CHAPTER 1

Introduction and Background Theory

1.1 Primary Energy Consumption

The primary energy (oil, natural gas, coal, nuclear energy, hydro-electricity, and renewable energy) is very important for a civilized society and the World because human livelihood depends on energy for residential, commercial, transportation, and industrial uses. BP statistical review of World energy (2013) showed that the demand for energy consumption is continually increasing. Figure 1.1 shows the trend of energy consumption from 2002 to 2012. World primary energy consumption was about 9,500 million tons of oil equivalent (Mtoe) in 2002 and grew on average by 1.8% a year. Although the World primary energy consumption decreased 1.1% in 2009, the consumption rebounded in 2010, and reached 12,500 Mtoe in 2012.
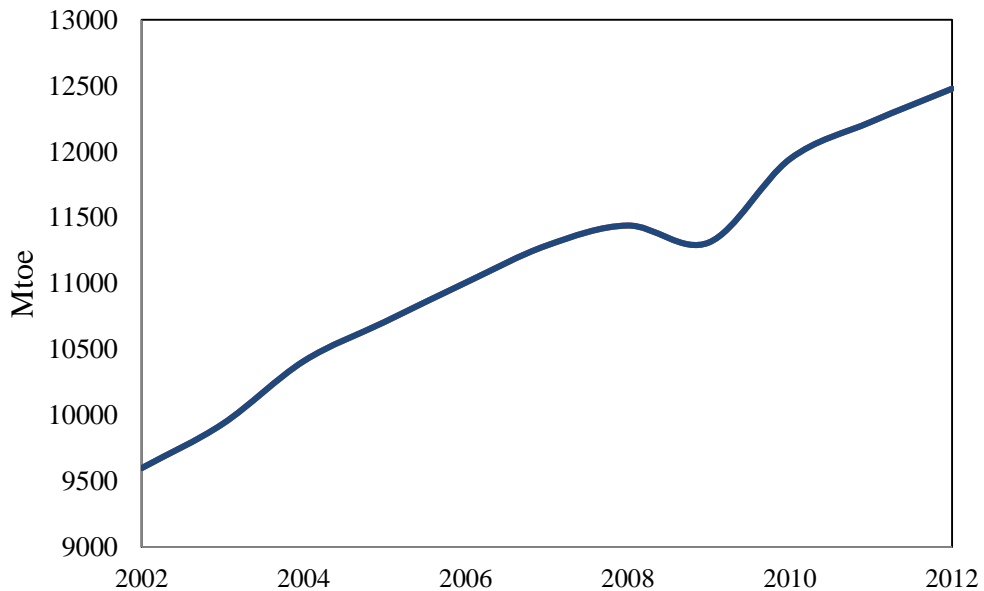
Figure 1.1 World primary energy consumption

(BP Statistical Review of World Energy , 2013)

For Asia Pacific, total primary energy consumption in 2012 was about 5,000 Mtoe (40% of total world) and grew on average by 4.7%. Coal was found to be the dominant fuel in the Asia Pacific region, the only region dependent on a single fuel for more than 50% of total primary energy consumption. Coal remains the most abundant fossil fuel by global reserves/production ratio at end of 2012.

In Thailand, the primary energy consumption in 2012 was about 120 Mtoe (0.9% of total world) and grew on average by 5.5%. Generally, oil is the most popular fuel (52.4 Mtoe). Natural gas consumption is 46.1 Mtoe. Coal consumption is 16 Mtoe, about 15% of total contribution.

Products of these fossil fuels usage such as CO_2, SO_2 and NO_x destructively affected the environment. But the fuels are still today providing almost 90% of the world's primary energy source. Coal is by far the most abundant fossil fuel which USA holds the largest individual reserves, followed by Russia and China (BP statistical review of World energy, 2013). Coal was the first fuel that proved to be excellent in generating electricity on a large scale during the industrial revolution. Currently, it remains a key fuel in energy blend (Garba, 2012).

