

Combustion Instability of Closely Packed Diesel Droplets Caused by Soot Contamination

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1 Introduction

Interactions between burning small fuel droplets have significant role in the combustion behaviour. Understanding the change of combustion behaviour in relation to the type of fuel and their proximity would provide a better insight in the prediction of fuel spray behaviour [1]. According to Okai et. Al. [2], multi-droplet burning stabilises the combustion irregularity and smoothen droplet liquid surface. Moreover, the onset of stability is earlier for multi-droplet arrays compared to isolated droplet which requires a strong interaction between a group of fuel droplets. On the contrary, for a high soot generating fuel such as diesel, the possibility of soot contamination on interacting droplets is very likely. Randolph & Law [3] stated that incomplete soot oxidation is observed in strong interacting conditions of closely spaced droplets. Competition between droplets for available oxidizer inside the combustion chamber in spray combustion was concluded by Labowsky and Rosner [4] which stated that oxidizer is prevented to reach the spray core due to this competition. The starvation of oxygen in the spray core promotes higher amount of incomplete combustion thus generates more soot from the hot combustion gas. On contact, the soot from the hot combustion gas is quenched and agglomerated to a shell on the surface of the droplet [5]. Also, such contamination reduces the stability of the liquid fuel surface with a prolonged disruptive phase. Deposition of agglomerated particles on the droplet surface reduces the liquid diffusion which suppressed the evaporation rate and at the same time promotes multiple sub-droplet ejections due to multiple appearance of high-pressure nucleation sites [6]. Therefore, stronger gas phase interaction is expected to have higher magnitude of fluctuation in the regression of squared droplet diameter due to a denser soot contamination [5]. This paper quantitatively determines the effect of gas phase interactions to the lifetime of disruptive phase by comparing fuels with different tendencies of emitting soot. The aim is achieved by visualising the contamination process and disruptive mechanisms of imaged fuel droplets. The first part of this paper discusses the variation of disruptive combustion on the regression of squared droplet diameter, D^2 . The second part discusses the quantitative measurement of disruptive phase, P_{III} of interacting multi-droplet. Lastly, this paper discusses the liquid-phase visualization of interacting multi-droplet. The result of this study provides significant insight on the stabilisation mechanism of interacting fuel droplets in combustion.

2 Experimental Setup

The fuel droplets were imaged at high speed with Photron-SA4 high speed colour camera. An IDT 19-LED high intensity illuminator was placed behind a diffuser for a backlit imaging setup during the lifetime of droplet tracking. A Nikon AF Micro NIKKOR 60 mm f/2.8D lens was used to image the droplet dynamics. A coiled kanthal wire was attached to a thermal heating device (SMOK 220W) and placed 1 mm away below the droplet for ignition. The recording speed was 10000 fps with 40x magnification. Images were recorded between the droplet ignition and flame extinction. Detailed illustration of the setup is shown in the previous work of Rasid & Zhang [5]. The initial droplet diameter was ensured to be 1 ± 0.05 mm for each ignition. Three fuel droplets were ignited simultaneously in this experiment. The inter-droplet distances were increased by a precise micrometer adjustment ranging from 1.25 mm to 5.00 mm away from each other to observe the effect of droplet interaction. The detailed illustration of droplet suspension is shown in Fig. 1. To clearly differentiate the effects of soot contamination during the combustion of grouped droplets, a commercial Shell diesel and oxygenated fuel of Biofuel-500 Gardeco bioethanol were used in this study. Both fuels were selected due to their large difference in sooting propensity. Ethanol is an oxygenated fuel. With the availability of oxygen atom to combine with oxygen molecule in air, more complete combustion is achieved with no soot production [7]. The imaged droplets were processed using a MATLAB code specifically developed to measure the dynamics of droplet dimensions.

