburnt hydrocarbon and soot particles and they have the potential to significantly impact the pollutant formation through altering the equivalence ratio within the core of fuel spray. Wide variations in the sizes were observed on the formation of bulges, and it also varied between sprays from different orifices of a multi-hole injector. These anomalies are mainly related to the complexity of nozzle sac flow affecting the early spray development.

1. Introduction

Development of super ultra-low engine out NO_x and Particulate Matter emissions will require a detailed understanding of the in-cylinder processes of fuel–air mixing, ignition and combustion occurring over a minuscule timescale inside the engine. Initial spray development and entrainment of surrounding air play a critical role in controlling the mixture formation and its distribution, which significantly impacts ignition, combustion and pollutant formation on a spatio-temporal scale. Experimental understanding and evaluation of the dynamics of these processes are essential for the development of models to effective predict the spray combustion and emission formation processes in diesel engines.

With the advent of high speed and high resolution optical diagnostics, new insights have been gained into fuel injection and combustion processes in application to IC engines [1–8]. Crua et al [9] have shown that a mushroom like structure precedes the main spray. Their ultra-high speed imaging of 5 million fps studies on near nozzle spray structure have revealed that the fuel trapped in the nozzle hole from previous injection vaporises and ejects prior to the liquid to form a mushroom head like structure. Similar phenomena of expulsion of residual fuel from the previous injection that led to the formation of mushroom head like structure was also observed by Ding et al [10] and this effect was observed in a single-hole diesel injector, when explored

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for different fuels at different injection pressures. Ghiji et al [11] also observed a similar phenomenon of cloud of air–fuel mixture ejecting from a diesel nozzle at the start of injection.

Following the start and during the early stages of fuel spray evolution, Pos et al [12] in their study on spatio-temporal evolution of diesel sprays found out that some of the sprays emerging from a solenoid operated six-hole common rail diesel injector experienced radial evolution and this appeared as a bulge locally at the periphery of sprays. These randomly appearing bulges were observed mainly during the early stages of injection and there were variations within the magnitude of these bulges from hole-to-hole in multi-hole injectors and this affected the spray penetration. In another study on atomization and mixing processes in diesel environment using high speed microscopic imaging, Manin et al [13] found an evidence of surface tension controlling the formation of droplets and ligaments in the near nozzle region of diesel like spays. The macroscopic studies on mixing and combustion characteristics of developed sprays have been studied extensively, where Payri et al [14] evaluated the velocity field in the diesel spray using Particle Image Velocimetry (PIV) in a constant volume chamber. While evaluating the flow fields in diesel sprays, Payri et al [15] also explored radial expansion under reacting and inert conditions at the spray tip. Kondo et al [16] used high speed chemiluminescence imaging technique to understand late combustion process in high pressure diesel sprays in a chamber to qualitatively evaluate the existence of flame during the late stages of combustion that influences the soot oxidation. Knox and Genzale [17] also used high speed investigations to study the combustion recession process in diesel sprays. Pos [18] have shown that the expulsion of fuel after the end of injection influences the soot emissions.

Most of the high pressure sprays combustion studies relevant to CI engines in the literature focused on using single orifice nozzles. However, in practical applications, most of the injectors used are multi-orifice injectors. Hence, the presence of multiple spray plumes can have significant influence on one another. Jung et al [19] compared the lift of length and the vapour plume angles between single hole nozzle and three-hole nozzle and the value were found to be different under the same experimental conditions. Polonowski et al's [20] experiments in an optical engine showed a reduction in flame lift of length with increase in the number orifices. Fuyuto et al [21] studied the backward flow of gases in a multi orifice injector sprays theoretically as well as experimentally and concluded that increasing number of orifices increases back flow velocity of gasses surrounding the spray flames. They attributed back flow of gasses as one of the reasons for shorter flame lift-off lengths for multi orifice injectors compared to the single orifice injectors found in the literature. Particle Image Velocimetry (PIV) studies on the air entrainment in a multi-hole diesel injector by Malbec and Bruneaux [22] showed that air entrainment into the spray plume will get affected by the close proximity of the other plumes. Particle Tracking Velocimetry (PTV) measurements by Fuyuto et al [23] around the spray plumes from an 8-hole injector indicated flow gases between spray plumes at a velocity of 2–3 m/s toward the nozzle tip. The presence of bulges as observed by Pos et al [12] along with the flow of gasses between the spray plumes can influence the interaction between the spray plumes in a multi-hole injector.

This article presents a new insight on how the radial dispersions developed near-nozzle during the early stages of fuel spray evolution influences ignition and formation of local soot pockets within these bulges in diesel spray flames under reactive conditions. The entrainment of these local soot pockets into the liquid core of the same spray as well as to the neighbouring sprays have been substantiated using ultra-high speed optical diagnostics in a multi-hole diesel injector.

2. 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 12.0 MPa and 1500 K respectively. Elevated temperature and pressure conditions inside the constant volume chamber were achieved by pre-combustion of lean acetylene-air mixture. Acetylene and air were precisely controlled and fed independently into the chamber through control valves and the gases were 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 fuel injection was set to occur when chamber pressure reached a certain value during cooling of combustion. A green LED was used to front illuminate the sprays, light scattered from sprays and the natural soot luminosity from combustion of sprays were acquired using a Photron FASTCAM SA-X2 high speed CMOS camera. Images were recorded at ultra high-speed of 135 kfps, 256 × 248 pixel^2 with a pixel resolution of 130 μm/pixel. The timing of fuel injection, LED illumination and camera was synchronized using a controller; the schematic of the experimental setup used for the present study is shown in Fig. 1. The LED light used was green color (520–540 nm) and the duration of LED illumination was for 2.5 ms from the start of injection electronic trigger. The exposure time of the camera for this study was set at 3.5 μs. According to Pickett et al [24] chemiluminescence signal is much weaker when compared to the soot luminosity and require image intensifier to capture the signal. Since the camera used for the present study was not equipped with image intensifier, the contribution of visible wave length chemiluminescence will be negligible in the captured images.

