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Puffing and micro-explosion of diesel–biodiesel–ethanol blends



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HIGHLIGHTS

- Ternary blends of diesel–biodiesel–ethanol droplet resulted in smooth burning puffing and micro-emulsion.
- Identified favourable composition of the blend that leads to micro-explosion of the droplet.
- Observed micro-explosion of secondary droplets resulted from puffing and explosion.

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ABSTRACT

The puffing and micro-explosion of a single burning droplet comprised of neat diesel, rapeseed methyl ester (RME); binary fuel mixtures of diesel–ethanol, diesel–RME, RME–ethanol; and ternary microemulsion of these fuel blends at various compositions have been studied using high speed backlight imaging method. Fuel droplet was suspended on the tip of a 130 μm gauge thermocouple and it was ignited using a glow plug heater. Based on the temporal variation of droplet projected area, the characteristics of fuel droplets studied were classified into smooth burning, puffing and explosion. A ternary plot has been proposed to identify the mixture composition of the blends that can result in smooth burning, puffing and explosion. Micro-explosion phenomenon was observed in the ternary blends with ethanol percentages between 10% and 40%. Secondary droplets resulted from the puffing and explosion of suspended parent droplet were observed to undergo further explosion. The time scales associated with complete disintegration of secondary droplets are found to be comparable to the mixing and the chemical reaction time scales of sprays in diesel engines.

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1. Introduction

In recent times, search for alternative fuels has been intensified due to depleting fossil fuel reserves and environmental impacts. With the increasing concern of the environment and more stringent regulations on exhaust emissions, the reduction in engine emissions is a major research objective for engine development. Ethanol is an attractive alternative fuel because it can be a renewable bio-based resource and it has hydroxyl group, thereby providing the potential to reduce particulate emissions in compression ignition (CI) engines. Complete replacement of diesel with ethanol for CI engines is not a feasible solution due to differences in physical and chemical properties, which affects injection and combustion processes. Blending ethanol with diesel not only eliminates the modifications to the engine fuelling and combustion systems

but also the reduction of carbon atoms in the fuel molecule helps in reducing soot emissions. However, due to poor miscibility of ethanol in diesel, only small amounts of ethanol (less than 5 vol. %) will form stable solution [1]. To prevent separation and to increase the ethanol content in diesel, a surfactant or an emulsifier should be used [2–5]. Fatty Acid Methyl Esters (FAME) could also be used as an amphiphile (a surface-active agent) to stabilize ethanol and diesel blends [2,6–11]. Oxygenated biofuels are also considered as one of the alternatives for CI engines [12–14]. Biodiesels are derived from biodegradable materials that can significantly reduce toxic emissions and the overall life cycle emission of carbon dioxide when burned as a fuel. Biodiesel contains FAME which could play emulsifier role when mixed with diesel–ethanol blends. Renewable nature of both ethanol and biodiesel makes diesel–bio diesel–ethanol blends a promising alternative fuel for diesel engines. Presence of biodiesel compensates the effect of ethanol on viscosity, density and lubricity of the ternary blended fuel [15]. In a detailed study on solubility of the diesel–biodiesel–ethanol blends, Kwanchareon et al. [7] concluded that water content

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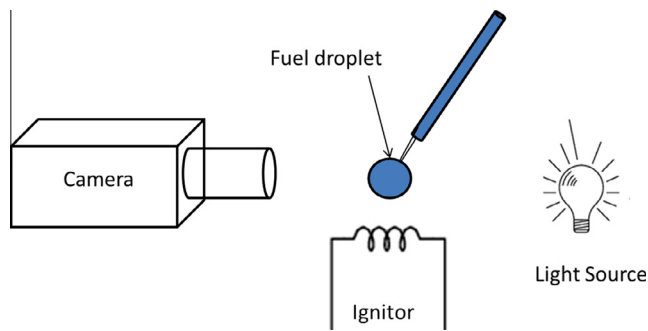


Fig. 1. Schematic of the experimental setup where droplet suspended on the thermocouple junction was ignited and back illuminated images of burning droplet were captured using high speed camera.

Table 1
Composition of binary fuels blends used in the study.

	Diesel (%)	RME (%)	Ethanol (%)
D90E10	90	0	10
D75E25	75	0	25
D50E50	50	0	50
BD90E10	0	90	10
BD75E25	0	75	25
BD50E50	0	50	50
BD25E75	0	25	75

Table 2
Composition of ternary fuels blends used in the study.

