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SINGLE DROPLET COMBUSTION OF ALTERNATIVE FUELS

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ABSTRACT

Due to an increase in emissions, alternative fuels are often being considered for fuel reliant systems. Biodiesel is often produced from vegetable oil feedstock. Evaluating the combustion characteristics of pure vegetable oil is beneficial in determining how the vegetable oil would benefit as a biodiesel addition or in other combustion systems. Glycerol and methanol are byproducts of biodiesel. There is potential in using methanol and glycerol in combustion systems rather than recycling the alcohols back in for biodiesel production. Ethanol is a promising alternative fuel that is currently in use in combustion systems. Using ethanol as a comparison for other alternative fuels is beneficial for evaluation.

Because almost all engines involve fuel atomization, it is critical to study single droplet combustion by experiments to fully understand combustion characteristics. In this study, single droplets of canola oil, olive oil, methanol, ethanol, and glycerol were investigated.

Canola oil and olive oil have similar droplet combustion dynamics. Both fuels engaged in a bubbling stage during the burning process. Methanol was the quickest to ignite. Once ignited, methanol had a similar burning rate to that of ethanol. Glycerol required the longest preheating period before ignition and the longest burning time.

Keywords: Droplet combustion, Alternative fuels

1. INTRODUCTION

Due to greenhouse gas emissions and the high reliability that the energy and transportation sectors have for petroleum, recent studies have focused on the usage of biodiesel. Nearly 95% of the world's transportation depends on petroleum based internal combustion engines [1]. The energy sector is responsible for 73% of total greenhouse gas emissions, and 16.2% of that total is contributed by the transportation sector [1].

Biomass-derived fuels have the potential to serve as alternatives to fossil fuels, because they are renewable and can substantially reduce exhaust emissions and greenhouse gases. Biofuels are considered with great potential to be used as "drop-in replacement" for conventional fuels [2,3]. However, the physical properties such as volatility, viscosity, surface tension and chemical composition of these fuels can be significantly different from conventional liquid fuels [4, 5]. Also, fuels produced from various renewable feedstocks have distinct properties. The variations in fuels and different properties of the fuel blends lead to different spray characteristics (e.g. liquid penetration length and vaporization rate) and combustion behaviors (e.g. flame temperature and emissions) [6-8].

The current study examines the droplet burning characteristics of methanol, glycerol, and ethanol fuels as well as canola and olive oil using a fiber support system. The experiments extract fundamental information about liquid fuel combustion that cannot be easily generated from full-scale engines to evaluate the burning characteristics in the context of transportation fuels and the response of fuels through blending in a fundamental way. The effort is important in evaluating the utilization of biofuels and the feasibility of using these fuels as "drop-in" fuels to reduce emissions during combustion.

1.1 Vegetable Oil

Biodiesel can be derived from vegetable and animal fats. [9]. Biodiesel is biodegradable, nontoxic, and biodiesel production can improve rural development from agricultural resources [9]. Additionally, studies show that the use of biodiesel can improve engine performance and reduce emissions compared to that of diesel [9].

The vegetable oil choice for biodiesel production is dependent on the geological location [9]. Soybean oil is the most used in the USA, rapeseed oil in European Countries, and palm oil in tropical countries [9]. Research has been conducted to determine the ideal vegetable oils to use for biodiesel production. It is found that biodiesel produced from olive oil has a high cetane number and oxidative stability [10]. Biodiesel produced from canola oil is found to have a low cold fiber plugging point, which makes the fuel ideal for use in colder climates [10]. Previous research conducted on canola oil-based biodiesel has found that biodiesel can be used in diesel engines without engine modifications [11].

A study on single droplet combustion of hydro processed vegetable oil found that pure hydro processed vegetable oil had a longer burning time than that of pure Jet A-1 [12]. Experiments found that Jet A-1 and hydro compressed vegetable oil mixtures could improve the burning performance and promote further use in the aviation sector [12].

Implementation of vegetable oil for various alternative fuels and biodiesel production shows promising results. Therefore, in this study, vegetable oils are tested alone as well.

1.2 Biodiesel Byproducts

In 2023, it was predicted that the global production of biodiesel would increase to 56.2 million tons, which is an 8% increase from 2022 biodiesel production [10]. The transesterification process, to produce biodiesel, reacts methanol with vegetable oils or animal fats to form biodiesel and glycerin [13]. The methanol is then removed after the biodiesel and glycerol have been separated [13]. Nearly 0.5kg of methanol is used to produce 1kg of biodiesel [13]. For every 1kg of biodiesel produced, roughly 0.1kg of glycerol is produced [14]. Therefore, it is of great significance to study the combustion characteristics of methanol and glycerol as the production of biodiesel increases.

