CHAPTER IV

RESULTS AND DISCUSSION

For production of lubricating base oils, different types of lubricating base oil are generally blended to produce finished products of the requisite specifications. The kinematic viscosity of the lubricating base oil mixture is the most important criterion. A means of predicting the viscosity of the mixture accurately from data on the viscosities of the lubricating base oil components would therefore be useful.

4.1 Lubricating base oil blends

Three types of lubricating base oils including 150 SN, 500 SN and 150 BS were chosen to determine the correlation. The blending by weight method was done from the three individual lubricating base oil. The composition of each of the blends is shown in Table 3.2, and using magnetic stirrer until obtaining the homogeneous sample. The blending sample by volume method was also prepared and used as a reference for comparison.

4.2 Physical properties of lubricating base oils

4.2.1 Kinematic viscosity and viscosity index

The ASTM D-445 standard method was followed for all viscosity measurements. The viscometer used was of the suspended level type, immersed in a water or oil bath controlled to $\pm 0.01^{\circ}$C. The viscosity measurements did not deviate by > 0.3% from the mean value. The ASTM-D2270 standard method was used to calculate the viscosity index.

The kinematic viscosities and viscosity index of individual lubricating base oil are shown in Figures 4.1-4.3. Different oils have different rates of viscosity change with temperature. For example, a distillate oil from a naphthenic base crude would show a greater rate of change of viscosity with temperature than would a distillate oil from a paraffinic crude. The viscosity index (VI) is a method of applying a numerical value to this rate of change, based on comparison with the relative rates of change of two arbitrarily selected types of oils that differ widely in this characteristic. A high VI indicates a relatively low rate of change of viscosity with temperature; a low VI indicates a relatively high rate of change of viscosity with temperature. In other words, if high VI oil and low VI oil had the same viscosity at, for example, room temperature, as the temperature increased the high VI oil would thin out less and, therefore, would have a higher viscosity than the low VI oil at higher temperatures. In Figures 4.1-4.3; the order of VI is arranged from low to high VI :- 150 BS<500 SN<150 SN.
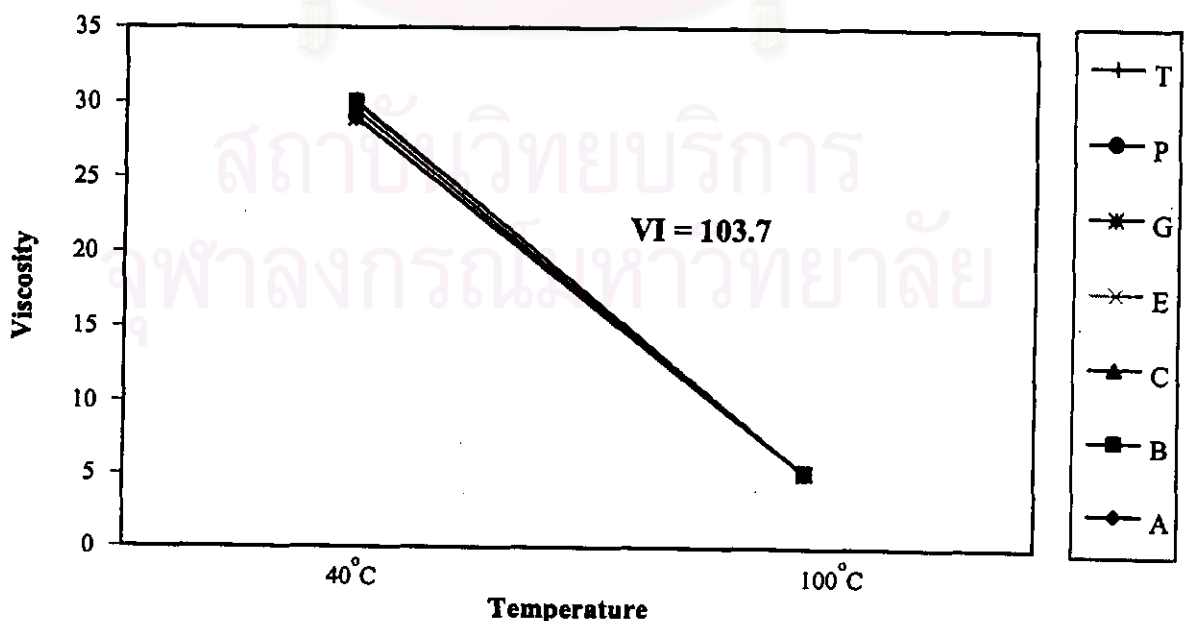

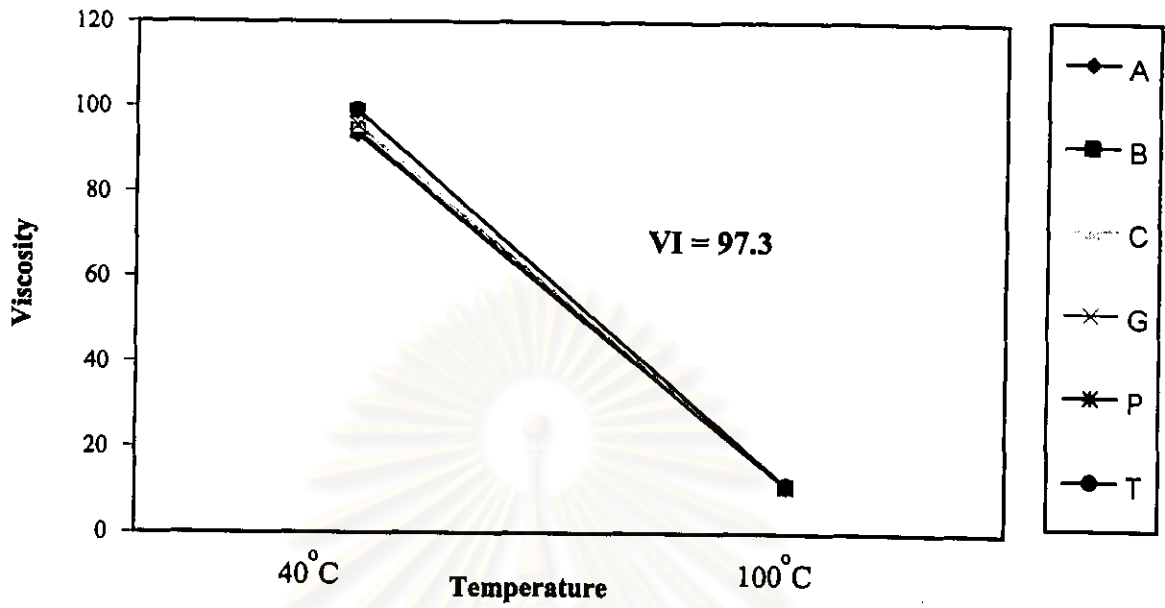Figure 4.1 : Viscosity index of 150 SN
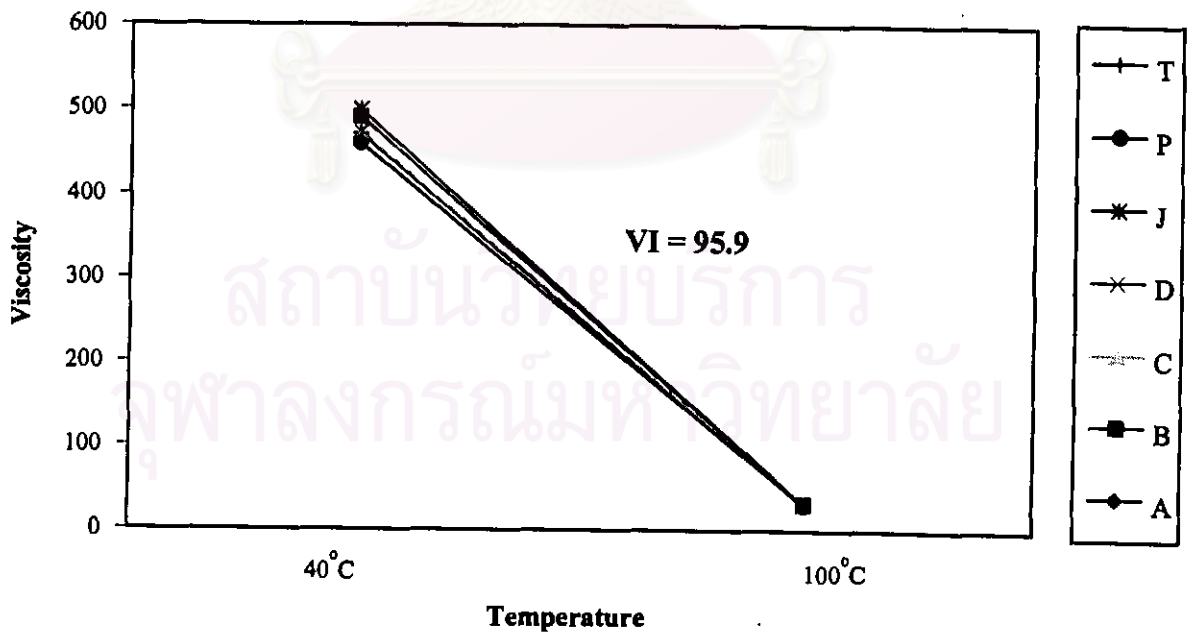
Figure 4.2 : Viscosity index of 500 SN

Figure 4.3 : Viscosity index of 150 BS

4.2.2 Density

The ASTM D-4052 standard method was followed to determine the density of all individual lubricating base oils that appear in this work. It is important because the preparation sample by volume must use this value to convert weighed quantities to volume. The observed temperature is $30^{\circ}C$. Figure 4.4 shows the density of individual lubricating base oil. The order of density is arranged from low to high density:- 150 SN< 500 SN<150 BS.

4.2.3 Flash point

The ASTM D-92 standard method was chosen to determine flash point of all individual lubricating base oils. It is important, from a safety point of view, because it is the lowest temperature at which auto-ignition of the vapor occurs above the heated oil sample. The flash point of individual lubricating base oil is shown in Figure 4.5. The order of flash point is arranged from low to high temperature:- 150 SN<500 SN< 150 BS.

4.2.4 Pour point

The pour point of all individual lubricating base oils was measured according to the ASTM D-97 standard method. It is an index of the lowest temperature of its utility for certain applications. The pour point of individual lubricating base oil is shown in Figure 4.6. The typical pour point of these lubricating base oils is equal -6 to $-9^{\circ}C$.

4.3 Kinematic viscosity of lubricating base oil blends

Liquid viscosities increase with increasing pressure. They usually decrease exponentially as the absolute temperature increases, either under isobaric conditions or as saturated liquids, following the empirical relationship[2,23]

$$\ln v = a e^{b/T}$$

where a, b = constants

$$\log_e \left(\frac{v}{a}\right) = \frac{b}{T}$$

$$\log_e v - \log_e a = \frac{b}{T}$$

$$\ln v - \ln a = \frac{b}{T}$$

It is often a good approximation to assume $\ln v$ is linear in reciprocal absolute temperature;

$$\ln v = \frac{b}{T} + a$$

There are two sets of the total 30 sets of samples that are shown in Appendix A. The first, set B, lubricating base oil was from incoming source and the second, set T, lubricating base oil was from domestic source. The kinematic viscosities of the component and blends at three temperatures of set B and set T are shown in Table 4.1 and Table 4.3, respectively. If the three determinations of kinematic viscosities, calculated from the flow time measurements, agree within the stated determinability (0.3%) for the product, use the average of these determinations to calculate the kinematic viscosities result to be reported.
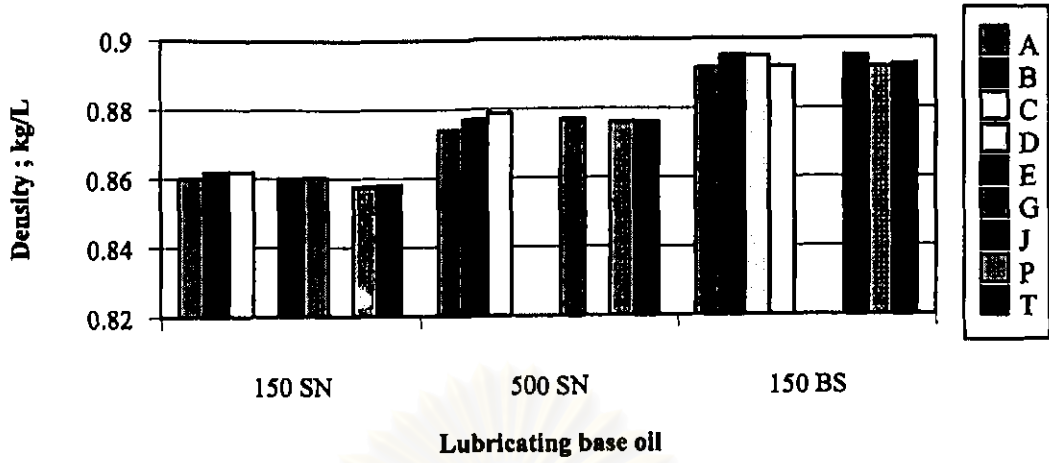
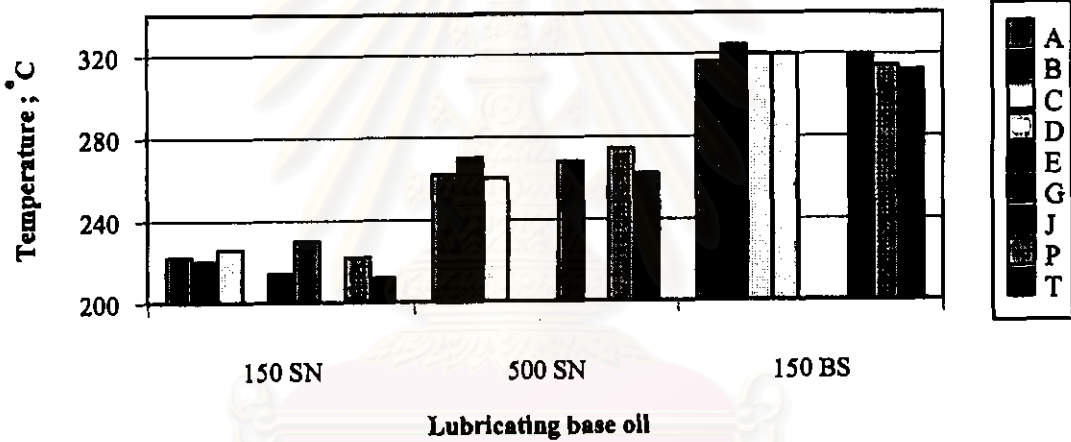Figure 4.4 : Density of individual lubricating base oil

