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An Experimental Investigation on Droplet Ignition of Bio-Diesel and its Blends

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Abstract-An experimental set up was assembled to carry out test for Diesel and Bio-Dieselas well as for blends. Ignition delay and temperature histories were recorded. Thermocouple arrangement was made to record the temperature history and digital video camera was used to capturing the entire combustionanalysis.

Ignition delay of Bio-Diesel and its blends with Diesel at atmospheric pressure and in the temperature range of 600 °C to 750 °C was studied. The result of same was compared with Bio-Diesel and its blends. The fuel droplet was introduced into the furnace chamber.

Combustion characteristics were measured for the Diesel and Bio-Diesel as well as for blends.It has been shown from reviewed literature that delay period was measured and correlated for different blends. The effect of delay period with temperature is found out. The apparentactivation energy was obtained.

Key words: Ignition delay, Diesel, Bio-Diesel, Combustion, Fuel Droplet, Activation Energy.

I.INTRODUCTION

In recent years, many researches [8] were conductedto develop alternative fuels because of the shortage ofpetroleum products and its increasing cost. Biodiesel isconsidered as a promising alternative fuel to the fossildiesel for full or partial replacement because it may be directly used as fuel for diesel engines without any priormodification of the design or equipment. Biodiesel is alsoassessed as a renewable fuel because it is free from sulfurand aromatic compounds. Experimental researches [8]on the emission characteristics of diesel engine fuelshowed that pure biodiesel and its blends withconvectional diesel can significantly reduce carbon monoxide (CO), hydrocarbon (HC), and particulate matter (PM). ByCompared to conventional diesel, the application ofbiodiesel to diesel engines still has several properties thoseneed to be improved, such as lower engine power outputand higher emissions of nitrogen oxides. Therefore, it is important to conduct more researches to formulate optimal operation conditions as biodiesel is used as fuel.

II. DROPLET COMBUSTION PHENOMENON

A. Primary breakup: After leaving the nozzle hole, jet breaks up into conical spray, this first break up is known as primary break up which result in large ligament and the droplets that form the dense spray near the nozzle. Cavitation and turbulence, which are generated inside the injection holes, are the main mechanism.

B. Secondary break up: The subsequent break up of existing droplet into smaller one is known as secondary break up is due to aerodynamic forces caused by the relative velocity between droplets and surrounding gas.

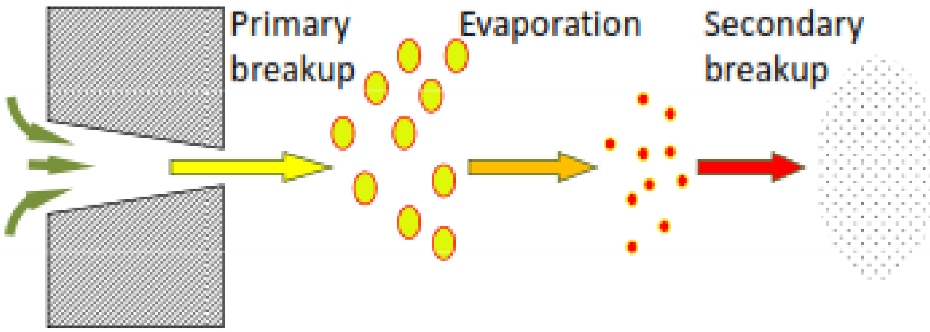


Figure 1 Stages of droplet ignition of fuel

C. Evaporation: atomization of fuel into smaller droplets near the nozzle exit to form a spray. There are mainly three phenomena observed,

- Deceleration of the drop due to aerodynamic drag
- Heat transfer to the drop near the air
- Mass transfer of vaporized fuel away from the drop.

III. LITERATURE REVIEWS

C. K. LAW [7] in 1982, well-thought-out under the title of "Recent Advances in Droplet Vaporization and Combustion" of multicomponent fuels including the miscible fuel blends immiscible emulsions and coal-oil mixtures.Understanding the fundamental mechanisms governing droplet vaporization and combustion were reviewed with d2-Law and its limitations; the major transient processes of droplet heating and fuel vapor accumulation.Results was concluded by the author were instantaneous droplet size& there were two major transient processes involved, namely droplet heating which mostly influences the initial droplet regression rate, and fuel vapor accumulation.
C. H. WANG [12]et. al. in 1984, studied on "Combustion and Micro explosion of Freely Falling Multicomponent Droplets" with droplet of n-hexadecane of multicomponent droplets freely falling in a hot, oxidizing gas flow were studied.Results two-component fuels substantiate a three-staged combustionbehavior,with diffusion being thedominantliquid-phase transport mechanism and micro explosion show that its occurrence dependssensitively on the mixture concentration as well as the stability of the droplet generation mode.
In 1993, M. RENKSIZBUL and BUSSMANN [4] investigated on "Multicomponent droplet evaporation at intermediate Reynolds numbers" with hydrocarbon droplet (decane-hexadecane) the convective evaporation of a binary hydrocarbon droplet (decane-hexadecane) in air at 1000 K and at a pressure of 10 atmospheres has been studied using numerical methods. He concluded that at elevated pressures, the evaporation ofrelatively