Spray combustion from a six-hole solenoid operated common rail diesel injector was imaged using the experimental setup explained above. The average diameter at the exit of six orifices was measured as 143 μm ± 5 μm. An injection pressure of 50 MPa and injection duration of 1.5 ms was used for this study. The temperature and pressure inside the chamber at the time of injection was 2.55 ± 0.04 MPa and 930 ± 30 K respectively. The approximate gas composition inside the chamber at the time of fuel injection was 11% O_2, 77% N_2, 8% CO_2 and 4% H_2O and this was obtained through the thermodynamic calculations based on the assumption of complete combustion of acetylene with air during pre-combustion.

3. Results and discussion

Fig. 2 shows the very early evolution of sprays from a six-hole injector during the needle opening period and these sprays have been numbered 1 to 6 starting from top in the clock-wise direction. The frame at which fuel spray appears at the injector nozzle tip is taken as the start of injection (SOI) and the time elapse with reference to SOI is represented on each image. Back scattering of green light from droplets 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.

High speed investigations revealed that the radial dispersion of the spray, local bulging was caused due to random and chaotic variations in the nozzle-hole flow due to cavitation that causes occasional discontinuity and intermittence to high speed liquid jet flow leaving the nozzle. This intermittence eventually causes stagnation effect because of varying velocity of intermittent liquid plume near the nozzle causing radial spreading. This effect of radial development is visible for the spray of orifice 2 at 66.6 μs after start of injection and its development can be seen at 96.3 μs aSOI for orifice 2. Similarly, local bulging was also observed for the spray from orifice 6 at 185 μs aSOI. These images show that the occurrences of bulges in sprays are different between different orifices of an injector for a given injection both in terms of spatial as well as temporal coordinates. Thus the amount of fuel trapped within a radially dispersed bulge is different for sprays emerging from different orifices of the nozzle for a given injection and it also varies between injections. Similar observations were also made by Pos et al [12] where they reported about a radially evolving bulge from the spray quickly

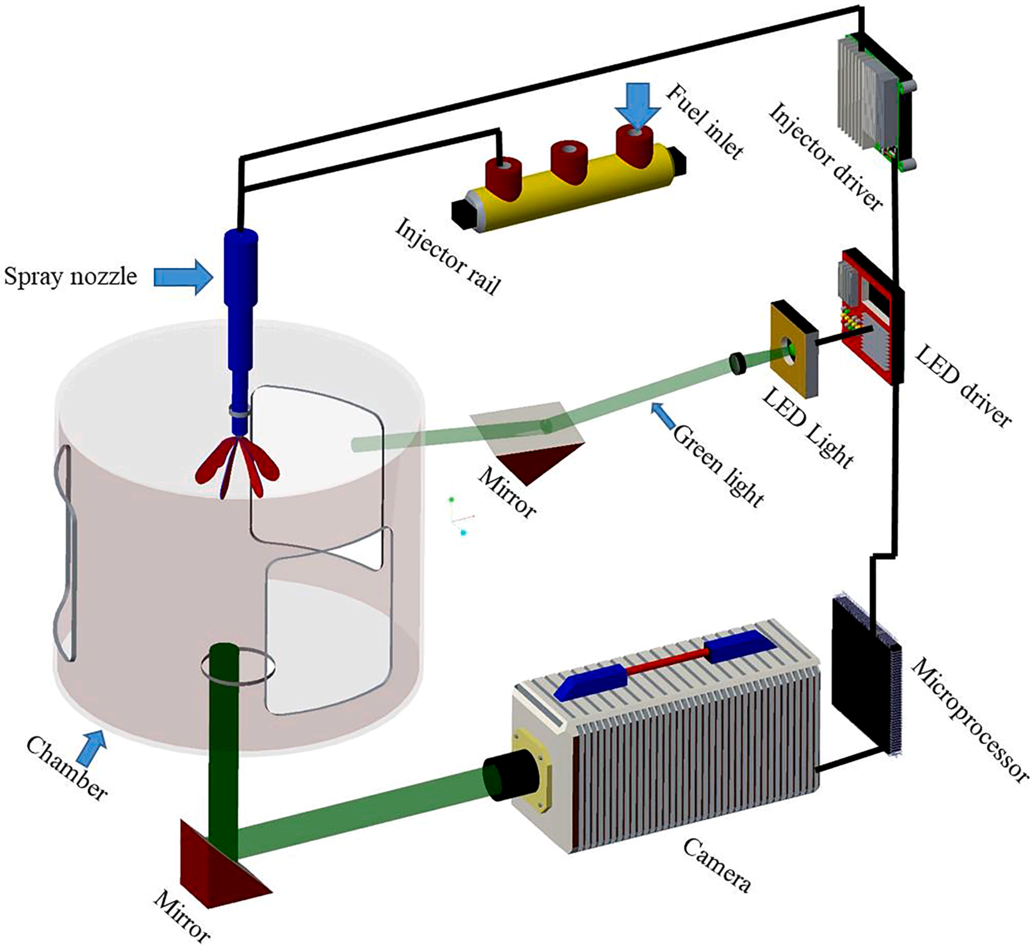


Fig. 1. Schematic of experimental setup used in present study. Spray was illuminated using green LED and spray combustion images inside constant volume chamber were captured using a high speed camera. Synchronization of injection, LED and camera were done using a programmable micro-controller. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

