The Effect of Oxygen Concentration on the Burning Characteristics of Kerosene Droplets Using Spark Ignition

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Abstract

This study used experimental methods to investigate the combustion characteristics of kerosene at different oxygen concentrations. The droplets were spark ignited at an ignition energy of 0.1J and initial droplet diameter was 0.4~0.5mm. Combustion at different oxygen concentrations were observed, including droplet burning rate and flame standoff ratio (FSR). The results indicated that ignition delay of kerosene was longer under the conditions of $21\%O_2/79\%N_2$ and resulting in a conical diffusion flame shape and the light was also less obvious. When the oxygen concentration was adjusted to 30%, the time required for ignition was significantly shortened and the light was centered on the top. At 100% O_2, the light-emission region apparently covered the droplet after ignition. The flame was apparently higher (FSR>6) and was more distant from the droplet when the droplet is burning under the condition of $21\%O_2/79\%N_2$. However, the flame became closer to the droplet (FSR>5) and reduced in diameter when the oxygen concentration was increased to $30\%O_2/70\%N_2$ and $100\%O_2/0\%N_2$. When the flame was approaching the droplet surface, the evaporation rate increased alongside the heat transfer inside the droplet. The burning rate at different oxygen concentrations was $K_{100\%O2} > K_{30\%O2} > K_{21\%O2}$. The results suggested during the process of droplet combustion, mass diffusivity affects diffusion of fuel vapor and oxidizer which results in change of the mass burning rate.
Keywrods: kerosene, droplet, spark, combustion

1 Introduction

Spray combustion systems are widely used in power systems, including diesel engines, gas turbines, carburetors and industrial combustion furnaces. Liquid flowing through a nozzle or stretching by a flow field produces numerous tiny droplets. These droplets are heated in the flow field and evaporated into combustible gases and start burning after mixing with oxidizers. Researchers used a single droplet as the study subject to understand the characteristics of droplet combustion. Alternatively, the power equipment for spark ignition is similar to the one found in SI engine (spark ignition engine) [1]. To analyze droplet combustion characteristics, many studies placed the droplet in a high-temperature environment and investigated droplet evaporation and combustion produced by the effects of high temperature. In addition, some studies also placed droplets in a micro-gravity environment and examined the transient change occurred during the process of droplet combustion in the absence of thermal convection.

To investigate the effect of temperature gradient on droplets, some researchers used spark ignition to examine the combustion characteristics of a single droplet [2-4]. Spark can provide a large amount of energy to droplets quickly and allow production of significant amount of high-temperature combustion gases on the surface of droplets to mix with oxidizers and undergo combustion [5]. Liu et al. [6] affixed methyl decanoate droplets to different sizes of SiC fibers to study the combustion characteristics of droplets and the results indicated thermal radiation, mass diffuse and phase change all contributed to the change of flame diameter. Bae et al. [7-8] examined the combustion of nonane and hexanol droplets in different oxidizers. The results showed that the flame standoff ratio of heliumdroplet was lower because nitrogen in the oxidizer reduced the temperature of the flame and the flame became closer to the droplet surface. In addition, higher average gas thermal conductivity also changed the heat transfer mechanism in the gas phase.

Change of the oxidizer will affect droplet combustion, which is helpful to elucidate the transfer characteristics in the gas phase. In this study, experimental measurements were used to investigate the

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correlations between the oxygen concentration in the oxidizer and change of the burning rate and flame of droplet.

2 Experimental method

The droplet combustion system selected in this study was consisting of five components (Fig. 1), including combustion chamber, droplet generator, electronic ignition control system, gas supply system and image capture system. The droplet generator is operated by ink-jet printing and deformation of the piezoelectric chip was driven by DC pulse from the output digital delay generator while squeezing the fuel stored in the fuel tank inside the droplet generator and producing droplets through the nozzle, which then become attached to the perpendicularly-aligned ceramic fibers. The diameter of droplets was around 600 μm. The electronic ignition control system consisted of two 1 mm-electrodes and the distance between the electrodes was 4mm. Digital delay generator and electronic control controlled the discharge time at 0.002ms to ensure the energy produced was around 0.1J. This study adjusted the components of the oxidizer by changing the oxygen/nitrogen ratio and maintained the overall oxidizer flow at 0.5 liter/min to allow droplet combustion to occur in the presence of the oxidizer containing different components. Phantom v7.3 high-speed camera was used to capture images and the resolution was 480×512 pixel, spatial resolution=0.0217mm, and images were taken at 200 frames/sec with a Nikon AF MICRO NIKKOR 60mm 1:2.8D lens. Aperture was adjusted to 2.8 for shooting with the exposure time set at 1μs and the 15W LED light of CERR Q5 was used as the backlight source.

