RESEARCH ARTICLE   OPEN ACCESS

Burning Behavior of Liquid Fuel Droplets

Shah Shahood Alam
Pollution and Combustion Engineering Lab. Dept. of Mechanical Engineering. Aligarh Muslim University, Aligarh, 202002, U.P. India.

ABSTRACT
Ignition of flammable liquids by hot surfaces is well known to automotive and aviation industries. However, only a limited data regarding hot surface ignition (HSI) of pure and commercial fuels is available in literature. Further, relatively few studies have determined the ignition delay and to our knowledge the combustion lifetime. In the present work, we have generated results from an efficient, reproducible, yet simple experimental setup involving a liquid fuel droplet, a horizontal heated stainless steel plate and quiescent environment. Tests were conducted for diesel, biodiesel and its blends as well as vegetable oils, applied/used as single droplets under variety of conditions to the heated surface. The droplet size range was approximately between 1500 micron to 2000 micron.

The objective of this experiment was to determine the minimum temperatures for HSI and also the temperatures where 100% probability of ignition was expected. Further, from this experiment, we were also able to obtain the ignition delay and droplet lifetime. As an extension to this study, a separate droplet combustion model was developed to closely study the general burning behavior of these droplets by generating temperature and species concentration profiles. The droplet mass burning rate was also determined. The results obtained in the present work were in a general agreement with the experimental and modeling observations of other studies.

Keywords: Hot surface ignition, liquid fuel droplets, ignition delay, combustion lifetime, droplet combustion model, numerical technique, simplified approach.

I. Introduction

The auto ignition temperature (AIT) of a substance is the minimum temperature required to initiate or cause self sustained combustion independent of an external ignition source. The terms auto ignition, self ignition, thermal ignition and spontaneous ignition temperatures are used synonymously [1].

While hot surface ignition of flammable and combustible liquids is a well-known hazard in the chemical processing, automotive, and aviation industries, only limited research has been conducted to understand the ignition mechanism.

Hot surface ignition of flammable and combustible liquids is a complex phenomenon and depends on many factors. These factors include surface properties such as material, geometry, size, and roughness; environmental factors such as air temperature, humidity, and airflow; and physical properties of the fluid such as flash point, volatility, and chemical composition. Other factors influencing ignition probability include exposure time and spray or droplet properties.

Risk for hot surface ignition exists in automotive engine compartments, where multiple flammable and combustible fluids are in close proximity to sufficiently hot surfaces such as engine and exhaust components. Turbochargers, for example, which

increase the power output of an engine by forcing an increased amount of air into the cylinder, are often the hottest point on an engine and can ignite certain fuels that come in contact with them. According to the NFPA, approximately 65% of highway vehicle fires in the United States originate in the engine compartment, resulting in an estimated $545 million in property damage and an average of 162 civilian deaths, annually.

The risk for vehicle fires caused by hot surface ignition of automobile fluids is heightened in motorsports such as car racing where high-speed collisions and mechanical failures are common. Motorsport vehicles generally use higher performance fuels than stock automobiles. Furthermore, these motorsport vehicles are typically modified with features and devices not found on stock vehicles. While these modifications are primarily introduced to enhance performance of the vehicle, certain modifications (i.e. turbochargers) can introduce additional safety hazards as compared with common vehicles [2].

Automobile safety is important to vehicle manufacturers and motorists alike. In 2001, 11,343 ground transportation vehicle fires were reported in Canada, resulting in over $84 million in damages and 23 deaths, while in the US there were 258,000 vehicle fires, leading to $1.4 billion in property damage and

365 deaths. While this constitutes less than 5% of the total fatalities due to motor vehicle accidents, fires result in significant capital loss and can have major impact on the environment.

It is also observed that vehicle fires can originate from hot surface ignition (HSI), where flammable or combustible fluids are released near hot surfaces. Specific scenarios of concern arise when engine compartment temperatures increase due to reduced ventilation and cooling air flow after a vehicle comes to a stop, either intentionally or during an accident. If it can be determined that the engine was running or was recently running prior to a collision, HSI is one possible cause of the fire. It is therefore important to investigate the critical HSI temperatures and ignition probabilities for a wide range of automotive fluids [3].

Further, fires produce significant losses of both life and property. A significant portion of such fire losses are due to the leakage of flammable operating fluids from lines or conduits surrounding machinery, and their subsequent contact with hot machinery components, which can lead to ignition and damaging fires.

As an example, the U.S. Air Force alone typically experiences over 100 aircraft engine fires per year in which leaking fluids play a role, and such fire scenarios are a frequent cause of more than 500,000 passenger vehicle fires that occur in the US. Every year, adding up to more than one billion dollars in property damage. Similar fluid fires occur in stationary gas turbines and manufacturing machinery, portable power equipment, fluid storage facilities, marine vessels and any other applications where flammable fluids may be released, such as leaks in fittings, and can encounter ignition sources, such as sparks, exhaust manifolds, or other hot components.

Fluid ignition due to contact with heated surfaces, particularly when the fluids are initially in a liquid state upon contact with the surface are quite complex when analyzed in terms of fundamental mechanisms. Each fluid has a myriad of material properties which can affect its surface spreading, boiling, heat transfer, vaporization, diffusion and ignition behavior and all have a pronounced effect on the surface conditions and temperature that result in ignition.

External environmental conditions, such as the surrounding atmospheric pressure, temperature and velocity fields and the composition of such atmospheres also affect observed ignition behavior. Ignition criteria is also influenced by characteristics of the heated surfaces, such as their physical shape, orientation (with respect to any forced ventilation air flow, gravity and flammable fluid impingement locations), outer surface temperature profiles, surface roughness features and relevant physical properties [4].

1.1 General Droplet Evaporation and Ignition Behavior

Evaporation rates and ignition delays for liquid droplets generally increased and decreased respectively as heated surface temperatures were increased. As a result, evaporation lifetime and ignition delay correlations to surface temperature are not identical. Stated differently, an increase in heated surface temperature may or may not increase overall evaporation rates, and ignition delays may or may not decrease regardless of the increase or decrease in evaporation rate, depending upon the given surface temperature, fluid properties and other factors [4].