Single droplet combustion experiments are a cost-effective way to test the combustion characteristics of various fuel types. Atomization is an important step in liquid fuel combustion, as atomization of a liquid fuel droplet increases the fuel surface area to burn and release energy [15]. It is for this reason that single droplet combustion experiments are crucial to understanding fuel combustion. Important data that can be obtained are the fuel's burning rate and ignition temperature. Setyawan et al studied the single droplet combustion characteristics of glycerol in comparison to petroleum diesel, biodiesel, and ethanol. The droplet was suspended on the tip of a fiber within an electric furnace [15]. More data is needed to fully understand the dynamics of the fuel. Therefore, in this study, methanol and glycerol are tested alone to provide more details on combustion characteristics.

1.3 Ethanol

From 2012 to 2022, the production of ethanol has grown by an average of 3.8% [16]. Ethanol is a renewable resource that can be produced from agricultural feedstock, cellulosic biomass, or materials that can be transformed into fermentable sugar [17]. The abundance of available ethanol makes the fuel an attractive option for combustion systems. Ethanol is mainly used as a transportation fuel or gasoline additive [16].

Previous research has been conducted to study the single droplet combustion characteristics of ethanol. Ethanol has been the subject of many studies because the fuel has the potential to replace the role of gasoline and kerosene as fuel [18]. Ethanol has a higher octane number than conventional gasoline and a higher laminar speed [17]. Studies of ethanol combustion characteristics for internal combustion engines have confirmed that ethanol's higher octane number contributes to higher compression ratios, optimal ignition timing, higher intake air levels, and resistance to the tendency to knock compared to conventional gasoline [16].

Numerous studies have already been conducted that study the combustion characteristics of ethanol. However, it is important to continue to study the single droplet combustion characteristics. Studies of the single droplet combustion of ethanol can provide insights into system and fuel optimization, and provide a comparison to other fuels.

2. MATERIALS AND METHODS

In 1980, a droplet combustion experiment was performed on the ISS and it was discovered that a zero-gravity environment is ideal for achieving a perfectly spherical droplet. It is for this reason that the free-fall droplet method is often employed [19]. A fiber support system is also a commonly used system. A study done by Cornell University deployed droplets of n-butanol, gasoline, and n-butanol/gasoline mixtures onto silicon carbide fibers and then released the setup into free fall upon ignition [20]. In this setup, spherical symmetry was promoted by low gravity as well as small droplet size and restricting droplet motion on the fibers [20]. Another study was performed that compared droplet combustion of heptane and heptane mixtures using the suspended droplet method and the free fall method [21]. A single vertical quartz fiber was used, and it was discovered that when fibers less than 50 um were used the droplet distortion and burning rate discrepancies between the suspended droplet and free-falling droplet were reduced [21]. The suspended droplet method can be used to promote spherical symmetry [22]. For this experiment, small droplet diameters and 16-um microfibers will be used to ensure that the droplet is as close to spherical as possible.

Droplets with diameters 0.25-0.32mm were dispensed from a 32-gauge syringe onto the intersecting point of 16-um silicon carbide fibers. The range of droplet sizes can be attributed to the manual dispensing of the droplet from the syringe and the differences in surface tension between the fuels tested.

Two hotwire loops served as the ignition system. The hotwire loops were placed on either side of the droplet and were powered by a DC power supply. The kanthal A-1 hotwire loops were each placed in an alumina insulator and soldered to flexible wire. Placing hotwire loops on either side of the droplet exposes the droplet to enough heat to be ignited with little pre vaporization occurring.

To keep the hotwires from interfering with the flame after ignition, a linear actuator retraction system was used. The schematic set up is shown in figure 1.

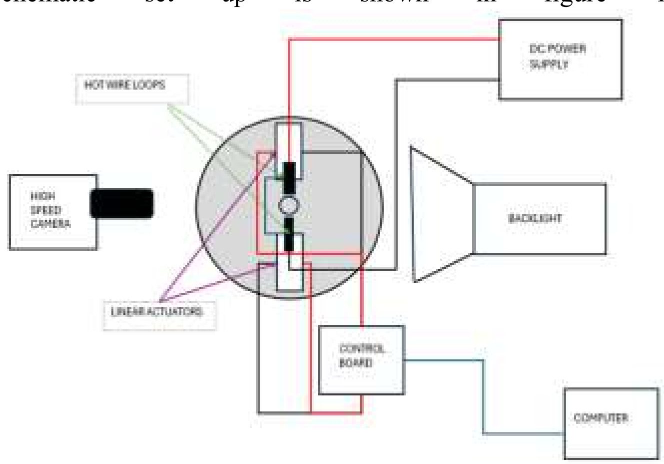

FIGURE 1: Experimental Setup

A 3D printed hotwire mount was designed to hold the hotwires securely on the linear actuators. To keep the hotwires from damaging the mount and the retraction system, oven bake clay was placed around the alumina insulators. This setup prevented the hotwires from burning through the mount and touching the linear actuators. The linear actuators were controlled using an Arduino UNO microcontroller.