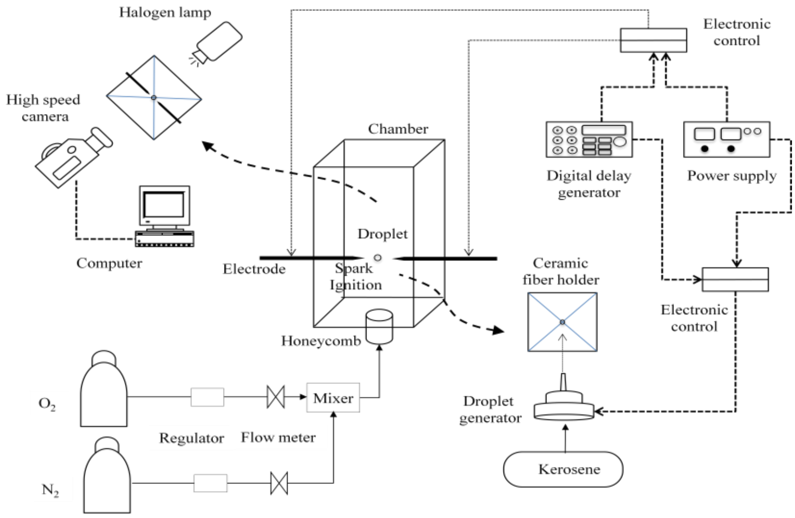


Figure 1. Experimental setup.

3 Results and Discussion

The present study investigated the effects of oxygen concentration on the combustion characteristics of kerosene, including flame shape of droplet, burning rate and flame standoff ratio (FSR).

3.1 The effects of oxidizers containing different components on flame shape during droplet combustion.

Figure 2 shows droplet combustion of kerosene in oxidizers containing different components: 21%O_2/79%N2, 30%O_2/70%N_2 and 100%O_2/70%N_2. The droplet was ignited by a spark with an ignition energy of 0.1J and the surface of droplet produces high temperature under the effect of ignition energy, resulting in droplet evaporation and releasing of combustion gases, which subsequently mixed with the oxidizer to initiate reactions. The time was counted from the end of the spark procedure and the droplets started to generate a light emission zone at lower oxygen concentration when time=20ms and the light emission zone expanded as time increased. In addition, a brighter area was produced on the top (Fig.2a). The intensity of the light of the flame also increased and became more uniform (Fig.2b). The ignition time of the droplet was further reduced in the presence of 100% oxygen. The flame was uniform and the brightness of the flame was high (Fig. 2c). The above results showed that the temperature at the surface of droplets increased rapidly in the absence of temperature gradient due to spark ignited energy and the resulting vapor spreads outward and mixed with the oxidizer to produce a flame, which raised the droplet temperature and accelerated the droplet burning rate (Fig. 3). Therefore, from the photo in Fig. 2, droplet vapor is mixed with oxygen which subsequently changes mass transfer under the effect of thermal convection and radiation, thereby affecting the flame shape of droplet and the intensity of emitted light. Increase of oxygen concentration causes the flame to become closer to the surface of droplet and accelerates the evaporation rate [9].