1.2 Ignition Delay

The ignition delay period may be defined as the time lag between the commencement of diesel injection into the cylinder and the point of first detectable rise in cylinder pressure due to exothermic energy release within the mixture. During the ignition delay period, a unified physicochemical process takes place in which all transformations, both physical and chemical, occur simultaneously.

In diesel engine, the ignition delay period is affected by the temperature, pressure and concentration of the charge. It changes the physical and chemical properties of the charge such as specific heat ratio, availability of oxygen concentration, pre-ignition reaction and afterward, the related energy release and also the formation of active species during the combustion of fuels.

The magnitude of specific heats mainly depends on number of atoms in the molecules and ignition delay is observed to be affected by chemical nature of combustible gases. It is further observed that hydrogen is a stronger inhibitor as compared to carbon monoxide.

High pressure diesel fuel spray is injected into the cylinder having gaseous fuel-air mixture at high temperature and pressure. The rate of vaporization of these fuel droplets depends on the size of droplets, pressure and temperature, volatility of the fuel, their distribution and velocity. The fuel evaporates from each droplet and mixes with air to form a flammable mixture.

This ignition delay period can be roughly divided into two parts:

1. Physical Delay- the period of physical delay is the time between the beginning of injection and the attachment of chemical reaction conditions. In this physical delay period the fuel is atomized, vaporized, mixed with air and raised in temperature.

2. Chemical Delay- the second part of ignition delay is called chemical delay in which pre-flame reactions start slowly and then accelerate until ignition takes place. Generally, chemical delay is longer than the physical delay. However, it depends on temperature. At higher temperatures, chemical reactions are

quicker and physical delay is longer than the chemical delay. The delay period refers to the sum of physical and chemical delay period [5].

Physical Factors Affecting Ignition Delay

The physical factors that affect the development of the fuel spray and the air charge state will influence the ignition delay. Some factors are as follows [6]:

Fuel droplet size

Injection velocity

Intake air temperature and pressure

Oxygen concentration

Combustion chamber wall effects

Fuel properties

1.3 Hot Surface Ignition in Open Air

Hydrocarbon liquids that are exposed to hot surfaces in the open air, when heated sufficiently, can ignite without the application of a flame or spark. The ignition of hydrocarbons by hot surfaces may occur when oil is released under pressure and sprays on a hot surface and lies on the surface for a period of time. Understanding the mechanism and dynamics of auto-ignition is an important step in preventing or controlling the ignition of hydrocarbons by hot surfaces in the open air [7].

1.4 Determination of Ignition Delay of Suspended Multicomponent Liquid Fuel Droplets Undergoing Combustion

A single suspended droplet technique was used for droplet combustion tests on different fuel samples and blends of different composition like dehydrated ethanol (A), rapeseed methyl ester (RME), diesel fuel (MD) and their blends of various proportions [8].

Liquid fuel droplet was settled with the help of medicine syringe on the suspension device manufactured from glass yarn and having an 800 μm radius ball on the end. At the time of experimental measurement, a heated furnace was pushed via deflective rails towards suspension device in a way, so that the distance between fuel droplet and thermocouple was 2-3 mm. This distance was controlled by synchronizing contacts which also operated a stopwatch switch-on. Droplet combustion control was provided by optical system equipped with radiant screen and binoculars.

Furnace was heated until initial temperature T_∞ was about 900 K. Fuel droplet with radius r_{lo} = 1.125±0.05 mm was settled on the glass yarn with the help of medicine syringe. Droplet size was variable with the sprayed fuel volume and was controlled while looking through binoculars at the graduated screen where droplet reflection was visible. Initial fuel droplet temperature was T_0= 293 K.

Interval between fuel droplet reaching the centre of furnace and appearance of flame around the droplet was fixated as ignition delay time τ_{ind}. A stopwatch also fixated a total time of droplet existence. Droplet burning time was calculated as a difference between total time of droplet existence and ignition delay time. Thermocouple inflexible mounted into the back-wall of furnace fixated droplet combustion temperature. Measurement error did not exceed ±5 K. In this manner, ignition delay times (in sec) of RME and MD for a fixed droplet radius of 1.125 mm (1,125 μm) were obtained at different values of furnace temperatures, T_∞.

II. Literature Review

Recent studies, which have evaluated the propensity of various flammable and combustible liquids to ignite on a hot surface have investigated the relationship between AIT and the minimum temperature required for hot surface ignition. One study determined the ignition of a variety of automotive and aviation fluids on a horizontal flat plate using a single drop of liquid in a quiescent environment. Their results showed a probabilistic nature of the ignition of fluids on a hot surface and provided a well-defined relationship between surface temperature and ignition probability for their apparatus.

Mizomoto et al [9] conducted experiments on evaporation process of single droplets of n-heptane. The initial diameter was taken approximately as 2mm and hot surface was made up of stainless steel. The surface temperature range was kept between 300ºC and 600ºC. It was observed that the evaporation lifetime curve was divided into regions according to the mode of evaporation of the droplet.

Moussa and Johnson [10] observed that streams of aircraft flammable fluids released from pressurized lines in a full-sized aircraft engine impinged on the heated surface as a jet and spread radially in all directions. After a short distance (typically 0.3 inches), the fluid broke up into rivulets, then ligaments, and droplets. It is not known whether the curved surface used in this experiment, (a typical cylindrical hot manifold apparatus) contributed to this physical behavior.

Mizomoto et al [11] proposed a numerical model to explain the mechanisms of evaporation and ignition for spherically symmetric n-cetane droplets on heated surfaces. The concentration profiles of fuel vapour around the droplet were predicted by integrating the unsteady diffusion equation using a simplified evaporation model of the droplet. The predicted locations of fuel vapour concentration around the droplet were found to be in a good agreement with the observed locations where the initial flame was formed. The fuel stoichiometric mole fraction was used as criteria for local spatial conditions suitable for ignition. A somewhat acceptable correlation was found with the actual measured times and locations of ignition in

experiment within the accuracy and limited range of conditions of interest.

