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Effect of a homogenous combustion catalyst on the combustion characteristics of single droplets of diesel and biodiesel

Mingming Zhu*, Yu Ma and Dongke Zhang
Centre for Energy
The University of Western Australia
35 Stirling Highway, Crawley, WA 6009, Australia
*corresponding author, email: zhum03@mech.uwa.edu.au

Abstract
The effect of a ferrous picrate based homogeneous combustion catalyst on the combustion characteristics of single droplets of diesel and biodiesel was studied. The experiments were performed using a high-temperature tube furnace operating at 973K and with a droplet size of 1.05mm. The results showed that the use of the catalyst shortened the burning time, improved the burning rate and increased the peak flame temperature of the droplets. Such effect was enhanced with increasing the catalyst dosing ratio but levelled off when the catalyst dosing ratio was greater than 1:1600. It was also found that the ignition delay of biodiesel was longer than that of diesel. However, the biodiesel droplets had a shorter burning time, faster burning rate and higher peak flame temperature as compared to the diesel droplets.

Keywords: homogeneous combustion catalyst combustion characteristics diesel biodiesel droplets

1. Introduction

Diesel engines are widely used in the transportation sector and heavy-duty industries because of their high efficiency and large power output capacity [1,2]. Due to ever rising petroleum price and increasingly more stringent emission regulations, there is a continuing need to develop alternative technologies to utilise diesel in a more efficient and cleaner manner. Adding homogeneous combustion catalysts into diesel is one promising technique, among others, to achieve higher engine efficiency and lower emissions [3, 4].

One type of the homogeneous combustion catalysts is organo-metallic based compounds [3], which play a catalytic role during diesel combustion within diesel engines. They are mechanically added into the diesel fuel in a very tiny amount at ppm levels to form a stable and uniform mixture before the diesel fuel is delivered into the on-board fuel tanks. The addition of such homogeneous combustion catalysts does not change the physical properties of the diesel fuel and no modifications of the diesel engines are required. A number of metal ions such as Iron [4,5, 6], Cerium [7], Platinum [8], Copper [9], Sodium [10], and Manganese [11] have proven to promote hydrocarbon combustion.

Biodiesel, which can be obtained from vegetable oil or animal fats, has been recently proposed as an alternative fuel to conventional petroleum-derived diesel fuel [12]. It is appealing for several reasons, including its lower emission of greenhouse gases, higher lubricity and lower sulphur concentration [12]. The effects of some homogeneous combustion catalysts on the performance of diesel engines fuelled with biodiesel fuels have also been studied. It was found that the use of catalysts could improve the properties of biodiesel fuel and reduce the brake specific fuel consumption and engine emissions [13,14,15].

A literature investigation has concluded that the majority of studies of homogeneous combustion catalysts have focused on the performance of diesel engines and little scientific effort has been placed on the working mechanisms of the catalysts in diesel and biodiesel combustion process. The complexity of the spray combustion of diesel or biodiesel in diesel engines make it is difficult to single out the effect of the catalyst on diesel or biodiesel combustion to be studied at a mechanistic level. Against this backdrop, a phenomenological study of combustion characteristics of single diesel and biodiesel droplets with and without a homogeneous combustion catalyst was performed in the present study.

2. Experimental Setup

The experiments of single diesel droplet ignition and combustion were carried out in the apparatus as illustrated in Fig.1. The experimental setup consists of a horizontal tube furnace with a temperature controller for providing a hot air environment, a droplet suspension system, a step motor for delivering the droplets into the furnace and a CCD camera for measuring the ignition delay time, total burnout time and flame temperature.

Caltex No.2 diesel oil and Biodiesel provided by BioWorks Australia Pty Ltd were used for experimentation. The homogeneous combustion catalyst used was a ferrous picrate based compound provided by Fuel Technology Pty Ltd, which has been found to increase the brake specific fuel consumption up to 4% and reduce engine emissions based on our own laboratory diesel engine tests. The composition of the catalyst is a ferrous picrate-water-butanol solution with various additives. These additives are mainly short-chain alkyl benzene and its derivatives, which help improve

* Corresponding author:
Phone: (+61) 8 6488 7097
Email: zhum03@mech,uwa.edu.au

the stability of the ferrous picrate-water-butanol-diesel mixture [4]. The specifications of the diesel and biodiesel oil and the catalyst are listed in Table 1. The catalyst was added into the base diesel fuel at dosing ratios of 1:6400, 1:3200, 1:1600, 1:400 (by volume), respectively.

