В даній роботі досліджується вплив жирнокислотного складу різних рослинних олій на поведінку полум'я в процесі горіння. Дослідження має важливе значення з точки зору заміщення горючих корисних копалин екологічно чистими рослинними оліями. Було протестовано п'ять олій, включаючи кокосову, пальмову, бавовняну, капокову та олію ятрофи. Олії спалювали на відкритому підносі при різних швидкостях повітря, реалізуючи три області згоряння, тобто згоряння з попередньо підготовленою паливно-повітряною сумішшю в зоні висхідного потоку, перехідна область та область дифузійного горіння в зоні нисхідного потоку. Стабільність полум'я перевіряли при швидкості повітря 49 см/с, 55 см/с та 64 см/с. Зображення полум'я фіксувалося за допомогою високошвидкісної відеокамери зі швидкістю 200 кадрів в секунду. Температуру полум'я вимірювали за допомогою термопари типу K. Результати показують, що більш високий вміст насичених жирних кислот робить полум'я яскравішим, а на фронті полум'я присутня більша кількість вейвлет-коефіцієнтів, зберігаючи стабільність полум'я в широкому діапазоні швидкостей повітря. Насичена жирна кислота має високу температуру спалаху, важко піддається горінню на фронті полум'я і уникає згоряння у вигляді дифузійного полум'я в області нисхідного потоку. Вміст жирних кислот також впливає на колір полум'я, про що свідчить олія ятрофи з переважно змішаним/синім полум'ям, виробляючи найвищу кількість теплової енергії, тоді як кокосова олія має переважно жовтий колір дифузійного полум'я. Більш тривалу затримку запалювання показує кокосова олія через високий вміст насичених жирних кислот. Чим вище вміст ненасичених жирних кислот, тим нестійкіше полум'я. Це вказує на те, що яскраво-жовтий колір полум'я є гарним джерелом теплової енергії випромінювання для стабільності полум'я. Дані щодо кольору та стабільності полум'я є дуже цінними для розробки ефективної та стабільної промислової печі на рослинних оліях. Дане дослідження дає уявлення про вплив хімічної будови та фізичних властивостей жирних кислот на характеристики горіння при виробництві теплової енергії. Для забезпечення високої температури газу в промисловій печі використовують рослинну олію з ненасиченими жирними кислотами, зберігаючи нижчу швидкість повітря. Але для стабільного процесу горіння у промисловій печі, олія з насиченими жирними кислотами є найкращим рішенням в широкому діапазоніщвидкостей повітря

Ключові слова: рослинна олія, вміст жирних кислот, процес горіння, колір полум'я, стабільність полум'я

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THE ROLE OF FATTY ACID STRUCTURE IN VARIOUS PURE VEGETABLE OILS ON FLAME CHARACTERISTICS AND STABILITY BEHAVIOR FOR INDUSTRIAL FURNACE

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1. Introduction

The depletion of petroleum production in the near future is gradually raising concerns related to energy security in the future. These factors have driven many attempts at creating renewable energy sources that may reduce the impacts on the economy and social environment caused by the burning of petroleum fuels [1].

Recently, the development of new technology tends to improve efficiency and energy management, as well as replacing fossil fuel with renewable energy [2]. One of the most significant renewable energy sources is a vegetable oil constructed by large molecules with long carbon chain. Vegetable oils in general are triglyceride molecules consisting of glycerol with three carbon chains as a backbone and three branches of fatty acids [3–5]. The long chain carbon structure of fatty acid resembles the diesel fuel molecular structure [6]. Therefore, fatty acids have potential as a good source of diesel oil. However, the direct application of this oil causes many problems in the engine due to the higher density and viscosity compared to that of diesel oil [7]. Further processing of the oil needs additional cost. Another potential direct application of vegetable oil is for the industrial furnace [2]. But further research is needed especially for efficient high thermal energy radiation production and flame stability. The present work provides the data for the efficient and stable operation of the industrial furnace using vegetable oil.

2. Literature review and problem statement

Vegetable oil is a renewable energy source and is one of the sub-groups of biofuel. The others are (i) bio alcohols (ii) bio crude and synthetic oils [1].

There are various available sources of vegetable oils. The vegetable oils have many advantages such as their emission is free from carbon, locally available, readily accessible and triglycerides in their chemical structures contain large amounts of oxygen [8]. However, the direct application of this oil causes many problems in the engine due to its high density and viscosity compared to diesel oil. Pure plant-based oils are composed of triglyceride molecules comprising of glycerol with 3 carbon chains as the main chain and 3 branches of fatty acids having a straight and long hydrocarbon chain. Previous research on direct combustion, hydrolysis or trans-esterification of pure vegetable oil has been conducted by other researchers.

The efficiency of the cooking stove using vegetable oil as a fuel is around 48.9 % higher than that using kerosene which is 34.9 % [2]. Saturated fatty acids of biodiesel FAME such as methyl ester coconut oil enhance combustion characteristics and reduce exhaust emissions as well as good diesel combustion characteristics and fewer exhaust emissions [9]. The burning of unsaturated fatty acid biodiesel has longer premixed combustion and higher pressure compared to saturated fatty acids of biodiesel [10]. The burning of Jatropha oil droplets burned at the junction of thermocouples occurs in two stages. The fatty acid component is burned in the first stage and the glycerol is in the second step [3]. Linseed oil methyl ester with high linolenic acid content (ester unsaturated fatty acids) is not suitable for diesel engines due to high nitrogen oxide emissions and low thermal efficiency [11]. The higher the unsaturated fatty acid content is, the higher the NO_x and the lower CO emissions are [12]. Unsaturated fatty acids and glycerol are very explosive so that the greater the number of unsaturated fatty acid component is, the higher the rate of oil burning is. All of the above studies mostly only observe the combustion characteristics of the methyl ester fuel in diesel engines in the enclosed combustor. The data obtained is limited to the engine pressure, efficiency, and emission. Recently works have been done to improve the physical properties, heating value and burning process of vegetable oil. The heating value could be increased by 10 to 15 percent by blending saturated and unsaturated vegetable flame [13]. The step combustion could be suppressed by using $Rh_2(SO_4)_3$ [6] so that the burning characteristics become very close to that of methyl ester bio diesel. However, the fatty acid structure in vegetable oil and flame behavior that plays an important role in the stability of combustion can not be observed. Special attention must be paid to research of chemical composition and physical properties of pure vegetable oils of alternative fuels. In other words, it is necessary to study the impact of such fuels on combustors, especially on industrial furnace equipment during long-term use.

Therefore, this study aims to provide discussion about the role of saturated and unsaturated fatty acid structure in various pure vegetable oils on burning characteristics and flame stability behavior.

3. The aim and objectives of the study

The aim of this study is to investigate the influence of various chemical compositions and physical properties of fatty acids on vegetable oil flame characteristics and stability behavior.

To achieve this goal, the following tasks were set:

– study on the shape and stability of the flame front;

– study on the flame speed estimated from the distance of the flame front to the leading edge of the tray;

– study on the influence of the flame color on the flame stability and the flame temperature at various vegetable oils and various airspeeds.

4. Material, methods and model of research

The vegetable oils tested include coconut oil, palm kernel oil, cotton seed oil, ceiba petandra oil and jatropha curcas oil. All vegetable oils were obtained from a commercial product. The fatty acid compositions for each vegetable oil were tested using GCMS Shimadzu QP 2010 S. The compositions obtained from the test are presented in Table 1. The physical properties of the vegetable oils together with their measurement techniques are presented in Table 2. The content of fatty acid, glycerol, gum and water of pure vegetable oil were determined by using GCMS Shimadzu QP 2010 S and the results are given in Table 3.

