CHAPTER IV
RESULTS AND DISCUSSION

Blends between refined palm kernel oil or refined palm oil and high-speed diesel were studied. Properties of the blends were investigated and related to their atomization characteristics. In addition, the properties were correlated to the blend concentration and temperature.

Table 4.1 Properties of the high-speed diesel, refined palm kernel oil and refined palm oil

Properties	High-speed diesel	Refined palm kernel oil	Refined palm oil
Specific gravity	0.805	0.905	0.895
Kinematic viscosity (cSt)	3.46	34.10	47.19
Surface tension (mN/m)	28.13	31.67	32.90
Pour point (°C)	< -11	25.30	6.00
Flash point (°C)	71	301	350
Carbon residue (wt%)	0.004	0.112	0.390

Table 4.1 shows properties of high-speed diesel, refined palm kernel oil, and refined palm oil. The kinematic viscosity, pour point, flash point and carbon residue of the two palm oils are very high compared with those of the diesel. In addition, the refined palm kernel oil has lower kinematic viscosity, flash point and carbon residue than those of the refined palm oil but has higher pour point. A reason may be the higher amount of long carbon-chain length compounds in the refined palm oil than

those in the refined palm kernel oil (Table A-7). It can be expected that most properties of the refined palm kernel oil or refined palm oil blends will be different from those of the diesel except specific gravity and surface tension.

4.1 Blend Properties

4.1.1 Kinematic Viscosity

Figure 4.1 shows the kinematic viscosity of the blends between refined palm kernel oil or refined palm oil and high-speed diesel as a function of the refined palm kernel oil or refined palm oil amount and temperature. The amount of the refined palm kernel oil or refined palm oil affects the kinematic viscosity of the blends to a higher extent at lower temperatures. The kinematic viscosity of the blends increases with an increase of the refined palm kernel oil or refined palm oil because the refined palm kernel oil and refined palm oil have higher viscosity than the diesel. Due to the high-speed diesel standard, which requires that kinematic viscosity of the high-speed diesel be lower than 4.1 cSt at 40°C (The ministry of commerce of Thailand, 1998), not more than 8 vol% of the refined palm kernel oil and 0.20 vol% of the refined palm oil can be added. But for commercially available biodiesel in Florida, it can be blended with diesel up to 75 vol% with an acceptable kinematic viscosity of 4.0 cSt (Tat and Gerpen, 1999). That is because the refined palm kernel oil and refined palm oil have higher kinematic viscosity than that of the diesel and commercially available biodiesel. The kinematic viscosity of the blends decreases when the temperature increases because of the lower of dynamic viscosity, which is the same trend as those with the commercially available biodiesel (Tat and Gerpen, 1999).

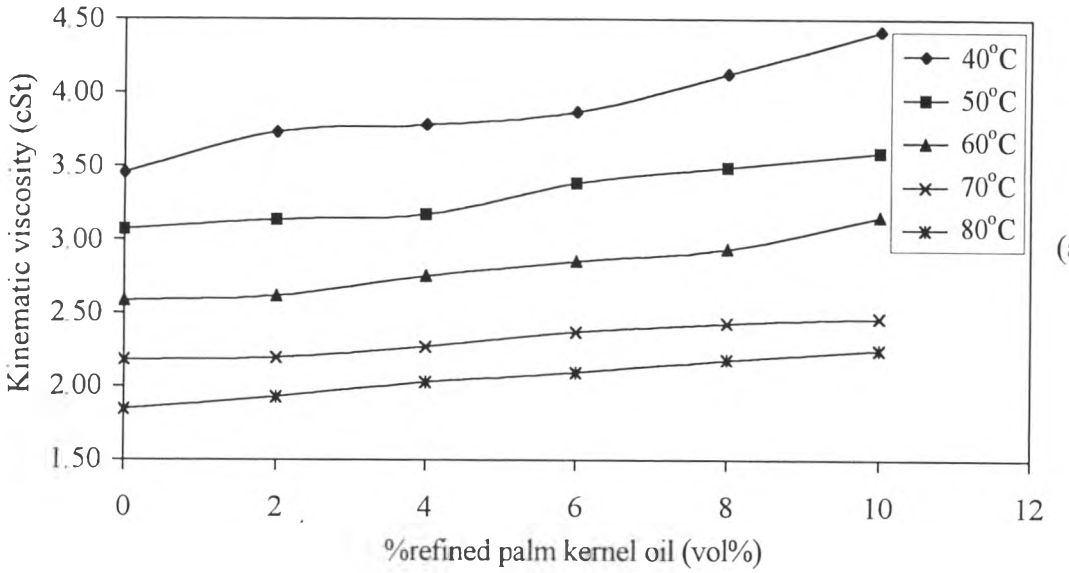
The relations of kinematic viscosity, temperature and concentration of the refined palm kernel oil can be correlated and shown by

$$\ln(\frac{k}{k_0}) = 0.019C - 5.453\ln(\frac{T}{T_0}) - 2.265 \qquad (4.1)$$

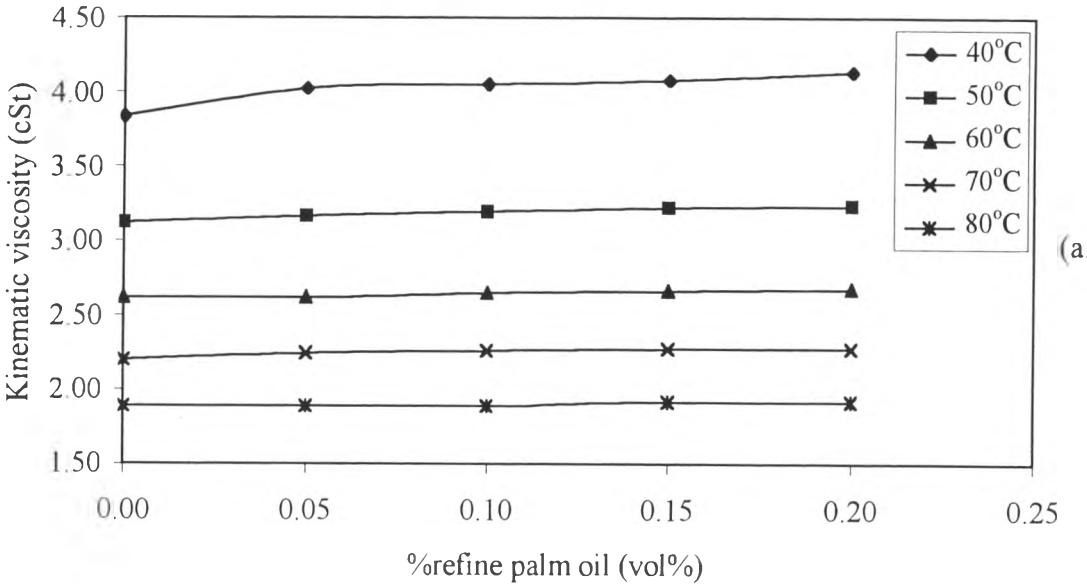
and

$$\ln(\frac{k}{k_0}) = 0.136C - 6.211\ln(\frac{T}{T_0}) - 2.491 \qquad (4.2)$$

for the refined palm oil blends.