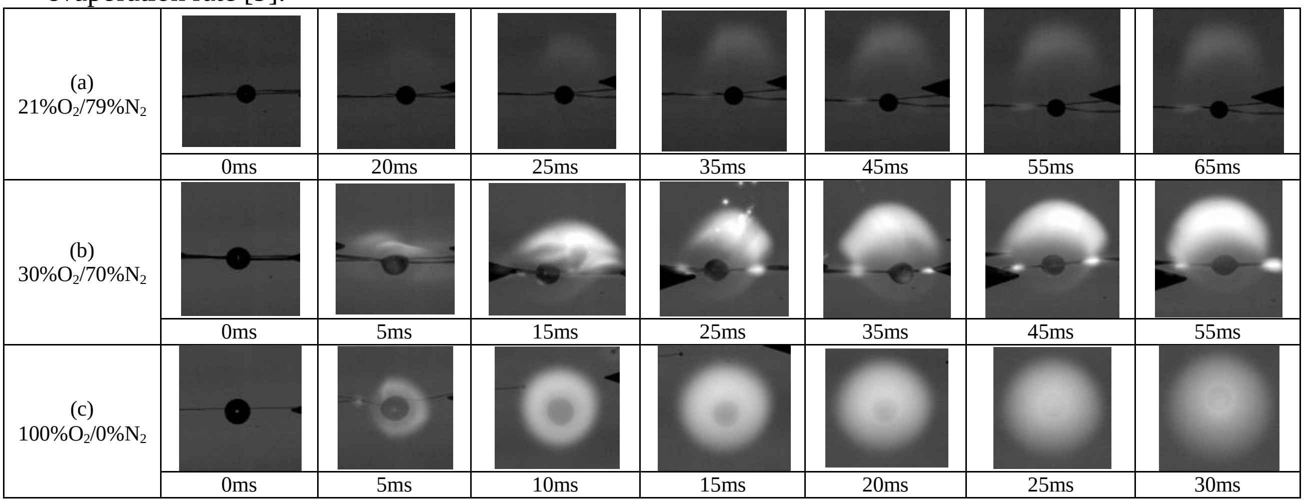


Figure 2. Combustion of kerosene droplets (D_0=0.4~0.5mm) at different oxygen concentrations

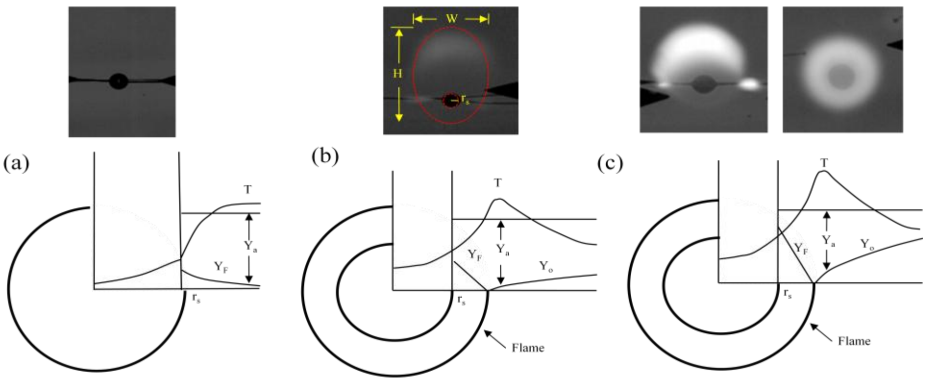


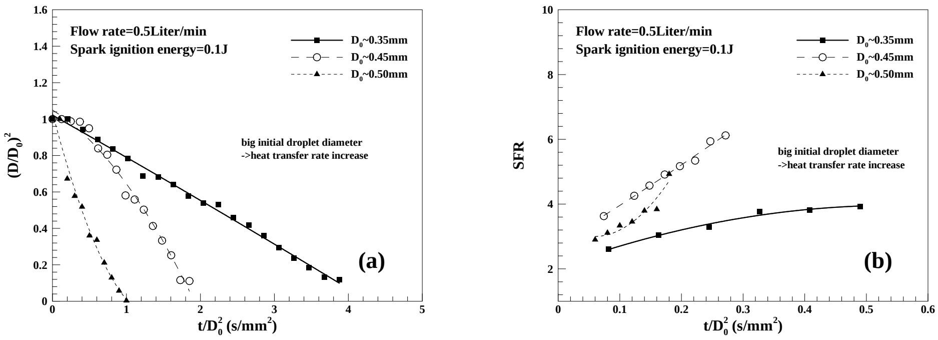
Figure 3.The schematic diagram of the process of droplet evaporation and combustion [1]

