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Phase behavior and important fuel properties of diesel-palm fatty acid distillate-anhydrous ethanol blends

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Abstract. Phase behavior and important fuel properties of diesel-palm fatty acid distillate (PFAD)-anhydrous ethanol blends were studied to prove that if PFAD mainly containing free fatty acid (FFA: $C_{15.97}H_{31.87}COOH$), a cetane like molecule that has 1-polar head and 1-nonpolar tail with inherent oxygen, was able to be used as the diesel extender, cetane improver, and the emulsifier for diesohol production. First, diesel-PFAD-ethanol blends between 0-100 wt.% of each component at every 10 wt.% interval were prepared and kept motionless at room temperature for 90 days. It was found that the clear liquid PFAD-diesel and diesel-PFAD-ethanol blends with long-term stability was obtained for PFAD ≤10 and ≤50 wt.%, respectively. Then, important fuel properties of diesel and the blends of interest at (2.5, 5.0, 7.5, and 10 wt.%) PFAD and (10, 20, 30, and 40 wt.%) PFAD-(10 and 20 wt.%) ethanol were tested according to standard test methods of ASTM. The results revealed that the pour points and viscosities of PFAD-diesel blends slightly increased for PFAD ≤7.5 wt.% and increased greatly at 10 wt.% PFAD. Moreover, also found that ethanol really acted as a cold-flow property improver of the blends, resulting the pour points and viscosities of diesel-PFAD-ethanol blends slightly increased for PFAD ≤30 wt.%. The cetane numbers of all the blends were high with the highest value at 65.7 of TB5. Although titrated acid values of the blends were quite high, copper strip corrosion properties of all blends and diesel were the same of No.1a. The lubricities of the interest were 15.5-46.1% better than that of commercial diesel. Other properties of the blends, except at 40 wt.% PFAD, were comparable with diesel and met the regulations of Thailand standard for high speed diesel. However, in conclusion, the FFA in PFAD renders it a high cetane, weakly acidic, and good lubricity molecule that can be directly used as a diesel extender, cetane improver, and the effective emulsifier for diesohol production while ethanol can effectively improve the cold-flow properties of the blends for direct used of PFAD as the diesel extender. Moreover, the liquid blends tested were also able to be used as the novel diesel substitute.

1. Introduction

Alternative fuels and additives for improving fuel properties from agricultural products such as vegetable oils, by-products from the vegetable oil industry and bio-ethanol are currently being intensively researched and developed worldwide. These researches help to solve the energy crisis and global environmental problems. Especially, carbon dioxide emissions into the atmosphere. In addition for agricultural countries like Thailand, these researches also help encouragement the country's economy.

For research and development to use bio-ethanol as a diesel substitute fuel by blending with diesel (diesohol). In America, there is a great progress of research, and development into a trade policy plan [1]. Vallinayagam et al. (2015), Jin et al. (2011), Shahir et. al. (2014), Shahir et. al. (2015), and Mofijur et. al. (2016) have reviewed the progress and pointed out the great obstacles and possibilities of the production and fuel properties of diesohol such as: i) ethanol has limited solubility and blending to diesel and when the water is mixed, the phase separation of the blend will intensify; ii) cetane number (CN) of ethanol are much lower than diesel so blending 10 vol. % ethanol in diesel decreases CN by approximately 30%, and iii) when ethanol was blended in diesel, it affects to viscosity, lubricity, heating value and flash point. It is therefore necessary to use an additive and/or co-solvent to improve the blending ability and the fuel properties of diesohol [7, 8]. In America, there are many companies that develop additives for the production of diesohol [9]. Pure energy corporation (PEC) of New York is the first company that develop additive which was blended 2-5 vol. % with anhydrous ethanol. The second, AAE Technologies of the United Kingdom, tested the use of 7.7% and 10% ethanol-diesel blends by adding 1% and 1.25% AAE additives. And the last, GE Betz develops additives from petroleum products, compared to the first two types, which are made from renewable resources. In Germany, Apace Research Ltd. reports the success of 84.5% diesel blend with 15% ethanol (5% water) and their additive 0.5 %.[10, 11]. Currently, research and development of diesohol in Thailand is not very. In 1998, there was a joint project between PTT Public Company Limited, Ford Motor Company, and National Metal and Materials Technology Center (MTECT) to study the potential of using diesohol as a diesel substitute by mixing 10 vol.% ethanol with 89 vol.% diesel and 1 vol.% imported additives (Beraid ED10 from Akzo Nobel) [12]. However, because the use of additives and co-solvent from abroad is very expensive, thus research and development of additives and co-solvent produced from domestic raw materials is very necessary.

