International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 1
ISSN: 2088-5334

The Effect of Fatty Acid Composition on Combustion Characteristics of Vegetable Oils

Muhaji [a,*], I. N. G. Wardana [b]

[a] Department of Mechanical Engineering, Universitas Negeri Surabaya, Campus Ketintang, Surabaya, 60231, Indonesia
[b] Department of Mechanical Engineering, Universitas Brawijaya, Jl. Mayjen Haryono 167, Malang, 65145, Indonesia
Corresponding author: *muhaji61@unesa.ac.id

***Abstract*— Vegetable oil is triglyceride molecules consisting of glycerol with three carbon chains as the backbone and three branches of fatty acids. Fatty acid molecules contain carboxylic acid and methyl ester (biodiesel). The properties of methyl esters from vegetable oils are almost similar to those of diesel oil. Therefore, fatty acids are a good potential source for diesel oil. This study aims to elucidate the effect of fatty acid composition on the combustion characteristics of vegetable oil. In this study, the combustion characteristics of the oil were observed experimentally by burning a single droplet on a heated stainless-steel plate. The results show that vegetable oil is burned in three stages: burning unsaturated fatty acids, saturated fatty acids, and glycerol at the first, second, and third stages, respectively. Compared to *ceiba pentandra*, cotton, and coconut oils, the combustion characteristics of *jatropha curcas linn* oil resemble most of the diesel oil. The burning of *ceiba pentandra* oil has two small explosions, while *jatropha curcas linn*, cottonseed, and diesel oils have only one small explosion, and no explosion occurs during the coconut oil burning. Unsaturated fatty acids and glycerol are highly explosive. The burning rate of the vegetable oil droplet is influenced by the flashpoints, fatty acid content, and dissociation energy of fatty acid bonds. The larger the number of the unsaturated fatty acid component, the higher the burning rate of the oil.**

***Keywords*— Vegetable oils; fatty acid composition; flame; three-stage combustion; explosion.**

Manuscript received 12 Dec. 2020; revised 25 Feb. 2021; accepted 7 Jun. 2021. Date of publication 28 Feb. 2022.

I. INTRODUCTION

Vegetable oils, in general, are triglyceride molecules consisting of glycerol with three carbon chains as the backbone and three branches of fatty acids. Fatty acids are a good potential source for diesel oil. Fatty acid molecules contain carboxylic acid (COOH) and methyl ester (CH_3) [1]–[7]. The properties of methyl esters from vegetable oils are almost similar to those of diesel oil [3]. When methyl esters (biodiesel) of vegetable oil are mixed with diesel oil for combustion in a DI engine, the emission of CO, HC, and SOx decreases [8]–[15], and it works very well in diesel engines. In addition, it can be noted that it has some significant features of which the higher flash point, higher cetane number, and higher oxygen content will be [8]. The combustion for biodiesel-diesel blends in a DI engine significantly reduces the particulate matter (PM) emissions from the diesel engine in terms of the emissions of nitrogen oxides (NOx), soot, and smoke [10]–[14]. The higher the biodiesel blend, the temperature of the combustion chamber will lower the exhaust gas temperature at the end of the chimney, which is likely to increase [13].

There have been several studies about methyl ester fatty acid as an additive to fuel [16]. The findings showed that oleic acid from coconuts is oxidized more rapidly than myristic and stearic acids. The methyl ester (biodiesel) reduces fuel-burning efficiency, power, torque, and thermal efficiency [9], [15], [17]. However, the specific fuel consumption increased. Other researchers [18]–[20] found that the addition of methyl esters-diesel blends up to B30 decreases the engine efficiency and could be used to replace diesel oil without modifying diesel engines.