	Diesel (%)	RME (%)	Ethanol (%)		Diesel (%)	RME (%)	Ethanol (%)
D80BD10E10	80	10	10	D70BD5E25	70	5	25
D70BD20E10	70	20	10	D50BD25E25	50	25	25
D60BD30E10	60	30	10	D60BD10E30	60	10	30
D50BD40E10	50	40	10	D35BD35E30	35	35	30
D80BD15E5	80	15	5	D50BD10E40	50	10	40
D90BD5E5	90	5	5	D55BD5E40	55	5	40
D70BD10E20	70	10	20	D40BD20E40	40	20	40
D60BD20E20	60	20	20	D40BD10E50	40	10	50
D50BD30E20	50	30	20	D30BD10E60	30	10	60

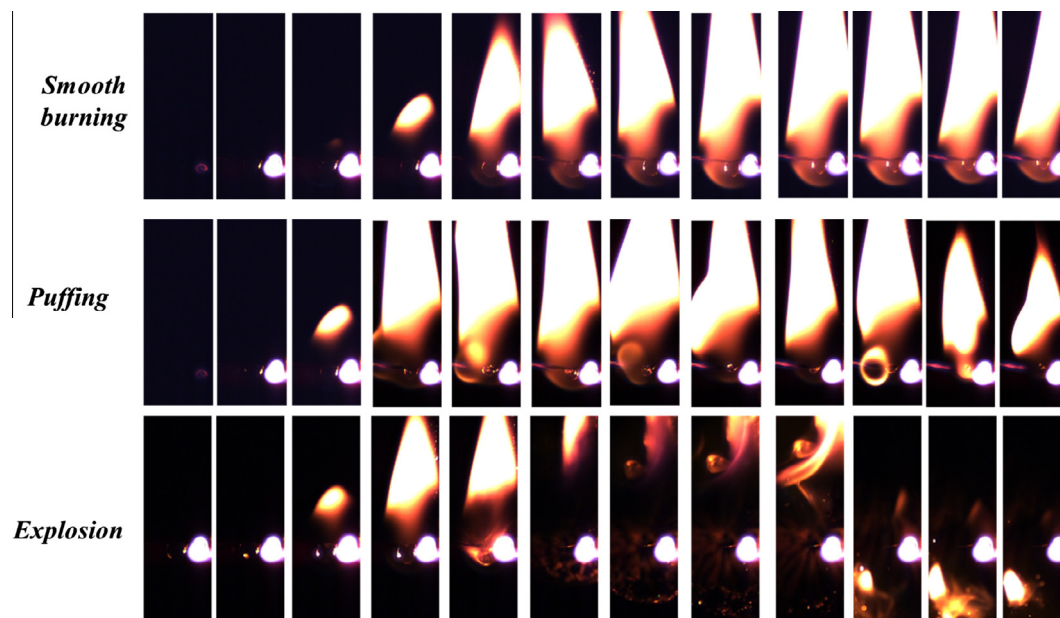


Fig. 2. Image sequence at random intervals, showing various phenomenon in combustion of micro emulsion droplets. No oscillations to the flame or droplet in case of smooth burning while flame and droplet oscillate in case of puffing. Droplet disintegrates and lifts the flame in case of explosion.

in the ethanol triggers phase separation in blends. Hence, anhydrous ethanol should be used for better stability.

Studies have established that multicomponent fuel droplets with vastly different volatile components can explode violently during combustion [16,17]. During vaporisation or combustion of multicomponent fuel droplet, higher volatile fractions can reach thermodynamically metastable superheat temperatures and leads to bubble nucleation. Rapid expansion of the vapour inside the droplet results in either total or partial disintegration of the parent droplet. If the whole droplets disintegrate into smaller droplets this phenomenon is termed as 'micro-explosion' and it is termed 'puffing' in the event of vapour blowing out of the droplet surface along with fine stream of droplets [18]. Micro-explosion and puffing are beneficial in fuel sprays as it aids secondary atomization and there by enhances mixing of dispersed fuel spray [18]. Micro-explosion phenomenon has been observed in the water-diesel micro-emulsion fuels [19–25]. These studies show that the size and distribution of emulsion water droplets inside the parent diesel droplet affects micro-explosion significantly. Very limited studies in the literature are focused on studying micro-explosion in fuel droplets of diesel–biodiesel–ethanol blends [16].

This study focuses on exploring puffing and micro-explosion phenomenon using suspended droplets of diesel–biodiesel–ethanol blends. Various compositions of three fuels were studied to identify the composition that favours puffing and micro-explosion.

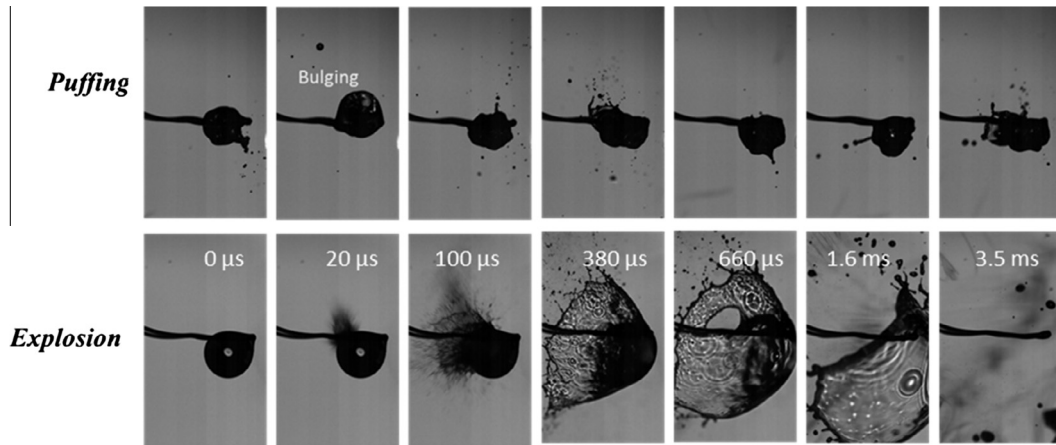


Fig. 3. High speed back illuminated images of burning droplet showing puffing and micro-explosion. Puffing images represents the phenomenon at random intervals whereas time interval from the start of micro-explosion is shown on the corresponding images.