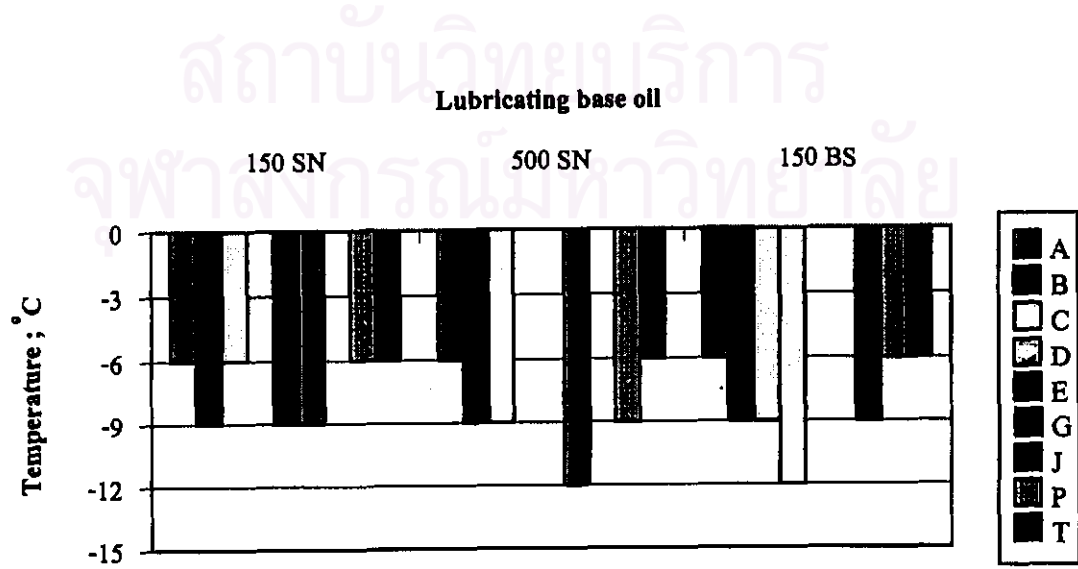Figure 4.5 : Flash point of individual lubricating base oil

Figure 4.6 : Pour point of individual lubricating base oil

Table 4.1 : Kinematic viscosities and the parameters of the individual lubricating base oils and their blends at three temperatures.

Blend number	Composition (weight fraction)			Kinematic viscosity (cSt)			Correlation parameters		
	x_L	x_M	x_H	$25^\circ C$	$40^\circ C$	$100^\circ C$	a	b	r^2
Lubricating oils									
L : B	1	0	0	60.85	30.04	5.22	-7.97	3585.90	0.9972
M : B	0	1	0	223.30	94.14	10.80	-9.50	4425.88	0.9975
H : B	0	0	1	1446.83	490.46	31.88	-11.51	5577.54	0.9976
Two component blends									
B1	0.75	0.25	0	82.44	39.24	6.19	-8.33	3781.27	0.9973
B2	0.50	0.50	0	113.17	54.43	7.41	-8.74	4004.79	0.9990
B3	0.25	0.75	0	157.91	69.29	8.87	-9.11	4206.00	0.9974
B4	0.75	0	0.25	123.19	56.37	7.92	-8.70	4010.35	0.9975
B5	0.50	0	0.50	254.79	107.29	12.06	-9.48	4459.77	0.9977
B6	0.25	0	0.75	576.07	220.60	19.08	-10.43	4984.71	0.9978
B7	0	0.75	0.25	341.67	142.78	13.87	-9.99	4701.31	0.9987
B8	0	0.50	0.50	537.24	205.39	18.11	-10.41	4955.82	0.9976
B9	0	0.25	0.75	865.52	313.76	23.90	-10.92	5249.04	0.9977
Three component blends									
B10	0.25	0.50	0.25	237.63	100.20	11.31	-9.52	4451.60	0.9976
B11	0.50	0.25	0.25	167.77	73.55	9.38	-9.07	4213.01	0.9974
B12	0.25	0.25	0.50	366.67	147.84	14.68	-9.95	4706.46	0.9978
B13	0.375	0.375	0.25	203.66	87.80	10.46	-9.30	4340.57	0.9977
B14	0.375	0.25	0.375	246.50	101.40	11.81	-9.43	4429.31	0.9966
B15	0.25	0.375	0.375	293.69	121.60	12.88	-9.72	4573.57	0.9978
B16	0.333	0.333	0.333	242.88	100.60	11.62	-9.46	4434.84	0.9969

Table 4.2 : Linear parameters obtained from experimental and prediction

| Blend number	x_i	Experimental						Prediction			
		c	d	r^2	p	q	r^2	c	d	p	q
Two component blends											
L - M	x_L	-849.46	4422.08	0.9991	1.56	-9.51	0.9991	-839.98	4425.88	1.53	-9.50
L - H	x_L	-1948.72	5459.30	0.9980	3.46	-11.27	0.9968	-1991.64	5577.54	3.54	-11.51
M - H	x_M	-1095.46	5516.45	0.9983	1.86	-11.37	0.9969	-1151.66	5577.54	2.01	-11.51
Three component blends (first type)											
(B8) - L	x_L	-1425.81	4921.86	0.9965	2.56	-10.34	0.9941	-1415.81	5001.71	2.54	-10.51
(B5) - M	x_M	90.77	4405.81	0.9917	-0.36	-9.34	1.0000	-155.84	4581.72	0.24	-9.74
(B2) - H	x_H	1487.05	3957.13	0.9934	-2.65	-8.61	0.9913	1571.65	4005.89	-2.78	-8.74
Three component blends (second type)											
$(x_M = 0.25)$	x_L	-1973.80	5189.77	0.9950	3.52	-10.80	0.9891	-1991.64	5289.62	3.54	-11.01
$(x_H = 0.25)$	x_L	-954.36	4692.95	0.9984	1.80	-9.97	0.9998	-839.98	4713.80	1.53	-10.00
$(x_L = 0.25)$	x_M	-1019.44	4959.50	0.9994	1.72	-10.38	0.9984	-1151.66	5079.63	2.01	-10.63
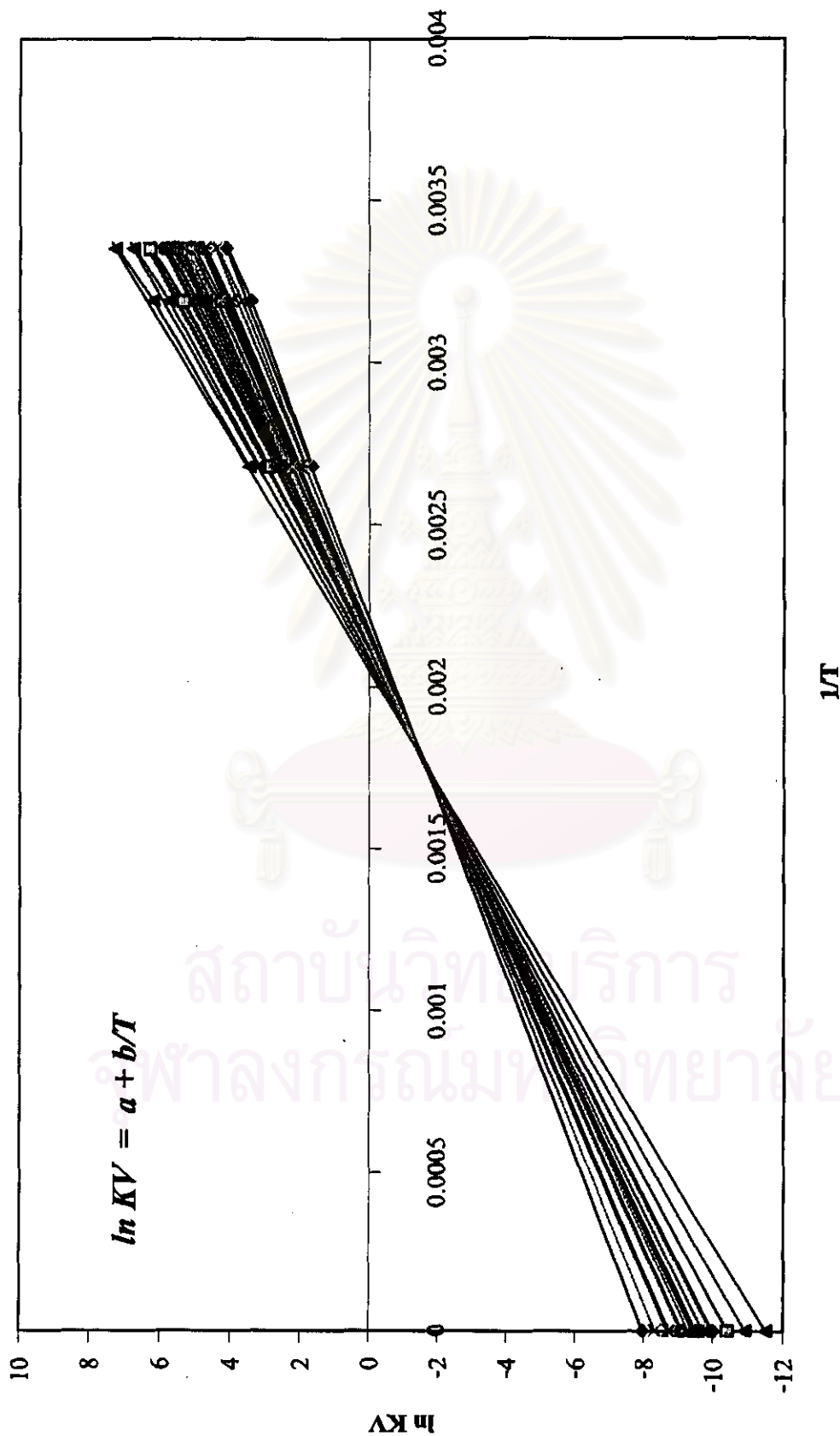
Figure 4.7 : Correlation between ln *KV* and *1/T*

Table 4.3 : Kinematic viscosities and the parameters of the individual lubricating base oils and their blends at three temperatures.

