

Combustion Phases of Evaporating Neat Fuel Droplet

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ABSTRACT

The combustion characteristics of fuel spray can be examined at a basic level by a fuel droplet combustion study. Evaporation processes of a fuel droplet involves few combustion phases mainly heating, boiling and disruptive phase. The transition of phases is found to be caused by two transient combustion process; mainly droplet heating and fuel vapour accumulation. The duration of combustion phases of tested neat fuel droplet in the present work is found to be consistent for each fuel. High volatility fuel is found to have the shortest duration of droplet heating and fuel vapour accumulation. Longer duration of boiling phase provides wider range of measureable burning rate to be done on tested fuel droplet. With precise quantitative measurement method conducted in the present work, high measurement repeatability is assured thus enabling the determination of droplet combustion stability categorization with clear definition throughout the lifetime of evaporating neat fuel droplet. Additionally, this paper summarises the common combustion phases involved during the evaporation of a neat fuel droplet.

1. Introduction

Theoretical study made on liquid spray combustion assumes a spherical symmetric dispersion of droplets [1]. A single and isolated fuel droplet study offers a simplified modelling for liquid spray combustion. A model termed D^2 -law was first proposed by Langmuir [2], and later established by Spalding [3] which predicts a constant gasification rate [4] with a linear reduction of squared droplet diameter throughout the lifetime of evaporating droplet. D^2 -law assumes the droplet to be spherically symmetric, having constant and uniform temperature. These assumptions were set by neglecting the transient effect of droplet heating (transient liquid phase) and fuel vapour accumulation (transient gas phase) [5]. However, the theoretical assumptions were not truly precise to analysed experimental results from fuel droplet combustion tests. Quantitative measurement made on evaporating fuel droplet observes a presence of transient heating and fuel vapour accumulation, separating the general combustion phase of evaporating droplet into few sections [6].

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The transient processes are droplet heating and vapour accumulation effect which are profound in a fuel with a low volatility and high boiling point [7].

Throughout the period of transient heating phase, the surface regression rate is slower than the internal heat conduction rate resulting a gradual increase of the burning rate with time. This implies that the major portion of the heat transferred to the liquid droplet is used on heating the droplet rather than evaporating the surface area through gasification process [8]. Several temperature spot exists within the droplet caused by the liquid movement through natural convection. Overheated spots has high probability to initiate homogeneous nucleation which later forms a bubble of vapour within the droplet [9]. Emergence of vapour bubble and thermal expansion causes the droplet to swell with a slight surface distortion. On the other hand, the accumulation of fuel vapour during transient gas phase indicates higher evaporation rate in comparison with vapour consumption [10]. The region of flame is observed to move further from the surface of the droplet, causing unsteady heating for gasification which in turn varying the gradient of D^2 regression [11]. Furthermore, Rasid and Zhang in both of their papers [12,13] discuss that the presence of particle would initiates a heterogeneous nucleation that forms multiple bubble of vapour to emerge within the droplet. Combined bubbles move towards the surface of the droplet as a mean of escape. The periphery of ruptured surface draws liquid from the core of the droplet thus protruding a ligament of liquid fuel which then ejected a sub-droplet [14]. Unsteady heat supplied from the flame and sudden loss of liquid mass deviates the surface regression from D^2 -law with fluctuating regressions. Therefore, the measurement of the droplet burning rate is unreliable during disruptive phase [15].

Constant gasification rate theorised in the classical quasi-steady model implies that droplet evaporation only involves boiling phase with linear reduction of squared droplet diameter. However, actual fuel gasification involved transient heating and fuel vapour accumulation period which divides the combustion phases into three categories for neat fuel, namely heating, boiling and disruptive phase. The aim of the present work is to determine all combustion phases involved during the combustion of a single and isolated neat fuel droplet; mainly diesel and ethanol despite interferences during transient evaporation processes. The findings on the present work could be practically implemented during neat fuel categorisation in terms of stability and burning rate determination. In light of advanced compression ignition study such as RCCI [16] and utilisation of experimental biodiesel [17], a complete understandings of combustion phases and transitions of neat fuel in the fundamental level is crucial towards suitable fuel selection and distillation in terms of fuel stability and volatility presented in the present work. The experimental work focuses on the repeatability of acquired results thus ensuring a reliable conclusion could be made on the transition of combustion phases and a more precise burning rate measurement method for a burning neat fuel droplet.

