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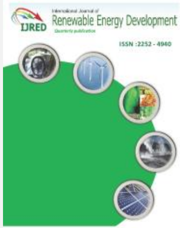

Premixed Combustion of Kapok (*ceiba pentandra*) seed oil on Perforated Burner

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ABSTRACT: Availability of fossil fuels in the world decrease gradually due to excessive fuel exploitation. This situations push researcher to look for alternative fuels as a source of renewable energy, one of them is kapok *(ceiba pentandra)* seed oil. The aim this study was to know the behavior of laminar burning velocity, secondary Bunsen flame with open tip, cellular and triple flame. Premixed combustion of kapok seed oil was studied experimentally on perforated burner with equivalence ratio (φ) varied from 0.30 until 1.07. The results showed that combustion of glycerol requires a large amount of air so that laminar burning velocity (S_L) is the highest at very lean mixture (φ =0.36) in the form of individual Bunsen flame on each of the perforated plate hole. Perforated and secondary Bunsen flame both reached maximum S_L similar with that of ethanol and higher than that of hexadecane. Slight increase of φ decreases drastically S_L of perforated and secondary Bunsen flame. When the mixture was enriched, secondary Bunsen and perforated flame disappears, and then the flame becomes Bunsen flame with open tip and triple flame (φ = 0.62 to 1.07). Flame was getting stable until the mixture above the stoichiometry. Being isolated from ambient air, the S_L of perforated flame, as well as secondary Bunsen flame, becomes equal with non-isolated flame. This shows the decreasing trend of laminar burning velocity while φ is increasing. When the mixture was enriched island (φ = 0.44 to 0.48) and petal (φ = 0.53 to 0.62) cellular flame take place. Flame becomes more unstable when the mixture was changed toward stoichiometry.

Keywords: cellular flame, glycerol, kapok (*ceiba pentandra*) seed oil, perforated flame, secondary Bunsen flame with open tip, triple flame

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1. Introduction

Availability of fossil fuels in the world decrease gradually due to excessive fuel exploitation. It occurs because of increasing need for conventional energy, in line with population growth at all of their activities. This situations push researcher to look for alternative fuels as a source of renewable energy, one of them is kapok *(ceiba pentandra)* seed oil.

Kapok is a tropical tree belongs to order malvales and family Malvaceae. The word *kapok* is used to refer fiber and seeds. Kapok fiber has the characteristics of a large lumen and the hydrophobic-oleophilic so suitable for use as (i) an absorbent to remove methylene blue from aqueous solution (Shim *et al.* 2013), (ii) absorption of the oil and separator filter of oil with water (Lim *et al.* 2007; Abdullah *et al.* 2010; Wang *et al.* 2012), (iii) removal of hazardous material because it has a uniform morphology (Hwang *et al.* 2013). Waste of kapok seed husks could be used as activated carbon to remove copper, cadmium (Rao *et al.* 2006) and lead, zinc (Rao *et al.* 2008) in aqueous solution.

Kapok seed oil (KSO) is one of the non-edible biodiesel feedstock that needs to be developed in