Palm fatty acid distillate (PFAD) is a cheap byproduct from the palm oil industry, which amount of ≈5% of raw material. Each year, Thailand has PFAD about 100,000 tons. Generally, PFAD appears a soft solid with white-yellow color at room temperature and it becomes a clear liquid with light brown color when it is heated up to the temperature of ≈50 °C. Normally, PFAD is used as raw material in animal feed, cosmetics, soap [13, 14], traditional fuels such as candle production and directly used in industrial boilers [15]. Tamiyakul et al. (2016) studied the conversion of PFAD to aromatic to use as raw material in the petrochemical industry. Syahrullai et al. (2013) studied the mixing of PFAD with petroleum oils to use as a lubricant. Shotipruk et al. (2009) studied the transformation of PFAD to hydrogen. There are many research studies on the conversion of PFAD to liquid fuels to use as a diesel substitute. Most research involves the production of esters of fatty acids (biodiesel) by esterification processes at both high pressure and atmospheric pressure [15, 19-23]. However, to date, there has not been found that PFAD is used as a substitute for diesel or an emulsifier for diesohol production. Under hypothesis; i) the FFA molecular structures of PFAD consist of the both of a polar head (-COOH) bonding with ethanol molecules and a non-polar tail ($-C_{15.97}H_{31.87}$) bonding with diesel molecules and ii) PFAD can improve CN and combustion characteristics of diesohol because the FFA molecules of PFAD ($C_{15.97}H_{31.87}COOH$) are similar to cetane ($C_{16}H_{34}$), PFAD might be used as a diesel extender, a cetane improver, and an emulsifier for diesohol production.

Therefore, this work aimed to demonstrate that PFAD can be directly used as the diesel extender, the cetane improver, and the emulsifier for diesohol production. However, there were a number of important points that had to be established, especially a stable liquid PFAD-diesel and diesel-PFAD-ethanol blend were capable of production and its fuel properties were suitable for use as diesel substitute. Thus, the long-term phase behavior and important fuel properties of PFAD-diesel and diesel-PFAD-ethanol blend were investigated.

2. Materials and methods

The PFAD used was purchased from Suksomboon Palm Oil, Co., Ltd, Chonburi, Thailand. The compositions of PFAD, which were analyzed by thin layer chromatography/flame ionization detector, were 93.8 wt.% free fatty acid (FFA), 1.9 wt.% triglyceride (TG), 2.2 wt.% diglyceride (DG), and 2.1

wt.% monoglyceride (MG). The commercial grade anhydrous ethanol, which was purity of 99.9%, was used in this work. The high speed diesel (HSD) used was purchased from a PTT fuel station in Songkhla, Thailand. According to regulations issued in 2015, Commercial HSD in Thailand has to contain 6-7 vol.% fatty acid methyl esters (FAME).

To investigate its long-term phase behavior, diesel, PFAD, and ethanol was blended in the desired portions (0-100 wt.%) at every 10 wt.% interval. All the samples were prepared in closed cap glass vials with the total weight of each sample being 10 g with each component being weighed within a tolerance of ±0.05% using a METTLER digital balance model AL204 (resolution of 0.0001 g) and well mixed by simple splash blending by handshaking for 1 minute at the temperature of 50±5 °C. Finally, all the samples were kept motionless at room temperature which varied daily within a range of 24-36 °C for 90 days to observe their long-term phase behavior.

To investigate its fuel properties, For PFAD-diesel blends, for each batch, PFAD and diesel were weighed in desire portion in a 2 liter beaker with a total weigh of 1,000 g., heated on a hot plate, and agitated using a 6-blade disk turbine (dimeter, 70 mm) driven by an electric motor at 275±25 rpm and a temperature of 50±5 °C for 10 minutes, then the PFAD-diesel blend was obtained. For diesel-PFAD-ethanol blends, the first step, PFAD and ethanol were blended together in desire portion in a 2 liter beaker, heated on the hot plate, and agitated using a magnetic bar stirrer at 500 rpm and a temperature of 50±5 °C for 5 minutes. In the next step, diesel was added to the beaker in desire portion which the total weigh of the each batch of 1,000 g, agitated using the 6-blade disk turbine driven by the electric motor at 275±25 rpm for 10 minutes, then the diesel-PFAD-ethanol blend was obtained

The important fuel properties of the samples of interest were tested for their cetane number and lubricity at the PTT Research & Technology Institute, Thailand, according to ASTM D613 and CEC F06-A-96 (using a high-frequency reciprocating rig (HFRR) compliant with ASTM D6079), respectively. Additionally, the cloud point, pour point, kinematic viscosity, acid value, copper strip corrosion, density, heating value, flash point, distillation 90% recovery, carbon residual, and sulfate ash content were tested according to ASTM D2500, ASTM D97, ASTM D445, ASTM D664, ASTM D130, ASTM D1298, ASTM D240, ASTM D93, ASTM D86, ASTM D189, and ASTM D482, respectively, at the Scientific Equipment Center and Chemical Engineering Laboratories, Prince of Songkla University, Thailand. The findings from the different blends were then comparatively evaluated with the regulated levels of these properties according to Thai standards of HSD, low speed diesel (LSD), and community biodiesel for agricultural engine (CBAE).