heavy hydrocarbon droplets is essentially controlled by liquid phase heating and Reynolds number decreases largely due to the deceleration of the droplet, as a dropletradius varies much more slowly.

S.C. ANTHONY LAM and ANDRZEJ SOBIESIAK[2] investigated on biodiesel, ultra-low sulfur diesel and, ethanol biodiesel droplet, ethanol. Experimental work on "Biodiesel Droplet Combustion" burning rate and temperature histories were reported. An Apparatus for determining droplet diameter & thermocouplearrangement tomeasure droplet temperature history was formulated and series of frames from a high-speed movie capturing the entire biodiesel burning sequence. Changes of droplet diameter-squared over time and temperature were studied. He found three stagecombustion, as: 1. Warm-up and combustion, 2. Combustion of the droplet with the liquid phase boiling, 3. Burn-off of vaporized fuel.

By Jiunn-Shyan Huang and Tsong-Sheng Lee [8] soybean oil and methyl alcohol were under consideration in 2006 researched on "Comparison of Single-droplet Combustion Characteristics between Biodiesel and Diesel". Combustion characteristics of Biodiesel and diesel was experimentally investigated at Reynolds numbers 93 to 192: I. Upper branch (93 to 192)& II. Lower branch (192 to 93).Multiple state phenomenon was observed for Biodiesel droplet at 119< Re $\leq$ 154 & Diesel droplet at 101 < Re $\leq$ 145, multiple flameconfiguration and burning rate at same Re,ratio of Biodiesel and Diesel droplet burning rate 1.4 to 1inenvelope,burning rate decreased by factor 4.35 and 3.03 for Biodieseland Diesel droplet respectively for upper branch when envelope flame transformed in to wake flame & flame of Diesel droplet deeper yellow color compare to Biodiesel.

By LAURENCAS RASLAVIČIUS&DONATASMARKŠAITIS[17] with dehydrated ethanol (A), Rapeseed methyl ester (RME), diesel fuel (MD) as a multi component fuel was under consideration in 2007 researched under the title "Research into Three-component Biodiesel Fuels Combustion Process Using a Single Droplet Technique". Different physical parameters like droplet temperature, gas phase temperature, ambient gas pressure and droplet burning velocity of the ignition delay process is investigated using the fuel droplet combustion stand. Result from this analysis was additives of dehydrated alcohol (A) to MD and RME reduces ignition Delay time.

Investigation on "Spray and Combustion Characteristics of Biodiesel, Diesel Blended Fuel in a Direct Injection Common-Rail Diesel Engine"[6] in 2008 was carried out by Hyun Kyu Suh et. al. with Soybean oil(BD5 & BD20). The effect of the blending ratio and pilot injection on the spray and combustion characteristics of diesel & biodiesel fuel in a direct injection common-rail diesel engine was considered.Exhaust emissions and engine performance were conducted at various biodiesel blending ratios and injection conditions for engine operating conditions. For Single injection, fuel injection profiles for diesel and biodieselblended fuels are very similar compare to pilot injection; an increase of the blending ratio induced a decrease of the peakinjection rate.Effect of fuel blending and injection pressure on single spray tip penetration is slight, and the pilot spray development of biodiesel is shorter compared with the pilot and main injectionof diesel fuel.

Jyotirmoy Barman [14] et. al. researched on "Experimental Investigation on of Biodiesel Diesel Droplet Ignition" in 2008.Ignition Delay of Bio-Diesel and its different blends with Diesel at atmosphere condition were measured with specific droplet.Bio-Diesel fuel has longer Ignition Delay thandiesel. Ignition Delay decreases for blends and depends on the amount of diesel in the blends.Activation Energy of Diesel and Bio-Diesel calculated.

In 2012, Mohammed EL-Kasaby & Medhat A. Nemit-allah [9] researched on Ignition Delay Period & Performance Test for Jatropha Oil Biodiesel.Biodiesel fuelJatropha-curcas as a non-edible methyl ester was the fuel. Combustion characteristics as well as engine performance are measured for different biodiesel – diesel blends. Final result was shown that B50 gives the highest peak pressure at 1750 rpm, while B10 at low speed, 1000 rpm.Higher percentage of NO in case of biodiesel compared with that of diesel is attributed tothe higher combustion temperature of oxygenated biodiesel resulted from advanced injection.