The tube furnace was used to generate the hot ambient air of 973K into which the diesel droplets were ignited and combusted. The temperature was regulated by a temperature controller with accuracy of ±1K. A droplet was produced by a micro-syringe of 10μL in volume and deposited on the tip of a quartz fibre of approximately 200±10μm in diameter. The actual shape of the suspended droplet was elliptical and a stated droplet size refers to an equivalent value, which was determined as the cubic root of the product of droplet width squared and droplet length [16]. The droplet size used in this study was 1.05±0.02mm. The Uncertainty of the droplet size was estimated by taking five samples, which was about 2% for the tested droplet size.

The droplet suspended on the fiber was delivered into the centre of the furnace with the assistance of a step motor. The velocity of the step motor was set to 1m/s, which allowed about 0.15s to insert the droplet from the entrance to the furnace centre. A high speed CCD camera (Basler PIA-210gc) was used to capture the images of the process from the moment when the droplet entered the furnace until it burned out. The frame rate of the camera was set to 200f/s to enable accurate determination of the ignition delay time and burning time. A personal computer was used to operate the step motor and the CCD camera.

With the assistance of the video images taken by the CCD camera, the ignition delay, burning time, burning rate and the flame temperature can be calculated. The ignition delay time (t_i) was defined as the time period between the moment when the droplet passed through the entrance of the furnace and the moment when the first visible flame was observed. The burning time (t_c) was the time period between the instance when the first visible flame was observed and the completion of the droplet combustion. The back-lighted images of a droplet surrounded by a luminous flame were recorded so that the temporal droplet sizes (d_s) during the combustion process were measured to calculate the burning rate. The burning rate was determined based on the classical d^2-law of droplet combustion [17]. From the d^2-t plot, the burning rate constant was defined as $K=-d(d_s^2/dt)$ [17].

The flame temperature was determined from the two-colour pyrometry [18,19] using the optical spectra from the visual thermal imaging taken by CCD camera. This method has been recently adopted to calculate the temperature of sooty flame using the pixel intensity of the images taken by a CCD camera. Even though the absolute error of the temperature measurement by this method is about 50K [18,19], the standard deviation of the present study is only about 20K (five repetitions for all flame temperature calculation).

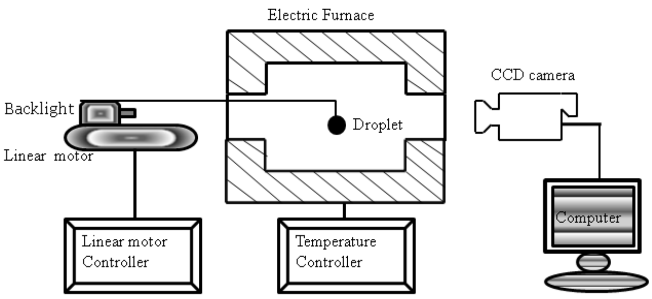

Figure 1 A schematic diagram of experimental apparatus

3. Results and Discussions

3.1 Ignition Delay and Burning Time

Figure 2 shows the effect of the catalyst on the ignition delay and burning time of both diesel and biodiesel droplets. It is seen that the addition of the catalyst into both diesel and biodiesel did not result in a measurable difference of the ignition delay. One possible reason is that the effect of the catalyst on the ignition delay was blurred by the measurement error (about 20ms in the present study). However, the use of the catalyst reduced the burning time of both diesel and biodiesel droplets. The burning time decreased with increasing the catalyst dosing ratio but this effect was levelled off when the catalyst dosing ratio was greater than 1:1600.

It is also manifested that the ignition delay of biodiesel was higher than that of diesel. This may be due to the difference in the chemical compositions between diesel and biodiesel. It is seen from Table 1 that the major components of biodiesel is C16 and C18 methyl esters. The C18 component mainly consists of one (C18:1) and two double-bonded (C18:2) methyl ester. The presence of double bond in biodiesel will reduce the cetane number and therefore increase ignition delay [20]. However, the biodiesel had a slightly shorter burning time compared to diesel fuel, which may be explained by the higher oxygen content and therefore a higher burning rate for biodiesel.

3.2 Burning rate

Figure 3 plots the temporal variation of the square of the droplet diameter, d_s, for both diesel and biodiesels with and without being dosed with the catalyst. It is seen that after an initial period of droplet heating, the d^2-law [17] is well obeyed. The burning rate constant K was also calculated and shown in Fig.3.