3. Results and discussions

3.1. *Phase behavior of diesel-PFAD-ethanol blends*

For PFAD-diesel blends, the experimental results for the long-term phase behavior of all the blends at the 90 day are shown in Fig. 1a. Most importantly, the results revealed that a stable liquid blend (10 wt.% PFAD) was able to be produced. Hence, the liquid blends of interest of 2.5, 5, 7.5, and 10 wt.% PFAD were then prepared as shown in Fig. 1b for further investigating the effect of PFAD on the important properties of the fuel.

For diesel-PFAD-ethanol, the experimental results for the long-term phase behavior of all the blends at 10 and 20 wt.% ethanol at the 90th day are shown in Figure 1c and 1d, respectively. Most essentially, the results shown that the ethanol can significantly increase the blending portions of PFAD for a stable liquid blend production to 40 and 50 wt.% for 10 and 20 wt.% ethanol, respectively meanwhile the PFAD can effectively improve the blending ability between diesel and ethanol. Therefore, the liquid blends of 10, 20, 30, and 40 wt.% PFAD at 10 and 20 wt.% ethanol were further investigated the effect of PFAD and ethanol on the important fuel properties.

3.2. *Important fuel properties of the blends of interest*

3.2.1 Effect of PFAD and ethanol on cloud point and pour point

Cloud point and pour point, which indicate the temperature at which a liquid fuel becomes a cloudy fuel

(a) 0 – 100 wt.% PFAD **(b)** 0 – 10 wt.% PFAD

(c) 0 – 90 wt.% PFAD at 10 wt.% ethanol **(d)** 0 – 80 wt.% PFAD at 20 wt.% ethanol

Figure 1. Long-term phase behavior at room temperature of the blends.

and the fuel cannot be poured respectively, are important cold flow properties of diesel fuel. Figure 2a shows the results of cloud point and pour point of PFAD-diesel blends. It can be seen that at the blending portions of PFAD were less than or equal to 7.5 wt.%, the cloud points of the blends were also equal to diesel while the pour point of the blends only slightly increased from diesel. However, when PFAD was blended at 10 wt.%, the cloud and pour points suddenly increased. Figure 2b shows the results of cloud point and pour point of diesel-PFAD-ethanol blends at the blending portions of ethanol of 10 and 20 wt.%. Most importantly, ethanol can effectively improve the cold flow properties of the blends. It can be seen that PFAD can be blended up to 20 wt.%, the cloud points of the blends and diesel were also the same while the pour point of the blends only slightly increased from diesel. When PFAD was blended at 30 wt.%, the both of cloud point and pour point were slightly higher than that of diesel. And then PFAD was blended at 40 wt.%, the cloud point and pour points suddenly increased. In summary, the cold flow properties of the PFAD-diesel and diesel-PFAD-10 and 20 wt.% ethanol blends up to 7.5 and 30 wt.% PFAD, respectively met the regulated levels of all the relevant Thai standards. The pour point of TB10, TB541, and TB442 also met the standards for LSD and CBAE and was only slightly higher than the regulated level for HSD. Thus, this blend is also suitable for use as a diesel substitute for LSD, CBAE, and even HSD, especially in a warm climate.

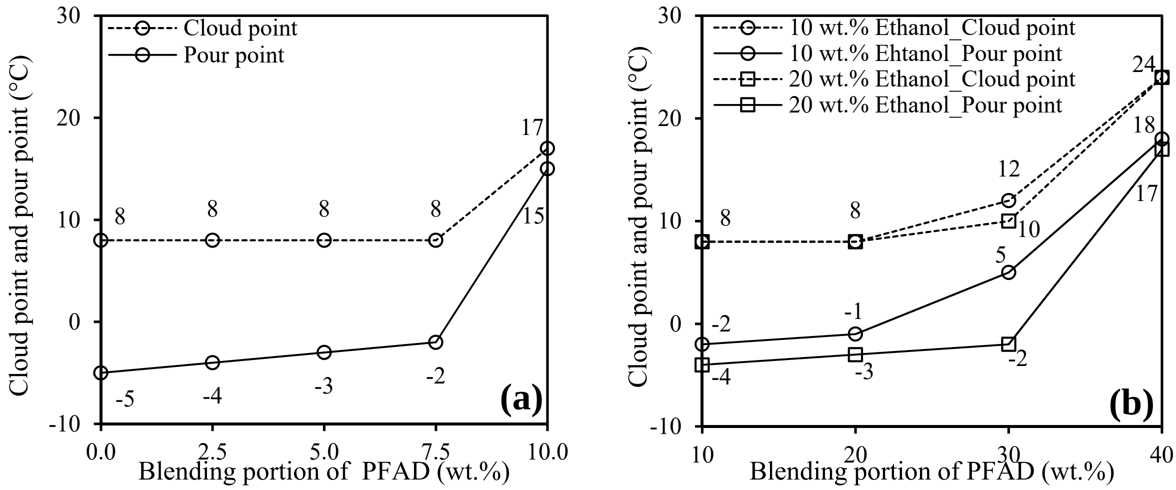

Figure 2. Effect of PFAD and ethanol on cloud point and pour point : (a) PFAD-diesel; (b) diesel-PFAD-ethanol.

