Premixed Combustion of Coconut Oil on Perforated Burner

I.K.G. Wirawan[a,b*], I.N.G. Wardana[b], Rudy Soenoko[b], Slamet Wahyudi[b]

[a] *Mechanical Engineering Department, Udayana University, Bali, INDONESIA*

[b] *Mechanical Engineering Department, Brawijaya University, East Java, INDONESIA*

ABSTRACT: Coconut oil premixed combustion behavior has been studied experimentally on perforated burner with equivalence ratio (φ) varied from very lean until very rich. The results showed that burning of glycerol needs large number of air so that the laminar burning velocity (S_L) is the highest at very lean mixture and the flame is in the form of individual Bunsen flame on each of the perforated plate hole. As φ is increased the S_L decreases and the secondary Bunsen flame with open tip occurs from $\varphi = 0.54$ at the downstream of perforated flame. The perforated flame disappears at $\varphi = 0.66$ while the secondary Bunsen flame still exist with S_L increases following that of hexadecane flame trend and then extinct when the equivalence ratio reaches one or more. Surrounding ambient air intervention makes S_L decreases, shifts lower flammability limit into richer mixture, and performs triple and cellular flames. The glycerol diffusion flame radiation burned fatty acids that perform cellular islands on perforated hole. Without glycerol, laminar flame velocity becomes higher and more stable as perforated flame at higher φ. At rich mixture the Bunsen flame becomes unstable and performs petal cellular around the cone flame front.

Keywords: cellular flame, glycerol, perforated flame, secondary Bunsen flame with open tip, triple flame

1. Introduction

Large number of coconut is available in Indonesia that grows in the lowlands near beach about 81,000 kilometers long. Coconut oil has the shortest carbon chain in vegetable oils group (Yuan *et al.* 2005) and it has similar chemical structure with petro diesel. Thus, coconut oil is suitable for Diesel engine. So far, coconut oil is used as non-premixed fuel, for example in pressure stove (Kratzeisen & Müller 2010) because of its lower exhaust emissions, more environmental friendly, lower calorific value compared to diesel (Machacon *et al.* 2001; Suresh *et al.* 2009; Singh *et al.* 2010; Alamu *et al.* 2010).

However, coconut oil still cannot be applied directly as non-premixed in diesel engine because of several disadvantages such as high viscosity, low volatility, composed mostly by unsaturated long-chain fatty acid with low reactivity, preheating necessity, atomization and particle emissions (Recep *et al.* 2001;

Ayhan 2009). It would be very useful if the coconut oil can be burned in premixed flame. In that case, the oil must be vaporized before injection into combustion chamber.

The disadvantages of coconut oil are also caused by its multi-component which consists of various fatty acids with different properties and glycerol which is highly hygroscopic (Benjapornkulaphong *et al.* 2009). These complicate the premixed flame behavior and, therefore, intensive studies are needed.

Several studies had been conducted with various fuel compositions. The behavior of premixed flame extinction and the laminar burning velocity had been widely investigated on multi-component fuel in experimental and numerical study (Qiao *et al.* 2010). Liquid petroleum gas fuel was used to investigate cellular flame formation under the effect of thermal diffusivity instability and laminar flame speed at different equivalence ratio (Abdulwahid *et al.* 2009). Liquid petroleum gas fuel had the composition of 40%

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Corresponding author:
E-mail: wirawan_ikg@yahoo.com

propane (C_3H_8) and 60% butane (C_4H_{10}) with oxidizer is environment air. The study which aims to clarify the laminar burning velocity, Markstein length, and cell formation had been conducted (Vu *et al.* 2011). The effects of Lewis number on the burning intensity of Bunsen flame had been investigated (Mizomoto & Yoshida 1987).

This paper discusses the premixed flame behavior of multi-component vegetable oil composed by fatty acids and glycerol. The analysis is stressed on laminar burning velocity of perforated flame and secondary Bunsen flame-open tip, cellular and triple flame which provide wider theoretical benefits in premixed combustion of vegetable oil.