The process was captured using a Chronos high speed camera and macro lens. A white poster board was placed behind the droplet. A backlight was placed behind the poster board so that the light would shine through the board, onto the droplet. The camera setup was placed approximately 1 ft from the droplet.

The camera was calibrated using an object with a known diameter before every experiment. The camera captured 2134 frames per second at a resolution of 1280 x 512. The frames were imported into Spotlight image processing software. The software allowed for the initial and droplet burning diameters to be calculated. The experiment was performed at least three times for each fuel. The experiment footage that had the best quality was chosen for analysis.

A pixel uncertainty analysis was performed on the droplet images. This method was based on uncertainty analysis that was used in previous research [23,24]. A circular area of interest was placed around the droplet in Spotlight. Outside of the area of interest is a pixelated transition area. This pixelated area was due to the digitization of a finite boundary [24]. Image processing available within Spotlight aids in defining the boundary and reducing uncertainty in the diameter. The digitalized transition area for the initial diameter of the droplets, after post image processing, was found to be 2 pixels. For a 0.25mm droplet, the diameter was measured to be 40 pixels. Therefore, the uncertainty in pixels of the initial diameter was approximately 5%. The smallest droplet size measured was approximately 14 pixels, so a 14% uncertainty exists for the smallest measured droplet diameter as it approaches extinction.

The burning of the droplet was assumed to follow the D^2 law of combustion. The law states the droplet is spherically symmetric and the diameter decreases with time upon ignition. For a droplet to be spherically symmetric, the convective flows are reduced, and the droplet flame and soot shell are spherical and concentric. Previous literature has found that the burning rate under conditions of natural convection is a function of Grashoff number [15]. For zero gravity conditions and optimal spherical symmetry, Reynolds number and Grashoff number approach zero [15]. Meaning that convective flows are close to zero. Anchoring a droplet onto fibers allows for zero forced convection to be obtained. Therefore, making Reynolds number almost zero [15]. Grashoff number can be minimized by reducing the droplet size [15]. Larger droplets suspended on thin fibers will take on an ellipse shape, whereas smaller droplets will form a spherical shape. The D^2 law is shown in equation 1.

$$D_t^2 - D_O^2 = -Kt \tag{1}$$

Where D_t is the diameter at time t, D_o is the initial diameter of the droplet, and K is the burning rate of the droplet. The burning rate was calculated over time during the burning process for each droplet.

Five fuels were chosen for this study: olive oil, canola oil, methanol, ethanol, and glycerol. Spectrum Naturals olive oil and canola oil were used. Spectrum Naturals was chosen because the brand is GMO free, and the extraction of the oils is chemical free. Lab grade ethanol, methanol, and glycerol were purchased from Innovating Science. The brand was chosen due to the high purity of the fuels provided.

3. RESULTS AND DISCUSSION

Droplets of methanol, ethanol, glycerol, canola oil, and olive oil were investigated. Different burning stages were present for each fuel type. The burning stages shown in figure 2 are the burning stages seen in ethanol, methanol, and glycerol.

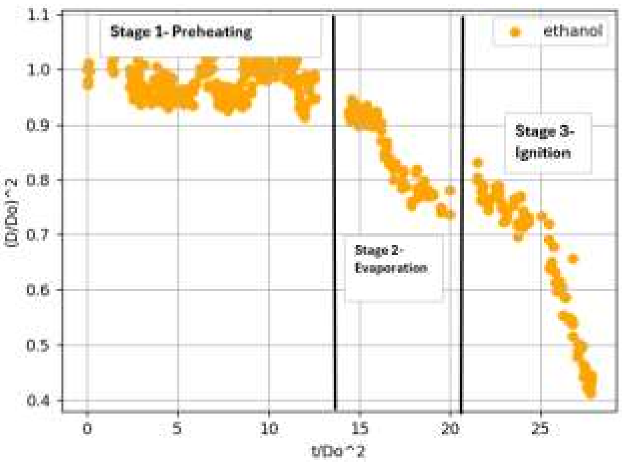

FIGURE 2: Burning stages of ethanol droplet

While the stages shown in figure 3 were present in all three fuels,the stages were prominent in ethanol. The droplet experienced a preheating phase that occurred while the hotwires were heating to a temperature sufficient for combustion. In this case, the droplet was heated from room temperature. Before ignition, the droplet began to steadily evaporate. Once ignition occurred, the droplet diameter decreased linearly with time.