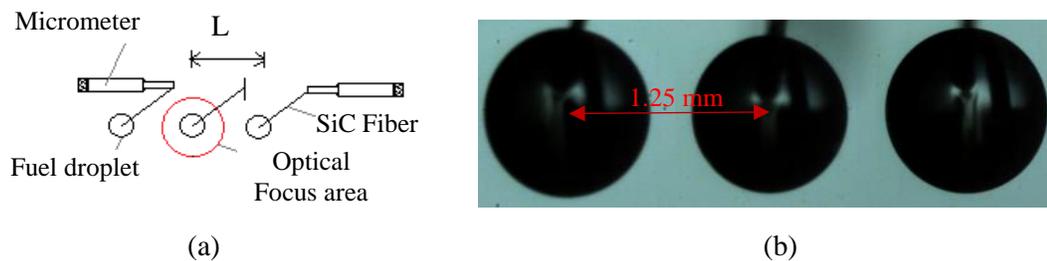


Figure 1: Horizontal arrangement of fuel droplets (a) illustration and (b) actual image

There are three distinct combustion phases present in the regression of squared droplet diameter, D^2 . These three phases represent the burning behaviour and stability of droplet throughout the combustion [5]. Phase I has a non-linear regression due to droplet swelling and at the same time shrinking because of evaporation [8]. Phase II has a linear slope, with squared droplet diameter of the droplet linearly reduced. In this phase, the combustion is considered steady. Burning rate constants, K are determined by measuring the slope which decrease linearly with time [9]. In phase III, particle agglomeration caused a disruptive burning with multiple sub-droplet shootings and diverts the linear slope away from D^2 -law; not suitable for the measurement of burning rate constant.

3 Evolution of Squared Droplet Diameter, D^2

Higher image magnification conducted in this study enables the measurement to detect even the slightest change in droplet dimensions. With this imaging technique, changes in burning behaviour were categorised by multiple phases with high repetitive measurement. Fig. 2 shows normalised regression of squared droplet diameter for each normalised inter-droplet distance L/D_0 . For diesel droplets shown in Fig. 2(a), the disruptive effects during combustion gradually decreased as the inter-droplet distances are moved further. The effect is most profound in the phase III region, with higher fluctuation magnitude of D^2 and longer

lifetime as the inter-droplet distance reduces. On the other hand, varying the inter-droplet distance for non-sooting bioethanol does not influenced the disruptive burning behaviour clearly shown in Fig. 2(b). Shorter inter-droplet distance prolonged the total burning lifetime of both cases, indicating the effect of denser fuel vapor surrounding the droplet as the combustion progresses. More fuel vapor is supplied to the imaged droplet (centre) by the evaporation of neighbouring droplets. Those mixture of volatile gasses burns together with enveloping flames which indicates a strong gas phase interaction [10].