2. Methodology

To achieve a conclusive quantitative study on the combustion of a single and isolated droplet, the experimental methodology was divided into three sections namely; fuel selection, experimental setup and image feature extraction.

2.1 Fuel Selection

The aim of the study is to determine the combustion phases between low and high volatility of a commercially utilized fuel. Based on their worldwide practicality, a regular diesel and bioethanol were selected based on their large volatility and stability differences. A regular Shell Diesel Fuel was utilized in the present work. The ethanol fuel utilised in the present work is a Biofuel-500 Gardeco,

sugar cane-derived bioethanol produced from industrial distillation; common production in Brazil. The thermo-physical properties of diesel and ethanol used are depicted in Table 1. In addition, the analysis focuses on determining the similarity of combustion phases between both selected neat fuels thus providing sufficient data for a general combustion phase involves during the evaporation of neat fuels.

Table 1
Thermo-physical properties of diesel and ethanol [18]

Properties	Diesel	Ethanol
Chemical composition	C ₁₀ H ₂₂	C ₂ H ₅ OH
Density @ 25 °C, kg/m ³	830	783.2
Specific gravity @ 25 °C	0.83	0.79
Molecular weight, g/mol	148.6	46.07
Stoichiometric AF ratio	14.6	9
Thermal conductivity @ 25 °C, W/m.K	0.142	0.171
Kinematic Viscosity @ 40 °C, mm ² /s	3.05	1.08
Boiling point, °C	170	78
Flash point, °C	79	16.6
Specific heat @ 25 °C, kJ/kg.K	1.81	2.44
Latent Heat of Vaporization, kJ/kg	250	840
Surface tension @ 25 °C, mN/m	28.2	22.1
Lower Heating Value, MJ/kg	43.2	26.8
Higher heating Value, MJ/kg	44.8	29.7

2.2 Experimental Setup

Figure 1(a) shows the experimental setup with a backlighting arrangement. Photron-SA4 high speed colour camera was used to track the evaporating fuel. The recording time was between ignition to the flame extinction. Testing was repeated at least 6 times for each fuel type to ensure measurement repeatability and precision. A backlighting arrangement consist of placing an IDT 19-LED high intensity illuminator beaming through a light diffuser behind the droplet and opposite to the camera lens. The liquid-phase imaging was done in 10,000 frames per second and x40 magnification. Illustration of the droplet suspension and ignition is shown in Figure 1(b). Droplets were transferred from the chemical bottle to the SiC fibre via a micro-fine syringe with a hypodermic needle. With the aid of Photron Fastcam Viewer software, the initial diameters of the droplet were kept at a constant size of 1 ± 0.05 mm between each test. 100 μ m silicon carbide fibre was utilised as the suspender for the droplet with horizontal arrangement. A pre-heated thermal wire heater made of Kanthal (800°C) was positioned 1 mm below to droplet and removed in quick succession upon the first appearance of flame. Initial tests were done on the ignition temperature of the droplet. It is found that the ethanol and diesel droplet ignites when the ambient temperature 1 mm above the Kanthal wire has reached 350°C and 400°C respectively. All fuel droplet combustion testing was done on ignited droplets to ensure the evaporation follows individual diffusion-controlled temperatures from the flame boundaries surrounding the droplet.

