REFERENCES

Bien, J. B. Bien, J.D. and Matysiak, B. (2000) Research on possibilities of sewage sludge utilization in the process of pyrolysis. In Pawlowski, L., Dudzinska, M.R. and Gonzalez, M.A. (Eds.), Thermal Solid Waste Utilization in Regular and Industrial Facilities. (pp. 103-111). USA: Kluwer Academic/Plenum Publishers.

Chapman DV., White SL. Rainbow PS. and Taylor M., (1988) Interactions between marine crustaceans and digested sewage sludge. Marine Pollution Bulletin, 19 (3), 115-119.

Chu CW. and Poon CS. (1999) The feasibility of planting on stabilized sludge-amended soil. Journal of Environmental and Engineering, 25 (4), 465-477.

Department of Alternative Energy Development and Efficiency - DEDE (2004) Thailand Energy Statistics 2004. Bangkok: Ministry of Energy.

Dickinson C.F. and Heal G.R. (1999). Solid–liquid diffusion controlled rate equations. Thermochimica Acta. 340-341, 89-103.

Doshi, V.A., Vuthaluru, H.B. and Bastow, T. Investigations into the control of odour and viscosity of biomass oil derived from pyrolysis of sewage sludge. Fuel Processing Technology, 86, 885-897.

Gaur, S. and Reed, T.B. (1998) Thermal Data for Natural and Synthetic Fuels. USA: Marcel-Dekker.

Hubert E. Stassen (1995) Small-Scale Biomass Gasifiers for Heat and Power. Washington, D.C: The World Bank.

Katherine J. Denniston, Joseph J. Topping and Robert L. Caret, (2001) General Organic, and Biochemistry. New York: McGraw-Hill.

Klass DL. (1998) Biomass for Renewable Energy, Fuels and Chemicals. San Diego, CA: Academic Press.

Max Lu, G.Q. and Lau, D.D. (1996) Characterization of sewage sludge-derived adsorbents for H_2S removal. Part 2: Surface and pore structural evolution in chemical activation. Gas Separation and Purification, 10(2), 103-111.

Philipp Oliver Morf (2001) Secondary Reactions of Tar during Thermochemical Biomass Conversion. Ph.D. Thesis at the Swiss Federal Institute of Technology Zurich. Zurich, Switzerland.

Radovic, L.R., Silva, I.F., Ume, J.I., Menéndez, J.A., León y León, C.A. and Scaroni, A.W., (1997). Carbon, 35, 1349.

Roger C. Petersen (1983) The chemical composition of wood, in Roger Rowell (Ed.) The Chemistry of Solid Wood. Washington, D.C.: American Chemical Society.

Speight, J.G. (1994) The Chemistry and Technology of Coal, New York: Marcel-Dekker.

Stassen, H.E. (1995). Small-Scale Biomass Gasifiers for Heat and Power. Washington, D.C.: The World Bank.

Yaman, S. (2004) Pyrolysis of biomass to produce fuels and chemical feedstock. Energy Conservation and Management, 45, 651-671.

APPENDICES

Appendix A: Kinetic Evaluation from TGA Data

Several mathematical manipulations have been developed to determine the kinetic parameters from the data obtained from TG experiment. These methods have been developed over the years since the early 1960s and are still applying effectively. One of classic and popular methods was proposed by Coats and Redfern (1964). This method starts at a reaction scheme A(s) → B(s) + C(g), and the rate of conversion of A can be written as

$$\frac{dx}{dt} = k(1-x)^n \qquad \text{(A.1)}$$

where x is the fractional conversion and k is the rate constant, expressed as

$$k = A\exp\left(-\frac{E}{RT}\right) \qquad \text{(A.2)}$$

where A and E are Arrhenius parameters known as the frequency factor and the activation energy, respectively, while n is the reaction order. Since not much theoretical justification can be provided for frequency factor and reaction order, in the case of solid decomposition, Gadalla (1985) recommends the use of terms "pre-exponential factor" and "exponent term", respectively, to avoid any misconception.

For a constant heating rate, $a = \frac{dT}{dt}$, the substitution for k in Eq. (A.1) can be made as follows:

$$\frac{dx}{dt} = \frac{A}{a}\exp\left(-\frac{E}{RT}\right)(1-x)^n\text{, or} \qquad \text{(A.3)}$$

$$\frac{dx}{(1-x)^n} = \frac{A}{a}\exp\left(-\frac{E}{RT}\right)dT \qquad \text{(A.4)}$$

In order to integrate Eq (A.4) within the limits of x = 0 to x and T = 0 to T, at first substitute $u = E/RT$. The approximate solution for the right-hand side of this integral is then given as

$$\int e^{-u} u^{-b} du = u^{(1-b)} e^{-u} \sum (-1)^n \frac{b^n}{u^{(n+1)}} \tag{A.5}$$

Substituting this solution into equation (A.4) for n not equal to zero hence

$$1 - \frac{(1-x)^{1-n}}{(1-n)} = \frac{ART^2}{aE\left[1 - \frac{2RT}{E}\right] e^{\left(-\frac{E}{RT}\right)}} \tag{A.6}$$

and for n = 1, equation (A.4) becomes

$$-\log\left[\frac{(1-x)}{T^2}\right] = \frac{AR}{aE\left[1 - \frac{2RT}{E}\right] e^{-\frac{E}{RT}}} \tag{A.7}$$

To determine the kinetic parameters for any reaction by using this method, one has to make a guess at the reaction order. Subsequently, by taking the log of both sides, equations (A.6 and A.7) transform into a linear function: $y = mx + c$. The reaction order for which the linearity of the function is best defined can then be used to determine the kinetic parameters by using the graphical technique.

The method of Coats and Redfern (1964) has been used successfully by many researchers. However, one of the drawbacks of this method is that the reaction order has to be known beforehand or one has to do extensive linear fit on the experiment data for various reaction orders until the error is optimized. Another limitation of this method is that for the cases where there is a stepwise conversion of multiple reactions, the treatment of data has to be done for separate steps individually (Gaur and Reed, 1998).