3.2 The effect of the initial droplet diameter on combustion

The characteristics of droplet combustion was affected by heat transfer on the surface and the oxidizer components, while the droplet size played an role in the heat transfer inside the droplet, thereby affecting the evaporation on the surface of a droplet. Figure 4 shows different sizes of droplets, D_0~0.35mm, D_0~0.45mm and D_0~0.50mm, were ignited by the same energy of 0.1J in the oxidizer containing 21%O_2/79%N_2. From the results, the burning time of the smaller droplet (D_0~0.35mm) is longer and started to reduce when the initial diameter of the droplet was D_0~0.45mm, whereas the burning time of a large droplet (D_0~0.50mm) was shorter and the diameter variation of the large droplet showed a significantly steeper slope. This suggests that a larger droplet absorbs more heat and consequently the combustion of a large droplet is faster than a smaller droplet at a later stage [10]. Because the combustion temperature is affected by droplet diameter during the process of droplet combustion, the thermal radiation from a flame and thermal conduction from the surface to the center of a droplet will vary based on the initial diameter. Flame standoff ratio was used to assess droplet evaporation and diffusion mechanism and the equation of flame standoff ratio (FSR) [12] is shown as follows (Fig. 3b):

$$FSR = D_f/D$$

Wherein D_f=(W+H)/2 is defined as flame diameter. Figure 4b shows FSR increases with increased t/D_{02} at a constant oxidizer flow rate and the greater the droplet size the shorter the burning time. The flames of small droplets are stronger, which is mainly due to thermal radiation of the flames and thermal convection from the surface to the center of droplets. The FSR of droplets with large diameters increases rapidly as burning time increases because, under the effect of ignition energy, droplets with larger initial diameters produce more droplet evaporation to mix with oxidizers and undergo combustion. As a result, the initial flame diameter was larger and a larger area of a flame generates more heat transfer and accelerates droplet combustion, which shortens the burning time of larger droplets.



(a) Variation of dimensionless droplet diameter-squared with time (b) Variation of flame standoff ration with time

Figure 4. Variation of dimensionless droplet diameter-squared and variation of flame standoff ration with time

3.3 The effects of initial droplet diameter on burning rate

In air environment, instantly ignite the droplet with the ignition energy of 0.1J and kerosene droplet is heated by the high temperatures of the flame and releases vapor, which will produce a chemical chain reaction containing high activation energy upon contact with oxygen in the oxidizer. The mass and energy produced after the reaction then spread from the flame to the inside or outside and the oxygen concentration in the nearby region also affects the burning rate (K). The equation is as follows [12]:

$$\left(\frac{\mathrm{D}}{\mathrm{D_0}}\right)^2 = 1 - \mathrm{K}\left(\frac{\mathrm{t}}{\mathrm{D_0}^2}\right)$$

At the same O_2 concentration, Figure 5 shows the effects of different initial droplet diameters on burning rate. From the results, the burning rate of a small droplet (D_0~0.35mm) was 0.228mm^2/s and increased to 0.48 mm2/s for a larger droplet (D_0~0.45mm). When the droplet diameter was 0.45mm, the burning rate increased to 0.996mm^2/s. Droplets with larger initial diameters are affected more significantly by ignition energy and cause more high-temperature fuel gases to mix with the oxidizer and then combust. Therefore, the larger the initial droplet size is, the higher the burning rate.

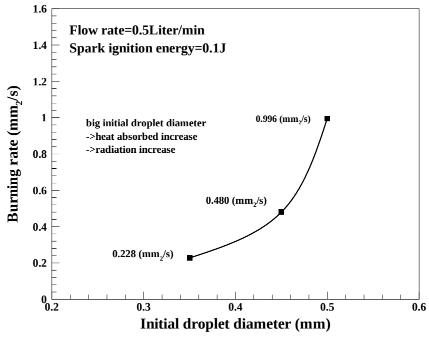
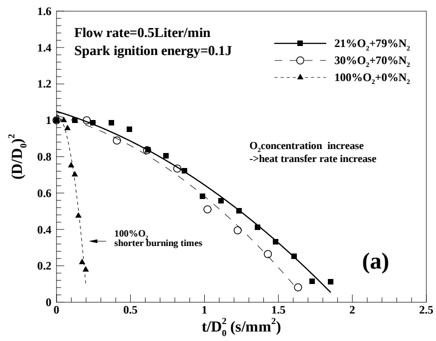


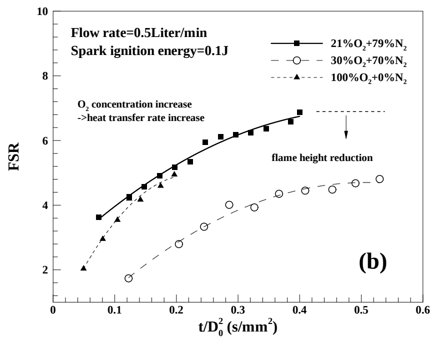
Figure 5. Influence of different initial droplet diameter on burning rate.