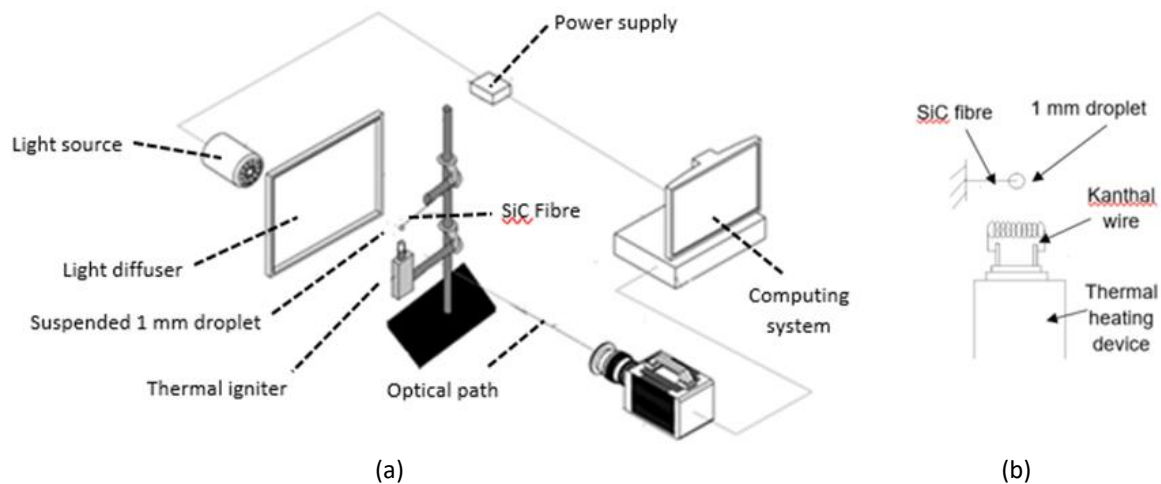


Fig. 1. Experimental setup

2.3 Feature Extraction

A MATLAB scripts specific for image segmentation was used to process the image for feature extraction and it is shown in Figure 2. Feature extractions were done by using a MATLAB script involving the measurements of minor and major diameters, orientations, average volumes and areas. Analysis on the extracted image features are based on theoretical D^2 -law [2] which emphasis on a linear reduction of squared droplet diameter, D^2 during the evaporation process of fuel droplet. In normal gravity, the shape of the suspended droplet is ellipsoid. By assuming volume equivalence between ellipsoidal and spherical droplet, an equivalent spherical diameter, D is calculated. Hence, the equivalent diameter is calculated by the cubic root from the product of squared minor diameter times major diameter [19]. Normalisation parameters were used consist of normalised squared diameter $(D^2/D_0)^2$ against normalised time $t/(D_0)^2$ to ensure precise dimension scaling in between samples. Some quantitative measurement errors are expected derived from a slight ignition delays and initial diameter variations. All errors are presented as a whole for each sample in a form of standard deviation within the quantitative measurement results and analysis.

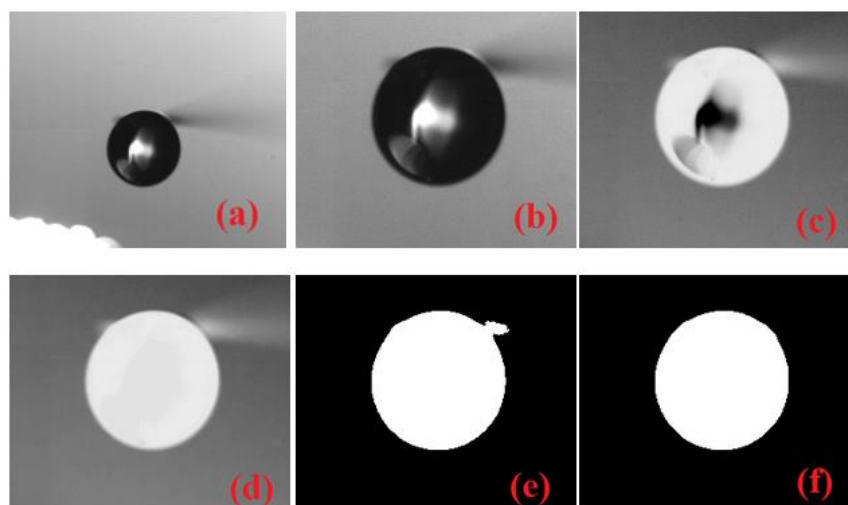
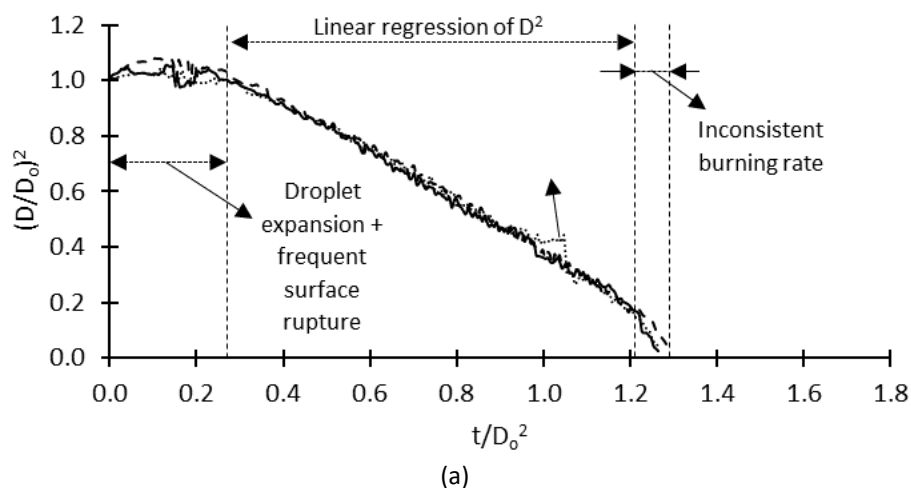