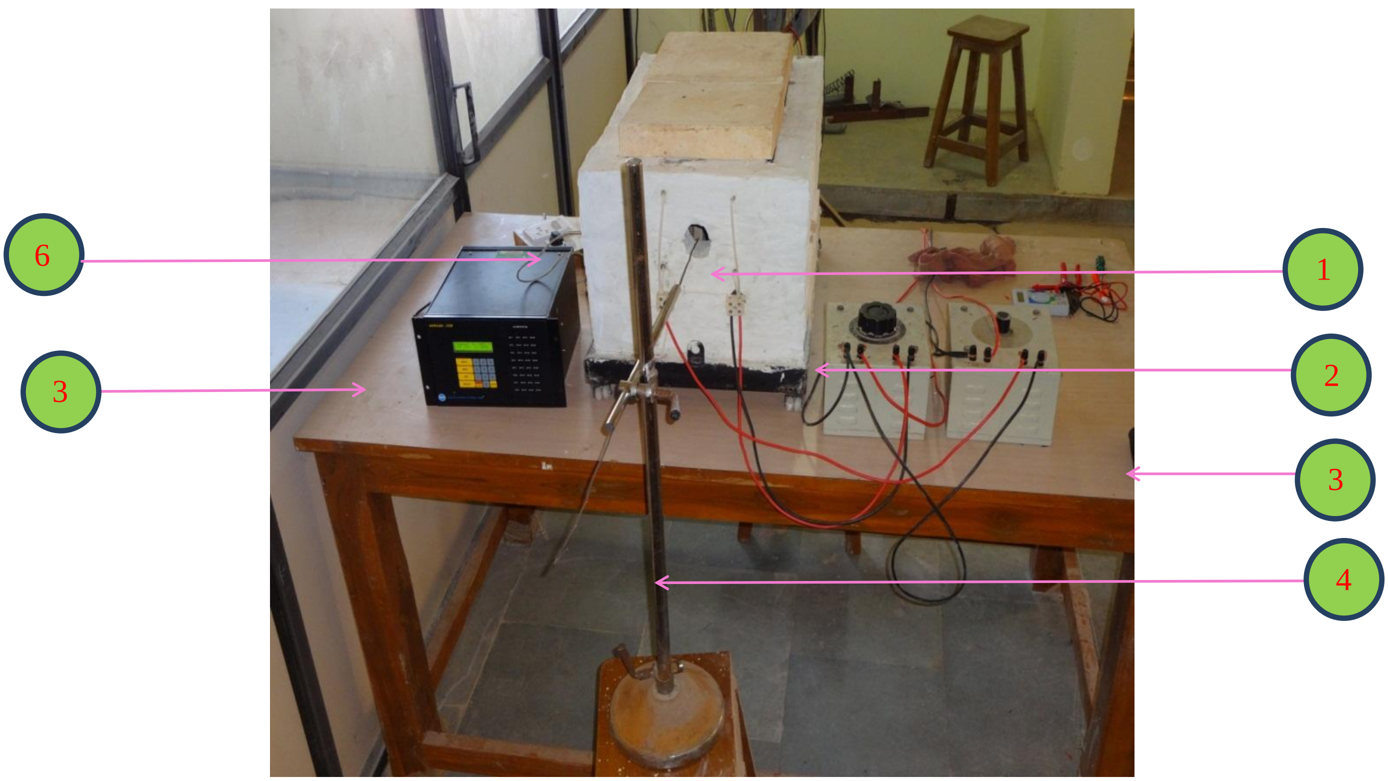
IV. EXPERIMENTAL SETUP AND PROCEDURE

A. Experimental details: Experimental investigation is carried out for the study of droplet ignition of suspended fuel in a chamber of fire brick with high temperature environment at atmospheric pressure. Below figure shows the different part with their salient features in the experimental set up. It will be divided into three different sub systems,

A. Droplet Formation

B. Furnace Chamber

C. Observation and Photographic Recording System



1. Opening Port (Diameter of 50 mm); 2.Combustion Chamber; 3.Kanthal Wire Wounded Heater (4 Numbers); 4.Windows (140x50mm); 5.Firebricks 6.Thermocouple (2 Numbers).

Figure 2 Photographic view of experimental set up

Sub systems of experimental work in following section the sub system are briefly explained.