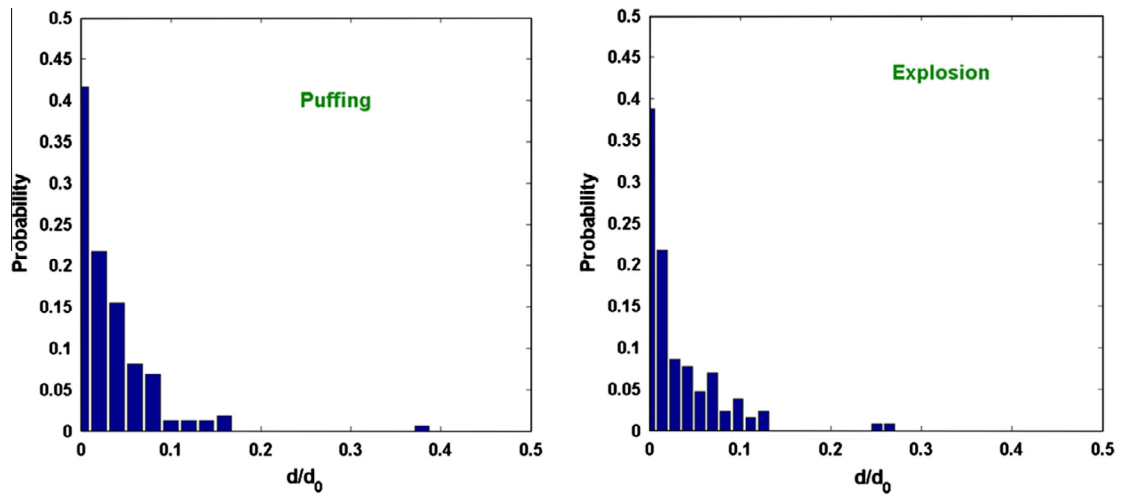


Fig. 4. Typical droplet size distribution after puffing and explosion events. Droplets distribution is similar in both cases with small probability of larger droplets from puffing compared to micro-explosion.

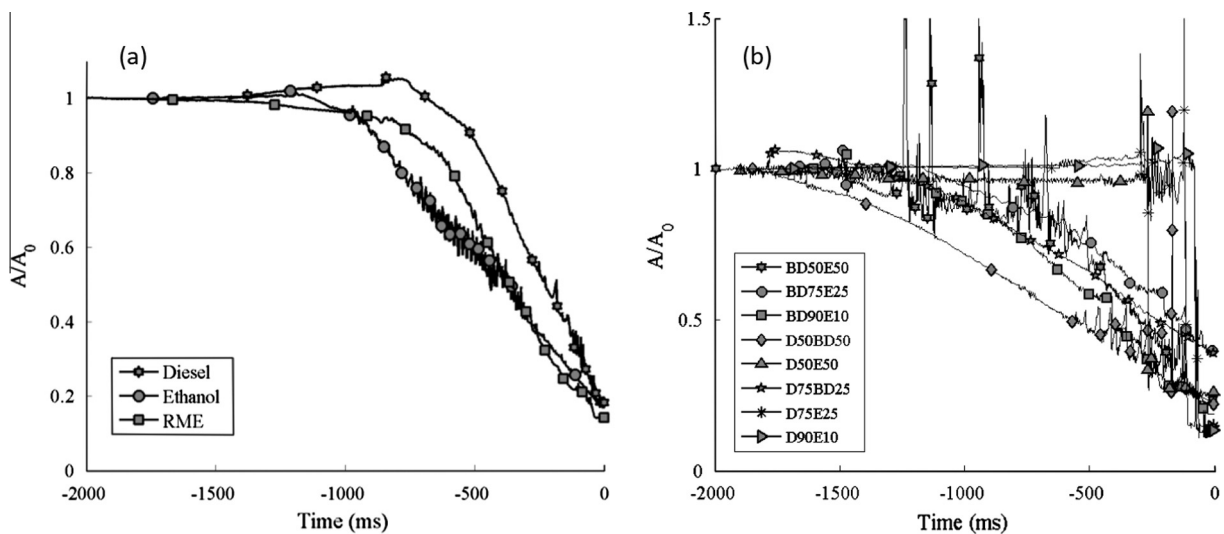


Fig. 5. Variation of droplet projected area with time for (a) pure fuels and (b) binary blends. Pure fuels and diesel–RME binary were observed to burn smoothly without significant oscillations to the droplet area. Whereas diesel–ethanol binary blends were observed to micro-explode. Puffing was observed in RME–Ethanol blends.

