CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Properties of coal, fuel oil and coal-oil mixture

4.1.1 Properties of coal and fuel oil

Typical analysis of coal and oil are given in Table 4.1. Two types of fuel oil : heavy fuel oil and light fuel oil and three types of coal : Ban Pu, Nong Ya Plong and Mae Moh coal were used in this work. Three types of coal can be classified into two ranks : Nong Ya Plong coal is bituminous and Ban Pu and Mae Moh coal are subbituminous.

4.1.2 Properties of coal-oil mixture (COM)

Table 4.2 shows the properties for COM of Ban Pu coal and fuel oil such as pour point, wt% sulfur, wt% ash and heating value. Figure 4.1 gives the dependence of pour point on coal concentration. It was observed that the pour point of COM decreased with increasing coal concentration. The pour point for COM of heavy fuel oil was higher than COM of light fuel oil due to its viscosity. It is interesting to note that the more coal loading the less fluidity of COM.

Figure 4.2 shows the variation of wt% ash of COM with coal concentration. The wt% ash of COM increased with increasing coal concentration because coal had higher wt% ash than fuel oil. Therefore, wt% ash of COM depended on coal loading. Figure 4.3 gives the dependence of heating value of COM on coal concentration. It was found that the heating value of COM decreased with increasing coal concentration because coal had a specific energy per unit weight less than fuel oil. For example, at 50 wt%, the heating value for COM of LFO and HFO were

0.72 and 0.74 times of LFO and HFO respectively.

In this part of study, pour point, wt% ash and heating value were the function of coal concentration. These results gave the basis to choose suitable coal concentration to obtain a fluidity of COM with an optimum heating value to use as the effective fuel. Therefore, this COM has less problem of ash accumulation which causes slagging, fouling and clinker in boiler.

Table 4.1 Coal and Fuel oil Analysis

Component	Mae Moh	Ban Pu	Nong Ya Plong	Heavy fuel oil	Light fuel oil
Proximate analysis(wt%) (Air dried basis)					
Moisture	14.30	11.99	6.61	-	-
Volatile matter	38.58	43.09	32.26	-	-
Ash	12.07	6.71	19.38	0.07	0.02
Fixed carbon	35.05	38.21	41.76	-	-
Total sulfur (dry basis)	3.59	1.85	0.69	2.07	2.16
Heating value (cal/g)	4527	4900	5526	10221	10616
Heating value (BTU/lb) (Moist, MM-free)	9462	9538	12650	-	-
Rank	Sub-bituminous C	Sub-bituminous B	High-volatile C bituminous		
Ultimate analysis(wt%) (Dry basis)					
C	54.95	58.91	62.49	85.32	85.45
H	3.81	4.18	4.63	12.39	12.37
O (by difference)	21.43	27.63	10.58	.00	.00
N	2.14	0.53	0.87	0.15	0.00
S	3.59	1.85	0.69	2.07	2.16
Ash	14.09	6.91	20.75	0.07	0.02

Table 4.2 Properties for coal-oil mixture of fuel oil and -75 microns Ban Pu coal at various coal concentrations (wt%).

wt% coal in COM	Pour point (°C)	Ash (wt%)	Sulfur (wt%)	Heating value (cal/g)
Heavy fuel oil				
HFO	28.0	0.07	2.07	10221
10	29.0	0.85	2.05	9993
20	31.0	1.62	2.03	9344
30	32.0	2.39	2.02	8775
40	33.0	3.18	1.99	8153
50	35.0	3.98	2.01	7597
Light fuel oil				
LFO	24.0	0.02	2.16	10616
10	28.0	0.77	1.97	10033
20	30.0	1.56	1.94	9401
30	31.5	2.39	1.82	8854
40	32.0	3.20	1.92	8294
50	34.0	3.96	2.02	7651

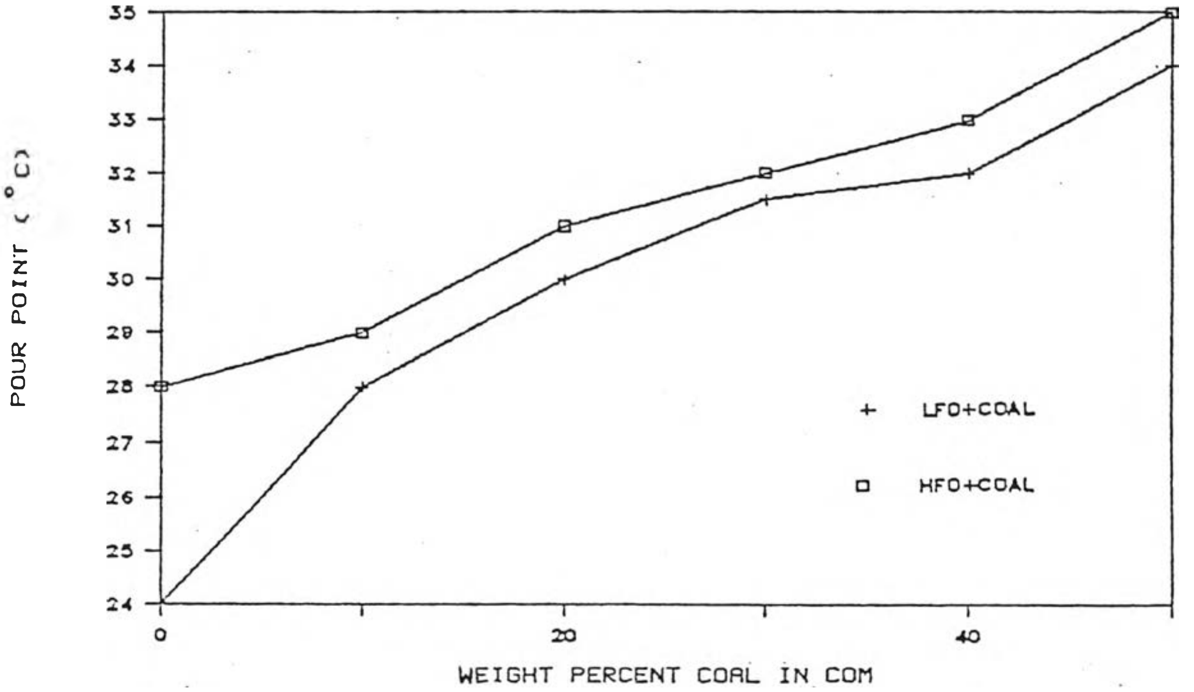

Figure 4.1 Variation of pour point with coal concentration for Ban Pu coal in different fuel oil types.

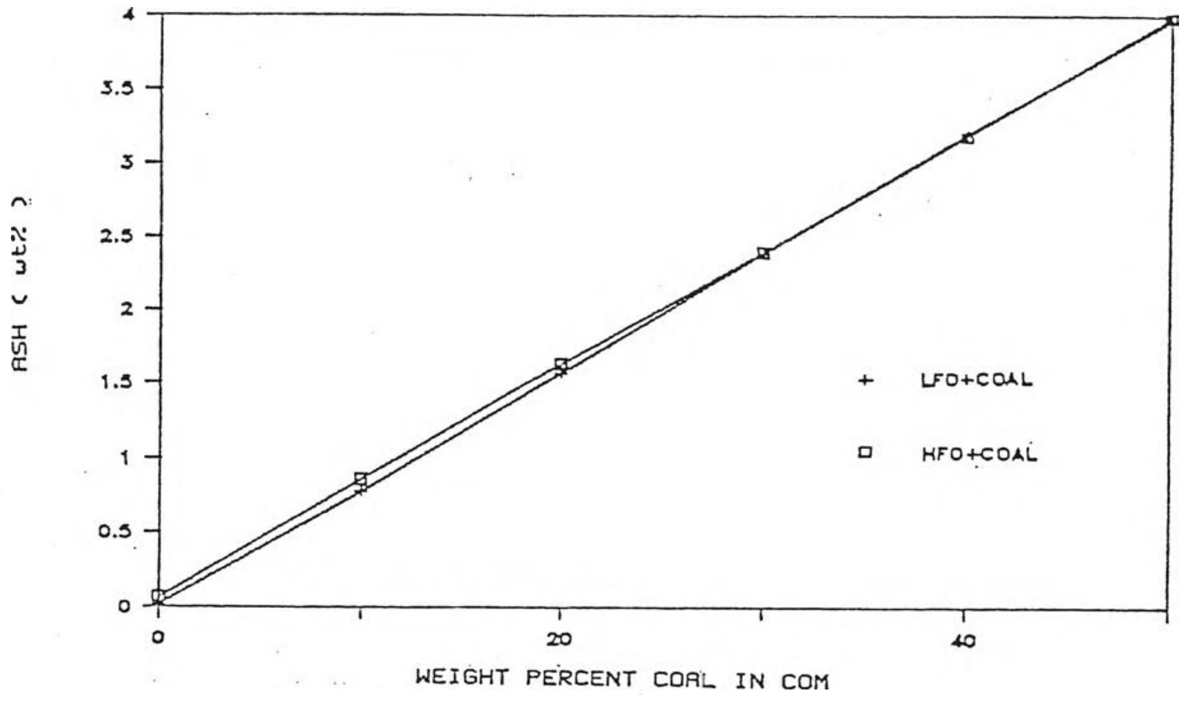

Figure 4.2 Variation of weight percent ash with coal concentration for Ban Pu coal in different fuel oil types.

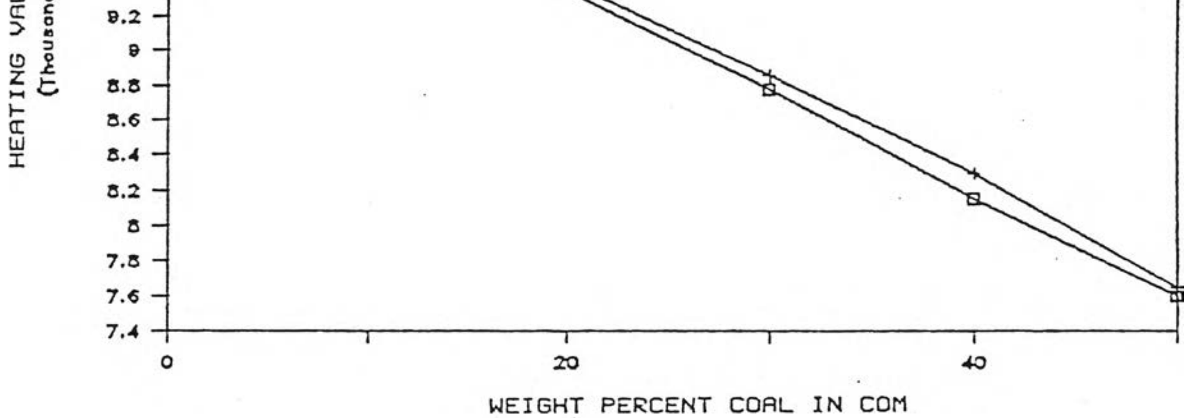

Figure 4.3 Variation of heating value with coal concentration for Ban Pu coal in different fuel oil types.

4.2 Rheological property of COM

4.2.1 Effect of coal loading and shear rate on slurry rheology

Table 4.3, 4.4, 4.5 and 4.6 give the rheological properties; shear stress versus shear rate for COM at 40 °C of -75 microns Ban Pu coal in LFO, Ban Pu coal in HFO, Mae Moh coal in HFO and Nong Ya Plong coal in HFO respectively. The flow curves of COM at various coal concentrations are shown in Figure 4.4, (Ban Pu coal in LFO) and Figure 4.5, 4.6, 4.7 (Ban Pu coal, Mae Moh coal in HFO and Nong Ya Plong coal in HFO). The rheograms are linear and exhibit either Newtonian or Bingham plastic behavior. The fuel oil is the lowest curve and actually shows Newtonian behavior. From these figures, when the coal concentration was increased, the onset of a yield stress was apparent, i.e. for Ban Pu coal in HFO, Ban Pu coal in LFO, Mae Moh coal in HFO and Nong Ya Plong coal in HFO were 40 %, 40 %, 20 % and 20 % respectively. The linear relation between shear stress and shear rate was preserved and the Newtonian behavior shifted to the Bingham plastic one. As coal concentration was increased, so do plastic viscosity (rheogram slope) and yield stress (rheogram intercept) increased (see Figure 4.4-4.7). The yield stress for 50 % COM of Ban Pu coal in HFO, Ban Pu coal in LFO, Mae Moh coal in HFO and Nong Ya Plong coal in HFO were 149.41, 169.91, 327.06 and 4165.84 dynes/cm^2 respectively, while Papachristodoulou and Trass (3) reported the yield stress value of 350 Pa (3500 dynes/cm^2) and Munro et al. of 371 dynes/cm^2.

The physical explanation of Bingham plastic behavior is that a network was formed inside the fluid as a result of interparticle forces, and an external stress equivalent to the yield stress had to be applied for the network to be destroyed and the flow to occur. In these cases the generalised Bingham model has been to fit well.

Table 4.3 Rheological data; shear stress and shear rate, for COM of light fuel oil and -75 microns Ban Pu coal at various coal concentrations (wt%) and 40 °C.

Speed (rpm)	Weight percent coal in COM											
	0		10		20		30		40		50	
	r	T	r	T	r	T	r	T	r	T	r	T
0.3	0.06	3.37	0.07	6.74	0.07	10.11	0.07	23.58	0.07	53.90	0.07	336.85
0.6	0.12	10.11	0.13	16.84	0.13	20.21	0.14	40.42	0.14	67.37	0.14	471.59
1.5	0.31	23.58	0.33	40.42	0.33	40.42	0.35	74.11	0.34	175.16	0.35	1010.55
3	0.62	40.42	0.66	70.74	0.67	74.11	0.70	134.74	0.69	309.90	0.70	1886.36
6	1.24	77.48	1.33	128.00	1.34	144.85	1.39	262.74	1.37	606.33	1.40	3435.87
12	2.48	161.69	2.65	242.53	2.68	282.95	2.78	525.49	2.75	1158.76	2.81	7006.48
30	6.21	474.96	6.63	606.33	6.69	808.44	6.96	1397.93	6.87	3058.60	7.02	17044.61
60	12.42	798.33	13.25	1192.45	13.38	1414.77	13.92	2560.06	13.75	5456.97	14.04	33819.74

r is defined as shear rate in unit 1/s
T is defined as shear stress in unit dynes/cm^2

Table 4.4 Rheological data: shear stress and shear rate, for COM of heavy fuel oil and -75 microns Ban Pu coal at various coal concentrations (wt%) and 40 ^{0}C.