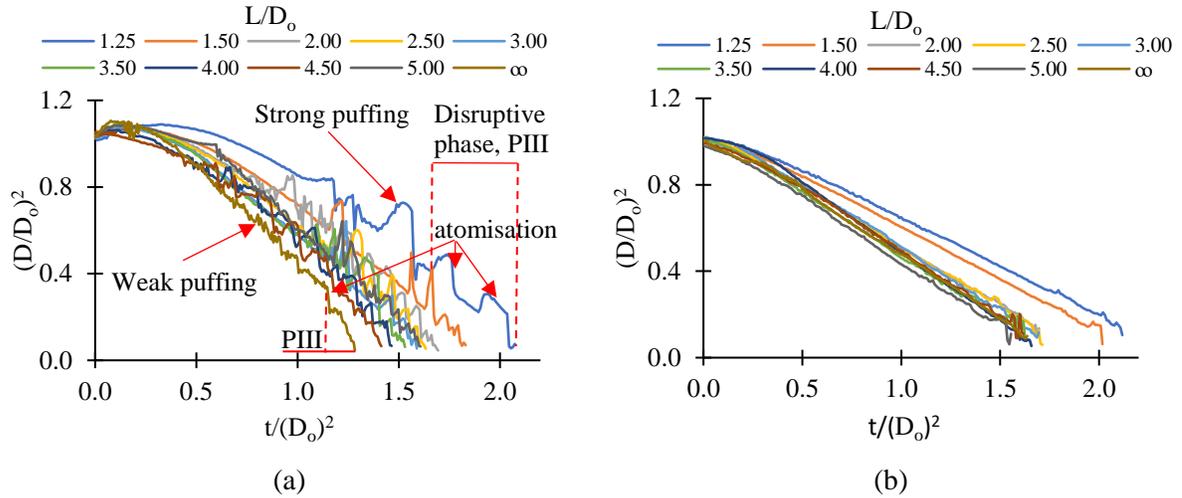


Figure 2: D^2 regressions of various inter-droplet distance of (a) Diesel and (b) bioethanol

4 Lifetime of Disruptive Burning Phase, PIII

Fig. 3 shows the lifetime of Phase III with increasing inter-droplet distance of diesel and bioethanol. With acceptable errors, there is a significant difference in Phase III between high and low sooting propensity fuel tested. The deviation from D^2 -law of diesel in this phase is longer throughout the combustion of diesel with stronger gas phase interaction. Diesel with inter-droplet distance of 1.25 has the longest disruptive phase with $0.2 t/t_0$ and gradually decreases in relation to the increase of inter-droplet distance until it reaches the disruptive lifetime of an isolated diesel droplet of $0.03 t/t_0$. In case of bioethanol, there is no direct correlation between interaction and disruptive phase.

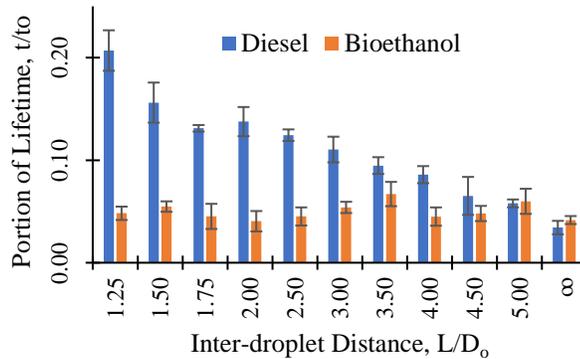


Figure 3: Lifetime of disruptive burning phase, PIII of diesel and bioethanol

The disruptive behaviour of interacting diesel droplet visualised in this experiment is in contrast with results by Okai et al [2], who discussed the stabilisation of combustion irregularity and smoothening of droplet liquid surface in case of multi-droplet interactions. Randolph and Law [3] observed an incomplete oxidation of soot in strong interacting condition of closely spaced droplets. Oxidiser is prevented to reach the centre droplet and the starvation of oxygen promotes higher amount of incomplete combustion thus generates more soot. This suggests the possibility of soot contamination of neighbouring droplets as they burn. Concluded by Rasid & Zhang [5], contamination of soot during droplet combustion prolongs the disruptive phase as well as increases the frequency of sub-droplet shooting which in this study; clearly shown in Fig. 2(a) and Fig. 3 for diesel.

