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Advancements in development and characterization of Single Droplet Combustion: A review

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ABSTRACT

Spray ignition represents a critical process in numerous propulsion and energy conversion devices. The combustion of single droplet is low cost utilization and an effective analysis method for fuel characterization based on its properties. Nowadays, many investigations had been done in single droplet combustion like free falling droplet, suspended droplet in normal gravity and microgravity. A review is presented of recent developments of the combustion of single droplets with discussion and future work in the field. This paper reviews the finding in the literature up to now in this evolving field specifically the experiment detail and the observation area. Moreover, it highlights the prospect experimental that can extend to explore for further research.

Keywords: Single droplet, free falling, suspended droplet, microgravity

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INTRODUCTION

Burning of liquid hydrocarbon get a lot of portion of the global requirement due to the flexibility and ease in transporting and storing [1]. The most important of combustion system are atomization and droplet formation of multicomponent fuel that lead to higher rates of evaporation, fuel/air mixing, and increased combustion efficiency. Multicomponent fuel is more complicated than pure fuel because simultaneous burning of different components occurs at the certain time. In general, phase transformation of highly superheated liquid into vapor occurs for multicomponent droplets in a conventional spray [2]. The Puffing and micro-explosion are among the most processes that are examined in multicomponent fuel. The speed of flame propagation increase caused by micro-explosion that resulted in improved fuel mixing, atomization and evaporation [3].

Spray ignition process is more complex which three distinct mode of ignition namely, droplet ignition, droplet cluster ignition, and spray ignition [4]. The evaporation, the formation of gaseous fuel-air mixture and chemical reaction are the stage of the ignition process. Temperature, pressure, equivalence ratios, homogenous fuel mixture are spray properties that determined the ignition. Identification of this properties is important in spray combustion with regard to flame stability and soot propagation. The ignition of a liquid fuel spray has a characteristic dimension few orders of magnitude larger than a droplet and represents the appearance of a global flame that is associated with the whole spray.

Isolated droplet combustion obtain the fundamental knowledge on spray combustion such as evaporation, chemical reaction, soot formation and radiation [5]. Single droplet combustion also provides the opportunity to investigate the interactions of chemical processes and the physical phenomena such as droplet size, surface tension, chemical compound of fuel, droplet vaporization and combustion [6][7]. The strong correlation between flame radiation intensity and the fuel spray droplet diameter which increase droplet diameter lead to increase the flame radiation intensity. However, an increase in the fuel droplet size lead to flame extinction and/or an increase in the sooting propensity [8]. The aim of this paper is to provide an overview on recent developments of the combustion of single droplets with discussion and future work in the field. This paper will review the finding in the literature up to now in this evolving field specifically the experiment detail and the observation area. Moreover, it highlights the prospect experimental that can extend to explore for further research.

Single Droplet Combustion

The combustion of single droplet is low cost utilization and an effective analysis method for fuel characterization based on its properties [9]. The aims of many researcher studies in single droplet combustions are to observe the phenomena in combustion process. To explore the droplet combustion, many methods of single droplet combustion has been carried out and still developing today. Many researchers studied single droplet in computational research and/or experimental research.

Computational research of single droplet classified in two groups transient and quasi-steady analysis [4]. The approach of these are Spherical-symmetric configuration in droplet that exposed hot oxidizing stagnant environment. The temperature of droplet surface is increase and vaporization begin while heat transferred from the environment to the droplet. In computational, ignition state used critical Damkohler number for quasi steady analysis and inflection point of gas temperature for transient analysis. In this study, the ignition delay was counted the droplet from entry the hot environment to the first flame generated. Droplet heat up, vaporization, and diffusion of fuel vapor can be identified as a physical ignition delay. The major difference between the quasi-steady analysis and transient models is due to the assumptions of single-step chemistry and quasi-steady gas phase in the former. Experimental studied on droplet combustion have been reported by several researcher that detail explained in point below.

Free Falling droplet

Combustion of single droplet with free falling method was begin in 1984 [10] and followed by another researcher in present [11] [12] [13]. Ink jet printing technique was used in this method because it could be generated the droplet which of controlled size, spacing, and velocity. The droplet enters the chamber by free fall. In chamber, the droplet was ignited and burned. The chamber was heated by nickel-chromium wire and fitted by fire brick for wall chamber insulation [14]. Porous bronze was made in chamber inlet to sustaining a flat flame that used to ignite the droplets [13]. The temperature of chamber varies between 980 and 1040 K along the distance over the gasification of droplet takes place [12]. The premixed gas that consist of oxygen, methane, and air control the combustion environment which is fed to the flat-flame burner [15]. The detail experiment set up of free-falling droplet shown in fig.1.