2. Experiments

The experimental study on premixed combustion of coconut oil was carried out in an experimental apparatus shown schematically in Fig.1. The coconut oil was evaporated in a boiler with steam temperature kept constant at 160°C. The oil steam from boiler was mixed with air from compressor at mixing chamber with equivalent ratio (φ) varied from lean (φ=0.45) to rich mixture (φ=1.75). Lean mixture is range below φ=0.90 and rich is above 1.14 while nearly stoichiometric is between φ=0.90 to 1.14. The reactant then flows into nozzle before it was ignited to form premixed flame at perforated plate installed on the top of the nozzle.
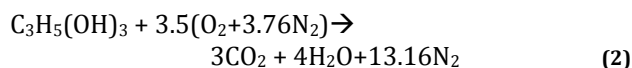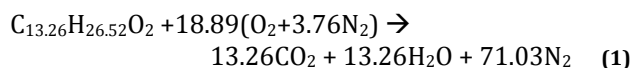
The perforated plated was installed to utilize thermal contact resistant for preserving temperature distribution which is more uniform in entire surface of the plate and ensure the uniformity flow for coconut oil with air during the combustion process. Perforated plate was made from steel and designed with geometrical matrix with 19 holes. The diameter of each hole was 2.5 mm and the distance between holes was 3.75 mm.

The flame image was captured by camera in four experimental conditions: (1) premixed flame of coconut oil in contact with surrounding ambient air, (2) premixed flame of coconut oil shielded from surrounding ambient air, (3) premixed flame of coconut oil without glycerol in contact with surrounding ambient air, and (4) premixed flame of coconut oil without glycerol shielded from surrounding ambient air.

The coconut oil used in this experiment consists of 85% fatty acid and 15% glycerol. The component of fatty acids in coconut oil is listed in Table 1. Most of the components are saturated medium-chain fatty acids. Only less than 10% are unsaturated long-chain with spontaneous combustion characteristics.

The reaction of coconut oil with the oxidizer was estimated by simple molar analysis described with equation 1 and equation 2 as follows:

$$C_{13.26}H_{26.52}O_2 + 18.89(O_2+3.76N_2) \rightarrow$$
$$13.26CO_2 + 13.26H_2O + 71.03N_2 \quad \textbf{(1)}$$

$$C_3H_5(OH)_3 + 3.5(O_2+3.76N_2) \rightarrow$$
$$3CO_2 + 4H_2O + 13.16N_2 \quad \textbf{(2)}$$

The equation 1 is the combustion reaction of equivalent fatty acids molecule from present data in table 1 and equation 2 is that of glycerol. From equation 1 and 2 the stoichiometric air fuel ratio (AFR_{stoic}) of coconut oil was 10.91 gram air/ gram fuel. In coconut oil without glycerol the AFR_{stoic} was 11.91 gram air/ gram fuel. The equivalent ratio (φ) was calculated as the ratio of stoichiometric air fuel ratio and actual air fuel ratio.
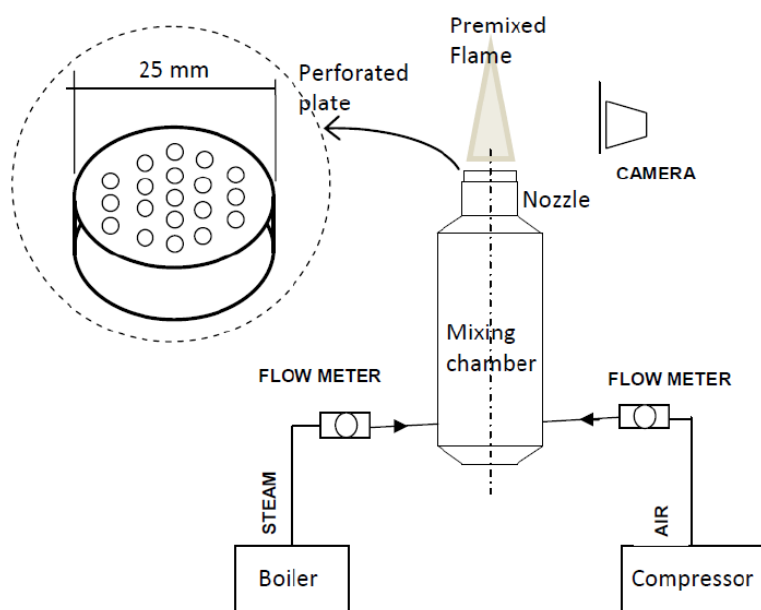