2. Experimental setup

2.1. Instrumentation

In the present experimental setup, fuel droplet was placed on the tip of thermocouple using a micro-pipette and the droplet was ignited using a glow plug heater. Evolution of the back illuminated burning droplet was observed using a high speed camera (Photron SA X-2). Images were recorded at 4000 frames/s (fps) with an exposure of $25\ \mu\text{s}$ to observe the changes occurring to the projected area of droplet over its life time. To observe puffing and explosion phenomenon closely, different set of images were taken at a frame rate of 50,000 fps and the camera exposure time was set to $5\text{-}\mu\text{s}$. The schematic of the experimental setup used in this study is shown in Fig. 1. Thermocouple of wire gauge $130\ \mu\text{m}$ was used in all experiments. Fuel droplet on the thermocouple was made up of approximately $1.5\ \mu\text{l}$ liquid which corresponds to a droplet diameter of $\sim 1.55\ \text{mm}$. However, the actual droplet size suspended on the thermocouple varied between $1\ \text{mm}$ and $1.5\ \text{mm}$ due to differences in fuel surface tension. The approach of suspending droplet on a thin thermocouple has been used in literature to study droplet evaporation and micro-explosion in other studies. The size of the thermocouple lead is $\sim 1/10$ th of the droplet size, Thermocouple itself did not initiate nucleation or puffing or the micro-explosion. Mura et al. [20] concluded that thermocouple did not influence the micro-explosion of water-diesel emulsion droplet.

2.2. Fuels preparation

Fuel emulsions of various mixture proportions were prepared using a magnetic stirrer at a temperature of $25\ ^\circ\text{C}$. Emulsions were prepared on the basis of mass ratio by weighing individual components of the emulsions using a digital mass balance with a second decimal accuracy. Macroemulsion is a mixture of two immiscible liquids with one liquid dispersed in the form of droplets of diameter greater than $0.1\ \mu\text{m}$ in the other liquid [26]. Macro emulsion is turbid, milky and unstable solution which will separate into two original liquids with time. Whereas microemulsion is a clear, thermodynamically stable dispersion of two immiscible liquids along with appropriate surfactants. The dispersed phase is distributed

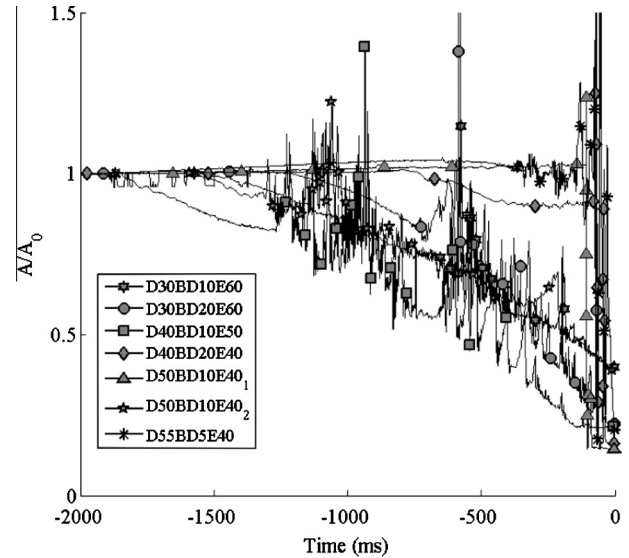


Fig. 7. Temporal variation of droplet projected area for a ternary micro emulsion of $\geq 40\%$ ethanol. Transitional behaviour from micro explosion to puffing was observed at 40% ethanol with some of the microemulsions showing both puffing and micro explosion. Puffing is predominant in case of microemulsions containing more than 40% ethanol.

in the form of small droplets with the diameter in the range of $100\text{--}1000\ \text{\AA}$ [26]. Diesel-ethanol blends formed macroemulsions, whereas all other mixture compositions seemed to form microemulsions. From the appearance of the blends, diesel-ethanol mixtures were milky macro emulsion while the ternary mixtures were a clear see through solution where of dispersed phase smaller than wave length of visible light. A list of binary and ternary fuel blends used in the study is indicated in Tables 1 and 2 respectively, along with their composition. In the nomenclature of blends, 'D' represents diesel, 'BD' represents RME bio-diesel and ethanol is represented as 'E'. Number subsequent to the corresponding alphabet indicates the percentage of that fuel in the blend.