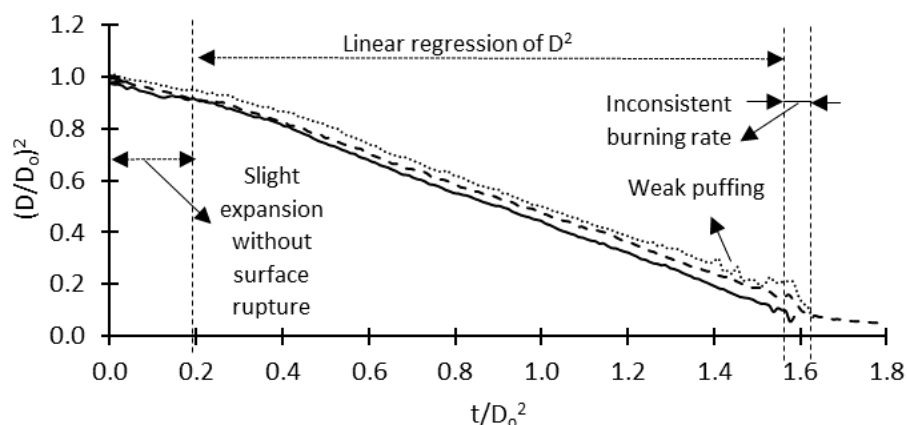
Fig. 2. Digital Image Segmentation Processes on droplet image from (a) raw image, (b) cropped image, (c) complementation, (d) holes filling, (e) thresholding and (f) Noise filtering

3. Results

Feature extractions were made on the segmented droplet images of diesel and ethanol shown in Figure 3. Droplet evolutions presented in this section are based on normalised squared droplet diameter $(D/D_0)^2$ against normalised time (t/D_0^2) ; generally termed as D^2 -law [2]. Normalisation of droplet diameters were utilised on the regression of squared droplet diameter, D^2 to minimise the error between each repetitive experimentation on samples. Both quantitative measurements done on the segmented images shows reducing squared droplet diameter of droplet as the time passes. Three distinct D^2 regressions are observed in both evaporating diesel (Figure 3(a)) and ethanol (Figure 3(b)) droplet.