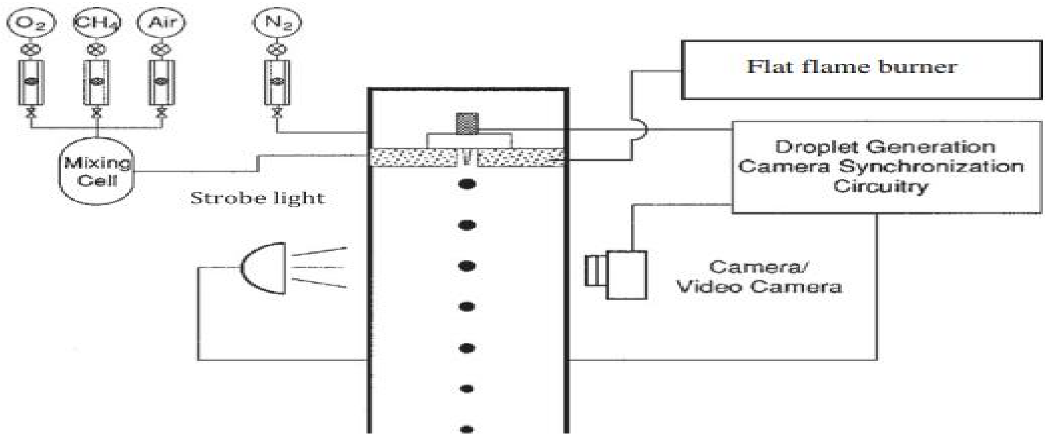


Fig 1. experiment set up of free falling droplet [12]

The droplet generation system was synchronized by back-lighted stroboscope photography to determine capture of the droplet image, while the simple photography with a fixed aperture and exposure time were record the images of the flame streaks [12]. CCD Camera with a long focus microscope and a DSLR camera were used to record the image of droplet and the flame during the free-falling process. The detail instrument describe clearly in their publication [16]; [13]. The function of stroboscope to exposure the camera and monitor the moving droplets during their lifetime [13]. The traces of burning process presented by flame streak throughout their lifetime (see fig.2) [13]

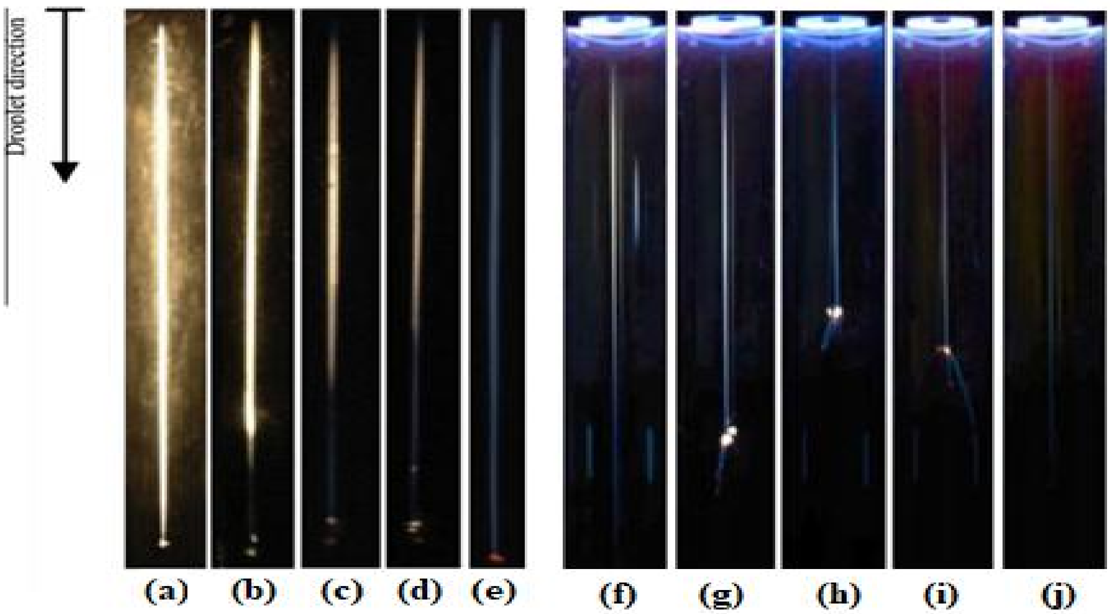


Fig 2. Flame streak image of diesel-castor biodiesel blend (a) diesel, (b) D75B25, (c) D50B50, (d)D25B75, (e) biodiesel [12]; (f) biodiesel, (g) B75E25, (h)B50E50, (i) B25E75, (j) E100 [13]