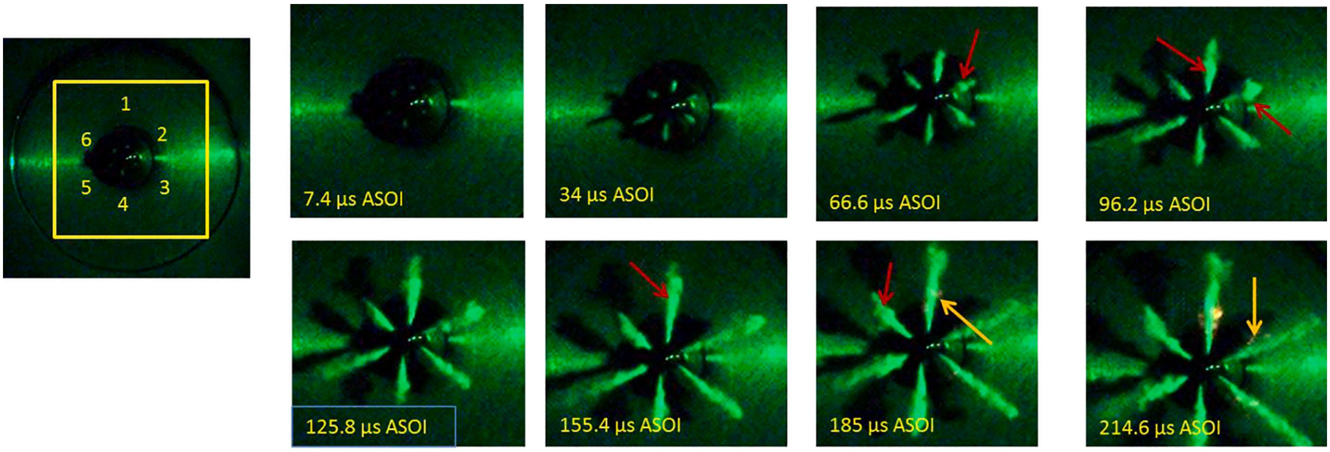


Fig. 2. Local bulging of spray during initial part of the spray development.

losing its axial momentum and evaporate at that location to form a favourable mixture to initiate ignition at that site compared to the other parts of the spray. This phenomenon was clearly observed in the high speed images of our investigations, where the early ignition sites were spotted on the periphery of spray from orifice 1 at 185 μs and at 214.6 μs respectively, these local ignition sites have been highlighted in Fig. 2 using an orange arrow.

Fig. 3 shows the sequence of spray images indicating the location of initial soot formation in sprays from different orifices as well as time of occurrence from SOI within an injection. The time at which initial soot formations observed in sprays were different and this was due to the variations in local spatial mixture distribution. The high speed investigations revealed that the location of initial soot formation coincides well within the location of bulge formation, which further substantiates

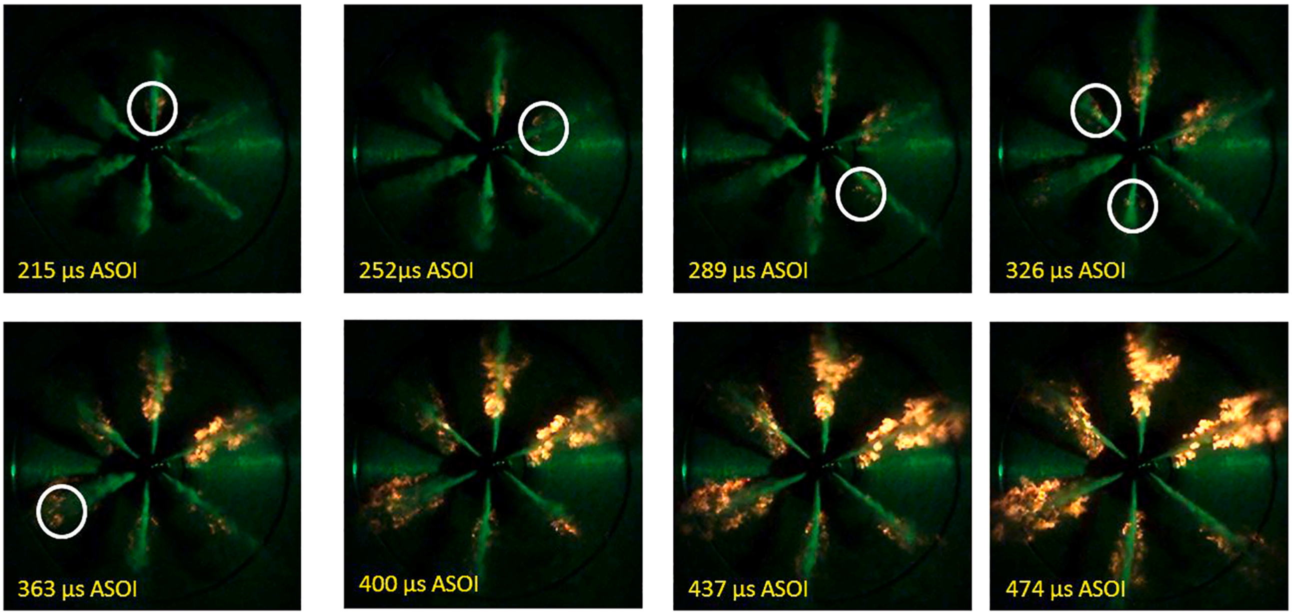


Fig. 3. Location of ignition for different sprays from six-hole injector. Location of ignition correlates well with the location of spray bulging indicates that spray bulges create local air fuel mixture favourable for ignition.

the proposed hypothesis of rapid evaporation of dispersed fuel within the bulges to form a locally favourable mixture to initiate ignition and development of flame kernel. It can also be observed that for sprays where significant bulging occurs closer to the nozzle i.e for orifices 1, 2 and 6, flames tend to develop closer to nozzle. Formation of these bulges closer to nozzle has the potential to affect the flame stabilisation location. Once the combustion starts locally, it progresses downstream to establish into a developed steady spray-flame. This observation indicates that formation of bulges can influence the location of the early start of ignition as well as flame lift of length during the initial part of transiently evolving diesel spray combustion process.

Once the spray-flame has stabilised, the local flame pockets originally developed due to ignition of the fuel–air mixtures in the bulges have been analysed and they are indicated in white circle as shown in Fig. 4. The analysis of high speed images revealed that as time progresses, the flame pockets from within the bulges located at the spray periphery in the regions of the shear layer gets trapped into weakly prevailing vortices. This gradually transport the soot pockets toward the nozzle in the direction opposite to that of spray motion that eventually gets entrained into the liquid core of the spray. This soot entrainment event was observed to occur consistently for all sprays that had bulges. Instead of totally entraining hot air into the core of the spray upstream of flame lift-off, the entrainment of hot burning soot into the core can eventually modulate the equivalence ratio distribution within the liquid core and this can lead to relatively higher soot formation in spray flames. At the instant when hot burning soot approaches the liquid core of the spray traveling with high speed, the hot soot quenches, as a result unburnt hydrocarbons and soot particles get entrained. The phenomena also leads to total annihilation of flame kernel as well as soot formed from spray bulges with time due to its entrainment into liquid core.