It is believed that the fundamental combustion characteristics of vegetable oils as fuel additives in diesel engines should be intensively studied. High boiling point differences in propanol and glycerol combustion at a low gravity condition may cause flame contraction and micro explosion [21]. Therefore, it is predicted that such micro explosion also occurs in vegetable oils because they contain fatty acids and glycerol, which have very high different boiling and flashpoints. Furthermore, three long chains of fatty acid are connected to glycerol as combustion characteristics of vegetable oils are very different from those of propanol and glycerol mixture. Moreover, water from burned vegetable oils causes a hydrolysis reaction that breaks up triglyceride molecules into fatty acids and glycerol. In addition, the fatty acids and glycerol will burn separately and have different burning times [1]. While another research shows the role of magnetic field orientation in vegetable oil premixed combustion, showing that the magnetic field increased the laminar burning velocity [22]. In addition, the combustion of pure *jatropha curcas linn* oil, hydrolyzed *jatropha curcas linn* oil, and methyl ester *jatropha curcas linn* occurred in three stages, two stages and one stage, respectively [23]. One explosion occurred in the *pure jatropha curcas linn* oil due to its high unsaturated fatty acid content. The combustion of jatropha oil droplet performs two steps of combustion; fatty acid burned in the first step and glycerol in the second step [1], [4], [7]. The on set of micro-explosion occurs shortly before the second step of combustion, and it becomes more frequent as the oil temperature increases. Thus, this study aims to elucidate the combustion characteristics of vegetable oils (*ceiba pentandra, jatropha curcas linn*, cotton, and coconut oils), which are important as the major alternative source of fuel.

II. MATERIALS AND METHODS

A. The Chemical Structure and Properties of Vegetable Oil

Vegetable oil is composed of triglyceride molecules consisting of glycerol with three carbon chains as the backbone and three branches of fatty acids with 18 or 16 carbon chains. Most triglyceride molecules contain atoms of carbon and hydrogen with only six oxygen atoms per molecule which means the contents of vegetable oils are similar to those of petroleum hydrocarbons. Therefore, vegetable oil is a good alternative fuel source, and triglyceride is eminently suitable as the fuel. During combustion, triglyceride is hydrolyzed from the ester. The hydrolysis reaction yields glycerol and three fatty acids, which are carboxyl acids.

The chemical composition of the vegetable oil was tested by Gas Chromatography (GC), and the results are shown in Table 1. The dominant components in *ceiba pentandra* oil are linoleic, palmitic, and oleic fatty acids and glycerol. *jatropha curcas linn* oil has oleic, linoleic, lauric, palmitic, and stearic fatty acids. Meanwhile, cotton oil has oleic, linoleic, palmitic, and stearic fatty acids, and coconut oil has lauric, myristic, palmitic, and oleic fatty acids.

TABLE I
CHEMICAL COMPOSITION OF VEGETABLE OILS

Chemical Composition Types		**Chemical Formulas**	**Chemical Bond Structures**	**Flash Points (°C)**	**Chemical Oil Compositions (%)**			
					***Ceiba pentandra* Oil**	***Jatropha curcas Linn* Oil**	**Cotton Oil**	**Coconut Oil**
Saturated Fatty Acids	Caprylic	$CH_3(CH_2)_6COOH$	8:0	176	-	1.70	-	3.07
	Capric	$CH_3(CH_2)_8COOH$	10:0	181	-	1.66	-	3.59
	Lauric	$CH_3(CH_2)_{10}COOH$	12:0	185	-	7.71	0.54	31.43
	Myristic	$CH_3(CH_2)_{12}COOH$	14:0	196	-	5.29	0.98	13.26
	Palmitic	$CH_3(CH_2)_{14}COOH$	16:0	201	22.50	11.45	21.13	9.32
	Stearic	$CH_3(CH_2)_{16}COOH$	18:0	206	7.67	3.16	7.32	4.50
	Arachidic	$CH_3(CH_2)_{18}COOH$	20:0	208	-	-	-	0.09
Unsaturated Fatty Acids	Oleic	$CH_3(CH_2)_7CH{=}(CH_2)_8COOH$	18:1	80	19.38	30.38	20.14	17.51
	Linoleic	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$	18:2	77	36.62	32.23	43.09	9.69
	Linolenic	$CH_3(CH_2)\ (CH{=}CHCH_2)_3CH_2)_6COOH$	18:3	61	1.20	-	-	0.05
	Eicosanoic	$CH_3(CH_2)_5CH{=}CH(CH_2)_{11}COOH$	20:1	85	-	-	-	0.05
Glycerol		$C_3H_5(OH)_3$	3:0	345	9.87	3.94	4.32	3.54
Gum Water		$C(CH_2OH)_4$	5:0	275	2.69	2.02	2.12	3.89
		H_2O	-	-	0.06	0.45	0.36	0.05
Total Saturated Fatty Acids					30.27	30.97	29.97	65.26
Total Unsaturated Fatty Acids					57.20	62.61	63.23	27.25
Total Fatty Acids					87.37	93.58	93.20	92.51