The experimental apparatus is shown schematically in Fig. 1. The tray made of a stainless steel with the length, width, and depth of 184 mm, 25 mm, and 15 mm respectively were filled with 63 ml vegetable oils. The oils were heated by an electric heating element with an electric power source from AC – power supply. The heater was located under the tray plate. The air flowing at room temperature from the wind tunnel with a rectangular nozzle exit of 30×30 mm to the tray was set uniformly from 49 to 64 cm/s. The room was kept in dark conditions during the experiment to obtain a good image of the flame. The vegetable oil on the tray was heated until it was evaporated and then was ignited to perform flame. The heating element was turned off and the blower was turned on just after the oil was burned. The air speed from the blower was varied as 49, 55 and 64 cm/s.

The flame image at each air speed was recorded by using high-speed digital CCD video, fuji ZR camera at 200 frames per second. Two cameras were positioned facing to the tray from the top left and right side of the tray. The images were framed and were arranged in rows as to show the dynamics of the flame.

The flame temperature profiles during the combustion were measured with 1 mm diameter K-type thermocouples for about 100 seconds at each airflow velocity from the blower. The signals from the thermocouples were recorded using a data logger. Thermocouples were located above the tray at 50 mm, 100 mm, and 180 mm from the tip of the tray as shown in Fig. 2 by T1, T2, and T3.

Table 1

Chemical composition and flash point of each fatty acid of pure vegetable oil

Chemical composition types (*xx*, *y*)		Formula	Flash point	Composition				
				Ceiba petandra oil	Jatropha curcas oil	Cotton seed oil	Coconut oil	Palm kernel oil
			(°C)	(%)	(%)	(%)	(%)	(%)
Saturated acid	Caprylic acid (C8:0)	$CH_3(CH_2)_6COOH$	176	–	–	–	7.0	3.3
	Capric acid (C10:0)	$CH_3(CH_2)_8COOH$	181	–	–	–	5.4	3.5
	Lauric acid (C12:0)	$CH_3(CH_2)_{10}COOH$	185	–	–	–	48.9	47.8
	Myristic acid (C14:0)	$CH_3(CH_2)_{12}COOH$	196	0.79	0.1	0.8	20.2	16.3
	Palmitic acid (C16:0)	$CH_3(CH_2)_{14}COOH$	201	19.2	15.0	24.8	8.4	8.4
	Stearic acid (C18:0)	$CH_3(CH_2)_{16}COOH$	206	2.6	7.0	2.2	2.5	2.4
	Arachidic acid (C20:0)	$CH_3(CH_2)_{18}COOH$	208	0.25	0.2	–	–	0.1
Unsaturated acid	Oleic acid (C18:1)	$CH_3(CH_2)_7CH=(CH_2)_8COOH$	80	21.88	44.7	17.2	6.2	15.4
	Linoleic acid (C18:2)	$CH_3(CH_2)_4(CH=CHCH_2)_2(CH_2)_6COOH$	77	53.78	32.8	55.0	1.4	2.4
	Linolenic acid (C18:3)	$CH_3(CH_2)(CH=CHCH_2)_3(CH_2)_6COOH$	61	1.5	0.2	–	–	–
	Eicosanoic acid (C20:1)	$CH_3(CH_2)_5CH=CH(CH_2)_{11}COOH$	85	–	0.1	–	–	0.1
Saturated acid				22.84	23.2	27.8	92.4	82.1
Monounsaturated acid				21.88	44.7	17.2	6.2	15.5
Polyunsaturated acid with two or more double bonds				55.28	33.1	55.0	1.4	2.4

Note: (Cxx:y): xx indicates the number of carbon, and y the number of double bonds in the fatty acid chain

Table 2

Physical properties of pure vegetable oil

Property	ASTM method	Instrument	Model	Value				
				Ceiba petandra oil	Jatropha curcas oil	Cotton seed oil	Coconut oil	Palm kernel oil
Density at 40 °C (kg/m^3)	D1298	Hydrometer	Nikky, Japan	974	921	955	936	940
Kinematic viscosity at 40 °C (cSt)	D445	Kinematic Viscometer	Leybold Didactic, Germany	45,55	35,48	41,65	55,55	52,65
Flash point (°C)	D93	Pensky-Martens closed cup tester	Leybold Didactic, Germany	260	240	250	265	270
Caloric value (kcal/kg)	D240	Bom Calorimeter	Parr Instrumen UAS	9,700.56	9,860.25	9,478.87	8,837.3	8,897.01
pH	D6423	pHep tester	UAS HANNA Instrument UAS	5,0	4,5	4,0	6,0	6,0

Table 3

Fatty acids, glycerol, gum, and water content of pure vegetable oils

Chemical component	Chemical bond structure	Chemical oil composition (%)				
		Coconut	Palm kernel	Cotton seed	Ceiba petandra	Jatropha curcas
Caprylic	8:0	3.07	3.50	–	–	1.70
Capric	10:0	3.56	3.00	–	–	1.66
Lauric	12:0	31.43	29.30	0.54	–	7.71
Myristic	14:0	12.21	10.25	0.78	–	3.29
Palmitic	16:0	9.36	8.50	21.13	22.50	11.45
Stearic	18:0	3.50	2.75	9.52	6.68	3.16
Arachidic	20:0	0.09	–	–	–	–
Oleic	18:1	16.40	24.00	16.23	19.38	30.38
Linoleic	18:2	9.65	11.30	43.09	36.62	32.23
Linolenic	18:3	0.05	0.25	–	1.20	–
Eicosanoic	20:1	0.05	–	–	–	–
Glycerol	3:0	4.54	3.6	5.32	9.87	4.94
Gum	5:0	5.89	3.32	3.12	3.69	3.02
Water		0.05	0.23	0.36	0.06	0.45
Total saturated fatty acid		63.27	57.30	32.37	29.18	28.97
Total monounsaturated fatty acid		16.40	24.00	16.23	19.38	30.38
Total poly unsaturated fatty acid		9.70	11.55	43.09	37.82	32.23
Total unsaturated fatty acid		26.10	35.55	59.32	57.20	62.61

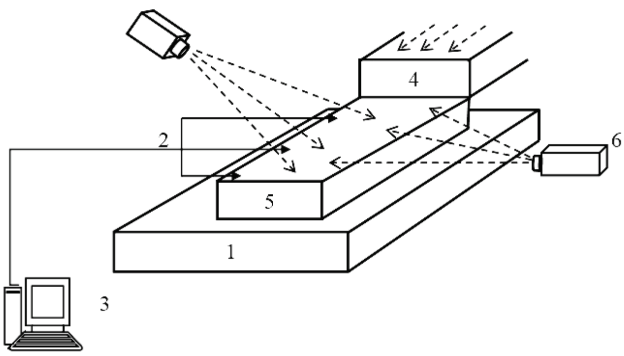


Fig. 1. Experimental apparatus:
1 – heating element; 2 – thermocouple; 3 – data logger;
4 – wind tunnel; 5 – open tray; 6 – high-speed camera