(a.1)



(a.2)

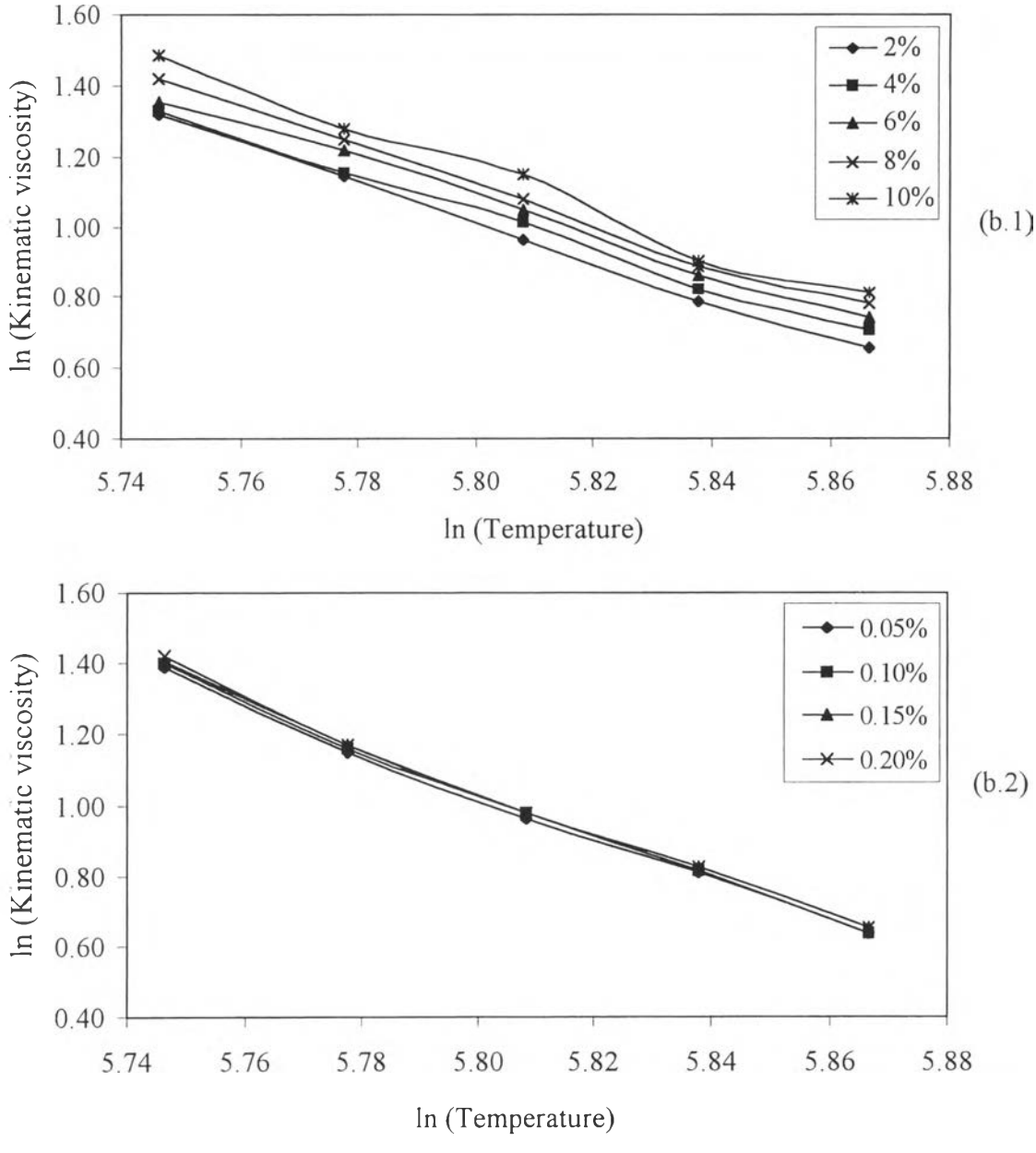


Figure 4.1 Kinematic viscosity of refined palm kernel oil (a.1 and b.1) or refined palm oil (a.2 and b.2) and high-speed diesel blends as a function of refined palm kernel oil or refined palm oil amount at various temperatures

The logarithm of kinematic viscosity is linearly dependent on the logarithm of temperature and concentration. Parameters of the equation were obtained through Polymath 5.0. The equations well represent the experimental data with a small deviation as shown in Figure 4.2.

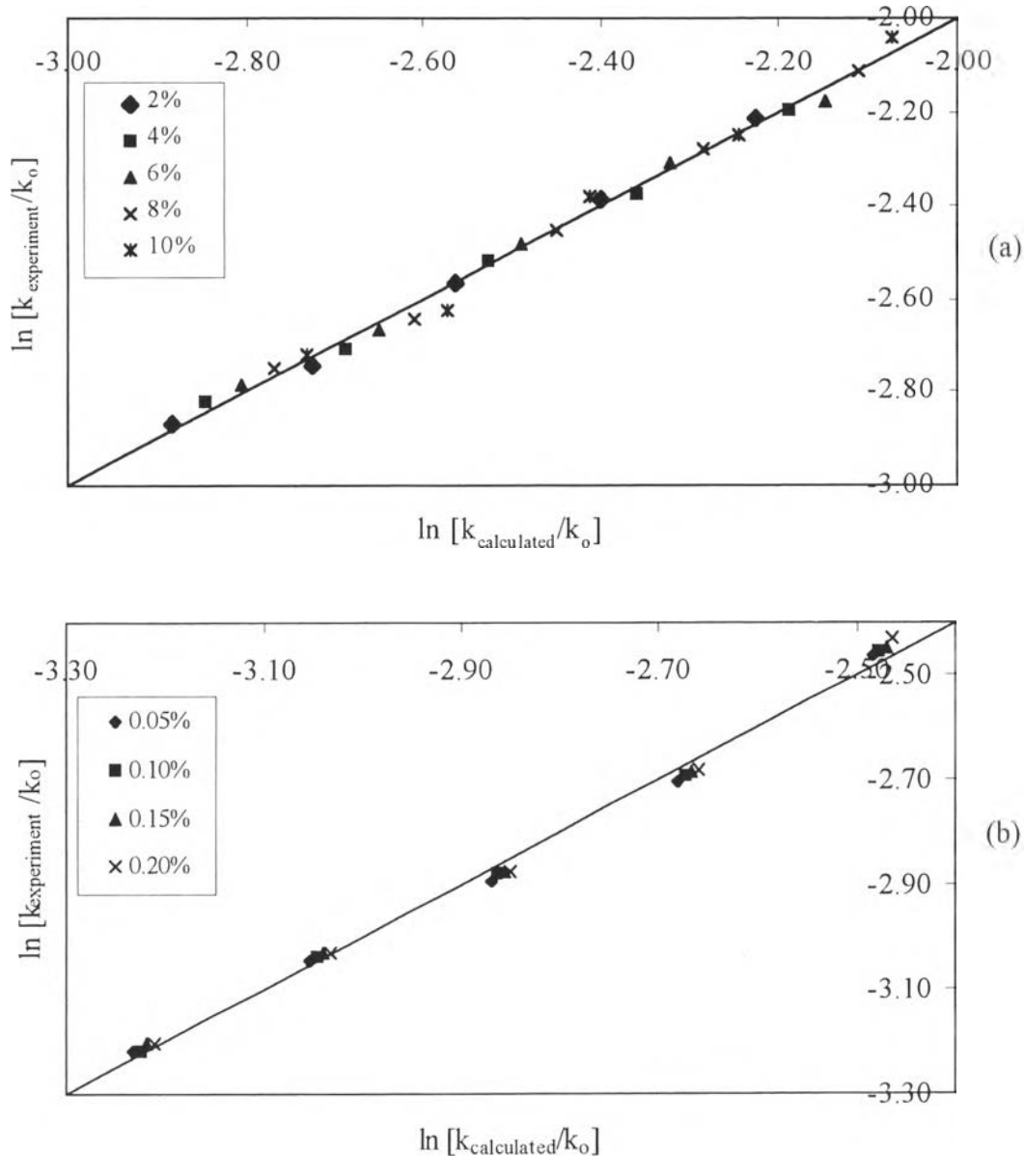


Figure 4.2 Comparison between the calculated and experimental kinematic viscosity of refined palm kernel oil and refined palm oil blends (a and b)