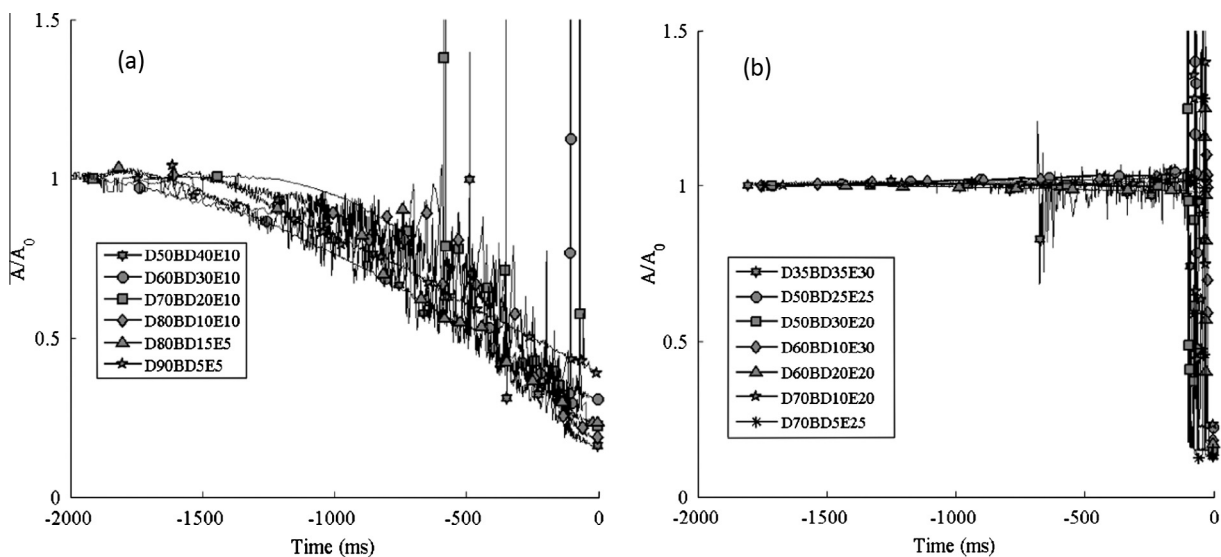


Fig. 6. Temporal variation of droplet projected area for a ternary micro emulsion of (a) up to 10% of ethanol and (b) between 10% and 40% of ethanol. Puffing and smooth burning are predominant for the micro emulsion with ethanol content up to 10% whereas droplets are observed to undergo micro explosion when the ethanol content is between 10% and 40% .

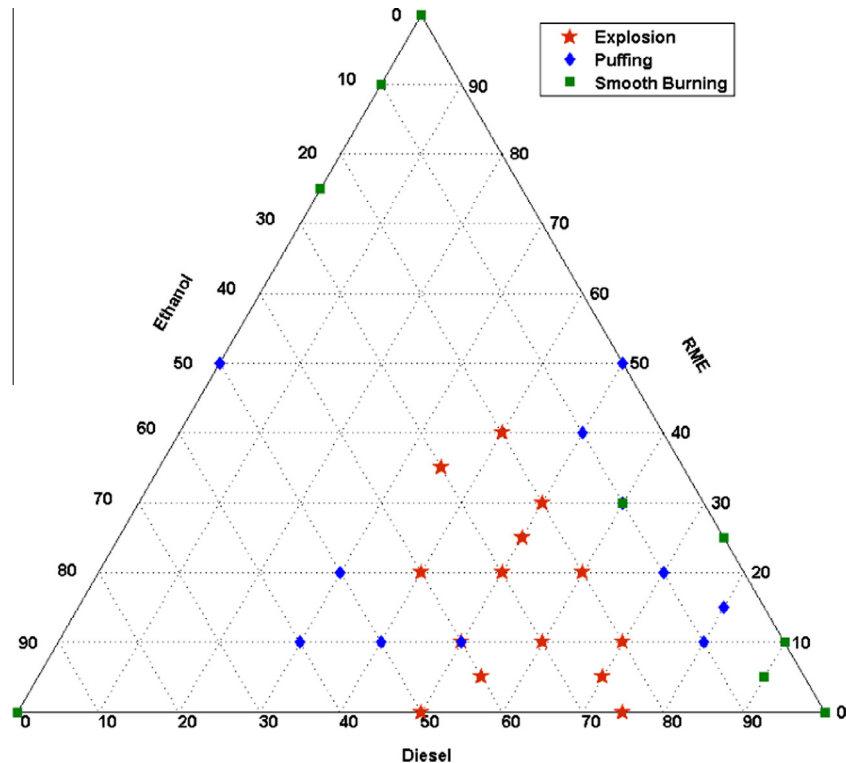


Fig. 8. Ternary plot showing behaviour of diesel–RME–ethanol burning droplet. Blends with ethanol percentage between 10% and 40% are favourable for droplet explosion.

3. Results and discussions

In the present study, binary blends of diesel–ethanol, diesel–RME, and RME–ethanol along with ternary microemulsions of all the above fuels at various proportions were studied. It was observed that diesel–ethanol binary mixtures were unstable and tend to separate beyond 10% of ethanol by mass in diesel without an emulsifying agent. However, such separation was not observed in RME–ethanol, diesel–RME and ternary mixtures. Adding RME to the diesel–ethanol mixtures resulted in a stable and clear microemulsion, otherwise unstable, milky emulsions. This shows that fatty acids in RME act as surfactant, which aids in the formation of a stable microemulsion.