Appendix B: Full Detail of Sewage Sludge Properties

B.1 General Characteristics

B.1.1 Appearance

As-received sewage sludge sample is fine soil-like particle. The dry particles are loosely packed into a larger piece that is crispy and easy to break. This textural property is rather similar for most samples. The unpleasant smell of sludge indicates the significant amount of volatile organic contents. The color of sludge varies from light to dark, green-brawn or red-brawn depending upon the original source. The difference in color possibly means the different components and their fractions of original materials. Nevertheless, some samples are obviously reddish-brawn in color and sandy in texture, which may be inferred to the significant amount of metal containing components. Absorption of moisture is possible when leaving the sample exposed to the air.

B.1.2 Homogeneity

Considered the origin of sewage sludge, it is generally created by human activities, naturally settled and collected in the water treatment plant. That means, the sludge can be originated from different environments among person, place, treatment system, processing, collecting, handling or even contamination. Thus, it can be considered as inhomogeneous material. The inhomogeneity can be observed on site after sludge processing and collecting. Because there is no physical mixing of the components in settled sludge, it is possible to virtually observe the distinguished layers of bulk components. This inhomogeneity property is analogy to that of other solids such as any coal (except Anthracite) or granite rock etc. (Schobert, 1990).

Therefore, in order to provide a good sample for this study, the samples were carefully collected following the standard method. Prior to use in the experiments, sludge specimens with enough quantity were well crushed and sieved in order to at least obtain the macroscopic homogeneity.

B.2 Compositions and Heating Value

The chemical reactions concerning to the development of processes for producing derived fuels and chemicals are highly related to the chemical structure of major organic compositions in sewage sludge. Like other fuels, they were served as the first priority of fuel evaluation prior to use in the thermal applications. Here, the sludge samples were analyzed for their compositions in term of proximate and ultimate analyses as well as for their heating values.

B.2.1 Proximate Analysis

Proximate analysis (standard ASTM D3172) is a particular group of tests designed as basis for coal characterization in connection with coal utilization. However, the standard is also allowed to use for evaluation of other solid fuels including sewage sludge as emphasized in this work. The method includes the determination of moisture, volatile matter, ash and fixed carbon contents (by difference). Table B.1 shows complete information of sewage sludge proximate compositions (as well as its ultimate compositions and heating value).

B.2.2 Ultimate Analysis

B.2.2.1 Elemental Compositions

In contrast to proximate analysis, ultimate analysis (ASTM D3178) provides the elemental compositions i.e. carbon, hydrogen, nitrogen, sulfur and oxygen (by difference). Analogy to the biomass component such as carbohydrate (or polysaccharide) that has general formula $(C_6H_{11}O_5)_n$, the sewage sludge may be represented in term of an empirical formula as $(C_6H_{11.6}O_{4.4}N_{0.8}S_{0.1})_n$, in average. The sludge organic has C/H ratio of 6.20 by weight or that atomic ratio of 0.52. However, some sludges has drastically low C/H ratio as 2.94 and as high as 8.10 by weight. The high hydrogen containing can be inferred to an aliphatic nature in sludge. The sludge organic also have nitrogen functionality and less proportion of sulfur functionality. The sludge organic has average C/O ratio of 1.03 by weight or that atomic ratio of 1.37.

Table B.1 Sewage sludge samples properties by source

Source	No.	M	Proximate analysis			Ultimate analysis					HHV
			V	A	FC	C	H	N	S	O	(MJ/kg)
Seepraya	1	4.8	40.4	55.1	4.5	20.8	3.4	3.4	0.9	16.4	9.4
	2	4.1	43.2	52.1	4.7	21.7	3.3	3.4	1.1	18.3	10.6
	3	4.9	45.6	47.0	7.5	22.9	3.9	3.7	1.0	21.6	10.7
	4	3.4	44.8	46.1	9.1	23.5	3.6	3.7	1.4	21.6	12.0
	5	4.9	43.2	49.0	7.8	22.7	3.5	3.4	1.1	20.3	10.6
	6	3.0	45.2	47.2	7.6	21.0	3.4	3.3	0.7	24.4	11.1
	7	2.4	43.3	48.7	8.0	20.7	3.2	3.1	0.8	23.5	10.6
	8	0.9	40.4	53.6	6.0	19.5	3.1	3.2	0.9	19.8	10.2
	9	3.0	38.5	57.5	4.0	17.7	3.0	2.7	0.5	18.7	8.3
	10	1.8	41.9	53.8	4.3	21.2	3.6	3.2	1.1	17.1	9.5
	11	7.3	38.1	59.7	2.2	17.6	3.1	2.9	0.8	16.0	8.5
Klong-tuey	1	5.2	53.2	40.6	6.2	29.1	4.5	4.7	1.2	20.0	12.9
	2	5.9	49.7	42.5	7.7	26.8	4.2	4.0	1.0	21.4	12.3
	3	6.7	50.5	43.6	5.9	26.8	4.0	4.0	1.3	20.3	11.6
	4	4.5	54.3	37.0	8.7	32.1	4.0	3.0	1.1	22.8	14.7
	5	4.9	52.1	41.8	6.1	27.8	4.3	4.3	0.8	20.9	14.0
	6	3.6	51.8	41.7	6.5	25.5	3.8	3.8	1.0	24.2	14.0
	7	2.5	49.7	42.6	7.8	26.6	3.9	3.9	1.1	22.0	13.6
	8	3.2	50.1	43.5	6.4	26.6	4.2	4.1	1.7	19.8	12.2
	9	4.3	50.0	44.6	5.4	26.3	3.7	3.9	1.5	20.0	13.8
	10	7.8	51.2	43.0	5.9	27.3	4.3	4.1	0.8	20.5	12.9
	11	7.1	51.2	41.4	7.4	28.0	4.3	4.3	1.0	21.0	13.1
Tungsonghong	1	6.3	44.3	52.9	2.8	21.5	3.6	3.2	1.2	17.7	10.5
	2	7.3	47.0	50.4	2.7	23.3	4.1	3.7	1.5	17.0	10.4
	3	5.1	49.1	48.6	2.3	23.4	3.8	3.8	1.3	19.2	9.8
	4	7.5	46.6	47.8	5.5	23.7	4.0	3.8	1.4	19.3	10.5
	5	6.6	48.7	46.4	4.9	25.0	4.2	3.9	1.6	18.9	11.2
	6	5.9	48.4	46.4	5.1	24.3	3.9	4.0	1.2	20.2	11.5
	7	5.2	47.2	47.7	5.1	25.2	3.9	4.0	1.3	18.0	11.2
	8	5.6	47.5	47.5	5.0	22.4	3.6	3.8	1.1	21.6	11.2
	9	5.4	49.2	45.7	5.1	24.7	4.0	4.0	1.2	20.5	11.9
	10	8.3	47.2	49.2	3.6	23.5	3.9	3.8	1.2	18.4	11.4
	11	5.7	48.9	46.7	4.3	26.1	4.7	4.2	1.9	16.4	12.0
	12	7.8	46.8	51.0	2.1	23.0	3.6	3.8	1.3	17.2	10.7
Sena Hospital	1	6.6	59.6	36.1	4.3	27.1	4.1	4.5	0.7	27.5	14.3
	2	8.5	60.2	36.5	3.3	31.7	4.9	5.3	1.0	20.6	14.9
	3	6.3	59.9	35.8	4.2	20.5	3.1	3.1	0.6	36.9	14.9
	4	5.9	51.7	40.8	7.5	26.7	4.2	4.5	0.5	23.4	12.6
	5	7.4	56.1	38.1	5.9	29.2	4.4	5.0	1.0	22.3	13.4
	6	2.7	54.6	38.2	7.2	28.4	4.2	4.7	0.7	23.8	13.4
	7	6.6	58.0	37.2	4.8	22.2	3.5	3.6	0.5	33.1	13.4
	8	6.3	55.4	39.4	5.2	28.0	4.0	4.2	0.6	23.8	13.3
	9	7.5	50.8	44.4	4.8	25.7	4.0	4.0	0.8	21.2	12.8
	10	7.5	52.4	43.4	4.2	27.4	4.2	4.2	0.7	20.1	12.2
	11	7.6	51.3	43.4	5.2	26.7	4.0	4.2	0.8	21.0	11.7