Blend number	Composition (weight fraction)			Kinematic viscosity (cSt)			Correlation parameters		
	x_L	x_M	x_H	$25^{\circ}C$	$40^{\circ}C$	$100^{\circ}C$	a	b	r^2
Lubricating oils									
L : T	1	0	0	58.30	29.04	5.14	-7.88	3546.46	0.9973
M : T	0	1	0	236.32	99.12	11.13	-9.58	4465.87	0.9976
H : T	0	0	1	1372.11	470.52	31.24	-11.40	5530.73	0.9977
Two component blends									
T1	0.75	0.25	0	80.78	38.58	6.14	-8.29	3763.35	0.9973
T2	0.50	0.50	0	113.46	52.08	7.42	-8.69	3984.58	0.9974
T3	0.25	0.75	0	162.28	71.54	9.05	-9.12	4219.71	0.9976
T4	0.75	0	0.25	115.10	53.93	7.76	-8.54	3945.72	0.9979
T5	0.50	0	0.50	240.83	102.10	11.73	-9.40	4417.31	0.9976
T6	0.25	0	0.75	545.72	209.87	18.69	-10.31	4933.30	0.9977
T7	0	0.75	0.25	355.69	144.28	14.14	-10.02	4720.61	0.9980
T8	0	0.50	0.50	545.88	208.52	18.25	-10.43	4968.60	0.9977
T9	0	0.25	0.75	852.00	311.10	23.79	-10.88	5234.77	0.9979
Three component blends									
T10	0.25	0.50	0.25	239.53	100.58	11.39	-9.52	4451.08	0.9975
T11	0.50	0.25	0.25	165.43	72.82	9.38	-9.02	4192.52	0.9974
T12	0.25	0.25	0.50	358.94	144.89	14.60	-9.89	4681.71	0.9977
T13	0.375	0.375	0.25	203.44	87.28	10.52	-9.26	4327.41	0.9974
T14	0.375	0.25	0.375	239.81	101.42	11.59	-9.44	4428.55	0.9976
T15	0.25	0.375	0.375	294.78	121.43	12.93	-9.71	4570.88	0.9976
T16	0.333	0.333	0.333	239.36	101.12	11.52	-9.46	4434.70	0.9976

Table 4.4 : Linear parameters obtained from experimental and prediction

| Blend number	x_i	Experimental						Prediction			
		c	d	r^2	p	q	r^2	c	d	p	q
Two component blends											
L - M	x_L	-912.72	4445.57	0.9997	1.66	-9.53	0.9996	-919.41	4465.87	1.70	-9.58
L - H	x_L	-1975.16	5419.69	0.9993	3.54	-11.19	0.9997	-1984.27	5530.73	3.52	-11.40
M - H	x_M	-1028.32	5488.82	0.9996	1.72	-11.30	0.9993	-1064.86	5530.73	1.82	-11.40
Three component blends (first type)											
(T8) - L	x_L	-1502.60	4941.94	0.9990	2.74	-10.39	0.9988	-1451.84	4998.30	2.61	-10.49
(T5) - M	x_M	91.27	4405.16	0.9958	-0.32	-9.36	0.9920	-72.72	4538.60	0.06	-9.64
(T2) - H	x_H	1426.13	3966.44	0.9990	-2.53	-8.62	0.9997	1524.57	4006.17	-2.67	-8.73
Three component blends (second type)											
(x_M = 0.25)	x_L	-1956.76	5168.04	0.9996	3.48	-10.76	0.9996	-1984.27	5264.52	3.52	-10.95
(x_H = 0.25)	x_L	-1034.24	4711.51	0.9994	2.00	-10.02	0.9995	-919.41	4732.09	1.70	-10.04
(x_L = 0.25)	x_M	-922.52	4913.84	0.9995	1.48	-10.26	0.9998	-1064.86	5034.66	1.82	-10.52
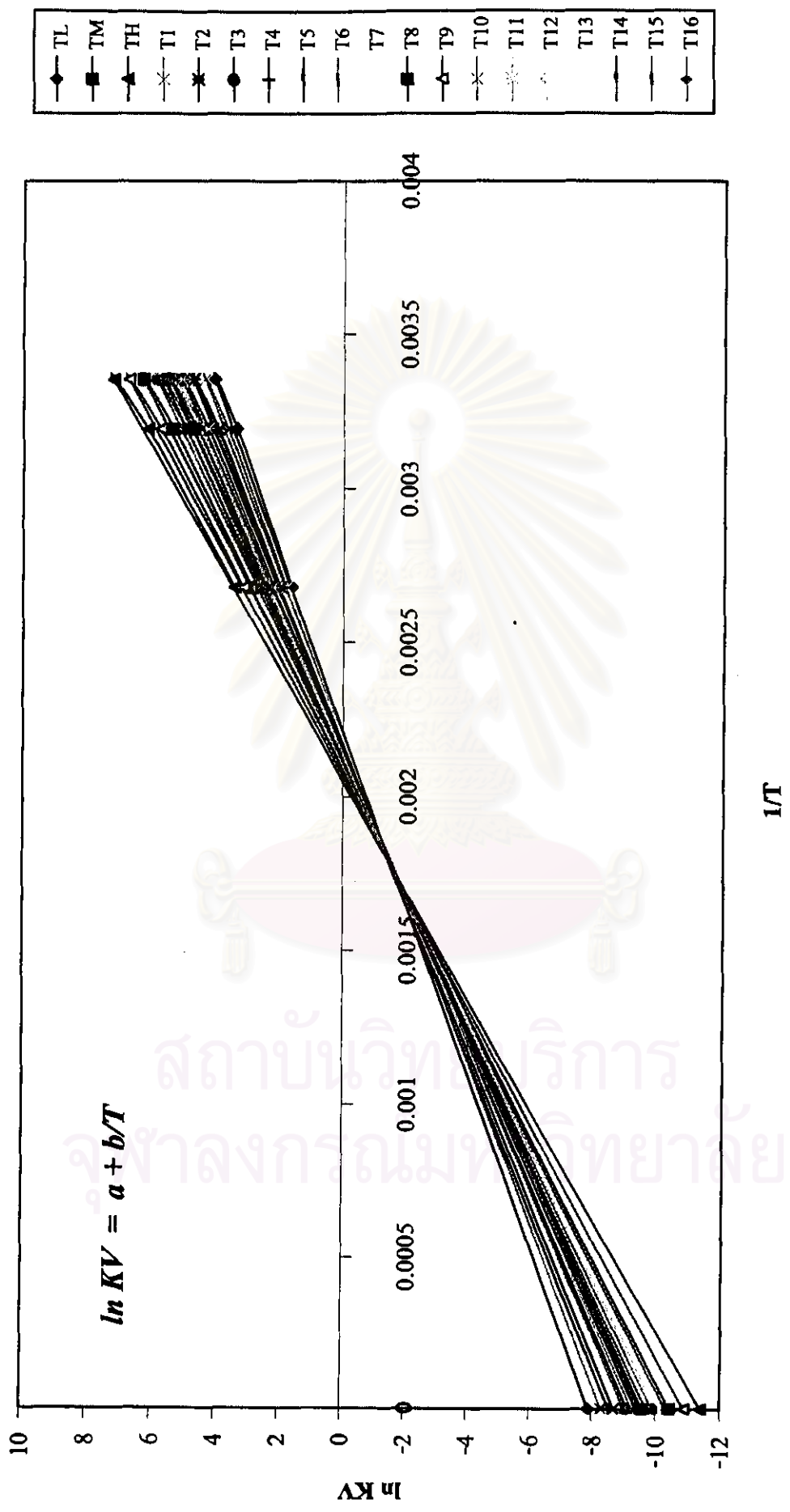
Figure 4.8 : Correlation between ln *KV* and *1/T*

The data obtained experimentally were plotted as $\ln \nu$ against $1/T$ shown in Figure 4.7 and Figure 4.8. In each case the plots were linear with a coefficient of determination (r^2) > 0.99. The correlation is as follows:

$$\ln \nu = a + \frac{b}{T}$$ Eq.(4.1)

where :

ν = kinematic viscosity

a = parameter a, y-intercept

b = parameter b, slope

T = temperature, K

The two parameters in the equation obtained by the least-squares method are also shown in Table 4.1 and Table 4.3.

Kinematic viscosity of B_L obtained experimentally at 25, 40 and 100°C are 60.85, 30.04 and 5.22 cSt, respectively. The plot was linear with a coefficient of determination (r^2) = 0.9972.

The two parameters in the Eq.(4.1) obtained by the least-squares method [24-29] are

$a = -7.97$, that is y-intercept of line B_L

$b = 3585.90$, that is slope of line B_L

Identical case is shown in Figure 4.8; for example, kinematic viscosity of T_3 obtained experimentally at 25, 40 and 100°C are 162.28, 71.54 and 9.05 cSt, respectively. The plot was linear with a coefficient of determination (r^2) = 0.9976. The two parameters in the equation obtained by the least-squares method are as follows:

$a = -9.12$, that is y-intercept of line T_3

$b = 4219.71$, that is slope of line T_3

4.4 Model for predicting kinematic viscosity

For two-component mixtures, the parameters (a,b), obtained for each type of mixture were plotted against the mixture composition (weight fraction), and in each case the plots were linear with a coefficient of determination $(r^2) = 0.99$. According to this, the following equations were obtained:

$$b = cx_i + d \qquad \text{Eq.(4.2)}$$

$$a = px_i + q \qquad \text{Eq.(4.3)}$$

where x_i is the weight fraction of the lubricating base oil component i.

For three-component mixtures obtained by blending a two-component mixture with the third lubricating base oil component and those with constant composition of a lubricating base oil similar to the analysis of the correlation parameters also indicated that the variation of a or b against x was linear. In the first type of three-component mixtures, the two-component concentration x_i is the weight fraction of the third lubricating base oil added to the two-component mixture considered as a lubricating base oil component. In the second type, x_i is the three-component concentration of one of the components whose composition varies in the mixture.

The parameters in these equations obtained by the least-squares method, for each type of mixture studied, are given in Tables 4.1-4.4. The experimental parameters fitted the above linear equations reasonably well, yielding coefficient of determination > 0.98. Figures 4.9-4.12 show these plots. Correlation between parameter b and composition for three-component mixtures of set B and set T is shown in Figure 4.9 and Figure 4.11 respectively. Correlation between parameter a and composition for three-component mixture of two sets is shown in Figure 4.10 and 4.12. All plots are linear with a coefficient of determination $(r^2) = 0.99$.
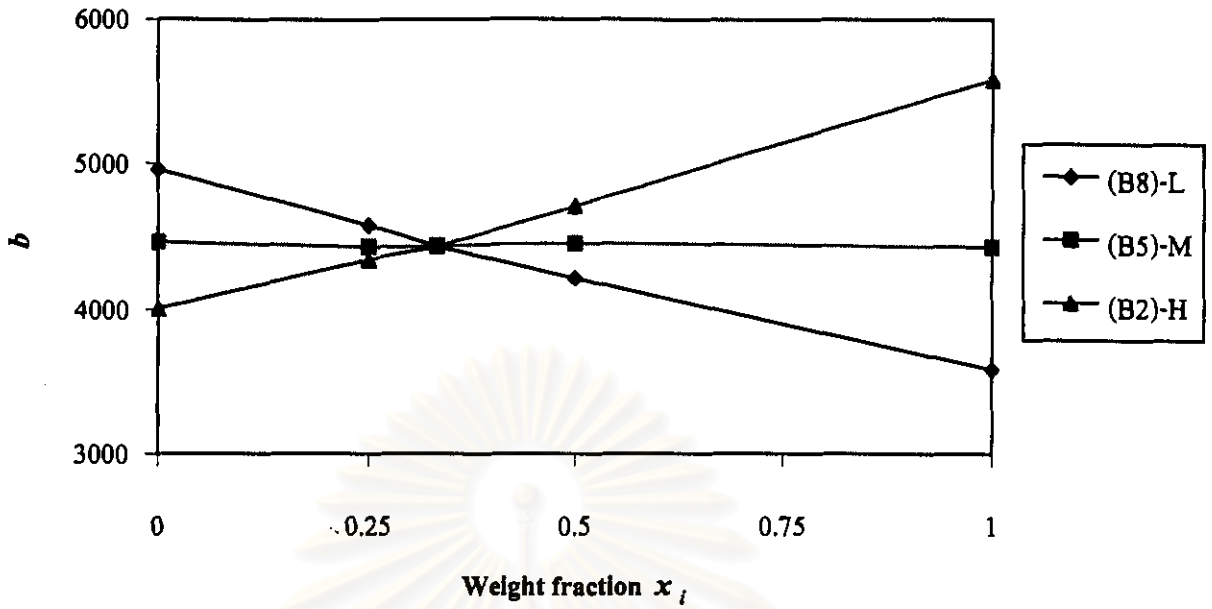
Figure 4.9 : Correlation between parameter b and composition
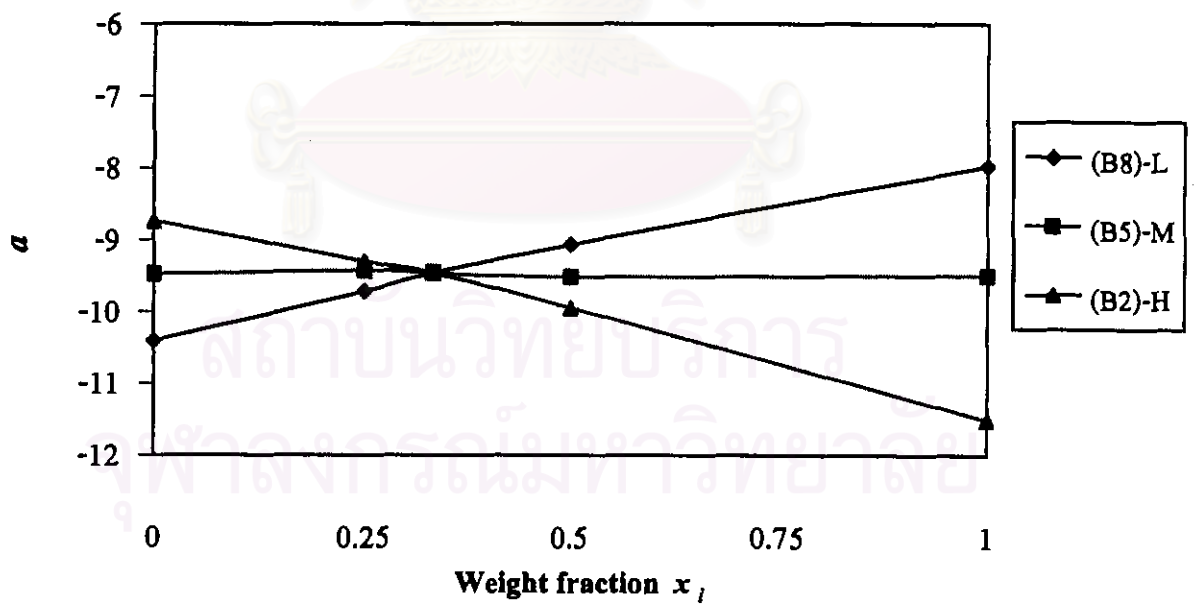
for three-component mixtures