It is very important to investigate the evaporation and ignition process of a fuel droplet on a hot surface in connection with internal combustion engines. Especially for evaporation. Many theoretical and experimental studies have been performed. Gottfried et al. [12] postulated an analytical model of the Leidenfrost phenomenon and predicted the evaporation time for a spherical droplet accounting for the heat transferred to it by conduction through the vapor film on the bottom half and by radiation to the entire droplet and also accounting for the mass removed from the droplet by evaporation on the lower surface.

Hiroyasu et al. [13] analyzed the evaporation of a spheroidal droplet under high temperature and high pressure. For a droplet evaporating in the spheroidal state, Wachters et al.[14] calculated the evaporation rate and the vapor layer thickness under a droplet. Gottfried et al.[15] and Satcunanathan [16] also presented a theory to predict the evaporation rate. For a large droplet, Baumeister et al. [17] solved the Navier Stokes, energy and continuity equations to obtain the evaporation rate and overall heat transfer coefficients. Many of the theoretical investigations cited above do not provide for the unsteady concentration and temperature profiles of the fuel around the droplet, which is most important for clarifying the ignition mechanism.

On the other hand, there are other theoretical investigations in which the ignition process of a fuel droplet in a heated gas is modeled. For example, El-Wakil and Abdou [18] discussed the ignition delay time by dividing it into a physical ignition delay and a chemical ignition delay. Faeth and Olson [19] analyzed the ignition mechanism under the assumption that ignition occurs when the concentration of a crucial chain branching intermediate reaches a critical value in the boundary layer around a droplet. Henein [20] predicted the ignition delay time with the assumption that the ignition occurs at the stoichiometric mixture.

Kadota et al.[21] predicted the ignition delay time with the assumption that the ignition occurs when the time integrated value of the reaction gets to unity.

Mizomoto et al.[22] investigated the evaporation and ignition process of a single droplet of n-cetane a hot surface in the hot surface temperature range $300{\sim}550^{0}$C, with initial droplet diameters vary between 0.7~3.3mm. It was found that the upper li of a hot surface temperature, at which the mode evaporation of droplet contacting with the hot surface disappears, shifts to a lower temperature with decreasing the initial droplet diameter, d_0. The

ignition delay time also increases at this surface temperature.

Gulder and Wong [23] presented a model for the spheroidal fuel droplet evaporation and ignition on a hot surface. The model predicted the average and surface temperature histories of the droplet, rate of evaporation, fluid mechanics of the vapor underneath the droplet and vapor concentration around the droplet as well as the rate of heat transfer from the hot surface to the droplet by conduction and radiation. The transient convective-diffusion equation was solved analytically to obtain an expression for the fuel vapor concentration profiles around the droplet. Numerical predictions of the developed model for the droplet surface temperature, rate of evaporation and evaporation lifetime were compared with experimental data. Satisfactory agreement was obtained for various diameters of n-hexadecane and n-heptane droplets. A procedure was outlined to estimate the total ignition delay of a droplet on a hot surface at elevated pressures. The predicted ignition delay times for n-hexadecane droplets agreed reasonably well with the experimental data for pressures lower than 1500 kPa.

Krystyna Buda-Ortins [24] conducted an experiment to determine the auto ignition temperatures of cooking oil. For each oil tested, the auto-ignition temperatures were in the same range. A total of 5 experiments were done with canola oil, 3 with soybean oil, and 3 with olive oil.

III.   Experimental Setup and Methodology

In the present work, an experimental set up is fabricated for conducting experiments on liquid droplets. The unique feature of this study is that it simultaneously provides information regarding ignition delay, hot surface ignition temperature and droplet combustion lifetime which can be read directly from an oscilloscope and a temperature controller.

The schematic diagram of the experimental setup used for obtaining hot surface temperature, ignition delay and combustion lifetime is shown here:
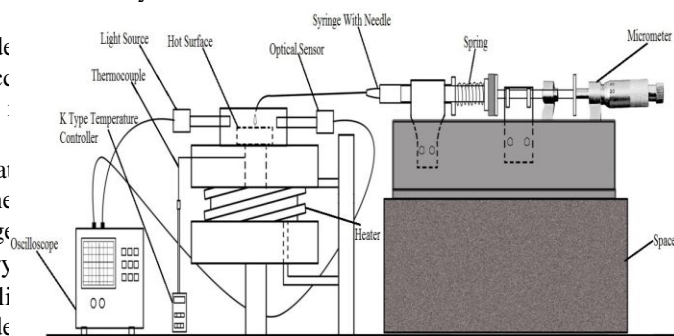

Figure 1: Schematic Diagram of the Experimental Setup

The setup mainly consists of the following:
1. Combustion Chamber   2. Droplet Generator
3. Display and Control

Because hot surface ignition is a complex process and is strongly coupled to experimental conditions, the present study utilized a simple experimental set-up involving a horizontal circular plate, a single drop of liquid fuel with no forced airflow.