Figure 3 shows the burning sequence of methanol, ethanol, and glycerol. The frames needed for the initial diameter were taken before the hotwires were turned on. Additional frames were pulled when ignition began and then 0.5,1.0, and 1.5 seconds after.

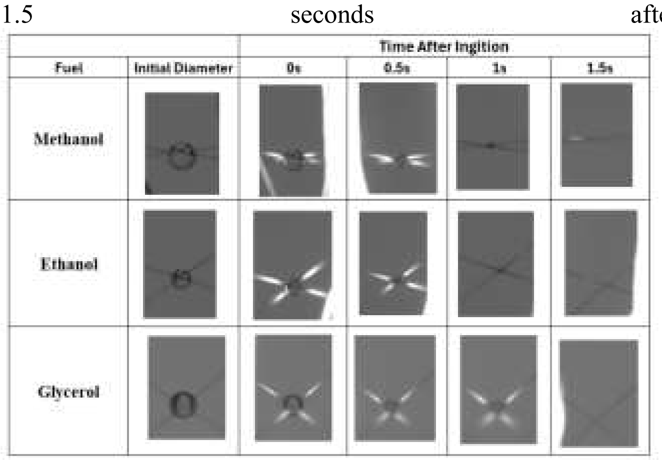

FIGURE 3: Droplet burning sequence of methanol, ethanol and glycerol

The vertical black lines present in the images reflect the silicon carbide fibers that the droplet is suspended on. This reflection is present in the images shown in figure 5 as well.

Glycerol needed a longer preheating period than methanol and ethanol to reach ignition. Glycerol also had a longer burn time of nearly 0.5 seconds compared to methanol and ethanol. For all three fuels shown in figure 3, a flame was not visible during the burning process. A reaction between the fuels and the silicon carbide fibers resulted in the fibers glowing to indicate ignition. Throughout the burning process, the three fuels remained visibly spherical.

The stages of droplet burning for olive oil and canola oil are shown in figure 4.

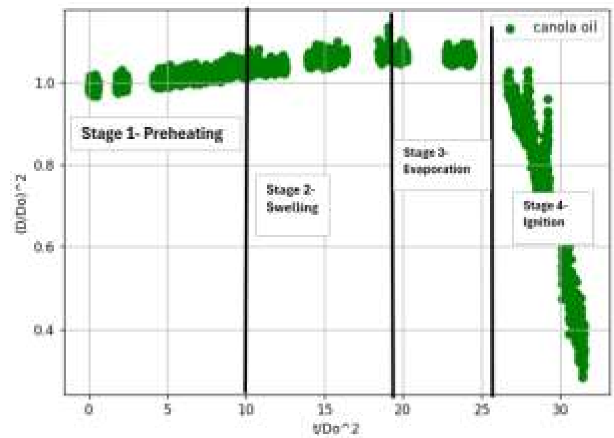

FIGURE 4: Burning stages of canola oil droplet

Unlike the fuels shown in figure 3, canola oil and olive oil experienced swelling before ignition. When the hotwires turned on, the droplets began to preheat and swell. After swelling, the droplets began to evaporate and then ignite. Once ignited, the droplet diameter decreased linearly with time.

Figure 5 shows a sequence of burning images of olive oil and canola oil at different instances after ignition.

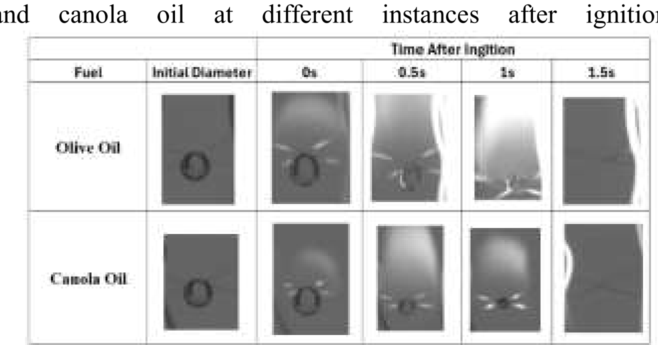

FIGURE 5: Droplet burning sequence of olive oil and canola oil

The initial diameter photo of the droplet was taken before the hotwires were turned on. The process at which the frames were taken was the same as that done for figure 3.