Figure 4.10 : Correlation between parameter a and composition
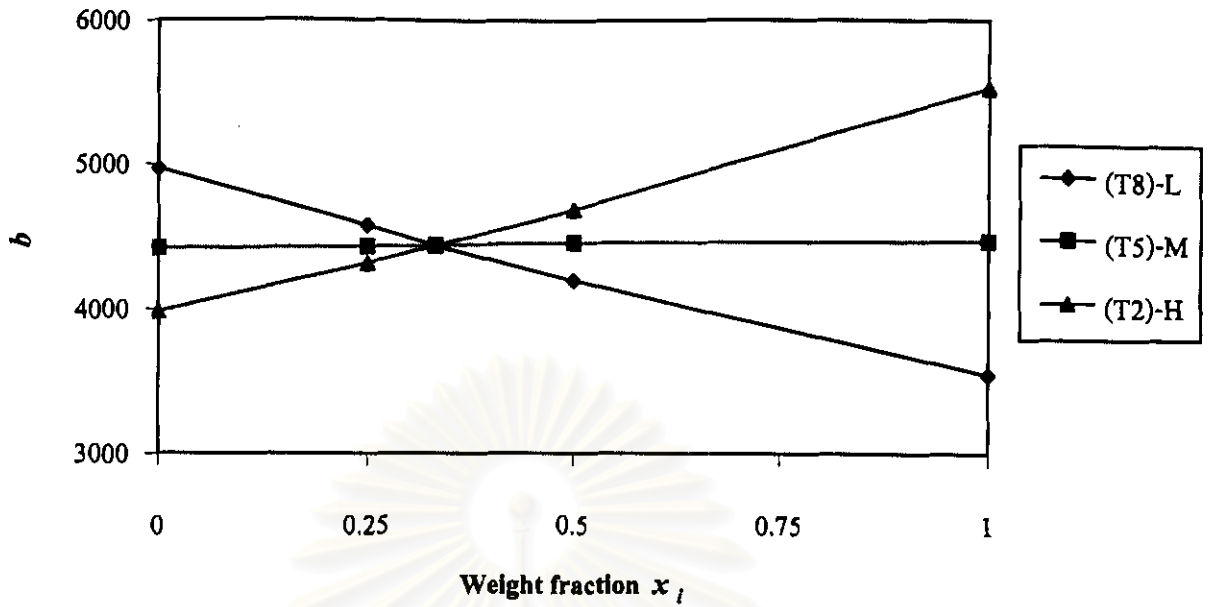
for three-component mixtures

Figure 4.11 : Correlation between parameter b and composition

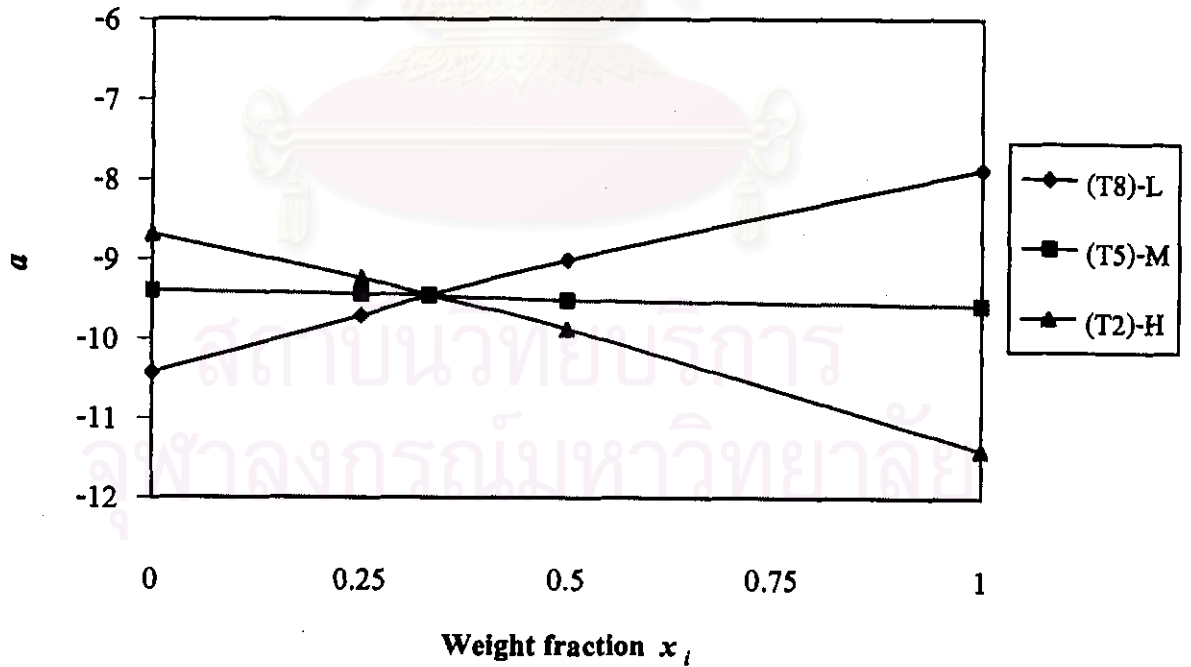**for three-component mixtures**

Figure 4.12 : Correlation between parameter a and composition

for three-component mixtures

For two-component blends of pure lubricating base oil according to the experimental equations (4.2) and (4.3), the following expressions can be derived for the linear parameters c, d, p and q, with $i = 1$:

$$c = b_1 - b_2 \qquad \text{Eq.(4.4)}$$

$$d = b_2 \qquad \text{Eq.(4.5)}$$

$$p = a_1 - a_2 \qquad \text{Eq.(4.6)}$$

$$q = a_2 \qquad \text{Eq.(4.7)}$$

$$\ln \nu_B = [a_1 x_1 + a_2 x_2] + \left[\frac{b_1 x_1 + b_2 x_2}{T} \right] \qquad \text{Eq.(4.8)}$$

It is thus possible to obtain the parameters of any mixture from the parameters of the lubricating base oil components. Application to multicomponent systems gives the following generalized equations:

$$\ln \nu_M = a_M + \frac{b_M}{T} \qquad \text{Eq.(4.9)}$$

The equations were applied to each type of the mixtures studied, referring the weight fraction x_i to lubricating base oil 1, and the results were compared with the experimental data.

In the first case, where the three-component mixtures were prepared by blending a two-component mixture with a lubricating base oil, the resulting equations for the linear parameters were:

$$c_1 = b_1 - b_B = b_1 - (b_2 y_2 + b_3 y_3) \qquad \text{Eq.(4.10)}$$

$$d_1 = b_B = b_2 y_2 + b_3 y_3 \qquad \text{Eq.(4.11)}$$

$$p_1 = a_1 - a_B = a_1 - (a_2 y_2 + a_3 y_3) \qquad \text{Eq.(4.12)}$$

$$q_1 = a_B = a_2 y_2 + a_3 y_3 \qquad \text{Eq.(4.13)}$$

all of them being constant; here, b_B and a_B correspond to the two-component mixtures of lubricating base oil 2 and lubricating base oil 3.

In the second case, for three-component mixtures with constant composition of a lubricating base oil 3, the following equations were found:

$$c_1 = b_1 - b_2 \qquad\qquad \text{Eq.(4.14)}$$

$$d_1 = b_2 \left(1 - y_3\right) + b_3 y_3 \qquad\qquad \text{Eq.(4.15)}$$

$$p_1 = a_1 - a_2 \qquad\qquad \text{Eq.(4.16)}$$

$$q_1 = a_2 \left(1 - y_3\right) + a_3 y_3 \qquad\qquad \text{Eq.(4.17)}$$

where y_3 is the weight fraction of lubricating base oil 3 in the three-component mixtures and is constant.

4.5 Comparison of model and data from testing

Since a good prediction was obtained for the linear parameters using the model, they were used to determine the viscosity of oil blends at three temperatures and the results were compared with the experimental data both prepared by weight and by volume methods. Table 4.5 and Table 4.6 show the results obtained from experimental and prediction of set B and set T, respectively. The viscosities of oil blends were calculated and compared with experimental data. Kinematic viscosities from prediction using weight method agree better with experimental values than volume method. It gave good results with absolute average deviation 4% at the temperatures 25°C and 100°C, but 16% at 40°C. The data obtained by this method were presented in Figures 4.13-4.18.

Table 4.5 : The calculated kinematic viscosities of lubricating base oil blends using model

Blend number	Temperature ($^{\circ}$C)	Kinematic viscosity (cSt)			%Dev.from	
		Experiment		Prediction	Experiment	
		by weight	by volume	Calculated	by weight	by volume
B1	25	82.44	82.72	79.76	-3.25	-3.58
	40	39.24	39.41	43.34	10.45	9.97
	100	6.19	6.23	6.17	-0.32	-0.96
B2	25	113.17	113.29	110.04	-2.77	-2.87
	40	54.43	54.68	57.81	6.21	5.72
	100	7.41	7.42	7.39	-0.27	-0.40
B3	25	157.91	158.24	151.81	-3.86	-4.06
	40	69.29	67.78	77.12	11.30	13.78
	100	8.87	8.89	8.85	-0.23	-0.45
B4	25	123.19	120.35	123.74	0.45	2.82
	40	56.37	54.73	65.76	16.66	20.15
	100	7.92	7.74	8.08	2.02	4.39
B5	25	254.79	252.48	277.87	9.06	10.06
	40	107.29	105.65	133.10	24.06	25.98
	100	12.06	11.94	12.66	4.98	6.03
B6	25	576.07	571.41	609.21	5.75	6.62
	40	220.60	218.19	269.37	22.11	23.46
	100	19.08	18.97	19.84	3.98	4.59
B7	25	341.67	354.20	332.83	-2.59	-6.03
	40	142.78	152.74	156.07	9.31	2.18
	100	13.87	14.16	13.87	0.00	-2.05
B8	25	537.24	541.90	528.91	-1.55	-2.40
	40	205.39	207.66	236.81	15.30	14.04
	100	18.11	18.12	18.16	0.28	0.22
B9	25	865.52	867.21	840.49	-2.89	-3.08
	40	313.76	316.00	359.30	14.51	13.70
	100	23.90	23.94	23.76	-0.59	-0.75

Table 4.5 : The calculated kinematic viscosities of lubricating base oil blends using model