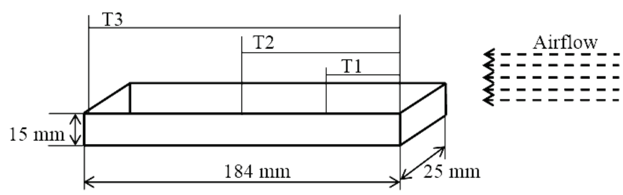


Fig. 2. Thermocouple positions

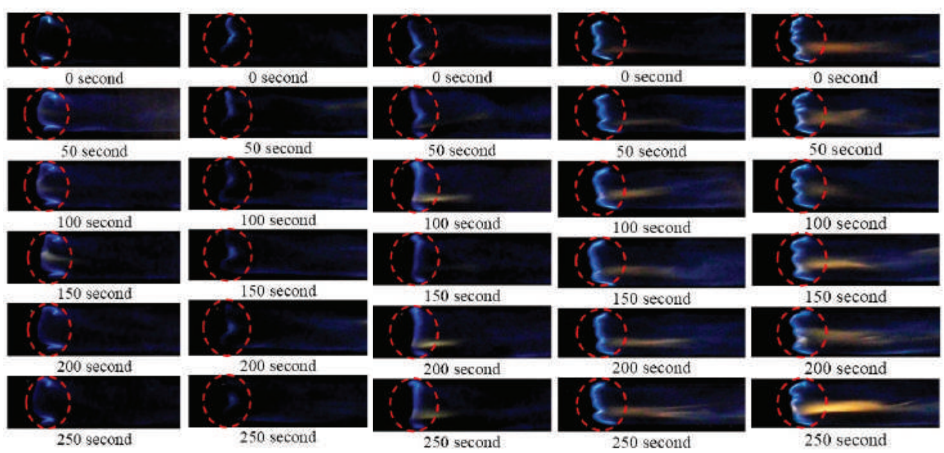
5. The results of the investigation of the fatty acid properties influence on the flame characteristics

5. 1. Effect of oil composition on stability and shape of the flame front

Fig. 3–6 shows the stability and shape of the flame front at various air velocities. Fig. 3 shows that at an air speed of 49 cm/s, the five types of vegetable oils generate flames that are still stable with wavelet form up to 250 seconds. As the air speed increases to 55 cm/s, the flame of the jatropha oil starts to become unstable with the flame from shape changed from 150 seconds, while the other vegetable flame is still stable without a change in the flame front shape as shown in Fig. 4.

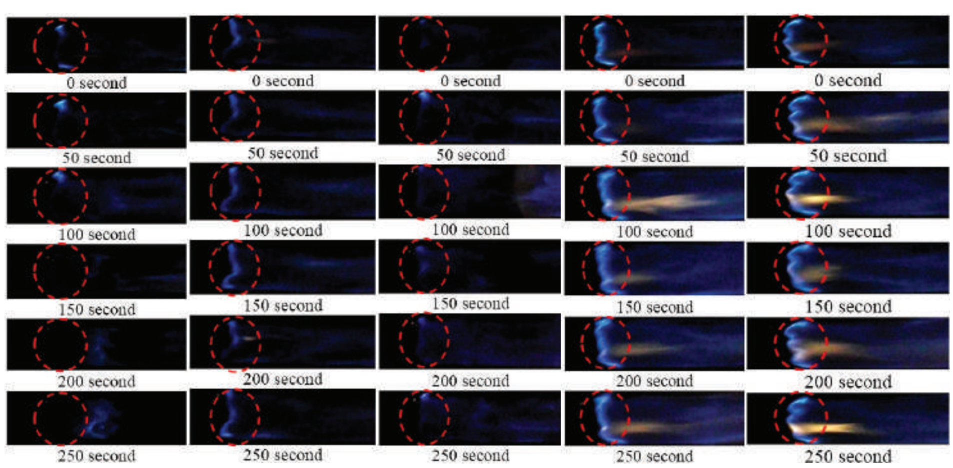
As shown in Fig. 5, when the air speed is further increased to 64 cm/s, the flame of Jatropha curcas oil, Ceiba petandra oil, and Cotton seed oil starts to become unstable with flame front shape modification, while the flame of Palm kernel oil and Coconut oil remains stable without flame front shape modification.

The flame front characteristics of various vegetable oils at various air speeds are presented in Fig. 6. It is shown that the flame of Jatropha curcas oil, Ceiba petandra oil, and Cotton seed oil tends to extinct when the air speed is increased. In other words, they are less stable compared to the flame of Palm and Coconut oil.



a *b* *c* *d* *e*

Fig. 3. Time variation of stability and shape of the flame front at an air speed of 49 cm/sec:
a – Jatropha curcas oil; *b* – Ceiba petandra oil; *c* – Cotton seed oil; *d* – Palm kernel oil; *e* – Coconut oil



a *b* *c* *d* *e*

Fig. 4. Time variation of stability and shape of the flame front at an air speed of 55 cm/sec:
a – Jatropha curcas oil; *b* – Ceiba petandra oil; *c* – Cotton seed oil; *d* – Palm kernel oil; *e* – Coconut oil

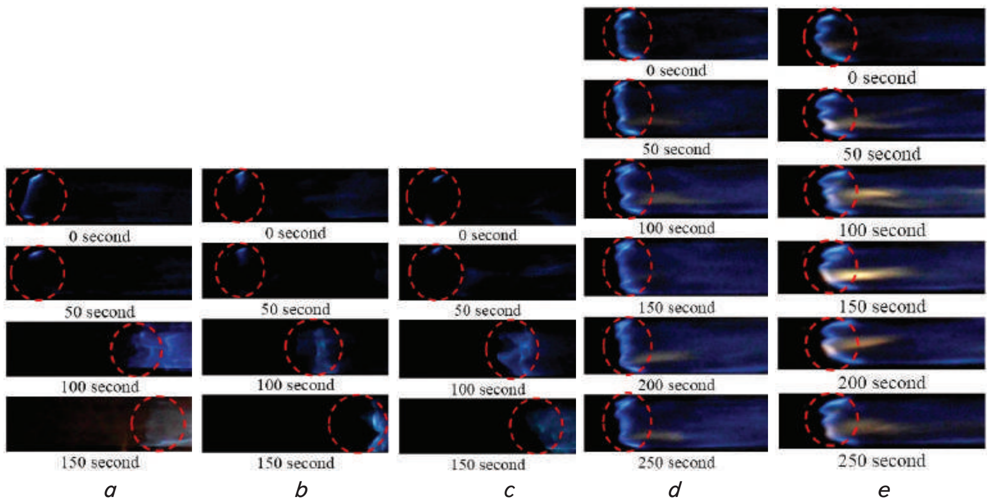


Fig. 5. Time variation of stability and shape of the flame front at an air speed of 64 cm/sec:
a — Jatropha curcas oil; *b* — Ceiba petandra oil; *c* — Cotton seed oil; *d* — Palm kernel oil; *e* — Coconut oil