A close-up view of the evolved flame kernel that was ignited from the bulge of the spray from orifice 6 and the dynamics of processes related to its transportation towards the nozzle and entrainment into the liquid core has been sequenced in Fig. 5. The soot oxidation process could not be totally eliminated during the transport of flame kernel towards the nozzle and its subsequent entrainment, as both effects contribute to annihilation of flame kernels and they are convolved. The observation of high speed images and its analysis revealed that flame kernel seen on the

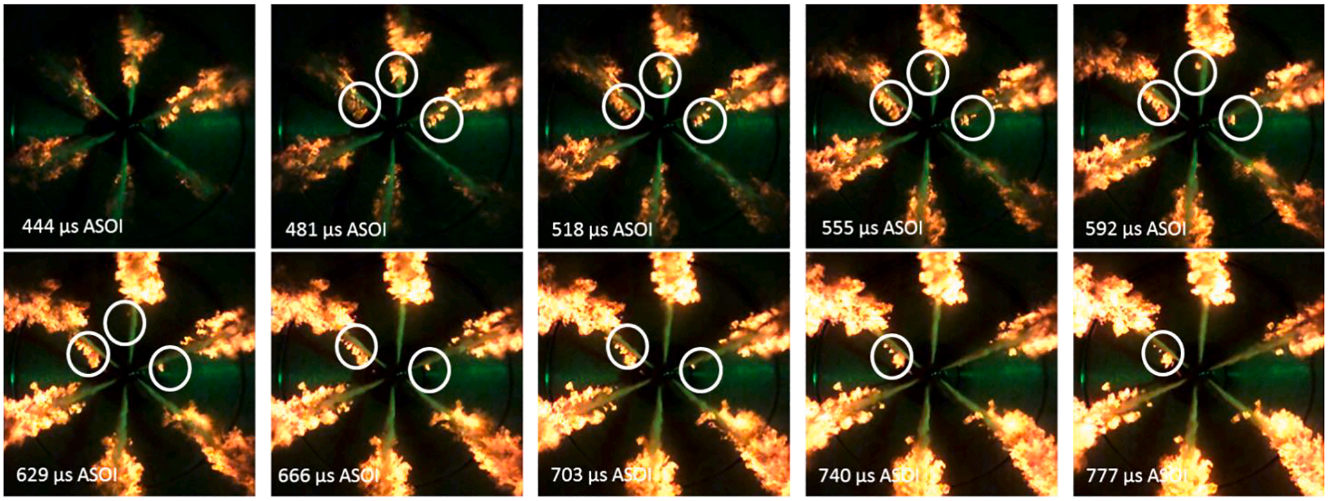


Fig. 4. Sequence of images showing annihilation of flame kernels formed due to spray bulges.

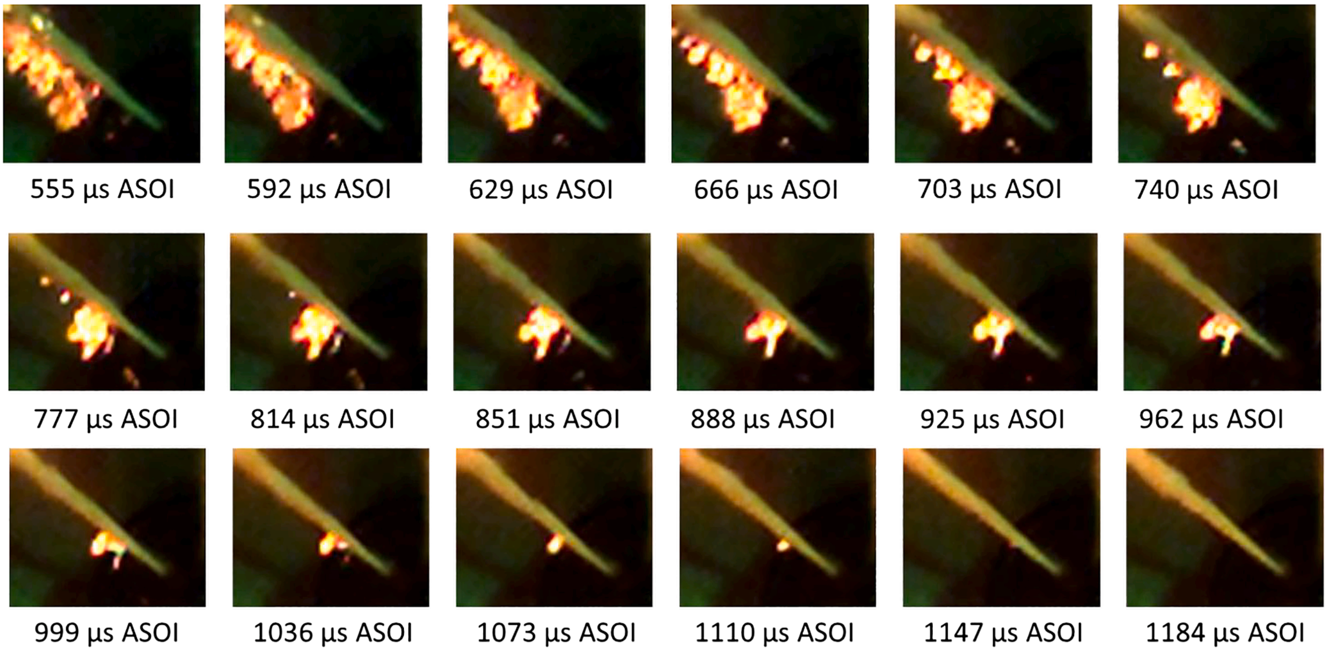


Fig. 5. A close up image sequence of flame pocket formed due to local bulge on spray from orifice 6. Images show entrainment of flame pocket into the spray and complete annihilation at the end.

downstream of the spray flame gets consumed through oxidation and entrainment rapidly into the liquid core. This process eventually results in small flame pockets closer to nozzle as seen at 740 µs aSOI, and as time progressed the rate of oxidation and entrainment also appears to be reduced. Nearly half of the visible sooting flame kernel was either oxidised or entrained in about 200 µs, from 555 µs aSOI to 740 µs aSOI while the other half took about 400 µs from 740 µs aSOI to 1147 µs aSOI. Complete annihilation of kernel was observed when the time progresses up to 1147 µs aSOI. The entrainment of hot gasses from sooting flame kernels into liquid core of spray can affect the combustion processes and there by affecting the formation of pollutants. Depending on the size of the bulge, hot burnt gasses entrained from the bulges can affect the pollutant formation significantly in spray flames.

