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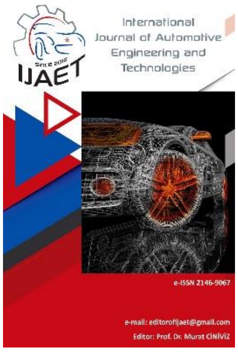

Original Research Article

Combustion of emulsified and non-emulsified biofuels

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ABSTRACT

Greener aviation and automotive industry are needed in the fight against climate change. Targets set out by key organizations call for emissions to be reduced. Biofuels present an innovative route to achieving such targets. The goal of this study is to investigate a sunflower oil-based biofuel in its non-emulsified and emulsified form. The aim is to create an experimental setup that can be used to carry out simple droplet combustion experiments, capable of igniting biofuel droplets. In addition to providing an understanding of emulsified and non-emulsified biofuels. The methodology outlines how a literature review was conducted to investigate the current experimental setup, which was used to help design a simple low cost set up for this research undertaking. The methodology also states that by analyzing the behavior and data collected during the testing phase, an insight into the behavior of such biofuels is obtained. The key parameters to be measured were the ignition delay times, the total combustion time period and the ignition temperatures. The observation of any phenomena was also to be noted. The results showed that ignition temperatures, ignition time delays and the total combustion time for an emulsified sunflower oil droplet are significantly lower compared to non-emulsified sunflower oil droplet. This is because of the presence of water in the emulsion which lowers the boiling temperature, enables phenomena such a micro-explosion and puffing to occur easily. As a result of such phenomena occurring, an improved and efficient combustion is completed. The impact of this work shows that by emulsifying biofuels in the form of vegetable oils, their properties to be used as a fuel are improved. There is great potential for use in the aviation sector with more research to be conducted on the emulsification of droplets.

Keywords: Micro-explosion, Alternative fuels, Sunflower oil, Emulsified Biofuels.

1. Introduction

As a result of the growing threat from climate change, the aviation industry has been challenged to reduce the environmental impact it creates. ACARE (Advisory Council for Aviation Research and Innovation in Europe) have outlined Flightpath Goals for 2050 which include: a 75% reduction in CO2 emissions per passenger kilometer and 90% reduction in NOx emissions. [1]

Biofuels present an innovative opportunity that can be utilized to pursue a greener aviation industry. The European Commission 2050 report recognizes this, stating that the ability to generate liquid fuels and energy is a critical segment of the energy supply needed for the future. [2]

Biofuels in the form of non-emulsified and emulsified sunflower oil will be investigated in this project. Biofuels can be produced from a range of vegetable oils. One of the reasons why sunflower oil was selected is because of the potential it has shown in various studies, which suggests it could play a role in the new generation of innovative biofuels technology. [1, 2].

The water-in-oil emulsification of sunflower oil was chosen as it is a simple approach in making biofuel. The combustion characteristics of the emulsified biofuel were investigated to provide an insight into how emulsification could be used in further research to improve the combustion performance.

To complete the aims, three key stages were carried out. The primary stage involves the completion of a literature review. This determines the type of vegetable oil to be used. The literature review also reviews current experimental setups used.

Following the literature review, the secondary stage involves designing a simple low-cost combustion setup that could be used. Key components such as heating elements are tested, once final modifications are complete, the next steps are taken. Once the setup is constructed, testing of the droplets can begin.

The final phase involves carrying out experiments and accumulating results. Once accumulated, they are analyzed and presented to provide a greater understanding of the combustion of emulsified and non-emulsified sunflower oil.

2. Literature Review

2.1. Use of biofuels in aviation & automotive

Biofuels present a golden opportunity that can be investigated in the race to make a greener aviation and automotive industry, as recognized by The European Commission 2050 report. However, along with the great potential brought by biofuels there are some challenges that need to be addressed. [1]

Given that biofuels are derived from renewable sources their total carbon footprint is lower than the fossil fuel based equivalent. This is one of the main driving factors in pushing the industry towards biofuels [2-5]. However, according to Gegg et al. other driving factors include the constant threat of volatile oil prices, future carbon tax prices, energy security and the requirement for fuel that compatible with the current engines and available infrastructure. [2]

Not only are biofuels able to provide part of the solution to the concerns listed above, but they have also shown their ability to improve aspects of engine performance. Mazlan et al. investigated the effects via simulation on a two-spool engine between kerosene and biofuels. The type of biofuels tested were Bio Synthetic paraffinic Kerosene and Camelina Bio Synthetic Paraffinic. The results obtained clearly show an increase in engine thrust and a reduction as well in the amount of fuel consumed. The trend was linearly observed as the percentage of biofuel in the kerosene increased.[6]

Similarly, an investigation on a three-shaft engine similar to the RB211 - 524 carried out by Azami et al. incorporated computer software simulation, to analyze a group of biofuels used in flight tests. The biofuels were a blend of kerosene and Jatropha Biofuel and a blend of Kerosene and Cameline Biofuel. Positive results were obtained, which showed enhanced gross and net thrust. The results also showed better fuel flow and lower specific fuel consumption. Similarly to Mazlan et al. as the percentage of biofuel increased there was a linear change in the positive results. [7]

This demonstrated the potential that with further research and understanding, biofuels would be able to bring a further increase in engine performance.

However, in order to reap the benefits of biofuels there are some hurdles that need to be overcome. One of the concerns involves the infrastructure, as a European Commission environment report highlighted the European production of biofuels for aviation relies on a small number of manufacturing plants. The biofuels produced by those plants equate to 5% of the aviation fossil fuel demand. This infrastructure concerns is also echoed by Prussi et al. who states that currently European biofuel industry is catered more for the road transportation market [3, 5].