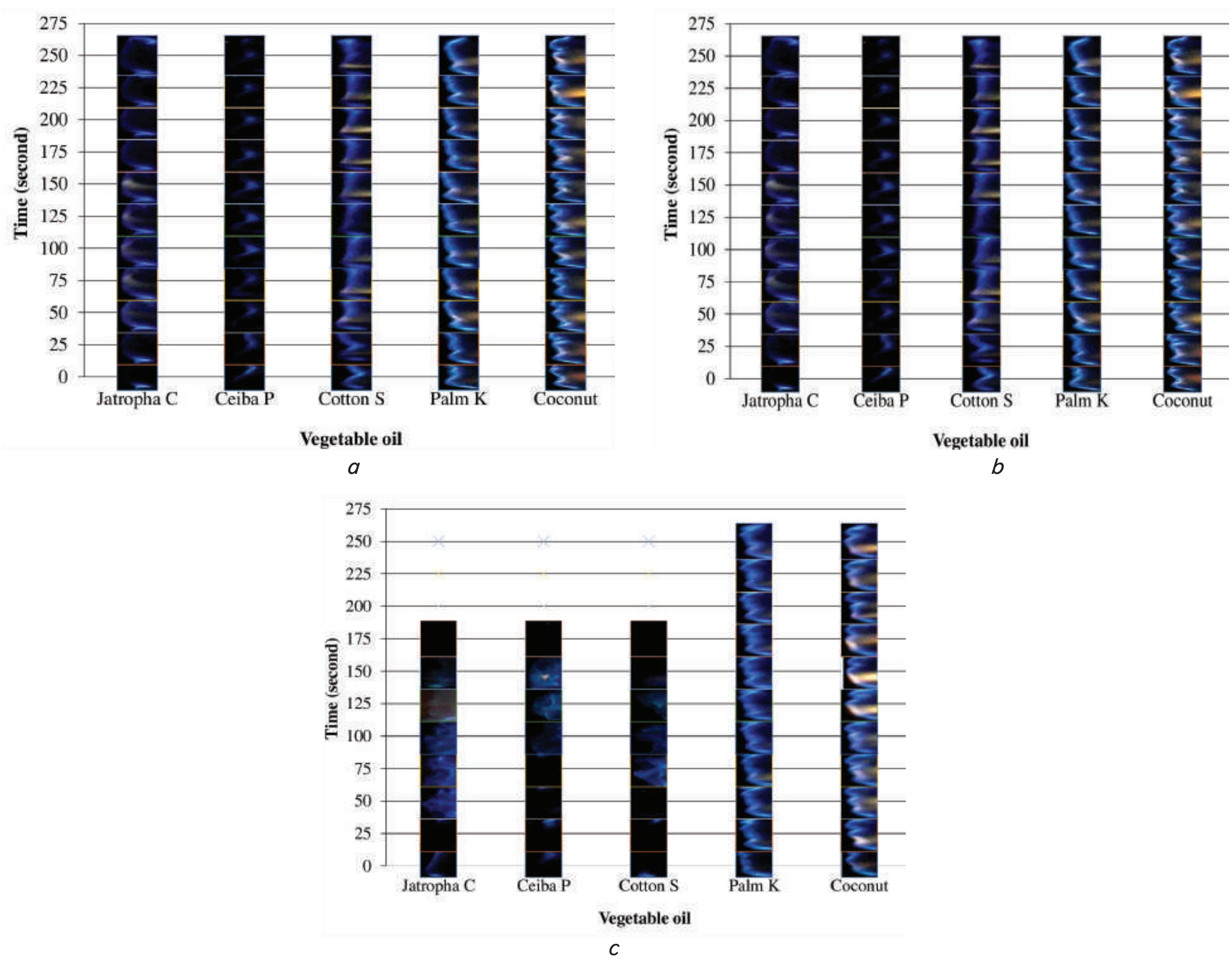


Fig. 6. Time variation of stability and shape of the flame front:
a — air speed 49 cm/sec; *b* — air speed 55 cm/sec; *c* — air speed 64 cm/sec

5. 2. Effect of fatty acid composition on the distance of the flame front to the leading edge of the tray

Fig. 7, 8 show the distance of the flame front to the leading edge of the tray. Fig. 7 shows the position of the flame front of five types of vegetable oils from the leading edge at an air speed of 49 cm/s from 5 to 225 seconds. The distance indicates the flame speed. The shorter distance indicates the faster flame speed. The flame of Jatropha oil has the fastest flame speed whereas Palm kernel oil has the lowest flame speed.

As shown in Fig. 8, by increasing the air speed up to 55 cm/s, the distance of the flame front almost unchanged. This shows that up to the air speed of 55 cm/s, the heat loss from the flame is not enough to change the combustion reaction that changes the flame speed.

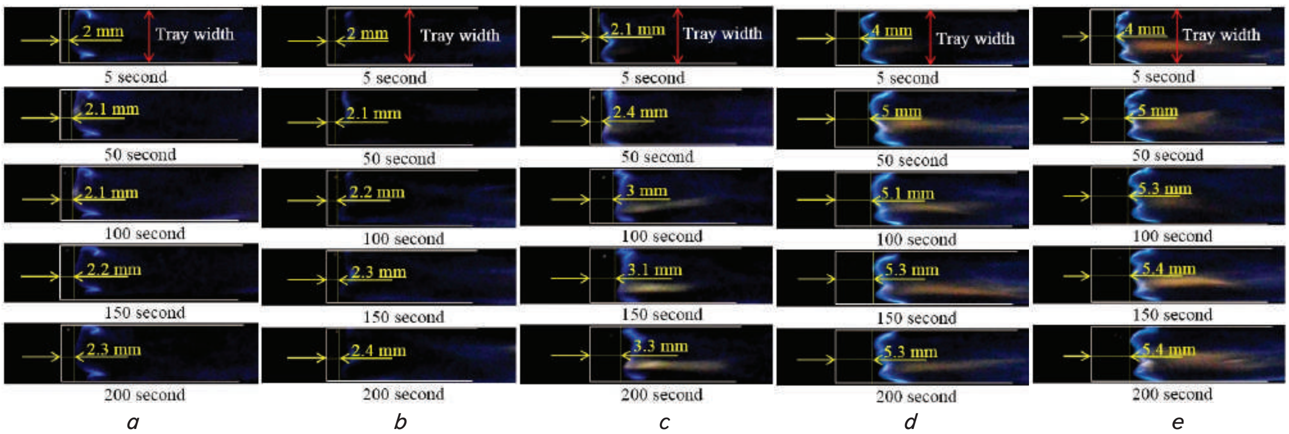


Fig. 7. Flame front distance from the tip of the tray at an air speed of 49 cm/sec:
a – Jatropha curcas oil; *b* – Ceiba petandra oil; *c* – Cotton seed oil; *d* – Palm kernel oil; *e* – Coconut oil

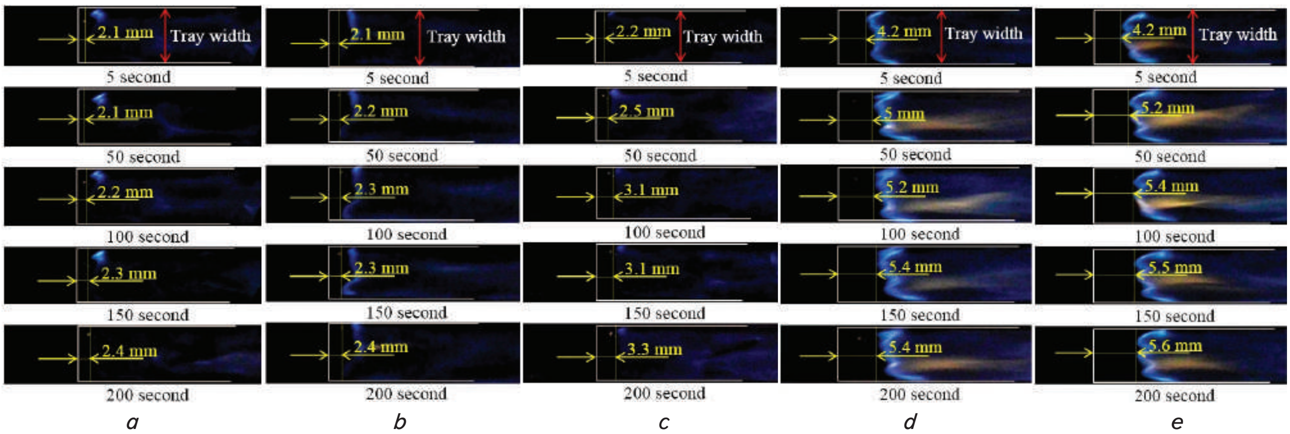


Fig. 8. Flame front distance from the tip of the tray at an air speed of 55 cm/sec:
a – Jatropha curcas oil; *b* – Ceiba petandra oil; *c* – Cotton seed oil; *d* – Palm kernel oil; *e* – Coconut oil

Fig. 9–11 show the comparison of various vegetable oil flame front distances from the tip of the tray at various air speeds. In general, there are two groups of vegetable oil flame distance.