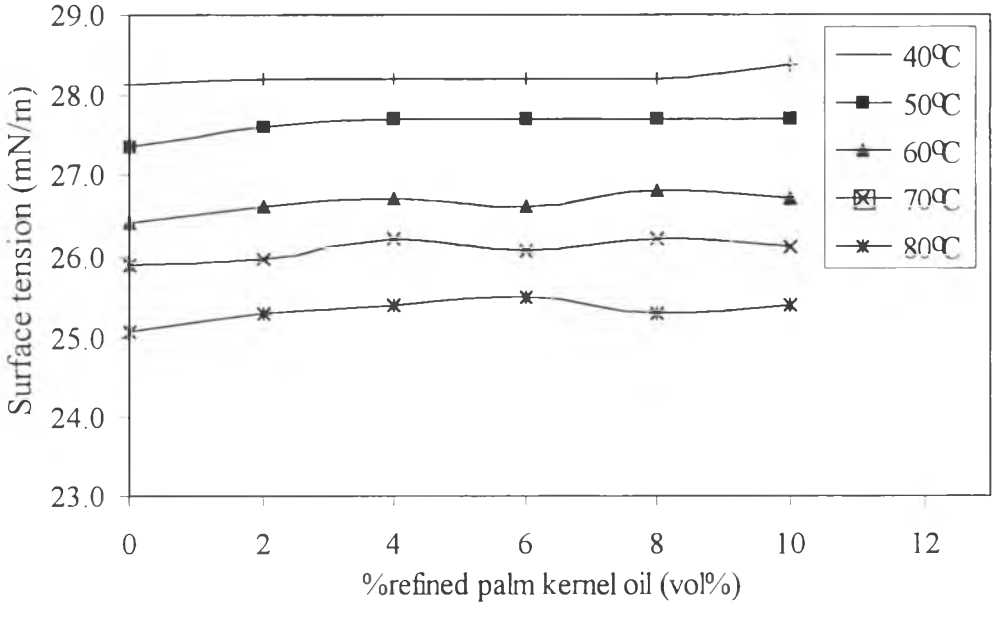
4.1.2 Surface Tension

Figure 4.3 shows the surface tension of the blends between refined palm kernel oil or refined palm oil and high-speed diesel as a function of the refined palm kernel oil or refined palm oil amount and temperature. The surface tension is hardly affected by the increase of the refined palm kernel oil or refined palm oil amount but decrease with the increase of temperature. These surface tension values are relatively close to those of some methyl ester biodiesel fuels at the same temperature (Allen and Watts, 2000). The molecular interaction between molecules of diesel and those of the refined palm kernel oil or refined palm oil may be a possible reason for the increase of the surface tension. The surface tension of the blends decreases with the decrease of the temperature. The surface tension of the refined palm kernel oil can be predicted by

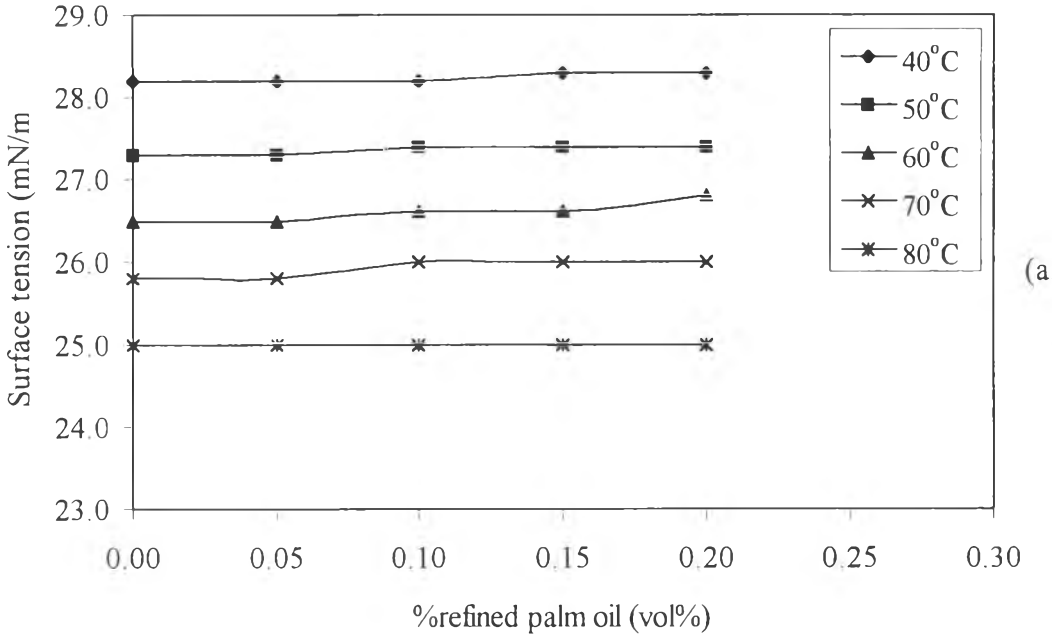
$$S = 0.01C - 0.07T + 50.72 \tag{4.3}$$

and for refined palm oil blends,

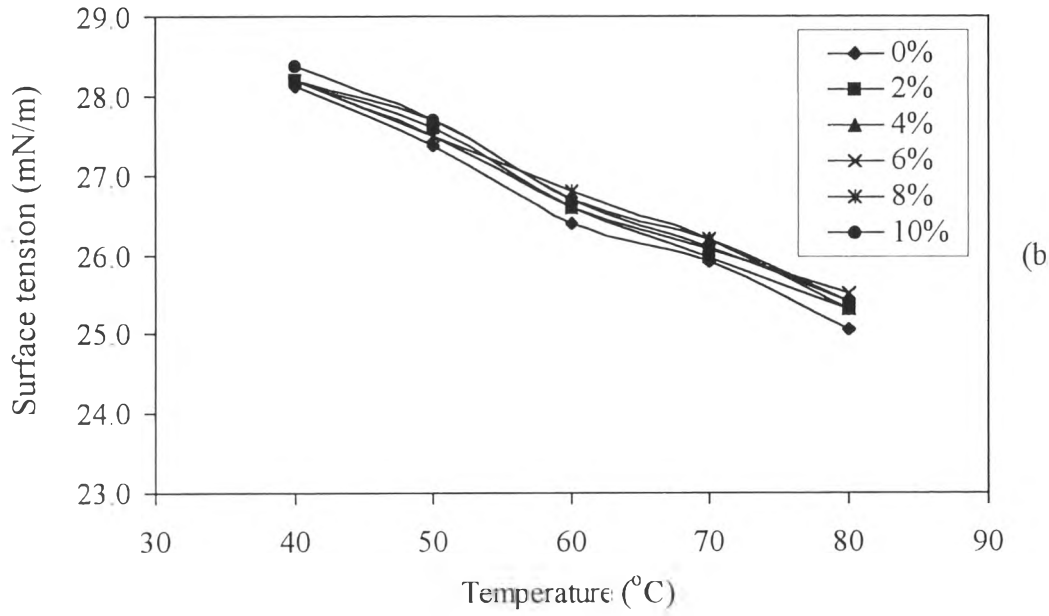
$$\frac{S}{S_0} = 0.028C - 0.752\frac{T}{T_0} + 1.607 \tag{4.4}$$