Suspended droplet

Normal gravity

Hot air chamber ignition

The droplet was suspended on the tip of a silicon carbide fibred, entered the hot chamber by step motor [17]. Horizontal tube chamber with a temperature control to provide a hot air environment until 1023 K. The high-speed CCD camera was used to capture the image of droplet entered the chamber until burned out. Another researcher was dropped the hot chamber to an appropriate position where the suspended droplet ready to ignited by passing through the chamber hole [18] [19]. The camera was placed orthogonally to capture and recording the whole process when the chamber drops until burning period end. The hot air environment was generated with an electric heater which were located in the right and left sides of the chamber. The experiments were performed in air at temperatures between 923 and1073 K, in which a fuel droplet was ignited and combusted.

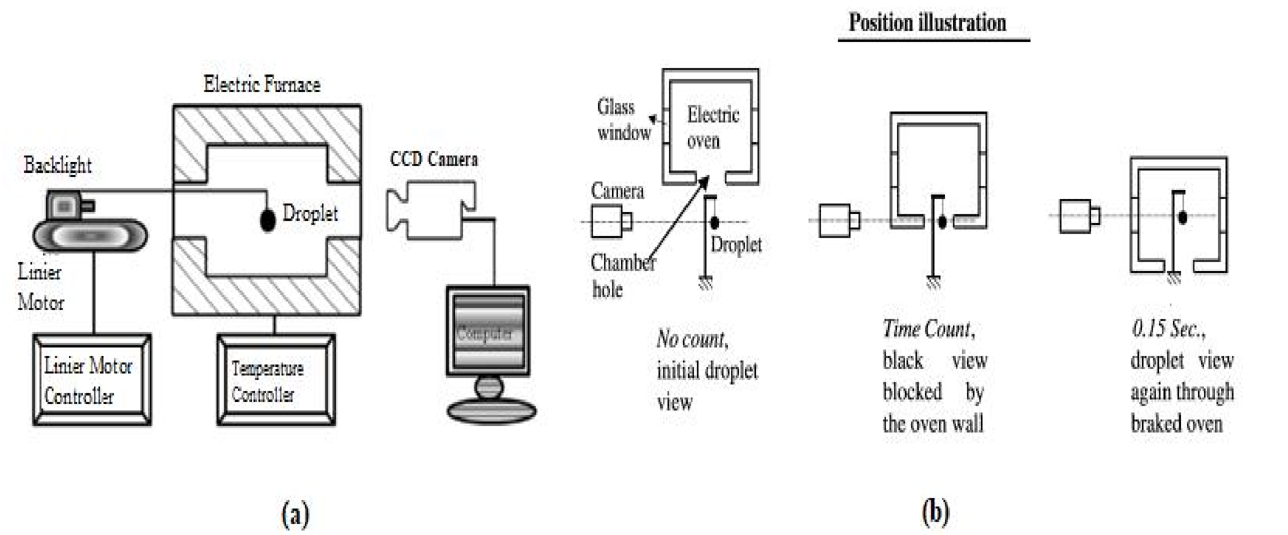


Fig 3. Hot air chamber experimental set up by (a) Zhu et al, 2017 [17], (b) Xu et al, 2003 [18]

The actual shape of the suspended droplet and the flame in the present experimentation were elliptical meanwhile in normal gravity due to the viscosity and kind of fuel (see fig. 4a). In this study, the pine sawdust and coconut shell biochar slurry fuels were prepared with water content ranging from 60% to 70% [17]. This experimental set up intended fuel with high density and viscosity due to the delivery process of suspended droplet entered the chamber using step motor that tend droplet to fall easily. In combustion process, solid residue burned subsequently with bright color and long-lasting time. Lower ash content of pine sawdust caused the amount of ash deposition on the fiber tip was less. In other experiment, light cycle oil mixed with diesel and tested in experimental set up in fig 3b, shown the result in fig 4b [18]. Flame shape was affected by the buoyancy force that appear in normal gravity. The soot tendency occurs during combustion, but there was not obvious coke formation for both the oils in fiber tip. Thus, at the tested chamber temperature the soot precursors might be formed not only in the flame zone but also in the fuel-rich zone. While the former might be mostly oxidized within the flame, the latter should work to densify the soot cloud gradually.