Table B.1 (cont'd) Sewage sludge samples properties by source

Source	No.	M	Proximate analysis			Ultimate analysis					HHV
			V	A	FC	C	H	N	S	O	(MJ/kg)
Uniliver	1	5.9	53.1	42.5	4.4	27.6	4.4	2.6	0.8	22.0	12.1
	2	4.8	51.6	43.5	4.9	25.4	4.1	3.5	0.8	22.8	12.2
	3	6.5	57.0	40.2	2.8	25.7	4.1	4.4	0.7	24.9	10.5
	4	2.6	52.9	42.1	5.0	24.5	3.9	3.9	1.1	24.5	10.9
	5	6.7	53.6	45.2	1.3	22.7	3.9	3.8	0.9	23.5	10.7
	6	4.3	53.3	41.4	5.3	26.0	4.2	3.5	0.7	24.1	10.6
	7	4.5	54.3	42.2	3.6	25.4	3.9	4.1	0.8	23.7	10.8
	8	5.1	52.7	45.0	2.3	21.3	3.6	3.3	0.9	25.9	9.3
	9	5.1	57.3	40.2	2.5	26.9	4.3	4.6	1.0	23.1	11.9
	10	5.4	54.8	42.5	2.7	24.3	3.9	3.9	1.2	24.3	10.2
	11	4.3	56.4	40.4	3.2	26.3	3.8	4.1	0.8	24.6	10.7
	12	7.7	56.9	42.1	1.0	25.6	4.0	4.1	0.7	23.5	11.2
Rattanakosintra	1	4.0	35.2	64.0	0.8	15.2	2.6	2.3	0.4	15.4	6.4
	2	4.3	34.9	63.0	2.1	17.2	3.1	3.0	1.3	12.4	7.4
	3	4.1	34.3	64.8	0.9	10.6	2.3	1.7	1.1	19.5	7.1
	4	6.3	35.0	61.0	4.0	17.2	3.1	3.1	1.5	14.1	7.7
	5	1.8	31.6	62.3	6.0	14.8	2.4	2.3	1.3	16.9	7.0
	6	3.5	31.5	65.7	2.8	14.1	2.6	2.2	1.1	14.4	6.9
	7	3.7	31.7	64.7	3.6	16.1	2.9	3.2	1.0	12.2	6.8
	8	2.5	31.9	65.1	3.0	13.9	2.3	2.9	1.4	14.4	7.0
	9	0.3	34.4	61.0	4.6	14.0	2.3	2.8	1.3	18.6	6.8
	10	3.5	35.4	62.0	2.6	15.2	2.6	2.9	1.2	16.1	7.8
	11	5.1	31.9	63.8	4.3	13.2	2.7	2.4	1.1	16.8	5.6
	12	7.9	31.4	64.5	4.0	12.8	2.6	2.2	1.2	16.6	5.7
Bangna	1	6.9	48.1	44.5	7.4	25.7	4.1	4.2	0.6	20.9	11.8
	2	4.8	46.6	47.3	6.1	25.1	3.8	3.9	0.8	19.2	11.2
	3	6.3	46.0	48.5	5.6	23.8	3.8	3.8	0.8	19.3	11.2
	4	6.4	53.1	39.7	7.2	28.6	4.6	4.7	1.1	21.4	12.7
	5	4.6	55.2	36.1	8.7	29.2	4.4	4.8	1.2	24.4	14.5
	6	2.9	55.1	36.1	8.7	28.9	4.6	4.9	1.1	24.4	14.8
	7	5.6	54.9	38.8	6.3	25.2	3.7	4.1	0.6	27.7	13.5
	8	4.3	44.8	47.0	8.2	27.4	4.1	4.8	0.8	15.9	11.0
	9	4.2	48.1	45.0	6.9	24.2	3.9	3.5	1.0	22.5	12.8
	10	7.3	47.5	47.2	5.3	24.2	3.9	3.5	1.1	20.2	12.3
	11	4.2	47.7	45.7	6.7	25.1	3.9	4.1	0.9	20.4	11.8
	12	6.7	52.7	40.6	6.7	28.9	4.3	4.9	0.9	20.3	13.1
Phuket	1	1.9	33.7	59.8	6.5	17.8	3.1	2.8	0.7	15.8	8.0
	2	3.1	33.3	61.2	5.5	16.3	2.6	2.4	0.7	16.8	7.7
	3	4.4	39.4	57.4	3.2	21.6	3.4	3.4	0.9	13.3	8.2
	4	4.6	44.7	51.2	4.1	21.6	3.4	3.4	0.6	19.8	10.0
	5	3.2	43.7	50.4	5.8	20.5	3.4	3.3	0.7	21.7	9.7