(a.1)


Surface tension (mN/m
29.0
28.0
27.0
26.0
25.0
24.0
23.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
%refined palm oil (vol%)
40°C
50°C
60°C
70°C
80°C

(a.2)


Surface tension (mN/m)
29.0
28.0
27.0
26.0
25.0
24.0
23.0
30
40
50
60
70
80
90
Temperature (°C)
0%
2%
4%
6%
8%
10%

(b.1)

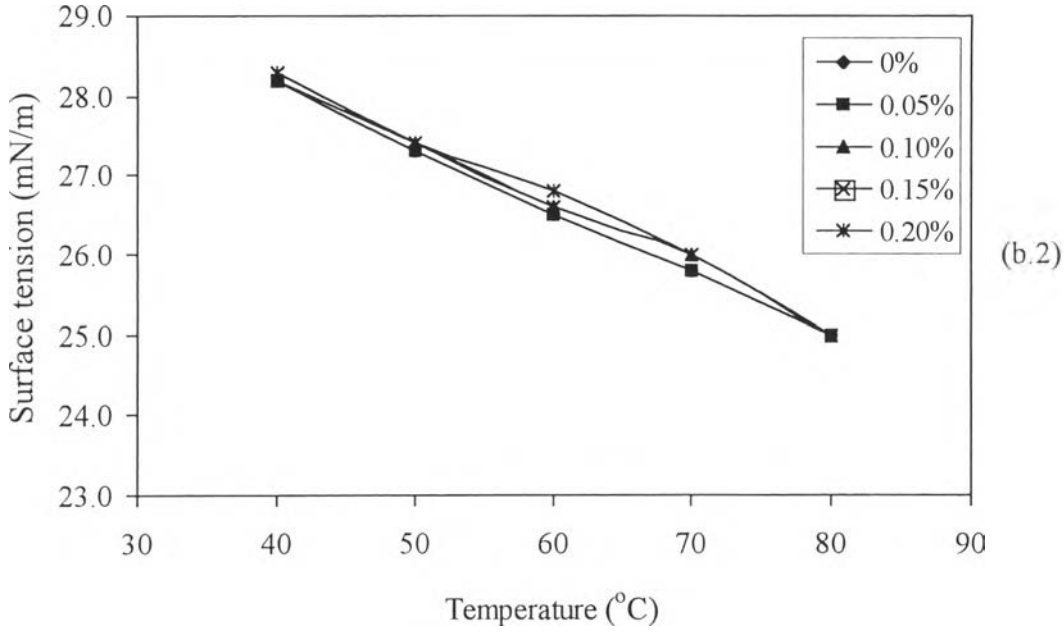
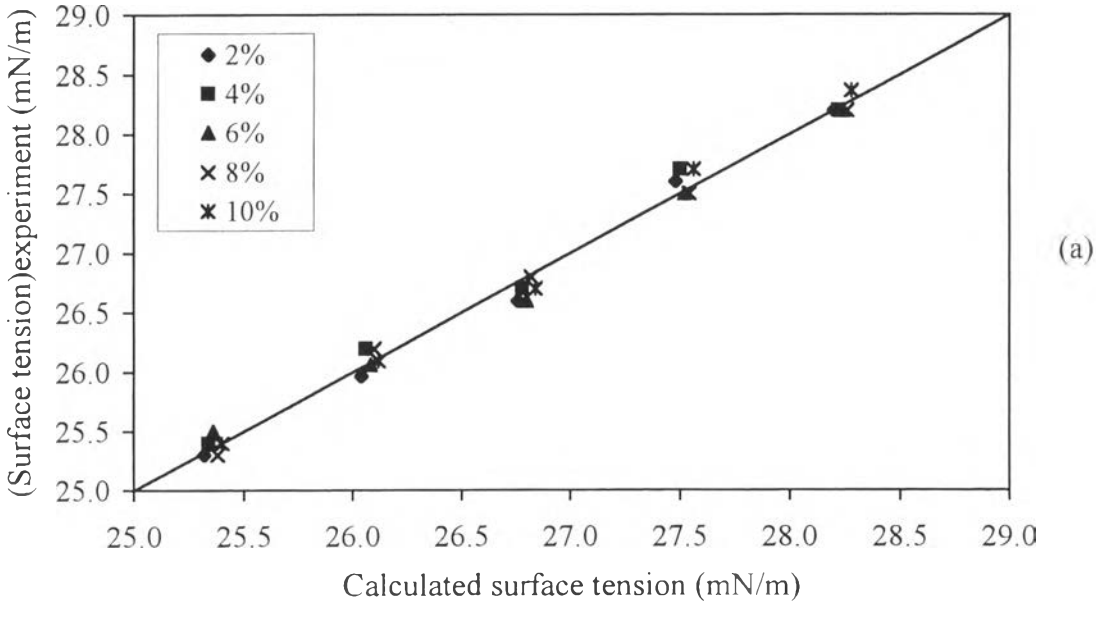
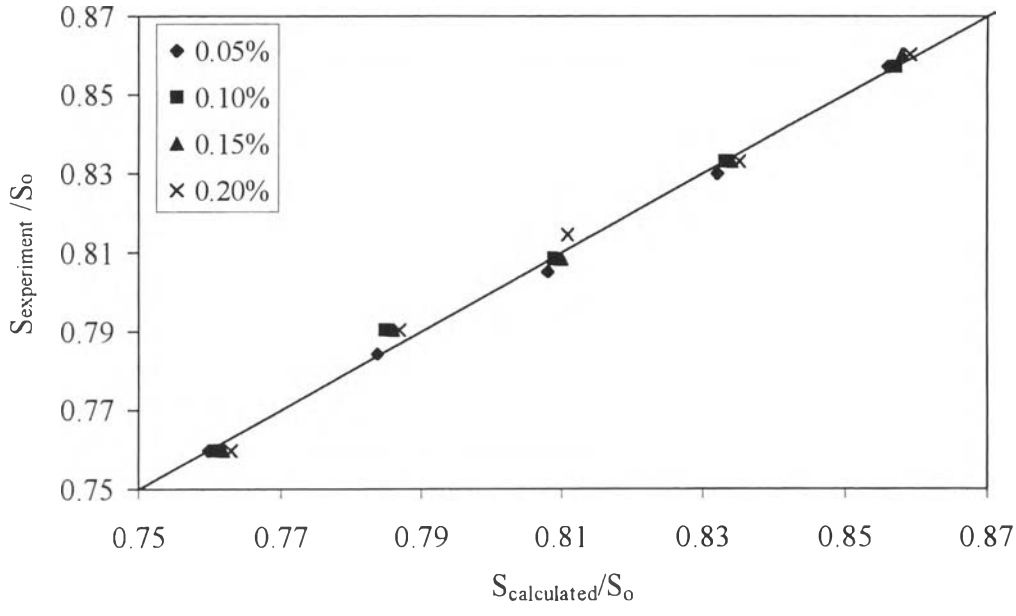


Figure 4.3 Surface tension of refined palm kernel oil (a.1 and b.1) or refined palm oil (a.2 and b.2) and high-speed diesel blends as a function of refined palm kernel oil or refined palm oil amount at various temperatures

The equations well represent the experimental data with a small deviation as shown in Figure 4.4.