Table 1 shows that *ceiba pentandra* oil comprises 30.17% saturated fatty acid, 57.20% unsaturated fatty acid, and 9.87% glycerol. The *jatropha curcas linn* oil composition is 30.97% saturated fatty acid, 62.61% unsaturated fatty acid, and 3.94% glycerol. Cotton oil consists of 29.97% saturated fatty acid, 63.23% unsaturated fatty acid, and 4.32% glycerol. Meanwhile, the composition of coconut oil is 65.26% saturated fatty acid, 27.25% unsaturated fatty acid, and 3.54% glycerol. Flashpoint of the vegetable oils increases with the increase of saturated fatty acid content. The flashpoint of saturated fatty acids and unsaturated fatty acids varies from 176°C-208°C and 61°C-85°C, respectively, whereas the flashpoint of glycerol is 345°C because saturated fatty acids have a single bond on their hydrocarbon chain; it is a zigzag, which can pair acids causing strong Van Der Waals attraction force between molecules. It needs more energy to separate the molecules, so that the melting point and flash point of saturated fatty acids are high. Unsaturated fatty acids have one or more double bonds in their hydrocarbon chains. The double bond will react easily with oxygen. The Van Der Waals attraction force between the molecules decreases with the number of unsaturated molecules in fatty acids. It needs less energy to break up the molecules, so its melting point and flash point are lower. The position of a double bond determines the power of the reaction. Reaction with oxygen will easily occur when the double bond gets closer to the tip so that the unsaturated molecule becomes more flammable, whereas glycerol has very strong hydrogen bonds between the molecules. This causes very strong Van Der Waals attraction forces between the molecules; thus, the melting point and flash point are very high.

The main physical properties (density, kinematic viscosity, flash point, heating values, and pH) of vegetable oils and diesel oil are shown in Table 2.

TABLE II
PHYSICAL PROPERTIES OF VEGETABLE OILS AND DIESEL OIL

Properties	**Methods**	**Instruments**	**Models**	**Value**				
				***Ceiba pentandra* Oil**	***Jatropha curcas Linn* Oil**	**Cotton Oil**	**Coconut Oil**	**Diesel Oil**
Density to T=30°C (kg/m³)	D1298	Hydrometer	Nikki, Japan	974	921	955	936	849
Kinematic Viscosity to T=30°C (cSt)	D445	Kinematic Viscometer	Leybold Didactic, Germany	45.55	35.48	41.65	55.55	7.05
Flash Point (°C)	D93	Pensky-Martens Closed Cup Tester	Leybold Didactic, Germany	260	240	250	265	60
Heating Value (kcal/kg)	D240	Bomb Calorimeter	Parr Instrument UAS	9700.56	9860.25	9335.87	9698.97	11307.25
pH	D6423	pH Tester	HANNA Instrument UAS	5.0	4.5	4.0	6.0	6.6

B. Experimental Apparatus and Measurement Techniques

The experiments were performed using experimental apparatus which is schematically shown in Fig. 1. Vegetables were dripped on a heated stainless-steel plate. The plate thickness was 0.3 mm, and its diameter was 35 mm. The plate was heated from below by a heater to a temperature of 270°C. The measurement of the plate temperature was carried out with a thermocouple and data logger with a measurement range of -200°C to 1372°C and accuracy of ± 0.35°C. The distance from the thermometer to the heated plate was about 300 mm. Vegetable oil droplets had an initial diameter of 1.75 mm at room temperature. Droplet diameter and flame dimension were measured using the ImageJ program. The flame image was recorded with a high-speed Casio ZR 200 camera at 420 frame/s. Data of flame images were captured by a CCD camera connected to a VCR, and then the VCR data were transferred to the JPG converter program, which gave the final image files in the process sequential data reduction. ImageJ program was utilized to identify the flame height and width. The oil droplet burning time was determined by the number of recorded frames multiplied by the time period between each frame, i.e., 0.00238 s.