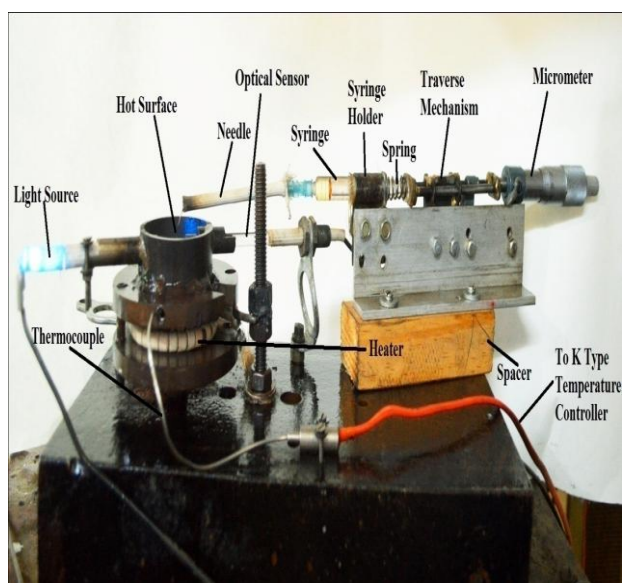The snapshot of experimental setup for hot surface ignition (side view and top view) is given below:

Figure 2: Experimental Setup Side View

Figure 3: Experimental Setup Top View

3.1 Combustion Chamber
The combustion chamber consists of two stainless steel circular plates of diameter 89.9mm connected through bolt. A space is provided between the plates by a small steel tube in order to accomplish the heating wire between them. A nichrome wire heating element is wounded around the tube to

provide heating. A steel annular tube is fitted to upper plate in order to make an arrangement for light source and optical sensor. Hot surface is the head of bolt which is machined in a bowl shape.
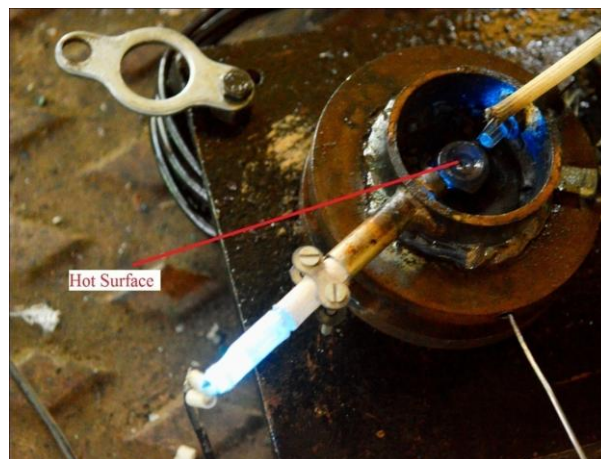The photograph of combustion chamber is shown below:

Figure 4: Hot Surface

3.2 Droplet Generation Procedure
Droplet generating mechanism consists of various parts like syringe needle of 25G, glass syringe, syringe holder, traverse mechanism, micrometer. The droplet is generated by giving the required length of stroke (in 10^{-3}mm) to a plunger of syringe through micrometer in such a proportion that droplet of size of few mm can be produced at the tip of syringe needle connected with syringe and traverse mechanism.
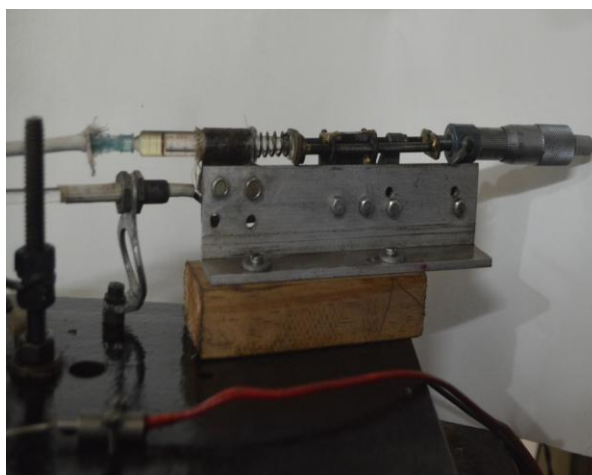

Figure 5: Droplet Generator

3.3 Display and Control
Display and control requires thermocouple, temperature indicator, K-type digital temperature controller, optical bench and optical sensors and an oscilloscope. Thermocouple is placed inside to side of the upper stainless steel plate so that it can reach to

bolt and connected to K-type temperature controller and temperature indicator.

The thermocouple consists of two different nickel alloys called Chromel (90 % nickel and 10 % chromium) and Alumel (95% nickel, 2% manganese, 2% aluminium and 1% silicon). It is inexpensive, and a wide variety of probes are available in its range (−200 °C to +1250 °C). The K type temperature controller used for this experimental setup is shown below.

Figure 6. Temperature Controller

Light source and optical sensors are directly connected to oscilloscope. The oscilloscope which we have used for the experimental setup is shown below.

Figure 7: Digital Storage Oscilloscope

A digital storage oscilloscope (DSO) uses digital memory to store a waveform. In order to do this, the incoming signal must first be digitized; once this is complete, the data in the memory can be continuously replayed through a digital to analogue converter and displayed on a CRT. Unlike analogue storage oscilloscopes, the captured waveform does not decay over time.

3.4 Methodology

During each test series, the steel plate was heated by the heater. Once the surface temperature had stabilized, an individual drop of liquid fuel at lab ambient conditions was dropped onto the hot metal surface from approximately 1–2 cm away. The drops were administered from a 1 ml glass syringe with a 26G needle. With each drop, data were collected on the oscilloscope. For every fuel at a fixed surface temperature, 5 drops were tested.

Once the required numbers of ignitions or non-ignitions were recorded at the initial surface temperature, the temperature of the hot sample surface was increased in approximately 20ºC increments with the help of temperature controller. The required numbers of ignitions or non-ignitions were recorded at each surface temperature to continue the test series. Typically, once all consecutive ignitions i.e. 5 were observed at a given surface temperature, the temperature was increased an additional 20ºC and 5 more drops were evaluated. If this resulted in an additional 5 consecutive ignition events, the higher temperature was taken as the upper temperature for the test. This final 20ºC increase in temperature ensured 100% probability of ignition.

The liquid fuel droplet was released through the droplet generator with the help of impact of a thin sheet. As it was falling on the hot surface, it hindered the light from the light source to the optical sensor and hence some reduced intensity of light was detected. This point was picked by a photo-sensor and was recorded on an oscilloscope. Then, as soon as this fuel-air mixture got ignited (appearance of flame), it was again recorded on the oscilloscope. This was the hot surface ignition temperature. The time lag between the two points on the oscilloscope represented the ignition delay.