Speed (rpm)	Weight percent coal in COM											
	0		10		20		30		40		50	
	r	T	r	T	r	T	r	T	r	T	r	T
0.3	0.06	10.11	0.07	16.84	0.07	23.58	0.07	67.37	0.07	134.74	0.06	673.70
0.6	0.12	13.47	0.13	30.32	0.14	40.42	0.15	94.32	0.14	269.48	0.13	1347.40
1.5	0.31	47.16	0.33	67.37	0.34	84.21	0.37	175.16	0.34	538.96	0.32	3368.50
3	0.62	94.32	0.67	128.00	0.69	161.69	0.74	323.38	0.68	1010.55	0.64	6602.26
6	1.24	181.90	1.33	252.64	1.38	309.90	1.47	579.38	1.36	1886.36	1.28	12732.93
12	2.48	363.80	2.67	498.54	2.75	592.86	2.94	1131.82	2.73	3772.72	2.55	25735.34
30	6.20	909.50	6.67	1219.40	6.88	1451.82	7.35	2762.17	6.81	9094.95	6.38	63529.91
60	12.40	1795.41	13.35	2381.53	13.75	2869.96	14.70	5497.39	13.63	18594.12	12.76	-

r is defined as shear rate in unit 1/s
T is defined as shear stress in unit dynes/cm^{2}

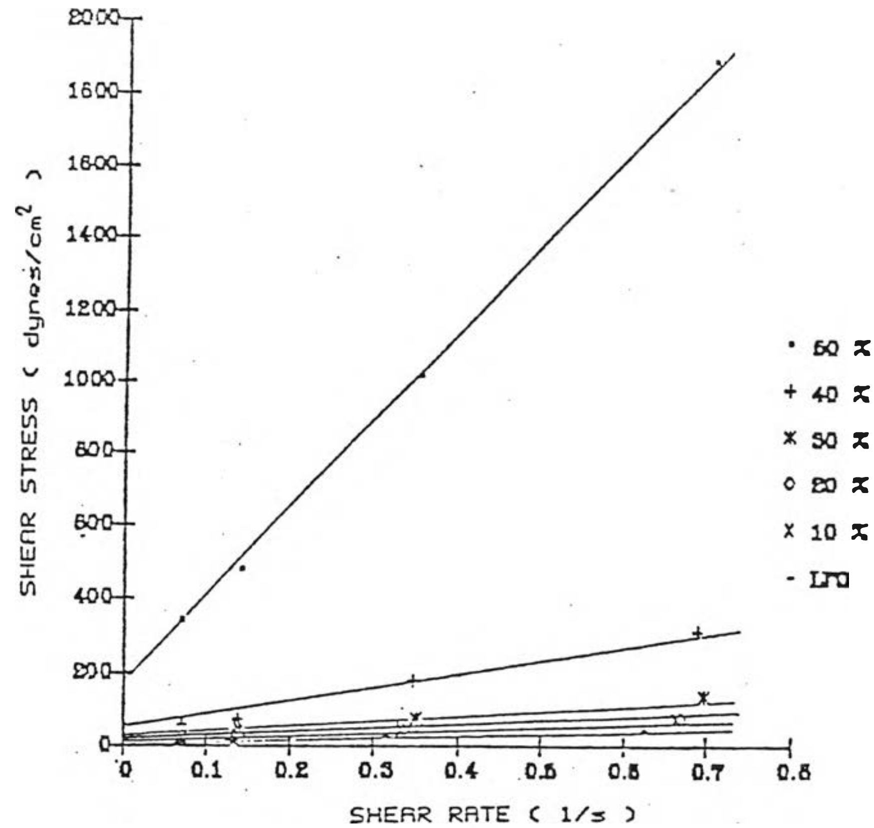

Figure 4.4 Rheogram of Ban Pu coal in light fuel oil; various coal concentrations, 40 °C.

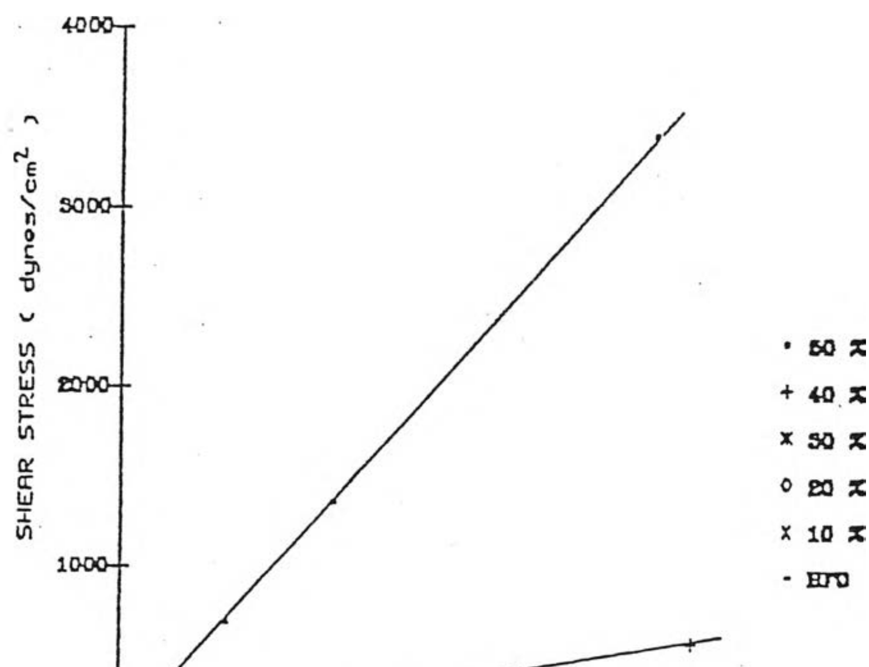

Figure 4.5 Rheogram of Ban Pu coal in heavy fuel oil; various coal concentrations, 40 °C.

Table 4.5 Rheological data; shear stress and shear rate, for COM of heavy fuel oil and -75 microns Mae Moh coal at various coal concentrations (wt%) and 40 °C.

Speed (rpm)	Weight percent coal in COM											
	0		10		20		30		40		50	
	r	T	r	T	r	T	r	T	r	T	r	T
0.3	0.06	10.11	0.07	16.84	0.07	53.90	0.07	53.90	0.07	202.11	0.07	606.33
0.6	0.12	13.47	0.13	33.69	0.14	80.84	0.13	94.32	0.14	336.85	0.13	1145.29
1.5	0.31	47.16	0.33	87.58	0.35	175.16	0.34	229.06	0.34	741.07	0.33	2492.69
3	0.62	94.32	0.65	171.79	0.71	350.32	0.67	458.12	0.68	1482.14	0.67	4850.64
6	1.24	181.90	1.31	320.01	1.41	633.28	1.34	835.39	1.37	2829.54	1.34	9499.17
12	2.48	363.80	2.61	616.44	2.83	1185.71	2.69	1616.88	2.73	5322.23	2.68	18863.60
30	6.20	909.50	6.53	1461.93	7.07	2829.54	6.72	3799.67	6.83	12665.56	6.69	45407.38
60	12.40	1795.41	13.06	2812.70	14.13	5443.50	13.44	7437.65	13.66	25061.64	13.39	-

r is defined as shear rate in unit 1/s

T is defined as shear stress in unit dynes/cm^2

Table 4.6 Rheological data; shear stress and shear rate, for COM of heavy fuel oil and -75 microns Nong Ya Plong coal at various coal concentrations (wt%) and 40 ^{o}C.

Speed (rpm)	Weight percent coal in COM											
	0		10		20		30		40		50	
	r	T	r	T	r	T	r	T	r	T	r	T
0.3	0.06	10.11	0.07	23.58	0.08	67.37	0.07	53.90	0.09	673.70	0.10	5052.75
0.6	0.12	13.47	0.14	33.69	0.16	80.84	0.14	121.27	0.18	808.44	0.13	6534.89
1.5	0.31	47.16	0.35	74.11	0.39	148.21	0.35	242.53	0.45	1414.77	0.32	10981.31
3	0.62	94.32	0.69	148.21	0.78	256.01	0.69	458.12	0.90	2021.10	0.64	16909.87
6	1.24	181.90	1.39	279.59	1.56	458.12	1.39	835.39	1.79	3301.13	1.28	27150.11
12	2.48	363.80	2.78	535.59	3.12	848.86	2.77	1576.46	3.59	5726.45	2.55	52009.64
30	6.20	909.50	6.94	1283.40	7.79	2048.05	6.93	3732.30	8.97	12867.67	6.38	-
60	12.40	1795.41	13.88	2492.69	15.58	3974.83	13.85	7222.06	17.93	24387.94	12.76	-

r is defined as shear rate in unit 1/s
T is defined as shear stress in unit dynes/cm^2

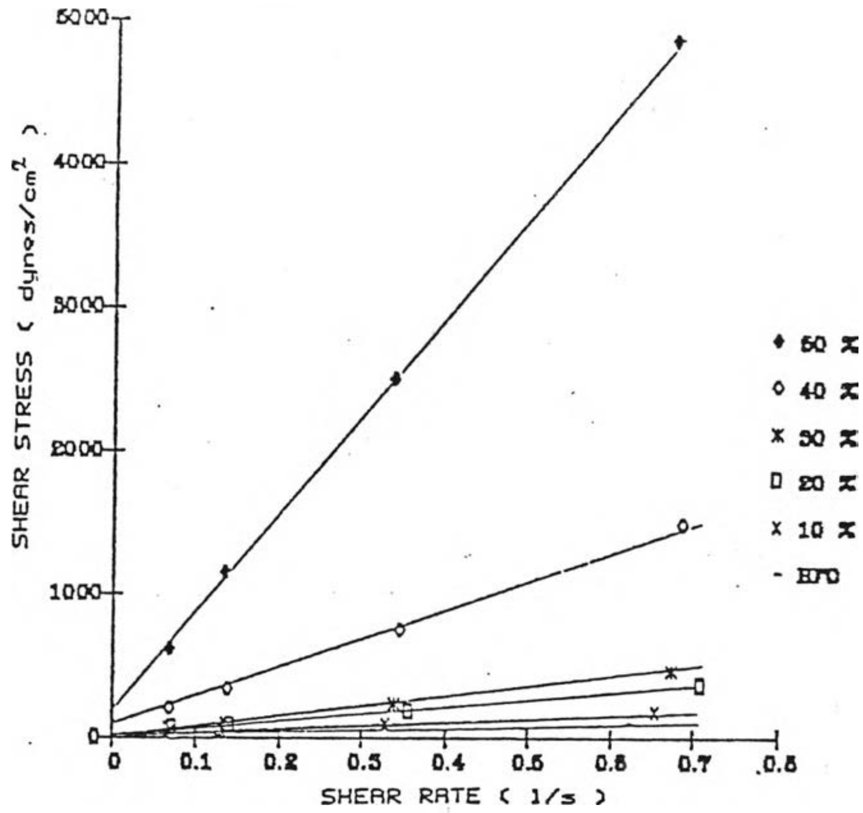

Figure 4.6 Rheogram of Mae Moh coal in heavy fuel oil; various coal concentrations, 40 °C.

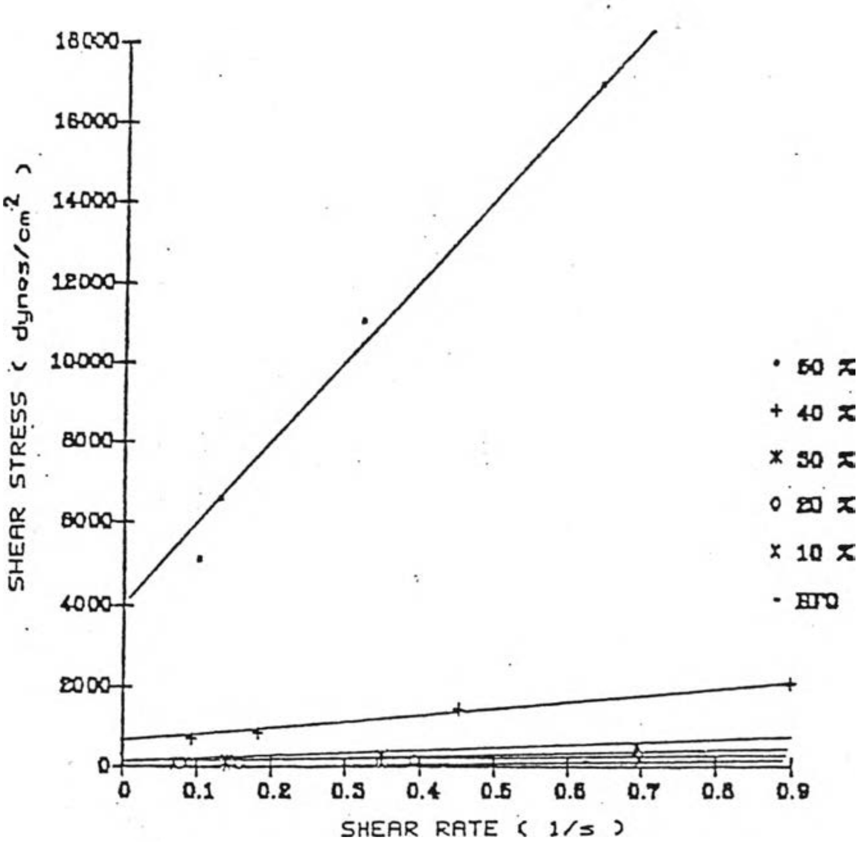

Figure 4.7 Rheogram of Nong Ya Plong coal in heavy fuel oil; various coal concentrations, 40 °C.

4.2.2 Effect of coal types on slurry rheology

The dependence of yield stress (rheogram intercept) and plastic viscosity (rheogram slope) on coal concentration for various coal types : Ban Pu, Mae Moh and Nong Ya Plong coal in HFO are presented in Table 4.7. Figure 4.8 and 4.9 show that yield stress of the slurries increases with increasing coal concentration. The relationships between yield stress and wt% coal for different coals are of exponential form as given in Table 4.8. The parameters of the equation depend on the type of coal and fuel oils.

Figure 4.10 and 4.11 show the flow curves of Mae Moh, Nong Ya Plong and Ban Pu coal in HFO for 30 wt% and 50 wt% COM respectively. COM of Bituminous coal (Nong Ya Plong) showed higher plastic viscosity and yield stress than COM of subbituminous coal (Ban Pu and Mae Moh) at the coal concentration range tested (See Figure 4.11 and Table 4.7). It is important to note that 1) different coal types gave the different rheological properties; plastic viscosity and yield stress. 2) the plastic viscosity of COM increased steadily from 10 to 40 % coal concentration and dramatically to a very high value at 50 wt% coal, e.g. plastic viscosity of COM of Ban Pu coal in HFO of 9945 cp was 68 times of HFO viscosity.

4.2.3 Effect of fuel oil types on slurry rheology

The dependence of yield stress on coal concentration for Ban Pu coal in light fuel oil and heavy fuel oil is presented in Table 4.7. Figure 4.8 shows the dependence of yield stress of the slurries on coal loading and give same exponential equation for COM of Ban Pu coal in LFO and HFO (see Table 4.8). Figure 4.12 shows flow curves of COM of Ban Pu coal in light fuel oil and heavy fuel oil at 50 wt% and 40 $^{\circ}$C. The COM of heavy fuel showed higher plastic viscosity than COM of light fuel oil but the yield stress for COM of HFO and LFO were almost the same. It is important to note that 1) the rheological properties such as; plastic viscosity increased with increasing fuel oil viscosity (see Table 4.7). 2) the yield stress of COM do not depend on fuel oil viscosity.