Fig. 1 Experimental apparatus

Table 1
Coconut oil composition from many references

Fatty acid	%(w/w)					
	Present Data	Kumar et al. 2010	Bouaid et al. 2010	Satyanarayana et al. 2011	Llamas et al. 2012	Palash et al. 2013
Caproic (C6:0)	0.240	-	-	-	-	-
Caprylic (C8:0)	4.852	8.86	6.05	-	8.30	-
Capric (C10:0)	5.031	6.17	4.25	-	3.00	-
Lauric (C12:0)	46.256	48.83	49.70	46.50	55.50	45.60
Myristic (14:0)	20.508	19.97	19.30	19.20	14.90	22.10
Palmitic (16:0)	10.706	7.84	11.10	9.80	6.40	10.20
Stearic (18:0)	3.711	3.06	6.55	3.00	2.50	3.60
Arachidic (20:0)	0.051	-	-	-	-	-
Behenic (22:0)	0.028	-	-	-	-	-
Palmitolic (16:1)	0.018	-	-	-	-	-
Oleic (18:1)	8.413	4.44	2.90	6.90	7.50	8.20
Linoleic (18:2)	0.060	0.76	-	2.20	1.90	2.70
Linolenic (18:3)	0.107	-	-	-	-	-
Eicosatrienoic (20:3)	0.020	-	-	-	-	-

3. Result and Discussion

The flame behavior at various equivalent ratios is presented in Fig.2 to Fig.6. Fig. 2 shows premixed flame of coconut oil with glycerol. Glycerol is intensively burned at φ from 0.93 until 1.14 (Wardana 2010), which is within stoichiometry. At rich mixture (φ = 1.61) the amount of glycerol burned is reduced because being far from the stoichiometry. It is shown from the top view in Fig. 3 that there are two flames structure: perforated Bunsen flame with secondary Bunsen open-tip flame at lean mixture (Fig. 3a) and triple flame with cellular flame at very rich mixtures (Fig. 3b).

When flame of coconut oil with glycerol was isolated from surrounding ambient air as shown in Fig. 4, perforated Bunsen flame takes place at φ 0.45 to 0.66. From φ 0.54 to 0.80 secondary Bunsen flame with open-tip occurs at downstream of the perforated Bunsen flame. Flame tends to extinct above φ = 0.93. This phenomenon indicates that coconut oil with glycerol needs large number of air or very lean mixture to perform flame so that its stability is greatly influenced by the ambient air.

The cause of cellular flame, secondary open-tip Bunsen flame, triple flame and flame extinction was elucidated by removing glycerol from the oil by hydrolysis process at a temperature of 300°C for 15 minutes (Alenezi *et al.* 2009; Wang *et al.* 2012). Flame of coconut oil without glycerol is shown in Fig. 5. The island cellular with triple flame which occurs at coconut oil with glycerol disappears and changes into petals cellular without triple flame at φ = 1.24 while perforated flame and secondary Bunsen flame with open-tip are still present. When flame was isolated from surrounding ambient air as shown in Fig. 6, flame is