Table B.1 (cont'd) Sewage sludge samples properties by source

Source	No.	M	Proximate analysis			Ultimate analysis					HHV
			V	A	FC	C	H	N	S	O	(MJ/kg)
Pathumthani Hospital	1	5.8	43.5	51.8	4.7	30.6	5.0	5.9	1.0	5.9	8.5
	2	10.1	47.3	48.0	4.7	30.9	4.9	5.2	1.0	10.0	10.1
	3	6.2	46.1	49.1	4.8	30.0	4.7	4.8	1.0	10.6	10.6
	4	3.2	56.2	34.3	9.5	29.7	4.6	5.2	1.1	25.1	14.7
	5	3.4	52.0	40.5	7.5	26.0	3.9	4.7	1.1	23.8	13.0
	6	4.3	50.3	44.3	5.4	28.1	4.5	4.6	0.7	17.7	12.9
	7	4.4	49.3	44.7	6.1	32.3	4.7	5.4	0.8	12.2	12.6
	8	5.5	56.4	36.1	7.6	30.8	4.7	5.3	1.1	22.0	13.9
	9	5.5	53.8	38.2	8.0	26.3	3.9	4.0	0.8	26.9	12.6
	10	5.8	58.1	34.8	7.1	30.2	4.4	5.1	1.2	24.3	15.0
	11	6.0	58.0	34.8	7.3	32.3	4.7	5.4	1.2	21.6	14.6
	12	7.3	60.0	30.6	9.4	28.4	4.6	4.7	0.9	30.9	14.7
On-nuch	1	8.0	24.0	73.5	2.4	11.1	2.3	1.5	0.7	10.9	4.5
	2	11.3	21.9	74.8	3.2	9.2	2.6	1.5	1.9	10.0	3.0
	3	12.7	20.7	76.2	3.0	9.1	2.5	1.5	1.7	9.0	2.8
	4	12.4	17.4	80.3	2.3	6.8	2.3	1.1	0.5	8.9	2.6
	5	9.8	22.1	76.6	1.2	8.7	2.4	1.3	0.6	10.4	3.2
	6	9.3	25.1	72.4	2.6	10.7	2.2	1.5	0.5	12.7	4.2
	7	9.1	25.5	72.1	2.4	9.3	2.2	1.6	2.0	12.8	4.9
	8	5.3	26.6	71.7	1.7	9.1	2.2	1.5	2.4	13.2	5.1
	9	5.1	22.9	73.8	3.3	7.5	1.7	1.3	1.9	13.8	2.6
	10	8.4	21.8	76.8	1.4	7.8	2.0	1.4	1.8	10.4	2.6
	11	7.8	26.9	71.0	2.1	9.3	2.3	1.6	2.4	13.4	3.4
	12	7.6	25.9	71.4	2.7	9.4	2.2	1.6	2.6	12.9	3.4
St. louis Hospital	1	6.5	48.6	48.8	2.5	25.5	3.9	3.7	0.8	17.3	10.5
	2	7.0	47.8	49.7	2.6	25.0	3.8	3.7	0.9	17.0	9.9
	3	5.1	48.6	47.9	3.5	23.5	3.6	3.3	0.8	20.8	11.0
	4	5.7	49.3	47.7	2.9	23.3	3.6	3.4	0.8	21.2	10.6
	5	4.5	51.9	43.3	4.8	26.1	4.0	3.8	1.1	21.6	11.9
	6	5.3	51.1	44.7	4.2	25.7	3.6	3.6	0.6	21.9	11.3
	7	8.2	51.5	45.9	2.6	24.7	3.8	3.7	0.8	21.1	12.0
	8	9.8	50.5	47.3	2.2	25.1	3.9	3.8	0.6	19.3	11.2
	9	9.6	51.7	41.2	7.1	25.3	3.9	3.8	0.7	25.3	11.4
	10	7.5	53.1	40.7	6.2	25.5	3.8	3.7	0.8	25.5	11.6
Pranungklao Hospital	1	7.1	50.4	42.9	6.7	27.1	4.2	4.4	0.8	20.6	13.1
	2	3.4	43.9	50.2	5.9	24.7	3.5	3.9	1.0	16.8	12.0
	3	4.4	43.5	51.7	4.9	22.8	3.5	3.5	0.8	17.8	11.3
	4	3.5	43.5	50.4	6.1	25.7	4.1	4.4	0.7	14.8	11.4
	5	5.4	49.2	42.8	7.9	25.2	3.8	3.9	0.7	23.5	13.0
	6	4.4	49.1	43.2	7.7	26.0	4.0	4.6	1.3	20.8	13.0
	7	4.5	49.4	44.4	6.2	26.3	3.8	3.9	0.6	21.0	12.4
	8	3.2	49.1	43.6	7.3	26.4	4.0	4.5	1.6	20.0	13.0
	9	3.0	49.3	43.3	7.5	26.3	4.1	4.5	1.6	20.2	12.6
	10	6.7	49.5	46.0	4.5	24.0	3.7	4.3	1.2	20.8	12.0