In comparison with other works, it could be summarized as follows:

Rheological behavior of COM

Authors	Coal	Suspending liquid	Onset of non-Newtonian behavior	Flow model	Ty_{max} $\left(\frac{dynes}{cm^2}\right)$
Gradishar et al.	Bituminous	Fuel oil	28 vol.%	Bingham plastic	-
Papachristodou-lou and Trass	Bituminous	Fuel oil	30 wt.%	Bingham plastic	3500
Munro et al.	Subbituminous	Fuel oil	30 vol.%	Bingham plastic	371
Somnuk	Subbituminous B	Fuel oil	40 wt.%	Bingham plastic	149
	Subbituminous C	Fuel oil	20 wt.%	Bingham plastic	327
	Bituminous	Fuel oil	20 wt.%	Bingham plastic	4166

It was also found that the various properties and types of coal and fuel oil gave the difference in COM formulation and properties. All COM showed non-Newtonian behavior, Bingham plastic but gave the difference in the onset value of non-Newtonian behavior and maximum yield stress.

Table 4.7 Effect of weight percent coal in COM on yield stress at 40 °C

COM	Weight percent coal in COM					
	0	10	20	30	40	50
	Yield stress, Ty (dynes/cm^2)					
Ban Pu coal + HFO	2.23	12.01	16.58	40.26	52.47	149.41
Ban Pu coal + LFO	4.88	7.47	9.06	16.93	57.26	169.91
Mae Moh coal + HFO	2.23	26.70	64.12	66.58	193.49	327.06
Nong Ya Plong coal + HFO	2.23	21.93	56.02	83.58	788.87	4165.84
	Plastic viscosity, u (centipoise)					
Ban Pu coal + HFO	144.98	178.30	207.86	371.05	1354.13	9945.48
Ban Pu coal + LFO	66.04	89.62	107.69	185.60	401.34	2399.55
Mae Moh coal + HFO	144.98	215.10	383.39	550.96	1823.96	6762.24
Nong Ya Plong coal + HFO	144.98	179.04	252.49	518.51	1324.60	18686.78

u and Ty are slope and intercept of rheogram, determined by linear regression of rheological data of Table 4.3, 4.4 , 4.5 and 4.6.

Table 4.8 The relations between yield stress and weight percent coal in COM at 40 °C.

COM	Formula	R^2
Ban Pu coal + HFO	$Ty = e^{(1.2461 + 0.0761 \times wt\% coal)}$	0.9466
Ban Pu coal + LFO	$Ty = e^{(1.2200 + 0.0699 \times wt\% coal)}$	0.9215
Mae Moh coal + HFO	$Ty = e^{(1.7080 + 0.0884 \times wt\% coal)}$	0.8772
Nong Ya Plong coal + HFO	$Ty = e^{(1.0708 + 0.1396 \times wt\% coal)}$	0.9643

Ty is defined as yield stress in unit dynes/cm^2

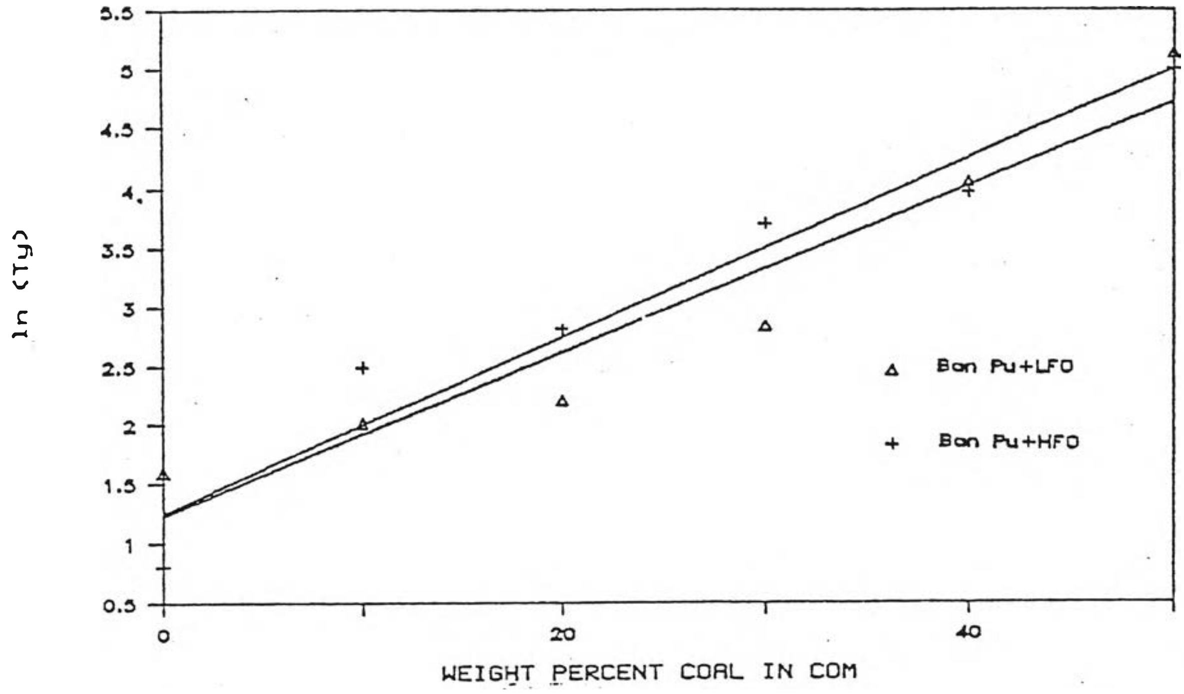

Figure 4.8 Dependence of yield stress on coal concentration; different fuel oil types, Ban Pu coal and 40 °C.

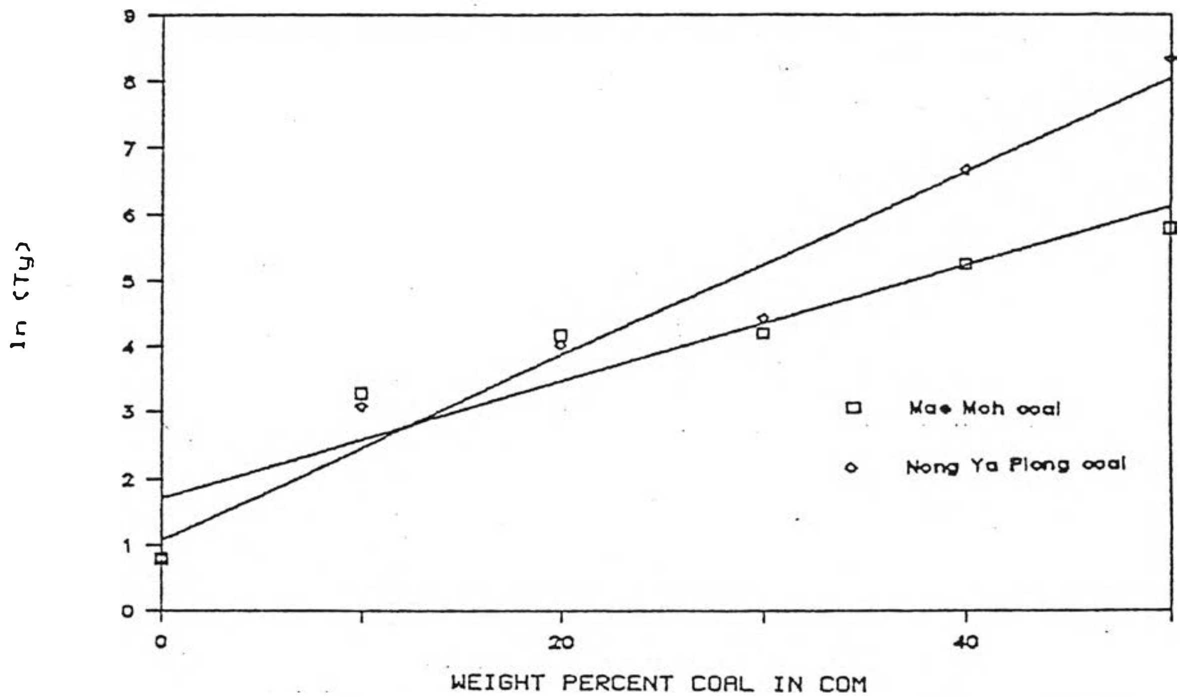

Figure 4.9 Dependence of yield stress on coal concentration; various coal types, heavy fuel oil and 40 °C.

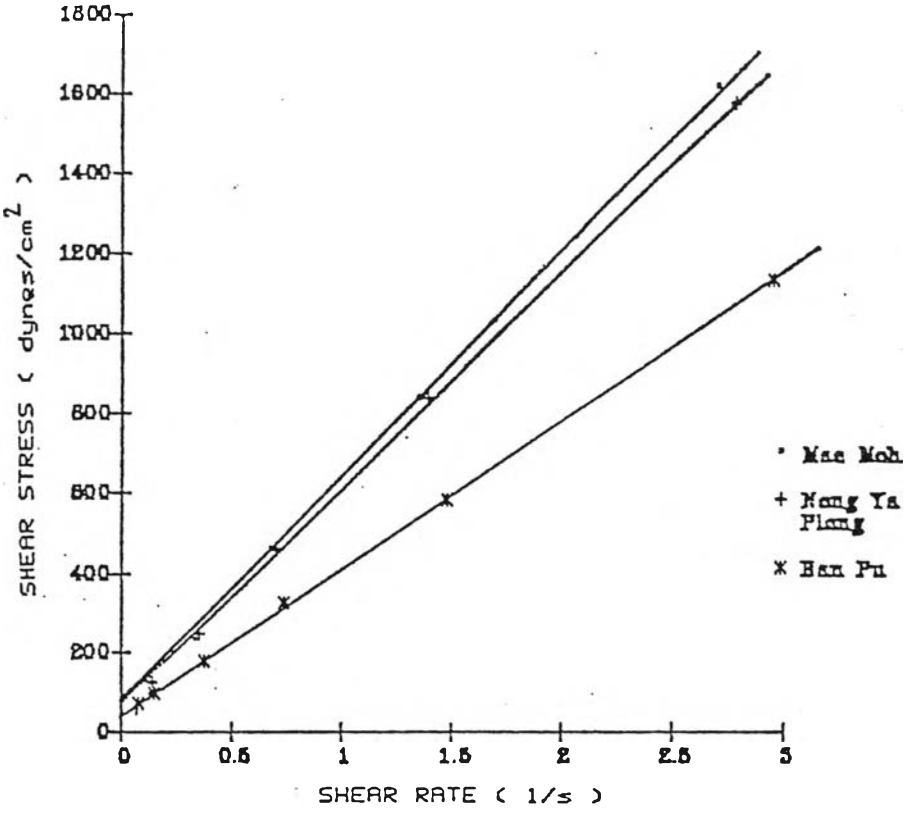

Figure 4.10 Rheogram of coal in heavy fuel oil; various coal concentrations; 30 wt% coal and 40 °C.

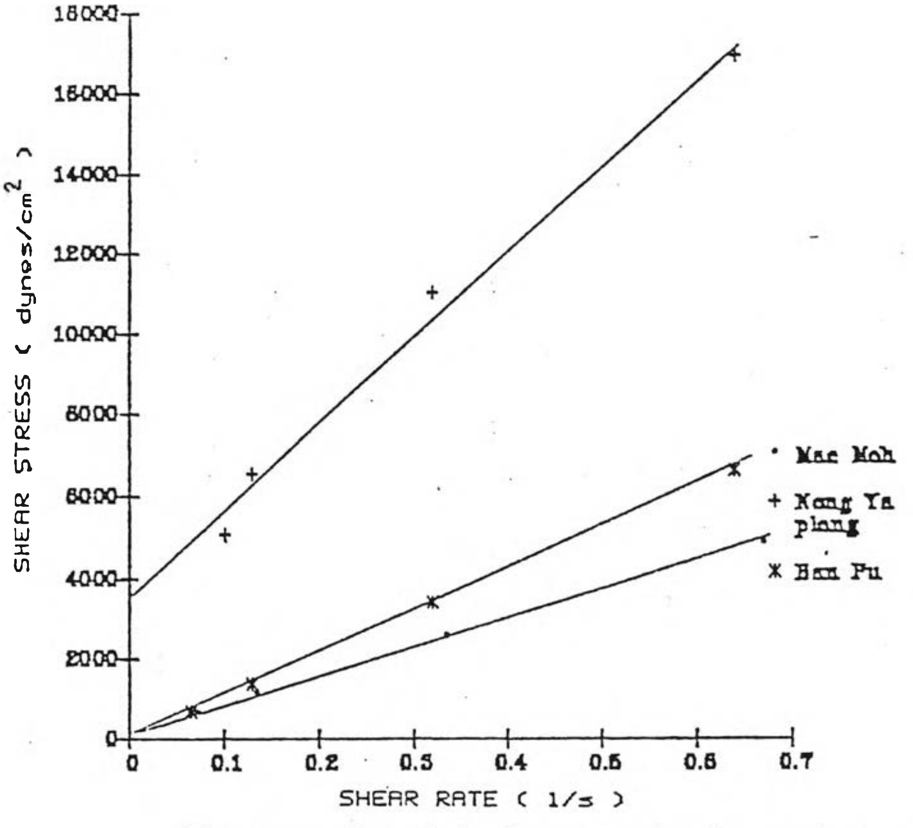

Figure 4.11 Rheogram of coal in heavy fuel oil; various coal concentrations; 50 wt% coal and 40 °C.

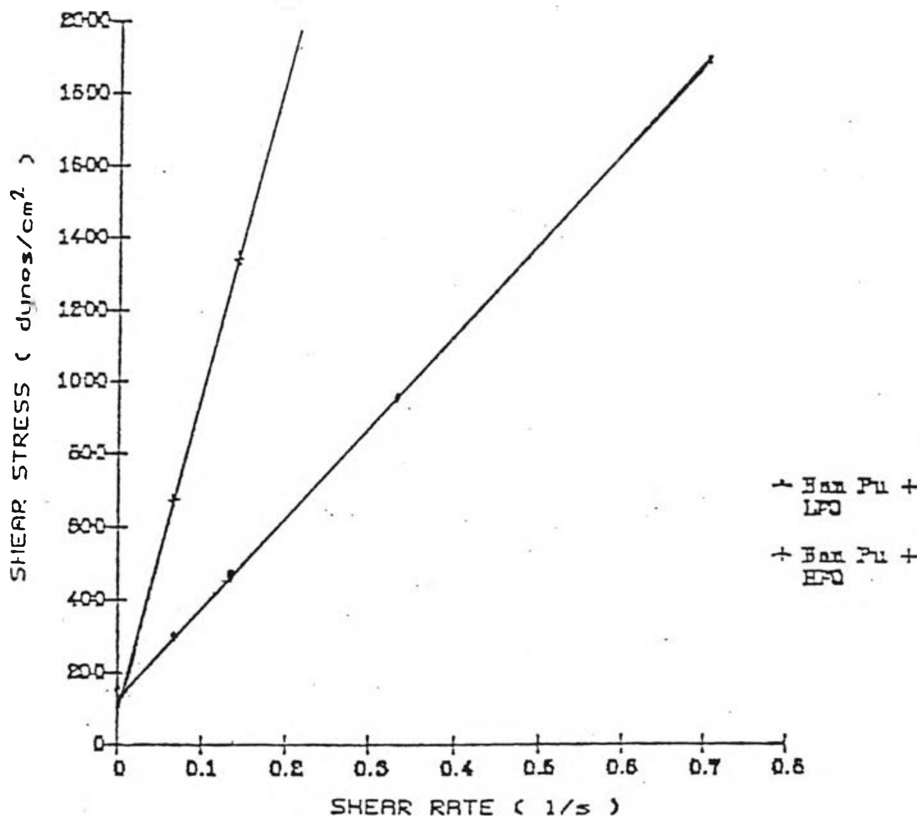

Figure 4.12 Rheogram of Ban Pu coal in different fuel oil types, 50 wt% coal and 40 °C.