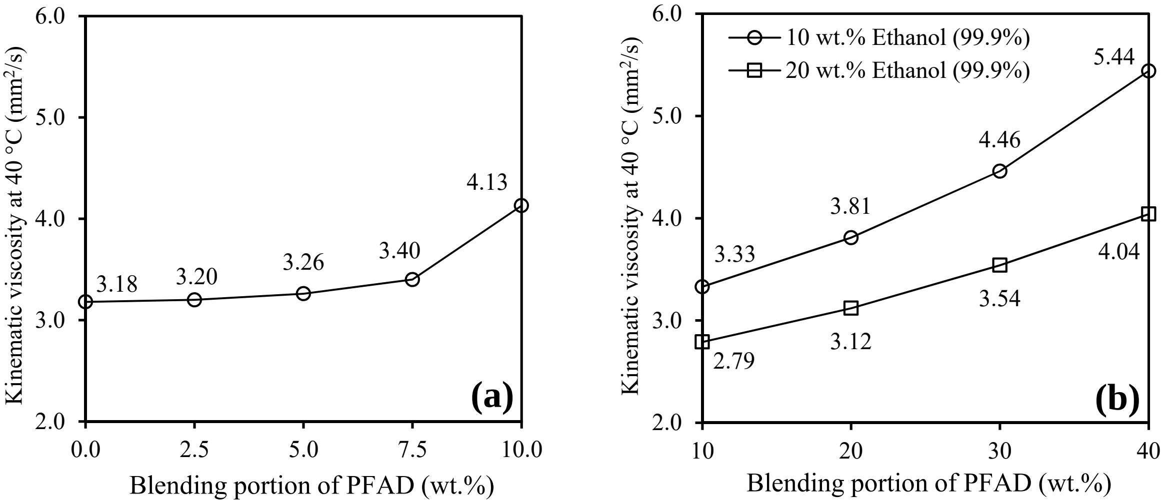

Figure 3. Effect of PFAD and ethanol on kinematic viscosity : (a) PFAD-diesel; (b) diesel-PFAD-ethanol.

3.2.2 Effect of PFAD and ethanol on kinematic viscosity

The kinematic viscosity is an important flow property of diesel fuel which significantly affects fuel injection and atomization, consecutive combustion behavior, and also engine performance and emission Figure 3a shows the results of kinematic viscosity at 40 ºC of PFAD-diesel blends. The result illustrated that the kinematic viscosity slightly increased at the portion of PFAD ≤7.5 wt.% and suddenly increased for the blended with PFAD 10 wt.%. For the results of kinematic viscosity at 40 ºC of diesel-PFAD-ethanol blends are shown in Figure 3b. Ethanol has the kinematic viscosity at 40 ºC of 1.08 mm^2/s which was 66% lower than diesel. Therefore, the use of ethanol as a blended fuel will reduce the viscosity of the blends significantly. It can be seen that at 10 wt.% PFAD when blended with 10 wt.% ethanol, the kinematic viscosity of the blend decreased from 4.13 mm^2/s (10 wt.% PFAD-diesel) to 3.36 mm^2/s which is only 4.7% higher than diesel (from 30%) and increased in portion to PFAD with 71 % higher than the diesel at 40 wt.% PFAD. And when the blending portion of ethanol was increased to 20 wt.%. It can be seen that the blends of PFAD ≤20 wt.% had kinematic viscosity slightly lower than diesel (-12.3 to -1.3%), as a result of low viscosity of ethanol and then the blending portion of PFAD was increased to 30 and 40 wt.%, the kinematic viscosity of the blends was increased and higher than diesel of 11.3 and 27%, respectively. However, in summary, although the kinematic viscosities of all the PFAD-diesel blends were slightly higher than that of diesel, they completely met all the relevant Thai standards, except the 10 wt.% PFAD blend for which the viscosity was slightly higher than the regulated level of HSD. In addition, the use of ethanol as the blended fuel can effectively improve the viscosity of the blends while PFAD can improve the viscosity of the blends to not too low. The results reveal that for the blends of 10 wt.% ethanol and PFAD ≤20 wt.%, they completely met all the relevant Thai standards. When PFAD was blended at 30 and 40 wt.%, the kinematic viscosities of the blends only met the standards for LSD and CBAE. And the kinematic viscosities of all of the blends of 20 wt.% ethanol completely met all the relevant Thai standards.