It is seen that the use of the catalyst improved the burning rates of both diesel and biodiesel fuel. For example, when the droplets were dosed with the catalyst at a dosing ratio of 1:3200, the burning rate was increased from 0.78mm^2/s to 0.85mm^2/s for diesel and from 0.86mm^2/s to 0.94mm^2/s for biodiesel, respectively.

It was manifested that when the catalyst dosing ratio was doubled, the burning rate did not increase proportionally. This is in accordance with the observation of the effect of the catalyst on the combustion time, as shown in Fig. 2.

It is also evident that the burning rate of biodiesel is $0.86 mm^2/s$, which is higher than that of diesel, $0.78 mm^2/s$, due to the oxygenates in the biodiesel.

3.3 Flame Temperature

Figure 4 shows the measured instantaneous peak flame temperature, as a function of time, for both diesel and biodiesel droplets, with and without the catalyst.

It is seen that the peak flame temperature reached a very high point, around 2400K, after the ignition and then decreased sharply, stayed at a constant level and then gradually decreased towards the end of the combustion process. This corresponds to the two phases of droplet combustion, which are premixed combustion just after the ignition and the succeeding quasi-steady diffusion combustion. The peak flame temperature used for the following discussion is the flame temperature when the droplet was in a quasi-steady diffusion combustion phase.

It is evident that the peak flame temperature increased with the use of the catalyst in both diesel and biodiesel fuels. For instance, at the catalyst dosing ratio of 1:3200, the peak flame temperature was increased from 1978K to 2011K for diesel droplets and from 2005K to 2032K for biodiesel droplets. However, when the catalyst dosing ratio was doubled from 1:3200 to 1:1600, the peak flame temperature was only slightly increased by about 10K.

The peak flame temperature of diesel droplets was around 1978K, which was lower than that of biodiesel droplets, at 2005K. This may help to explain the faster burning rate and shorter burning time of biodiesel droplet, as illustrated in Fig.3.

3.4 Discussion

From the observations described above, the possible mechanisms of the catalyst in both diesel and biodiesel combustion process can be explained as follows. It has found that the decomposition temperature of ferrous picrate is round 200-250°C. During the combustion process of both diesel and biodiesel droplets, when the droplet surface temperature reaches the decomposition temperature of ferrous picrate, the ferrous picrate will decompose and release iron atoms into the flame, which will promote the oxidation of the fuel vapour. This results in a higher reaction rate and an increase in the peak flame temperature of the catalyst dosed droplets. Consequently, the heat transfer to the burning droplet was enhanced by the higher flame temperature, resulting in a higher effective combustion rate and short combustion time.

4. Conclusions

The effect of a ferrous picrate based catalyst on the combustion characteristics of single diesel and biodiesel droplets was investigated. It was found the use of the catalyst shortened the burning time, increased the burning rate and the peak flame temperature of both diesel and biodiesel droplets combustion. Such effect was enhanced with increasing the catalyst dosing ratio but levelled off when the catalyst dosing ratio was greater than 1:1600. It was also found that biodiesel had a longer ignition delay but a shorter burning time, higher burning rate and peak flame temperature than that of diesel fuel.

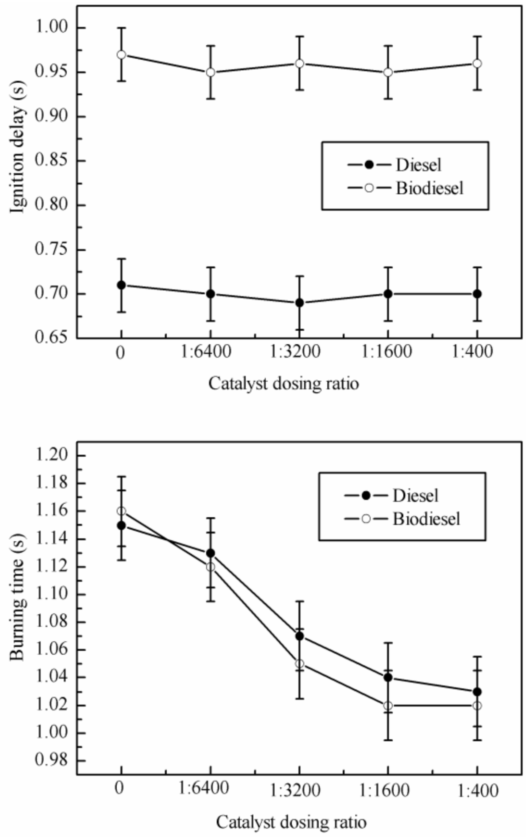

Figure 2 Effect of the catalyst dosing ratio of ignition delay and combustion time