4.3 Apparent viscosity of COM

4.3.1 Effect of temperature on viscosity of COM

The results of the effect of temperature on the viscosity of COM at various coal concentration are presented in Table 4.9. Figure 4.14 shows the variation of viscosity with coal concentration at various temperatures. It was found that the COM viscosity increased with coal concentration and decreased with temperature in the same manner as the base oil. For example, at 20 wt% the viscosity of 80 °C was one-tenth of 40 °C. The explanation is that a network was destroyed by heat due to increasing temperature. Therefore, the temperature of 40 °C was recommended to use for storage while temperature of 70 °C was used for transportation of COM in pipeline or to the boiler.

4.3.2 Effect of fuel oil types on viscosity of COM

Table 4.10 shows the effect of fuel oil types on viscosity of COM at various coal concentrations. Figure 4.15 gives the dependence of COM viscosity on coal concentrations for both fuel oil types. It was found that the COM viscosity increased with increasing coal concentration and increasing oil viscosity. For example, at 40 wt%, the COM viscosity of HFO was three times of LFO. It is interesting to note that the most important factor in the viscosity build-up was the viscosity of base oil (continuous phase) at the same temperature.

4.3.3 Effect of particle size distributions on viscosity of COM

The results of the effect of PSD viscosity of COM at various coal concentrations is presented in Table 4.11. Figure 4.15 shows the variation of viscosity wtth coal concentration at various particle size distributions. It was found that the viscosity increased with increasing coal concentration and decreasing average particle size. For example, at 40 wt% the COM viscosity of -75 microns was about two times of 90 - 106 microns powdered coal. Therefore, the higher viscosity of COM was due to the finer particle size.

In this part of study, temperature, fuel oil types and PSD affected the COM viscosity. The increasing COM viscosity was caused by decreasing PSD, decreasing temperature and increasing fuel oil viscosity. The fineness coal particles and high fuel oil viscosity, which increased COM viscosity, reduced the rheological property but improved COM stability and reduced additive consumption. In this case, the fineness PSD and high fuel oil viscosity decreased the settling rate of coal particles (COM stability and additive study in section 4.4). When high fuel oil viscosity such as HFO which was cheaper than LFO and fineness PSD which gave high cost in size reduction, were used, method to improve rheological properties was to increase temperature.

For most COM, the high coal concentration was required. Usually, major COM plants used 30-50 wt% coal concentration in HFO due to its properties, but the suitable coal size depended on its optimum cost. The suitable COM formulation could be achieved feasibility study.

Table 4.9 Effect of temperature on viscosity for COM of -75 microns Ban Pu coal and heavy fuel oil at various coal concentrations (wt%), and speed 30 rpm

Weight percent coal in COM	Viscosity(centipoise)				
	Temperature (°C)				
	40	50	60	70	80
0	270	126	60	37	25
10	362	170	96	51	34
20	431	214	135	70	44
30	820	362	199	139	76
40	2700	1336	636	420	259
50	18860	7740	4700	2240	1564

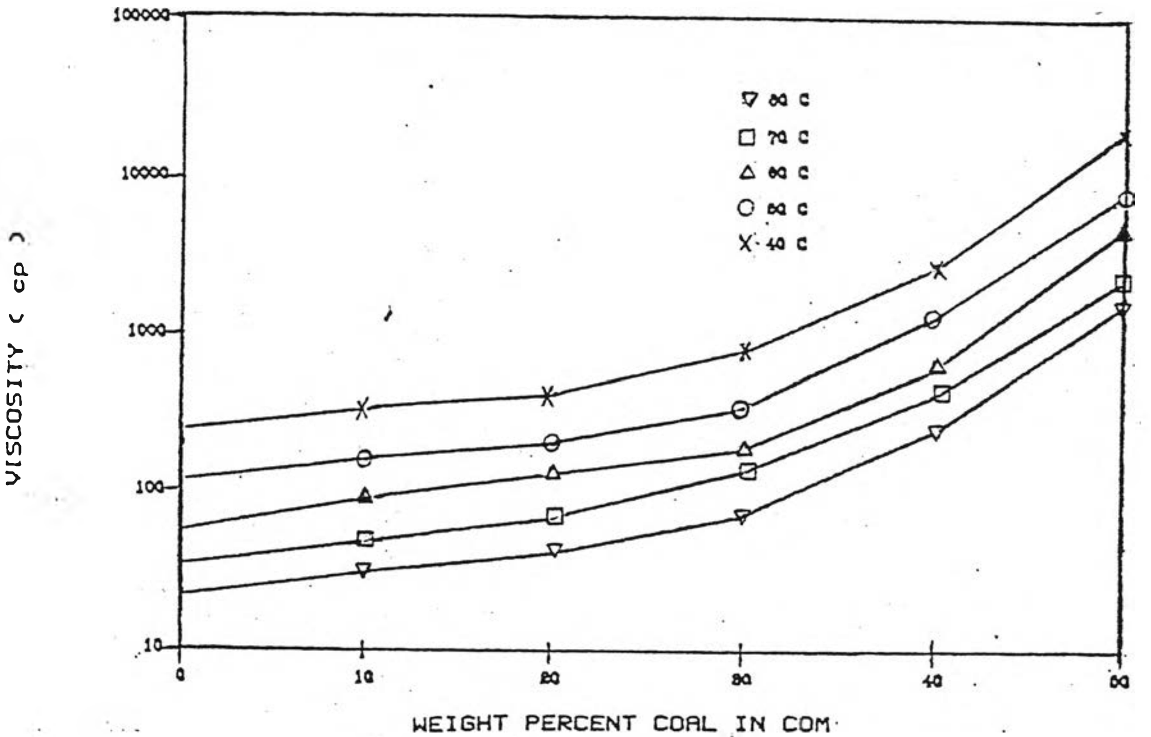

Figure 4.13 Viscosity as a function of coal concentration for Ban Pu coal and heavy fuel oil; various temperatures.

Table 4.10 Effect of oil type on viscosity for COM of -75 microns Ban Pu coal and fuel oil at various coal concentrations (wt%), speed 30 rpm and 40 °C

Weight percent coal in COM	Viscosity(centipoise)	
	Type of oil	
	LFO	HFO
0	141	270
10	180	362
20	240	431
30	415	820
40	908	2700
50	5060	18860

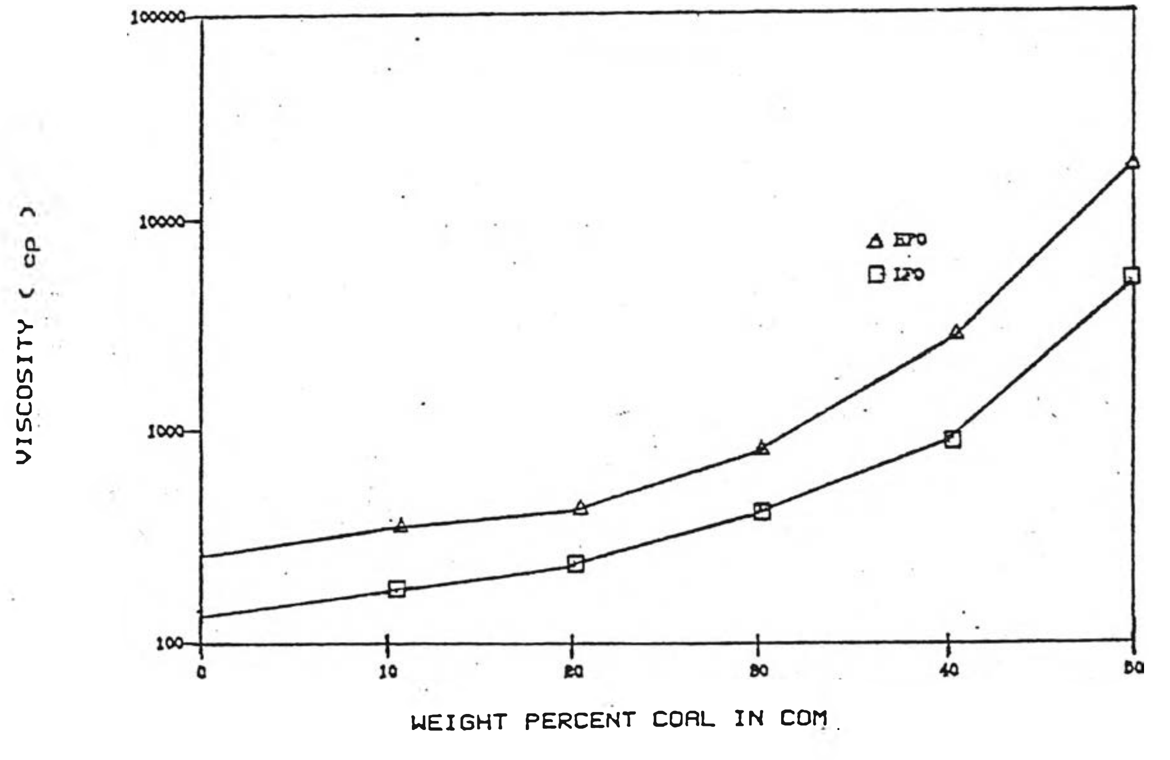

Figure 4.14 Viscosity as a function of coal concentration for Ban Pu coal and different fuel oil types.

Table 4.11 Effect of particle size distribution on viscosity for COM of Ban Pu and heavy fuel oil at various coal concentrations (wt%), speed 30 rpm and 40 °C

Weight percent coal in COM	Viscosity(centipoise)		
	Particle size distribution(microns)		
	-75	75-90	90-106
10	362	324	268
20	431	429	392
30	820	688	564
40	2700	1800	1292
50	18860	8760	3760

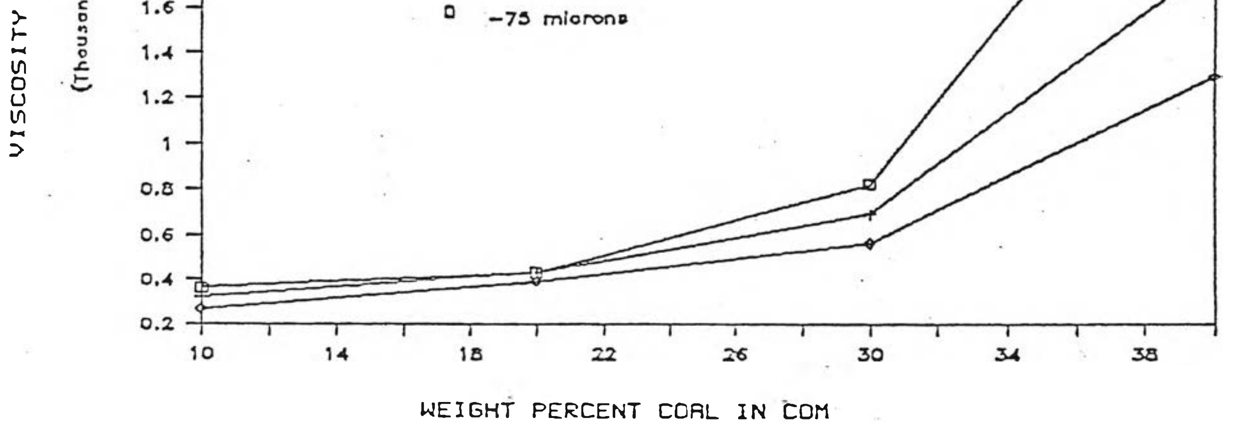

Figure 4.15 Viscosity as a function of coal concentration for Ban Pu coal and heavy fuel oil; various particles size distributions.

4.4 Stability of COM

4.4.1 Calibration of specific volume and weight percent coal for COM

Table 4.12 presents the variation of specific volume (Spv) of COM with wt% coal for Ban Pu, Mae Moh, and Nong Ya Plong coal in HFO and Ban Pu coal in LFO. Specific volume is converted from density. Figure 4.16 shows the different calibration curve for different coal and oil types and gives linear dependence of specific volume on wt% coal. The least-square fit for the data gave the relations between specific volume and wt% coal as presented in Table 4.13. These equations were used to convert the specific volume to wt% coal for sedimentation experiment.

4.4.2 Effect of time on sedimentation

The results of effect of time on sedimentation for Ban Pu coal in LFO with 3 wt% of additive are given in Table 4.14. Figure 4.17 shows the change of wt% of coal at bottom of sedimentation column with time for COM with 3 % Ethomeen C-15 and COM with 3 % Ethomeen C-20. It can be seen that at 50 °C equilibrium sedimentation was attained in 24 hours. Certainly, 24 hours was optimum time to study the COM stability using various additives.

Table 4.12 Calibration of specific volume and weight percent coal for COM Of -75 microns coal and fuel oil

Weight percent coal in COM	Ban Pu		Mae Moh		Nong Ya Plong	
	density (g/cc)	Spv (cc/g)	density (g/cc)	Spv (cc/g)	density (g/cc)	Spv (cc/g)
HFO	0.9305	1.0747	0.9305	1.0747	0.9305	1.0747
10	0.9612	1.0404	0.9668	1.0343	0.9739	1.0268
20	1.0044	0.9956	0.9926	1.0075	1.0030	0.9970
30	1.0449	0.9570	0.9946	1.0054	1.0571	0.9460
40	1.0917	0.9160	1.0098	0.9903	1.0970	0.9116
50	1.1308	0.8843	1.0974	0.9112	1.1336	0.8821
LFO	0.9269	1.0769				
10	0.9590	1.0427				
20	0.9935	1.0065				
30	1.0359	0.9653				
40	1.0827	0.9236				
50	1.1401	0.8771				

Spv is defined as specific volume in unit (cc/g)

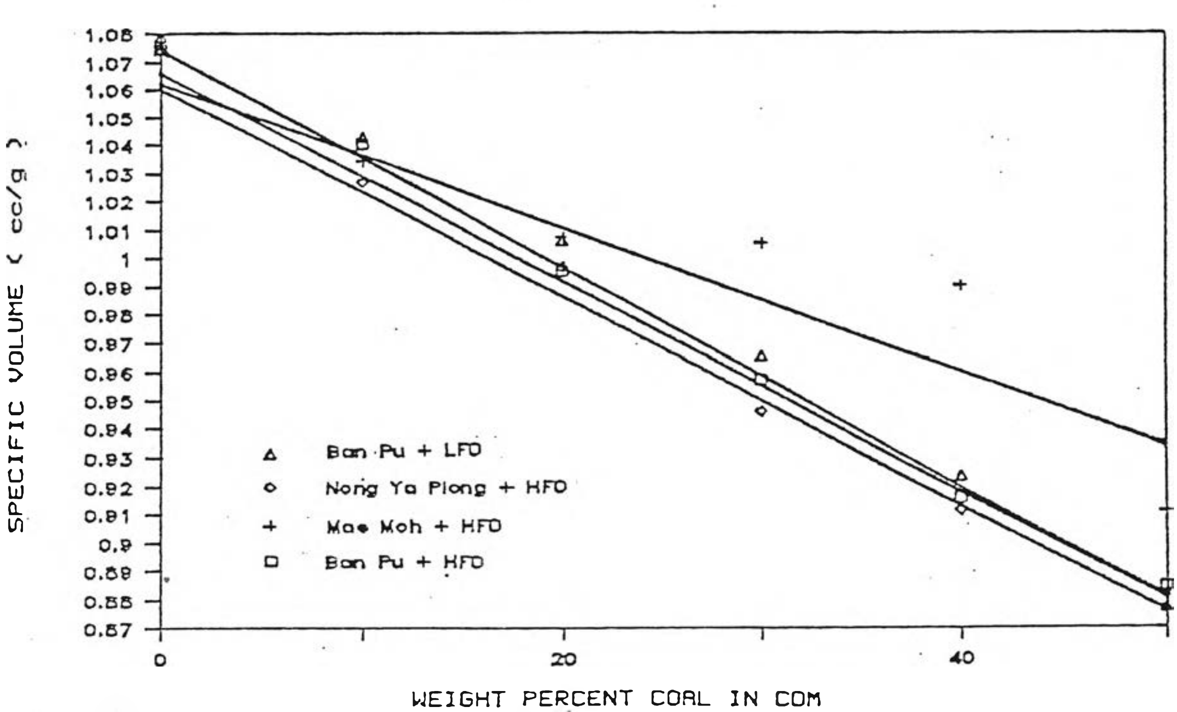

Figure 4.16 Specific volume of typical Coal-Oil Mixture.