3.2.3 Effect of PFAD on cetane number

Cetane number is defined as the ease which diesel fuel ignites. Operating diesel engines with fuel with an inadequate cetane number results in poor starting characteristics and significantly higher levels of noise, fuel consumption, and exhaust emissions. Thus, in general, a high cetane number is a desirable feature of diesel fuel. [24]. The results for cetane number of all the samples are shown in Fig. 4.

Figure 4a shows the results of CN of the PFAD-diesel blends. It can be seen that CN of all of the blends were much higher than that the regulated levels of all the relevant Thai standards. The CN of the commercial diesel was as high as 65.3 because it also contained the high cetane number molecule,

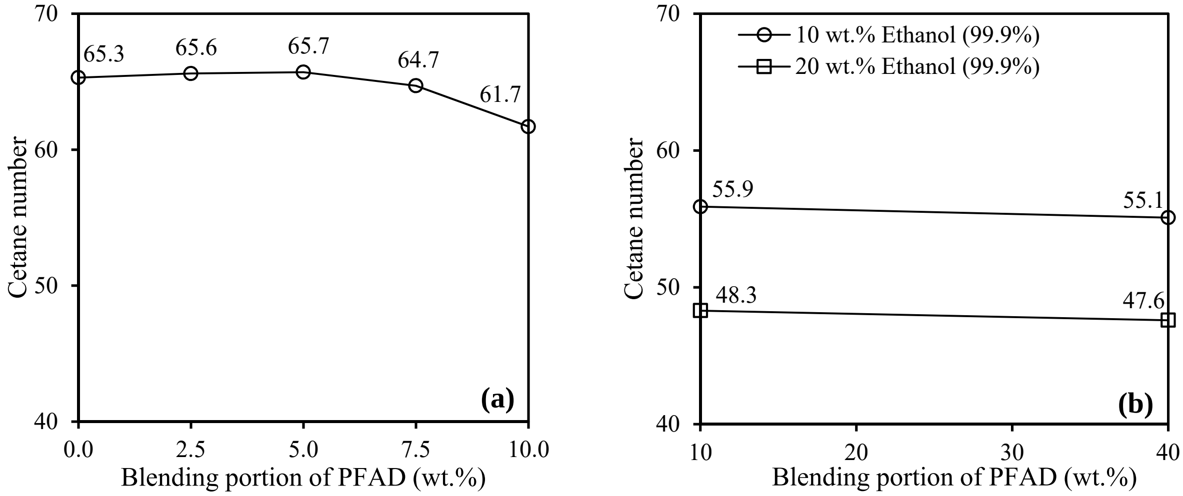

Figure 4. Effect of PFAD and ethanol on cetane number : (a) PFAD-diesel; (b) diesel-PFAD-ethanol.

FAME at 6-7 vol.%. This result agrees well with the tested cetane number of petroleum diesel with 5 vol.% added FAME [25]. In addition, Figure 4a also show that at the blending portion for PFAD ≤5 wt.%, the CN of the blends was slightly increased. Although the CN of these blends did not increase significantly, these results also illustrated that FFA molecules of PFAD which are similar to cetane are actually the molecule with a high CN as earlier hypothesized. When blending portions of PFAD were increased up to 7.5 and 10 wt.%, the CN of these blends slightly decreased. This is a result of increased viscosity which effects fuel injection and atomization, and combustion behavior. The results of effect of ethanol on CN was shown in figure 4b. The results revealed that ethanol had a great effect on CN because it is quite low CN about 5-6. It also can be seen that at the blending portion of PFAD was 10 wt.%, when ethanol was blended at 10 and 20 wt.%, CN of these blends was decreased about 9.4 and 21.7 % respectively. When PFAD was blended at 40 wt.%, CN of the blends slightly decreased. However, in summary, although the CN of all the diesel-PFAD-10 and 20 wt.% ethanol blends was very lower than that of diesel (-14.4 and -26.0% respectively), they also completely met all the relevant Thai standards, except the 40 wt.% PFAD and 20 wt.% ethanol blend for which the CN was slightly lower than the regulated level of HSD.