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Indonesia. KSO biodiesel when used directly would not meet the requirements of Standard Biodiesel Indonesia, because it contains cyclopropenoid group. Cyclopropenoid is a reactive group that is easy to polymerize, making biodiesel viscous and thus could clog of fuel injection nozzle for diesel engine (Hudaya *et al.* 2013). Trans-esterification process of KSO produces *ceiba pentandra* methyl ester (CPME) which is used to improve the properties of biodiesel such as viscosity, density, flash point, heating value and oxidation stability so that meet of biodiesel standard ASTM D6751 is recommended. Oxidation stability could be improved by means of biodiesel blended with petrodiesel that meet the standard EN 14214 (Silitonga *et al.* 2013; Ong *et al.* 2013). Biodiesel of CPME qualified SNI 047182-2006 standards are also produced from the trans-esterification with using naturally potassium hydroxide catalyst (Handy *et al.* 2013). Biodiesel optimal results were obtained by two-step acid-based trans-esterification. Biodiesel conversion of 99.5% obtained in optimum conditions of 1.0 wt. % KOH (catalyst concentration) and ratio molar of oil to methanol 6:01 (volume ratio) at a temperature of 65^{o}C for reaction time of 45 minutes. The properties of fuel in accordance with the limits specified ASTM D6751 standards (Sivakumar *et al.* 2013). KSO biodiesel production could also be done through supercritical methanol trans-esterification process. The optimum reaction conditions for supercritical methanol trans-esterification of KSO to produce biodiesel is as follows: the molar ratio of oil to methanol is 30:1, temperature is 322 °C, pressure is 16.7 MPa, and a reaction time is 476 seconds, with the results of fatty acid methyl ester (FAME) is 95.5% (Ong *et al.* 2013). So far, more KSO was used as a non-premixed combustion. Engine running with kapok methyl ester (KME) was investigated experimentally. The thermal efficiency of the engine at B25 mixture is higher than conventional diesel by 4% and the resulting exhaust emissions such as HC, CO, NO and smoke is similar (Vedharaj *et al.* 2013).

The research of vegetable oil combustion is commonly focused on non-premixed combustion. The results are applicable only for diesel engine. In order to extend the vegetable oil application, such as for spark ignition engine, study on premixed combustion of vegetable oil needs to be undertaken. Premixed combustion research using vegetable oil is still limited, especially in KSO. Thus, the premixed combustion research using KSO becomes important. However, KSO needed to be evaporated before it could be used in premixed combustion.

KSO is very interesting to be studied because of the hygroscopic glycerol and fatty acids that have different properties. Both of these will affect flame behavior in premixed combustion such as laminar burning velocity, Bunsen flame with open tip, cellular and triple flame.

Researches on premixed combustion were mostly done using conventional fuels. Laminar burning velocity was measured with variation at equivalence ratio, initial pressure, preheating temperature by using a natural gas-air mixture (Liao *et al.* 2004). Cylindrical burner was used on the experiment of Bunsen flame with open tip when hydrogen-methane-nitrogen mixture at varying concentrations ratio was diluted using inert gas (Ishizuka *et al.* 1982). Lewis numbers less than one was caused by thermal diffusion and a hydrodynamic instability so that cellular flame occurred (Kadowaki 2005). Co-flow type was used to see triple flame with different equivalence ratio of the reactants flow on inner and outer burner (Sahu *et al.* 2009).

This paper discusses the behavior of laminar burning velocity, secondary Bunsen flame with open tip, cellular and triple flame using KSO, which provide wider theoretically benefits in the premixed combustion of vegetable oils.

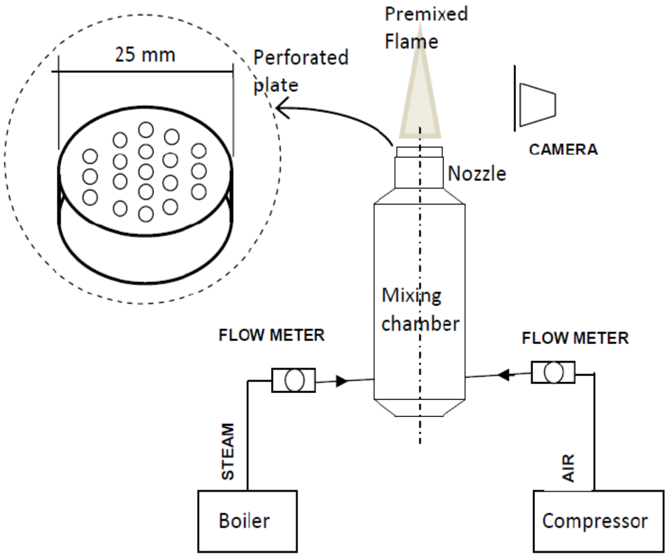

Fig. 1 Experimental apparatus

2. Experiments

KSO premixed combustion was studied experimentally using experimental apparatus shown schematically in Fig.1. Boiler were used for evaporating KSO with constant steam temperature at 160^0C. The oil from evaporating process was mixed with air from compressor in mixing chamber at equivalent ratio (φ) varied from 0.30 to 1.07. The reactant mixture then flows into the nozzle before ignited in order to form premixed flame at perforated plate installed above the nozzle.