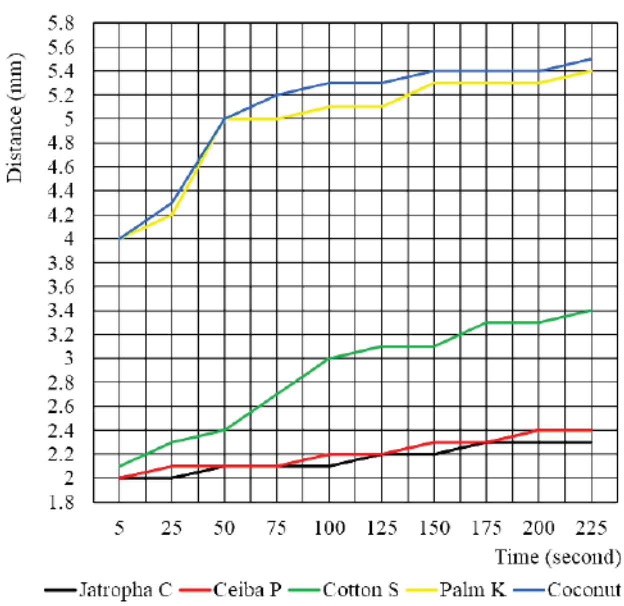


Fig. 9. Flame front distance from the tip of the tray at an air speed of 49 cm/sec

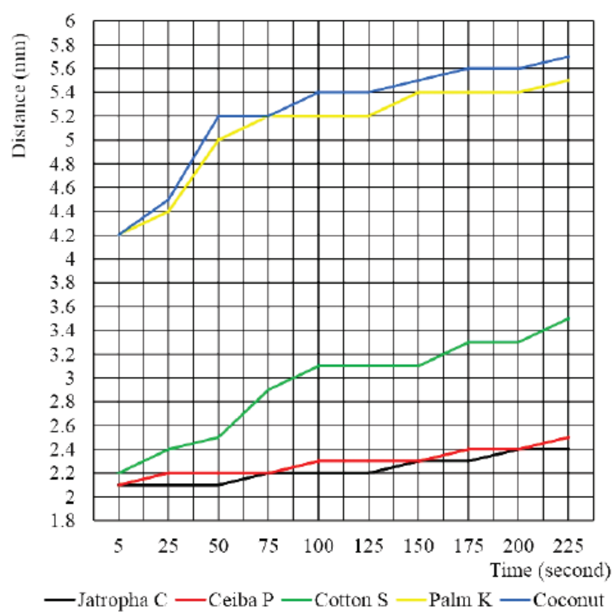


Fig. 10. Flame front distance from the tip of the tray at an air speed of 55 cm/sec

The flames of Jatropha oil, Ceiba Pentandra oil, and Cotton seed oil have short flame front distance from the tip, whereas the flames of Palm oil and Coconut oil have a longer distance from the tip. The flame group with a shorter distance to the tip, namely Jatropha, Ceiba petandra, and Cotton oil flames tends to extinct at an air speed of 64 m/s, indicating that they are less stable.

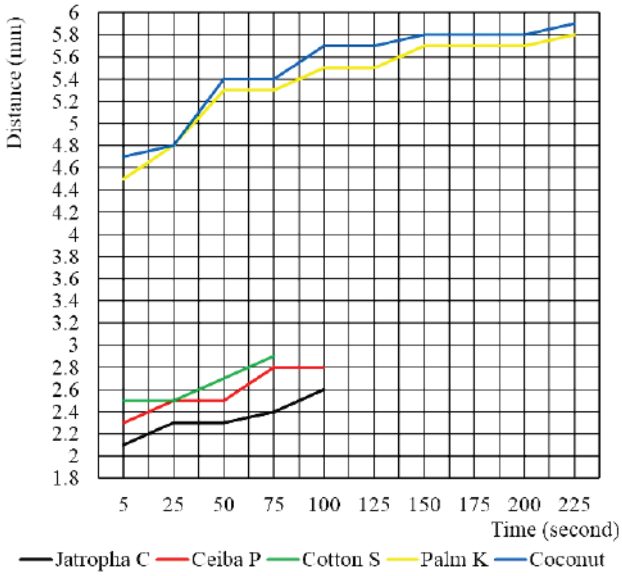


Fig. 11. Flame front distance from the tip of the tray at an air speed of 64 cm/sec

5. 3. Effect of oil composition on flame color

Fig. 12–16 show the variation of flame color of five types of vegetable oils during the burning process from 5 to 100 seconds at an air speed of 49 cm/s. The flame front is thin bright blue indicating the premixed flame followed by the transparent blue indicating transition region from premixed to the diffusion flame in the downstream region.

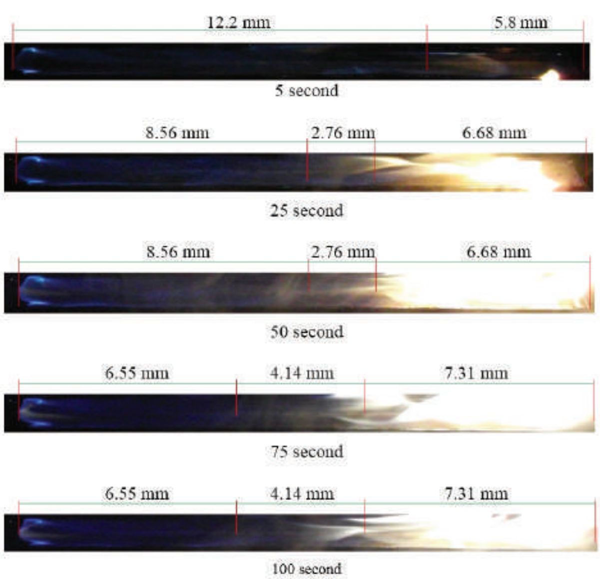


Fig. 12. Jatropha curcas oil flame at velocity of 49 cm/sec

Fig. 17–21 show the quantitative length of the flame region. The flame of Jatropha, Ceiba petandra, and Cotton oils has long premixed flame region, whereas those of Coconut and Palm kernel oil have the very short premixed flame region. It is shown from Fig. 12–21 that the flames of Jatropha curcas oil, Ceiba petandra oil, and Cotton seed oil have less bright color with longer premixed flame region while the flame of Palm kernel oil and Coconut oil has brighter color with shorter premixed flame region indicating that the former three oils are more reactive than the latter two oils. In that case, more carbons are burned in the premixed flame region. Only a few escaped to burn in the diffusion region at the downstream so that the diffusion flame color becomes less bright.