| Blend number	Temperature (°C)	Kinematic viscosity (cSt)		Prediction	%Dev.from	
		Experiment			Experiment	
		by weight	by volume	Calculated	by weight	by volume
B10	25	237.63	236.88	240.04	1.01	1.33
	40	100.20	99.70	116.42	16.19	16.77
	100	11.31	11.29	11.53	1.95	2.13
B11	25	167.77	166.02	174.42	3.96	5.06
	40	73.55	73.28	87.50	18.97	19.41
	100	9.38	9.32	9.65	2.88	3.54
B12	25	366.67	363.25	380.50	3.77	4.75
	40	147.84	145.64	176.21	19.19	20.99
	100	14.68	14.66	15.05	2.52	2.66
B13	25	203.66	198.55	204.11	0.22	2.80
	40	87.80	85.48	100.68	14.67	17.78
	100	10.46	10.31	10.52	0.57	2.04
B14	25	246.50	244.34	258.26	4.77	5.70
	40	101.40	100.12	124.48	22.76	24.33
	100	11.81	11.79	12.08	2.29	2.46
B15	25	293.69	293.34	302.60	3.03	3.16
	40	121.60	120.42	143.41	17.94	19.09
	100	12.88	12.84	13.19	2.41	2.73
B16	25	242.88	242.35	251.00	3.34	3.57
	40	100.60	100.54	121.24	20.52	20.59
	100	11.62	11.61	11.85	1.98	2.07
%AAD	25				3.27	4.24
	40				16.26	16.75
	100				1.70	2.34
%MAD	25				1.15	1.49
	40				16.26	16.75
	100				1.53	1.76
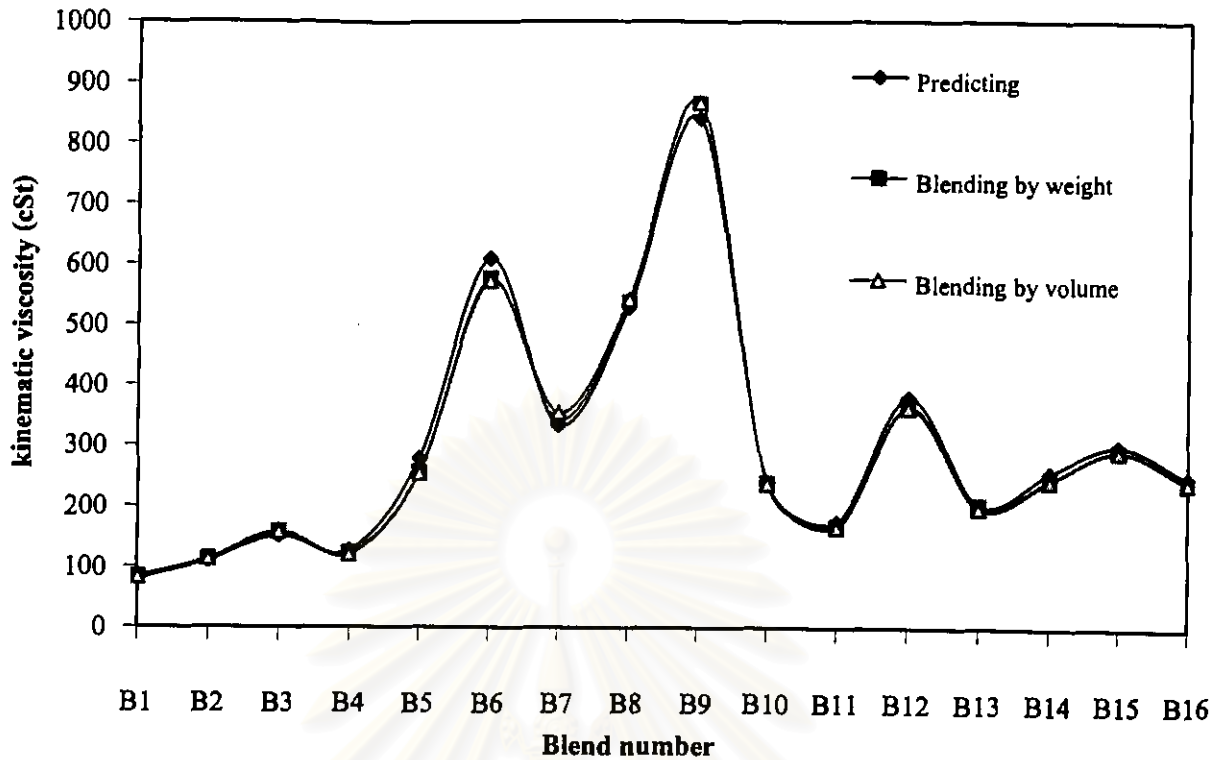
Figure 4.13 : Comparison of viscosity between prediction model and
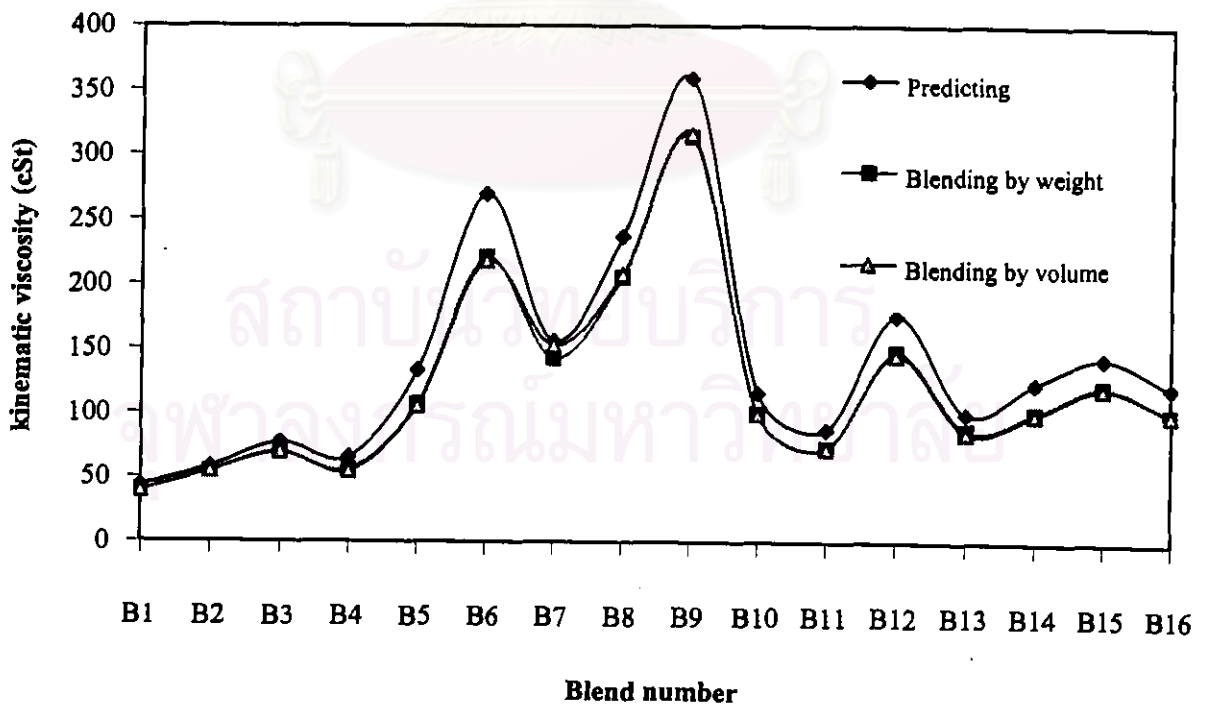
experimental data at 25°C

Figure 4.14 : Comparison of viscosity between prediction model and
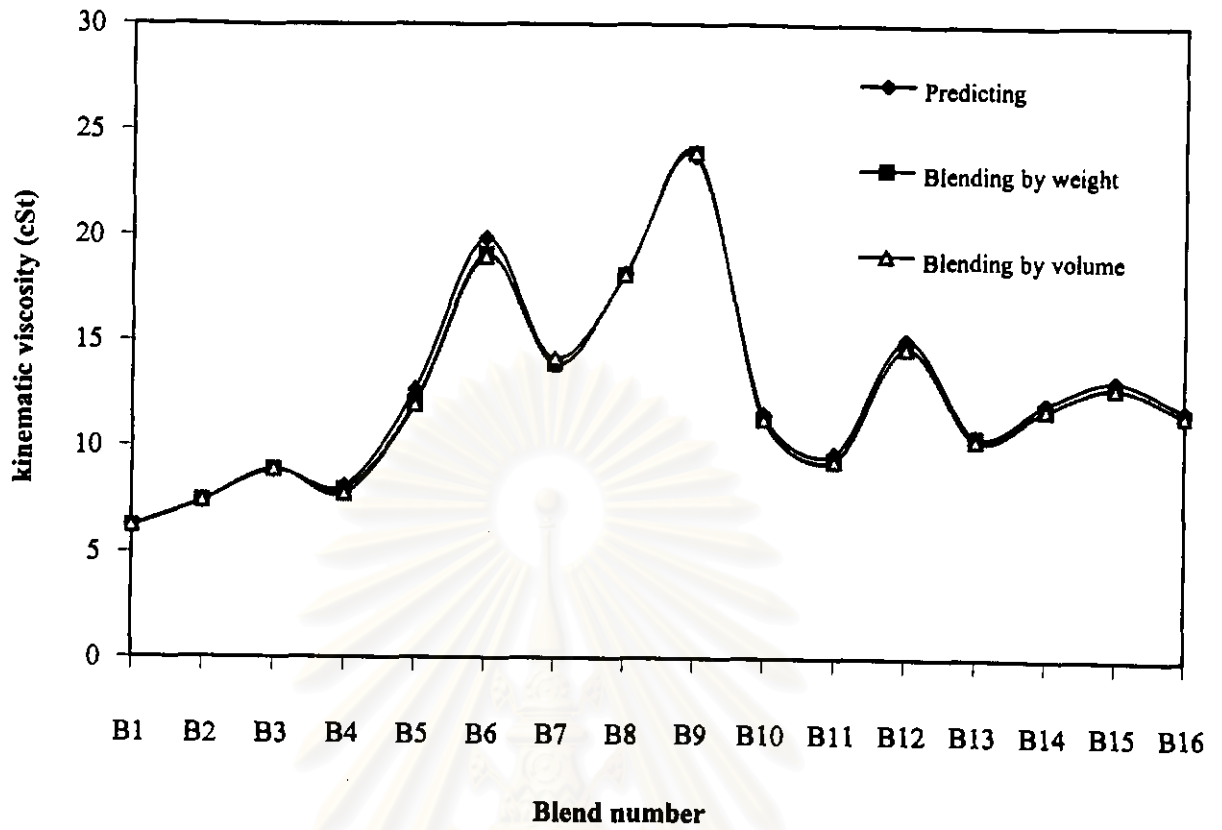
experimental data at 40°C

Figure 4.15 : Comparison of viscosity between prediction model and experimental data at 100°C

Table 4.6 : The calculated kinematic viscosities of lubricating base oil blends using model

Blend number	Temperature (°C)	Kinematic viscosity (cSt)			%Dev.from	
		Experiment		Prediction	Experiment	
		by weight	by volume	Calculated	by weight	by volume
T1	25	80.78	80.78	78.32	-3.05	-3.05
	40	38.58	38.55	42.70	10.68	10.77
	100	6.14	6.16	6.14	0.00	-0.32
T2	25	113.46	113.70	110.69	-2.44	-2.65
	40	52.08	51.88	58.15	11.66	12.09
	100	7.42	7.46	7.43	0.13	-0.40
T3	25	162.28	163.47	156.44	-3.60	-4.30
	40	71.54	70.95	79.21	10.72	11.64
	100	9.05	9.09	9.00	-0.55	-0.99
T4	25	115.10	114.80	121.35	5.43	5.71
	40	53.93	53.19	63.39	17.54	19.18
	100	7.76	7.66	7.95	2.45	3.79
T5	25	240.83	240.34	265.74	10.34	10.57
	40	102.10	101.92	128.17	25.53	25.76
	100	11.73	11.71	12.46	6.22	6.40
T6	25	545.72	544.07	581.92	6.63	6.96
	40	209.87	209.62	259.17	23.49	23.64
	100	18.69	18.61	19.54	4.55	5.00
T7	25	355.69	359.55	342.58	-3.69	-4.72
	40	144.28	142.76	160.17	11.01	12.20
	100	14.14	14.23	14.10	-0.28	-0.91
T8	25	545.88	547.16	530.80	-2.76	-2.99
	40	208.52	208.24	237.78	14.03	14.19
	100	18.25	18.19	18.26	0.05	0.38
T9	25	852.00	853.99	822.43	-3.47	-3.70
	40	311.10	310.66	353.00	13.47	13.63
	100	23.79	23.89	23.65	-0.59	-1.00

Table 4.6 : The calculated kinematic viscosities of lubricating base oil blends using model