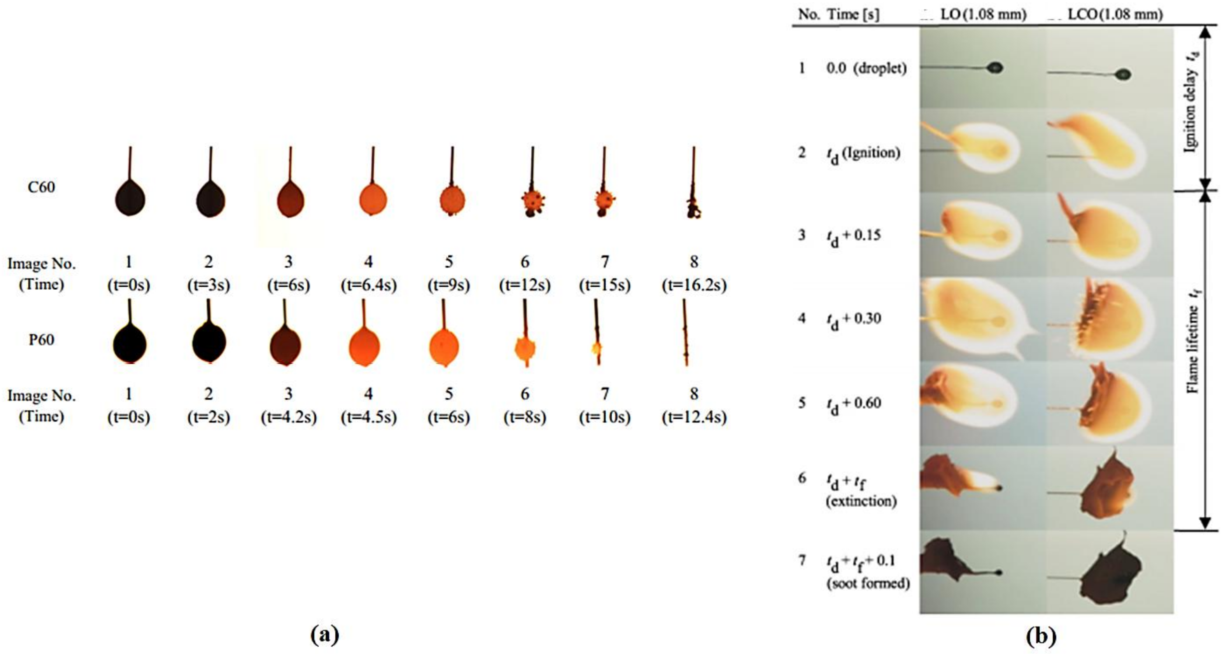


Fig. 4 Typical droplet combustion in experimental set up by (a) Zhu et al, 2017 [17], (b) Xu et al, 2003 [18]

Hot wire ignition

The droplet was suspended on a quartz fiber having a 0.2 mm diameter and ignited using coiled Nichrome wire [2,20]. Different researcher placed droplet in mounted K-thermocouple and ignited using Ni-Cr wire was powered by a DC power supply of 15 V providing a heating power of about 50 W [21]. Another igniter used was a Mini-Igniter™ model 301 micro-igniters for fuel droplet that suspend on intersection of two ceramic microfiber. The igniter was charged by a voltage of 122 V at 12 Amps (1464 W) [22]. High speed camera was used in this experimental to record the sequence of flame evolution.