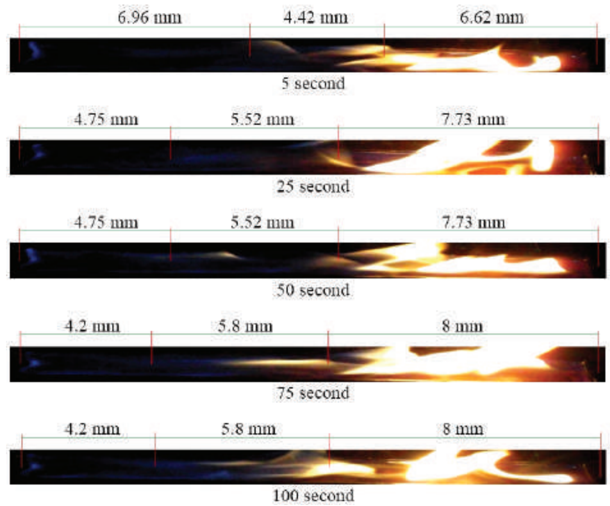


Fig. 13. Ceiba petandra oil flame at velocity of 49 cm/sec

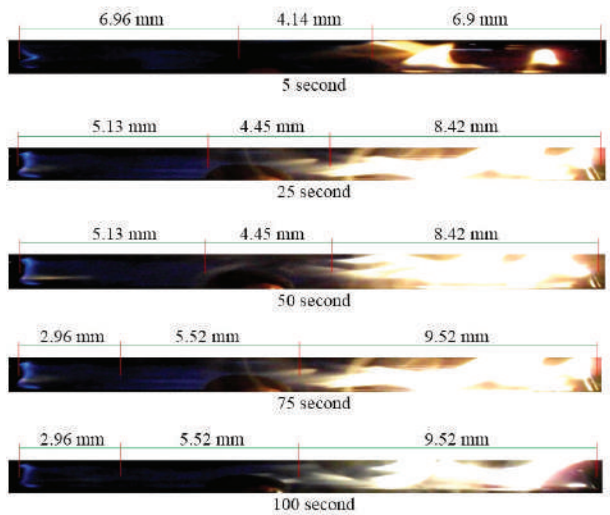


Fig. 14. Cotton seed oil flame at velocity of 49 cm/sec

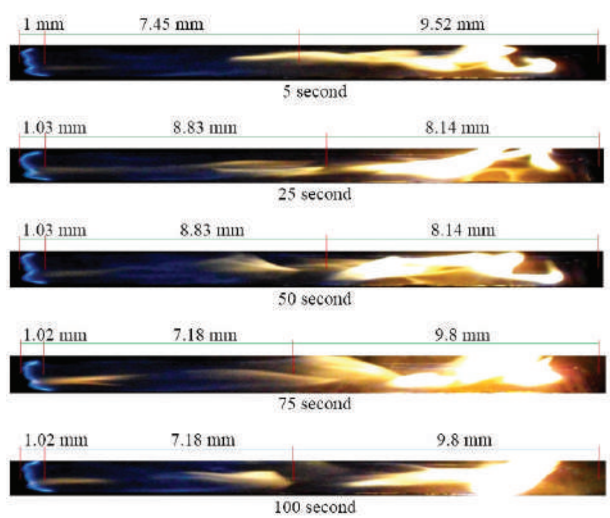


Fig. 15. Palm kernel oil flame at velocity of 49 cm/sec

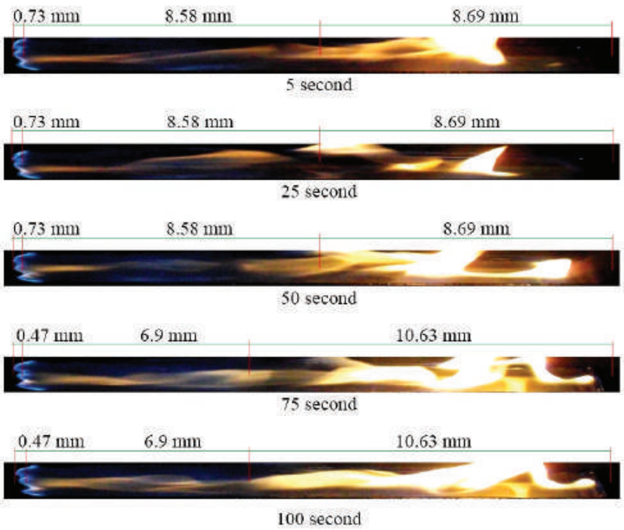


Fig. 16. Coconut oil flame at velocity of 49 cm/sec

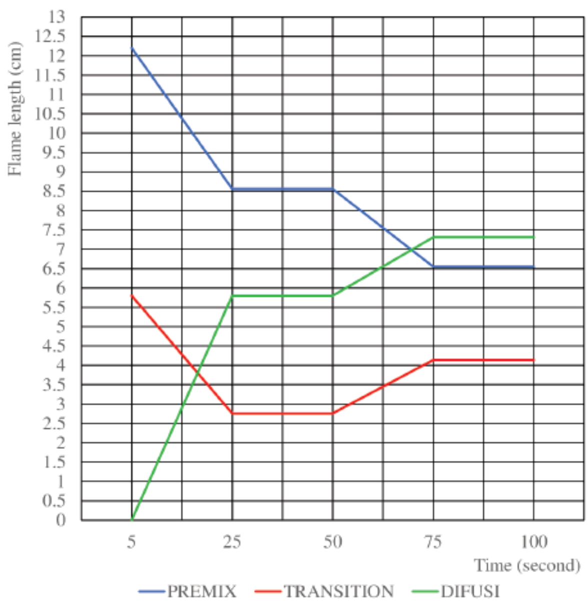


Fig. 17. Flame type of jatropha curcas oil with the air velocity of 49 cm/sec

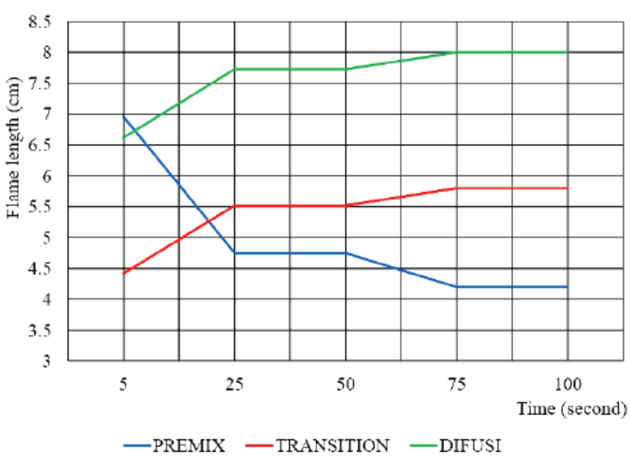


Fig. 18. Flame type of ceiba petandra oil with the air velocity of 49 cm/sec

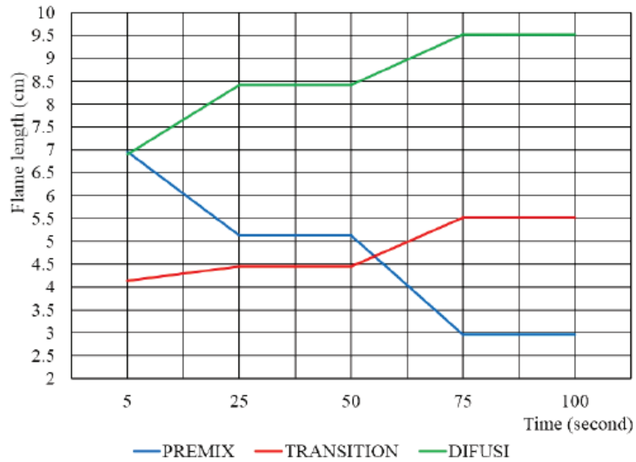


Fig. 19. Flame type of cotton seed oil with the air velocity of 49 cm/sec

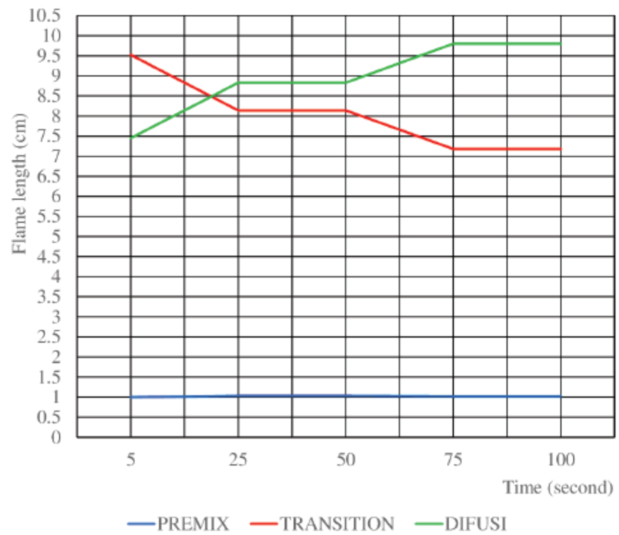


Fig. 20. Flame type of palm kernel oil with the air velocity of 49 cm/sec

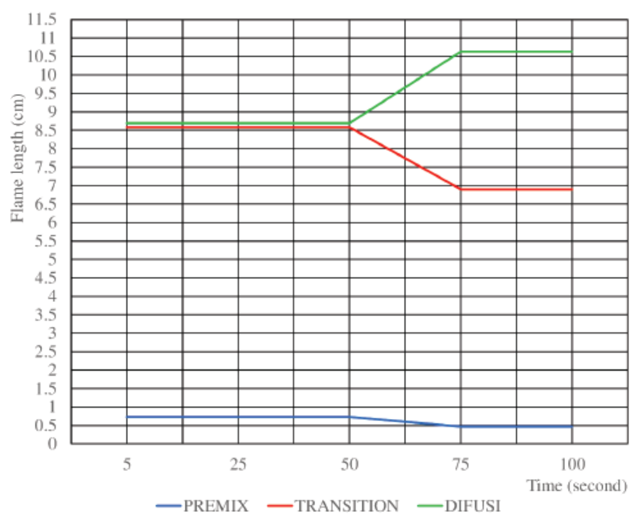


Fig. 21. Flame type of coconut oil with the air velocity of 49 cm/sec

5. 4. Effect of oil composition on flames temperature

Fig. 22–24 show the temperature of the flame at various air velocities. The figures show that each vegetable oil generates the highest temperature at the flame front. This shows that the premixed flame has the highest temperature for the fastest combustion reaction. The higher the air speed the lower the temperature due to the convective heat loss.

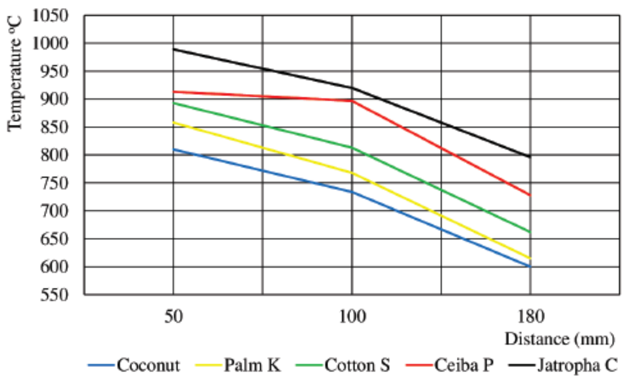


Fig. 22. Flame temperature at various front distance from tip of tray at air speed of 49 cm/sec

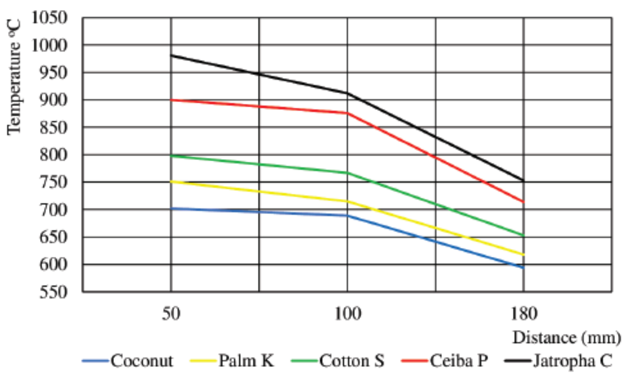


Fig. 23. Flame temperature at various front distance from tip of tray at air speed of 55 cm/sec

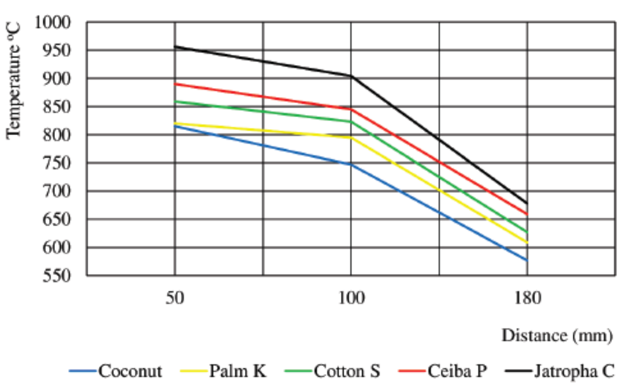


Fig. 24. Flame temperature at various front distance from tip of tray at air speed of 64 cm/sec

From Fig. 22–24 it can be seen that the flame which is dominated by the diffusion flame region tends to have a lower flame temperature than the flame which is dominated by the premixed flame region. The flame temperature of Jatropha, Ceiba petandra and Cotton oils tends to decrease with increasing air speed while those of Coconut and Palm kernel oils almost unchanged with air speed. This shows that the flame with less diffusion flame region is more sensitive to the convective heat loss, indicating that irradiative heat energy from the diffusion flame region plays a dominant role in overcoming the convective heat loss.