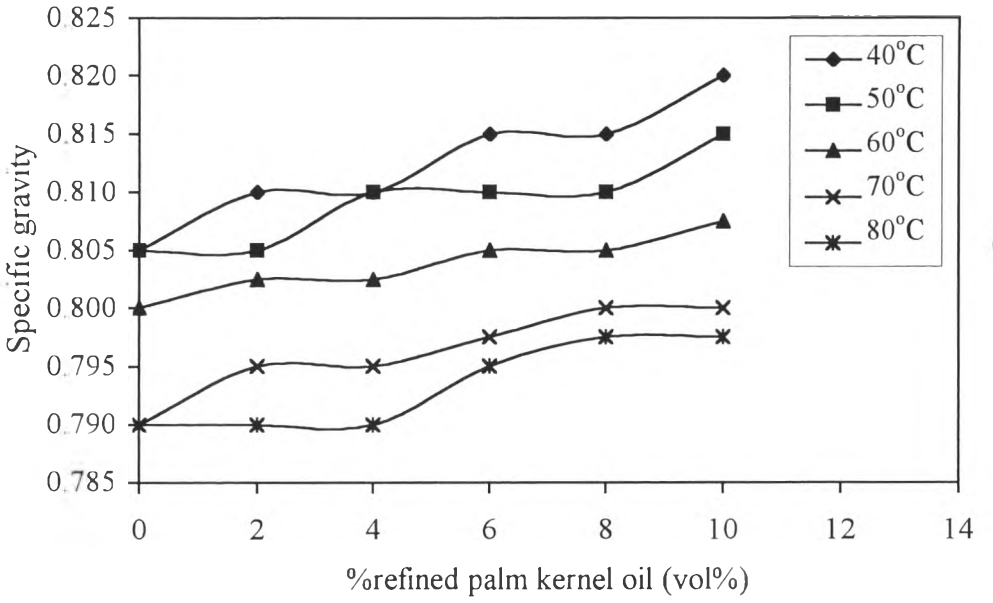


(b)

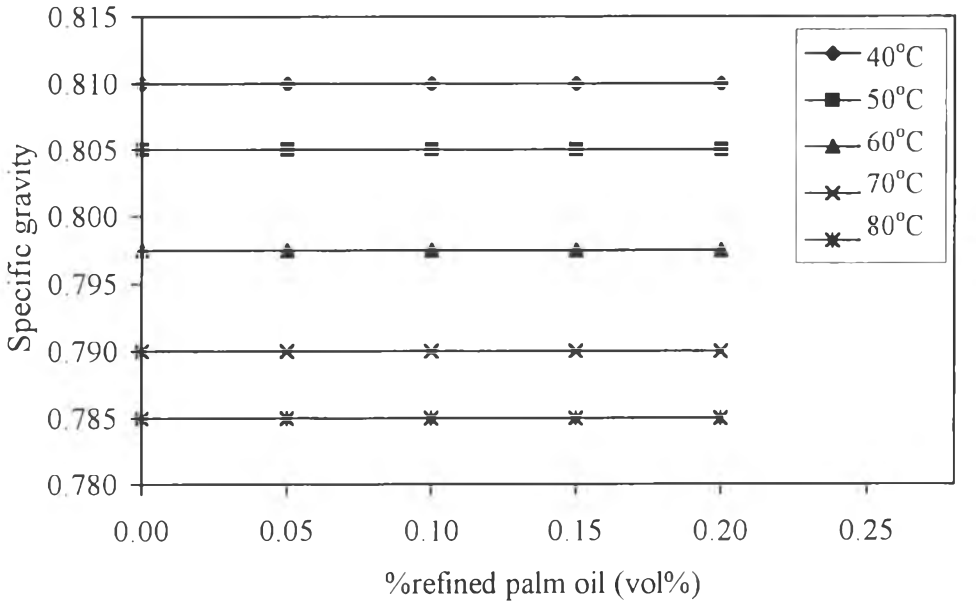
Figure 4.4 Comparison between the calculated and experimental surface tension of refined palm kernel oil and refined palm oil blends (a and b)

4.1.3 Specific Gravity

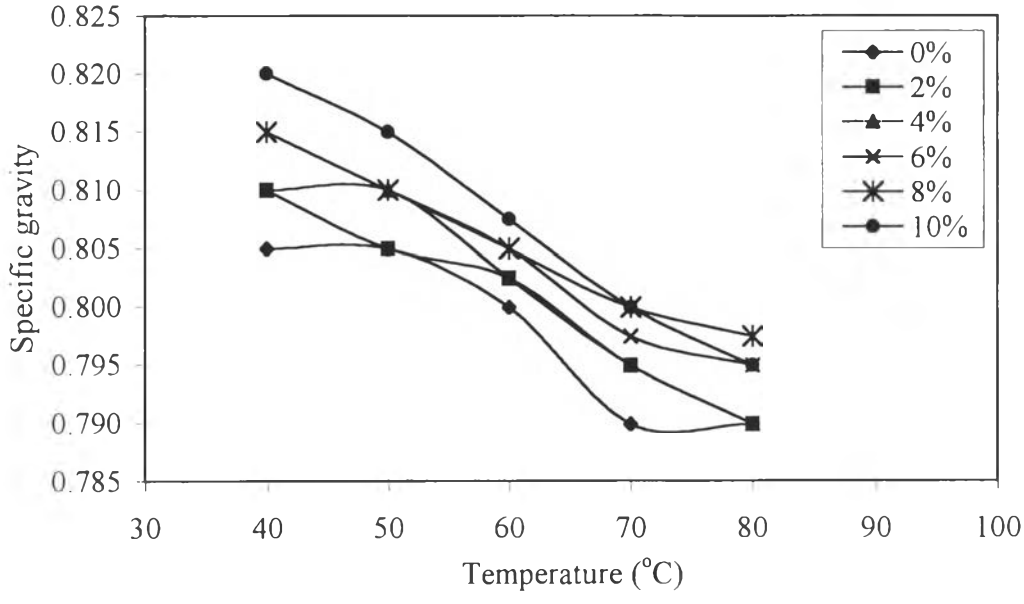
Figure 4.5 shows the specific gravity of the blends. The specific gravity of the blends is almost constant and the same as that of the diesel for the refined palm kernel oil blends and completely the same as the diesel for the refined palm oil blends. The blends' specific gravity is in an acceptable range between 0.81 to 0.87 (The Ministry of Commerce of Thailand, 1998). The reason may be the relatively close specific gravity of the refined palm kernel oil or refined palm oil and the diesel as shown in Table 4.1. The specific gravity of the blends decreases as the temperature increases due to the decrease of the density of the blends.