Although European countries will need to address this, other countries may be able to provide more biofuel to help supply demand. For example, Cortez et al stated that due to the previous Brazilian experience in biofuels and the development of air transportation within the country, it presents a positive case for considering high production of biofuels [8].

Another key issue outlined by the European Commission and Wang et al is the cost of biofuels. The feedstock price and its volatility could create a supply issue. The European Commission stated that the price for aviation fossil fuel is €600 per ton, whilst certain biofuels could range from €950 to €1015 per ton. Wang et al also stated that one of the factors restricting biofuels to reach a commercial level is the high capital costs required [3, 4]. These are complex issues that need to be addressed on multiple levels. For example, partially addressing the cost issue, governments could be motivated to introduce subsidies for biofuels in exchange for more carbon tax credits.

2.2. Sunflower Oil

The biofuel emulsified and non-emulsified droplets in this study will use sunflower oil. This section will outline some of the characteristics of vegetable oils and sunflower oils in general. In general, there are many incentives to use vegetable oil to produce biofuels as they are: a renewable source of energy, widely available, biodegradable and has a low Sulphur content. With reference to sunflower crops, it has an efficient rooting system that allows it to make the most of the natural supplies of soil nitrogen and soil moisture. In addition to this, sunflower crops do not require lots of effort to cultivate. The crop is also able to provide economic output as an edible and non-edible resource [9 - 11].

Furthermore, Requena et al. conducted a comparative review of rapeseed, soybean and sunflower oil. They found that although sunflower crops require the most land use out of three, they have the most positive contribution to reduction of carbon dioxide. Due to the amount of carbon dioxide consumed by the plant [12]. After reviewing these sources, there is strong positive case to pursue further research and understanding into sunflower based oils.

Sunflower oil has already shown positive results in the automotive industry, where it has been blended and used with diesel to create Biodiesel. An investigation carried out by Hemanandh et al. tested the emissions and performance of a diesel engine. A hydro-treated refined sunflower oil was used to create the biodiesel. The investigation altered the loads, speed and blends of the hydro-treated refined sunflower oil. The results showed that emission such as Carbon Monoxide and Nitric Oxide were reduced, when the biodiesel was used. In addition to this, the brake thermal efficiency increased, and the brake specific fuel consumption decreased when the biodiesel was used [13].

Similarly, Amini-Nikai et al. compared the fuel and emission properties of sunflower based biodiesel and standard diesel fuel. Overall, the results showed that biodiesel had positive combustion characteristics, and a lower amount of pollution compared with regular diesel [14].

When analyzing the two investigations, it is clear that there are both performance and emission-based benefits to the diesel engine when the biodiesel is incorporated. The challenge would be to ensure that the same effects can be achieved or extrapolated for jet engines.

In order for sunflower crops to be used widely in the aviation industry they may need to utilize a technological boost. An analysis into the chemical properties of cultivated sunflower and silverleaf sunflower showed promising ability. The results showed that both types of sunflower crops hold the organic composition, that can be used to help form a better sunflower biofuel crop. The ideal crop could be formed from the two samples; it would have a higher biomass and more cellulose [15]. After reviewing the investigation, there is potential for bioengineering to provide an enhanced solution, however more research is needed.

An alternative to creating a new crop is adjusting the process that creates the biofuel. Zhao et al. has shown it is possible to convert sunflower residual waste to a bio jet fuel using a ZSM-5 catalyst. However, the conversion rate was relatively low at 30.1% as a result more refining steps were required [16]. Despite this, there were encouraging signs from both investigations that showed sunflowers can be used as bio-jet fuel. Additionally, future improvements in both methods would provide a better yield/conversation rate. Improvement is achievable given the results outcome and funding that is available. As a result, sunflower oil was chosen as the first-choice biofuel to be used in the study. As it is seen as a future aviation biofuel that will be needed to diversify the sources of fuel and biofuels.

2.3. Experiment setups used to carry out droplet combustion

This section will analyze and compare setups, to review which features would be compatible for the scope of this project.

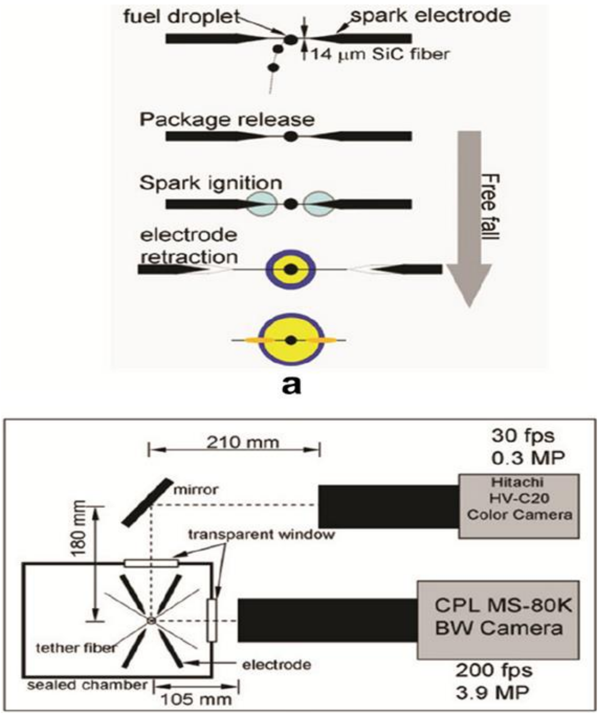

Fig. 1. Spark Electrode Experimental Setup [20]

One of the most popular experimental setups, used by Liu et al, makes use of four spark electrodes as shown in Figure 1. The spark electrodes are arranged in the shape of the letter 'X', poised to intersect on the Silicon Carbide fiber, also shaped in the form of the letter 'X'. The droplet is placed on the center of the fiber intersection typically using a piezoelectric generator. A piezoelectric droplet generator allows droplets to be created around 0.5mm in diameter. After the spark electrodes ignite the fuel droplet, they retract. The droplet goes into free fall and the behavior is measured by two cameras. The images recorded by the camera are then used to assess the droplet burning history [17 - 20].