| Blend number	Temperature (°C)	Kinematic viscosity (cSt)		Prediction	%Dev.from	
		Experiment			Experiment	
		by weight	by volume	Calculated	by weight	by volume
T10	25	239.53	238.64	241.19	0.69	1.07
	40	100.58	100.25	117.01	16.34	16.72
	100	11.39	11.36	11.59	1.76	2.02
T11	25	165.43	164.08	170.66	3.16	4.01
	40	72.82	72.33	85.91	17.98	18.78
	100	9.38	9.29	9.58	2.13	3.12
T12	25	358.94	356.74	373.71	4.11	4.76
	40	144.89	144.24	173.71	19.89	20.43
	100	14.60	14.54	15.01	2.81	3.23
T13	25	203.44	197.85	202.88	-0.28	2.54
	40	87.28	85.02	100.26	14.87	17.93
	100	10.52	10.33	10.54	0.19	2.03
T14	25	239.81	239.49	252.54	5.31	5.45
	40	101.42	101.27	122.16	20.45	20.63
	100	11.59	11.57	11.99	3.45	3.63
T15	25	294.78	291.45	301.72	2.35	3.52
	40	121.43	120.16	143.28	17.99	19.24
	100	12.93	12.92	13.26	2.55	2.63
T16	25	239.36	237.70	254.81	6.45	7.20
	40	101.12	100.42	121.03	19.69	20.52
	100	11.52	11.44	11.92	3.47	4.20
%AAD	25				3.99	4.58
	40				16.58	17.33
	100				1.95	2.50
%MAD	25				1.57	1.90
	40				16.58	17.33
	100				1.77	2.05
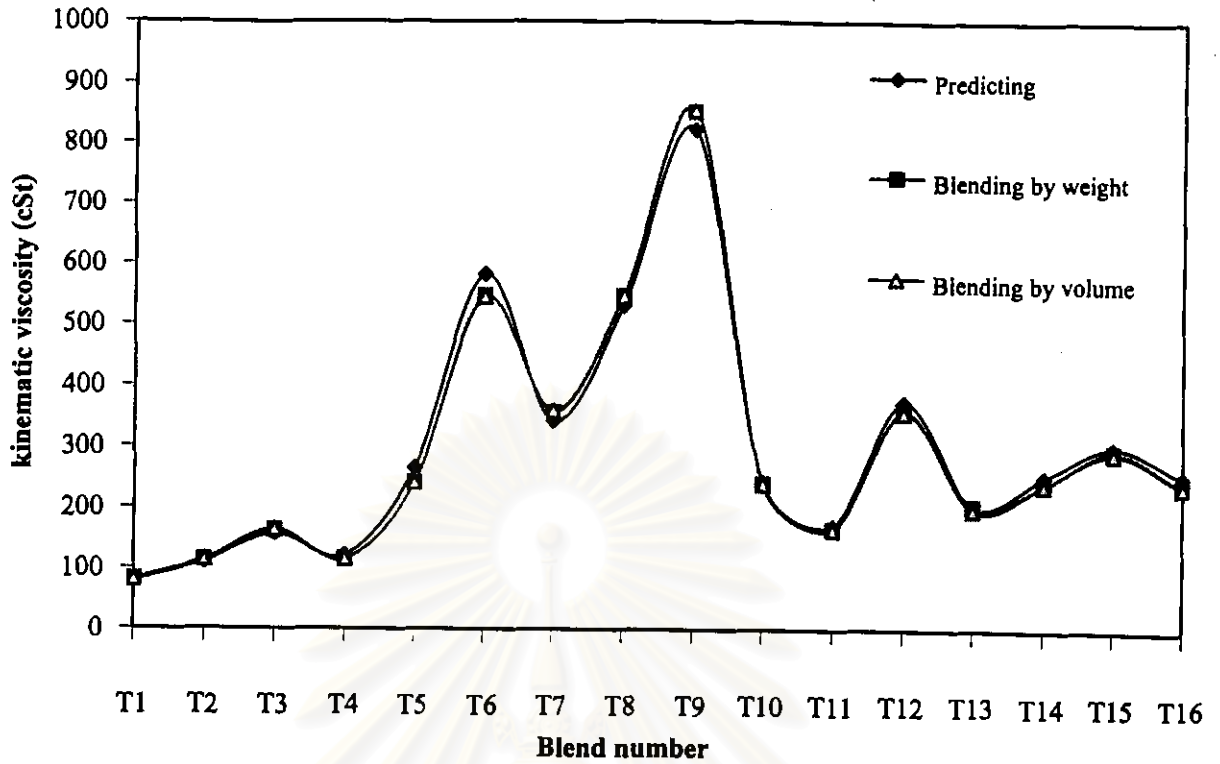
Figure 4.16 : Comparison of viscosity between prediction model and
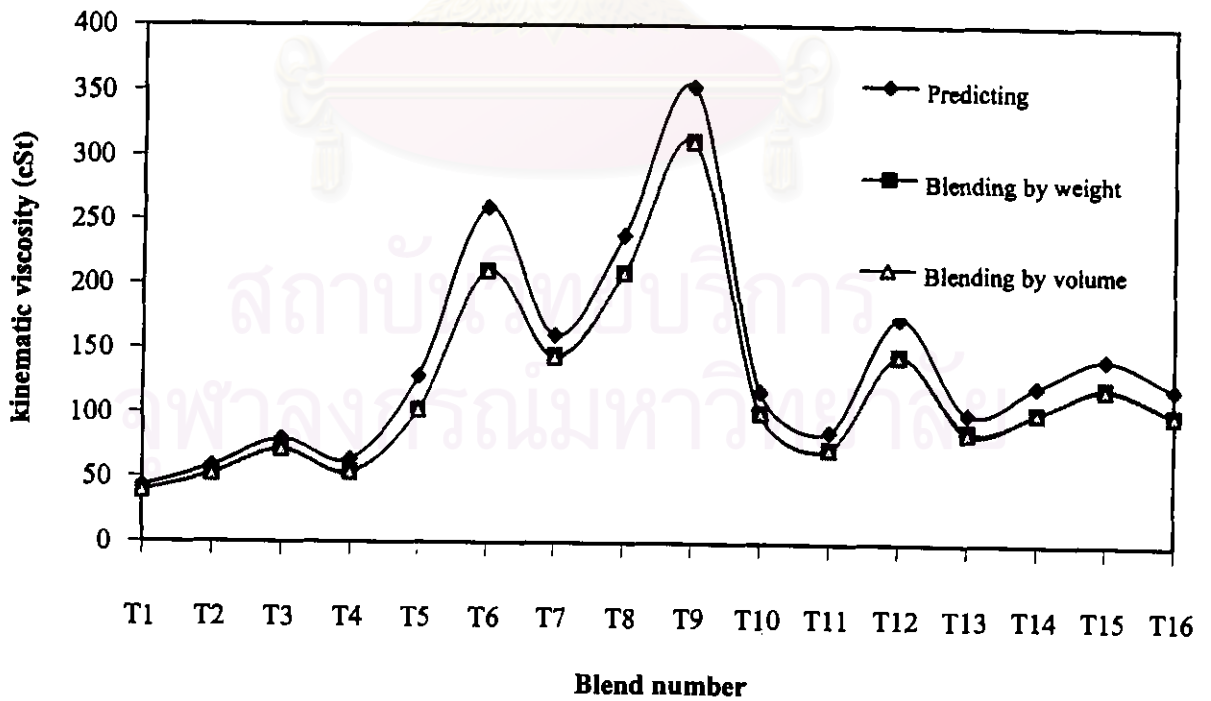
experimental data at 25°C

Figure 4.17 : Comparison of viscosity between prediction model and
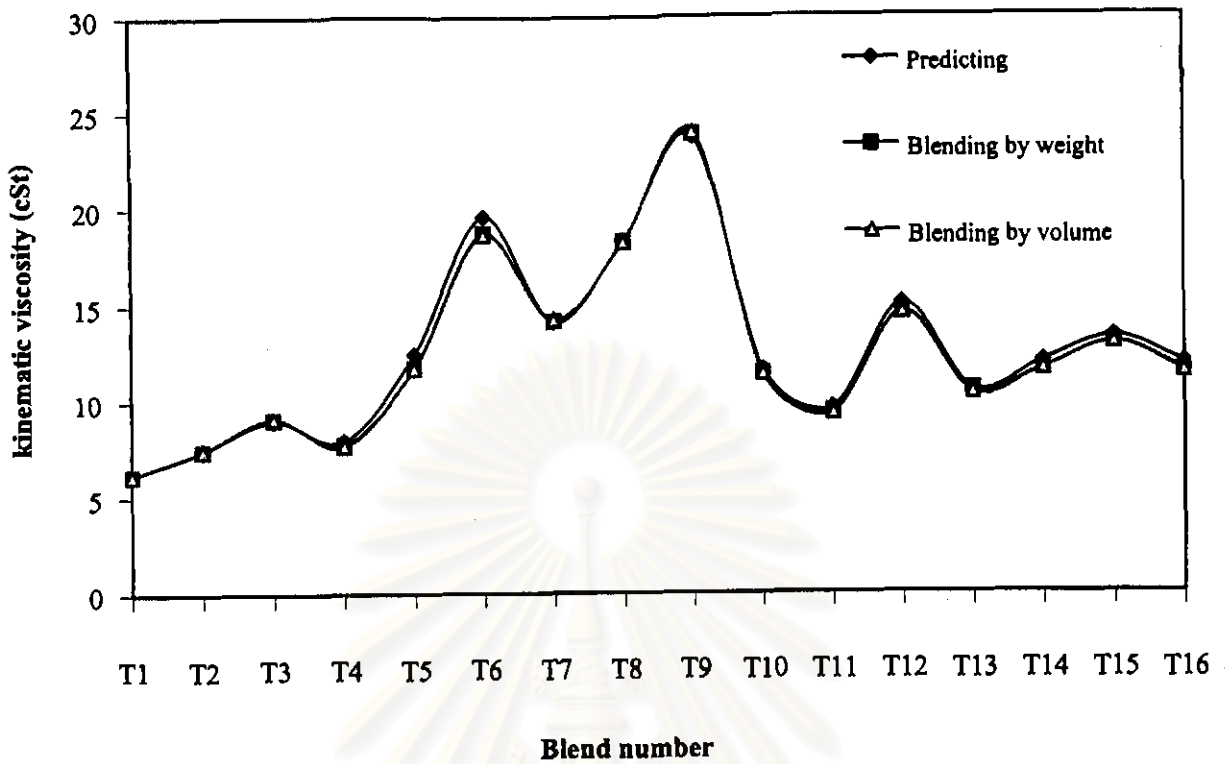
experimental data at 40°C

Figure 4.18 : Comparison of viscosity between prediction model and experimental data at 100°C

<u>Example1</u>: Prediction of kinematic viscosity of two-component blends by using this model.

Given: low viscosity oil V (100°C)   = 5.22 cSt,   weight fraction = 0.5

high viscosity oil V (100°C)   = 10.82 cSt,   weight fraction = 0.5

Determination: viscosity of blend mixture at 100°C.

Lubricating	Composition (weight fraction)			Correlation parameter		
base oils	x_L	x_M	x_H	a	b	r^2
L : B	1	0	0	-7.97	3585.90	0.9972
M : B	0	1	0	-9.50	4425.88	0.9975

Calculation:

Blend	x_i	c	d	p	q
L-M	x_L	$c = b_1 - b_2$	$d = b_2$	$p = a_1 - a_2$	$q = a_2$
=		$= b_L - b_M$	$= b_M$	$= a_L - a_M$	$= a_M$
(B_2)		$b_L = 3585.90$	$b_M = 4425.88$	$a_L = -7.97$	$a_M = -9.50$
		$b_M = 4425.88$		$a_M = -9.50$	
		$c = -839.98$	$d = 4425.88$	$p = 1.53$	$q = -9.50$

Formula: $ln\ V$ = $a + b/T$

b = $cx_i + d$

= $(-839.98 \times 0.5) + 4425.88$

=   4005.89

a = $px_i + q$

= $(1.53 \times 0.5) + (-9.50)$

=   -8.735

$ln\ V$ = $(-8.735) + [4005.89/(100 + 273.15)]$

V =   7.39 cSt

or formula: $ln\ V$ = $[a_1x_1 + a_2x_2] + [(b_1x_1 + b_2x_2)/T]$

= $[(-7.97 \times 0.5) + (-9.5 \times 0.5)] +$

$[(3585.90 \times 0.5) + (4425.88 \times 0.5)] / (100 + 273.15)$

= $-8.735 + (4005.89/373.15)$

V =   7.39 cSt

Example2: The weight fractions of blends are calculated by back substitution of the

viscosity into this model.

Given: low viscosity oil v (100°C)   =   5.22 cSt and

high viscosity oil v (100°C)   = 10.82 cSt

Determination: weight fraction of the viscosity oil for a blend of 6.19 at 100°C.

Formula:

$$ln\ v\ =\ [a_1x_1 + a_2x_2] + [(b_1x_1 + b_2x_2)/T]$$

$$ln\ 6.19\ =\ [(-7.97 \times x_1) + (-9.50 \times x_2)] +$$

$$[(3585.90 \times x_1) + (4425.88 \times x_2)] / (100 + 273.15)$$

$$x_1\ =\ 0.746$$

The weight fraction of blends for low viscosity oil = 0.746 and high viscosity oil = 0.254

4.6 Comparison of model and data from the literatures.

Several mathematical correlations have been suggested to calculate viscosity of blend system from known component values. Outlines of these correlations are given in Section 2.3 and a summary of models to predict viscosity is also listed in Table 4.9. A comparison of this model with ASTM D-341 and Besharah method, indicated that at 25°C a better accuracy is achieved by this model, at 40°C a better accuracy is achieved by ASTM D-341, at 100°C all three models are comparable in abilities for predicting kinematic viscosity.

Although the viscosity predicted using ASTM D-341 method is in good agreement with experimental one, its applicability is limited to the blend system with only two-component. Therefore, before using the calculation procedure must be converted weight fraction to volume fraction and also noted that the accuracy of calculation may be significantly lost if adaptation its method for use with other temperatures, extrapolated to temperatures far above or below 100 and 40°C.

There are database of 20 sets of samples prepared by weight method and 10 sets prepared by volume method in this study. The high accuracy for this model was found at 25 and 100°C. The accuracy was lost at 40°C which suggests that in order to obtain the accuracy reported must be compensated by using an offset when calculating the viscosity from lubricating base oils. Therefore, the experiment should be performed at temperature more than three points for the good results when using statistics linear regression analysis but it can be performed at only three points to determine the viscosity because the standard oils which were used to calibration the viscometer tubes, were limited to calibrat at temperatures 20.00, 25.00, 37.78, 40.00, 98.89 and 100.00°C. The advantages of this model are that minimal input parameters are fed into a model and can be applied to predict viscosity for the system of two-component and higher. It is thus convenient to formulate the formula and also obtain the satisfactory accurate results.