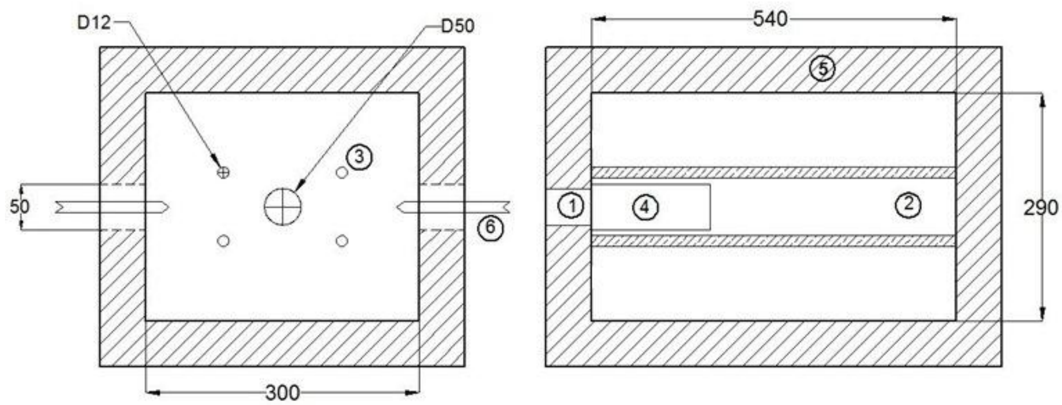
B. Droplet formation: Droplet of fuel is produced with help of medical syringe [17] and settled on steel rod. With the suitable arrangement the droplet is introduced into the furnace. A very fine needle is used to produce the droplet from glass tube by heating it with oxyacetylene flame. The needle fix on to the glass syringe. Fine droplets miniature dimension is produced by applying pressure to the syringe.

The droplets are generated by the fine needle of very small diameter openings to vary the size of droplet size. Fine needle gives the monodisperse droplets of controlled dimension. Then with the help of fine needle, the monodisperse droplet is suspended in the steel wire of diameter 500 micron.

Figure 3 Droplet formation

C. Furnace chamber: An experimental set up is prepared with a fire bricks chamber with inner dimensions of 540 × 300 × 290 mm having two windows 140 × 50 mm on the two opposite walls of the furnace is made to record the droplet ignition photographically. One opening on the side wall (50 mm diameter) is made for the introduction of fuel in the furnace. There is one opening hole of diameter 50 mm for inserting the fuel droplet to the furnace.

The furnace will be heated with the help of four numbers 1.5 KW Kanthal wire wounded heaters. The locations of heaters are shown in the Figure 4.



1. Opening Port (Diameter of 50 mm); 2.Combustion Chamber; 3.Kanthal Wire Wounded Heater (4 Numbers); 4.Windows (140x50mm); 5.Firebricks 6.Thermocouple (2 Numbers).

Figure 4 Schematic diagram of furnace chamber

D. Specifications of Furnace Chamber: Here are the technical specifications of furnace in which the fuel combustion is carried out.The temperature in the furnace is controlled by varying the current flow through the Kanthal wire wounded heaters with the help of variacs. A 5 mm diameter Chromel-Alumel (K-Type) thermocouple is used to measure the temperature of the furnace.

Table 1 Specification of furnace

Component	**Dimension**
Furnace Chamber	Internal Length 540 mm Internal Width 300mm. Height 290 mm
Fire Bricks	Insulation Purpose
Kanthal Wire Wounded Heaters	Capacity of 1.5 KW. Diameter 12 mm
Thermocouple	Chromel – Alumel (K-Type)
Data acquisition system	Display Temperature Reading in ^{o}C (Uniscan 3200)

Variac	Capacity 0-260 V

The temperature of the furnace is in the range of 600 ^{o}C - 750 ^{o}C.

E. Observation and Photographic Recording System: The droplet ignition is recorded with the help of a digital Camera in a video mode. As the droplet is introduced in the furnace through the opening, the digital camera in the video mode starts recording the progress of the droplet heating and ignition. The ignition time is determined from the digital camera time record.

The initial size of the droplet is found by photographing the droplet before introducing in the furnace. Considerable effort was expended towards minimizing this non-uniform temperature region relative to the ignition delay, and the present experimental design and procedure were consequences of the best of such efforts.

The droplet is suspended on the thin steel wire which is exposed to a hot air temperature environment under atmospheric condition. The temperature during the ignition will be controlled by varying Variac for increasing temperature and decreasing temperature.

A bare Chromel Alumel (K-Type) thermocouple with diameter of 5 mm is placed at the droplet position and for the temperature history recording. The temperature reading is displayed on the data acquisition system.