Broadband natural soot luminosity of spray combustion observed in the near vicinity of the nozzle of approximately 10 mm from the injector tip were processed for all the six sprays using Matlab image processing algorithm to elucidate the extent of soot luminosity distributed around each spray plume. This was analysed by counting the total number of

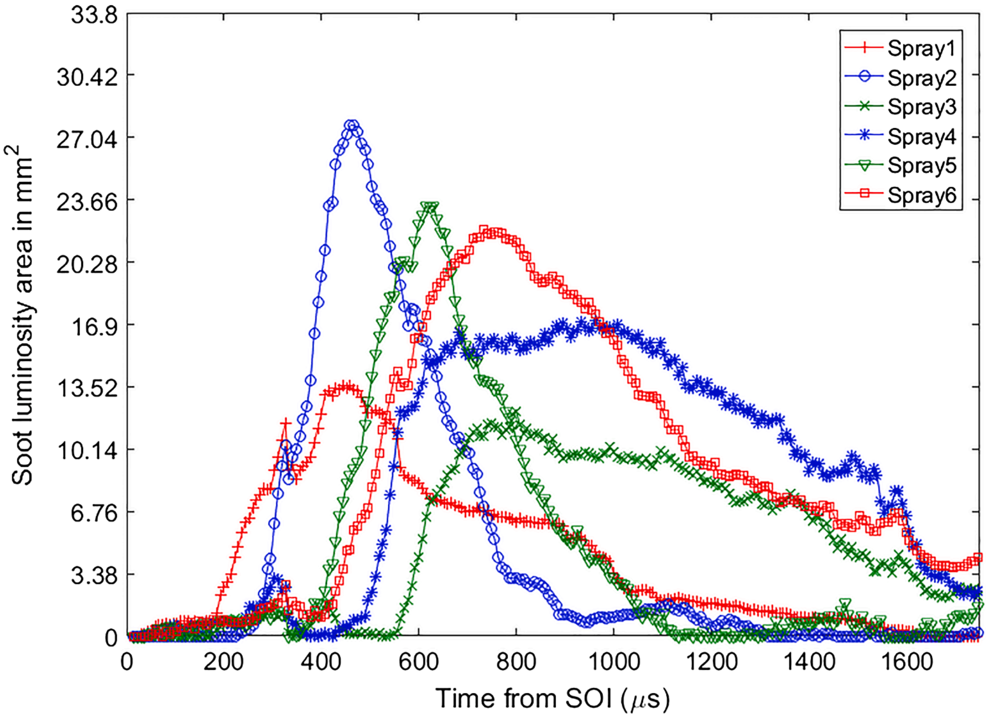


Fig. 6. Variation in the soot luminosity area close to the nozzle with time for a typical spray event. Initial increase in the area shows ignition of fuel–air mixture from bulges and subsequent reduction shows convolved effect of oxidation and entrainment of sooting flame into the liquid core of spray.

luminous pixels distributed around each spray plume, which represents the extent of flame spread. Thus the change in the total area will provide insights into a convolved effect of oxidation of soot formed from the bulges as well as entrainment of oxidising sooting into the liquid core of the main spray. The results from the analysis for each of the spray flame from the nozzle tip to a distance of 10 mm from the nozzle tip are shown in Fig. 6. The initial raise in the natural soot luminosity area are associated with development of flame from the ignition of fuel–air mixture in the bulges observed in the periphery of spray. As time progresses, entire fuel–air mixture trapped within bulge ignites and this develops into a luminous sooting flame. Due to variation in the sizes of the bulges formed in the initial part of each spray, as shown in Fig. 2, there are differences in flame area formed around each spray plume as seen in Fig. 6. It can also be observed in Fig. 6 that ignition and its associated soot formation starts at different time instant for different spray plumes and this could be related to variations in near nozzle spray development, the size of the bulge, and variations in the local fuel–air mixture distribution around each spray plume. For all the spray plumes, the local soot luminosity area developed from bulges reaches a peak before it starts to decrease with time. This reduction in the flame area may be related to entrainment of un-oxidised sooting flame left near nozzle at each time instant. When the bulges are larger during the early part of the spray formation or closer to the tip as observed for spray 1 and spray 2 in Fig. 2, ignition for these two sprays was found to occur earlier compared to the other plumes as seen in Fig. 6. Due to variations in the nozzle flow, spray development, radial dispersion, size of bulge, local mixing, ignition and varying degree of soot formation, the amount of burnt gasses entrained into each of the spray plumes will be different, thus the soot yield can be very different between sprays of a multi-hole nozzle within a given injection.

Ignition and soot formation for the sprays were observed to be relatively closer to the nozzle compared to the literature due to the formation of bulge in these sprays and it is reflected in the measured soot entrainment length. Soot entrainment length is defined as the distance between the nozzle tip and the nearest location of the soot entrainment along the spray axis. In this work, nearest flame location was identified based on the soot luminosity using Matlab image processing algorithm. The variations in soot entrainment location for a 10% variation in the threshold value was found to be less than 5%. The obtained soot entrainment length variation with time for sprays from different orifices has been shown in Fig. 7. In general, during the initial part of spray combustion, the soot entrainment length was found be shorter when compared to the flame lift-off length values reported in the literature [18]. This is due to combustion of local fuel–air mixture pockets formed due to initial bulging of the spray. Once these flame kernels formed due to bulges gets entrained into main spray, the soot entrainment length shifts downstream of the spray and is observed to be closer to the lift-off length values reported in [25,26]. The detected soot entrainment length for sprays indicates slight movement of flame towards the injector tip. This trend occurred when the flame in the bulge gets entangled into the regions closer to the turbulent shear layers and gradually transported downstream to entrain into the core through the augmentation of radial velocity field directed towards the liquid core in the near nozzle region of the spray flame. A sudden increase in the soot entrainment length indicates complete entrainment of nearest flame pocket into the spray. These ultra high-speed natural soot luminosity observations corroborate with the flow field measurements surrounding the sprays of multi-hole injector by Malbec and Bruneaux [22] and from the single hole injector flow field measurements of Nishda et al [27] where the gas entrainment into the spray jet occurs through radial velocity field closer to the injector. The air entrainment measurements in diesel-like gas jets by Bruneaux et al [28] showed a weak vortex like structures closer to the injector tip and this explains the counter movement of ignited flame from the bulge to move towards the nozzle**.** The studies by Fuyoto et al [21,23] indicates the movement of hot burned gasses towards the injector. The recent measurements by Wei et al. [29] using micro-PTV very close to the near nozzle region indicates velocity vectors pointing radially normal to the spray jet closer to the nozzle. These flow field observations in the literature together with our visual tracking of the flame as well as flame lift-off length measurements show that besides soot oxidation, there is simultaneous transport of sooting flame kernel from the bulges towards the nozzle and it gets entrained all through its