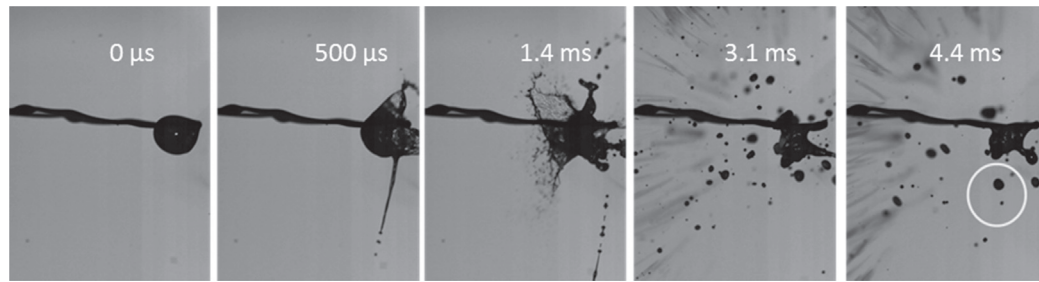
3.1. Puffing and micro explosion of droplet

Experiments were performed using various fuels of different composition. The distance between heating filament and the droplet was maintained at about 2 mm to ignite the droplets smoothly without contact. The time lapse between starting of heating element and ignition of droplet was observed to vary between 1 and 1.5 s based on the composition of fuel. Three types of droplet burning phenomena are observed, viz. smooth burning, puffing and explosion. Fig. 2 shows instantaneous images of different phenomenon occurring at random intervals of droplet burning. In case of smooth burning, droplets ignite and continue to burn without any significant oscillations to droplet or flame until the entire amount of fuel in the droplet was consumed. Where as in puffing, violent oscillation of the droplet and the flame was observed. These oscillations were due to continuous puffing of fuel vapours from inside of the droplet, which can be observed in the high speed back illuminated images shown in Fig. 3. These fuel vapour jets create strong perturbations to the flame around the droplet. However, the intensity of this puffing was not enough to break-up the droplet. The burning phenomenon was termed as

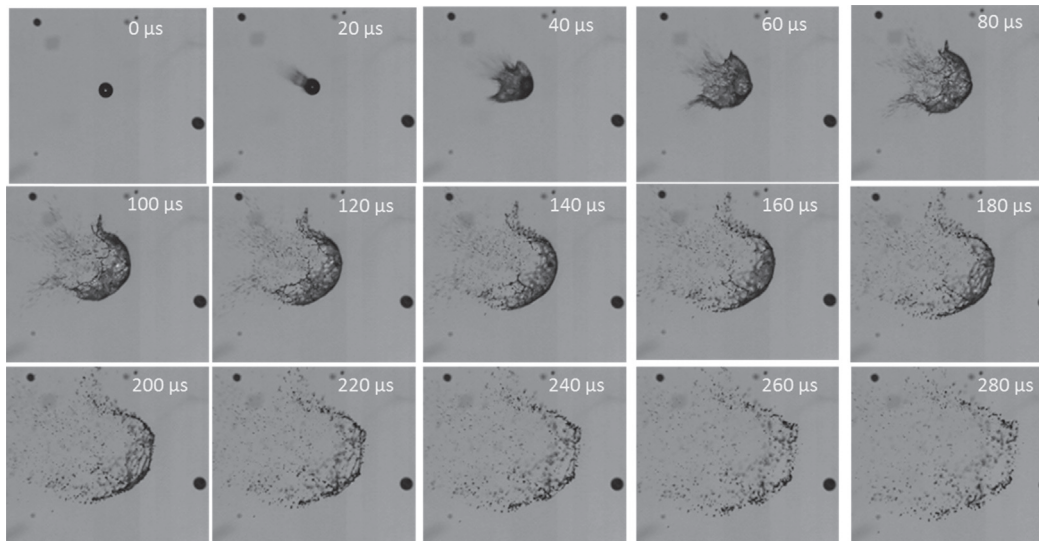
micro-explosion when the parent droplet suddenly disintegrates into much smaller multiple droplets as shown in Fig. 2. The fuel droplet ignites and burns smoothly before exploding into smaller droplets which further ignite and burn on their path even after break-up.

Instantaneous images taken at 50,000 fps with an exposure time of 5 μ s using a high intensity back lighting arrangement are shown in Fig. 3. Images represent corresponding phenomenon of puffing at random time intervals. During puffing, bulging of the droplet due to evaporation and expansion of high volatile fuel components was observed. Ejection of vapour from the droplet resulted in various intensity puffs, spewing droplets of various sizes in all directions. Some puffs were strong enough to create a local explosion on the droplet surface, leaving behind partially exploded parent droplet along with generation of multiple size secondary droplets. In the experiments, it was observed that the secondary fuel droplets resulted from the puffing underwent further explosion or puffing which will be discussed in the next section. The explosion phenomenon occurs almost instantaneously and shatters the droplet completely as shown in Fig. 3. Before explosion, droplet did not show any bulging due to internal evaporation as in case of puffing. However, explosion starts like a strong puff on one side of the droplets and shatters it into a thin sheet which further breaks into several small size secondary droplets. The intensity of explosion was strong and this resulted in the formation of several compression and expansion waves, their structures were clearly observed on the liquid sheet.