Table 4.7 : The calculated kinematic viscosities of lubricating base oil blends using 3 models
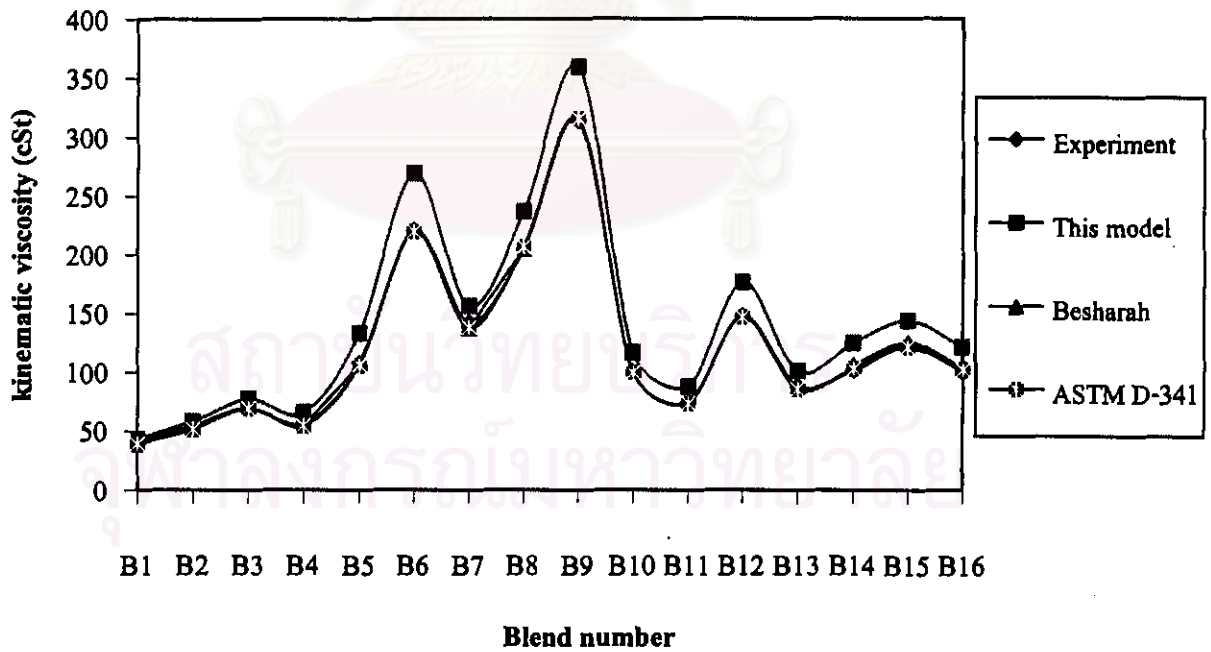
Blend number	Temperature ($^{\circ}$C)	Kinematic viscosity (cSt)			
		Experiment by weight	This model by predicting	Besharah method	ASTM D-341 method
B1	25	82.44	79.76	82.43	
	40	39.24	43.34	39.14	39.13
	100	6.19	6.17	6.17	6.18
B2	25	113.17	110.04	113.28	
	40	54.43	57.81	51.72	51.68
	100	7.41	7.39	7.36	7.38
B3	25	157.91	151.81		
	40	69.29	77.12		69.23
	100	8.87	8.85		8.89
B4	25	123.19	123.74	118.14	
	40	56.37	65.76	54.60	54.69
	100	7.92	8.08	7.73	7.71
B5	25	254.79	277.87	249.92	
	40	107.29	133.10	106.12	106.03
	100	12.06	12.66	11.91	11.82
B6	25	576.07	609.21		
	40	220.60	269.37		219.98
	100	19.08	19.84		18.95
B7	25	341.67	332.83	340.03	
	40	142.78	156.07	137.46	138.19
	100	13.87	13.87	13.91	13.88
B8	25	537.24	528.91	534.12	
	40	205.39	236.81	205.33	206.74
	100	18.11	18.16	18.13	18.06
B9	25	865.52	840.49		
	40	313.76	359.30		315.31
	100	23.90	23.76		23.83

Table 4.7 : The calculated kinematic viscosities of lubricating base oil blends using 3 models
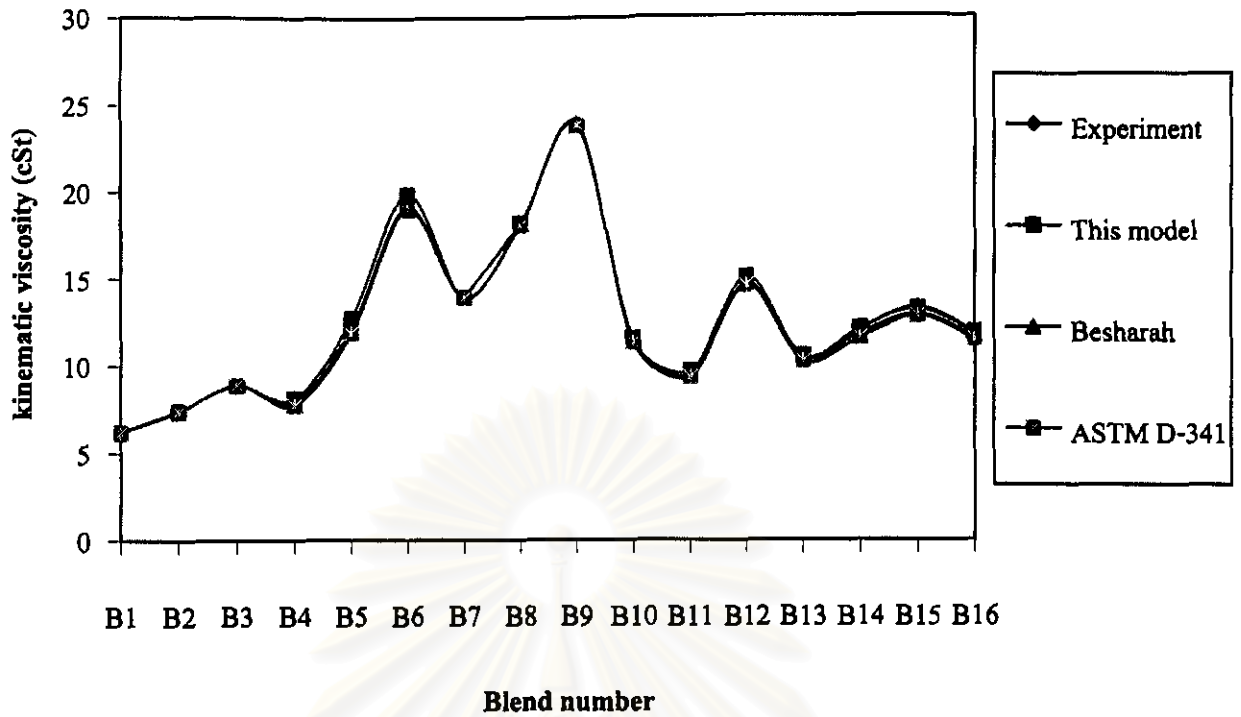
Blend number	Temperature (°C)	Kinematic viscosity (cSt)			
		Experiment by weight	This model by predicting	Besharah method	ASTM D-341 method
B10	25	237.63	240.04		
	40	100.20	116.42		99.91
	100	11.31	11.53		11.30
B11	25	167.77	174.42		
	40	73.55	87.50		73.36
	100	9.38	9.65		9.29
B12	25	366.67	380.50		
	40	147.84	176.21		146.88
	100	14.68	15.05		14.54
B13	25	203.66	204.11		
	40	87.80	100.68		85.46
	100	10.46	10.52		10.23
B14	25	246.50	258.26	268.88	
	40	101.40	124.48	106.02	102.92
	100	11.81	12.08	12.10	11.56
B15	25	293.69	302.60	321.85	
	40	121.60	143.41	124.48	120.85
	100	12.88	13.19	13.30	12.80
B16	25	242.88	251.00	263.70	
	40	100.60	121.24	103.91	101.92
	100	11.62	11.85	11.89	11.47
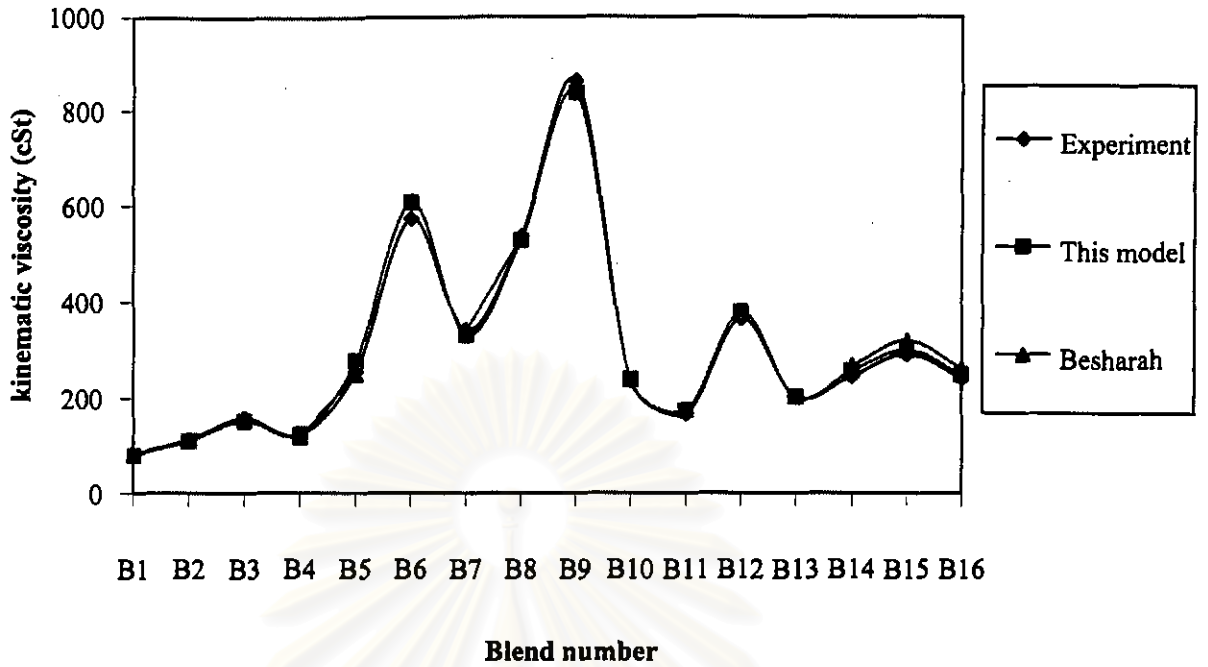
Figure 4.19 : Comparison of viscosity between 2 models

and experimental data at 25°C

Figure 4.20 : Comparison of viscosity between 3 models

and experimental data at 40°C

Blend number

Figure 4.21 : Comparison of viscosity between 3 models

and experimental data at 100°C

Table 4.8 : The calculated kinematic viscosities of lubricating base oil blends using 3 models

Blend number	Temperature (°C)	Kinematic viscosity (cSt)			
		Experiment by weight	This model by predicting	Besharah method	ASTM D-341 method
T1	25	80.78	78.32	80.60	
	40	38.58	42.70	38.72	38.45
	100	6.14	6.14	6.15	6.14
T2	25	113.46	110.69	113.38	
	40	52.08	58.15	51.08	51.78
	100	7.42	7.43	7.43	7.41
T3	25	162.28	156.44		
	40	71.54	79.21		70.97
	100	9.05	9.00		9.03
T4	25	115.10	121.35	112.49	
	40	53.93	63.39	52.14	52.68
	100	7.76	7.95	7.58	7.57
T5	25	240.83	265.74	273.21	
	40	102.10	128.17	111.30	101.85
	100	11.73	12.46	11.66	11.60
T6	25	545.72	581.92		
	40	209.87	259.17		211.00
	100	18.69	19.54		18.57
T7	25	355.69	342.58	353.59	
	40	144.28	160.17	142.79	142.85
	100	14.14	14.10	14.20	14.16
T8	25	545.88	530.80	542.18	
	40	208.52	237.78	209.06	209.15
	100	18.25	18.26	18.29	18.22
T9	25	852.00	822.43		
	40	311.10	353.00		311.18
	100	23.79	23.65		23.72