The droplet is ellipsoid close to the shape of sphere and its equivalent diameter is calculated from the cubic root of the square of the minor axis multiplied by the major axis [12]. Thus droplet is not exact sphere but an ellipse. Size of droplet [11] is equivalent value determined as the cubic root of the product of the droplet width squared and droplet length i.e. $(\text{width})^{2/3} * (\text{length})^{1/3}$.

F. Experimental procedure: The suspended stationary fuel droplet (750-950 micron) is moved inside through a small opening at its front. This fuel droplet is suddenly exposed to a hot air environment in the combustion chamber at atmospheric pressure. In order to measure the initial droplet diameter, a photograph of droplet is taken by a digital

Table 2 Ambient condition for the experimental work

Parameter	**Ambient Condition**
Pressure	Atmospheric Pressure
TemperatureVariation	600 ^{o}C to 750 ^{o}C
Size of Droplet	750– 950 micron

camera just before the experiment. The droplet is ellipsoid close to the shape of sphere and its equivalent diameter is calculated from the cubic root of the square of the minor axis multiplied by the major axis.
The instant of ignition was detected according to the intensity of flame existence. Since the mixture of blended fuel changes when the droplet is exposed to the atmosphere, care is taken to ensure the experiment proceed smoothly. The time needed from the suspension of a droplet by a glass nozzle to wire during the experiment is about 2 to 3 seconds, including the time in which a photo of initial diameter is taken. The experiments are carried out at atmospheric pressure and room temperature.

Then the droplet ignition is monitored and data's are recorded with the digital camera from the window of the combustion chamber. Experiments were carried by varying droplet size 750-950 microns under different temperature ranges of the diesel from 600 ^{o}C to 750 ^{o}C. The fuels which are used during the experiment are diesel, bio-diesel and blends of diesel and bio-diesel (by varying the percentage of diesel in the bio-diesel fuel). There ignition delay time is compared on the graphs plotted with the variance of temperature and droplet diameter.

G. Properties of Bio-Diesel under investigation: Below is the list of comparison of the few important properties of Bio-Diesel with Diesel under consideration. [3] & [9]

Table 3 Comparison of properties Bio Diesel with its blend [3] & [9]

Properties	Diesel	Jatropha Bio-Diesel (BD 100)*	After 20% of Blend (Jatropha with Diesel) (BD 20)*
Density	0.841	0.862	0.828
Viscosity in stokes (cSt)	4.5	5.0	3.3
Calorific Value (kcal/kg)	10031	8890	9685
Cetane number	48	52	49
Carbon Residue	-	0.6% w/w	0.7% w/w
Ash Content	-	0.02% w/w	0.01% w/w
Sulphur Content	-	0.031% w/w	0.004% w/w
Flash Point	-	184 ^{0}C	74 ^{0}C

***Appendix** [B]*

V. RESULTSANDDISCUSSIONS

A. Pure Diesel and Bio-Diesel: Figure 5 shows the ignition delay time τ_{id} of Bio-diesel and Diesel fuels as a function of temperature. The diagram shows the ignition delay for both bio-diesel and diesel fuel. For both the fuel delay period decreases as the temperature increases, however the difference is smaller at higher temperature. As the temperature increased the difference was decreases more. Table 4 show the data of ignition delays at atmospheric pressure in the furnace at various temperatures for both the reference fuel pure Diesel and pure Bio-diesel.

Table 4 Ignition delay data for a Diesel and Bio-Diesel fuel atdifferenttemperatures

Temperature ^oC	600	625	650	675	700	725	750
Time (Bio- Diesel),sec	2.25	1.87	1.69	1.61	1.33	1.16	0.95
Time (Diesel),sec	1.49	1.18	1.09	0.95	0.81	0.69	0.60

Figure 6 shows the ignition delay for various blends of bio-diesel and diesel. It is observed from these figures that ignition delay for blends of bio-diesel and diesel vary with temperature. The ignition delays for blends lie between the values for the pure Diesel and pure Bio Diesel as shown in the Table 5.

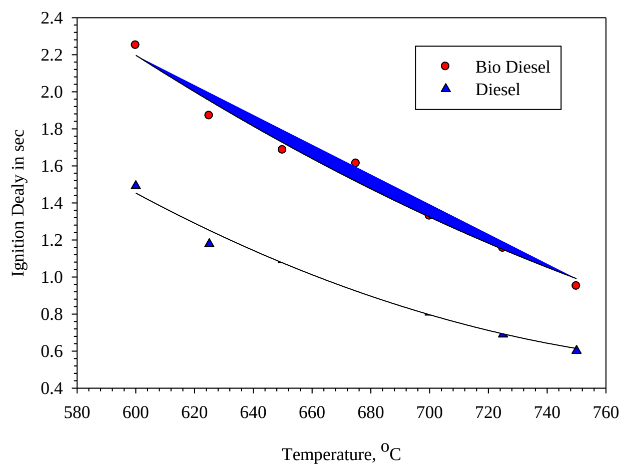


Figure 5 Ignition delay of Diesel and Bio-Diesel fuel at different temperatures

B. Effect of Droplet Diameter Variation: Figure 7 and 8 show the effect of variation in droplet diameter for ignition delay with temperature for two sizes of droplet. From these figures the variation in ignition delay with change in droplet diameter is not very significant at a given temperature. This trend is observed for both bio-diesel and diesel; it remains almost same for both the reference fuel.