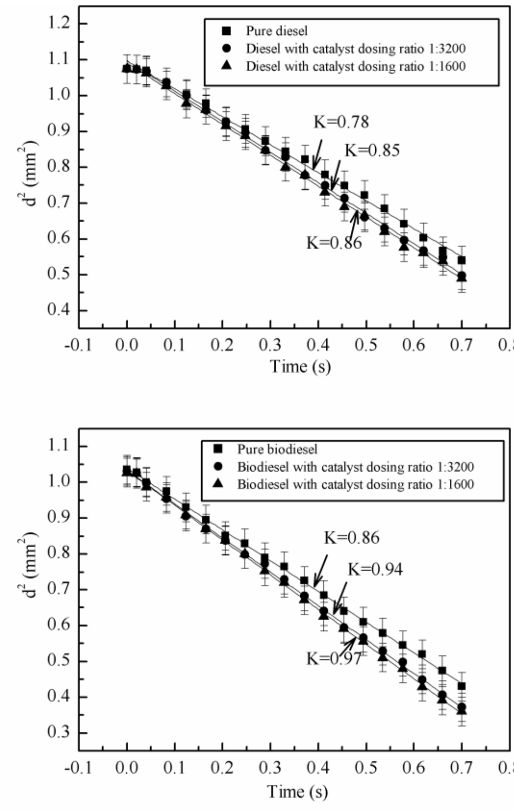

Figure 3 d^2-t plots for the droplets burning of diesel and biodiesel with and without the catalyst

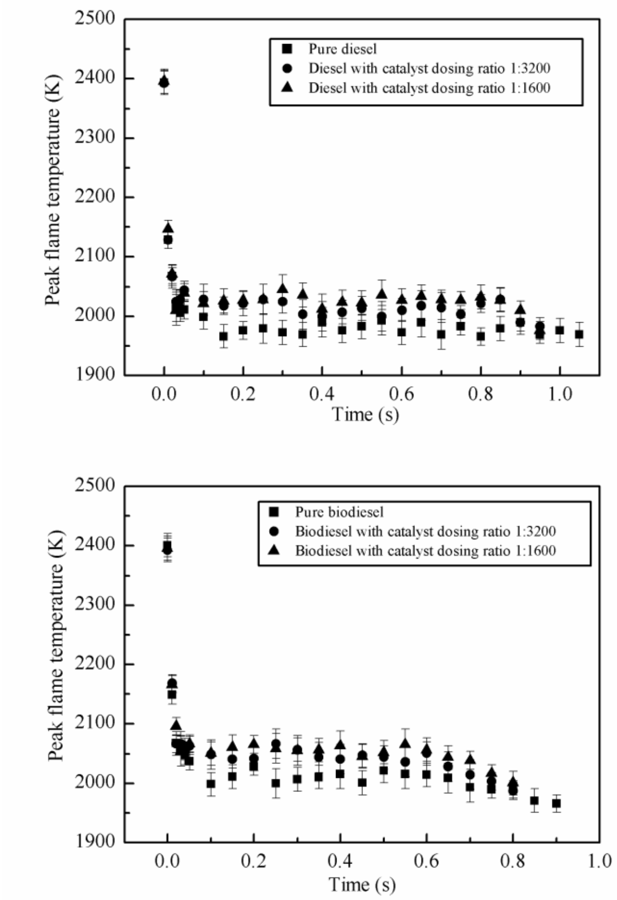

Figure 4 Effect of the catalyst on the peak flame temperature of both diesel and biodiesel droplets

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Table 1: Main chemical components and physical properties of biodiesel, diesel and catalyst

Species	[a]Component	[a]mol%	Density (g/ml) (15°C)	Boiling Point(°C)	Viscosity, cSt (40 °C)	Flash Point (°C)
	C16:0 ($C_{15}H_{31}$)$COOCH_3$	18.95%				
	C18:0 ($C_{17}H_{35}$)$COOCH_3$	5.96%				
Biodiesel	C18:1 ($C_{17}H_{33}$)$COOCH_3$	41.98%	0.878	205-443	3.42	100
	C18:2 ($C_{17}H_{31}$)$COOCH_3$	23.89%				
	C18:3 ($C_{17}H_{29}$)COOCH3	2.78%				
	<C10	8.71%				
Diesel	C10-C18	75.07%	0.845	200-400	2.02	75
	>C18	16.22%				
FTC catalyst			0.876	140-210		43

[a] GC-MS analysis