Table 4.13 The relations between specific volume and weight percent coal in COM

COM	Expression	R^2
Ban Pu coal + HFO	Spv = -0.00389(wt% coal) + 1.075414	0.9981
Ban Pu coal + LFO	Spv = -0.00402(wt% coal) + 1.082885	0.9977
Mae Moh coal + HFO	Spv = -0.00271(wt% coal) + 1.071870	0.8783
Mong Ya Plong coal + HFO	Spv = -0.00388(wt% coal) + 1.070140	0.8931

Spv is defined as specific volume in unit (cc/g)

Table 4.14 Effect of time on sedimentation for COM of -75 microns Ban Pu coal in light fuel oil with 3 wt% additives, 25 wt% coal concentrations at 50 °C

Time (hr)	COM		COM + Ethomeen C-15		COM + Ethomeen C-20	
	Density (g/cc)	wt%	Density (g/cc)	wt%	Density (g/cc)	wt%
3	1.0355	29.16	1.0267	27.08	1.0245	26.56
8	1.0373	29.55	1.0272	27.21	1.0401	30.21
13	1.0581	34.29	1.0565	33.92	1.0420	30.64
17	1.1294	49.13	1.0593	34.53	1.0452	31.36
21	1.1312	49.46	1.0666	36.15	1.0471	31.81
24	1.1311	49.45	1.0678	36.41	1.0452	31.36

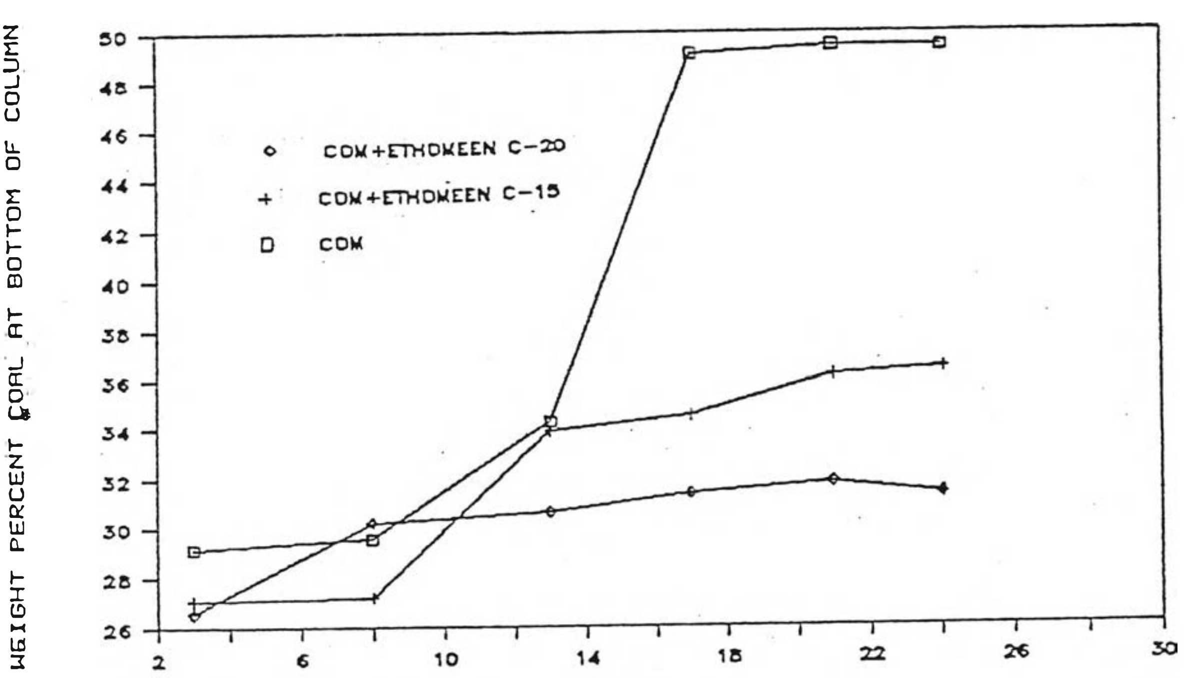

Figure 4.17 Weight percent coal at bottom of column as a function of time for 25 % COM Ban Pu coal in light fuel oil measured with the sedimentation column for different additives.

4.4.3 Effect of weight percent coal in COM on sedimentation ratio

Table 4.15 shows the effect of wt% coal on sedimentation ratio for various additives. From Figure 4.18, SR value at equilibrium time of 24 h depended on wt% coal. It can be seen that above 25 wt% Ban Pu coal in LFO and 30 wt% Ban Pu coal in HFO, the SR value began to increase rapidly and it was difficult to observe the differences in stabilizing effect by different additives. For 10-25 % coal in light fuel oil, SR of COM with 3 % Ethomeen C-20 (0.54-0.64) was lower than SR of COM with 3 % Triton X-400 (0.73-0.76), thus, Ethomeen C-20 was more effective than Triton X-400.

Below 25 wt% coal in LFO and 30 wt% coal in HFO , the curves of SR value versus wt% coal were well separated for different additives. Therefore, 25 wt% coal in COM was suitable concentration to study the COM stability using various additives. It was also found that using 3 % Triton X-400, SR of 10-30 % coal in HFO (0.64-0.67) was lower than SR of coal in LFO (0.73-0.84).

4.4.4 Effect of weight percent additive in COM on sedimentation ratio

The results of effect of wt% additive on the sedimentation ratio for different additives are given in Table 4.15. Figure 4.19 shows the decrease of SR with increasing wt% additive. From this figure, the effectiveness of different additives in lowering the SR as a function of wt% additive showed a leveling off above 2 wt% additive for COM of coal in LFO and above 1 wt% additive for COM of coal in HFO. The basis of choosing 2 wt% and 1 wt% of additive were suitable for COM of light fuel oil and heavy fuel oil respectively. It was also found that using 1-2 % Triton X-400 SR of coal in HFO (0.63) was lower than the SR of coal in LFO (0.78-0.83).

Table 4.15 Effect of weight percent coal on sedimentation ratio for COM of -75 microns Ban Pu coal and fuel oil with 3 wt% additives at 50 °C

Component		Weight percent coal in COM				
		10	20	25	30	40
Light fuel oil						
COM (no additive)	wt%	47.38	47.41	49.47	48.48	-
	SR	1.00	1.00	1.00	1.00	-
COM + Triton X-400	wt%	34.75	36.19	37.66	40.82	-
	SR	0.73	0.76	0.76	0.84	-
COM + Ethomeen C-20	wt%	25.52	29.92	31.81	46.34	-
	SR	0.54	0.63	0.64	0.96	-
Heavy fuel oil						
COM (no additive)	wt%	50.08	48.36	-	51.42	52.39
	SR	1.00	1.00	-	1.00	1.00
COM + Triton X-400	wt%	31.96	32.27	-	33.91	45.43
	SR	0.64	0.67	-	0.66	0.87

SR ; Sedimentation ratio is defined as the ratio of the weight percent of coal from bottom sampling for a stabilized dispersion to the weight percent of coal under the same conditions for a dispersion with no additive.

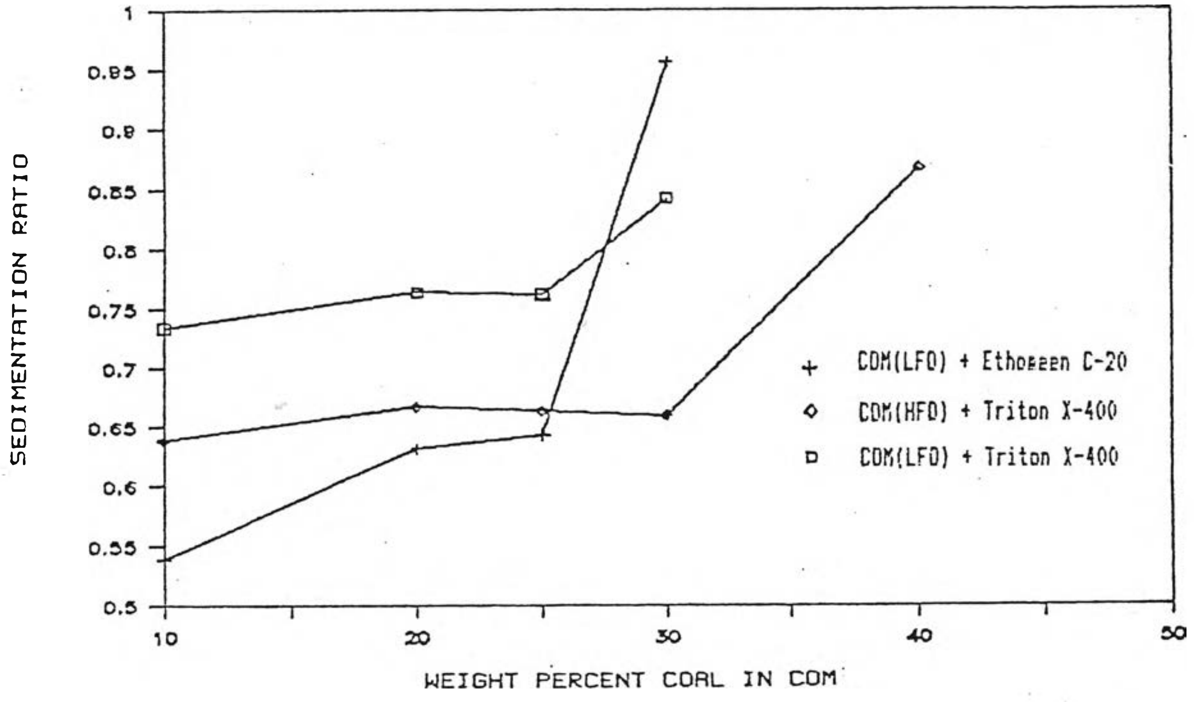

Figure 4.18 Sedimentation ratio as a function of weight percent coal for Ban Pu coal in light fuel oil and heavy fuel oil with two additive types.

Table 4.16 Effect of weight percent additive on sedimentation ratio for COM of -75 microns Ban Pu coal and fuel oil at 25 wt% coal for light fuel oil, 30 wt% coal for heavy fuel oil, various additives at 50°C

Component		Weight percent additive in COM				
		0.25	0.5	1	2	3
Light fuel oil						
COM (no additive)	wt%	-	49.47	49.47	49.47	49.47
	SR	-	1.00	1.00	1.00	1.00
COM + Triton X-400	wt%	-	43.75	40.92	38.53	37.66
	SR	-	0.88	0.83	0.78	0.76
COM + Ethomeen C-20	wt%	-	45.82	41.76	31.94	31.81
	SR	-	0.93	0.84	0.65	0.64
Heavy fuel oil						
COM (no additive)	wt%	51.42	51.42	51.42	51.42	-
	SR	1.00	1.00	1.00	1.00	-
COM + Triton X-400	wt%	41.57	35.94	32.63	32.27	-
	SR	0.81	0.70	0.63	0.63	-

SR ;Sedimentation ratio is defined as the ratio of the weight percent of coal from bottom sampling for a stabilized dispersion to the weight percent of coal under the same conditions for a dispersion with no additive

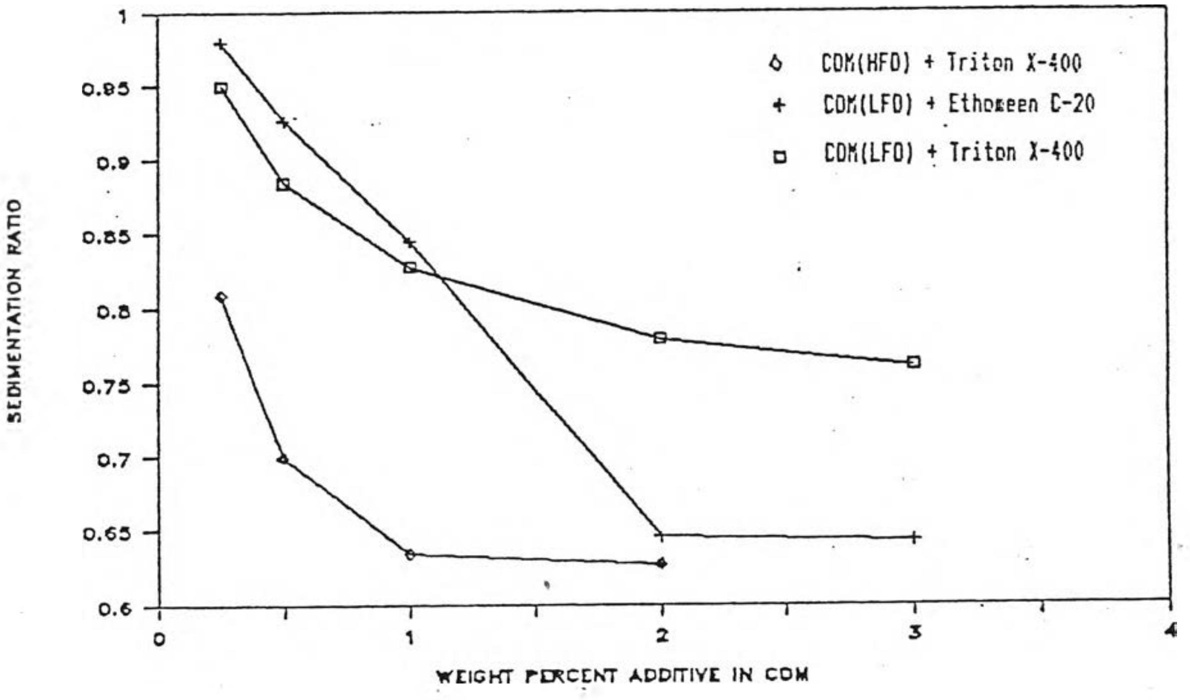

Figure 4.19 Sedimentation ratio as a function of weight percent additive for Ban Pu coal in light fuel oil and heavy fuel oil with two additive types.