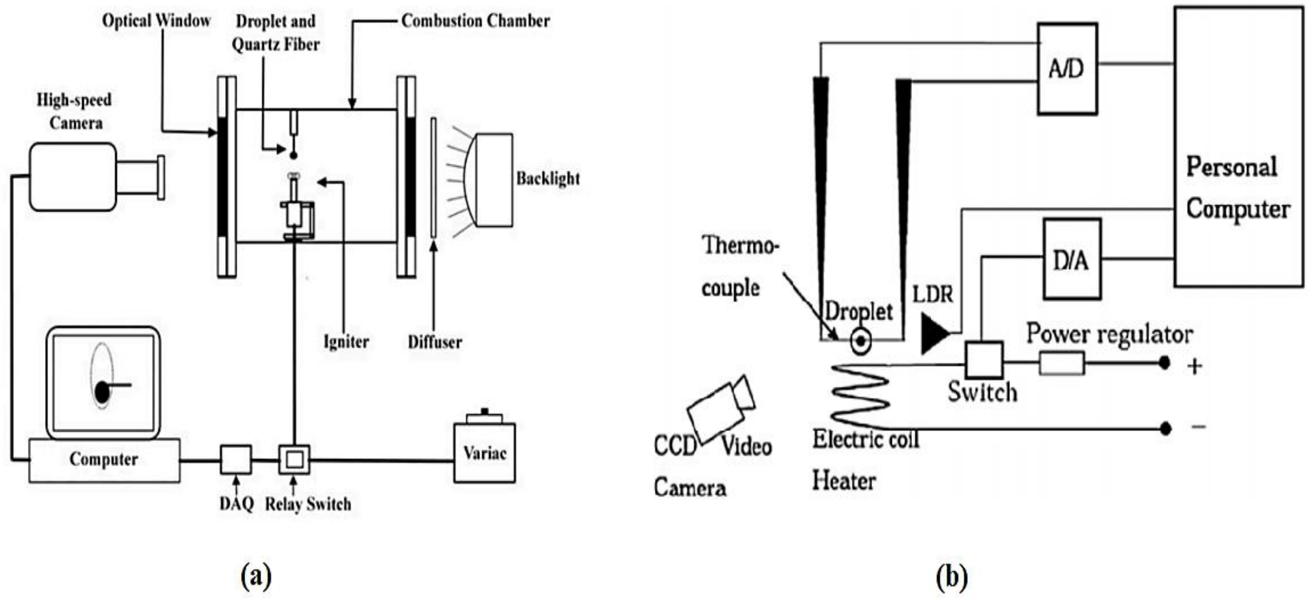


Fig 5. Suspended droplet in normal gravitation with hot wire ignition experimental set up by (a) Rao et al, 2017 [2], (b) Wardana, 2010 [21]

Single droplet combustion in normal gravity has flame shape that effect on buoyancy force. Mostly, the flame shape growth until high like a spike. The flame height was used to analyze the correlation of density of fuel with the volatility. The non-ovoid flame shape was identified the disruptive burning or instability of combustion and also analyzed that fuel contain of aromatic substance.

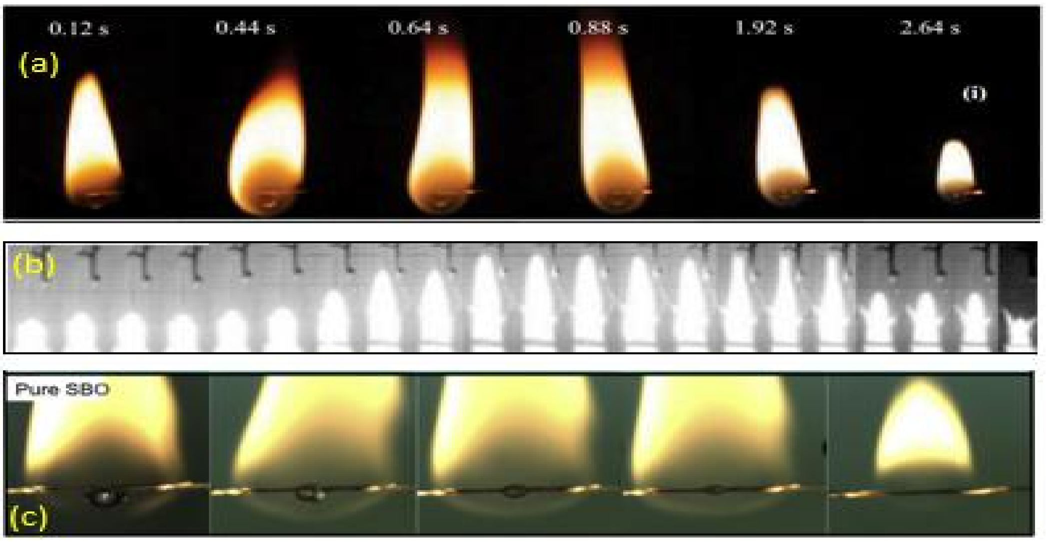


Fig. 6 Flame shape in normal gravity suspended droplet by (a) Rao et al 2017[2], (b) Wardana,2010 [21], (c) Hoxie et al 2014 [22]

Microgravity

Many apparatuses were designed to exhibit the spherical droplet flames by minimize the influence of external convection and buoyancy force. A drop package in height over 7.6 m distance was created to provide 1.2 s of low gravity [23]. The experiments were prepared with droplet placed on cross-sectional tether fiber with Si-C fiber as an electrode. The four electrodes were used to heat up the droplet become the flame. The initial droplet diameter was ranged 0.5 until 0.6 mm. The droplet burning history was recorded by high resolution digital video imaging (3.9 MP per frame, 200 fps). The droplet and soot shell boundary were highlighted by backlight image. Colored video camera 30 fps was used to capture flame and providing information about the flame structure. The drop package detail in fig. 7a, the layout of both cameras and the combustion chamber is detailed in fig. 7b.