This type of experimental setup involving spark electrodes seems much simpler than the one described by Ma et al, where a hydrocarbon fuel droplet was combusted in sub and super critical environments [21]. This type of setup required a lot more equipment as shown by figure 2 Analysis of the three experimental set ups discussed [19, 21, 22], show similar camera placement. For optimal images, the camera should record parallel or perpendicular views of the droplet combustion.

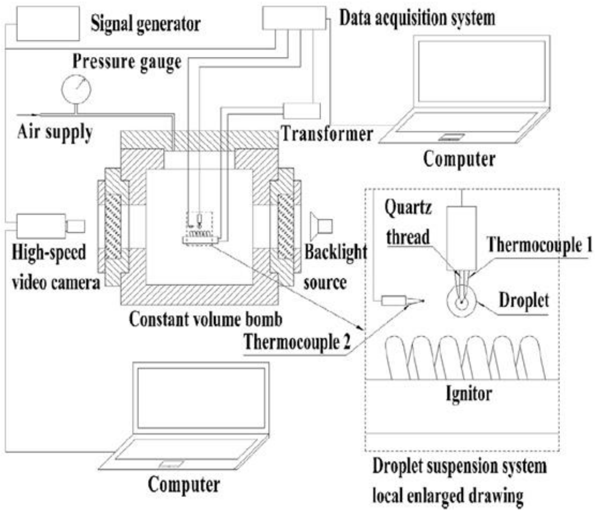

Fig. 2 Experimental setup [22]

However, when reviewing the two setups and the subsequent data, it is clear that elements of both setups could be useful for this study. The more popular method uses a piezoelectric droplet generator, which ensures consistency with the droplet size and shape for this project. Whereas the ignition method used by Ma et al and Liu et al. [19, 21], is a simpler and cheaper way of igniting the fuel droplet.

A droplet combustion method used by Rasid et al, is shown in Figure 3.

This method uses a boss, clamp and stand to hold the droplet and ignition source in a fixed position [22]. When comparing this experimental setup to the setup used Liu et al, it becomes clear that a sealed chamber is not a necessity for experiment setup that can be conducted at room temperature under atmospheric pressure conditions.

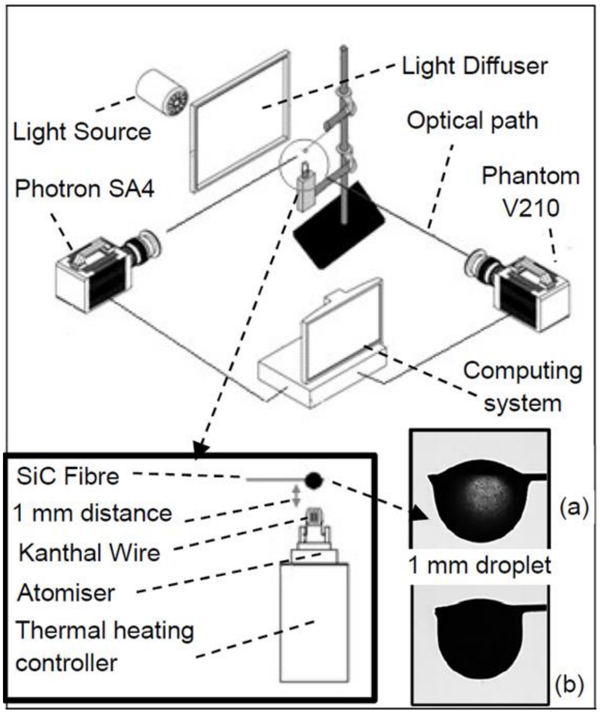

Fig. 3 Rasid et al experimental setup [2]

When analyzing the setups by Rasid et al and Ma et al [21, 22], the former uses a Kanthal Wire and a thermal heating atomizer to ignite the fuel droplet. This methodology is similar but simpler setup compared to Ma et al's. In this study, we utilized a Kanthal wire that's connected to a variable power pack. This experimental design would be a hybrid design of the two and would allow the heating element temperature to be controlled. This provides better control of the ignition temperatures.

Analysis of the three experimental set ups discussed [19, 21, 22], show similar camera placement. For optimal images, the camera should record parallel or perpendicular views of the droplet combustion.

2.4. Key Measurements and observation

2.4.1 Time – ignition delay

Reham et al's reserach on biofuel emulsions states ignition delay happens because of the water content in the fuel or emulsified fuel [23]. Debnath et al and Ithnin et al have shown agreement in stating ignition delay and micro explosion correlate to an improvement in the combustion efficiency for fuels which have been emulsified. In the investigation carried out by Ithnin et al which analyzed the water in diesel emulsion fuels, against standard diesel fuel. The results showed an increase in thermal efficiency [24, 25]. Although the project scope does not cover analyzing the emissions, the delay times recorded ignition can be used to determine such effects in future work. Reham et al also states that the ignition delay of a biofuel emulsion can reduce the peak pressure at the lower loads. In addition to this it can also increase the heat release rate [23]. Reham et al and Liang et al find that in order to reduce the ignition time, oxygen concertation should be increased [23, 26]. This suggests although a longer ignition delay may not always be advantageous the ideal ignition time can be created by varying the oxygen concentration which can be useful.