The evaporation starts with a short increment of D^2 in the early lifetime of the diesel droplet followed by an increasing gradient of D^2 reduction. On the other hand, the D^2 of ethanol continues to decrease by time with a non-linear regression without any measureable increment of D^2 . During this period, the droplet undergoes a heating process and the liquid temperature continues to increase towards its boiling point. Natural convection produced from the flame promotes internal circulation of the liquid droplet. As a result, higher liquid temperature near the surface of the droplet is brought inward towards the core [8]. Diesel droplet undergoes slight expansion of its measured D^2 but ethanol does not appear to show any expansion of droplet diameter. However, the liquid expansion due to thermal heating is definitely present. This can be justified by the non-linearity of D^2 regression which indicates continuous evaporation of the droplet while expanding at the same time [20]. The distinct differences of D^2 regressions during heating process are due to their respective boiling point. Diesel has a boiling point of 170°C whereas ethanol 78°C . Figure 4(b) shows that diesel has a longer heating period than ethanol as a result of having a more than double the value of its boiling point. This indicates that a fuel with higher boiling point will have larger expansion- evaporation ratio during their heating period which resulting a noticeable increment of D^2 measurement shown in Figure 3(a). The liquid expansion can be observed clearly during the visualisation of liquid-phase shown in Figure 5(b) for both diesel and ethanol. The expansion of diesel droplet is apparent compared to ethanol droplet which continues to reduce in size.





(b)

Fig. 3. Regression of squared droplet diameter of (a) diesel droplet and (b) ethanol droplet

Once the temperature of the liquid droplet reaches near its boiling point, the regression of D^2 began to reduce linearly for both droplets shown in Figure 3. Although there is definitely a presence of temperature gradient across the surface towards the core of the droplet due to their large sizes (1 mm) [6], the liquid-gas diffusion on the surface of the droplet remains steady as the liquid surface maintains its temperature near the boiling point because of its close proximity to the flame. During this phase, there is a slight puffing of nucleated vapour from within the droplet thus distorts its surface. Nevertheless, the reduction of D^2 remains fairly linear with some fluctuation due to the liquid surface distortion. Without having any sudden liquid mass loss, the gradient is retained throughout this phase through diffusion-controlled combustion [7]. The regression of D^2 in this phase conforms with D^2 -law which states that a squared diameter of evaporating droplet reduces linearly with time [2] thus making the measurement of burning rate during this phase reliable. The duration of boiling phase of the diesel droplet is shorter compared to ethanol shown in Figure 4(b). Slower heating of the diesel liquid results shorter boiling phase and this period can be extended by the improvement of fuel volatility. From the liquid-phase visualisation shown in Figure 5(c), the surface of the diesel droplet distorts mildly whereas the ethanol droplet has little to no distortion. This is evidenced by the fluctuation within the D^2 regression of diesel droplet shown in Figure 3(a) representing the surface distortion during boiling phase. Also, ethanol steady regression is smoother indicating that the surface distortion during boiling period is minimal.

The gradient of D^2 regression of both fuel droplets were measured which represents the burning rate of the fuel and they are shown in Figure 4(a). Although ethanol has lower boiling point (higher volatility in general) than diesel, its burning rate is lower with $0.5836 \text{ mm}^2/\text{s}$. The total liquid-gas diffusion would include not just on the volatility, but mainly on the ambient temperature of evaporating droplet. From the quasi-steady model of evaporating droplet [3], diesel flame temperature is calculated to be 1884.53 K and ethanol 1484.66 K . Higher flame temperature of diesel provides higher ambient temperature surrounding the liquid surface thus promoting a more rapid liquid-gas diffusion during boiling phase.