stable from lean (φ = 0.66) until rich mixture (φ = 1.75). Flame of coconut oil without glycerol did not undergo extinction.
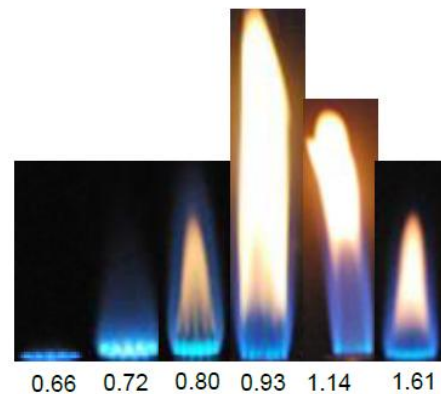

Fig. 2 Flame structure of coconut oil with glycerol

Fig. 3 Top view of: (a) perforated Bunsen flame with secondary Bunsen open tip flame, φ = 0.72; (b) Triple flame with cellular flame, φ = 1.61

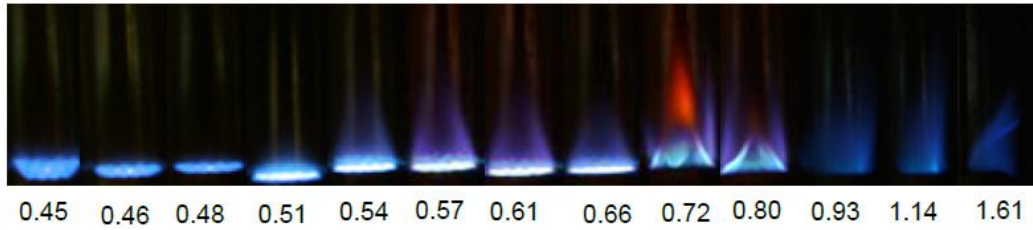| 0.45 | 0.46 | 0.48 | 0.51 | 0.54 | 0.57 | 0.61 | 0.66 | 0.72 | 0.80 | 0.93 | 1.14 | 1.61 |

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

From those data it can be concluded that coconut oil with glycerol need very large number of air to burn glycerol due to its hygroscopic properties. When the concentration of air in the reactant is low or the mixture is rich glycerol causes the formation of the triple flame, cellular flame, and the extinction. Since the open tip of Bunsen flame always takes place at coconut oil with and without glycerol, it may be caused by any mechanism which will be discussed latter on. Booth glycerol and long-chain fatty acids produce cellular flame of different types which will also be discussed afterward.
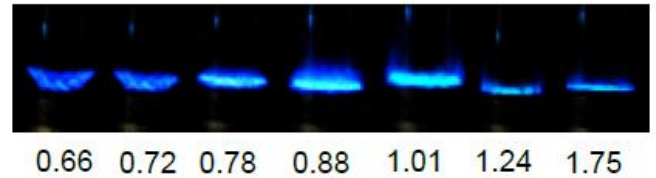

| 0.66 | 0.72 | 0.78 | 0.88 | 1.01 | 1.24 | 1.75 |

Fig. 6 Flame shapes of coconut oil without glycerol isolated from surrounding ambient air

3.1 Laminar Flame Velocity

Reactant velocity (v) is described in equation (3).

$$v = \frac{Q_{Fuel} + Q_{Air}}{A_b} \qquad (3)$$

where: Q_{fuel} is volume flow rate of fuel, Q_{air} is volume flow rate of air, and A_b is burner cross section area. Laminar flame speed (S_L) can be estimated by using equation (4) as:

$$S_L = v.\sin\alpha \qquad (4)$$

where: α is the half angel of the Bunsen flame cone tip.
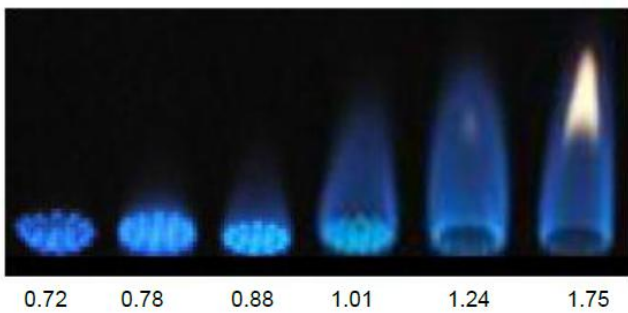
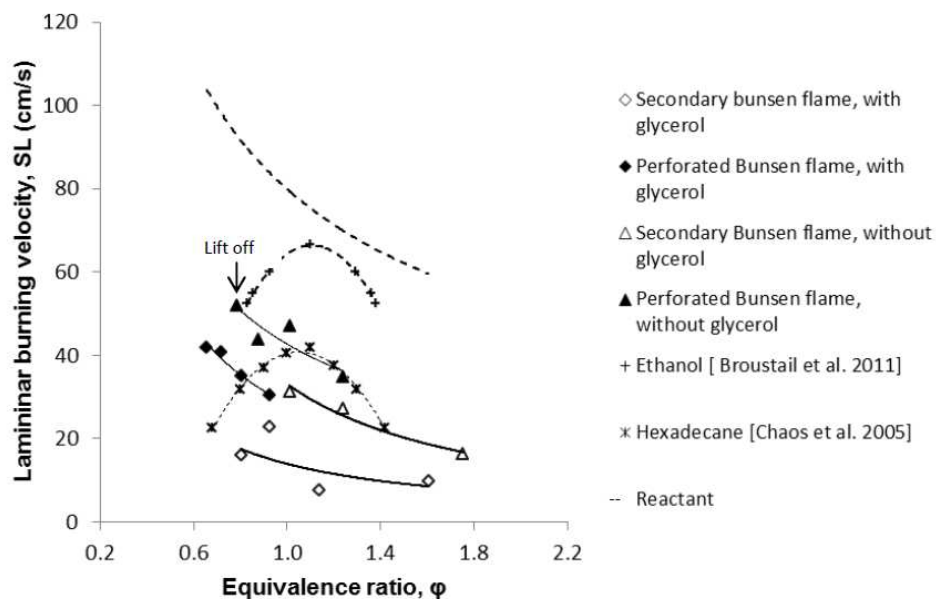**Fig. 5** Flame shape of coconut oil without glycerol

Fig. 7 Laminar burning velocity of coconut oil versus equivalence ratio
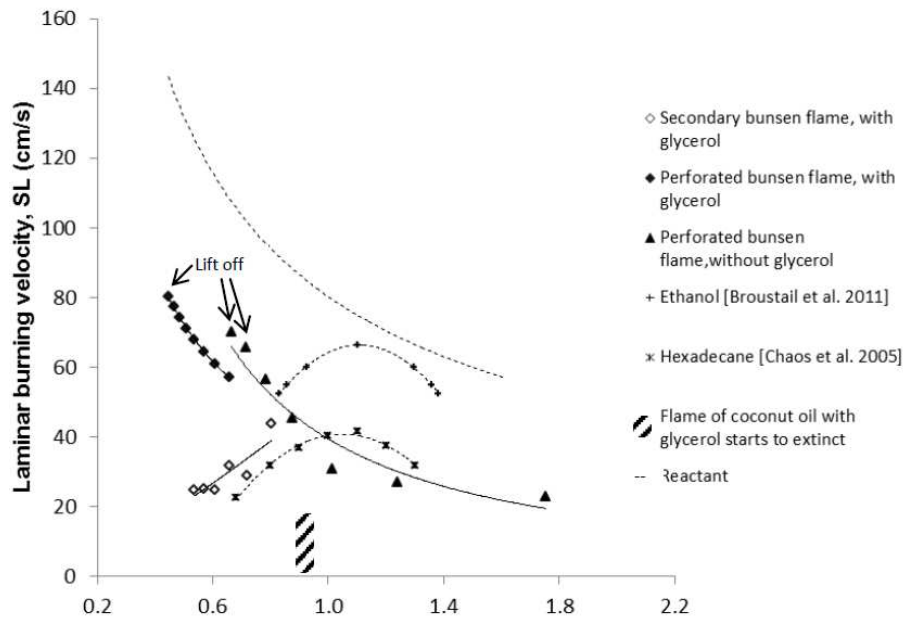
Fig. 8 Laminar burning velocity of coconut oil versus equivalence ratio isolated from ambient air