The method employed by Kim et al to measure the ignition time is quite simple. Essentially an ignition point is set, in the examples of Kim et al a yellow flame was chosen. Then calculation of the time from the start of the experiment till that point, which equals the ignition delay [27, 28]. After reviewing the experimental setup and the implementation procedure, this task could be done manually using a stopwatch or by setting a timer on the high-speed cameras.

2.4.2 Thermal measurement and observation

In the investigation carried out by Ma et al and Rasid et al the key thermal measurements made were only based on the droplet temperature. However, in other more complex investigations the key temperatures noted included the air temperature within the chamber, or the temperature of the waterbed used to prevent excessive heating. This shows temperatures recorded would vary depending on the setup. In Hyemin et al's paper on combustion of an emulsion droplet in a rapid compressing machine was the only paper that really mentioned flame temperature, even though nothing numerical was specified it was briefly discussed. Across the four papers the flame behavior and image were more heavily discussed than the temperature [21, 22, 28, 29]. From analyzing the papers, it seems essential to record the droplet temperature in order to analyze its thermal behavior. In this study the droplet temperature will depict how the rate of temperature is affected by the biofuel emulsion in comparison with the non-emulsified fuel.

2.4.3 Visual observation

An investigation carried out by Avulapati et al was based on diesel-biodiesel-ethanol blends. The combustion analysis showed through the use of a series of images how the flame and droplet varied. For example, it depicted images of smooth burning, puffing and explosion. Puffing refers to when vapor is released from a section of the droplet [30]. Similar to Avulapati et al, all droplet combustion experiments utilize cameras to take pictures of the droplet combusting. This is mainly due to the short combustion time of the droplets tested [22, 28-28]. It is clear that the droplet shape is a key part of assessing behavior.

Liu et al and Khan et al show images that can be used to find the diameter of the droplet [29, 31]. Whilst Hyemin uses a scale provided on the image to find the diameter, Liu et al utilized a software called 'Image Pro v6.3', which digitally measures the diameter [19, 29]. It is clear the digital measurement is more appealing as the accuracy is greater than using a scale provided.

3. Methodology

This study aims to measure the combustion characteristics of the emulsified and non-emulsified biofuels. The experimental phase formed a major part of the study.

Key measurements were identified and accurately recorded. It was important to ensure the methods employed to record the measurements allowed repeatability.

In addition to this, an equally important aspect of the study was creating a low-cost simple experimental setup. The success of the study was heavily determined by the ability of the experimental setup to deliver combustion results.

During the initial phases of the study, an experimental setup was devised. Given that the study was not based on previous research for a customer. An experimental setup was formed by reviewing the literature and it was driven by the budget and time constraints of the resources. For example, by reviewing Rasid et al [22], it was clear combustion droplets experiments do not have to be carried out in a sealed chamber, if there are no pressure or elevated temperature requirements. Given there is no such pressure and temperature required, an open setup was employed. A sealed chamber would also increase costs that cannot be justified. Therefore, the use of a boss, clamp and stand shown by Rasid et al [22] was employed. This setup allows the droplet to hold secured at a specific height. As shown by Liu et al [19] the droplet can be formed on a silicon carbide fiber wire. However, when analyzing this type of setup to hold the droplet and prevent it from being outside the field view of the camera, it became apparent that the experimental setup could have been further advanced. For example, instead of using a silicon carbide wire, a beaded thermocouple wire can be used. Onto which a droplet is deposited. The additional benefit of this approach is that a contact temperature can be recorded of the droplet throughout the combustion process.