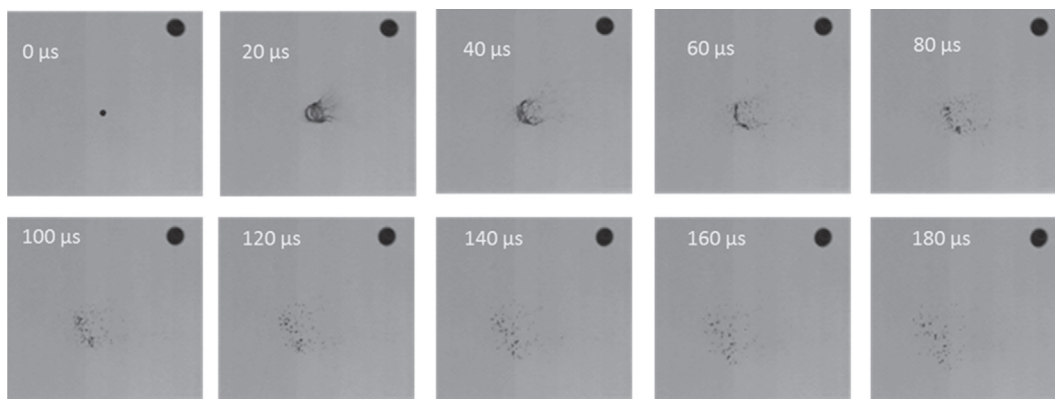
Size of the secondary droplets resulted from a typical event of puffing and micro explosion were obtained using image processing tool box of Matlab[®] software. The size distributions of secondary droplets (normalized by initial size) are shown in Fig. 4. Most of the secondary droplets were below 1/10 of the size compared to the parent droplet. Secondary droplet size distribution for both the events appears to be similar with a small probability of larger droplets in case of puffing.



(a) Sequence of explosion of primary droplet



(b) Image sequence of micro explosion of larger (~300 μm) secondary droplet



(c) Image sequence of micro explosion of smaller (~80 μm) secondary droplet

Fig. 9. Image sequence showing micro-explosion of secondary droplets resulting from the explosion of suspended droplets. Micro-explosion of droplets start as strong puffing making droplet bag or sheet like structure before it breaks up into smaller droplets.

To identify the behaviour of droplet burning, close up images of burning droplet taken at 4000 fps were analysed for evaluating the variation in droplet projected area. Images were first converted to grayscale and then binarised. Droplet projected area was computed using these binarised images. The time at which droplet completely burns or disappears from field of view in case of explosion was considered as time '0' and images up to 2000 ms before were considered for area computations. The computed area was normalised using initial area of the droplet (A/A_0) and plotted with time in Figs. 5–7. For pure fuels, i.e. diesel, RME and ethanol, droplet area reduces smoothly without any significant oscillations as shown in Fig. 5(a). Hence, it shows that these fuels burn smoothly without any puffing or explosions. It should be noted that the

variation in initial droplet size and the presence of thermocouple at the end of droplet burning results in non-zero and non-uniform end points on the plots. Marginal increase in the area ratio initially was due to change in droplet shape due to change in surface tension of fuel droplet because of rise in temperature. Fig. 5(b) represents variation of normalised droplet area for binary blends. Sharp spikes on the curve indicate intense puffing whereas sudden dip in the curve represent partial or total explosion of the droplet. Mixing diesel in RME or ethanol in RME up to 25% did not show any significant puffing or explosion. However, equal mixture of RME and ethanol exhibited puffing behaviour. This shows that significant amount of ethanol was required for rapid expansion of bubbles inside a RME droplet for puffing. Results also indicate that

even adding small amount of ethanol (10%) to diesel results in explosion. However, as mentioned earlier, diesel, ethanol binary mixtures form highly unstable macroemulsions.

Experimental results for the ternary micro-emulsion of diesel, RME and ethanol at different proportions are presented in Figs. 6 and 7. Droplet area for the ternary micro-emulsion blends with less than or equal to 10% ethanol content is shown in Fig. 6(a). It shows that most of these blends exhibit puffing behaviour though none of them showed any tendency towards explosion. This might be due to the fact that the amount of ethanol in these blends was not enough to explode the droplet by rapid evaporation. All of the blends with ethanol percentages between 10% and 40% considered in this study showed explosion behaviour as shown in Fig. 6(b). Most of the droplets explode suddenly without any significant bulging or puffing of the droplets. This indicates that evaporation of ethanol occurs rapidly enough to shatter the droplets. Increasing the ethanol percentage beyond 40% in the mixture composition was not favourable for explosion as shown in Fig. 7. Droplets of the ternary mixture with 50% diesel, 10% RME and 40% ethanol did not show a consistent trend. Droplets exhibited puffing in one instance and explosion when repeated. A similar behaviour was observed with 60% diesel, 30% RME and 10% ethanol. This shows that transition between micro-explosion to puffing occurs at around the lower and higher limits of 10% and 40% of ethanol distribution inside the droplet.