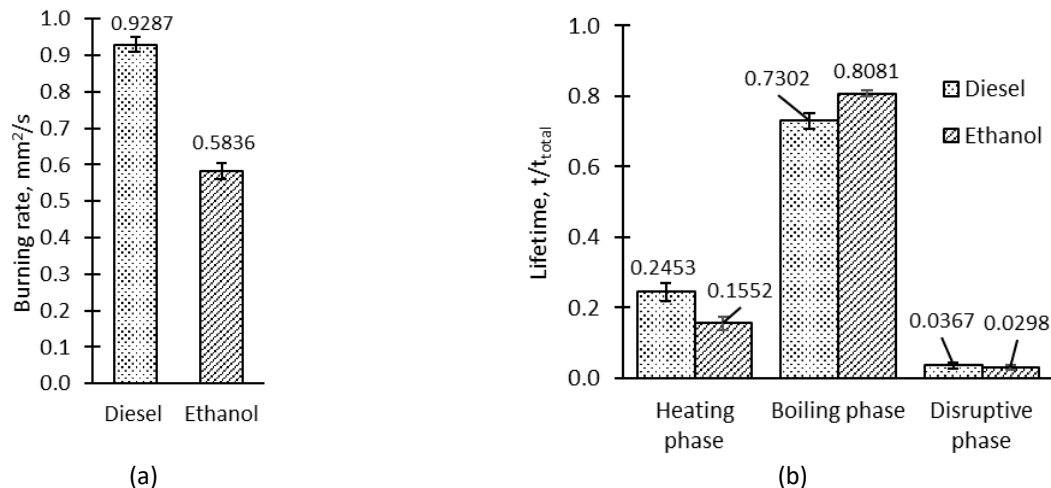


Fig. 4. Quantitative measurement on (a) burning rate and (b) lifetime of combustion phases

As the steady boiling phase progresses, more nucleation of vapour bubbles are observed to appear inside the droplet and can be seen in Figure 5(d). Heat loss from the distancing flame through the vapour accumulation effect [21] steeping the temperature gradient from the surface towards the core of the droplet. As a result, some high temperature liquid from the surface circulated towards the core thus producing several high temperature spots within the droplet [9]. These spots initiate homogeneous nucleation of vapour bubble in small size and combines with each other as the evaporation progresses [22]. The surface of the droplet began to rupture as the bubble grows large thus forcing the liquid sub-droplet to be ejected away from the parent droplet due to pressure drop within the periphery area [14]. Hence, the droplet undergoes multiple occurrences of sudden loss of liquid mass. Because of this, the diameter of the droplet reduces significantly and the burning rate increases. The inconsistent ejection of sub-droplet resulting a non-linear regression of D^2 which can be seen in Figure 3 during disruptive phase thus deviated the regression from the D^2 -law making the disruptive phase an unreliable period of burning rate measurement [15]. The intensities of surface rupture play an important role towards the size of ejected sub-droplet. Ethanol is known to have a lower viscosity compared to diesel. Nucleated bubbles inside a lower viscosity liquid are easier to escape through the surface. Smaller bubble size is sufficient to penetrate the surface of the droplet, resulting higher pressure within the periphery thus weaker ejection strength. The differences between the size and strength of sub-droplet ejection between diesel and ethanol can be seen in Figure 5(d). Because of the intensities difference, diesel has a longer disruptive phase shown in Figure 4(b) and steeper gradient of burning rate as shown in Figure 3(a).

High precision and repeatability of experimental work on both neat fuel droplets proves the reliability of tests done with a very low deviation. Therefore, the common combustion phases of burning neat fuel droplet can be summarise and shown in Figure 6. Three major combustion phases with distinct characterisation has been classified in the present work which consist of heating phase, boiling phase and disruptive phase.