5 Liquid-Phase Visualisation of Interacting Fuel Droplets

Fig. 4 shows the liquid-phase visualisation of various droplet interaction throughout the combustion of diesel and bioethanol. Several important mechanisms are chosen and highlighted in this paper for a better insight of their respective differences. Upon ignition, soot produced from itself and neighbouring droplet continuously quenched to the imaged droplet. These quenched particles agglomerated and caused higher localised heat throughout the droplet and nucleates into a bubble [11]. Closer inter-droplet distance of diesel experienced much early rupture of bubble nucleation which promotes earlier fluctuation in the regression with 0.50, 0.69, 0.74 and 0.78 t/t_0 for case A, B, C and D respectively shown in Fig. 4. Also, the size of the rupturing bubbles is shown to be reduced as the inter-droplet distance increased which in turn reduces the magnitude of fluctuation in the D^2 regression shown in Fig. 2(a). On the other hand, multiple smaller bubbles appeared in bioethanol before rupturing. Prior to ignition, a region of stratified fuel vapor and surrounding air is formed during deployment and growth. Some soot particulate was observed to be formed during the ignition period but eventually burned during the transition to diffusive burning. The energy source added from the igniter to the rich stratified gas-phase of fuel and oxidiser mixture rapidly accelerates fuel pyrolysis which briefly forms soot [12]. This mechanism was observed in every interacting bioethanol droplet with similar fashion; regardless of their inter-droplet distances.

Puffing shortly follows the bubble ruptures, with closely packed interacting droplet ($L/D_0 = 1.25$) ejected few soot particles that contaminated the droplet earlier, shown in Fig. 4(A). This shows that closely packed droplets contaminated the droplet with higher density which in turn ejects few particles together with volatile vapor during puffing process. Puffing of less contaminated droplets ejects mostly volatile vapor from the nucleated bubbles as depicted in Fig. 4(B) and 4(C). The puffing of bioethanol is very much different to diesel. Fig.4(D) shown that more agglomerated particles were ejected during puffing process. This is due to its higher amount of pressurised bubble ruptures that pushed the particle out. Much lower viscosity of bioethanol caused the pressure to easily ejects the particles through the droplet surface. This in turn cleanses the droplet from soot particles each time they are built up on the surface. The bubble ruptures and puffing mechanism repeatedly occurred during the combustion process in Phase II before transitioned to Phase III. Throughout Phase II, the density of soot contaminations was visualised in each case. In the order of A to D in Fig. 4, closer proximity of neighbouring droplets contaminates the imaged droplet with higher density thus clearly explains their differences in disruptive combustion.

As the combustion progresses, denser agglomerated soot particles on the surface hinders the liquid diffusion even more and at the same time traps a higher pressure of nucleated bubbles. Stronger puffing ejects higher pressure of volatile vapor and pushed a small number of liquid droplets. This onsets Phase III with multiple ejections of smaller sub-droplets from the main droplet. The sudden loss of droplet mass deviated the regressions from D^2 -law. Earlier onset of Phase III was visualised for stronger droplet gas phase interaction due to a higher rate of soot contamination. Disruptive burning of interacting and isolated diesel droplets progressed by a similar manner; by multiple sub-droplet ejections. According to Rasid &

Zhang [5], contaminated single droplet of diesel ejects soot particle that explodes in Phase III, further reducing the burning rate constant. The contamination of soot in their study was initiated prior to ignition; which is quenched to an agglomerated shell of particles. However, the condition of contamination process is different in this study. Horizontal arrangements of droplets do not heavily contaminate the droplet as most of soot particles contained in hot combustion gasses moves upward. Furthermore, the ignited droplet was in neat condition and gradually contaminated throughout the combustion, segregating the particles on the droplet surface. Segregated particles on the droplet surface provides more area for the liquid sub-droplet to be ejected through without having higher proportions of particles to liquid droplet in the atomisation process. In this case, higher magnification of visualisation is needed to clearly see the contamination process of gas phase interacting droplets due to a very small amount of nano-sized soot particles. Clear visualisation of soot contamination mechanism (vertically arranged) is presented in previous work of Rasid & Zhang [5]. Nevertheless, this paper clearly demonstrates the certainty of soot contamination during droplet gas phase interaction which is determined to be more profound in high carbon fuel combustion.