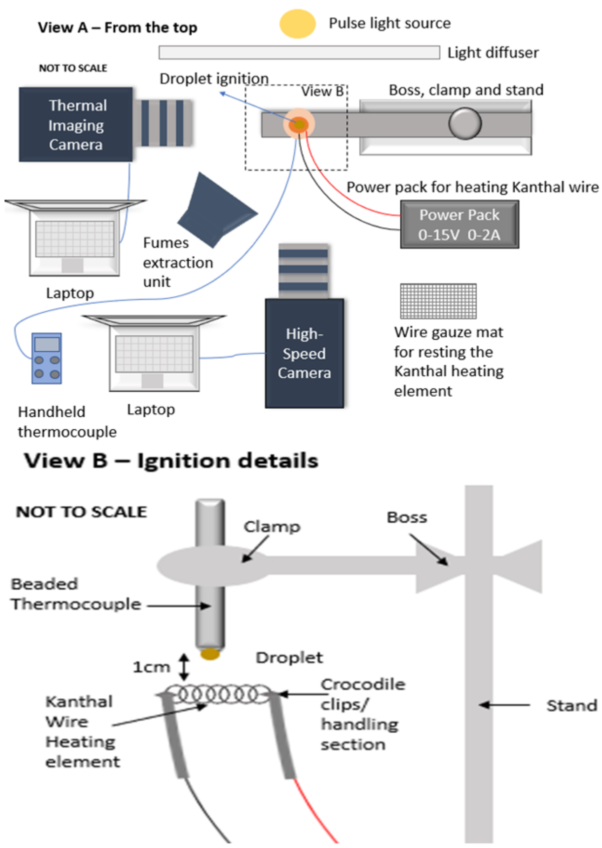

Fig. 4 Initial Experimental Setup Design

With regards to the heating aspect of the experimental setup. As shown by Liu et al and Ma et al [19, 21], there are two effective ways of igniting the fuel droplet. The spark electrode method is effective as the retractability after ignition is advantageous. As any thermal imaging camera and thermocouples are not affected by the constant heat source. The use of a heat source using a wire shown by Rasid et al [22] is cheaper in comparison to the spark electrodes. Also, by adjusting the current and voltage the temperature can be altered, giving more control over ignition. However, a negative aspect was that the heating element was in a fixed condition. The heating design initially chosen involved using a wire heating element in the form of a Kanthal wire. However, a small piece of this wire was purchased to test the capability. Unfortunately, the kanthal wire couldn't ignite the sunflower oil droplet (this was accounted for in the planning and the setup was modified), due to the higher ignition temperatures. However, the Kanthal wire method could be used in the future for other vegetable oils with lower ignition temperatures. A butane gas burner was employed as it was more portable and able to easily reach the ignition temperatures of the sunflower oil. Although Figure 5, shows two butane burners, one was sufficient to carry out the experiment. Two can be used to allow for better image quality as the horizontal forces acting on the droplet cancel out.

In terms of the methods employed to time and record the droplet combustion stages, a review of current literature showed Rasid et al, Ma et al and Liu et al, as well as many others [19, 21, 22] all use software in combination with the high-speed camera for timing aspect. It was also noted that thermal imaging cameras and a high-speed camera were utilized to record the behavior and timeline of events. For this study a similar method was employed. A high-speed camera was used, the high-speed camera was positioned at right angle to the droplet, in order to record High quality images of the combustion. A digital stopwatch was placed in view of a standard camera which allowed the time to be measured.

The method employed by Liu et al and others [17-20] to deposit the droplet involves the use of a piezoelectric droplet generator. This was able to consistently create a small droplet. Due to the high cost of this, it was not feasible for the study. Therefore, a syringe was used to create droplets of 1.0mm ± 0.5mm.

In order to make the most appropriate and descriptive measurements and observations with the given time and budget constraints current papers were reviewed [18, 19, 21-31]. The two mains aspects that were measured included the time and temperatures. In addition to this, visual observations will need to be made of the images and recordings. These will provide a comprehensive description of the combustion experiment.

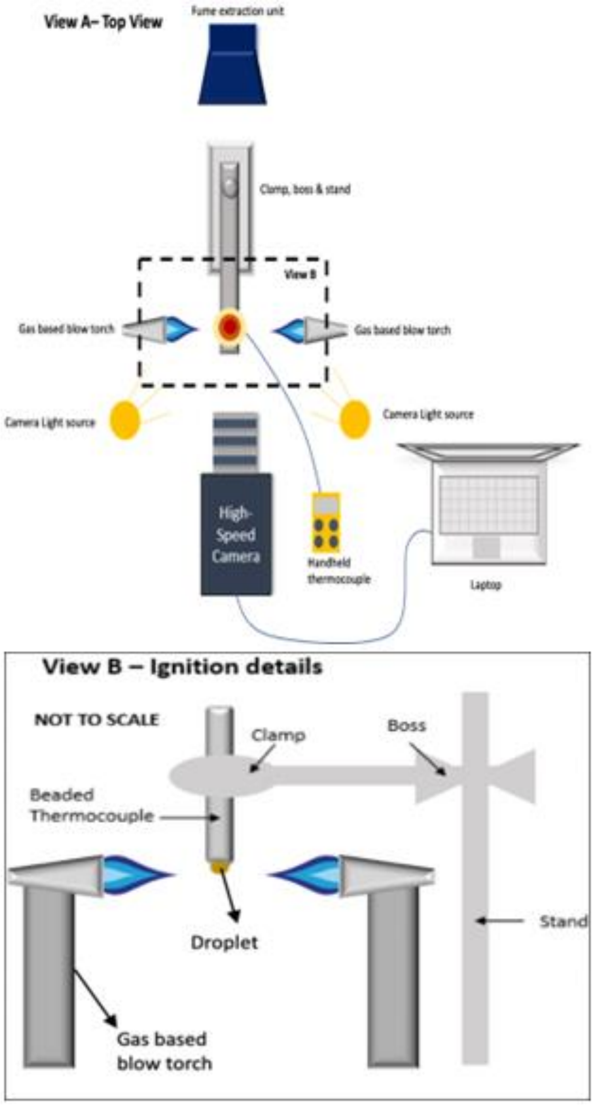

Fig. 5 Final Experimental Setup Design

The homogenization procedure used to emulsify the oil and water was based on the method of ultrasonication. Ultrasonication is the application of high frequency vibration implemented via sonotrode in order to reduce the interfacial tension between two immiscible liquids of an emulsion. Emulsified water in oil droplet samples were drawn from emulsification process which was optimized for stability enhancement and the experimental apparatus is described in details in Sahota and Dakka [32] The composition of the emulsion, i.e., the percentage by mass of oil and water used, was chosen based on the recommendation of Mura, et al. [33], who tested the ignition properties of water in sunflower oil emulsions and suggested that this composition, 60% sunflower oil, 30% water and 10% surfactant per mass produces finely dispersed emulsions.