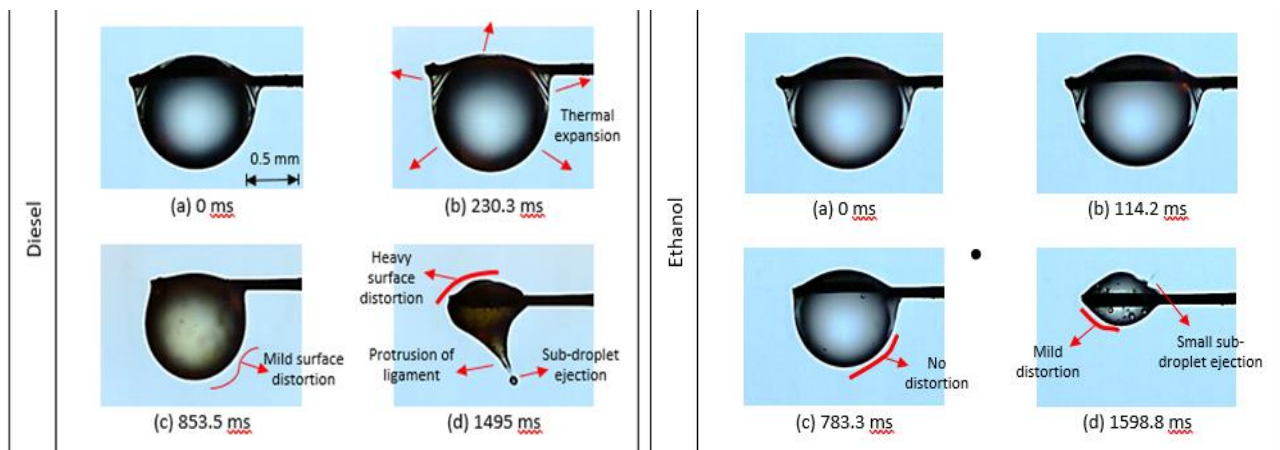


Fig. 5. Liquid-phase visualisation on diesel and ethanol droplet during (a) initial suspension, (b) heating phase, (c) boiling phase and (d) disruptive phase

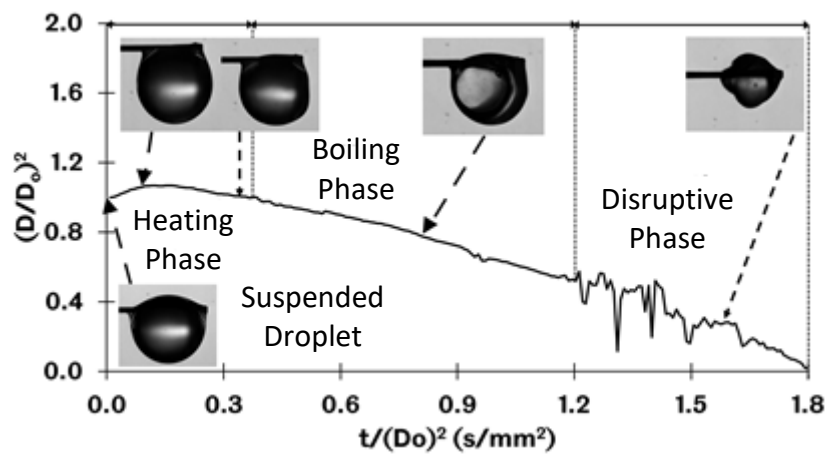


Fig. 6. Proposed general combustion phases of suspended neat fuel droplet

4. Conclusions

Throughout the lifetime of a burning neat fuel droplet, the droplet liquid-phase undergoes a very distinct change of evaporative characteristics. Therefore, from the liquid-phase visualisation alone, the combustion phases of a burning neat fuel droplet can be determined and classified. Three major phases can be observed and measured during experimental droplet combustion tests and they are

- i. Heating phase. During the heating phase, the regression of D^2 is non-linear with a slight increase in D^2 for low volatility fuel. Droplet that is subjected to an elevated ambient heat expands. Simultaneously, the droplet surface undergoes a liquid-gas diffusion process which in turn reduces the diameter of the droplet. As a result, a curve in D^2 regression can be identified and the total length of this curve can be classified as the heating phase.
- ii. Boiling phase. During boiling phase, the liquid temperature reaches near the boiling point of the respective fuel. The surface of the fuel droplet undergoes steady liquid-gas diffusion thus reducing the D^2 of the droplet linearly. Throughout the lifetime of this phase, a reliable measurement of the droplet burning rate can be measured. Few bubble nucleation that leads to puffing can be observed during boiling phase due to the

temperature gradient across the droplet. However, the surface distortion is mild and does not deviate the D^2 regression from the theoretical assumption of D^2 -law.

- iii. Disruptive phase. During disruptive phase, the frequency of bubble nucleation increases. The nucleated bubble combines with each other, forming a larger bubble that burst through the droplet surface with a high ejection strength. As a result, sub-droplet can be observe ejecting outward, causing sudden mass loss of liquid fuel. Hence, the D^2 regresses steeper and non-linear due to a strong puffing during the bubble breakup. The D^2 regression is found to deviate from the D^2 -law thus unreliable to be included in the measurement of droplet burning rate.

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