6. Discussion of the results of the effect of oil composition at various air speeds on stability and shape of the flame front, the distance of the flame front to the leading edge of the tray, flame color, flame temperature

Fig. 3–6 show that the stability and shape of the flame front of each vegetable oil are different. More stable flame of coconut oil and palm kernel oil compared the other vegetable oils is due to the larger number of the flame fingers and brighter yellow flame color. The flame finger is due to the high content of saturated medium chain fatty acids, lauric acid and myristic acid (Table 1, 3) while the brighter yellow flame is due to high flash point (Table 2) that causes the longer ignition delay. The burning of saturated fatty acids results in a long and stable flame life due to most of carbon atoms of lauric acid and myristic acid escape from the premixed flame region for the high flashpoints and burn with bright yellow color in the diffusion flame region. This region is a good source of radiation heat energy for maintaining the flame stability. It is seen in Fig. 4, 5 that at higher air speed, the flame of Jatropha curcas oil, ceiba petandra oil and cotton seed oil starts to be unstable, lift off and then blow off. This is because of the highly reactive unsaturated fatty acid composition which is very dominant to produce blue and transparent flame. Therefore, the very low thermal radiation cannot overcome the heat loss due to quenching at higher air speed. Vegetable oils burn in three stages, which are combustion stages of unsaturated fatty acids, saturated fatty acids and glycerol. Unsaturated fatty acids are burned in the first stage since it has the lowest flash point. Then 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 2, 3). The constituent components of vegetable oils have very different flash and boiling points as well as reactive properties. The constituent components burn individually and require a longer time. Fig. 3–6 also reveal that oils with 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 oils are highly reactive.