Fig.7 shows S_L of coconut oil estimated from Fig.2 and Fig. 5 by using equation 4. It is seen that S_L of coconut oil perforated flame at very lean mixture almost equal as that of hexadecane flame at stoichiometry. As φ is increased S_L of perforated flame decreases and the flame started to disappears at φ= 0.93. The secondary Bunsen flame takes place at the downstream of perforated flame from φ=0.80 with S_L lower than that of perforated flame which also decrease with increasing φ. Without glycerol, perforated flame start to take place at a slightly larger φ with S_L became higher. Maximum S_L still occurs at lean mixture that is higher than that of hexadecane (Chaos *et al.* 2005) but nearly the same as that of ethanol (Broustail *et al.* 2011). The S_L tends to decrease with increasing φ. The flame is still stable even in the form of secondary Bunsen flame until the mixture is very rich. This shows that flammability limit of coconut oil is much wider than that of the conventional fossil fuel.

Fig. 8 shows S_L of coconut oil estimated from Fig.4 and Fig. 6. It can be seen at Fig. 8 that when the flame is isolated from ambient air the S_L of perforated flames reached the highest and even higher than that of ethanol (Broustail *et al.* 2011) at very lean mixture (φ =0. 45). As φ is increased the S_L decreases and the perforated flame disappear from φ =0.66 while the secondary Bunsen flame starts to take place at the downstream of perforated flame from φ =0.54 with S_L tends to increase following the trend of that of hexadecane (Chaos *et al.* 2005). The flame starts to extinct when φ is nearly one or more. When the glycerol is removed from the oil the perforated flame start to form from φ =0.72 with S_L higher than that with glycerol. The S_L decreases with increasing φ. The flame is still stable in the form of perforated flame until the

mixture become very rich (φ =1.61). Again, this shows that glycerol need much air to burn so that it is stable at very lean mixture while fatty acids which are multi-components is stable at higher φ up to very reach mixture.

3.2 Secondary Bunsen Flame with Open Tip

At very lean mixture the number of air in the mixture is sufficient for complete combustion. S_L is high and the Bunsen flame occurs on each hole of perforated nozzle. As φ is increased the fraction of fuel in the mixture increases which absorb more energy for igniting the mixture. Consequently S_L of longer-chain saturated fatty acids (palmitic and stearic acids) and glycerol is so low that results in secondary Bunsen flame in the downstream of perfored flame.

Fig. 9 Secondary Bunsen Flame Open Tip: (a) coconut oil with glycerol φ = 1.14, (b) oil without glycerol φ = 1.24

For S_L is much lower than mixture velocity the secondary Bunsen flame tends to stretch which cause open tip. At higher φ saturated longer-chain fatty acids and glycerol become difficult to burn and eventually escaped toward product zone to produce a yellow sooty diffusion flame in the tip of the flame. It is clearly seen from Fig. 9a that the open tip formation in the flame of coconut oil with glycerol at φ = 1.14 is mainly caused by unburned glycerol that escapes into product zone. At coconut oil without glycerol (Fig. 9b) the open tip at φ = 1.24 is caused by long chain saturated fatty acids. This indicates that glycerol needs more air to burn than long-chain fatty acids. The open tip Bunsen flame mechanism made by both of escaped unburn fuel and pollutant is based on the Damkohler number concept (Ishizuka & Sakai 1986).