Table B.1 (cont'd) Sewage sludge samples properties by source

Source	No.	M	Proximate analysis			Ultimate analysis					HHV
			V	A	FC	C	H	N	S	O	(MJ/kg)
Yannawa	1	5.4	34.1	64.8	1.0	15.2	2.6	2.3	0.4	14.6	5.7
	2	8.0	32.7	66.0	1.2	13.9	2.4	2.0	0.5	15.2	5.6
	3	4.8	33.3	64.6	2.0	16.5	2.7	2.4	0.5	13.2	6.7
	4	3.5	32.1	62.6	5.3	15.5	2.5	2.4	0.4	16.6	6.6
	5	2.3	32.6	62.5	4.9	16.8	2.7	2.5	0.5	15.1	6.5
	6	3.5	30.3	65.7	4.0	14.8	2.4	2.2	0.5	14.4	6.6
	7	2.7	31.6	63.4	5.0	16.1	2.6	2.4	0.5	15.0	6.7
	8	2.1	32.8	63.5	3.8	15.2	2.6	2.4	0.2	16.1	6.9
	9	0.2	34.0	62.2	3.9	15.0	2.3	2.2	0.4	17.9	6.8
	10	2.8	33.9	63.0	3.1	14.9	2.3	2.3	0.3	17.2	6.8
	11	4.5	34.7	64.1	1.2	15.3	2.7	2.5	0.6	14.8	6.5
	12	4.7	32.2	66.1	1.7	14.4	2.5	2.4	0.6	14.1	6.5
Tasai	1	5.2	33.4	65.3	1.3	14.9	2.2	2.2	0.7	14.7	7.8
	2	4.7	35.9	61.7	2.4	18.7	2.7	3.0	1.0	13.0	8.0
	3	2.2	33.9	64.1	2.0	13.0	2.2	1.9	0.6	18.2	8.0
	4	1.8	31.1	64.7	4.3	14.8	2.2	2.0	0.4	16.0	5.7
	5	3.6	30.9	67.1	2.0	12.6	1.9	1.5	1.0	15.9	5.9
	6	2.5	30.1	67.9	2.0	12.8	2.0	1.7	0.6	15.0	5.7
	7	3.1	31.2	66.4	2.4	9.8	1.8	1.9	0.5	19.5	5.1
	8	2.2	29.4	68.9	1.7	9.6	1.6	1.9	0.4	17.6	4.8
	9	1.2	28.8	69.6	1.6	12.6	1.9	1.5	0.5	13.9	4.7
	10	2.0	28.2	71.1	0.7	12.5	1.9	1.6	0.5	12.6	4.9
	11	4.4	27.9	71.0	1.1	10.3	1.8	1.5	0.5	14.9	3.8
	12	5.6	26.0	73.4	0.6	10.4	1.7	1.5	0.4	12.6	4.3
Ramin-dra	1	6.3	36.5	59.7	3.9	18.7	3.2	2.3	0.9	15.3	11.1
	2	5.0	35.5	61.4	3.1	18.4	3.0	2.5	0.9	13.7	7.8
	3	2.2	34.9	60.4	4.7	18.1	2.9	2.2	0.8	15.6	8.0
	4	3.3	34.2	60.7	5.2	18.9	3.1	2.3	0.8	14.3	8.3
	5	2.2	31.5	63.3	5.2	16.6	2.7	2.1	0.9	14.4	8.4
	6	3.7	31.0	63.1	5.9	16.9	2.5	2.3	0.8	14.3	7.6
	7	4.2	33.9	62.2	3.8	18.4	2.9	2.2	0.7	13.5	9.4
	8	5.2	32.8	64.4	2.8	17.8	2.9	2.2	0.8	11.9	9.3
	9	3.0	34.2	62.6	3.2	16.8	2.7	2.1	0.7	15.1	9.8
	10	4.0	38.4	59.9	1.7	18.7	3.1	2.4	0.8	15.1	11.7
	11	6.1	36.3	62.3	1.3	18.6	3.0	2.3	0.9	12.9	11.9
Sahaphat Industrial Estate	1	5.1	36.4	60.5	3.2	17.7	3.3	1.7	2.3	14.6	8.8
	2	2.6	36.4	59.4	4.2	17.3	3.4	1.6	2.2	16.3	8.4
	3	6.7	36.6	61.0	2.4	17.7	3.7	1.7	2.1	13.7	8.6
	4	5.1	38.0	59.9	2.1	17.4	3.3	1.7	1.9	15.8	8.2
	5	4.2	37.6	60.2	2.2	17.2	3.1	1.6	1.8	16.1	9.4
	6	5.1	38.7	58.7	2.6	19.7	3.6	1.9	1.8	14.4	9.3
	7	5.3	36.4	61.6	2.1	20.1	3.7	1.9	1.7	10.9	8.7
	8	5.1	37.2	61.0	1.8	17.1	3.2	1.5	1.5	15.8	8.9
	9	3.4	37.5	58.2	4.3	18.4	3.2	1.6	1.6	17.0	9.7
	10	4.9	39.4	56.0	4.7	16.6	3.6	2.2	1.3	20.3	7.8
	11	4.2	42.0	53.9	4.0	20.5	3.5	1.9	1.7	18.4	10.2
	12	4.8	41.6	55.4	3.1	20.1	3.6	1.9	1.7	17.4	10.0