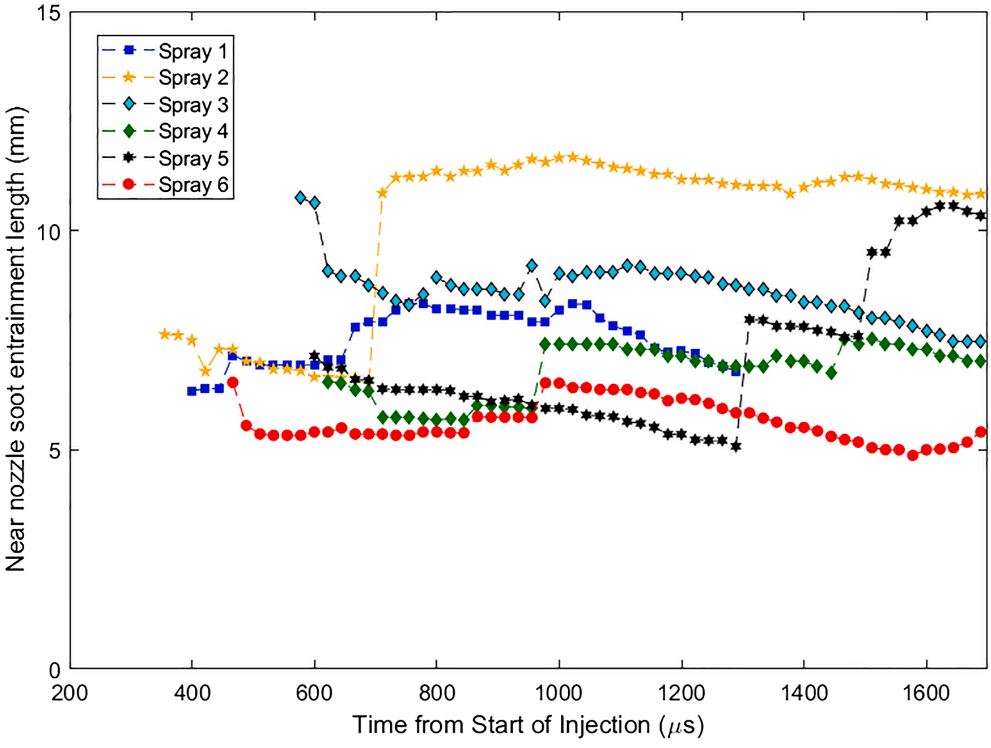


Fig. 7. Near nozzle soot entrainment length variation with time for different spray flames from different orifices of a multi hole injector in a single spray event.

transport.

The reason could be that the fast moving spray imparts tangential shear to the nearly stagnant flame kernel that was present within the radially expanded bulge at the periphery of the spray, which induces a weak rotational motion at the flame kernels present in the vicinity of turbulent vortex shear layers of high speed turbulent spray. Combined effect of this rotational flow filed long with the surrounding gas motion causes the sooting flame kernel to transport towards the nozzle while getting entrained. Presence of multiple sprays in the close proximity may cause two counter rotating vortices, at times when the bulges as well as the vortices are large they tend to interact with the neighbouring vortex as well as the flame kernels present within the bulges. In addition to this highly expanding flames from the combustion of sprays could also alter the flow field around the spray plume when compared to the single spray plume under non-combusting environment, widely studied in the literature. Thus the observed effect could be the outcome of various convolved effect hypothesised and a schematic depicting the processes are shown in Fig. 8.

To study the variation in soot entrainment length between injection events, images of spray from orifice number 6 are analysed for soot entrainment length and results are shown in Fig. 9. It is observed that due to variation in the size of initial spray bulge between different spray events, there is a variation in the soot entrainment lengths between the spray events. However, the values are significantly lower compared to the flame lift-off lengths observed in the literature. It is also observed that the gradual reduction in the soot entrainment length with time is consistent between the spray events indicating movement of flame bulge towards the nozzle tip while getting entrainment in the spray. This variation is not observed in some of the cases where the bulge formed is smaller and annihilation of flame kernel occurs rapidly before its movement. A sudden increase in the soot entrainment length in some of the cases indicates the complete entrainment of flame kernels closer to the nozzle.

A closer observation of ultra high-speed images revealed that pockets of sooting flame from the combustion of these fuel–air mixtures from within bulges are transported also from one spray to get entrained in to the neighbouring spray. These spray-to-spray interactions occurring by the bulges through the transport flames from within the bulges with that of the flow field surrounding each spray from a multi-hole nozzle are depicted in Fig. 10. From the sequence of images shown in Fig. 10(a), it can be observed that a flame kernel formed from the bulges of spray 6, as it moves towards the nozzle the flame kernel gets entrained into the neighbouring spray 5. This phenomenon shows that flow field near the injector tip is complex and flow field around the spray plume can be influenced by the presence of other spray plumes. This process of flame entrainment to within the same spray or to a neighbouring spray will result in flame quenching besides oxidation at the point of interaction. Thus products of unburnt hydrocarbons and nano soot particles from the quenched flame gets entrained into the liquid core that can modulate its equivalence ratio that may lead to a relatively increased soot emission from spray flames but more investigations are required for quantification of this effect. Similarly, Fig. 10(b) shows interaction between the spray flames of spray 6, 1 and 2. From the sequence of images it can be observed that sooting flame kernel from spray 1 gets entrained into the spray 2 as it moves closer to the nozzle at 1.22 ms ASOI. A similar effect is observed between spray 6 and spray 1 at 1.81 ms ASOI. This shows that in the spray combustion of multi-hole injectors, proximity of the other spray flames could influence the combustion process due to interacting flow fields. A schematic of this hypothesis of interacting flow fields between the spray flames from neighbouring orifices is shown in Fig. 11.