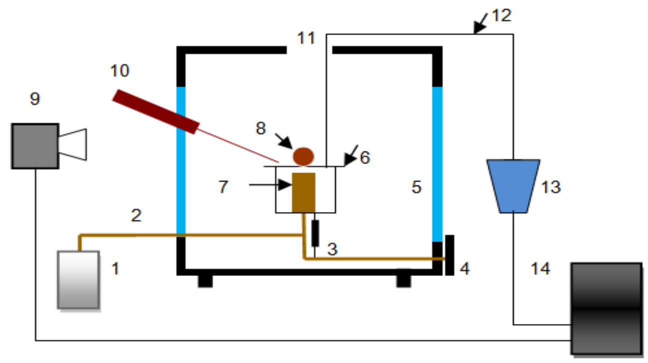

Fig. 1 Experimental apparatus: (1) lpg, (2) gas house, (3) lighters, (4) on/of, (5) combustion chamber with glass walls, (6) stainless steel plate, (7) heater, (8) vegetable oil droplet, (9) ccd camera, (10) micropipette, (11) the smoke exhaust, (12) thermocouple, (13) data logger, and (14) computer

The oil droplet burning rate was determined from the volume of the droplets divided by burning time. The flame explosion was visualized from the evolution of the flames, and the explosion time was obtained from the flame evolution images in the frames multiplied by the time of each frame, i.e., 0.00238 s. All measurement data show the same trend indicating that an oil droplet burns in three stages.

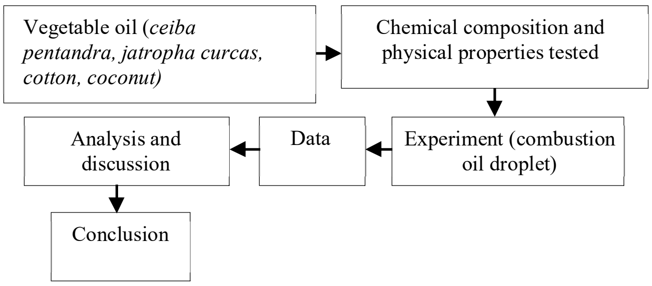

Fig. 2 Flow chart of the research

III. RESULT AND DISCUSSION

A. The Burning Stages

Figs. 3, 4, 5, and 6 show the combustion stages of vegetable oil. The results are compared with diesel oil, as seen in Fig. 7. The flame size evolution of vegetable oil droplets is shown in Figs. 8, 9, 10, and 11, compared with the flame size evolution of diesel oil in Fig. 12. Fig. 3 until Fig. 12 shows that the vegetable oil combustion process has different flame characteristics from diesel oil. Vegetable oils burn in the combustion stage of unsaturated fatty acids, saturated fatty acids, and glycerol. Unsaturated fatty acids (monounsaturated and polyunsaturated fatty acids) are burned in the first stage since it has the lowest flashpoint, then the saturated fatty acids are burned in the second stage because its flash point is higher, and glycerol is burned in the third stage for the highest flash point (Table 1). On the other hand, diesel oil burns completely within a very short time in one stage. The influence of the flashpoint on the combustion time has been reported by Wardana *et al.* [2] and Xu *et al.* [24] that the decrease of the oil flash point reduces the combustion time. The unsaturated fatty acids were reported to have a faster reaction rate, making them burn earlier. A similar result of multi-stage combustion for vegetable oil was also reported by Wardana *et al.* [1], which explained that *Jatropha curcas linn* oil burns at the junction of thermocouples undergoing two-stage combustion;

fatty acids are burned in the first stage, and then glycerol is burned in the second stage. On the other hand, it is explained that in the combustion of cottonseed oil and *jatropha* oil, there is one combustion stage in the cottonseed oil and four combustion stages in jatropha oil [25]. Diesel oil combustion, however, is completed in merely one stage because it contains olefin, aromatics, and paraffin hydrocarbons, which are unstable, highly reactive, having low flash points and a lot quicker combustion. The constituent components of vegetable oils have hugely different value of the flash and boiling points as well as reactive properties. The constituent components burn individually and require a longer time. Figs. 3 to 10 also reveal that oils with a lower unsaturated fatty acid content have the darkest flame color (weaker luminosity) and the longest combustion time. This fact indicates that unsaturated fatty acids in vegetable oil are highly reactive.