Another researcher was set up the experimental configuration of the drop tower about 3.5 m in height [24]. Piezoelectric generator was used to control injection of multiple droplets in size about 500 μm. The droplets placed on the crossing point of two ceramics fibers (Idervon) mainly made of Al_2O_3 and SiO_2, whose diameter was 2.5 μm. The pair of heaters produced high temperature was used to heat up the droplet during the package drop. The detail of combustion chamber and the cameras shown in fig. 7c.

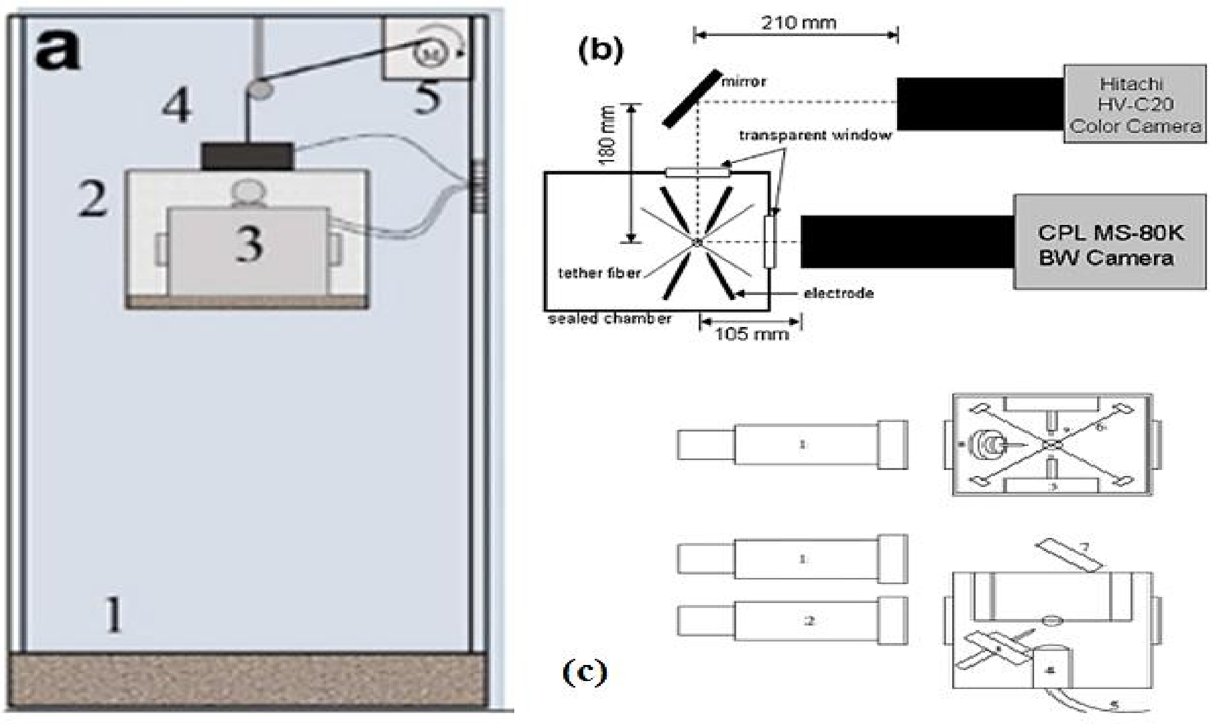
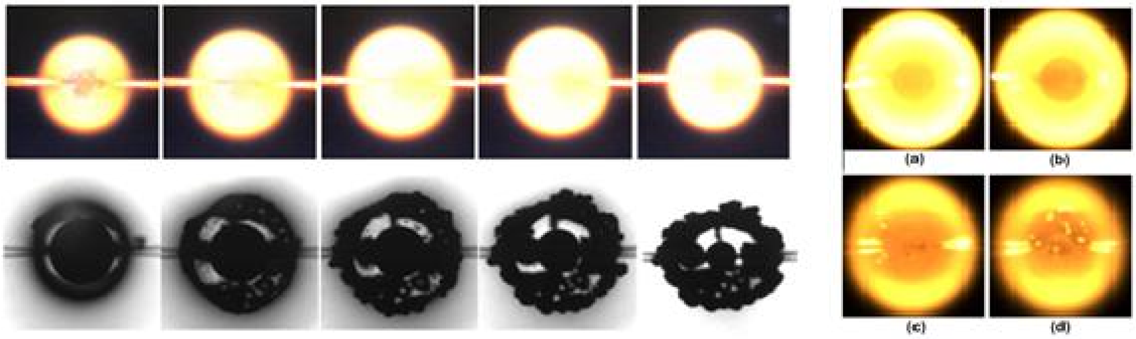


Fig 7. experimental set up to get spherical flame in microgravity atmosphere (a) drop package system, (b) chamber designed by Liu et al, 2013 [23], (c) designed by Pan & Chiu, 2013 [24]

Quantitative measurements of the evolution droplet, soot shell, and flame diameters are obtained by video imaging that recorded the droplet from ignition, burning process until flame extinct. The illustration image of spherical flame shown in fig. 8 that develop in microgravity environment. The interaction between support fiber and the spherical flame as marked by two horizontal needle-like glows in each of the images.