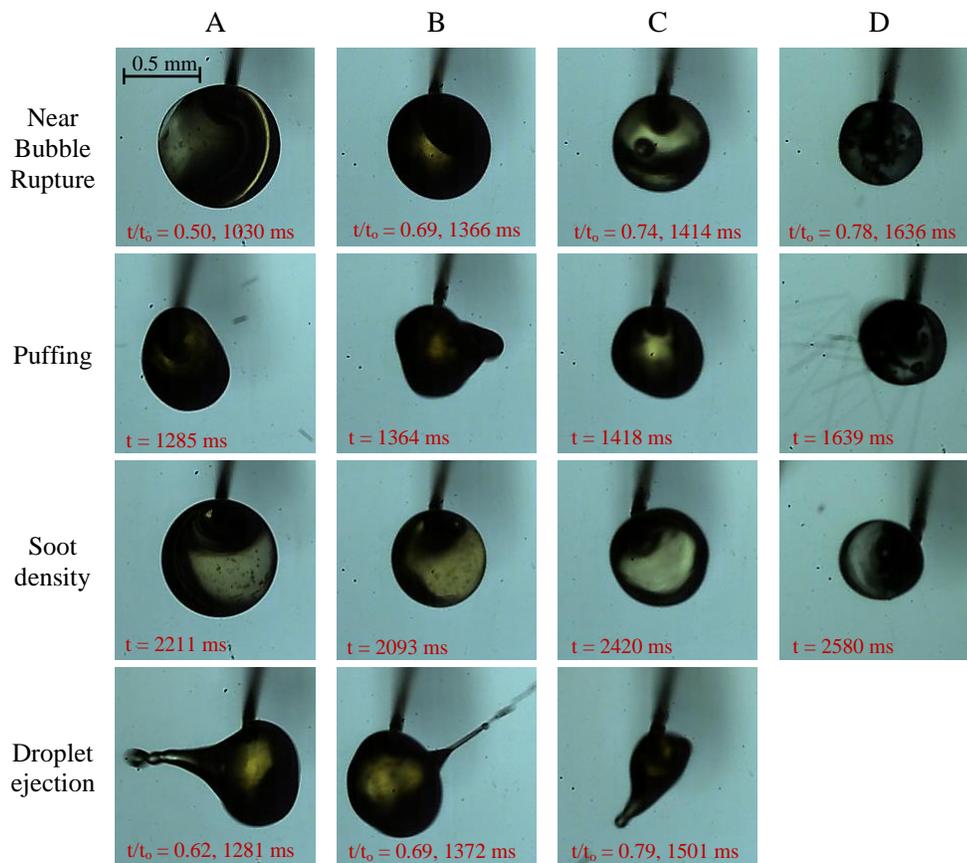


Figure 4: Liquid-phase visualisation on the combustion behaviour of (A) diesel, $L/D_0 = 1.25$, (B) diesel, $L/D_0 = 5.00$, (C) diesel, $L/D_0 = \infty$, (D) bioethanol, $L/D_0 = 1.25$

6 Conclusions

The mechanism of disruptive combustion in interacting droplets has been determined by comparing the differences between the burning of high and non-sooting fuel droplets. It was found that there is a possibility of soot contamination from burning closely packed interacting droplets which in turn destabilised the combustion process. The results are summarised as follows:

1. Combustion stability of interacting fuel droplets has been determined by analysing the regression and changes in the slope of squared droplet diameters in various inter-droplet distance. Enhanced visualisation conducted in this study provided a clear visualisation on the contamination process as well as highly repetitive measurements on the combustion phase of interacting fuel droplet during combustion.
2. The neighbouring high carbon fuel droplets continuously contaminate the imaged droplet throughout the combustion thus gradually disrupted the steady combustion toward higher magnitude of instabilities.
3. Higher density of contaminations was visualised as the inter-droplet distance is smaller thus providing a clear explanation of earlier onset of Phase III as well as increasing trend on the magnitude of disruptive combustion
4. Segregated particles quenched on the droplet surface is found to be one of the main factors for the onset of disruptive phase. The results obtained in this paper provides clear explanations of such disruptive mechanism even in isolated high carbon fuel droplet.

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