0.825
0.820
0.815
0.810
0.805
0.800
0.795
0.790
0.785
Specific gravity
0
2
4
6
8
10
12
14
%refined palm kernel oil (vol%)
40°C
50°C
60°C
70°C
80°C

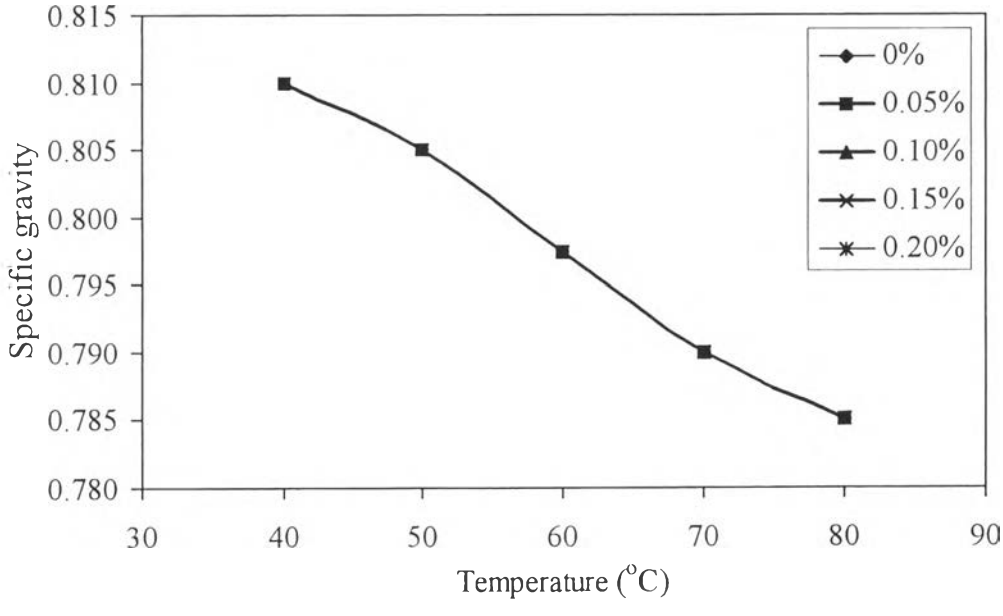
(a.1)


0.815
0.810
0.805
0.800
0.795
0.790
0.785
0.780
Specific gravity
0.00
0.05
0.10
0.15
0.20
0.25
%refined palm oil (vol%)
40°C
50°C
60°C
70°C
80°C

(a.2)



(b.1)



(b.2)

Figure 4.5 Specific gravity of refined palm kernel oil (a.1 and b.1) or refined palm oil (a.2 and b.2) and high-speed diesel blends as a function of refined palm kernel oil or refined palm oil amount at various temperatures

4.1.4 Pour Point

Table 4.2 shows that the pour point of the blends increases as the amount of the refined palm kernel oil increases. For the refined palm oil blends, over the range of the refined palm oil added, pour point remains constant. This may be because the low amount of the refined palm kernel oil or refined palm oil is added and the pour point of the diesel is very low. There is, however, a significant difference between the pour point of the blends with different oils due to the difference composition in the oils (Table A-7). Pour points of all studied blends are acceptable by the diesel standard, which requires that the pour point must be less than 10°C (The Ministry of Commerce of Thailand, 1998). This means that the blends have no cold performance problem (Srivastava and Prasad, 2000).

Table 4.2 Pour point of refined palm kernel oil or refined palm oil and high-speed diesel blends

vol%		Pour point (°C)		Average (°C)	STDEV
		1	2		
Refined palm kernel oil	0	<-11	<-11	<-11	0.000
	2	<-11	<-11	<-11	0.000
	4	-11.0	-11.0	-11.0	0.000
	6	-9.5	-9.5	-9.5	0.000
	8	-8.0	-8.0	-8.0	0.000
	10	-6.0	-6.0	-6.0	0.000
	100	25.0	25.5	25.3	0.354
Refined palm oil	0	<-11	<-11	<-11	0.000
	0.05	<-11	<-11	<-11	0.000
	0.10	<-11	<-11	<-11	0.000
	0.15	<-11	<-11	<-11	0.000
	0.20	<-11	<-11	<-11	0.000
	100	6.0	6.0	6.0	0.000

4.1.5 Flash Point

Flash point of the blends between the refined palm kernel oil or refined palm oil and the high-speed diesel are shown in Table 4.3. From the table, the flash point tends to be constant and equal to the flash point of the high-speed diesel because of the very low amount of the two palm oils that added in the diesel. Addition of a small amount of the refined palm kernel oil or refined palm oil has almost no effect on the flash point of the blends, the blends can be stored safely in the same condition as the high-speed diesel storage (Srivastava and Prasad, 2000). The flash point of the blends are acceptable, which is less than 52°C (The Ministry of Commerce of Thailand, 1998).

Table 4.3 Flash point of refined palm kernel oil or refined palm oil and high-speed diesel blends

vol%		Flash point (°C)		Average (°C)	STDEV
		1	2		
Refined palm kernel oil	0	70.0	72.0	71.0	1.414
	2	72.0	72.0	72.0	0.000
	4	70.0	72.0	71.0	1.414
	6	72.0	72.0	72.0	0.000
	8	72.0	72.0	72.0	0.000
	10	72.0	72.0	72.0	0.000
	100	300.0	302.0	301.0	1.414
Refined palm oil	0	73.0	74.0	73.5	0.707
	0.05	74.0	73.0	73.5	0.707
	0.10	74.0	74.0	74.0	0.000
	0.15	74.0	73.0	73.5	0.707
	0.20	73.0	74.0	73.5	0.707
	100	350.0	351.0	350.5	0.707

4.1.6 Carbon Residue

As shown in Table 4.4, the carbon residue of the diesel and refined palm kernel oil and refined palm oil blends slightly increases as the amount of the refined palm kernel oil or refined palm oil increases. One reason may be the higher amount of long carbon-chain length in the palm oils than those of the diesel. The refined palm kernel oil blends have higher carbon residue than those of the refined palm oil blends because of the lower amount of the refined palm oil added in the high-speed diesel. As the blends have the carbon residues in the acceptable level (less than 0.05 wt%) (The Ministry of Commerce of Thailand, 1998), a low amount of carbon residue is likely to deposit in the combustion chamber (Srivastava and Prasad, 2000).

Table 4.4 Carbon residue of refined palm kernel oil or refined palm oil and high-speed diesel blends

vol%		Carbon residue (%)		Average (%)	STDEV
		1	2		
Refined palm kernel oil	0	0.0052	0.0032	0.0042	0.0014
	2	0.0100	0.0110	0.0105	0.0007
	4	0.0310	0.0060	0.0185	0.0177
	6	0.0350	0.0270	0.0310	0.0057
	8	0.0420	0.0360	0.0390	0.0042
Refined palm oil	0	0.0010	0.0020	0.0015	0.0007
	0.05	0.0050	0.0100	0.0075	0.0035
	0.10	0.0058	0.0060	0.0059	0.0001
	0.15	0.0030	0.0090	0.0060	0.0042
	0.20	0.0090	0.0050	0.0070	0.0028

4.1.7 Distillation

Table 4.5 shows the temperature at which 90% of diesel and two blends are recovered. The distillation temperatures of the blends at 90% recovered are acceptable, which is less than 357°C (The Ministry of Commerce of Thailand, 1998). The higher the distillation temperature of the blends, the higher the amount of high-boiling point components, which corresponds to the oils composition as shown in Table A-7. As a result, the acceptable degree of formation of solid combustion deposit can be expected (Srivastava and Prasad, 2000).