4.4.5 Effect of additive types on sedimentation ratio

The fourteen available anionic, cationic and nonionic additives (Table 3.3) were tested for their effect on COM stabilization based on evaluating their sedimentation ratio relative to an unstabilized COM. All results listed in Table 4.17 are for COM's composed of 25 wt% coal in LFO with 2 wt% additive. The SR of 0.61-0.76 for the cationic additives was lower than 0.88-1.00 for the anionics or 0.77-0.84 for the nonionics. This was explained by the flocculation and network formation occuring during the subsidence and the formation of a loose network which leaded to an open subsidence bed. Despite the individual differences in additives, the cationic additives as a class were the most effective in retarding the accumulation of a dense bottom sediment.

4.4.6 Effect of additive on sedimentation ratio of different coal types and particle size distribution

In this work , cationic additives, Ethomeen C-20, Ethomeen C-15 and Triton X-400 were used to study the effect of additives on sedimentation ratio for COM composed of 30 wt% different coal types in HFO with 1 wt% additive, the results are presented in Table 4.18. The SR for Nong Ya Plong coal (bituminous) was 0.46-0.49 , which was lower than 0.49-0.63 for Ban Pu coal (subbituminous B) and 0.54-0.65 for Mae Moh coal (subbituminous C). It was found that for different coal types, cationics were effective additives to improve COM stability. For the larger particle size distribution, 106-150 microns, additives were ineffective because the large particles could settle rapidly due to gravitational forces which were greater than interparticle forces. It is important to note that the uniformity of the settled bed depended on the particle size distribution, the rates of flocculation and the network formation which depended upon the interparticle forces.

In summary, cationic additive, Ethomeen C-20 was the most effective. SR of Ban Pu coal in LFO with 2 % Ethomeen C-20 was 0.61, SR of Ban Pu coal, Nong Ya Plong coal and Mae Moh coal in HFO with 1 % Ethomeen C-20 were 0.49, 0.46 and 0.54 respectively.

Rowell et al. (15) investigated the effectiveness additives for COM composed of bituminous coal in # 6 fuel oil by using sedimentation column at 50 °C. It was found that 24 hours was equilibrium time, 25 wt% was suitable coal concentration and 0.25 wt% was optimum additive. They also found that cationic stabilizers were the most effectiveness additives and Ethomeen C-20 was the most effectiveness additive which gave the lowest SR (0.58). Therefore, our results of COM stability study of Ban Pu, Nong Ya Plong and Mae Moh coal in HFO agreed very well with Rowell et al.

Table 4.17 Effect of additives (stabilizing agents) on sedimentation ratio for COM of -75 microns Ban Pu coal and light fuel oil at 25 wt% coal with 2 % additives at 50 °C

Component	wt% coal	SR
	Bottom	
COM (no additive)	49.47	1.00
COM + Anionic stabilizers		
COM + Span 60	43.42	0.88
COM + Span 40	47.45	0.96
COM + Arlacel 83	47.43	0.96
COM + Arlacel 20	49.29	1.00
COM + Cationic stabilizers		
COM + Ethomeen C-20	29.93	0.61
COM + Ethomeen C-15	35.34	0.71
COM + Triton X-400	37.65	0.76
COM + Nonionic stabilizers		
COM + Brij 78	37.87	0.77
COM + Brij 76	41.47	0.84
COM + Brij 56	39.72	0.80
COM + Tween 40	40.78	0.82
COM + Tween 20	40.80	0.82
COM + Surfonic N-95	40.80	0.82
COM + Igepal CO-610	41.05	0.83

SR ;Sedimentation ratio is the ratio of the weight percent of coal from bottom sampling for a stabilized dispersion to the weight percent of coal under the same conditions with no additive

Table 4.18 Effect of additives(stabilizing agents) on sedimentation ratio for COM of coal in heavy fuel oil at 30 wt% coal with 1 wt% additives, various coal types, coal sizes at 50 °C

Component	wt% coal	SR
	Bottom	
-75 microns Ban Pu coal		
COM (no additive)	51.42	1.00
COM + Ethomeen C-20	25.19	0.49
COM + Ethomeen C-15	31.72	0.62
COM + Triton X-400	32.26	0.63
-75 microns Nong Ya Plong coal		
COM (no additive)	47.89	1.00
COM + Ethomeen C-20	21.94	0.46
COM + Ethomeen C-15	22.58	0.47
COM + Triton X-400	23.65	0.49
-75 microns Mae Moh coal		
COM (no additive)	57.36	1.00
COM + Ethomeen C-20	30.86	0.54
COM + Ethomeen C-15	36.54	0.64
COM + Triton X-400	37.51	0.65
106-150 microns Ban Pu coal		
COM (no additive)	48.48	1.00
COM + Ethomeen C-20	46.05	0.95
COM + Triton X-400	47.09	0.97

SR ; Sedimentation ratio is defined as the ratio of the weight percent of coal from bottom sampling for a stabilized dispersion to the weight percent of coal under the same conditions for a dispersion with no additive

4.5 Thermal analysis

Thermogravimetric analysis (TGA) was used in this work to study the combustion phenomena of COM compared with coal and fuel oil. For a burning profile, Derivative Thermogravimetry (DTG) yielded a plot of the rate of weight loss as the sample burns in air against crucible temperature, while the furnace was heated at 15 K/min starting from room temperature and an air flowrate of 90 ml/min.

4.5.1 Thermal analysis of HFO, Ban Pu coal and LFO

Thermogravimetric (TG) curves for Ban Pu coal, HFO and LFO showed the weight loss of the sample burnes (Figure 4.20). The burning profile from a DTG curve for Ban Pu coal, HFO and LFO are showed in Figure 4.21. For Ban Pu coal, the first peak at around 100 °C was due to the loss of inherent moisture and was not normally included in the burning profile characterization. The magnitude content of this response was, of course, dependent on the inherent moisture content of the sample. The main characteristic point was around 400 °C which indicated that the rate of weight loss was at a maximum, also called the peak temperature, and was the parameter used chiefly in the assesment of a coal combustibility.

For HFO and LFO, the burning profile curves displayed more major burning peaks (3-4 peaks) which are due to their compositions and showed a high peak temperature of around 280-290 °C. The peak temperature showed at lower temperature than coal because fuel oil was more reactive and combustible than coal.

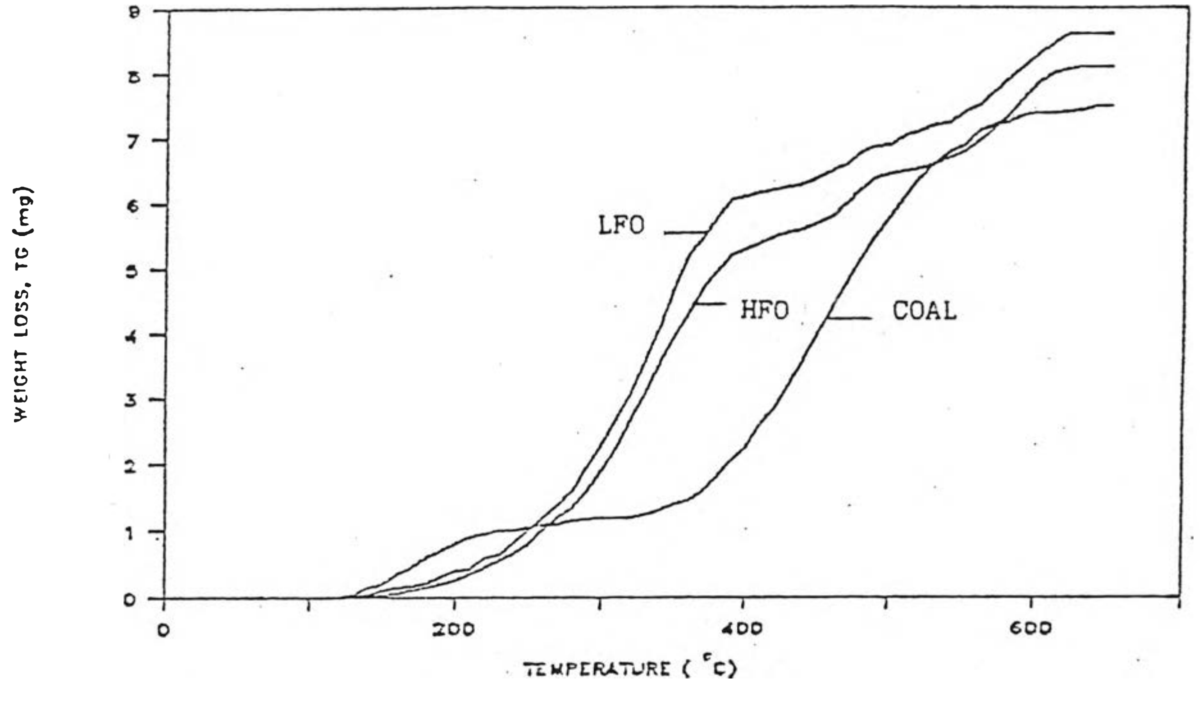

Figure 4.20 TG curve for HFO, Ban Pu coal and LFO.

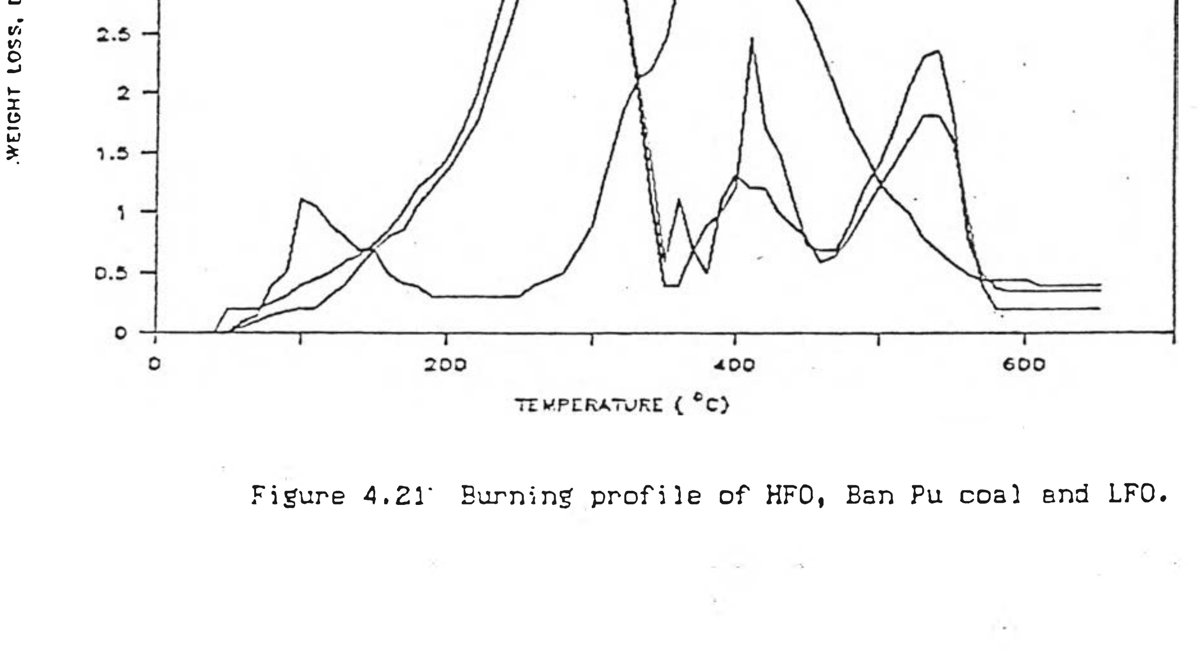

Figure 4.21 Burning profile of HFO, Ban Pu coal and LFO.

4.5.2 Thermal analysis of COM

Figure 4.22 and 4.24 show TG curves for Ban Pu coal, fuel oil and 50 wt% COM. Figure 4.26 and 4.28 show TG curves for COM at 10 %, 20 %, 30 %, 40 %, and 50 %, coal in HFO. Figure 4.30 and 4.32 show TG curves for COM at 10 %, 20 %, 30 %, 40% and 50 % coal in LFO.

From Figure 4.23 and 4.25, it can be seen that the burning profile curve of 50 % COM had two main peak temperatures while fuel oil and coal had one main peak temperature. The first main peak temperature around 290-290 °C and 400-440 °C for the second peak were related to that of combustion of fuel oil and coal in COM respectively.

Figure 4.27 and 4.31 show burning profile curves for COM at low coal concentrations (0-20 wt%) which are similar to those of fuel oil and have a peak temperature around 260-290 °C. For COM at higher coal concentrations (30-50 wt%), the burning profile curves showed two main peak temperatures around 260-290 °C and 400-440 °C and were related to the peak temperature of fuel oil (260-290 °C) and coal (400-440 °C) as shown in Figure 4.29 and 4.33. The explanation was that COM went through two stages of losing the maximum weight, the first occured due to the combustion of the gas phase of fuel oil in COM and continued the coal combustion when it reached ignition coal temperature in the second stage. After complete combustion, ash was left. It is important to note that the combustion stages for COM were classified into two stages; a gas phase and a solid phase combustion.

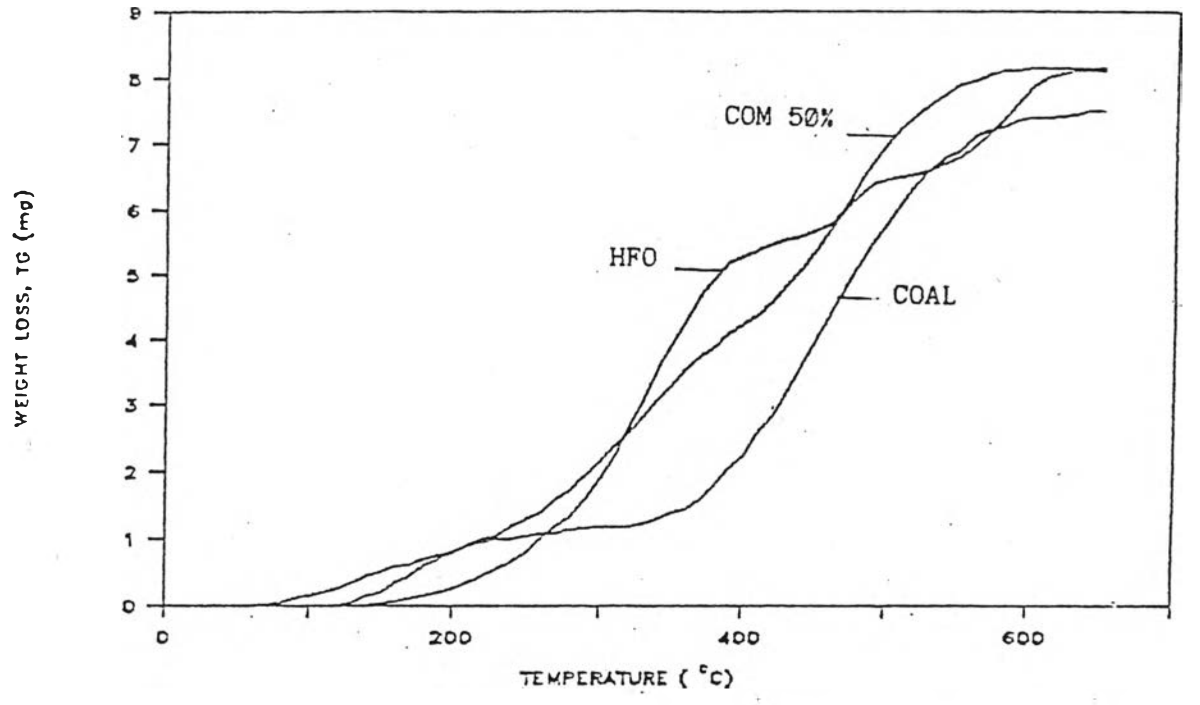

Figure 4.22 TG curve for HFO, Ban Pu coal and COM composed of 50 wt% Ban Pu coal in HFO.