4. Conclusions

New insights observed on the formation of bulges during the early stages of injection and how it controls the ignition and soot formation in diesel spray flames have been substantiated in this article through the use of ultra-high speed optical diagnostics for diesel sprays under high temperature and high pressure conditions in a constant volume combustion chamber. The bulge formed at the periphery of the spray during the early part of the fuel injection was observed to lose its momentum. The fuel trapped within the bulge is relatively less dense and they evaporate quickly to form a locally stagnant favourable mixture that can undergo ignition relatively early compared to the rest of the spatial locations of spray. Once the fuel–air mixture in the bulge ignites, it propagates to the remaining portion of the spray leading to a stabilised

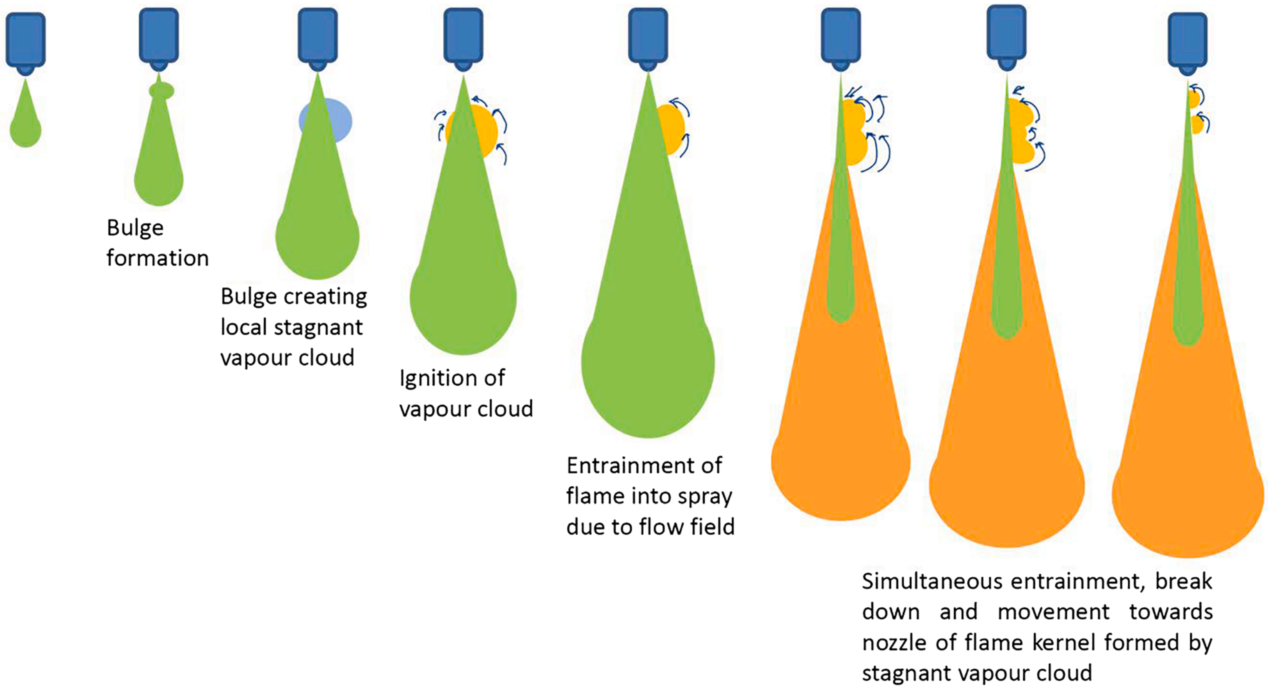


Fig. 8. A schematic depiction of entrainment of flame kernels formed by bulges in to the spray.

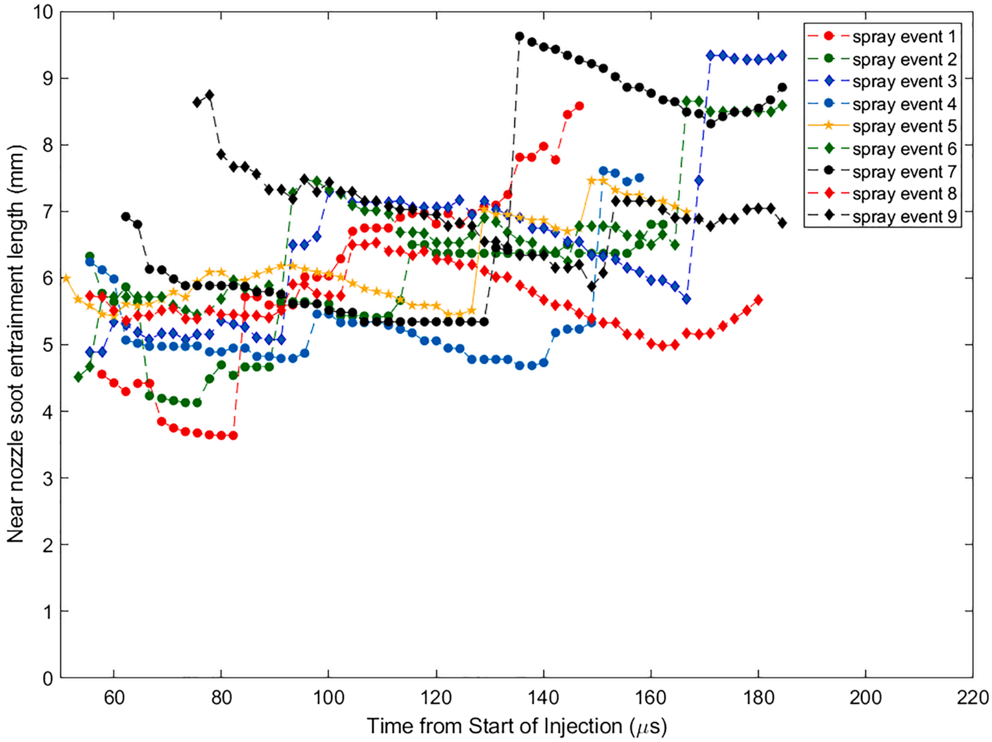
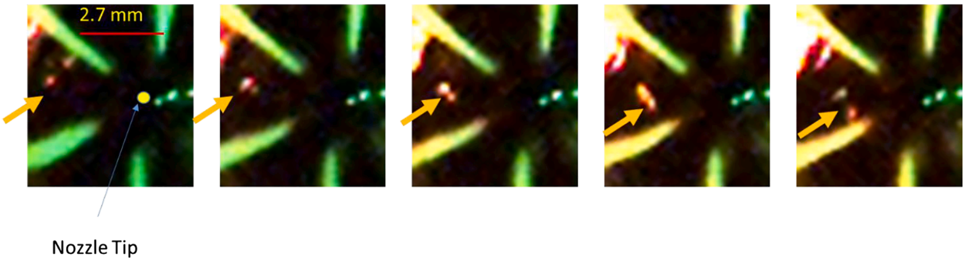
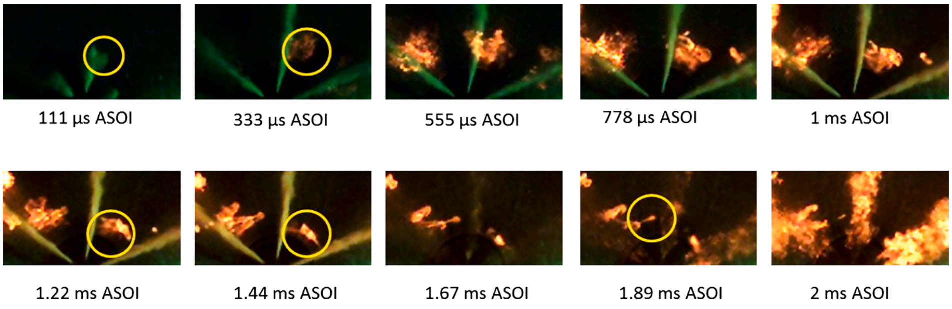