Another point was the time where the flame extinguished, which was also recorded. The time between the start of ignition process in the form of a flame and flame extinction gave the droplet lifetime. Hence, through this experiment we were able to record three important combustion parameters, namely, hot surface ignition temperature, ignition delay and droplet combustion lifetime (which are quite difficult to obtain through theoretical considerations or droplet combustion modeling).

3.5 Determination of Temperature and Concentration Profiles around the Burning Droplet through a Droplet Combustion Model

For modeling droplet combustion due to hot surface ignition, a droplet combustion model has been evolved in the present study which is based on the following assumptions:
1. The droplet is spherical. This assumption has been experimentally verified by Mizomoto et al. [11] for hot surface temperatures ranging from approximately 410˚C-600˚C and for initial droplet diameters of less than 2 mm. Hence for modeling purposes we have taken the hot surface temperature in the range of 465˚C-500˚C and the initial droplet diameter as $1514\ \mu m$ (1.514mm).

2. The atmosphere around the droplet is an ideal gas at atmospheric pressure.

3. The droplet is at its boiling point temperature and liquid-vapor equilibrium prevails at its surface.
4. The droplet processes are diffusion controlled.
With these assumptions, the unsteady gas phase, spherically symmetric, species concentration and energy equations were respectively obtained as:

$$\frac{\partial Y}{\partial t} = D_g \frac{\partial^2 Y}{\partial r^2} + \frac{2D_g}{r} \frac{\partial Y}{\partial r} \qquad (1)$$

$$\frac{\partial T}{\partial t} = \alpha_g \frac{\partial^2 T}{\partial r^2} + \frac{2\alpha_g}{r} \frac{\partial T}{\partial r} \qquad (2)$$

T, Y are temperature and mass fraction of the species respectively; r is the radial distance from the droplet center; t is the instantaneous time; D_g and α_g are the gas phase mass and thermal diffusivities respectively.

The above equations are a set of linear, second order partial differential equations which can be solved numerically using finite difference technique. They become quite similar when thermal and mass diffusivities are made equal for unity Lewis number.

The boundary and initial conditions based on is this combustion model are as follows:

$at \ r = r_f; \ T = T_f, \ Y_{o,f} = 0, \ Y_{F,f} = 0$

$at \ r = r_\infty; \ T = T_\infty, \ Y_{o,\infty} = 0.232,$

$at \ t = 0; \ r = r_{lo}, \ T = T_b, \ Y_{F,S} = 1.0$

where $r_l = r_{lo}(1 - t/t_d)^{1/2}$ for $(0 \leq t \leq t_d)$, is the moving boundary condition. Here, T_f and T_∞ are temperatures at the flame and ambient atmosphere respectively. $Y_{F,S}$ and $Y_{F,f}$ are fuel mass fractions at the droplet surface and flame respectively. $Y_{o,\infty}$ and $Y_{o,f}$ are oxidizer concentrations in the ambience and at the flame respectively, t is the instantaneous time, t_d is the combustion lifetime of the droplet, r_{lo} is the original or initial droplet radius and r_l is the instantaneous droplet radius at instantaneous time "t".

The location where the maximum temperature $T = T_f$ or the corresponding concentrations $Y_{F,f} = 0$ and $Y_{o,f} = 0$ occur, was taken as the flame radius r_f. Time "t" was obtained from the computer results. For input to the code, combustion lifetime was taken from experimental results, flame temperature was calculated using a

stoichiometric reaction between oxidizer and fuel. Other important thermo physical properties were taken from various sources.

For steady state droplet burning (as in the present case), the combustion lifetime $t_{d_{ss}}$ or t_d is given as:

$$t_{d_{ss}} = \frac{4r_{lo}^2}{k_{b_{ss}}} \qquad (3)$$

Where , $k_{b_{ss}} = 8\frac{\lambda_g}{\rho_l C_{pg}} \ln(1 + B_{T_{ss}})$ (4)

$k_{b_{ss}}$ or k_b is the steady state burning constant. Experimental results for spherically symmetric droplet combustion suggest that mass burning rate m_f can be expressed as:

$$m_f = \frac{\pi r_l \rho_l k_b}{2} \qquad (5)$$

Temperature profiles for the inflame and post flame zones were obtained by solving the energy equation (equation 2). Thermal diffusivity α_g at ambient conditions for pure diesel fuel was calculated as 0.32147cm²/s. The combustion lifetime t_d for pure diesel oil droplet of initial diameter 1514 μm and with surface temperature of 500°C was taken as 0.7s from the experimental results. α_g and t_d were then used as input to the computer code.

Species concentration profiles of fuel vapor and oxidizer were determined through the solution of equation (1) using a separate code. The temperature and species concentration profiles are shown in Figure 4.4.

Droplet mass burning rate m_f was calculated using correlation (5). The variation of m_f (mg/s) with time for diesel fuel and a blend of 90% diesel and 10% bio-diesel is shown in Figure 4.5.

IV. Results

The following data were generated on experimental setup (in the form of Tables 4.1 and 4.2) provided below, using three vegetable oils namely coconut, ground nut and olive oil and two commercial fuels which included straight diesel and diesel blended with biodiesel.

Table 4.1: Ignition Delay and Combustion Lifetime of Fuel Droplets

Fuel: Pure Ground Nut Oil
Hot Surface Temp: 420^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	480	620
0.07	1693	500	760
0.10	1907	560	1160

Fuel: Pure Ground Nut Oil
Hot Surface Temp: 460^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	340	500
0.07	1693	360	680
0.10	1907	400	980

Fuel: Pure Ground Nut Oil
Hot Surface Temp: 500^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	240	480
0.07	1693	260	660
0.10	1907	300	880

Fuel: Pure Coconut Oil
Hot Surface Temp: 420^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	440	460
0.07	1693	520	560
0.10	1907	560	660

Fuel: Pure Coconut Oil
Hot Surface Temp: 460^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	420	440
0.07	1693	500	500
0.10	1907	540	600

Fuel: Pure Coconut Oil
Hot Surface Temp: 500^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	400	420
0.07	1693	420	480
0.10	1907	520	560

