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Ignition and combustion characteristics of single droplets of a crude glycerol in comparison with pure glycerol, petroleum diesel, biodiesel and ethanol

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ABSTRACT

The ignition and combustion characteristics of single droplets of a crude glycerol were experimentally studied and compared with those of pure glycerol, a petroleum diesel, a biodiesel, and ethanol. A single fuel droplet was suspended at the tip of a silicon carbide fibre undergoing heating, ignition and combustion in an electrically heated horizontal tube furnace at an air temperature ranging from 948 K to 1048 K. The ignition and combustion behaviour of the droplet were recorded using a CCD camera. Ignition delay time, total combustion time, burning rate, and flame standoff ratio were estimated. At a same temperature, the ignition delay time and total combustion time followed the order of pure glycerol > crude glycerol > ethanol > biodiesel > diesel, while the burning rate followed the order of crude glycerol > diesel > biodiesel > ethanol > pure glycerol, suggesting that the impurities, mainly water and methanol, had a profound influence on the combustion characteristics of crude glycerol. The flame standoff ratio slightly decreased after ignition but continuously increased with time afterwards for the crude glycerol and remained almost unchanged for the pure glycerol, indicating the significant influence of impurities on the quasi-steadiness of the flame.

1. Introduction

Biodiesel, an alternative liquid transport derived from renewable sources of fatty acids such as vegetable oils and animal tallow, has become of worldwide interest, often advocated by environmental and conservation movements and special interest groups [1,2]. The global biodiesel production has increased rapidly in recent years, reaching 28.3 million metric tonnes (MMT) in 2014 [3]. A by-product of the biodiesel production process is glycerol and, with approximately 0.1 kg of crude glycerol being created for every 1 kg of biodiesel produced [4], the global crude glycerol production in 2014 was estimated to be 2.8 MMT, which is significantly greater than the glycerol market, currently at 2 MMT globally, could possibly absorb [4]. Hence, it is necessary to search for alternative uses of the overproduced glycerol.

A number of processes, such as pyrolysis, fermentation and steam reforming have been proposed to convert glycerol into products of certain values such as hydrogen [5], acrolein [6], syngas [7], and chemicals [8]. However, these conversion technologies are either expensive, or the product volume and value too low, or require large throughputs to make an economical sense, while the crude glycerol supplies are incompatibly small and scattered over different regions.

However, direct combustion of glycerol in utility boilers or internal combustion engines for combined heat and power and heat (CHP) is a plausible alternative [9]. Direct combustion of glycerol offers a few advantages over the other technologies such as simplicity, flexible scale operation, maturity, and cost effectiveness.

As an alternative fuel, glycerol has been tested for combustion using burners and diesel engines [9,10]. Pure glycerol was shown to burn effectively in a heating boiler with the use of a high-swirl refractory burner [10]. In a set of tests with a diesel engine generator rated at 43 kW, the generator fuelled with pure glycerol produced a continuous power of 41.5 kW [9]. However, the combustion of glycerol is inherently challenging due to the high viscosity, low energy density, high auto-ignition temperature, and low heating value [11].

In addition, the combustion of crude glycerol is further complicated by the impurities brought in during the biodiesel

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production process, which would be too costly to remove. The impurities include, depending on the process and operating conditions, methanol (6.2–12.6 wt%), water (6.5–28.8 wt%), soap (up to 26.5 wt%), fatty acid methyl ester (FAME) (up to 28.8 wt%), glycerides (up to 7.0 wt%), free fatty acid (FFA) (up to 3.0 wt%), as well as ash (2.7–3 wt%) [12]. Of particular note is that crude glycerol also contains high concentrations of sodium as a result of excess catalyst used in the transesterification process [12], which could have significant and adverse effect on the flame, combustion equipment, and environment [13]. Thus, in order to better utilise the glycerol as a fuel, it is important to study its ignition and combustion characteristics in comparison to those of other, better understood fuels and to especially understand the effect of the impurities on the combustion behaviour of crude glycerol.