(a) (b)

Fig 8. Spherical flame in experiment by (a) Liu et al, 2013[23], (b) Pan & Chiu, 2013 [24]

Observation area / phenomena

Burning Rate

The burning rate is an important parameter that characterizes performance of a fuel in a practical engine environment. Burning rate in droplet experimental defined as the evolution of the droplet diameter that measured of how fast a liquid fuel is consumed. Jet-A has higher boiling point and lower burning rate due to the fuel composed by aromatic or paraffins with large molecular weight [23]. Another study found that compared with primitive fuels such as biodiesel, binary fuel mixtures of alcohol and biodiesel exhibit higher burning rate [24]. It is clear that the burning rate of biodiesel is slightly lower than that of diesel because of its lower heat content and higher boiling point [12]. The evolution droplet that correlation with the burning rate shown in fig. 9.

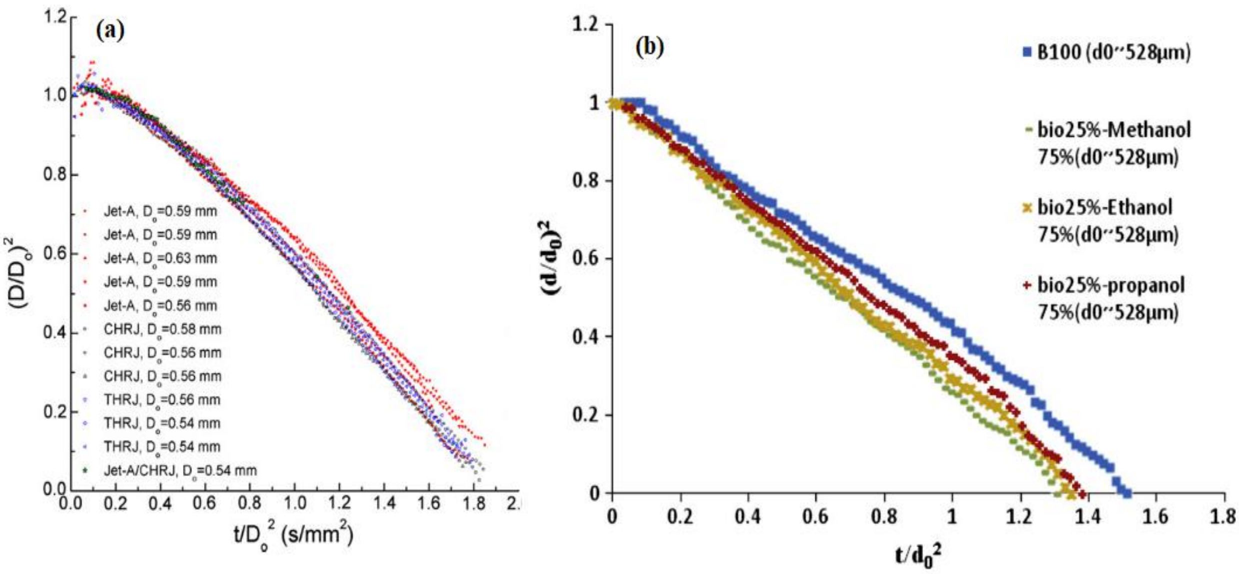


Fig 9. evolution of burning rate (a) Jet-A and it blend, (b) biodiesel and its blend. [23,24]

Soot Propagation

Soot propagation was exhibit clearly in suspended droplet experimental. The most clearly of soot propagation was occurred in spherical flame that create in microgravity environment. Based on fig. 2a, diesel flame has a strong yellow brightness indicating the presence of soot. The yellow brightness reduces visually when biodiesel is added (see fig 2b). The drastic reduction of yellow brightness change to blue flame which is the pure biodiesel burned out (fig 2e). High sooting propensity in diesel due to aromatic compound and sulfur contain in the fuel. It's different with biodiesel of minimal sooting propensity due to none of sulfur and aromatic content. Therefore, light blue flame produce in burns of neat biodiesel, with practically no soot formation [12]. Another researcher explains about soot formation in jet A-1 and its blend. The soot propagation as marked by the brighter yellowish flame with an orange hue at the top edge of pure Jet A-1 appears (fig. 6a) [2]. Soot aggregates was indicated by the yellow zone between the droplet and flame in microgravity (fig 8). Jet-A droplets have the brightest flames due to the high aromatic content [23]. Residual soot distribution was detected in yellowish, orange, or reddish color at the outermost line of flame [24].