3.1 Experimental method and repeatability

The method of testing needed to ensure repeatability, and this was considered in simplifying the final design. Once the clamp, boss and stand are set up and the high-speed camera and fume extraction are positioned correctly, the biofuel droplet is deposited onto the beaded thermocouple. The syringe has volume markers along its length which are used to ensure the same droplet size is formed each time. The butane burner is ignited and positioned at a measured distance from the droplet and then the flame is slowly rotated, and ignition commences. Maintaining a constant distance is essential to ensure repeatability. In the experiments conducted the distance was 15cm. This was captured by the high-speed camera. A stopwatch is triggered once the flame starts to heat up the droplet to record the time period.

3.2 Assessments, requirements and assumptions

Throughout the experiment the key parameters that were recorded and assessed were the droplet temperature, time period, ignition delay time and the visual behavior of the emulsified and non-emulsified droplets.
The key requirements defined at the start of the project were to create and provide a framework that can be used to carry out simple droplet combustion experiments. In addition to providing an understanding into emulsified/non- emulsified biofuels.
By creating a working experimental setup that is able to record data, the first requirement was met. The assumptions made were, that the droplet size is constant, and the flame temperature of the butane gas burner is constant. The effect of the suspension heat transfer into the droplet is negligible.

The data recorded for the non-emulsified and emulsified biofuel included: Ignition delay time, Total combustion time and Ignition temperature. In total there were 6 sets of data.
A statistical method was used to calculate the means for a 95% confidence level.
The equations used were:

$$\mu = M \pm Z\sqrt{\frac{s}{n}} \quad (1)$$

Where μ = Population means, M = Sample means, Z = Z statistics determined by confidence level, s = standard deviation and n = sample size.

Table 1: Population Means for 95% Confidence Level

Data Set	μ	M	Z	s	n
NE 1	6.74 ± 0.1432	6.74	1.96	0.31	18
NE 2	9.66 ± 0.2864	9.66	1.96	0.62	18
NE 3	446.89 ± 7.6548	446.89	1.96	16.57	18
E1	2.12 ± 0.064	2.12	1.96	0.16	24
E2	3.45 ± 0.144	3.45	19.6	0.36	24
E3	114.02 ± 5.6171	114.02	1.96	14.04	24

In the left-hand column NE = Non-Emulsified Biofuel, E= Emulsified Biofuel, 1 = Ignition Delay, 2 =Combustion Time Period and 3 = Ignition Temperature.
Overall, when analyzing the table, the population mean range is low therefore there is high confidence in the method.

4. Results and Discussion

The second key aim of the study was to provide an understanding of emulsified/non-emulsified biofuels. This will be done in this section by analyzing the behavior and data collected during the testing phase. Given that the experimental setup was made with a low cost and simplicity in mind, the results retrieved are elementary at this phase. However, they do show some key areas which will be explored in this section. In future work, given that a setup has been established more advanced measurements and data could be collected.
The results recorded the time taken to complete the combustion cycle; the time taken to ignite the droplet from the moment heat is

applied – referred to as ignition delay. Lastly the ignition temperatures were recorded. Visual observations were also made. These parameters will now be explored. A key point to note is that the sample sizes for the two types of biofuels were different as shown by the methodology. For comparison purposes only the most important 18 datasets from the non-emulsified fuel were included. Corresponding sample numbers from each biofuel set do not have any meaning.

The ignition times and the total combustion times shown in Figure 6 illustrate the key difference between the emulsified and non-emulsified biofuels. The emulsified fuel has a lower ignition delay time and a lower total combustion time. In addition to this, it can be seen that the gaps between the two sets of line show that the non-emulsified fuel has a slow combustion phase after ignition. This suggests that pure sunflower oil, which is the non-emulsified biofuel essentially takes a long time to burn. As a result, the emulsified fuel burns faster and quicker. When analyzing figure 7 it becomes clearer as to why this is the case.

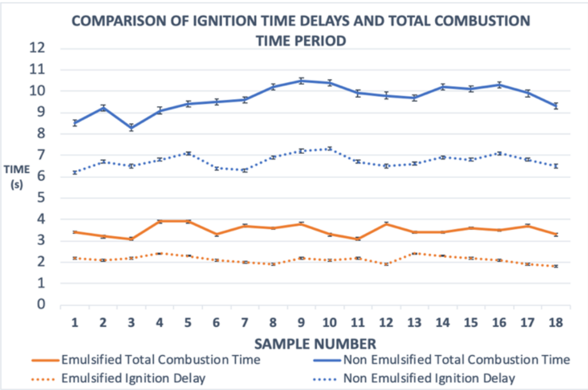

Fig. 6 Graph comparing the ignition and total combustion time for both types of biofuels

Ignition temperature naturally affects the ignition time delay which impacts figure 7 Figure 7 shows that the ignition temperatures for the emulsified fuel are significantly lower compared to the non-emulsified fuel. Figure 6 and Figure 7 both correlate with each other. They show the lower the ignition temperature the lower the ignition delay time, which is in line with what's expected. The large difference in temperature shown in Figure 7 accounts for the significant difference in time periods.

This suggests that emulsification makes the biofuel more flammable and hence it's able to combust quicker. However, Figure 7 does not really explain the root reason why the combustion period is longer. For that, the composition of the biofuel and figure 8 provides a better understanding. The water in the emulsion is what causes the emulsified droplet to have a reduced ignition delay time and a lower combustion time period. As shown by figure 8, upon ignition the emulsion droplet has more explosive characteristics allowing it to spread out the particles - which set alight much faster in comparison to the non-emulsified fuel droplet. From this it can be concluded that the water in the emulsified droplet helps create this micro explosion phenomena, which in turn leads to a more efficient combustion process. In comparison, the non-emulsified fuel remains stagnant on the beaded thermocouple acting as one whole unit.