The present preliminary experimental work was aimed to gain a fundamental understanding of the ignition and combustion behaviour of single droplets of crude glycerol and compare them with those of several well studied liquid fuels including diesel biodiesel and ethanol. The experimentation was performed by suspending single droplets in hot air in an electrically heated furnace. The ignition delay time, combustion time, burning rate, and flame standoff ratio were determined with the aid of a CCD camera imaging technique. The effect of air temperature on the ignition and combustion characteristics was studied. This approach would provide a useful means to understand the combustion characteristics of glycerol, which would ultimately lead to better use of crude glycerol in combustion applications. The results would shed light on the feasibility of utilising crude glycerol in diesel engines for power generation as one of the simplest and easiest means of crude glycerol utilisation. Since diesel, biodiesel and ethanol are well studied for their application in diesel engines [14–16], comparing the ignition and combustion characteristics of crude glycerol against these fuels will also provide essential guidance in utilising glycerol in diesel engines.

2. Experimental

Employed in the current study were pure glycerol and ethanol acquired from Sigma Aldrich (Perth Australia), a crude glycerol and biodiesel provided by Wilmar International (Gresik, Indonesia) and a petroleum diesel (Caltex No.2) obtained from a local service station. The chemical compositions and physical properties of these fuels are shown in Table 1 and the composition of the crude glycerol is listed in Table 2.

Table 2
The properties of crude glycerol.

	(wt%)
Composition	
Free glycerol	68.2
Methanol	2.2
Water	22.6
Soap	1.3
Fatty acid methyl ester (FAME)	0.5
Free Fatty Acids (FFA)	1.8
Ash	3
Elemental analysis	
C	31.85
H	10.25
N	0.32
Na	0.76
P	0.11
S	0.02

The ignition and combustion behaviour of these fuels were studied using a single droplet combustion technique as schematically shown in Fig. 1 and described elsewhere [20,21]. Briefly, the experimental set-up consists of a droplet suspension system, a horizontal tube electric furnace (600 mm in length and 40 mm in diameter) with temperature control for providing a hot air environment, a step motor for delivering the droplet into the furnace, and a CCD camera for capturing the images.

In a typical experimental run, the furnace was preheated to a desired temperature from 948 K to 1048 K, the typical combustion temperatures in diesel engines. A droplet was produced by a micro pipette of 10 μL and was deposited on the tip of a silicon carbide fibre of 0.142 mm in diameter. Aided by the step motor, the droplet was transported to the centre of the furnace at a linear velocity of 1 ms^{-1}. The high speed CCD camera with an exposure time of 1000 μs (50 fps) captured the time-sequenced images of the droplet during its ignition and combustion process. The step motor and camera were controlled from a computer. In order to capture the evolution of the droplet size, a halogen lamp was used to backlit the images of the burning droplet. Note that when the droplet was attached to the tip of the silicon carbide fibre, it was deformed to an ellipsoidal shape due to gravity. The equivalent droplet diameter was determined from the height (d_{max}) and width (d_{min}) of the droplet measured from the CCD images according to the following equation [22,23]:

Table 1
Key physical and thermodynamic properties of fuels tested.

Fuel property	Fuels				
	Crude glycerol	Pure glycerol	Biodiesel	Diesel	Ethanol
Formula	n/a	$C_3H_8O_3$	n/a	n/a	C_2H_6O
Molecular weight (g mole^{-1})	n/a	92.09	~308	~200	46.07
Density (kg m^{-3})	1205[a]	1261[a]	878[a]	840[a]	789[a]
Heating value (MJ kg^{-1})	14.84[a]	18[a]	42.2[a]	44.8[a]	29.7[a]
Boiling point (K)	403[a]	563[a]	628[a]	533[a]	350[a]
Cetane number	~6.7	5	51.7	52	12
Heat of vaporisation (MJ kg^{-1})	n/a	0.67	0.30	0.34	0.92
Viscosity (mPa s)	1200[a]	1500[a]	3.42[a]	2.02[a]	1.144[a]
Auto-ignition temperature (K)	673[a]	796[a]	646[a]	588[a]	638[a]
Flash point (K)	463[a]	450[a]	422[a]	328[a]	282[a]
Specific heat capacity (kJ kg^{-1})	~2.8	2.43	2.2	1.8	2.72
Thermal conductivity (Wm^{-1} K^{-1})	n/a	0.2900	0.1490	0.1169	0.2040
Adiabatic flame temperature (K @973 K)	n/a	2201	2291	2413	2078
Stoichiometric fuel/air ratio (w/w)	n/a	5	11	12	9
Spalding number	n/a	4	9	8	3

[a] Indicates that the data were measured by the authors. The other data were taken from the literature [17–19].