Table 5 Ignition delay data's for blends of Diesel and Bio-Diesel fuel at differenttemperatures (5-20% of Bio-Diesel)

Temperature ^oC	Ignition Delay in sec					
	Fuel		Blends of Bio-diesel and Diesel			
	Pure Bio-Diesel	Pure Diesel	5 BD	10 BD	15 BD	20 BD
600	2.25	1.49	1.52	1.57	1.60	1.65

625	1.87	1.18	1.20	1.24	1.26	1.30
650	1.69	1.09	1.11	1.15	1.17	1.21
675	1.61	0.95	0.97	1.00	1.02	1.05
700	1.33	0.81	0.82	0.84	0.86	0.88
725	1.16	0.69	0.70	0.73	0.74	0.76
750	0.95	0.60	0.62	0.64	0.65	0.67

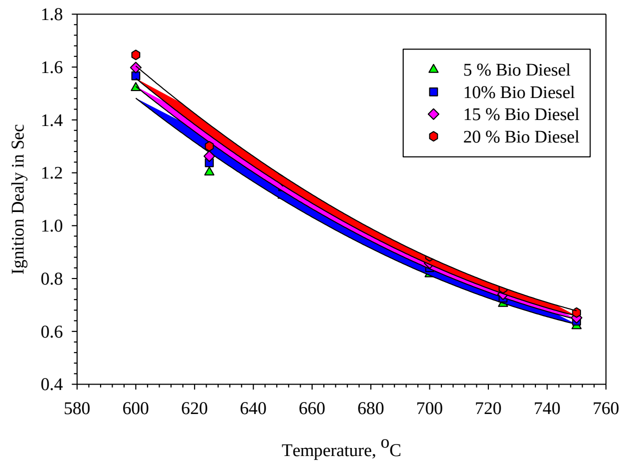


Figure 6 Ignition delays of blends of Diesel and Bio-Diesel fuel at different temperatures (5-20% of Bio-Diesel)

C. Determination of Activation Energy [14]: Figure 9 and Figure 10 shows the ignition delay data on the graph ln t versus 1/T (K^{-1}) coordinate. The data's for the diesel, Bio diesel and blends with diesel is plotted with generalized functional relation [14],

$$\tau_{id} = AP^{-n}\exp\left(E_A/RT\right)$$

Where the pre-exponential factor AP^{-n} is assumed to be independent of temperature is the gas constant, T is the temperature in K and E_A is the Activation Energy.The Activation Energy can be determined from the slope of 1/Temperature and ln t which is equal to (E_A/R), where R is the gas constant. If the gas constant value of 8.314 J/mol.K is used, the unit of activation energy will be in Joules.Taking the natural logarithm of this equation gives:

$$\ln\tau_{id} = -n\ln AP + \left(E_A/RT\right)$$

Or, $$\ln\tau_{id} = \text{constant} + \left(E_A/RT\right)$$

Or $$\ln\tau_{id} = \text{constant} + \left(E_A/R\right)\left(1/T\right)$$

Table 6 Ignition delay data's for Diesel and Bio-Diesel fuel at different temperatures with the variation of droplet diameter

Droplet Diameter	**Droplet Diameter 750 micron**		**Droplet Diameter 950 micron**	
Temperature in °C	**Pure Bio Diesel**	**Pure Diesel**	**Pure Bio Diesel**	**Pure Diesel**
600	2.25	1.49	2.30	1.52
625	1.87	1.18	1.91	1.20

650	1.69	1.09	1.72	1.11
675	1.61	0.95	1.64	0.97
700	1.33	0.81	1.36	0.83
725	1.16	0.69	1.18	0.70
750	0.95	0.60	0.97	0.61