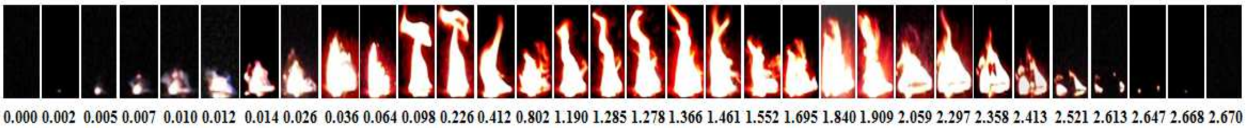

Fig. 3 Flame evolution of ceiba pentandra oil (s)

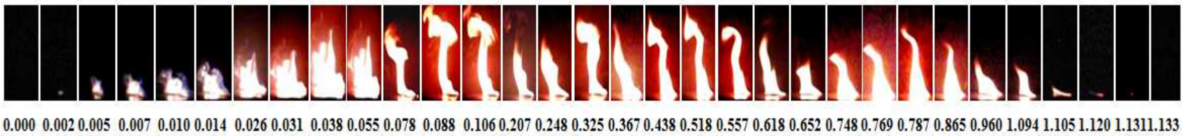

Fig. 4 Flame evolution of jatropha curcas linn oil (s)

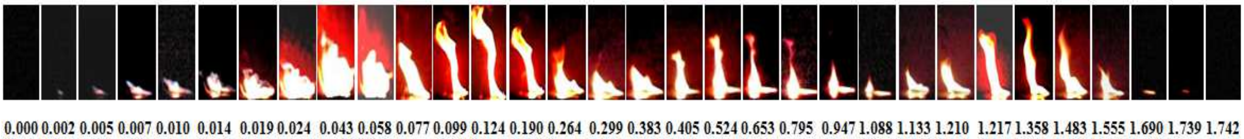

Fig. 5 Flame evolution of cotton oil (s)

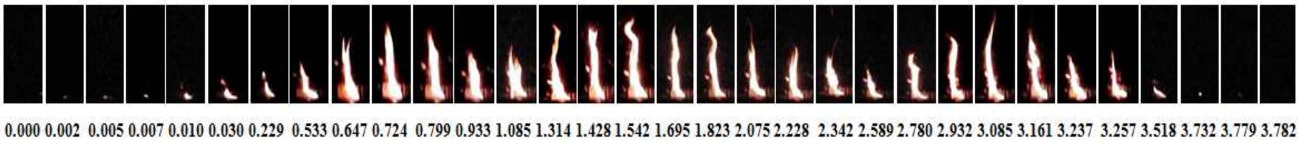

Fig. 6 Flame evolution of coconut oil (s)

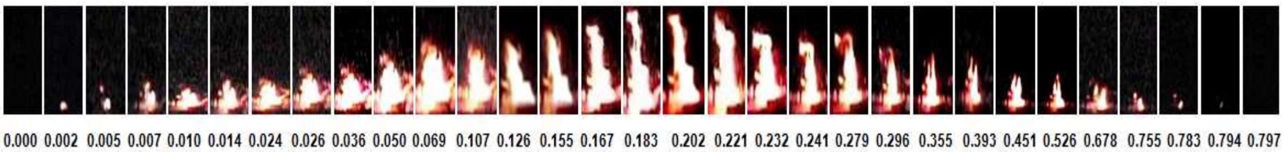

Fig. 7 Flame evolution of diesel oil (s)

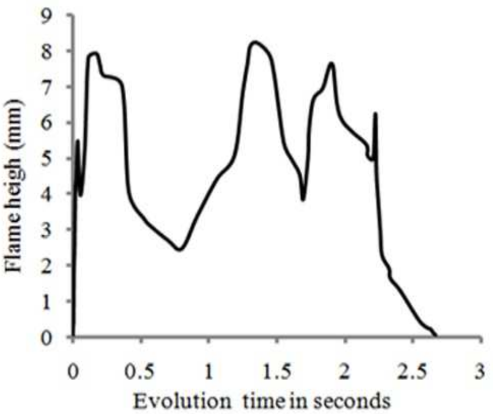

Fig. 8 Flame height evolution of *ceiba pentandra* oil (mm)

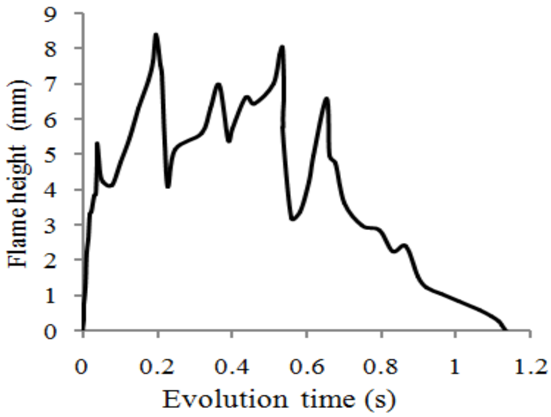

Fig. 9 Flame height evolution of *jatropha curcas linn* oil (mm)