The function of perforated plate was to utilize thermal contact resistant in preserving temperature distribution which is more uniform in entire plate surface and to stabilize the uniformity flow for KSO with air during combustion. Perforated plate was designed from steel with 19 holes. The each hole was set with 2.5 mm diameter and 3.75 mm distance between them.

The flame image was captured by camera in two experimental conditions: (1) premixed flame of KSO in contact with surrounding air (2) premixed flame of coconut oil shielded from surrounding air.

The KSO used in this study consists of 85% fatty acid and 15% glycerol. It was obtained in Malang East Java. The component of fatty acids in KSO is listed in Table 1. These fatty acids were tested in laboratory research and testing integrated in Gajah Mada University Yogyakarta. Most of the components are unsaturated long chain fatty acids. More than 79% of those are mono and polyunsaturated long chain with spontaneous combustion characteristics. The total molecular weight of fatty acid described with equation 1. The reaction of KSO with the oxidizer was estimated by molar analysis described with equation 2 and equation 3 as follows:

$$MW_t = \sum_{1}^{n} (MWxC) \qquad \textbf{(1)}$$

where:

MW_t = Total molecular weight

MW = molecular weight of fatty acid

C = content of fatty acid

N = number of fatty acid

$$0{,}00853 C_4H_6O_2 + 0{,}00028\ C_6H_{12}O_2 + 0{,}00009\ C_8H_{16}O_2 + 0{,}00072\ C_{10}H_{20}O_2 + 0{,}00071\ C_{12}H_{24}O_2 + 0{,}01222\ C_{14}H_{28}O_2 + 0{,}02462\ C_{16}H_{32}O_2 + 0{,}00387\ C_{16}H_{30}O_2 + 0{,}0016\ C_{17}H_{34}O_2 + 0{,}20153\ C_{18}H_{34}O_2 + 0{,}53786\ C_{18}H_{32}O_2 + 0{,}130337\ C_{18}H_{30}O_2 + 0{,}00026\ C_{20}H_{40}O_2 + 0{,}00995\ C_{22}H_{44}O_2 + 0{,}04229\ C_{20}H_{32}O_2 + 0{,}00672\ C_{24}H_{48}O_2 + 0{,}01837\ C_{24}H_{46}O_2 + 33{,}20(O_2+3.76N_2) \rightarrow 18{,}03CO_2 + 32{,}33H_2O + 124{,}83N_2 \qquad \textbf{(2)}$$

$$C_3H_5(OH)_3+3.5(O_2+3.76N_2) \rightarrow 3CO_2+4H_2O \qquad \textbf{(3)}$$

The equation 2 is the combustion reaction of fatty acids molecule from present data in Table 1 and equation 3 is that of glycerol. The stoichiometric air fuel ratio (AFR stoic) of KSO obtained from equation 1, 2 and 3 was 14.58 gram air/ gram fuel. In KSO without glycerol the AFR stoic was 16.23 gram air/ gram fuel. The φ was calculated as the ratio of stoichiometric air fuel ratio and actual air fuel ratio.