Fuel: Pure Clove Oil
Hot Surface Temp: 450^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	520	940
0.07	1693	540	1060
0.10	1907	680	1180

Fuel Pure Clove Oil
Hot Surface Temp: 480^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	420	840
0.07	1693	500	960
0.10	1907	600	1080

Fuel: Pure Clove Oil
Hot Surface Temp: 510^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	320	740
0.07	1693	420	820
0.10	1907	540	980

Fuel: Pure Diesel Oil
Hot Surface Temp: 500^0c

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	580	700
0.07	1693	640	820
0.10	1907	740	900

Fuel: Pure Diesel Oil
Hot Surface Temp: 530^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	560	640
0.07	1693	620	740
0.10	1907	700	860

Fuel: Pure Diesel Oil
Hot Surface Temp: 560^0C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	540	600
0.07	1693	600	700
0.10	1907	660	820

Shah Shahood Alam Int. Journal of Engineering Research and Applications
www.ijera.com
ISSN : 2248-9622, Vol. 5, Issue 6, (Part -3) June 2015, pp.43-54

Fuel: Jatropha Biodiesel Oil
Hot Surface Temp: 435^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	520	480
0.07	1693	560	540
0.10	1907	620	640

Fuel: Jatropha Biodiesel Oil
Hot Surface Temp: 465^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	480	460
0.07	1693	540	540
0.10	1907	600	620

Fuel: Jatropha Biodiesel Oil
Hot Surface Temp: 495^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	460	440
0.07	1693	500	520
0.10	1907	560	600

Fuel: 90% diesel + 10% Biodiesel
Hot Surface Temp: 485^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	560	680
0.07	1693	620	780
0.10	1907	740	860

Fuel: 90% diesel + 10% Biodiesel
Hot Surface Temp: 515^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	540	660
0.07	1693	600	760
0.10	1907	700	820

Fuel: 90% diesel + 10% Biodiesel
Hot Surface Temp: 545^{0}C

Length of micrometer stroke in (mm)	Fuel droplet size in (micron)	Ignition delay I_d (ms)	Combustion lifetime t_d (ms)
0.05	1514	500	640
0.07	1693	580	720
0.10	1907	680	780

Table 4.2: Minimum Temperatures for HSI and Temperatures where 100% Ignition is expected.

Fuel/ Vegetable oil	Minimum Temperature for HSI (^{0}C)	Temperature for 100% HSI (^{0}C)
Pure Ground Nut Oil	340	420
Pure Coconut Oil	320	415
Pure Clove Oil	360	450
Diesel	430	500
Jatropha Biodiesel	380	435
90% Diesel + 10% Biodiesel	400	485

4.1 Discussion on Results

HSI temperatures of different fuels were determined based on the temperature of the surface taken where ignition occurred, as described in the experimental methodology. The minimum temperature for HSI was the temperature where there was least probability for the drop to be ignited. This temperature was recorded along with the temperature where 100% probability for HSI was expected. These observed data for different oils are summarized in the table 4.2 above:

In the experiment, it was observed for the same droplet size of liquid fuel droplet, ignition delay and combustion lifetime of the oil decrease as the hot surface temperature increases. Whereas, an increase in the droplet size led to a corresponding enhancement in ignition delay and combustion lifetime for the same hot surface temperature. The results (Figs 4.1- 4.3) are shown for straight diesel fuel, Jatropha biodiesel fuel and a blend having 10% Jatropha biodiesel and 90% straight diesel. The trend in the behavior of ignition delay with surface temperature of the present study agrees in principle with the experimental work of Mizomoto et al [22].

A plot of temperature and species concentration profiles around a burning spherical droplet is depicted in Figure 4.4. The solution of energy equation 2 was obtained numerically in the form of temperature profile covering the inflame and post flame regions. Droplet surface temperature was assumed equal to the boiling point temperature T_b of the fuel. Figure 4.4 indicates that the temperature profile starts from the boiling point temperature (536.4 K), reaches a maxima at the flame zone where T_f is equal to 2297 K and then gradually decreases to the ambient temperature value of 298 K.

The radius at which the maximum flame temperature T_f occurs is the corresponding flame radius r_f. For simplicity, the flame temperature was calculated using first law of thermodynamics with no dissociation effects with the help of a computer programme developed in the present work. This temperature profile was obtained through computed results for one particular time of droplet burning, when dimensionless time $t/t_d = 0$, that is, the time when the combustion has just started ($t = 0$).

Species concentration profiles (fuel vapour concentration profile for the inflame zone and oxidiser concentration profile for the post flame zone) were obtained by solving the species diffusion equation (equation 1) numerically. In Figure 4.4, the computed results indicate that in the inflame zone, the fuel vapour concentration is maximum at the droplet surface, i.e. $Y_{F,S} \approx 1$, and gradually decreases to zero at the flame ($Y_{F,f} = 0$). The oxidiser (oxygen) diffuses from the ambient atmosphere in the post flame zone where its concentration is 23.2 % ($Y_{o,\infty} = 0.232$) and gradually reduces to zero at the flame ($Y_{o,f} = 0$). Both fuel vapour and oxidiser are consumed at the flame. These results are in general agreement with the results of other droplet combustion models [25].