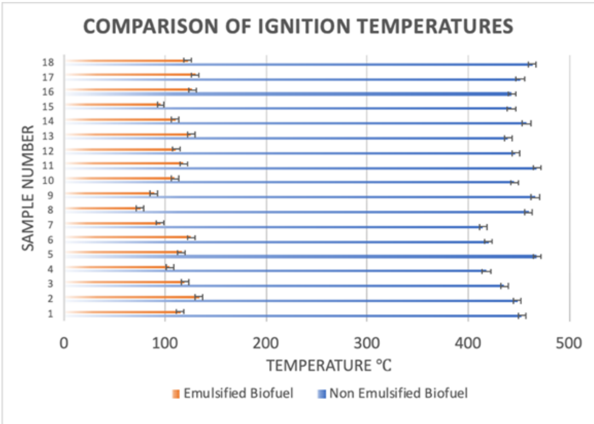

Fig. 7 Comparison of Ignition Temperatures

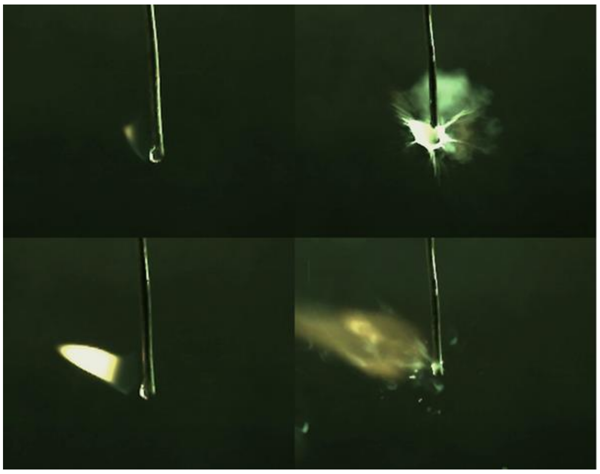

Fig. 8 Progression of combustion from initial ignition of Emulsified(R) and Non-Emulsified droplet(L)

Other phenomena picked up by the camera include puffing. Micro-explosions are rapid breakdown of emulsion droplet caused by explosive boiling of the liquid sub droplet which has a lower boiling point this case is water. Whereas puffing is the bubble growth which leads to partial or full break-up of the main oil droplet. These definitions are derived from Shinjo et al [34]. When analyzing Figure 7 it can be seen that the ignition temperatures of the emulsified fields fluctuate around 110ºC mark, this is because water has a boiling point of 100 ºC. Once the water is approaching its boiling point, micro-explosions and puffing occur which cause faster combustion.

It becomes clear that most of the implications and results are validated. For example, the difference in ignition times is also shown in Reham et al [23] where an emulsified fuel has lower ignition delay times. This is due to water content in the fuel, also stated by Avulpati et al [30]. Similarly, Avulpati et al [30] results suggest the agreement with the fact that more water content in the fuel will lead to lower ignition temperatures. Although Liang et al [26] states that longer ignition time delay may have some benefits, its apparent in our experiment that the reverse is also true. A lower ignition time delay allowed quicker and more complete combustion of the fuel.

Furthermore, Shinjo et al [34] agrees with conclusion drawn about micro explosions. Shinjo et al [34] states that it has a positive effect on the combustion of fuels, which concurs with our results. As the combustion was more complete. This was noted particularly by the visual observations and picked up by the recordings and images. The images and recording show that the emulsified droplet burned quickly with there being little or no residue on the beaded thermocouple. However, the non-emulsified droplets combustion often left significant residue on the beaded thermocouple and the flame died out before fully completing the combustion of the remaining biofuel.

Avulapati et al and Shinjo et al [30, 34] also show that the puffing phenomena effect is positive as it leads to droplet rapid disintegration and complete combustion.

The tolerance for the time recorded is ±0.5 seconds, whereas the tolerance for the thermal data such as ignition temperatures is ± 0.05º C. The data for time was recorded using an internal clock on the camera, and the temperature data was given by a handheld thermocouple. This was recorded as part of the camera view, whilst the experiment was conducted. Given the weight of these tolerances, they have minimal implication on the results recorded. The digitalization of the equipment used helped to eliminate errors.

With reference to assumptions, it was assumed that the droplet size was the same for each experiment and the temperature of the flame from the gas burner was constant. In reality however, the droplet sizes did vary slightly, and the flame temperature would have varied with the amount of gas remaining in the burner. These may have had some effect on the results. For example, a lower flame temperature would have led to higher ignition delay times. However, these were addressed by ensuring the gas burner had plenty of fuel and that the size of the flame was constant. The burner had a flame size setting which made this possible. In addition to this, the syringe had volume marks which made it possible to ensure the same sized droplet could be obtained, 1.5mm ±0.5mm.

Puffing and micro-explosion in water/Fuel droplets increases the liquid fuel surface area considerably. This promotes the fuel evaporation rate and enhances fuel vapor air mixing. Consequently, leading in reduction of the inertia of ignition process ensuring complete combustion of the fuel vapor and reduction in emission. It is not surprising to note in figure 6, the ignition and complete combustion time is lower as compared to non-emulsified droplets [35].