Table 4.8 : The calculated kinematic viscosities of lubricating base oil blends using 3 models

| Blend number	Temperature (°C)	Kinematic viscosity (cSt)			
		Experiment by weight	This model by predicting	Besharah method	ASTM D-341 method
T10	25	239.53	241.19		
	40	100.58	117.01		100.49
	100	11.39	11.59		11.36
T11	25	165.43	170.66		
	40	72.82	85.91		72.08
	100	9.38	9.58		9.23
T12	25	358.94	373.71		
	40	144.89	173.71		144.48
	100	14.60	15.01		14.45
T13	25	203.44	202.88		
	40	87.28	100.26		84.91
	100	10.52	10.54		10.22
T14	25	239.81	252.54	243.14	
	40	101.42	122.16	104.12	101.17
	100	11.59	11.99	12.06	11.48
T15	25	294.78	301.72	294.06	
	40	121.43	143.28	122.85	120.26
	100	12.93	13.26	13.10	12.80
T16	25	239.36	254.81	239.55	
	40	101.12	121.03	102.65	100.52
	100	11.52	11.92	11.78	11.41
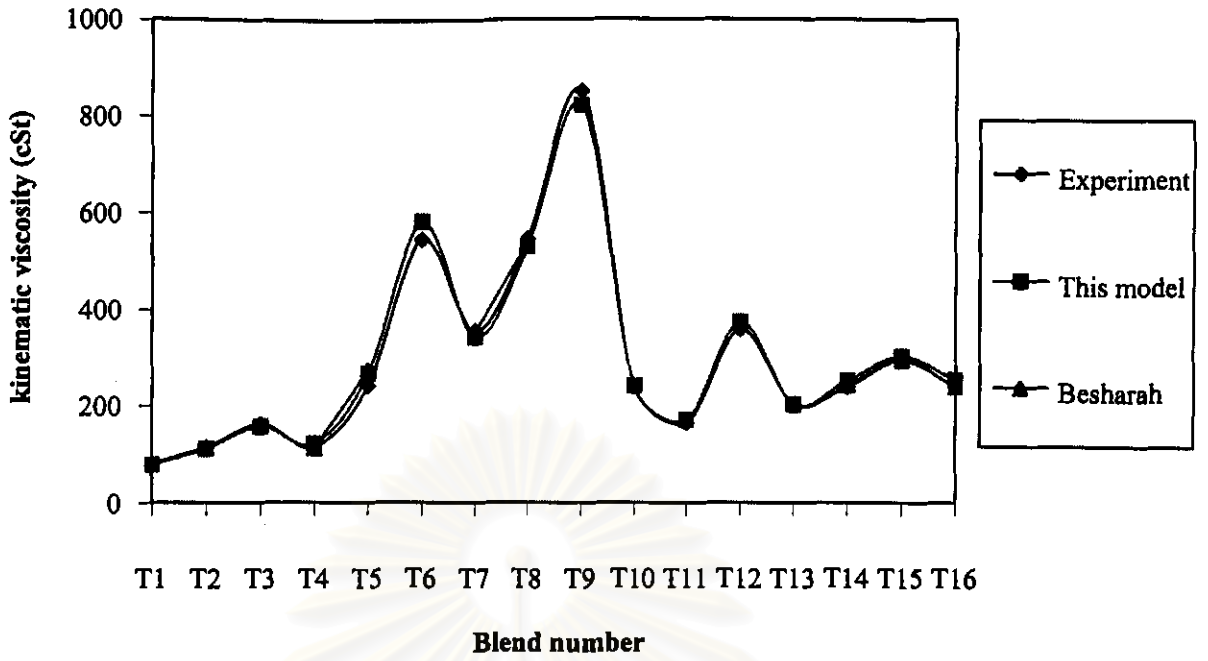
Figure 4.22 : Comparison of viscosity between 2 models

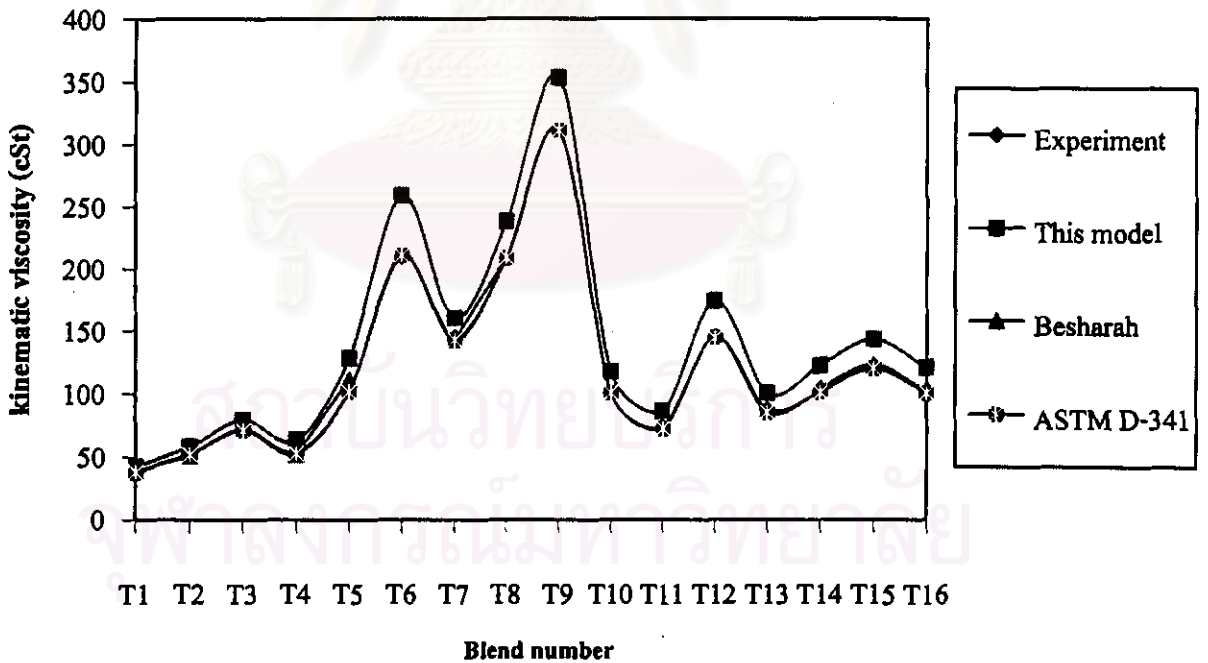and experimental data at 25°C

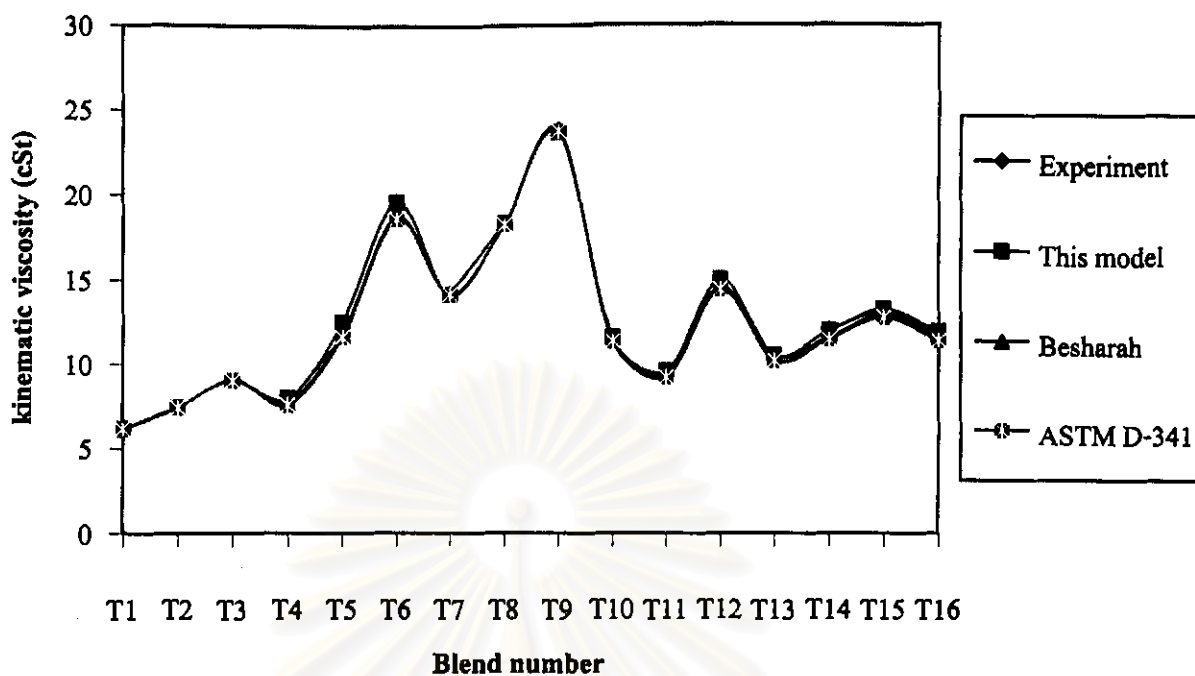Figure 4.23 : Comparison of viscosity between 3 models

and experimental data at 40°C

Figure 4.24 : Comparison of viscosity between 3 models

and experimental data at 100°C

<u>Example3</u>: Prediction of kinematic viscosity of three-component blends by using ASTM D-341.

Given: low viscosity oil ν (40°C) =   30.04 cSt, ν (100°C) =   5.22 cSt

          medium viscosity oil ν (40°C) =   94.14 cSt, ν (100°C) =   10.80 cSt

          high viscosity oil ν (40°C) = 490.46 cSt, ν (100°C) =   31.88 cSt

Density @30°C of low, medium, and high viscosity oil are 0.8618, 0.8770 and 0.8951 kg/L

Determination: viscosity of blends mixture at 40°C when prepared by weight, the fraction is as follows :- L : M : H = 0.375 : 0.25 : 0.375

<u>Calculation</u>:

Step I : Predicting the viscosity of a two-component mixture of low viscosity oil and high viscosity oil that contains 0.5 weight fraction low viscosity oil.

Step II : Predicting the viscosity of a mixture of medium viscosity oil and a two-component obtained in Step I, that contains 0.25 weight fraction medium viscosity oil.

<u>Step I</u> :

At 40°C;   volume fraction high viscosity oil $= \left[\dfrac{(E-A)\,(C-D)}{(E-F)\,(A-C)} + 1 \right]^{-1}$

E $=$ log log $Z_{H(40)}$ $=$ 0.4299

C $=$ log log $Z_{L(40)}$ $=$ 0.1725

D $=$ log log $Z_{L(100)}$ $=$ -0.1122

F $=$ log log $Z_{B(100)}$ $=$ 0.1798

Substitution:

$$0.50 = \left[\frac{(0.4299 - A)(0.1725 + 0.1122)}{(0.4299 - 0.1798)(A - 0.1725)} + 1 \right]^{-1}$$

A $=$ 106.03 cSt

At 100°C; volume fraction high viscosity oil $= \left[\dfrac{(F-B)\,(C-D)}{(E-F)\,(B-D)} + 1 \right]^{-1}$

B $=$ 11.82 cSt

Step II :

$$E = \log \log Z_{H(40)} = 0.3071$$

$$C = \log \log Z_{L(40)} = 0.2960$$

$$D = \log \log Z_{L(100)} = 0.0256$$

$$F = \log \log Z_{B(100)} = 0.0404$$

Substitution:

At 40°C;

$$0.75 = \left[\frac{(0.3071 - A)(0.2960 + 0.0256)}{(0.3071 - 0.0404)(A - 0.2960)} + 1\right]^{-1}$$

$$A = 102.92 \ cSt$$

At 100°C; volume fraction high viscosity oil $= \left[\frac{(F - B)(C - D)}{(E - F)(B - D)} + 1\right]^{-1}$

$$B = 11.56 \ cSt$$

Example4: Prediction of kinematic viscosity of three-component blends by using Besharah method.

Given :

Temperature ($^{\circ}$C)	Kinematic viscosity (cSt)			
	B10	B11	B12	B13
25	237.63	167.77	366.67	203.66
40	100.20	73.55	147.84	87.80
100	11.31	9.38	14.68	10.46

Determination: viscosity of blend mixture B14 at 40°C, that contains the weight fraction is as follows:- L : M : H = 0.375 : 0.25 : 0.375

Calculation:

$$(\ln v)_{mix} = \sum_i x_i \ln v_i + v^E$$

$$v^E = a_{12}x_1x_2 + a_{23}x_2x_3 + a_{13}x_1x_3 + a_{123}x_1x_2x_3$$

after substitution into these two equations:

$$a_{12} = 0.3788$$

$$a_{23} = 0.3782$$

$$a_{13} = 1.28 \times 10^{-8}$$

$$a_{123} = -4.06$$

Then kinematic viscosity at 40°C of sample B14 = 106.02 cSt

Table 4.9: Summary of models to predict viscosity.

Method	Equation
This model	$$\ln v \ = \ a \ + \ \frac{b}{T}$$ $$a \ = \ px_i + q$$ $$b \ = \ cx_i + d$$
ASTM-D341	at $40°C$: volume fraction high viscosity oil $$= \ \left[\frac{(E-A)\,(C-D)}{(E-F)\,(A-C)} + 1 \right]^{-1}$$ at $100°C$: volume fraction high viscosity oil $$= \ \left[\frac{(F-B)\,(C-D)}{(E-F)\,(B-D)} + 1 \right]^{-1}$$
Besharah method	$$\left(\ln v\right)_{mix} \ = \ \sum_i x_i \ln v_i + v^E$$ $$v^E \ = \ a_{12}x_1x_2 \ + \ a_{23}x_2x_3 \ + \ a_{13}x_1x_3 \ + \ a_{123}x_1x_2x_3$$

Table 4.10: Comparison of predicting kinematic viscosity by using 3 models.

	ASTM D-341	Besharah method	This model
Advantage	☺ Good agreement with experiment	☺ Good agreement with experiment	☺ Minimal input parameters into a model ☺ Can be applied to predict viscosity for the system of two-component and higher ☺ It is easy to determine viscosity ☺ High accuracy at 25 and 100 $^\circ$C
Disadvantage	☹ Limited to blend with only two-component ☹ Before using the calculation must be converted weight fraction to volume fraction ☹ The accuracy of calculation may be lost if adaptation its method for use with other temperatures, far above or below 100 and 40 $^\circ$C.	☹ Necessary to evaluate the interaction parameters	☹ The accuracy was lost at 40 $^\circ$C