The swelling between the initial droplet diameter and the time before ignition is apparent when ignition first occurs. Both canola oil and olive oil droplets swelled and formed an oval shape. As ignition progressed, the droplet diameter began to decrease. For both fuels, the burning process was finished approximately 1 second after ignition. Both canola and olive oil droplets formed internal bubbles during the ignition process. These bubbles caused micro explosions and asymmetrical shapes. The bubbles formed within the olive oil and canola oil droplets are likely due to internal effects, and bubbles forming inside the droplets can cause micro explosions [15]. Diameter measurements were not recorded at these instances.

Comparing the images shown in figures 3 and 5, clear differences are present in the burning behaviors of canola and olive oil and methanol, ethanol, and glycerol. Methanol, ethanol and glycerol did not deviate from a spherical shape while burning. No bubbles or other deformities appeared during the ignition process. Canola and olive oil experienced more swelling before ignition.

Figure 6 shows a comparison of diameter and time normalized by the initial diameter for each fuel tested.

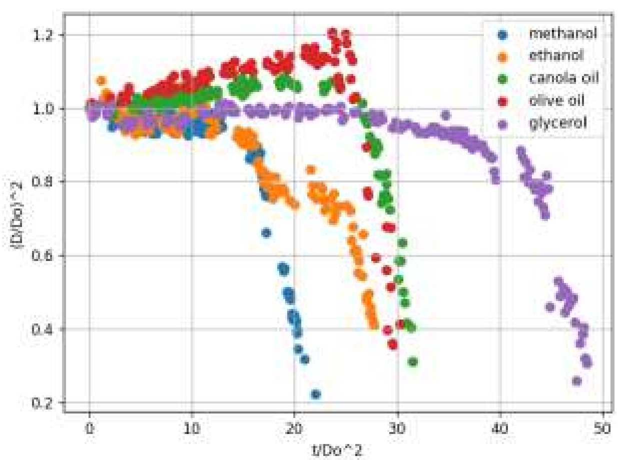

FIGURE 6: Square of the normalized droplet diameter as a function of the normalized time for various fuel types

Normalizing time and burning diameter by the squared initial droplet diameter allows for the burning diameter in comparison to time to be analyzed while eliminating the effects of the varying initial diameters between the fuels.

Methanol was the quickest to ignite, while glycerol took the longest to ignite. Ethanol droplets began to evaporate before the ignition occurred, while methanol experienced little evaporation before ignition. Canola oil and olive oil showed similar combustion behaviors. Olive oil presented with more swelling before ignition than canola oil.

Each of the fuel droplets ignited at a different time due to the varying preheating periods required. However, for each fuel tested the diameter of the droplet decreased linearly with time. Methanol displayed the fastest burning rate of the fuels tested. Glycerol had the slowest burning rate. On the slope of the droplet ignition, a minor change is visible as the time increases. This indicates that the burning rate decreases as the droplets approach extinction. This behavior is present for methanol and ethanol. Canola and olive oil did not display this behavior. The presence of internal bubbling and micro explosions during the ignition process could be a contributor to this.

4. CONCLUSION

In this study, the combustion characteristics of ethanol, methanol, glycerol, canola oil, and olive oil droplets were evaluated. A silicon carbide fiber support system was implemented to anchor the droplet during the combustion process. Experiments were performed three times for each fuel, and the results with the best image quality were chosen for analysis.

The burning stages were observed for all fuels. Methanol was the quickest to ignite and had the fastest burning rate. Ethanol had a similar burning rate to methanol, but the droplet showed signs of evaporation before ignition. Glycerol had the longest preheating time before ignition and the slowest burning rate. The differing reaction rates could be due to the varying compositions between the fuels tested. Glycerol, olive oil, and canola oil have more complex structures than ethanol and methanol.

The combustion dynamics of olive and canola oil were different from the other fuels tested. Internal effects caused bubbles to form within the droplets, causing micro explosions and points of asymmetry. This could be due to the differences in surface tension and composition compared to the other fuels tested.

In all, the study shows that methanol has similar combustion characteristics to ethanol, and that glycerol had a slower burning rate than the other fuels tested. These results can aid in future work being done to optimize combustion systems using biodiesel byproducts. In addition, the observations from the experiment reveal more information about the combustion characteristics of vegetable fuels, biodiesel, and its byproducts. The non-blended fuels are characterized alone to allow for a better understanding of further mixture behaviors.

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