Fig. 9. Near nozzle soot lift-off length variations for orifice number 6 between different spray events. Variations between the spray event for the same orifices show that bulge formation will vary between spray events.



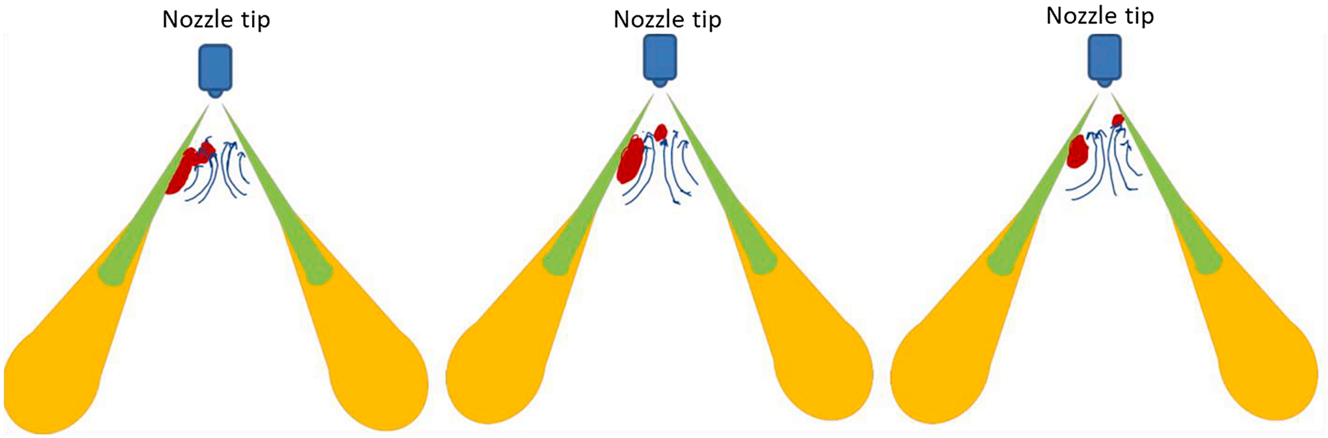
(a) Entrainment of soot kernel formed from the bulge of orifice 6 in to spray formed by orifice 5



(b) Entrainment of flame kernel formed from the bulge of one orifice in to the spray from other orifice between orifices 6, 1 and 2.

Fig. 10. Sequence of images showing entrainment of flame kernel formed from the bulging of one spray plume into another spray plume very close to the injector tip. In (a) glowing spot marked by the arrow shows the flame kernel. In (b) Bulging and interactions are shown marked using circle at different time instances. This shows that the flow field very close to the tip is influenced by the presence of other spray plumes. (a) Entrainment of soot kernel formed from the bulge of orifice 6 in to spray formed by orifice 5. (b) Entrainment of flame kernel formed from the bulge of one orifice in to the spray from other orifice between orifices 6, 1 and 2.

spray-flame. Thus the bulges formed in sprays can alter the ignition characteristics of fuel sprays, controlling the ignition delay as well as the flame lift-off location and flame stabilization. It was interesting to observe that a locally ignited fuel–air mixture in the bulge tends to move towards the nozzle and gets entrained into the liquid core of the same spray-flame, which eventually modulates the equivalence ratio in the



Flame kernel formed by stagnant vapour cloud getting entrained into the spray.

In case of large bulge, part of the flame kernel far from the spray get detached and influenced by the entrainment flow field of adjacent spray and move towards it.

Part of the flame kernel from left spray move towards the right spray and gets entrained into it.

Fig. 11. A schematic depiction of entrainment of flame kernel formed by the bulges from one spray into the other spray due to local flow field around each spray flame.

core of the spray and that can enhance soot formation. Entrainment of flame kernel formed from within the bulges of one spray plume into another spray plume upon moving close to the injector tip is another interesting observation and that shows a complex nature of flow field prevailing in multi-hole injectors. These newly observed flame entrainment processes between different orifices of the multi-hole injector for a given injection a well as for the same orifice were mainly associated with the anomalies of early spray development due to complexities of internal nozzle sac flow prevailing within diesel injection system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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