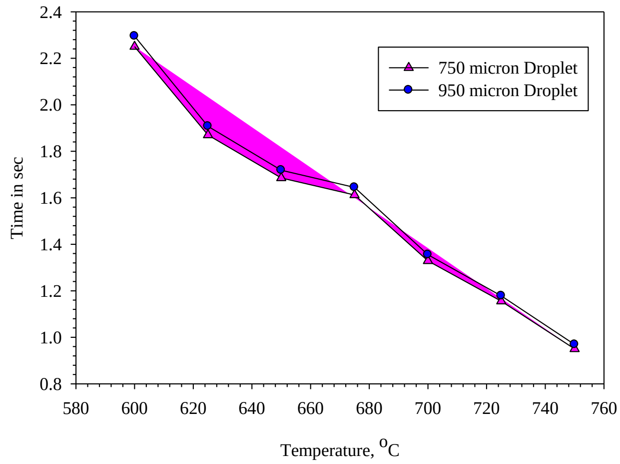


Figure 7 Droplet diameter variations in Bio-Diesel at different temperatures

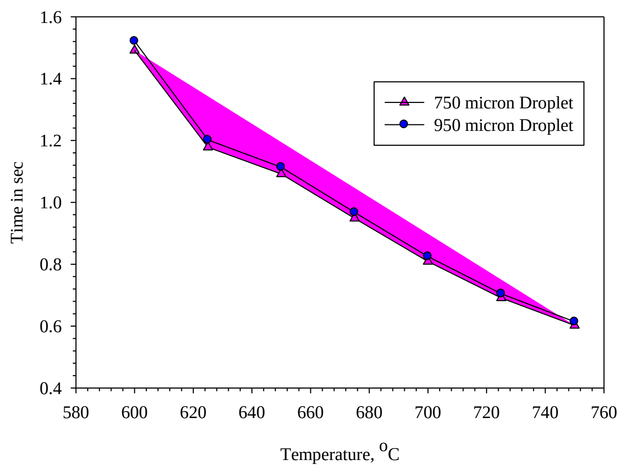


Figure 8 Droplet diameter variations in Diesel at different temperatures

These equations indicate that the plot of ln t versus 1/T is a straight line, with a slope of E_A/R. These equations provide the basis for the experimental determination of activation energy E_A. The linear relationship between ignition delay and temperature is:

$$\ln \tau_{id} = \text{constant} + \left(E_A/R\right)\left(1/T\right)$$

For the Diesel:

The activation energy of diesel is determined from the slope of this line is 5214.5, the relationship between slope and activation energy is:

$$\text{slope} = E_A/R$$

Where R is the gas constant in units of J/mol.K, the activation energy is in joule.

$$5214.5 = E_A / 8.314$$

Therefore, E_A=43353.353 J

For the Bio-Diesel:

The activation energy of Bio-diesel is determined from the slope of this line is 4811.7,

$$4811.7 = E_A / 8.314$$

Therefore, E_A=40004.4738 J

The computed value of activation energy is listed in the Table 7.

Table 7 Activation energy E_A for the blends

Fuel Blend	Activation energy E_A in Joule
BD 5	43168.78
BD 10	42420.52
BD 15	41505.98
BD 20	40674.58

It has been found that the value of apparent Activation energy E_A is 40004.4738 J for Bio-diesel, 43353.353 J for Diesel. Above mentioned Data shows the variation in the Activation energy with change in quantity of Bio-diesel in the fuel blends. The Activation Energy value is 40674.58 J for BD 5 to 43168.78J for BD 20 in blends of Diesel and Bio Diesel as mentioned in Table 7.

Table 8 Ignition delay data of Bio-diesel as a function of reciprocal of temperature and natural log of time

Temperature in ^oC	1/Temperature x 10^{-3} (K^{-1})	Ignition Delay (ln t)	
		Diesel	**Bio-diesel**
600	1.145	0.81100	0.39945
625	1.114	0.62585	0.16390
650	1.083	0.52179	0.08783
675	1.055	0.47764	-0.05289
700	1.028	0.28411	-0.21217
725	1.002	0.14439	-0.36985
750	0.978	-0.05129	-0.50756

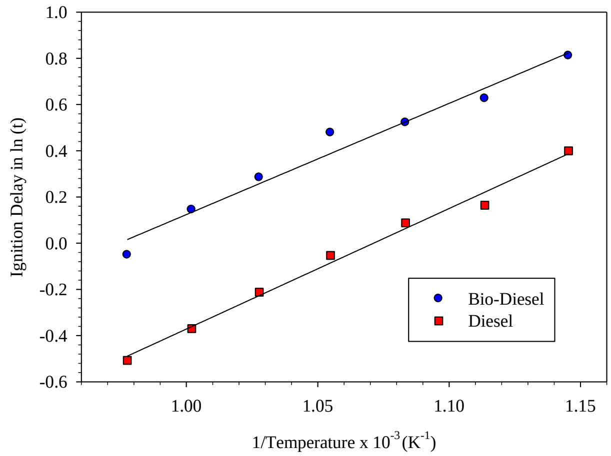


Figure 9 Ignition delay curves of Diesel and Bio-Diesel as a function of reciprocal of temperature