Table 4.5 90% recovered of refined palm kernel oil or refined palm oil and high-speed diesel blends

Blends	90% recovered (°C)
100% Diesel	345
8% refined palm kernel oil	350
10% refined palm oil	349

4.1.8 Cetane Index

A decrease and increase in the calculated cetane index are observed with the blends. The change of the cetane index can be explained by first looking at how the index was calculated, Equation (4.5) (ASTM D976).

$$\text{Cetane index} = -420.34+0.016G^2+0.192G\log M+65.01(\log M)^2-0.0001809M^2 \quad (4.5)$$

where G is API gravity and M is mid-boiling point. From Equation (4.5) and Table 4.7, the API gravity of the refined palm kernel oil blends is lower than that of the diesel but the mid-boiling point is higher. This lowers the cetane index of the refined palm kernel oil blends. On the contrary, the refined palm oil blends have higher cetane index than that of the diesel because of the higher mid-boiling point. With high cetane index, the refined palm oil blends can be ignited in a combustion

chamber easier than the refined palm kernel oil blends. The indices are acceptable, which is higher than 47 (The Ministry of Commerce of Thailand, 1998).

Table 4.6 Calculated cetane index of refined palm kernel oil or refined palm oil and high-speed diesel blends

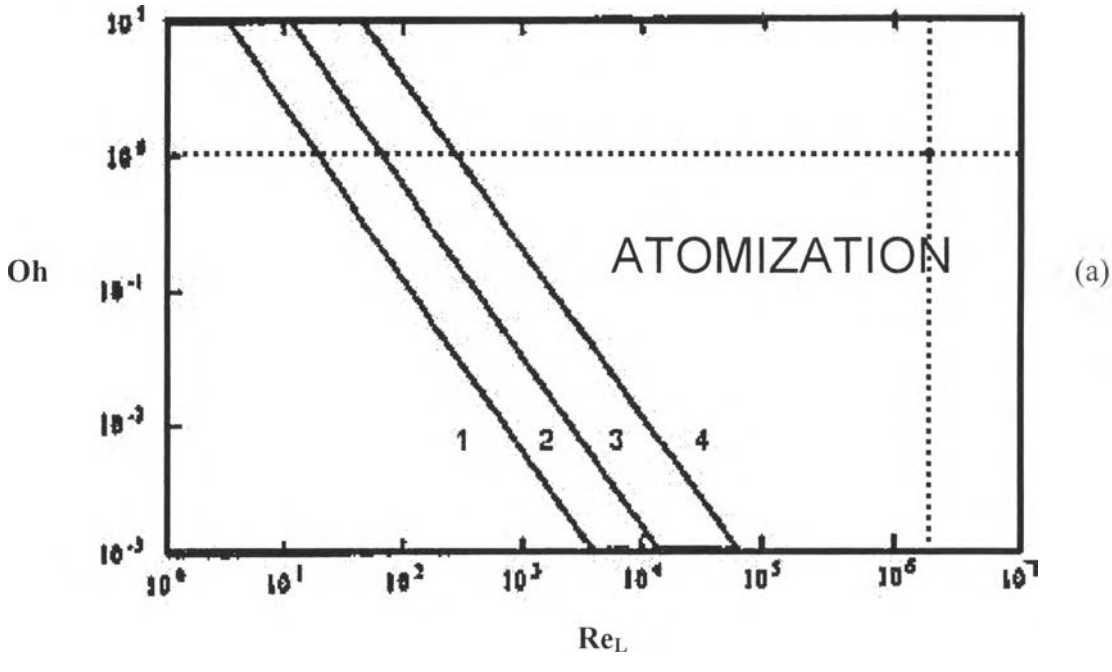
vol%		Calculated Cetane index		Average	STDEV
		1	2		
Refined palm kernel oil	0	57.2	57.2	57.2	0.000
	2	56.4	56.4	56.4	0.000
	4	56.4	56.4	56.4	0.000
	6	55.6	55.6	55.6	0.000
	8	54.8	54.8	54.8	0.000
Refined palm oil	0	75.8	75.8	75.8	0.000
	0.05	77.6	77.6	77.6	0.000
	0.10	77.6	77.6	77.6	0.000
	0.15	77.6	77.6	77.6	0.000
	0.20	77.6	77.6	77.6	0.000

Table 4.7 API gravity and mid-boiling point of refined palm kernel oil or refined palm oil and high-speed diesel blends

vol%		API gravity			Average	STDEV
		1	2	3		
Refined palm kernel oil	0	38.4700	38.4700	38.4700	38.4700	0.000
	2	37.9611	37.9611	37.9611	37.9611	0.000
	4	37.9611	37.9611	37.9611	37.9611	0.000
	6	37.4552	37.4552	37.4552	37.4552	0.000
	8	36.9524	36.9524	36.9524	36.9524	0.000
	10	35.9556	35.9556	35.9556	35.9556	0.000
Refined palm oil	0	48.7548	48.7548	48.7548	48.7548	0.000
	0.05	48.7548	48.7548	48.7548	48.7548	0.000
	0.10	48.7548	48.7548	48.7548	48.7548	0.000
	0.15	48.7548	48.7548	48.7548	48.7548	0.000
	0.20	48.7548	48.7548	48.7548	48.7548	0.000
vol%		mid-boiling point (°C)			Average (°C)	STDEV
Refined palm kernel oil	0	289	289	289	289	0.000
	2	289	289	289	289	0.000
	4	289	289	289	289	0.000
	6	290	290	290	290	0.000
	8	290	290	290	290	0.000
Refined palm oil	0	282	282	282	282	0.000
	0.05	293	293	293	293	0.000
	0.10	293	293	293	293	0.000
	0.15	293	293	293	293	0.000
	0.20	293	293	293	293	0.000

4.2 Atomization Characteristics of the Blends

Figure 4.6 shows the atomization characteristics of the refined palm kernel oil blend, refined palm oil blend and high-speed diesel. The Oh and Re_L of the blends are in the atomization regime and these values are very close to those of the high-speed diesel. This implies that atomization of the blends can be achieved and spray quality can be expected to be compatible with that of high-speed diesel. Furthermore, the addition of the refined palm kernel oil or refined palm oil in the high-speed diesel hardly affects the atomization characteristics of the high-speed diesel.