3.2.4 Effect of PFAD and ethanol on acid value, copper strip corrosion, and lubricity

PFAD and ethanol contain molecular structures of carboxyl group (-COOH) and hydroxyl group (-OH), respectively, which were acidic molecule. Thus, when these were used as a fuel, it might affect the high corrosive wear in the fuel system and engine parts. The titrated acid value results of diesel, PFAD, and ethanol were 0.05, 230.8, and 0.2, respectively. Figure 5a and 5b show the results of the acid values of PFAD-diesel blends and diesel-PFAD-ethanol, respectively. It can be seen that the acid values of the blends increased linearly with the portion of PFAD while diesel and ethanol did not significantly affect the acid value of the blends. However, the copper strip corrosion results of all the blends and diesel were the same of No. 1a which met the regulated levels of all the relevant Thai standards. This meant that the molecular structures of PFAD and ethanol were only weak acid and did not affect the high corrosive wear. In a previous study, similar results were reported of a blend of degummed mixed crude palm oil with diesel, with high acid values [26, 27].

In addition to corrosive were, friction wear of the some moving parts, such as fuel pumps and fuel injectors, due to the poor lubricity of the fuel was another important point that had been studied. The lubrication mechanism is a combination of hydrodynamic lubrication and boundary lubrication. In hydrodynamic lubrication, a layer of liquid prevents contact between the opposing surfaces. Fuels with higher viscosities will provide better hydrodynamic lubrication. Boundary lubrication are compounds

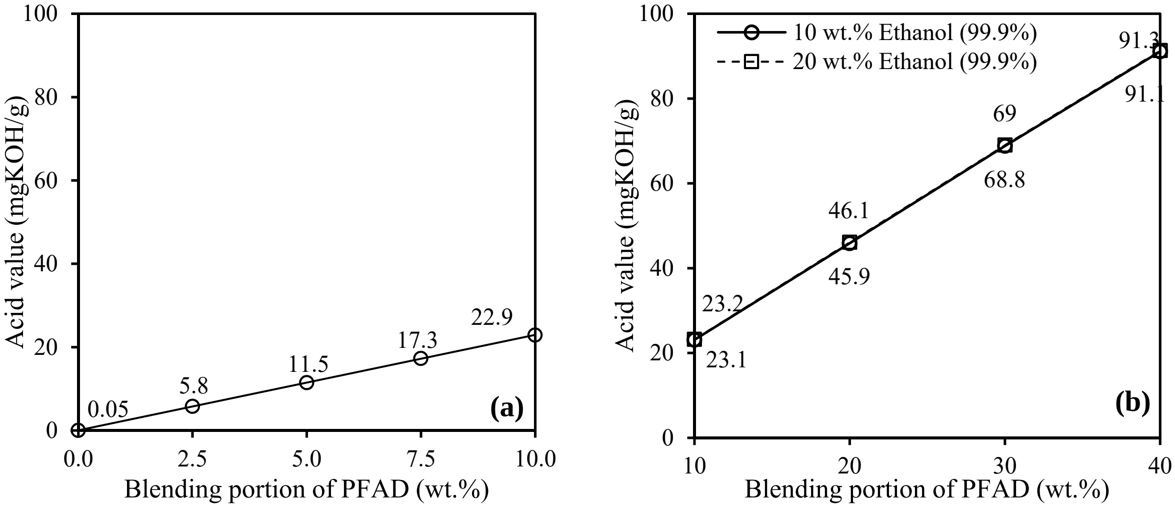

Figure 5. Effect of PFAD and ethanol on acid value : (a) PFAD-diesel; (b) diesel-PFAD-ethanol.

that form a protective anti-wear layer by adhering to the solid surfaces [24].

The tested wear scars for commercial diesel, TB10, TB541, and TB442 were 206, 174, 111, and 130 μm, respectively, which met the regulated levels of all the relevant Thai standards. The wear scars of TB10, TB514, and TB424 were lower than that of diesel of 15.5, 46.1, and 36.9%, respectively with kinematic viscosities at 40 °C of 4.13, 5.44, and 4.04, respectively. When comparing commercial diesel with the 10 wt.% PFAD blend (TB10), the results revealed that the TB10 had better lubricity than that of diesel as a result of higher viscosity. It can be concluded that PFAD can improve the hydrodynamic lubrication but still cannot clearly identified that PFAD can improve the boundary lubrication. However, when ethanol was blended, the viscosities of the blends were reduced, resulting in lower hydrodynamic lubrication. However, it can be seen that the TB442 with lowest viscosity has the best lubricity while the TB10 with higher viscosity should have the better lubricity than the TB442. Therefore, this can clearly identify that PFAD can improve the boundary lubrication of the blends effectively.

3.2.5 Effect of PFAD and ethanol on other properties

The effects of PFAD and ethanol on other important fuel properties including density, heating value, flash point, distillation 90% recovery, carbon residual, and sulfate ash are shown in Table 1.

The density of fuel does not directly affect the fuel's combustion efficiency, but is directly related to the mass and thermal energy of the fuel injected into the combustion chamber. The density of PFAD was slightly higher than that of diesel about 7% while ethanol had about 5% less density than that of diesel. Thus, the densities of the blends was increased when PFAD was blended, and was decreased when ethanol was blended. The density of all the blends ranged from 833 to 847 g/l which were acceptable according to all the relevant Thai standards.