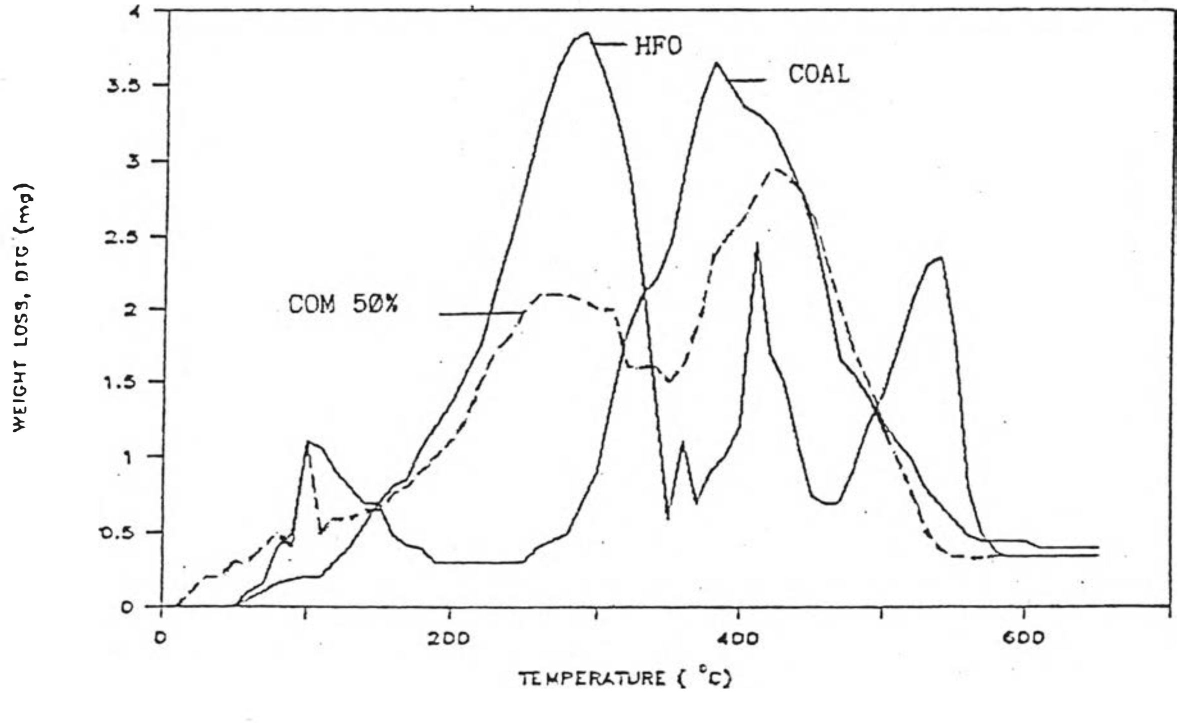

Figure 4.23 Burning profile of HFO, Ban Pu coal and COM composed of 50 wt% Ban Pu coal in HFO.

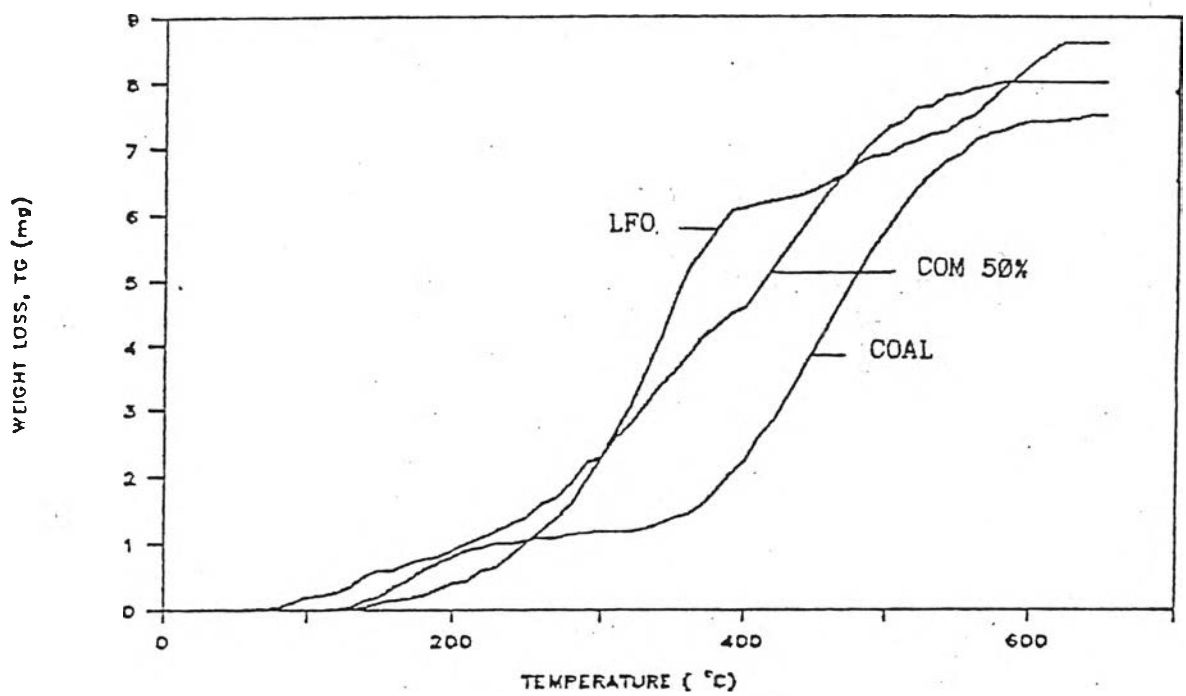

Figure 4.24 TG curve for LFO, Ban Pu coal and COM composed of 50 wt% Ban Pu coal in LFO.

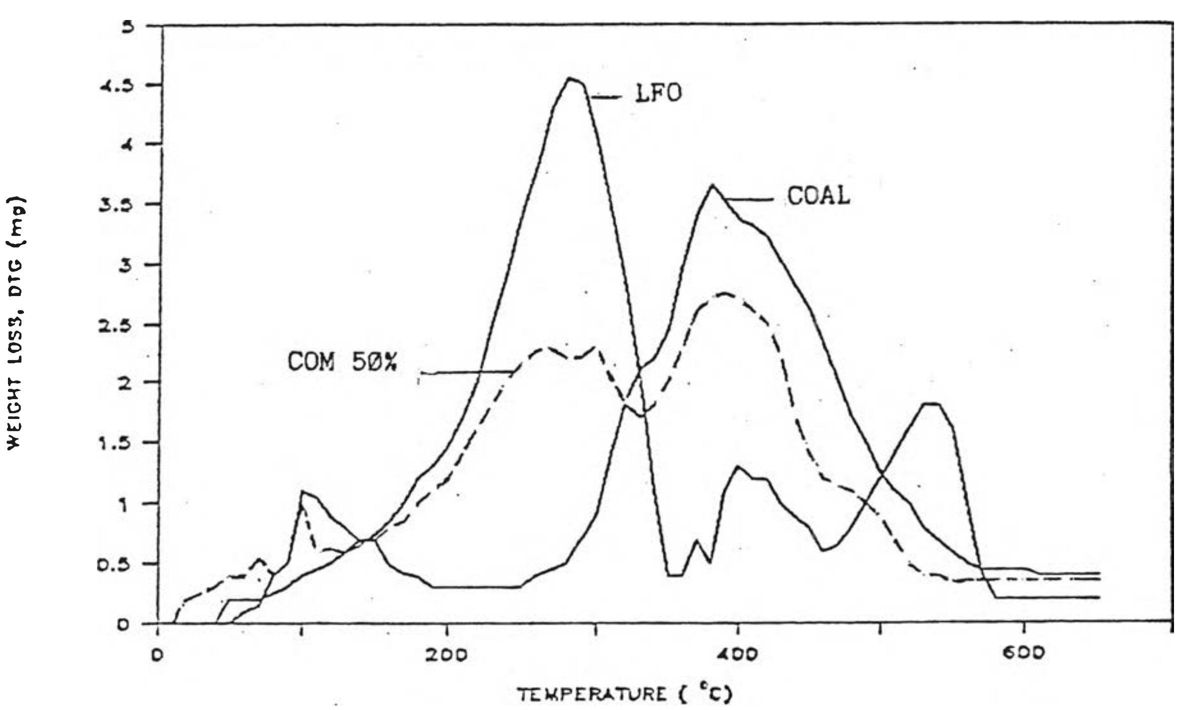

Figure 4.25 Burning profile of LFO, Ban Pu coal and COM composed of 50 wt% Ban Pu coal in LFO.

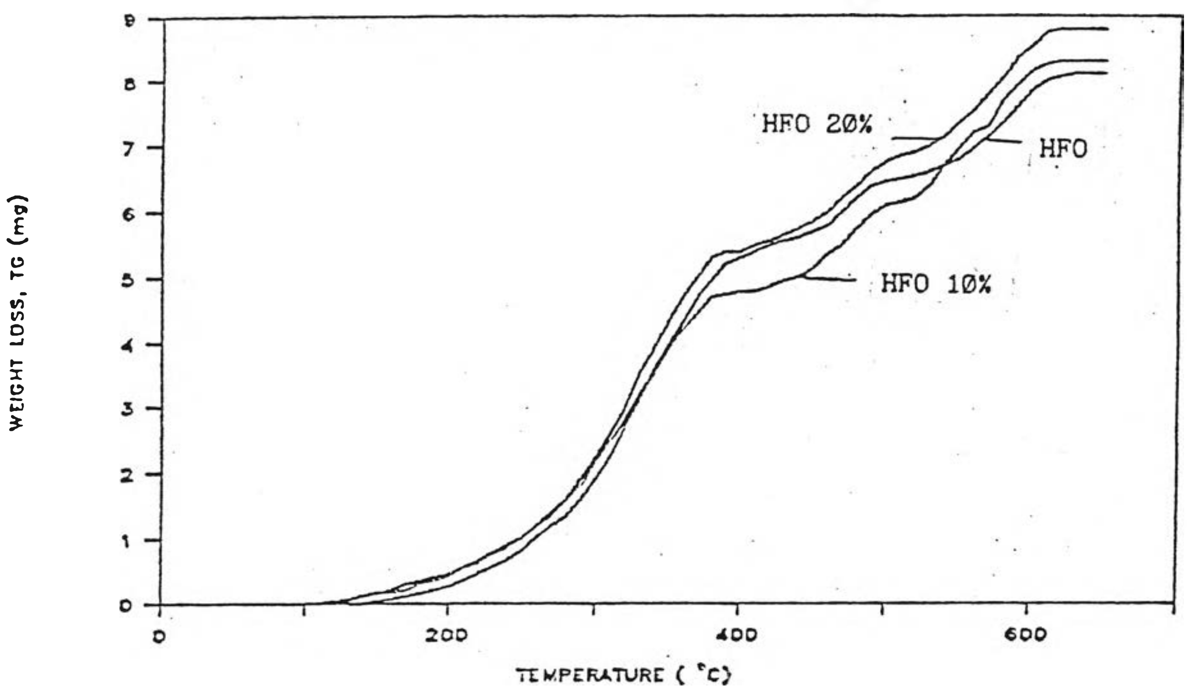

Figure 4.26 TG curve for HFO and COM composed of 10 and 20 wt% Ban Pu coal in HFO.

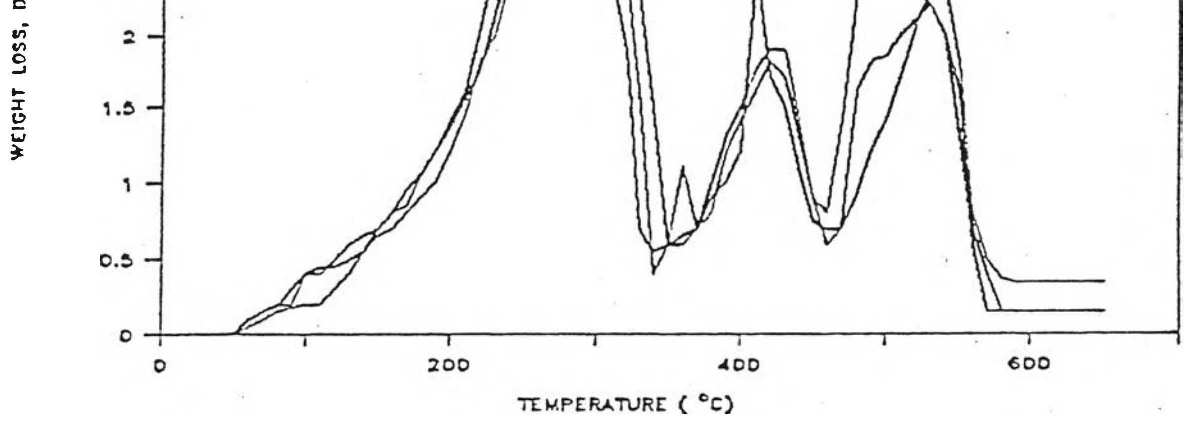

Figure 4.27 Burning profile of HFO and COM composed of 10 and 20 wt% Ban Pu coal in HFO.

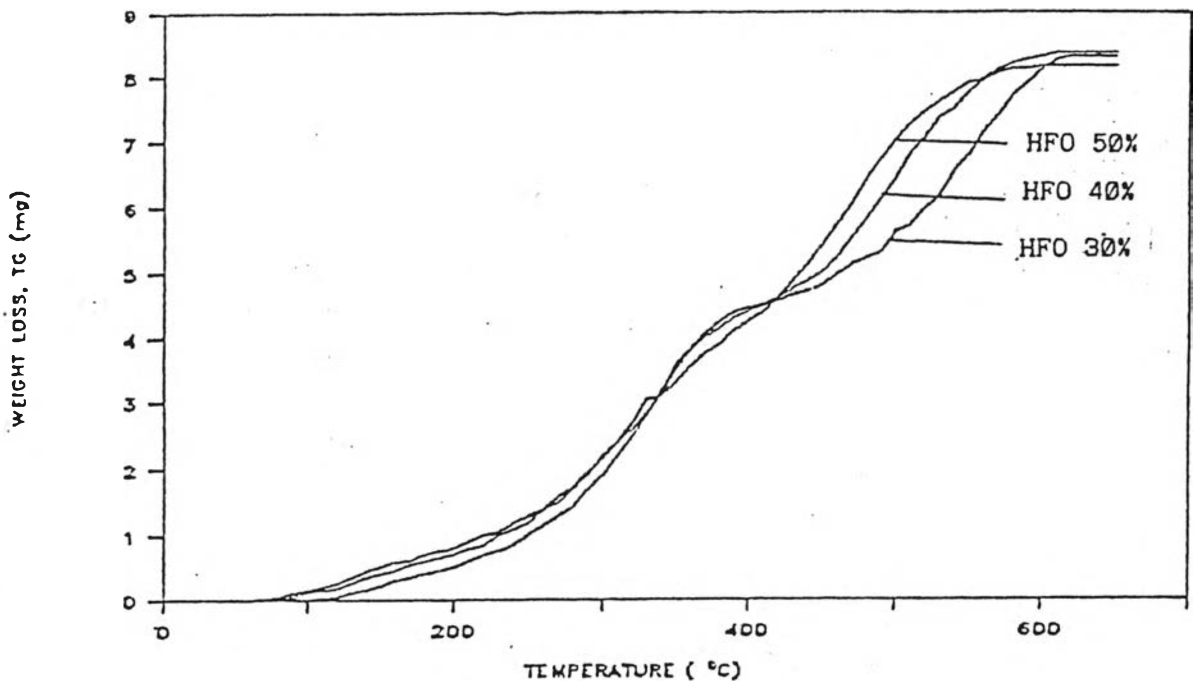

Figure 4.28 TG curve for COM composed of 30, 40 and 50 wt% Ban Pu coal in HFO.