3.4 The effects of oxygen concentration on $(D/D_o)^2$ and FSR

Figure 6 demonstrates the effects of oxidizers containing different components on the combustion characteristics of droplets. The results indicate the burning time of a droplet in an oxidizer reduces when the oxygen concentration increases from 21%O_2 to 30%O_2. The droplet instantly burnt-out when the oxygen concentration is at 100%, suggesting the linear relationship of droplet diameter squared and time shortens as oxygen concentration increases [10]. Increase of oxygen concentration will allow the flame become closer to the droplet surface and accelerate the evaporation rate [9], resulting in increased heat transfer. Zone I and Zone II of Figure2 (c) are affected and decrease gradually due to increased oxygen concentration and the burning rate is also affected. Figure 6(b) shows variations of the flame standoff ratio with O_2 concentration. From the results, when a droplet is burning in an oxidizer containing 21% O2, the flame is significantly higher (FSR> 6) and farther away from the droplet. As the oxygen concentration increases to 30%O_2/70%N_2 and 100%O_2/0%N_2, the flame gradually approaches the droplet (FSR> 5), the flame diameter is shorter and the flame is closer to the droplet surface which changes the heat transfer mechanism in gas phase. As for the effects of burning rate, please refer to Section 3.5.



(a)Variation of dimensionless droplet diameter-squared with O_2 concentration



(b)Variation of flame standoff ration with O_2 concentration

Figure 6. Variation of dimensionless droplet diameter-squared and flame standoff ration with O_2 concentration

3.5 The effects of oxygen concentration on burning rate

When the oxygen concentration was 21%, the burning rate was 0.48mm^2/s and the burning rate also slightly increased to 0.563 mm^2/s when the oxygen concentration was increased to 30%. In addition, the burning rate increased to 4.16 mm^2/s when the oxygen concentration was 100%, an approximately 7 to 8-fold increase. Mass burning rate also increased with the increase of oxygen concentration. As shown in Figure 7, the maximum mass burning rate was 11.72×10^{-4} (g/s). This indicated that the flame was closer to droplet surface due to increased oxygen concentration. The evaporation rate increased as well [9], and the thermal-radiation effects of the flame also increased with enhanced heat transfer, which consequently increased heat transfer inside the droplet. Therefore, the burning rate of different oxygen concentration was $K_{100\%O2}>K_{30\%O2}>K_{21\%O2}$.

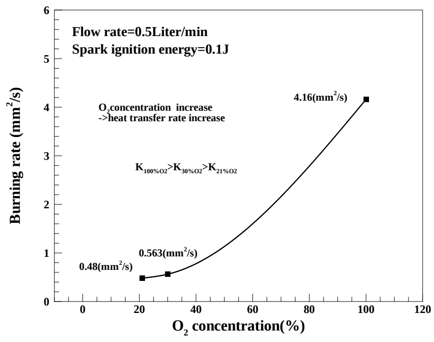


Figure 7. Influence of different O_2 concentration on burning rate

3 Conclusions

Kerosene droplets are ignited by a spark in oxidizers composing of the different components for investigation of its combustion characteristics. The results indicate that for different initial droplet diameters, the larger droplets have higher burning rates and the burning rate increases with burning time in the 21% O_2/79% N_2 oxidizer. Ignition of the droplet with a fixed initial diameter in oxidizers containing different components demonstrated the burning rate of the droplet is higher as the oxygen concentration increases. The phenomena in this study were caused by droplets spark igniting. This finding is different from previous studies in that no apparent temperature gradient was observed in the oxidizer and droplets during the initial state. The spark rapidly released energy to droplets and generated a significant amount of high-temperature fuel gases to mix with the oxidizer and then combusted. Moreover, fuel gases generated by droplets change the diffusion rate under the effect of temperature. The combustion resulted from the mixture of fuel gases and oxygen occurs earlier and more intense as the oxygen concentration increases, which also changed the heat transfer mechanism of the gas phase and droplets, thereby raising the burning rate.

Acknowledgments

The authors would like to thank the Ministry of Science and Technology, Taiwan, for financially supporting this research under MOST 103-2221-E-150-056 and MOST 103-3113-E-008-001.

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