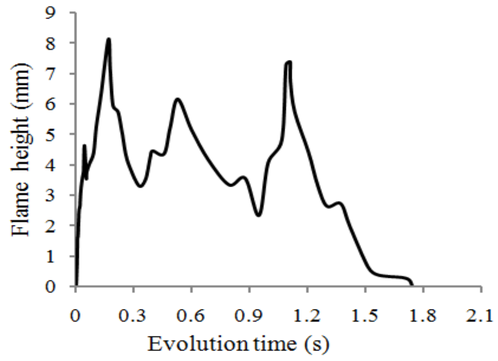

Fig. 10 Flame height evolution of cotton oil (mm)

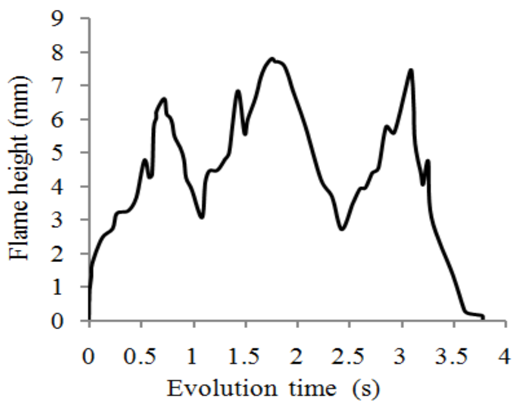

Fig. 11 Flame height evolution of coconut oil (mm)

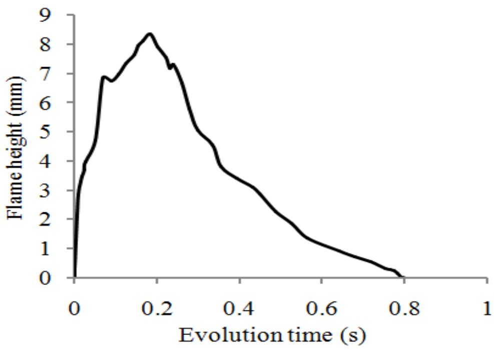

Fig. 12 Flame height evolution of diesel oil (mm)

B. The Explosion Mechanism

The explosion mechanism of the vegetable oil droplets burned on the hot stainless steel plate was recorded by means of a high-speed CCD Camera and is shown in Figs. 13, 14, 15, and 16. Fig. 17 shows the flame width of vegetable oils compared to that of diesel oil. The sudden enlargement of the flame indicates a flame explosion. The explosion of vegetable oil is caused by unsaturated fatty acids and glycerol, whereas, in diesel oil, it is caused by unsaturated hydrocarbons. For *ceiba pentandra* oil (Figs. 13 and 17), two small explosions occurred at 0.036th and 1.840th seconds, respectively. In *jatropha curcas linn* oil (Figs. 14 and 17), one small explosion took place at the 0.038th second. Cotton oil (Figs. 15 and 17) had one small explosion lasting for 0.043 second. Table 1 shows that *ceiba pentandra* oil contains 57.20% unsaturated fatty acid and 9.87% glycerol; *jatropha curcas linn* oil consists of 62.61% unsaturated fatty acid and 3.94% glycerol, and then cotton oil consists of 63.23% unsaturated fatty acid and 4.32% glycerol. The first explosion at *the ceiba petandra* was caused by unsaturated fatty acids, while the second explosion was caused by high glycerol contents (9.87%). This is because unsaturated fatty acids and glycerol are unstable and highly reactive at high temperatures; both of them are highly explosive. On *jatropha curcas linn*, cotton, and coconut oils, glycerol combustion did not spark the second explosion because their glycerol contents were relatively small.