Table B.1 (cont'd) Sewage sludge samples properties by source

Source	No.	M	Proximate analysis			Ultimate analysis					HHV
			V	A	FC	C	H	N	S	O	(MJ/kg)
Sansook	1	4.4	24.7	72.0	3.3	14.2	2.4	2.1	0.2	9.2	5.7
	2	4.8	21.4	74.5	4.0	10.3	1.8	1.5	0.3	11.5	3.1
	3	5.2	24.3	72.9	2.8	9.9	1.9	1.6	0.4	13.4	3.2
	4	2.2	25.3	73.6	1.1	10.3	1.9	1.6	0.6	12.0	4.5
	5	5.2	29.0	70.4	0.6	10.7	1.9	1.6	0.4	15.0	4.6
	6	4.1	26.4	71.1	2.5	9.9	1.8	1.5	0.4	15.4	4.8
	7	4.2	25.1	70.9	4.0	9.7	1.9	1.5	0.3	15.6	4.3
	8	4.8	23.2	75.9	0.9	10.3	1.9	1.8	0.5	9.6	4.1
	9	4.7	24.1	75.0	0.9	9.8	2.2	1.7	0.6	10.7	4.4
Waste Treatment Department	1	6.7	57.1	34.2	8.7	34.5	5.0	3.5	1.3	21.4	16.3
	2	3.9	53.4	34.7	11.8	32.4	4.1	3.4	1.7	23.7	14.8
	3	3.6	48.9	45.2	5.9	25.6	3.9	3.6	1.2	20.6	13.2
	4	4.3	51.7	36.6	11.6	27.9	3.7	2.7	0.9	28.2	13.7
	5	5.4	51.0	38.4	10.6	35.6	4.7	3.4	0.9	16.9	13.6
	6	5.5	47.2	44.5	8.3	26.7	3.5	2.7	1.0	21.6	12.1
	7	6.4	53.3	38.1	8.6	31.0	4.0	3.1	1.1	22.8	14.4
	8	5.2	58.5	32.2	9.3	36.2	5.3	3.6	1.7	20.9	15.5
	9	8.4	55.2	38.0	6.8	32.7	4.0	3.2	1.0	21.1	14.0
	10	7.4	53.2	40.5	6.3	31.7	4.4	3.3	1.0	19.1	13.0
	11	7.2	54.3	39.9	5.8	30.5	4.0	3.2	0.9	21.5	13.1
	12	9.2	52.4	38.1	9.5	28.5	3.8	3.4	1.1	25.0	13.3
Ayudhya Hospital	1	4.5	35.1	62.1	2.8	18.7	2.7	2.5	0.8	13.2	8.2
	2	4.5	33.9	63.3	2.8	15.3	2.6	2.0	0.7	16.2	6.0
	3	3.9	31.4	66.5	2.1	15.5	2.6	1.9	1.4	12.1	6.2
	4	8.0	40.2	58.8	1.1	19.8	3.1	2.7	1.3	14.4	10.7
	5	2.9	38.4	57.0	4.6	19.6	2.9	2.9	1.7	15.9	9.7
	6	0.8	42.0	54.4	3.5	20.0	2.9	2.9	1.4	18.3	8.8
	7	3.3	37.4	59.5	3.2	20.4	3.1	3.0	0.9	13.2	8.2
	8	4.3	31.7	64.0	4.3	21.4	3.8	3.1	1.6	6.0	6.4
	9	6.7	38.5	57.1	4.4	19.6	3.0	2.9	1.2	16.2	8.8
	10	7.2	37.7	59.2	3.1	19.5	2.9	2.9	1.1	14.3	9.2
Ladkrabung Industrial Estate	1	6.2	42.6	56.1	1.2	20.1	3.0	2.7	1.6	16.3	8.1
	2	3.2	43.4	55.4	1.2	19.3	2.7	2.3	2.1	18.3	7.8
	3	4.2	42.9	55.5	1.6	19.1	2.9	2.7	1.5	18.4	7.9
	4	5.2	44.0	51.9	4.1	23.8	3.4	3.3	2.0	15.6	10.1
	5	5.5	53.3	42.9	3.8	26.8	3.7	3.5	2.5	20.5	13.6
	6	3.6	51.6	44.1	4.3	26.2	3.7	3.5	1.6	20.9	12.9
	7	5.7	41.9	54.6	3.5	23.9	3.2	2.8	1.7	13.8	8.9
	8	5.3	45.6	51.3	3.1	20.8	2.9	2.3	1.7	21.1	10.0
	9	6.0	45.2	52.4	2.4	22.0	3.5	3.2	2.6	16.4	9.8
	10	4.3	46.8	50.3	3.0	24.4	3.4	2.9	2.9	16.2	10.3
	11	6.2	43.8	53.5	2.7	22.3	3.0	2.3	2.2	16.8	9.7

B.2.2.2 H/C and O/C Atomic Ratio

The detailed discussion on H/C and O/C atomic ratios would be useful in the predicting the quality of unknown organic substance from well-known ones. By adaptation the data from Table 4.1, 4.2 and B.1, H/C and O/C atomic ratios of sewage sludge were averaged as 1.94 and 0.73, respectively.

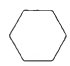
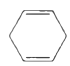
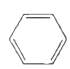
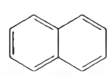
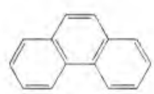
For H/C atomic ratio, it is good to consider different kinds of hydrocarbons through paraffinic- cyclic- and aromatic compounds. The information of H/C atomic ratios of some compounds was examined and represented in Table B.2. For instance, the H/C atomic ratio of hexane is 2.33 and that of cyclohexene is 1.67. Those of aromatic compounds are less than 1.00. Since sewage sludge was considered highly heterogeneous, it possibly contains a mixture of all categorized compounds. As mention above, H/C atomic ratios of sewage sludge was averaged as 1.94 with a small deviation. Thus, it can be inferred that, in average, organic content in sewage sludge would be closely categorized into parafinic or cyclic compounds.

In contrary, O/C atomic ratio was believed to relate to the level of oxygenated components and consequent heating value of substances. More detail was discussed in Section B.3.

B.2.3 Heating Value

Energy content or heating value of material was considered as a crucial property for thermal applications. It is used as the first priority for evaluating the energy potential of material. The level of energy contained depends upon the quality of the organic content in the materials. Also seen in Table 4.1, 4.2 and B.1, typical heating values of different sewage sludges are varying in range between around less than 4.0 MJ/kg and as high as almost 14.0 MJ/kg. The average value is at 9.7 MJ/kg. However, those of hospital and industrial sludge samples are between the average values and that on the high side.