Table 1
Kapok seed oil (*ceiba pentandra*) composition from many references

Fatty acid	% (w/w)		
	Present data	Sivakumar et al. 2012	Silitonga et al. 2013
Butiric (C4:0)	0,853	-	-
Caproic (C6:0)	0,028	-	-
Caprylic (C8:0)	0,009	-	-
Capric (C10:0)	0,072	-	-
Lauric (C12:0)	0,071	-	0,1
Myristic (14:0)	1,222	0,11	0,1
Palmitic (16:0)	2,462	23,20	19,2
Palmitolic (16:1)	0,387	-	0,3
Heptadecanoic (C17:0)	0,16	-	-
Stearic (18:0)	-	5,68	2,6
Oleic (18:1)	20,153	29.69	17,4
Linoleic (18:2)	53,786	35,11	39.7
Linolenic (18:3)	13,0337	-	1,5
Arachidic (20:0)	0,026	1,89	0.6
Arachidonic (20:4)	0,995	-	-
Behenic (22:0)	4,229	0,25	-
Lignoceric (C24:0)	0,672	1,51	-
Nervonic (24:1)	1,837	-	-
Malvalic (18:CE)	-	-	18.5

3. Result and Discussion

KSO composed of fatty acids and glycerol. More than 79% of fatty acids components are unsaturated fatty acids and the other 21% are saturated straight-chain long hydrocarbons with ranges from 4 to 24 carbons with carbocyclic or COOH end. Fatty acids and glycerol could affect reaction of the combustion process and the flame characteristics.

KSO flame on the perforated burner at various equivalence ratios is shown in Fig. 2 to 4. Figure 2 shows that Glycerol intensively burned from φ = 0.32 to 1.07 (Wardana 2010). There were more glycerol burned in lean mixture (φ = 0.44) which made φ away from stoichiometry. Fig. 3a shows perforated flame with secondary Bunsen flame and Fig. 3b shows triple flame at lean mixture.

(2)

(3)

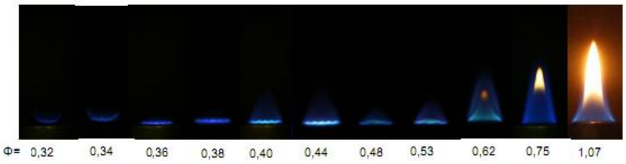

Fig. 2 Flame structure of KSO oil with glycerol


(a) (b)

Fig. 3 view of KSO (a) perforated flame at φ=0.44, triple flame at φ=0.62

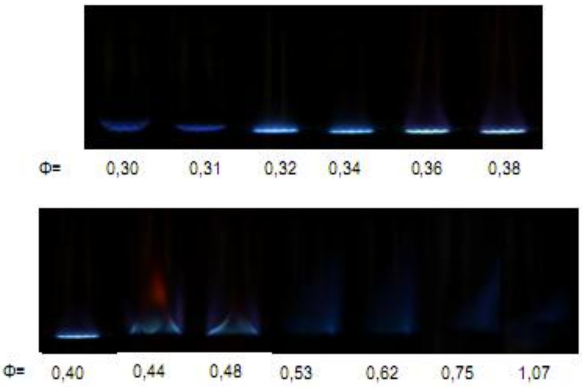

Fig. 4 Flame shapes of KSO with glycerol isolated from ambient air

Fig. 4 show the flame isolated from the surrounding ambient air at φ = 0.30 to 1.07. At φ = 0.30 to 0.31 of perforated flame lifts off. When φ increases the perforated flame occurs at φ = 0.32 to 0.40 followed by secondary Bunsen flame. At φ = 0.40 to 1.07 perforated and secondary Bunsen flame becomes unstable in the form of cellular and extinction flame. This phenomenon shows that KSO requires a large amount of air or flame formed in the lean mixture so that flame stability is influenced by the air supply.

3.1 Laminar Flame Velocity

Reactant velocity (v) is described in equation (4).

$$v = \frac{Q_{fuel} + Q_{air}}{A_b} \qquad \textbf{(4)}$$

where:
Q_{fuel} = volume flow rate of fuel
Q_{air} = volume flow rate of air
A_b = burner cross section area.

Laminar flame speed (S_L) could be estimated by using equation (5) as:

$$SL = v \sin \alpha \qquad \textbf{(5)}$$

where: α = half angel of the Bunsen flame cone tip.