The heating value is not regulated in all Thai standard. This property was directly related to the energy supply of fuel. The measured heating values of diesel, PFAD, and ethanol were 44.90, 39.17, and 22.78 MJ/kg, respectively. Since the heating value of PFAD and ethanol were lower than that of diesel (-12.8 and -49.3% respectively), thus heating value of all the blends were lower than that of diesel. However, the results illustrated that the heating values of all the blends were slightly lower than that of diesel only and ranged from 38.18 to 44.76 MJ/kg which were 0.3-15.0% lower than that of diesel.

The flash point is the minimum temperature that causes enough vapour to burn, and it will burn immediately when exposed to flame. In practice, the flash point is important in the fire hazard of transportation, storage, and use of fuel, but not directly related to the combustion and engine performance. The measured flash points of PFAD-diesel blends were slightly higher than that of diesel. Therefore, there blends completely met all the relevant Thai standards. For the diesel-PFAD-ethanol blend, the flash point of the blends was not studied in this work. However, from previous literature study

Table 1. Effect of PFAD and ethanol on other fuel properties.

Sample	Diesel (wt.%)	PFAD (wt.%)	Ethanol (wt.%)	Density at 15ºC (g/l)	Higher heating value (MJ/kg)	Flash point (°C)	Distillation 90% recovery (°C)	Carbon residual (wt.%)	Sulfate ash (wt.%)
TB2.5	97.5	2.5	-	833	44.76	70	336	0.02	≤0.005
TB5.0	95	5	-	835	44.61	72	336	0.01	≤0.005
TB7.5	92.5	7.5	-	837	44.47	73	337	≤0.005	≤0.005
TB10	90	10	-	838	44.32	74	337	≤0.005	≤0.005
TB811	80	10	10	832	42.10	-	-	0.026	≤0.005
TB721	70	20	10	840	41.50	-	-	-	-
TB631	60	30	10	846	41.00	-	-	-	-
TB541	50	40	10	851	40.39	-	-	0.008	≤0.005
TB712	70	10	20	829	39.90	-	-	0.011	≤0.005
TB622	60	20	20	835	39.33	-	-	-	-
TB532	50	30	20	842	38.76	-	-	-	-
TB442	40	40	20	847	38.18	-	-	≤0.005	≤0.005
-	100	-	-	831	44.90	68	336	0.05	≤0.005
-	-	100	-	807[a]	39.17	-	-	-	-
-	-	-	100	788	22.78	13[b]	-	-	-

[a]density at 50 ºC
[b]Kwanchareon et al., 2007

, it was found that the flash point of the blended fuel was close to the flash point of the alcohol used in the blending [28]. Thus, the flash points of these blends were similar to that of the flash point of ethanol. That means that these blends had the flash points that did not meet of all the relevant Thai standard.

The distillation 90% recovery value is the temperature at which the fuel was distillated at 90 vol.%. It indicated the presence of long molecules that resulted in the incomplete combustion and black smoke. The distillation 90% recovery results of PFAD-diesel were slightly higher than that of diesel and met the Thai standard. The distillation 90% recovery of diesel-PFAD-ethanol blends was not studied in this work because ethanol has low boiling point about 80°C so it was not significantly affect the distillation 90% recovery of the blends.

The carbon residual the sulfate ash is the fuel property that indicates the amount of carbon deposited on engine parts and the sulfate ash indicates the amount of impurities contained in a fuel that cannot be burned. This will affect the wear and plug of the engine parts for long-term use. The results revealed that the carbon residual significantly decreased as the blending portion of PFAD increased. While the sulfate ash of all the blends were similar to diesel. In summary, these properties of all blends met the regulated levels of all the relevant Thai standards.

4. Conclusions

For investigating of the long-term Phase behavior (90 days). It was concluded that the clear liquid PFAD-diesel blend with long-term stability was obtained for PFAD ≤10 wt.%. and ethanol was able to act as an effective solvent to improve phase behavior of PFAD while PFAD was able to act as the effective emulsifier for diesel-ethanol blend, in which the clear liquid blends with long-term stability were obtained for blending PFAD up to 40 and 50 wt.%. at 10 and 20 wt.% ethanol, respectively.