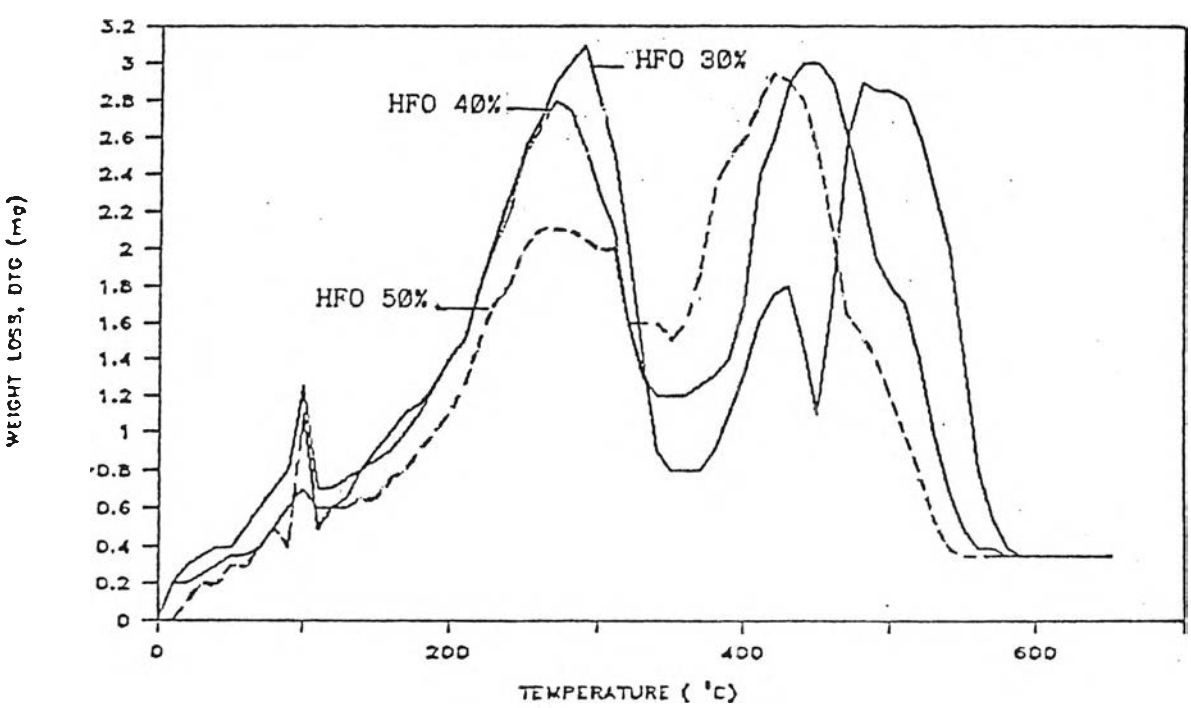

Figure 4.29 Burning profile of COM composed of 30, 40 and 50 wt% Ban Pu coal in HFO.

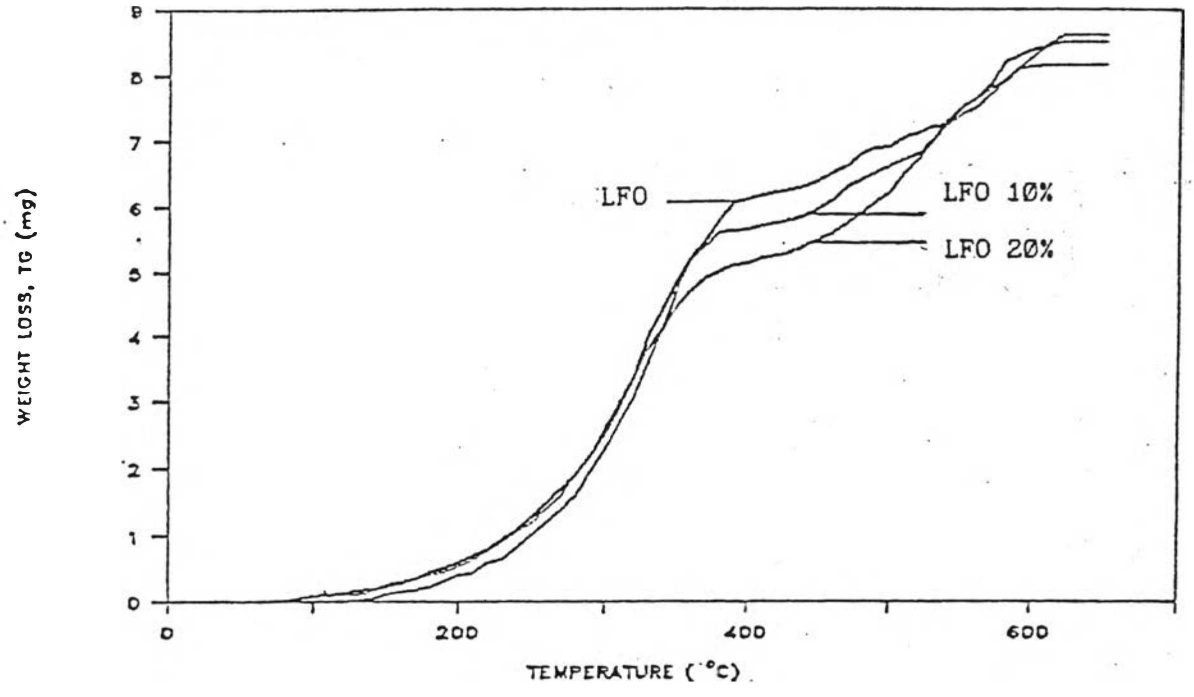

Figure 4.30 TG curve for LFO and COM compoosed of 10 and 20 wt% Ban Pu coal in LFO.

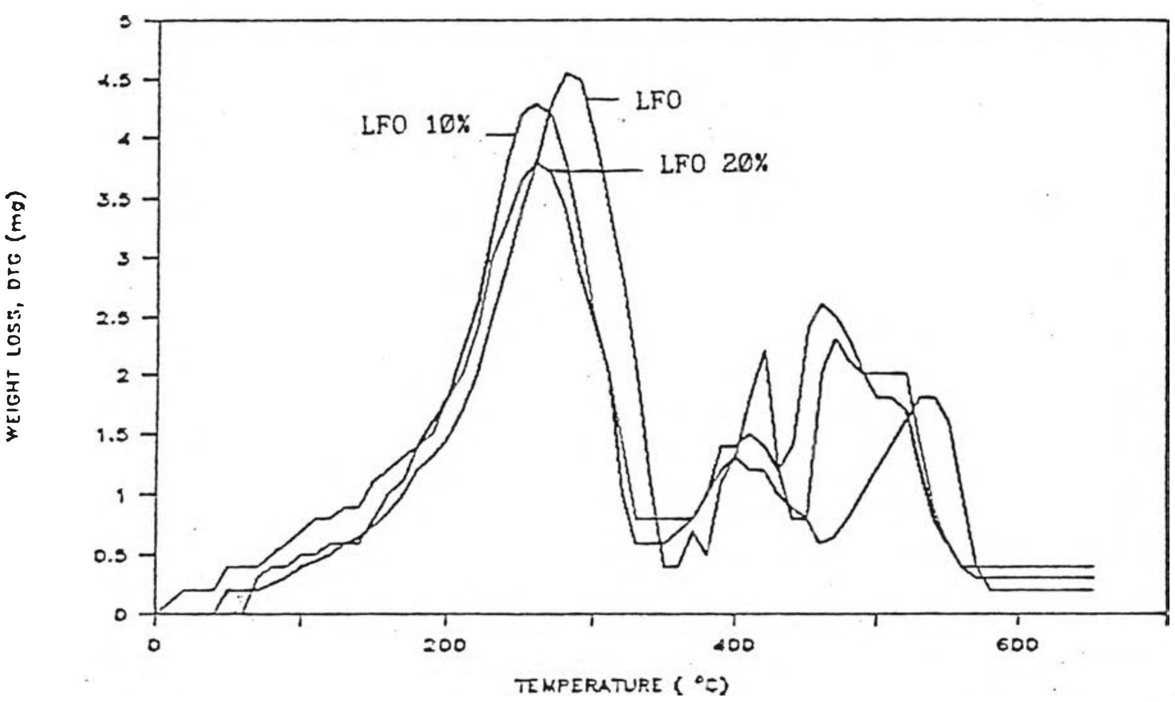

Figure 4.31 Burning profile of LFO and COM composed of 10 and 20 wt% Ban Pu coal in LFO.

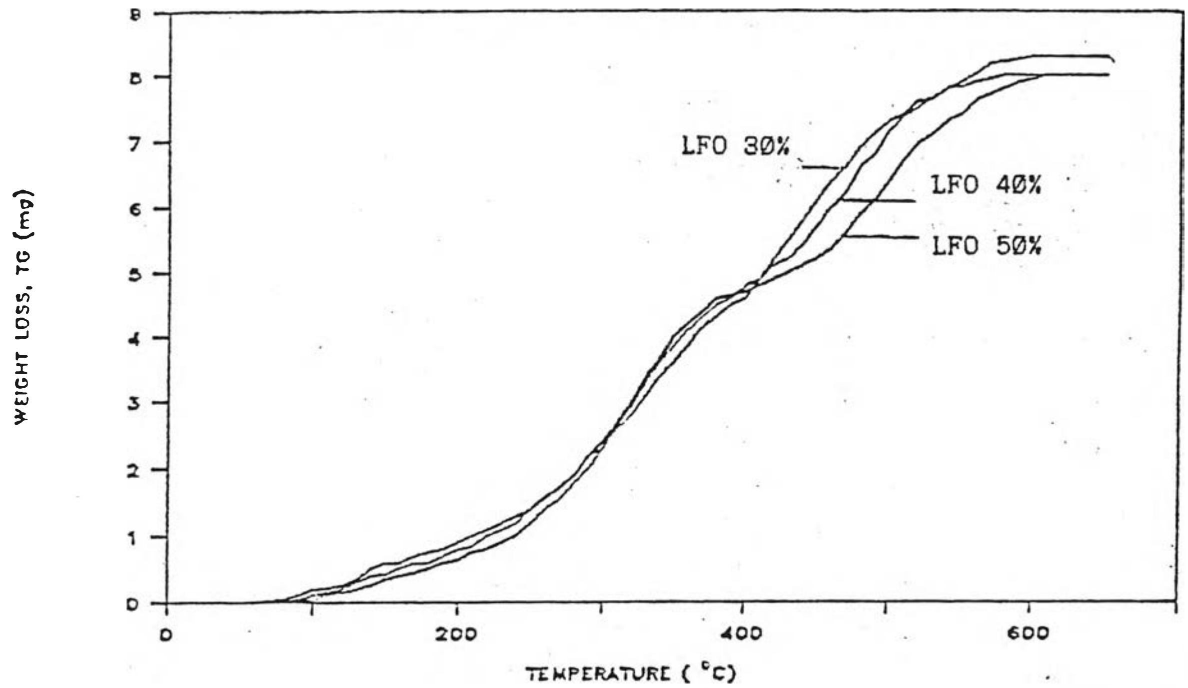

Figure 4.32 TG curve for COM composed of 30, 40 and 50 wt% Ban Pu coal in LFO.

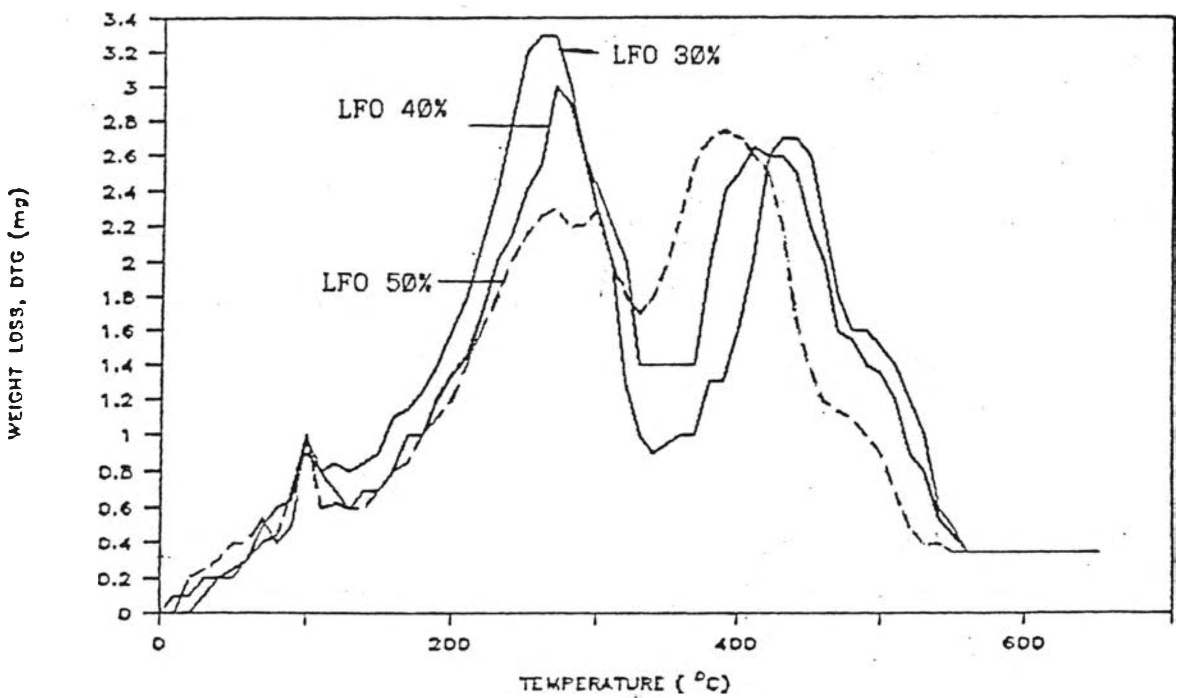

Figure 4.33 Burning profile of COM composed of 30, 40 and 50 wt% Ban Pu coal in LFO.