During the fuel heating process of premixed and non-premixed water in fuel droplets, where a large number of small water droplets were evenly distributed inside a large fuel droplet, or a one large water droplet resides inside a fuel droplet respectively, demonstrated that prior to micro-explosion, the occurrence of coalescence of water sub droplets. The relative reduction in size of water sub droplets translates into an increase in the fuel droplet temperature just before micro-explosion, thus lowering the likelihood of micro-explosion. Changing the distribution of the dispersed phase sub droplets will impact on the probability of micro-explosions and therefore can be used as a design tool to control the fuel air mixing. This sub droplet distribution is also influenced by internal circulation due to the relative velocities between the droplet and ambient air.

Furthermore, droplet heating will cause thermocapillary effects (Marangoni) responsible for the migration of the sub droplets towards the hot side promoting the mechanism of sub droplet coalescence. Because of this water sub droplet formation mechanism, a distinction between two micro explosion processes, for larger droplets in the millimeter range when complete phase separation between the water and oil can be observed typical of this experimental study as compared to typical fuel droplets sizes injected in engines with relatively small mean diameters in the order between 10-20 micro meters, where complete coalescence of the sub droplets is not achieved before micro-explosion. Explosive boiling of sub droplets is responsible for the break-up of the droplet.

Nucleation is the initial formation of bubble nucleus. Which later leads to explosive boiling. In general, nucleation is located at the interface between the water and the fuel. Surfactants are added to water in oil in order to enhance stability and the emulsion formation will depend on the HLB value (Hydrophilic-Lipophilic Balance). Low to medium HLB surfactant value is suitable for formation of W/O emulsion. Previous studies have shown that the occurrence of micro-explosion is dependent on the droplet Ohnesorge number which is defined as the ratio kinematic viscosity over the square root of the droplet density, droplet surface tension and droplet characteristic length. Lower surface tension will increase the Ohnesorge number and consequently less chance the droplet will experience micro-explosion [36]. In the study by Ballester et al., [37] water in oil emulsion was utilized in a pilot furnace, and the effects of water addition were analyzed.

Addition of water to oil significantly accelerated the evaporation of droplets in the flame and reduced the flame temperature. After non-emulsified droplet ignition, the classical droplet combustion period was observed. In this period, a stable flame was generated around the droplet, and droplet temperature rose continually with heat feedback from the flame. In the case of emulsified droplets, ignition occurred due to micro-explosion as indicated in figure 8, because as the droplet temperature increased superheated water sub droplets penetrated the fuel droplet surface, as a consequence of this a distorted flame sheet was created as compared with classical droplet combustion. This flame sheet distortion is due to the burning of the small child droplets that detached impulsively from the surface of the fuel droplet, this is illustrated in figure 8. Micro- explosion increases the contact area between the fuel and oxidizer, thus achieving better fuel vapor air mixing and higher combustion efficiency improving the combustion performance. Because micro-explosion consumes numerous heats for vaporization as the temperature of the droplet increases beyond the water boiling point. This makes the burning time lower as compared with non-emulsified fuels.

In this study sunflower oil was utilized without further processing, however the previous studies conducted in diesel engines utilized biodiesel and biodiesel blends with petroleum diesel fuels. Biodiesel is derived from vegetable oils such as sunflower oil through transesterifications. In general engine performance studies of biodiesel and its blends with diesel fuel yielded lower emissions for CO, CO_2 and HC but in some cases higher NOx emissions were recorded. The purpose of this study is preliminary investigation of emulsification of water in sunflower oil in order to tackle the issue of further reduction of NO_x emissions, thus achieving adequate results in reduction of exhaust gas emissions based on ASTM-D6751. The presence of water will lower the flame temperature and consequently reduce NO_x emissions. Water emulsification of Sunflower oil has low energy content. This has been demonstrated in figure 7, as compared with sunflower oil. However, biodiesel fuel derived from it has an energy content of around 37.5MJ/kg which is a bit lower than petroleum diesel fuel. This implies that efficiency and output is marginally lower for biodiesel compared with petroleum diesel. The energy content of the blends can be estimated [% diesel x 42.5+ % Bio-diesel x 37.5] which implies for 20% biodiesel the estimated energy output is 41.5MJ/kg. As a result, this fuel can be utilized in diesel engines with no engine modification with the advantages of lower emissions meeting the regulation and specification of ASTM-D6751. As the aim to provide an understanding into emulsified/non- emulsified biofuels has been completed. Future work may focus on other vegetable oils or continue more detailed testing of emulsified biofuels.

5. Conclusions

Overall, both aims of the study were successfully completed. The first aim of creating an experimental setup which could carry out such testing was done by reviewing literature and designing a setup. Once the setup was designed, key components such as the heating elements were tested and substituted to ensure the experiment was able to meet the requirements of igniting sunflower oil droplets.

The results showed that ignition temperatures, ignition time delays and the total combustion time for an emulsified sunflower oil droplet is significantly lower compared to non-emulsified sunflower oil droplet.

This is due to the presence of water which lowers the boiling temperature, enabling phenomena such as micro-explosion and puffing to occur. As a result of such phenomena occurring, the combustion for emulsified droplet was completed without any residue left on the beaded thermocouple, unlike the non-emulsified sunflower oil droplet. The impact of this work shows that by emulsifying biofuels in the form of vegetable oils, their ability to be used as a fuel potentially for the aviation and automotive industry are improved. Future work may concentrate on more in-depth testing of sunflower oils and a greater range of emulsions.

Nomenclature

μ = Population means
M = Sample meaning
Z = Z statistics determined by confidence level
s = standard deviation
n = sample size
W/O = Water in Oil

Conflict of Interest Statement

The research received no funding. Therefore, there is no conflict of interest.

CRediT Author Statement

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