When vegetable oil burns, its water content hydrolyses the oil to break up into glycerol and fatty acids. For coconut oil (Fig. 17), the explosion did not occur, as it consists of very, little 27.25% of unsaturated fatty acids and 65.26% of saturated fatty acid (Table 1). A saturated fatty acid is stable with a high flashpoint. Besides, it burns slowly. Diesel oil (Figs. 16 and 17) has one small explosion, much smaller than that of vegetable oils lasting for 0.069s. It is seen from figure 16 that *jatropha curcas linn* oil flame characteristics most closely resemble those of diesel oil. The combustion of diesel oil was enhanced by its high content of 75% unsaturated hydrocarbons (aromatic hydrocarbon and olefin hydrocarbon). Aromatic and olefin hydrocarbons are unstable and highly reactive. Wardana *et al.* [1], Wang *et al.* [7], and Muhaji *et al.* [23] have found that in *jatropha curcas linn* oil, micro explosions occurred between the first step combustion of fatty acids and the second step burning of glycerol. Explosions were also reported when glycerol and propanol burned at low gravity [24].

C. Burning Rate

The rates of vegetable oil combustion compared to diesel oil are shown in Fig. 17. The combustion rate occurred sequentially from high to low, starting from *jatropha curcas linn* oil at 0.00248 cc/s, cotton oil at 0.00161 cc/s, *ceiba pentandra* oil at 0.00105 cc/s, and coconut oil at 0.00074 cc/s, respectively. Meanwhile, diesel oil has a combustion rate of 0.00352 cc/s. The burning rate of vegetable oil is influenced by several factors, such as flash point of fatty acids (Table 1), unsaturated fatty acid content, and dissociation energy of fatty acid bonds. The burning rate of vegetable oil increases with the decrease of the flashpoint of the fatty acids; its value also increases with the increase of the unsaturated fatty acid content. Third, vegetable oils with more unsaturated fatty acid content have less dissociation bond energy so that the chemical bonds can break up easily, and the oil flammability is greater.

Fig. 13 The explosion flame of *ceiba pentandra* oil, (a) first explosion and (b) second explosion (s)

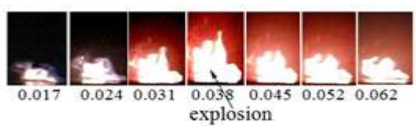

Fig. 14 The explosion flame of jatropha curcas linn oil (s)

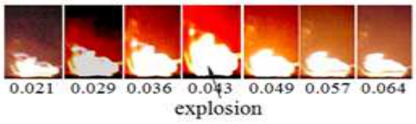

Fig. 15 The explosion flame of cotton oil (s)

Fig. 16 The explosion flame of diesel oil (s)

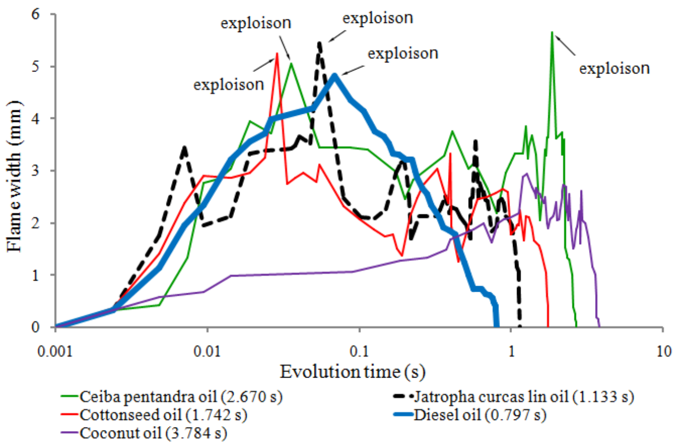

Fig. 17 Flame width of vegetable and diesel oils (s)

IV. Conclusion

The experiments concerning vegetable oil droplet combustion on a hot stainless-steel plate recorded by the high-speed camera allow some conclusions. First, the vegetable oil is burned in three stages: the burning of unsaturated fatty acids saturated fatty acids, and glycerol at the first, second, and third stages. Compared to *ceiba pentandra*, cotton, and coconut oils, the combustion characteristics of *jatropha curcas linn* oil resemble most of the diesel oil. The burning of *ceiba pentandra* oil has two small explosions, while *jatropha curcas linn*, cottonseed, and diesel oils have only one small explosion, and no explosion occurs during the coconut oil burning. The burning rate of the vegetable oil droplet is influenced by the flashpoints, fatty acid content, and dissociation energy of fatty acid bonds.

Acknowledgment

This experiment is part of the Competitive Research Grant funded by the Ministry of Research, Technology and Higher Education, Republic of Indonesia. We thank the Government of Indonesia for the financial support of this research.

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