Figure 4.5 shows that the droplet mass burning rate is maximum in the begining for both Diesel fuel and its blend and then reduces gradually as the droplet gets consumed.
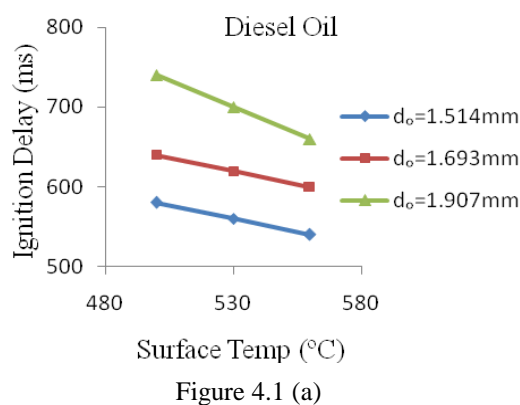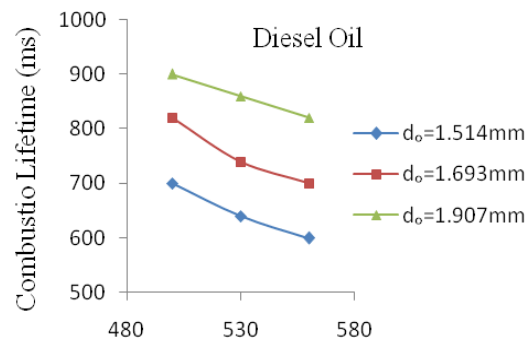
4.2 Plots of Results

Figure 4.1 (a)
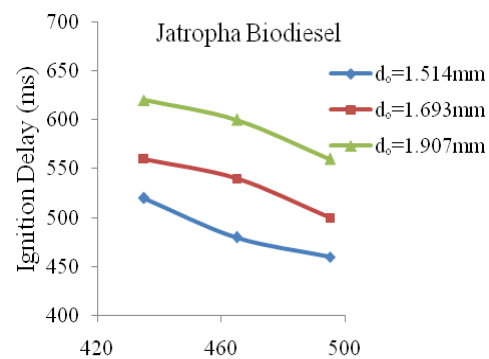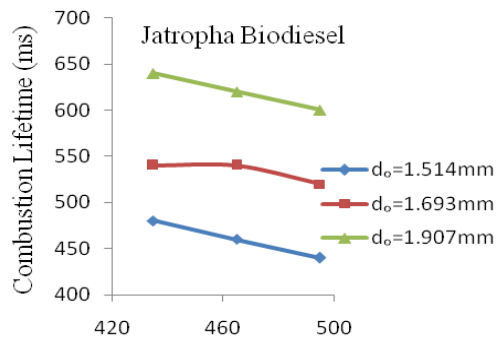

Figure 4.1 (b)

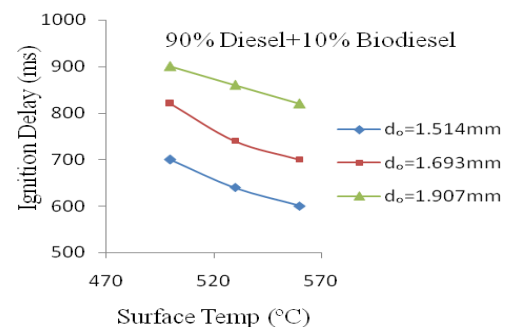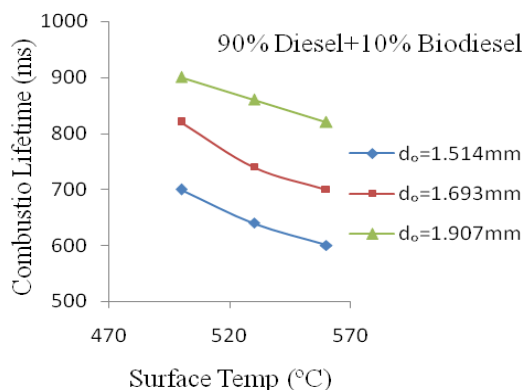Figure 4.2 (a)

Figure 4.2 (b)

Figure 4.3 (a)

Figure 4.3 (b)

Figure 4.1-4.3: Variation of Ignition Delay and Combustion Lifetime of Jatropha Biodiesel (a and b), Diesel Oil (c and d) and Diesel-Biodiesel Blend (e and f) with increase in Hot Surface Temperature.
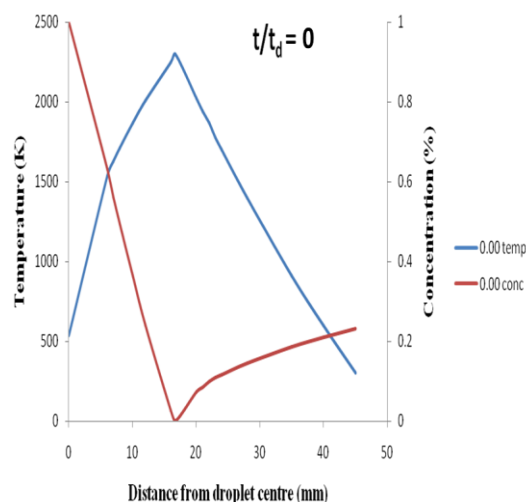

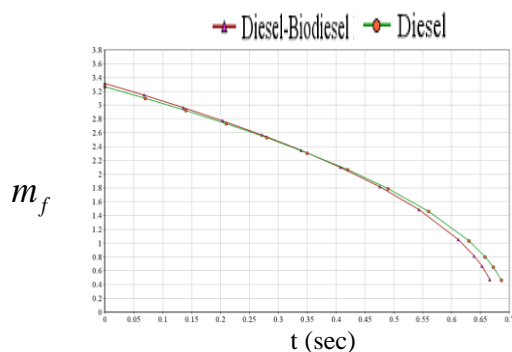Figure 4.4: Temperature and Species Concentration Profiles for Diesel Fuel at $t/t_d = 0$

Figure 4.5: Variation of Mass Burning Rate m_f with time for Diesel and Diesel-Biodiesel Blend

V. Conclusions and Scope for Future Work

The ignition process of a liquid droplet of different fuels on a hot surface has been investigated in detail over a wide range of the hot surface temperatures. The following conclusions are made:

1. Minimum temperature for HSI and temperature for 100% HSI of diesel is more than that of biodiesel and other pure vegetable oils.
2. For the same droplet size, ignition delay and combustion lifetime of the oil decreases as the hot surface temperature increases. This trend was in agreement with the experimental results of Mizomoto et al. [9] and [22].
3. With an increase in the droplet size, there was an increase in ignition delay and combustion lifetime for the same hot surface temperature.
4. Blending of jatropha biodiesel with straight diesel in an appropriate proportion leads to a decrease in ignition delay and droplet combustion lifetime..
5. Using the droplet combustion model of the present work, temperature and concentration profiles surrounding a spherical diesel fuel droplet were generated. It was observed that the fuel vapour diffused outwards from the droplet surface whereas the oxidizer diffused inwards from the surrounding air, leading to the formation of a diffusion flame around the droplet.
6. The plot of droplet mass burning rate with time showed a decreasing trend for both straight diesel and diesel.-biodiesel blend