Table B.2 H/C atomic ratios of some well-known compounds

Compound	Structure	Carbon	Hydrogen	H/C
Alkanes				
- Hexane	$CH_3(CH_2)_4CH_3$	6	14	2.33
- Octane	$CH_3(CH_2)_6CH_3$	8	18	2.25
- Hexadecane	$CH_3(CH_2)_{14}CH_3$	16	34	2.13
Cyclic-compounds				
- Cyclohexane		6	12	2.00
- Cyclohexene		6	10	1.67
- Cyclohexadiene		6	8	1.33
Aromatics				
- Benzene		6	6	1.00
- Naphthalene		10	8	0.80
- Phenanthrene		14	10	0.71

B.2.4 Comparison between Sewage Sludges and Other Materials

Consider the heating value of different solid materials represented in Figure B.1, it seems that sewage sludge has low to moderate fuel quality comparing to other materials. In order to maintain the minimum fuel property requirement for underline applications, the evaluation and selection of sewage sludge prior to practical use in thermal process should be done carefully. The minimum heating value of existing solid fuel used in industrial practice starts from 9.0 MJ/kg or about the averaged value of sewage sludge in this study. In this case, the sludge that has the moderate heating value or higher are recommended for selection to use in the underline application.

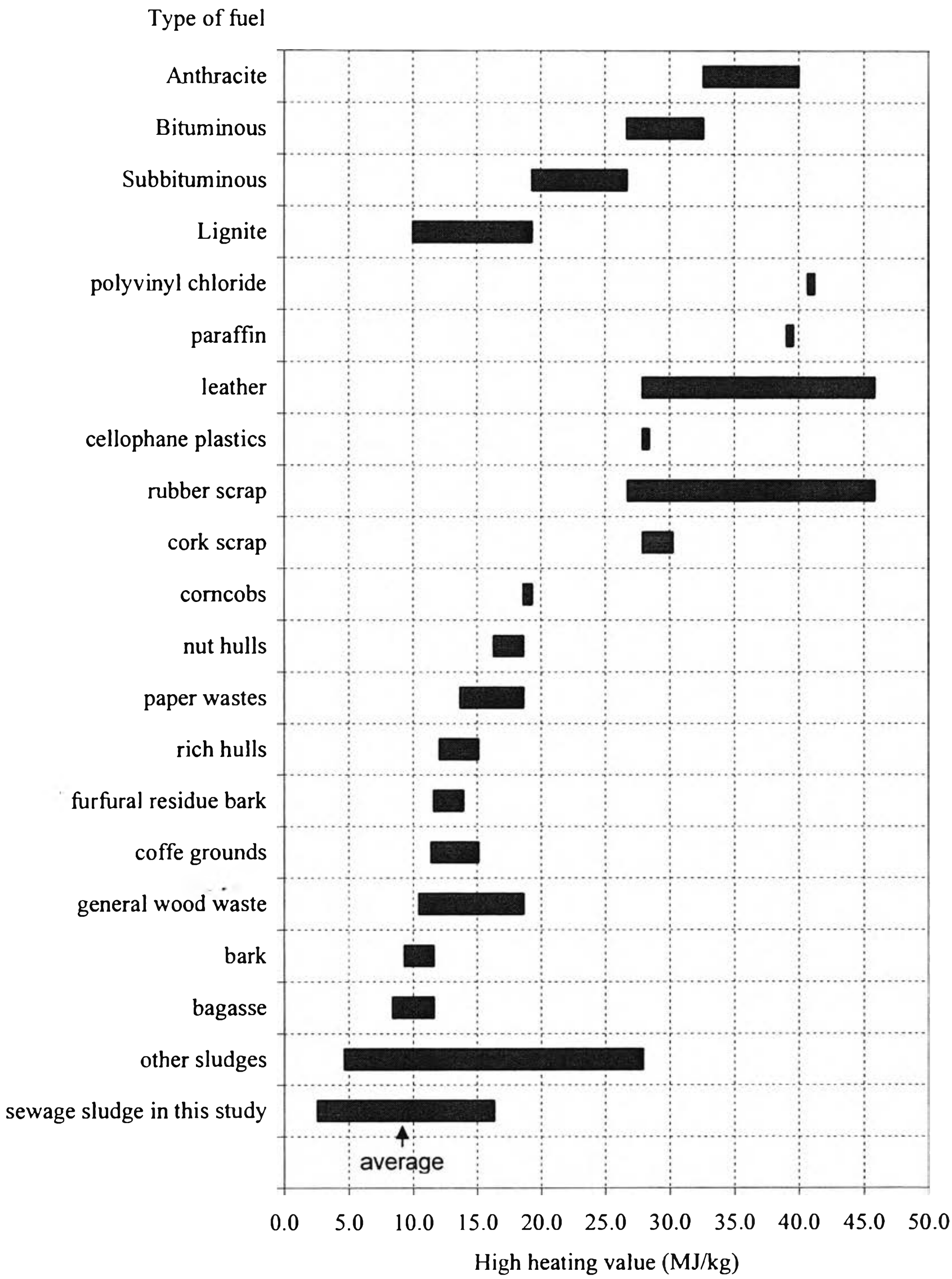


Figure B.1 Heating values of various solid fuels used in industry (adapted from Perry's Chemical Engineering Handbook).

B.3 Some Aspects in Relationship between Heating Value and Compositions

It was noticed that there shall be some correlations between compositions and property of material that has a variety in itself. Also, the sewage sludge has a close correlation between its composition and heating value. The expression for predicting the heating value of sewage sludge from its proximate and ultimate analyses were established and presented in Chapter 4.

Nevertheless, some information that was not included in Chapter 4 was discussed here. It is the fact that the fraction of oxygenated component is related to the heat of combustion of substances in the same series. For instance, butane (C_4H_{10}), butanol (C_4H_9OH) and butanoic acid (C_4H_9COOH) have the heating values of 2880, 2675 and 2193 kJ/mol, respectively (Schobert, 1990). This fact was also demonstrated for sewage sludge when the O/C ratio was plot with heating value (Figure B.2). The heating value decreases as the O/C ratio increase. The trend was in turn following the rule of thumb.