Fig. 5 shows the laminar burning velocity, S_L estimated from Fig.2 using the equation 4. It is seen that the maximum S_L of perforated flame occurred at a very lean mixture is between that of hexadecane (Chaos *et al.* 2005) and ethanol flame (Broustail *et al.* 2011) at stoichiometric. Perforated flame lifts off at φ = 0.32 to 0.34. The increase of φ from 0.36 to 0.44 decreases perforated flame burning velocity. Secondary Bunsen flame is formed from φ = 0.40 to 0.53 with declining burning velocity. When φ increased to φ = 1.07, Bunsen flame with open tip were formed with declining burning velocity. This shows that flammability limits of KSO is much wider than conventional fossil fuels at lean mixture.

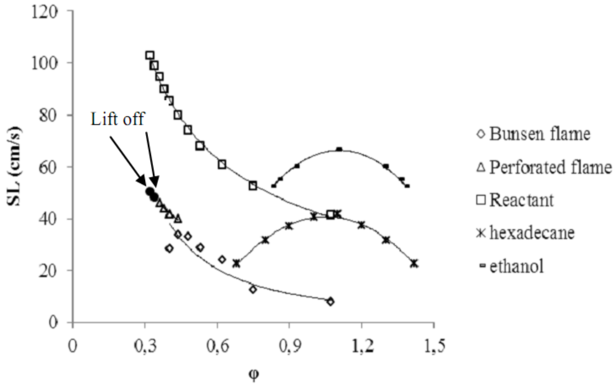

Fig. 5 Laminar burning velocity of KSO versus equivalence ratio

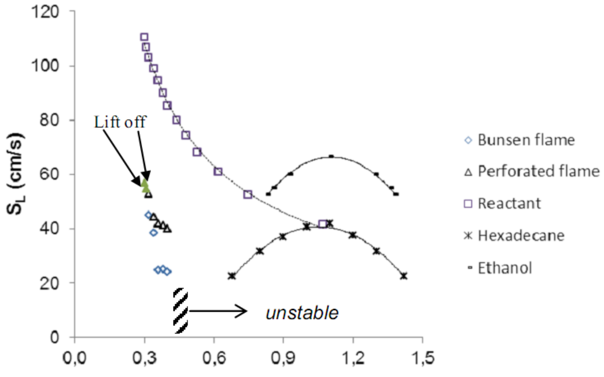

Fig. 6 Laminar burning velocity of KSO versus equivalence ratio isolated from ambient air

(3

Figure 6 presents S_L of KSO estimated from Fig. 4 using equation 5 when the flame is isolated from the ambient air. It could be seen that SL of perforated flame at very lean mixture almost equal to that of ethanol flame (Broustail *et al.* 2011) and higher than that of hexadecane flame (Chaos *et al.* 2005) at stoichiometry. Increasing φ from 0.32 to 0.40 causes a burning speed of both perforated and secondary Bunsen flame decreases. Perforated flame extinct above φ = 0.40 and cellular flame disappears above φ = 0.40 from where to the flame becomes unstable (Fig. 4). Once again, this indicates that glycerol requires a large amount of air to burn so the flame is stable in very lean mixtures.

3.2 Bunsen Flame with Open Tip

Opening tip on the Bunsen flame occurs when using a large amount of inert gas on diluted mixture, while the fatty acid and glycerol mixtures showed the maximum flame temperature on reaction zone toward dilation of flame tip. Amount of fuel that does not burn on the arm of a hydrogen molecule of fatty acid and glycerol were found exit through the open space. These event causes fuel leaks and pollutant emissions on the diffusion flames burning on the fuel mixture that resulted Bunsen flame with open tip.