Scope for Future Work
The present experimental set up can be further modified or refined. These modifications are as follows:

1. Since the HSI of combustible liquids depend on many factors like nature of surface material, its geometry and roughness, more experimental data can be obtained for different hot surfaces by changing these variables.
2. We can also estimate hot surface ignition by incorporating forced airflow in the experimental set up.
3. There can also be an application of thermal shield around the setup so that heat radiated by the heater could be solely used to raise the temperature of surface only.
4. The apparatus can be refined to generate droplet sizes of less than 1000 μm, using more precised instrumentation so that analysis could be made for a variety of droplet size ranges.

5. The set up can be modified to include the effects of more volatile liquids.

6. We can also determine the effect of viscosity on these parameters by using fuels of different viscosities.

References

[1] Jeff D. Colwell, Reza Ali, "Hot Surface Ignition of Automotive and Aviation Fluids," Fire Technology, Vol. 41, pp. 105-123, 2005.

[2] Scott Davis, Sean Kelly, Vijay Somandepalli, "Hot Surface Ignition of Performance Fuels," Fire Technology,Vvol. 46, pp. 363-374, 2010.

[3] Beth Weckman , Alan Shaw, William Epling, "Evolution of the Ignition of Diesel Fuels on Hot Surfaces," Fire Technology, Vol.46, pp. 407-423, 2010.

[4] Michael J. Bennett , "Ignition of Combustible Fluids by Heated Surfaces," Process Safety Progress, Vol.20, no.1, 2001.

[5] M. L. Mathur, R.P. Sharma, "Internal Combustion Engines", Dhanpat Rai Publications, New Delhi, 2008.

[6] John B. Heywood "Internal Combustion Engine Fundamentals." Tata McGraw Hill Edition, New Delhi, 2011.

[7] "Ignition Risk of Hydrocarbon Liquids and Vapors by Hot Surfaces in the Open Air," Third Edition, American Petroleum Institute, December 2003.

[8] L. Raslavicius, D. Marksaitis, "Research into Three-Component Biodiesel Fuels Combustion Process Using a Single Droplet Technique," Transport, Vol. 22, pp. 312-315, 2007.

[9] M. Mizomoto, H. Hayano, and S. Ikai, "Evaporation and Ignition of a Fuel Droplet on a Hot Surface, Part 1: Ignition," Paper No. 162-13, Bulletin of the JSME, Vol. 21, No. 162, December 1978.

[10] A.M. Johnson, N.A. Moussa, " Hot Surface Ignition Tests of Aircraft Fluids," Final Report for May 1987- May 1988, AFWAL-TR-88- 2 101, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratory, Wright- Patterson Air Force Base, Ohio, November 1988.

[11] M. Mizomoto, A. Morita, and S. Ikai, "Evaporation and Ignition of a Fuel Droplet on a Hot Surface," Part 4: Model of Evaporation and Ignition," Combustion and Flame, pp 94-105, 1983.

[12] B. S. Gottfried, C. J. Lee, K. J. Bell, "The Leidenfrost Phenomenon: Film Boiling of Liquid Droplets on a Flat Plate," International Journal of Heat and Mass Transfer Vol.9:1167- 1188, 1966.

[13] H. Hiroyasu, T. Kadota, T. Senda, Transactions of Japan Society of Mechanical Engineer Vol. 39(328): 3779-3787, 1973.

[14] L.H. J. Wachters, H. Bonne, H. J. Nouhuis, "The Heat Transfer From a Hot Horizontal Plate to Sessile Water Drops in the Spheroidal State," Chemical Engineering Science Vol.21:923-936, 1966.

[15] B. S. Gottfried, K. J. Beu, De-hydrochlorination "Characteristics of Waste PVC Wires by Thermal Decomposition," Industrial & Engineering Chemistry Fundamentals Vol. 5 (4):561-568, 1966.

[16] S. Satcunanathan, Journal of Mechanical Engineering and Science. Vol.10 (5); pp: 438-441, 1968.

[17] K. J Baumeister, T. D Hamill, F. L. Schwartz, G. J. Schoessow, Chemical Engineering Progress; Set. 62(64):52-61, 1966.

[18] M. M. EI-Wakil, M.I. Abdou, Fuel: Vol.45 (3):177- 205, 1966.

[19] G. M Faeth, D. R Olson, "The Ignition of Hydrocarbon Fuel Droplets in Air," SAE Paper No. 680465, 1968.

[20] N. A. A. Henein, "Mathematical Model for the Mass Transfer and Combustible Mixture Formation around Fuel Droplets," SAE Paper No. 710221,1971.

[21] T. Kadota, H. Hiroyasu, H. Oya, Transactions of Japan Society of Mechanical Engineer Vol.41 (348):2475- 2485, 1975.

[22] M. Mizomoto, A. Morita, and S. Ikai, "Evaporation and Ignition of a Fuel Droplet on a Hot Surface, Part 3: Effects of Initial Diameter," Bulletin of JSME, Vol. 22, no.171, 1979.

[23] Omer L. Gulder, J. K. S. Wong, "Spheroidal Evaporation and Ignition of Fuel Droplets on a Hot Surface," Proceedings of the Combustion Institute, Vol.20, pp. 1751-1760, 1985.

[24] Krystyna Buda-Ortins, "Auto-Ignition of Cooking Oils," Dept. of Fire Protection Engineering, University of Maryland, 2010.

[25] W. A. Sirignano, "Fluid Dynamics and Transport of Droplets and Sprays," Cambridge University Press, 1999.