Table 9 Ignition delay data of blends of Bio-diesel as a function of reciprocal of temperature and natural log of time (BD 5 to BD 20)

Temperature in ^{0}C	1/Temperature x 10^{-3} (K^{-1})	Ignition Delay (ln t)			
		5 BD	10 BD	15 BD	20 BD
600	1.145	0.419250	0.448808	0.468611	0.498170
625	1.114	0.183706	0.213264	0.233067	0.262626
650	1.083	0.107630	0.137189	0.156992	0.186551
675	1.055	-0.033092	-0.003533	0.016269	0.045828
700	1.028	-0.202516	-0.172957	-0.153155	-0.123596
725	1.002	-0.350044	-0.320486	-0.300683	-0.271124
750	0.978	-0.477909	-0.448351	-0.428548	-0.398989

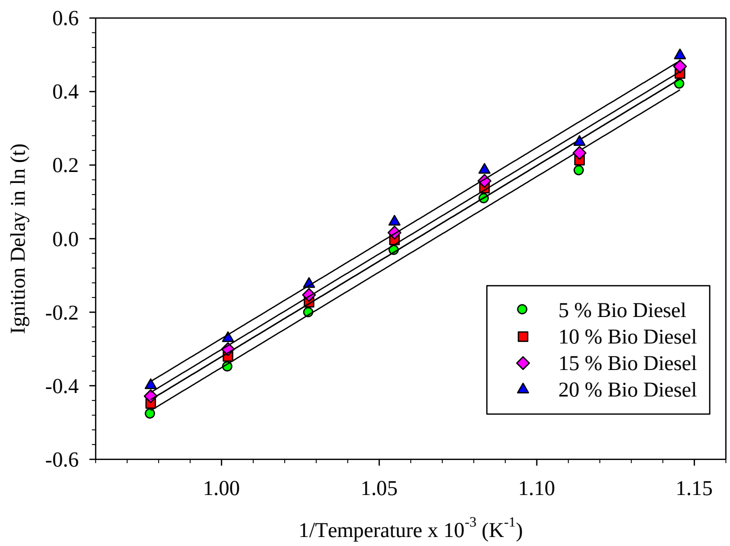


Figure 10 Ignition delay curve of blends of Bio-Diesel as a function of reciprocal of temperature (BD 5 to BD 20)

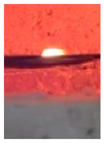
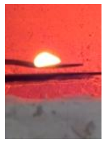
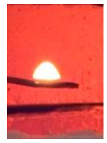
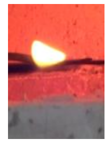
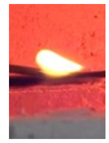
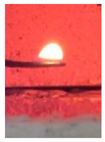
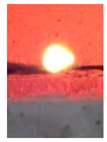
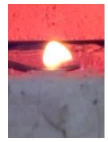
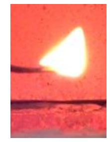
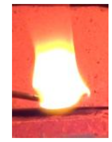
Temperature	600 °C	625 °C	650 °C	675 °C	700 °C	725 °C	750 °C
For Diesel							
For Bio Diesel							

Table 10 Photographs of Bio Diesel and Diesel droplet ignition at elevated temperature

Above shown the of table 10 images which are taken at different elevated temperature for the reference fuel. The difference in the flame structure is represented itself in the photographs which depicted us the effect of elevated temperature on it. The color of flame for the Diesel is slightly red / orange whereas for the Bio Diesel the color of flame is yellowish.

VI. CONCLUSION:

The study of droplet combustion and ignition analysis was mainly concentrated on to compare the ignition behavior of pure Diesel and pure Bio-diesel and blends of Bio-diesel.

- The study was for two different droplet diameters at atmospheric pressure.
- Ignition delay of Bio-diesel is larger than Diesel and the delay was increased as the % of Bio-diesel in the blends was increased. For pure Diesel delay was decreased from 1.49 sec at 600^0C to 0.60 sec at 750^0C.For pure Bio-Diesel delay was decreased from 2.25 sec at 600^0C to 0.95 sec at 750^0C.
- The effect of Droplet diameter was of very little significance as there was very small increment in the ignition delay found.

Activation Energy (E_A) was measured by the slope of the curve ln t versus 1/T. As the % of Bio-diesel in the blends was increased the value of E_A was found decreased up to 2 % with pure diesel.

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