As shown in Fig. 7–8, the group with short flame front distance is oil with high unsaturated fatty acid content (jatropha curcas oil, ceiba petandra oil, and cotton seed oil). This is due to the shorter time it takes to burn. On the other side, the group with long flame front distance is oil with dominant saturated fatty acid composition (coconut oil and palm kernel oil). This is due to the longer time it takes to burn. This confirms that the unsaturated fatty acid is more reactive than the saturated one. The high rate of the flame front streamwise motion or the flame front distance increases of coconut and palm kernel oils is due to the high flash point of saturated fatty acid causing the delay in evaporative time. As shown in Fig. 9–10, at lower air speed the flame of the cotton seed oil has the same trend with coconut oil and palm kernel oil. As tabulated in Table 3, the saturated fatty acid in cotton seed oil is higher than in jatropha and ceiba petandra oils. Consequently, in the beginning, the unsaturated fatty acid is burned and as the time elapse the unsaturated fatty acid tends to vanish and saturated fatty acid begins to take part in the burning process. At high air velocity of 64 cm/s (Fig. 11), the flame of jatropha curcas oil, ceiba petandra oil and cotton seed oil is extinguished at 125 seconds while coconut oil and palm kernel oil have the farthest flame front distance from the tip of the tray at about 5.8 mm. This is due to the fact that the unsaturated fatty acid in jatropha curcas oil is reactive, however, they produce transparent blue with low thermal radiation which is not enough for stabilizing the flame so that the flame extinct. In contrast, the saturated fatty acids in coconut oil and palm kernel oil have a high flash point (Table 2), thus requiring long evaporation time, which produces a yellow flame with higher thermal radiation for stabilizing the flame.

Fig. 12–16 show that vegetable oil burns in 3 stages. In the first stage, the unsaturated fatty acid is burned in the flame front for its lowest flash point (Table 1) which is followed by the burning of saturated fatty acids at stage two and the combustion of the glycerol at the third stage at the downstream for its hygroscopic nature. The thick bright blue in the flame front indicates the reaction zone of premixed combustion. This is the unsaturated fatty acids which have the lowest flash point and is reactive, easily evaporated and easily mixed with air to burn in premixed blue flame but less stable because less heat radiation to maintain stability. The transparent blue flame downstream of the premixed flame front is the secondary flame of saturated fatty acid that escapes from the premixed reaction zone and burns in the second stage of combustion. When the saturated fatty acid content starts to run out while the glycerol begins to evaporate, in this condition the saturated fatty acids begin to infiltrate and get trapped in glycerol. The bubble pressure of saturated fatty acid vapor increases and finally at a certain pressure the bubble explodes into a micro explosion. This micro explosion causes a bright flame in the third stage that provides thermal radiation for stabilizing the flame. The length of diffusion flame with yellow color tends to increase as the time elapse from 5 to 100 seconds indicating that the saturated fatty acids and glycerol take time to evaporate. This is because the long-chain fatty acids and glycerol are difficult to burn for they are less reactive, less volatile and difficult to mix with air so that they escape to the downstream to burn as a diffusion flame with yellow color. This yellow color is due to soot radiation that serves as a heat supplying the flame to become stable. The diffusion flame of coconut oil is the longest and the flame tends to be shorter and shorter in palm kernel oil, cotton seed oil, ceiba petandra oil, and jatropha curcas oil due to the lesser in saturated fatty acids content. Highly unsaturated fatty acid content makes the premixed flame thinner. The lesser the unsaturated fatty acids the thicker the premixed flame due to the reaction takes longer time than the reactant transit time. The longer yellow diffusion flame region at the more saturated fatty acid content, however, provides higher radiation thermal energy stabilizing the thicker premixed flame. It can be seen from Fig. 16 that the wavelet number of the premixed flame front tends to increase with increasing the saturated fatty acid content in the oil. This is due to the fact that the unsaturated fatty acid reacts faster so that the flame speed is high and makes the flame propagate forward. In contrast, the saturated fatty acid reacts slower so the flame speed is lower and makes the flame move backward. The silhouette yellow color that emerges from the trough of the wavelet confirms that the saturated fatty acid creates the wavelet flame. The wavelet structure constructs inverted flame that balances the transport of heat and reactant mass to the reaction zone. This is the other factor that stabilizes the flame together with thermal radiation from the yellow flame.

Fig. 22 shows jatropha curcas oil with the highest temperature reaching 989 °C, followed by ceiba petandra oil 913 °C, cotton seed oil 893 °C, palm kernel oil 858 °C and coconut oil 810 °C at the air velocity of 49 cm/sec. As the air velocity increases, the flame temperature decreases and the lowest temperature at the air velocity of 64 cm/s also occurs at the coconut oil flame. The higher the velocity of air the steeper the streamwise temperature drops shown in Fig. 24. The flame temperatures of vegetable oils are influenced by several factors, namely carbon chain and the number of double bonds (indicating the degree of unsaturation). Increased heat from burning saturated fatty acids is characterized by an increase in the amount of carbon. These characteristics greatly affect many physical and chemical properties, such as: viscosity, density, cetane number and calorific value and therefore have a significant impact on ignition delay [14, 15]. Unsaturated fatty acids have double bonds. The doubled and tripled bonds cause the molecule to become weak and make them unstable, highly reactive and oxidize more readily, all of which causes them to burn faster. This is due to unsaturated fatty acids have the lowest flash point (Table 2). The high combustion rate results in higher flame temperature. The energy releasing rate was influenced by three factors, i. e. flash point, caloric value (Table 2) and combustion duration (Fig. 3–6). Jatropha curcas oil has the lowest flash point and the highest caloric value compared to other vegetable oils. Therefore, jatropha curcas oil has the highest temperature from other vegetable oils.

This study gives insight into the influence of fatty acid chemical structure and physical properties on the combustion characteristics for thermal energy production. When high-temperature gas is needed in the industrial furnace, vegetable oils with unsaturated fatty acids like Jatropha, Ceiba petandra, and cotton oil are the choice by keeping the lower air speed. But when the industrial furnace with stable combustion process is the goal, the oil with saturated fatty acids like Coconut and Palm kernel oil is the choice.

7. Conclusions

1. The large content of lauric acid and myristic acid and high flash point in coconut oil and palm kernel oil cause the delay in combustion that move the flame downstream to the longest flame front distance from the tip of the tray. At the downstream, its combustion produces the brightest yellow color that maintains the stable flame.

2. The number of wavelet on the flame front depends on the content of saturated and unsaturated fatty acids. The unsaturated fatty acid burns faster and causes the flame to propagate faster forward while the saturated fatty acid reacts slower and causes the flame to propagate slower moving backward. The greater wavelet number at the flame front stabilizes the flame since the lower flame speed produces inverted premixed flame and shoot that irradiates heat to the flame.

3. Jatropha curcas oil has the longest period of premixed transition and blue flame color, but is unstable due to the absence of radiant heat sources. Coconut oil has the longest diffusion yellow flame color because medium chain saturated fatty acids and glycerol have high flash points that become difficult to burn and eventually escape from the reaction

zone. The escape of saturated fatty acid and glycerol from the reaction zone results in the formation of soot resulting in a diffusion/yellow flame.

4. The highest combustion temperature is produced by jatropha curcas oil. This is influenced by the low viscosity, flash point and high caloric value of jatropha curcas oil.

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