For studying of the important fuel property of interesting. It was concluded that the pour points and viscosities of PFAD-diesel blends slightly increased for PFAD ≤7.5 wt.% and increased greatly at 10 wt.% PFAD. Moreover, also summarized that ethanol really acted as a cold-flow property improver of the blends, resulting the pour points and viscosities of diesel-PFAD-ethanol blends slightly increased for PFAD ≤30 wt.%. The cetane numbers of all the blends were high with the highest value at 65.7 of TB5. Although titrated acid values of the blends were quite high, copper strip corrosion properties of all blends and diesel were the same of No.1a. Thus, FFA and ethanol were weak acidic molecules that did not cause an excessive corrosion. The lubricities of TB10, TB541, and TB442 were 174, 111, and 130 µm, respectively which were 15.5-46.1% better than that of commercial diesel. Other properties of PFAD-diesel blends, TB811, TB721, TB631, TB712, TB622, and TB532 were comparable with diesel and met the regulations of Thailand standard for high speed diesel. When higher portion of PFAD was blended to be TB541 and TB442; cloud point, pour point, and kinematic viscosity increased while other properties were acceptable.

However, in conclusion, the FFA in PFAD renders it a high cetane, weakly acidic, and good lubricity molecule that can be directly used as a diesel extender, cetane improver, and the effective emulsifier for diesohol production while ethanol can effectively improve the cold-flow properties of the blends for direct used of PFAD as the diesel extender. Moreover, the liquid blends tested were also able to be used as the novel diesel substitute.

Acknowledgments

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References

[1] National Renewable Energy Laboratory 2001 *Advanced petroleum based fuels program and renewable diesel program* (Milestone report: Technical barriers to use of ethanol in diesel fuel)
[2] Vallinayagam R, Vedharaj S, Yang WM, Lee PS, Chua KJE and Chou SK 2014 *Appl. Energy* **130** 466
[3] Jin C, Yao M, Liu H, Lee CF and Ji J 2011 *Renew. Sustain. Energy Rev.* **15** 4080
[4] Shahir SA, Masjuki HH, Kalam MA, Imran A, Rizwanul Fattah IM and Sanjid A 2014 *Renew. Sustain. Energy Rev.* **32** 379
[5] Shahir SA, Masjuki HH, Kalam MA, Imran A and Ashraful AM 2015 *Renew. Sustain. Energy Rev.* **48** 62
[6] Mofijur M, Rasul MG, Hyde J, Azad AK, Mamat R and Bhuiya MMK 2016 *Renew. Sustain. Energy Rev.* **53** 265
[7] Hansen AC, Zhang Q and Lyne PWL 2005 *Bioresour. Technol.* **96** 277
[8] Letcher TM 1983 *South African J. Sci.* **79** 4
[9] Marek N and Evanoff J 2001 *Proc. of the air and waste management association 94th annual conf. and exhibit.* (Orlando: FL)
[10] http://www.apecenergy.org.au/welcome/activities/meetings/ewg25/NotableDevelop-Thailand.rtf
[11] http://www.greenhouse.gov.au/transport/comparison/pubs/2ch7.pdf
[12] Srithammarong P 2003 *Proc. of MTEC annual meeting* (Bangkok: Thailand) p 120
[13] Mielke T 2010 *Palm and Lauric Oils Conf. & Exhibit.* Price Outlook (POC) (Kuala Lumpur: Malaysia)
[14] Malaysian Palm Oil Board 2010 *www.mpoh.gov.my*
[15] Wan Z, Lim JK and Hameed BH 2015 *J. Taiwan Institute of Chem. Eng.* **54** 64
[16] Tamiyakul S, Anutamjarikun S and Jongpatiwut S 2016 *Cataly. Communicat.* **74** 49
[17] Syahrullail S, Hariz MAM, Abdul Hamid MK and Abu Baker AR 2013 *Procedia Eng.* **68** 166
[18] Shotipruk A, Assabumrungrat S, Pavasant P and Laosiripojana N 2009 *Chem. Eng. Sci.* **64** 459
[19] Lokman I, Goto M, Rashid U and Taufiq-Yap YH 2016 *Chem. Eng. J.* **284** 872
[20] Cho HJ, Kim SH, Hong SW and Yeo YK 2012 *Fuel* **93** 373
[21] Cheryl-Low YL, Theam KL and Lee HV 2015 *Energy Convers. Manag.* **106** 932
[22] Chongkong S, Tongurai C and Chetpattananondh P 2009 *Renew. Energy* **34** 1059
[23] Lokman I, Goto M, Rashid U and Taufiq-Yap YH 2016 *Chem. Eng. J.* **284** 872
[24] Chevron Corporation 2007 *Diesel fuels technical rev.*
[25] Jaroonjitsathain S, Sae-ong P, Siangsanorh S, Akarapanjavit N, Noomwongs N and Boonchukosol K 2001 *JSAE* 20119277
[26] Leevijit T, Prateepchaikul G, Maliwan K, Mompiboon P and Eiadtrong S 2017 *Renew. Energy* **101** 82
[27] Leevijit T, Prateepchaikul G, Maliwan K, Mompiboon P, Okaew S and Eiadtrong S 2016 *Fuel* **182** 509
[28] Kwanchareon P, Luengnaruemitchai A and Jai-In S 2007 *Fuel* **86** 1053