A summary of the burning behaviour of fuel blend droplets studied are represented in a ternary plot and is shown as Fig. 8. The plot clearly indicates the existence of a critical region that is favourable for droplet explosion with ethanol concentrations varying between 10% and 40% in the ternary microemulsion blend. Reducing or increasing ethanol content drives droplet towards puffing behaviour or smooth burning in some cases. Two of the ternary blends studied viz. D60BD30E10 and D50BD10E40 showed both tendencies of puffing as well as micro-explosion indicating a transition between the droplet burning phenomenon around these concentrations. All three pure fuels i.e. diesel, RME and ethanol showed smooth burning behaviour. Mixing ethanol or diesel in RME up to 25% did not show any difference in the burning behaviour of these fuels. However, 50% ethanol or diesel in RME resulted in puffing of droplets. Diesel–ethanol binary blends showed micro-explosion at ethanol concentration as low as 10%. However, these blends were very unstable macroemulsions and they tend to separate into two distinct phase over a time period. Non-exhibition of explosion of droplet with stable binary blends (diesel–RME, RME–ethanol) indicate that all three fuel components are required to make a stable microemulsion that favour micro-explosion.

3.2. Micro explosion of secondary droplets

Several interesting cascades of secondary and tertiary break up of droplets were observed from puffing or explosion of parent droplet. Fig. 9(a) shows the primary explosion of the parent droplet. The droplets formed after primary explosion are encircled, which were one and two orders of magnitude smaller than the parent droplet, these droplets were continuously imaged as they underwent further micro-explosion. Sequences of the secondary explosion occurring for these two droplets are shown in Fig. 9 (b) and (c) respectively. An initial droplet of the size approximately 1.4 mm undergoes a series of puffing and explosions to disintegrate into various sizes of droplets as shown in Fig. 9(a). Two encircled secondary droplets of the size $\sim 300 \mu\text{m}$ and $80 \mu\text{m}$ are observed to explode further as shown in Fig. 9(b) and (c) respectively. For both the droplets, explosion started from a strong puffing of vapour in random direction and transformed the droplet into thin liquid sheet of bag like structure which further disintegrated into smaller droplets. This revealed that the way the

micro-explosion occurred in these free falling droplets was exactly similar to the way it happened to the suspended parent droplet. Droplets resulted from the explosion of primary and secondary droplets are of wider size range and some of these droplets closer to droplet sizes in diesel spray, which also observed to undergo further micro-explosion. The time scale of this event was of the order of micro seconds and it appears to depend on the size of droplet, with smaller droplets needing lesser time for complete disintegration. The observed time scales indicate that these microscopical events occur in the order of ' μs ', similar to the time scales encountered in diesel engines, thus it is evident that micro-explosion is eminent when ternary mixtures are used in engines.

4. Conclusions

A systematic experimental study was carried out on a burning droplet of diesel, rapeseed methyl ester (RME), and ethanol blends to study the micro-explosion phenomena. Fuel droplet suspended on a thermocouple was ignited and observed using high-speed shadow imaging. Based on experiments, the burning of the fuel droplets studied were classified into smooth burning, puffing and explosion. The behaviour of all the blends studied has been represented on a ternary plot to identify conditions for micro-explosion. It was observed that the presence of ethanol content between 10% and 40% in the blend favoured micro-explosion. Higher or lower percentages of ethanol beyond this range resulted in puffing of the fuel droplet. Micro-explosion was not observed in binary blends of RME and ethanol even at ethanol percentage as high as 50%. Micro-explosion was observed in diesel–ethanol blends; however, these blends are not stable without addition of RME. Secondary droplets resulted from the puffing and explosion of primary droplet were observed to undergo further explosion. The time scale for the complete disintegration of the droplet from the start of explosion were smaller for the smaller droplet, and it was comparable to the time scales associated with spray mixing process in diesel engines. From NIST data, the variation of boiling temperature with pressure for ethanol indicates an increase in its boiling temperature with pressure (approximately 500 K at 45 bar) [27]. The temperature of in-cylinder air during injection and early combustion will of the order 800 K which could be a sufficient source of superheat leading to rapid evaporation of ethanol that causes puffing and micro explosion. In a study on micro explosions of fuel droplets under high pressure, Wang and Law [28] demonstrated that increasing pressure enhances the onset of micro explosion. From the above data, it can be corroborated that diesel–biodiesel–ethanol blends used in our study have a potential to undergo micro explosion at conditions encountered in diesel engines during injection and pre combustion phases. However, for precise understanding, studying micro explosion of diesel–biodiesel–ethanol blends at elevated pressures could be an interesting problem for future research.

Acknowledgements

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