KSO with a mixture of very lean, the amount of air on the mixture is enough to complete combustion. High burning speed of flame occurred on every hole at perforated nozzle. The equivalence ratio φ increases, fraction of fuel on the mixture also increases so that the more energy absorption to ignite the mixture. As a result, the laminar burning velocity of long-chain saturated fatty acids and glycerol are very low, it produces of secondary Bunsen flame at perforated flame downstream. Laminar burning velocity is much lower than the reactant velocity, the Bunsen flame tends to stretch so that open tip. Equivalence ratio φ enriched a long chain saturated fatty acids and glycerol becomes difficult to burn, eventually escaped towards product zone to produce a yellow sooty diffusion at flame tip. It is clearly seen from the Fig. 7 that the formation of the open tip of KSO flame at φ = 1.07. Mechanism of Bunsen flame with open tip formed by both escaped unburnt fuel and pollutants is based on the concept of Damkohler number because laminar burning velocity is much lower than the reactant velocity (Ishizuka & Sakai 1986).

Fig. 7 Bunsen flame with open tip of KSO

3.3 Cellular Flame

Fig. 8 shows the detailed structure of cellular flame of KSO when the ambient air is not contact with flame. Cellular flame occurs because the heat is not enough to burn the fuel that is, Lewis number (Le) is smaller than 1. Fig. 8a shows cellular flames at lean mixture (φ = 0.44). In this case, fraction of air in the mixture is not enough to burn glycerol in KSO. Glycerol escapes to product zone becoming diffusion flame. Radiant heat of glycerol diffusion flame provides heat energy for burning of medium chain fatty acids but it is not enough to burn the long one. Therefore, cellular flame is generated on the perforated plate. This phenomenon is similar with that reported in Kadowaki *et al.* (2011).

At higher φ, the air is not enough for maintaining diffusion flame and the radiant heat disappears. Therefore, the long and medium chain fatty acids produce petals cellular flame in the Bunsen flame as shown in Fig. 8b. This result is similar with that discussed in Wirawan *et al.* (2013).

Fig. 8 Cellular flame of KSO Islands cellular at φ = 0.44, (b) petal cellular at φ = 0.62

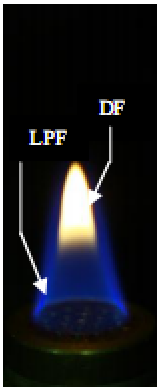

Fig. 9 Triple flame shape of KSO at φ = 0.75

3.4 Triple Flame

In Fig. 2, triple flame of KSO is formed at φ = 0.62 to 1.07 where the flame is left in contact with ambient air. Fig. 9 shows the detailed structure of the triple flame at φ = 0.75. Flame composed by rich premixed flame (RPF) in the upstream region, diffusion flame (DF) in the middle, and the lean premixed flame (LPF) in the downstream region. Flame structure is formed from a premixed combustion process of KSO caused by instability of thermal diffusive. RPF is due to heat flux propagation increasing and unburned gas temperature in the upstream so that flow leads convergent and flame front becomes convex.

Glycerol in KSO is difficult to be burned in the reaction zone because the air is not enough and escapes to product zone becoming diffusion flame. Diffusion flame both could not expand the reaction zone due to fuel lack and could not move in the direction of reaction zone due to air lack. Inability of diffusion flame propagation causes free convection in the downstream of pumping cool air toward the reaction zone to meet and react with RPF to produce LPF in the downstream region. Triple flame formed by free convection of hot gas recirculation region at lean premixed flame or unstable flame occurs when the hot gas moving downstream as found by Jime'nez & Cuenot (2007).

4. Conclusion

Kapok seed oil premixed combustion has been studied experimentally on perforated burner with equivalent ratio varied from very lean until rich mixture. The results showed that at very lean mixture Bunsen flame is performed on every hole of perforated plate. The velocity of both perforated and secondary Bunsen flame decreased when equivalent ratio increased. Both open tip Bunsen and triple flame were formed in higher equivalent ratio.

When the flame was isolated from the ambient air, the slight increase of equivalence ratio makes laminar burning velocity decreases drastically. The open tip Bunsen and triple flame disappear while perforated and secondary Bunsen flame is still occurs. Cellular flame was formed with higher equivalent ratio. This phenomenon shows that premixed combustion of kapok seed oil requires a large amount of air.

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