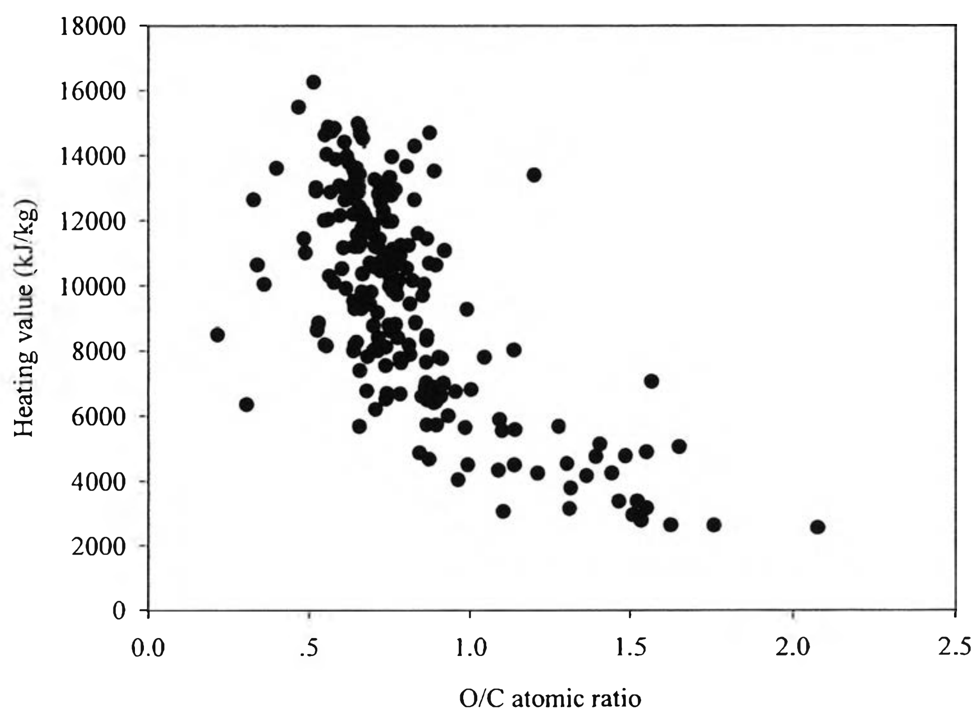


Figure B.2 Correlation between the heating value of sewage sludge and its O/C atomic ratio.

CURRICULUM VITAE

Name: Mr. Puchong Thipkhunthod

Date of Birth: January 2, 1979

Nationality: Thai

University Education:

2000-2002 Master Degree of Petrochemical Technology, The Petroleum and Petrochemical College, Chulalongkorn University, Bangkok, Thailand

1996-2000 Bachelor Degree of Chemical Engineering, Faculty of Engineering, Thammasat University, Bangkok, Thailand

Publications:

1. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Siemanond, K., Kitiyanan, B. and Rirksomboon, T. (2005) Predicting the heating value of sewage sludge from Thailand by proximate and ultimate analyses, Fuel, 84 (7-8), 849-957.
2. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Siemanond, K., Kitiyanan, B. and Rirksomboon, T. (2006) Pyrolytic characteristics of sewage sludge, Chemosphere, 64 (6), 955-962.
3. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P. and Rirksomboon, T. (2006) Description of pyrolysis of sewage sludge by the decomposition of biomass species, Journal of Analytical and Applied Pyrolysis, in press

Proceedings:

1. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Siemanond, K., Kitiyanan, B. and Rirksomboon T. (2004) Pyrolysis of Thai Sewage Sludge, Proc. of the Joint International Conference on Sustainable Energy and Environment - SEE, Cha-am, Thailand.
2. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Siemanond, K., Kitiyanan, B. and Rirksomboon T. (2004) Sewage Sludge Heating Value Prediction through Proximate and Ultimate Analyses, Proc. of the Joint International Conference on Sustainable Energy and Environment - SEE, Cha-am, Thailand.
3. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Rirksomboon, T., Kitiyanan, B. and Siemanond K. (2003) A Correlation of Sewage Sludge Characteristics to Its

Pyrolysis Behaviors, Proc. of Regional Conference on Energy Technology towards a Clean Environment, Phuket, Thailand.

4. Thipkhunthod, P., Punnaruttanakun, P., Wootthikanokkhan, J., Siemanond, K., Kitiyanan, B., Rirksomboon, T., Rangsunvigit, P. and Meeyoo V. (2002) Pyrolysis: An alternative to Solid Waste Treatment, Proc. of Annual Conference of the Thai Institute of Chemical Engineering and Applied Chemistry (TIChE), Bangkok, Thailand.
5. Thipkhunthod, P., Puengpatipan, J., Siemanond, K. and Wilkes, J.O. (2002) Finite Element Method for Chemical Engineering Applications, Proc. of Annual Conference of the Thai Institute of Chemical Engineering and Applied Chemistry (TIChE), Bangkok, Thailand.
6. Thipkhunthod, P., Siemanond, K., Meeyoo, V. and Rangsunvigit, P. (2001) Experimental and Prediction of Water and Hydrocarbon Adsorption on Activated Alumina Prepared via Sol-gel Technique, Proc. of the 6th World Congress of Chemical Engineering - WCCE, Melbourne, Australia.

Presentations:

1. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Rirksomboon, T., Kitiyanan, B. and Siemanond, K. (2006) Sewage sludge pyrolytic characteristics and description by biomass fractionation, 17th International Symposium on Analytical and Applied Pyrolysis, Budapest, Hungary.
2. Thipkhunthod, P., Meeyoo, V., Rirksomboon, T., Rangsunvigit, P., Kitiyanan, B. and Siemanond K. (2003) Effect of volatile-ash ratio on kinetic parameters of sewage sludge pyrolysis, The National Convention and grand exhibition on Solid Waste and Toilet Technology, Bangkok. Thailand.
3. Thipkhunthod, P., Meeyoo, V., Rangsunvigit, P., Rirksomboon, T., Kitiyanan, B. and Siemanond, K. (2002) A Correlation of Pyrolysis Mechanisms to Sewage Sludge Characteristics, 15th International Symposium on Analytical and Applied Pyrolysis, Leoben, Austria.