3.3 Cellular Flame

Fig. 10 shows detailed structure of cellular flame of coconut oil with glycerol (Fig. 10a) and that of coconut oil without glycerol (Fig. 10b). Cellular flame occurs in unstable combustion process due to insufficient heat for burning of fuel, that is, in Lewis number (Le) much smaller than 1. In Fig. 10a cellular flame in combustion process of coconut oil with glycerol exists at rich mixture (φ =1.14) where the number of air in the mixture is small not enough for burning of glycerol. Therefore, glycerol escapes to product zone becoming diffusion flame. Radiant heat from diffusion flame of glycerol serve heat energy for fast burning of medium-chain fatty acids (see Table 1) but it is not enough to burn the long-chain of fatty acid in the multi-component that compose the oil. This process results in island cellular flame on the perforated plate. This phenomenon is similar with that reported in Kadowaki *et al.* (2011). When glycerol is removed from the oil radiant heat from glycerol flame disappears. The long and medium chain fatty acids produce petals cellular flame in the Bunsen flame as shown in Fig. 10b. This result is similar with that discussed in Wang *et al.* (2009).

Fig.10 Cellular formation on (a) coconut oil with glycerol φ = 1.14, (b) coconut oil without glycerol φ = 1.24
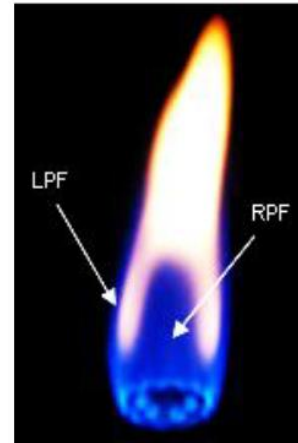

Fig.11 Form of coconut oil with glycerol flame at φ = 1.61

3.4 Triple Flame

In Fig. 2 triple flame of coconut oil is formed at rich mixture from φ = 1.14 to 1.61. Fig. 11 shows detail structure of triple flame of coconut oil with glycerol at φ = 1.61. The flame composed by rich premixed flame (RPF) at upstream region, diffusion flame in the middle, and lean premixed flame (LPF) in the downstream region. The structure comes from combustion process of coconut oil at rich mixture which produces rich premixed flame. Glycerol in coconut oil is difficult to be burnt at reaction zone since the air is not sufficient and it escapes to the product zone becoming diffusion flame. The diffusion flame both cannot expand from reaction zone because of fuel deficiency and cannot move toward reaction zone because of air deficiency. The inability of diffusion flame propagation causes free convection in the downstream region which pumps the cool air towards the reaction zone to meet and react with the rich premixed flame to produce lean premixed flame in the downstream region. Triple flame will be created by recirculation of hot gas free convection in lean premixed area or unsteady flame occur when hot gas travelling downstream as found by Jime´nez & Cuenot (2007).

4. Conclusion

Coconut oil premixed combustion behavior has been studied experimentally on perforated burner with φ varied from very lean until very rich. The results showed that at very lean mixture Bunsen flame is performed on every hole of perforated plate and their average laminar burning velocity reaches the highest, even it is higher than ethanol flame.

When φ is increased the secondary Bunsen flame with open tip occurs from φ =0.54 at the downstream of perforated flame. Perforated flame speed decreases and it disappears at φ = 0.66 while the secondary Bunsen flame velocity increased following that of hexadecane

flame trend. The secondary Bunsen flame extincts when the equivalence ratio reaches one or more.

External air causes flame velocity decrease, shifts flame stable into richer mixture, and performs triple and cellular flames. The radiation heat energy from glycerol diffusion flame performs islands cellular flame on perforated hole.

Without glycerol, laminar flame velocity becomes higher and more stable as perforated flame at higher φ. At reach mixture the Bunsen flame becomes unstable and performs petal cellular flame.

Acknowledgment

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