(a)

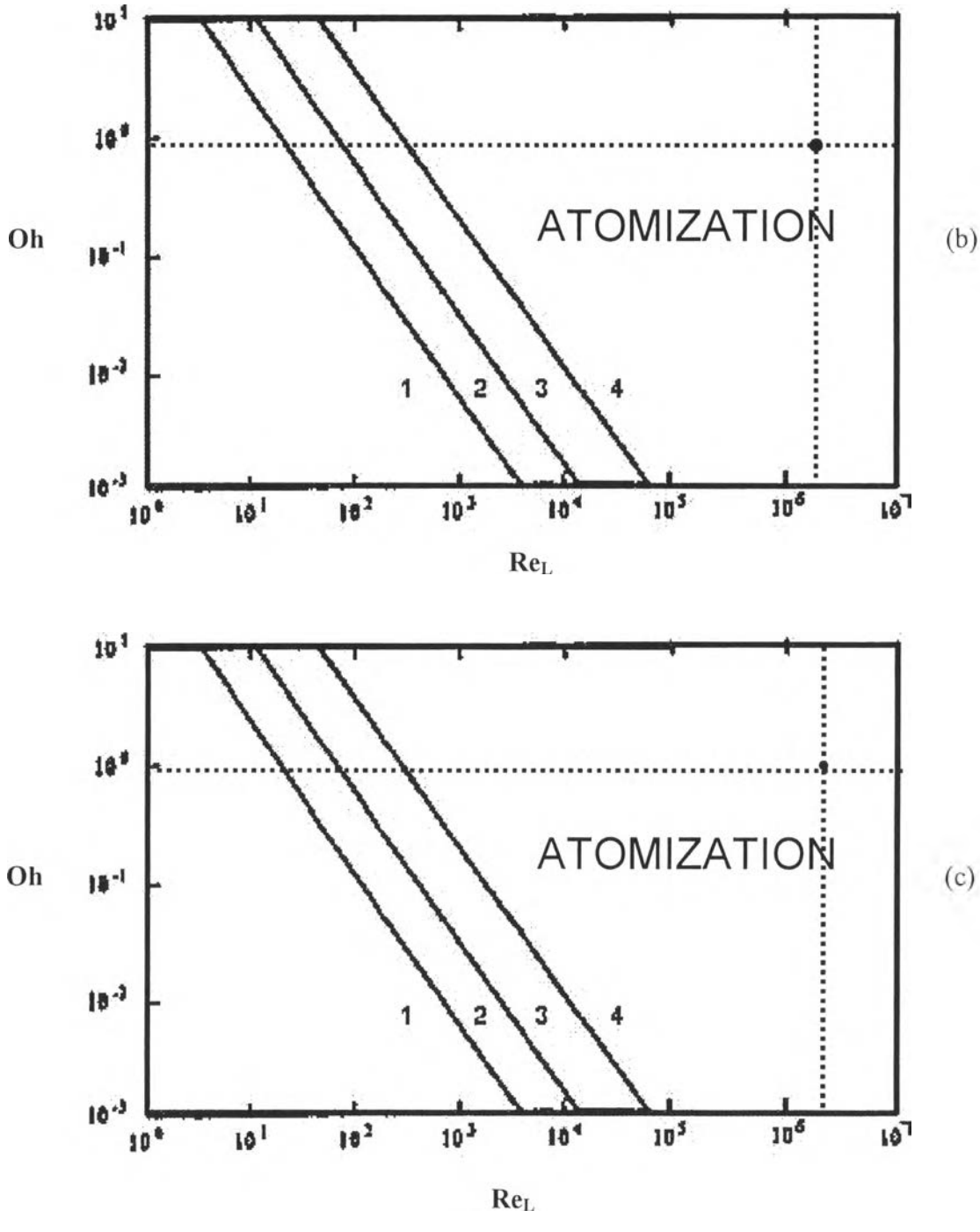
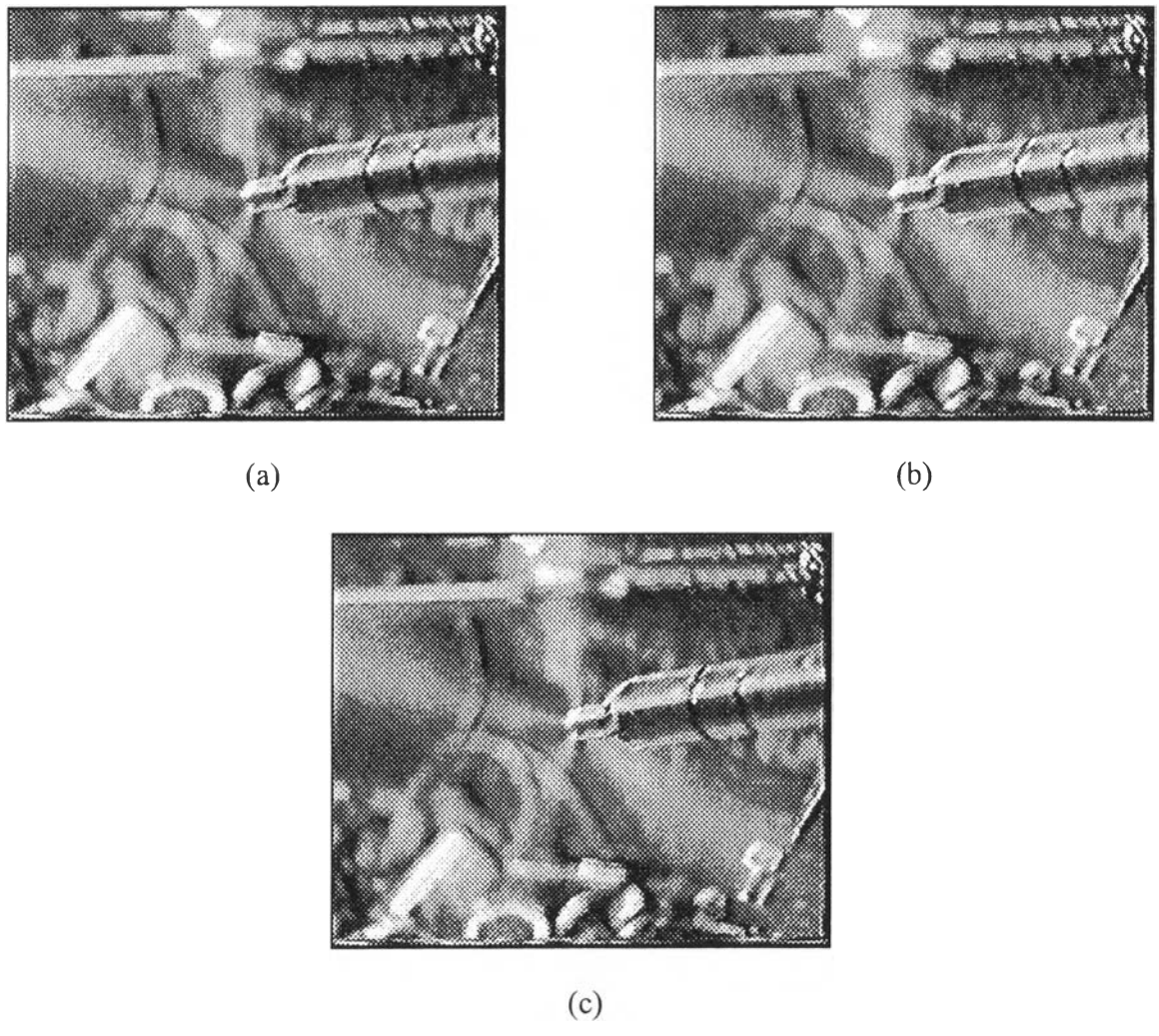


Figure 4.6 Atomization characteristics of refined palm kernel oil, refined palm oil blends and high-speed diesel (a, b, and c)

To confirm these theoretical calculations, the experiment of the atomization was performed and results are shown in Figure 4.7.

Figure 4.7 shows the atomization of the refined palm kernel oil and refined palm oil blends; and high-speed diesel from a single hole injector with 0.2 mm hole diameter. The spray patterns of these three oils are the same. It implies that the blends have no effect on the atomization in the high-speed diesel engine.



(a) (b)

(c)

Figure 4.7 Atomization of refined palm kernel oil, refined palm oil blends and high-speed diesel from single hole injector (a, b, and c)