micro-explosion

A micro-explosion is defined as an explosion that caused by bubble in internal boiling event that is strong enough to explode inside or ejected out of the droplet. Micro-explosions lead to secondary atomization that increases burning rates, attributed to completed combustion and reduced sooting propensity [12]. Micro-explosions occur when the more volatile component trapped in droplet, boiled and produced bubble that expand and ejected out of droplet become secondary droplet. Detail phase of secondary droplet shown in fig 10.

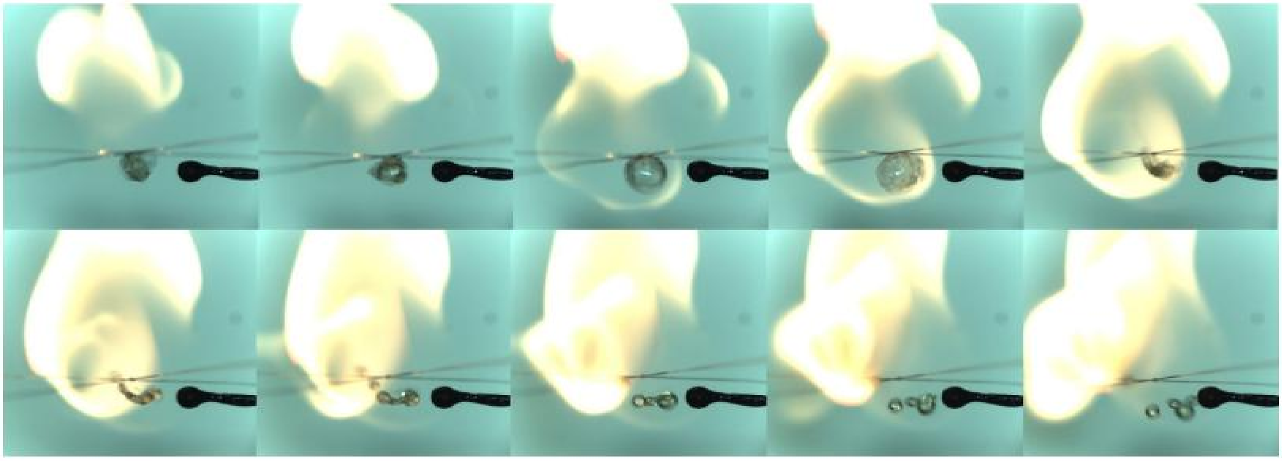


Fig. 10 detail of secondary droplet [25]

Many micro-explosion phenomena have been investigated in terms of multicomponent fuel as a blended fuel. Nucleation sites increase inside the droplet when Jet A-1 blended with butanol 50% [2]. More nucleation sites occurred, increased the bubble growth and leads to micro-explosion. The increase of bubble diameter depends on the percentage of more volatile compound in fuel blend. The bubble grows in large diameter due to the coalescence of several micro bubble [20]. More micro bubble has been coalescence, faster bubble grows to break up droplet and ejected.

Conclusion

The combustion of single droplet is low cost utilization and an effective analysis method for fuel characterization based on its properties. Nowadays, many investigations had been done in single droplet combustion like free falling droplet, suspended droplet in normal gravity and microgravity. Recent developments of the combustion of single droplets with discussion and future work in the field was presented in this study. The burning process in free falling droplet method shown by flame streak throughout their lifetime. The researcher used hot air chamber and hot wire ignition to make combustion process in normal gravity. Flame shape in normal gravity like an ovoid and spike due to buoyancy force. Drop package used to create microgravity condition and produce flame in spherical shape. They studied in normal and microgravity condition to observe the soot propagation, burning rate, and micro-explosion phenomena. A strong yellow brightness flame indicating the presence of soot. The evolution of the droplet diameter indicated the burning rate. Micro-explosion is an explosion that caused by bubble growth in internal boiling event that is strong enough to explode inside or ejected out of the droplet. The micro-explosion caused the unstable flame which is the flame shape not fully spherical in microgravity condition and non-ovoid or non-spike flame in normal gravity. However, it is still needing more observation and further studies on correlation of multi component droplet, flame shape and percentage of soot propagation, in single droplet combustion to overcome the shortage and lack of information in this field.

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