1.2 Origin of Coal

Coal is a fossil fuel from organic sediments in ancient swamps. Due to the natural process such as flooding, the forests were buried and densed under tho soil in low-lying wetland areas of the Earth. For millions of years, the deposits were increased more and more, the forests sank deeper and deeper, and they were compressed while the temperature rose. The plant matter was protected from biodegradation and oxidation by mud or acidic water as the process continued. This trapped the carbon in immense peat. The matter was eventually covered and deeply buried by sediments. Under high pressure and high temperature, this material was slowly transformed into various coal deposits (Taylor et al, 2009; Miller, 2011; Pintana et al., 2014). Coal is composed primarily of carbon along with variable quantities of other elements, chiefly hydrogen, sulfur, oxygen, and nitrogen.

Coals can be classified in various ways. The most widely used classification schemes are based on the degree to which coals have undergone coalification. The geochemical process that transforms plant material into coal is called coalification (Miller, 2011; Singer, 1981). The process was based on the application of temperature and pressure over millions of years and involved several sequential reactions from the base material and the plant life. The following is description of coalification.

Anthracite is the hardest, very brittle, and has more carbon, which gives it higher energy content. It is shiny black and homogeneous. It is a high rank of coal for industrial and residential applications. Bituminous is formed under high heat and pressure. The carbon content in bituminous is less than anthracites, but more volatile matter and heating value. It burn easily and good for producing gas because of high volatile content. Subbituminous is brownish black or black. Most is homogeneous with smooth surfaces. It has moisture content about 15 to 30 percent. On long exposure to air, it disintegrates. Lignite is the softest and is low in carbon but high in hydrogen, oxygen, and moisture content. It deposits tend to be relatively young coal deposits that were not subjected to extreme heat or pressure. It is brown to black in color and laminar structure and may be apparent a fraction of woody fibers. Peat is the first step in the formation of coal. It is not yet a commercial fuel because of its very high moisture content and low heating value. It is defined as a combustible soft, porous or compressed fossil sedimentary deposit of plant origin with normally quite low of the sulfur content, and light to dark brown color. On the other hand, the ash content of peat can vary 2 to 70 percent from a variety of sources.

The coal properties by coalification are shown in Table 1.1. This classification does not include several coals, principally nonbanded varieties, which have unusual physical and chemical properties and which come within the limits of fixed carbon or heating value of the high volatile bituminous and subbituminous coals. All of these coals either contain less than 48% dry matter.

Basis of analytical data is important to understand previous coal analyses. The coal analyses with different bases are shown in Figure 1.2.

Table 1.1 The properties of coals by coalification (Singer, 1981)

Coal	Fixed carbon (% in d.m.m.f.[a] basis)	Volatile matter (% in d.m.m.f.[a] basis)	Heating Value (a.d.[b] basis)
Anthracitic			
1. Meta-anthracite	≥98	≤2	N/A
2. Anthracite	92-98	2-8	N/A
3. Semianthracite[c]	86-92	8-14	N/A
Bituminous			
1. Low volatile	78-86	14-22	N/A
2. Medium volatile	69-78	22-31	N/A
3. High volatile A	≤69	≥31	≥32.56[d]
4. High volatile B	N/A	N/A	30.24[d]-32.56
5. High volatile C	N/A	N/A	26.75-30.24 24.42-26.75
Subbituminous			
1. Subbituminous A	N/A	N/A	24.42-26.75
2. Subbituminous B	N/A	N/A	22.10-24.42
3. Subbituminous C	N/A	N/A	19.30-22.10
Lignite			
1. Lignite A	N/A	N/A	14.65-19.30
2. Lignite B	N/A	N/A	≤14.65

[a] Dry mineral matter free basis

[b] Air dry basis

[c] If agglomerating, classify in low volatile group of the bituminous coal.

[d] Coals having 69% or more fixed carbon on the dmmf basis shall be classified by fixed carbon, regardless of heating value.

e It is recognized that there may be nonagglomerating varieties in these groups of the bituminous coal, and there are notable exceptions in high volatile C bituminous coal.
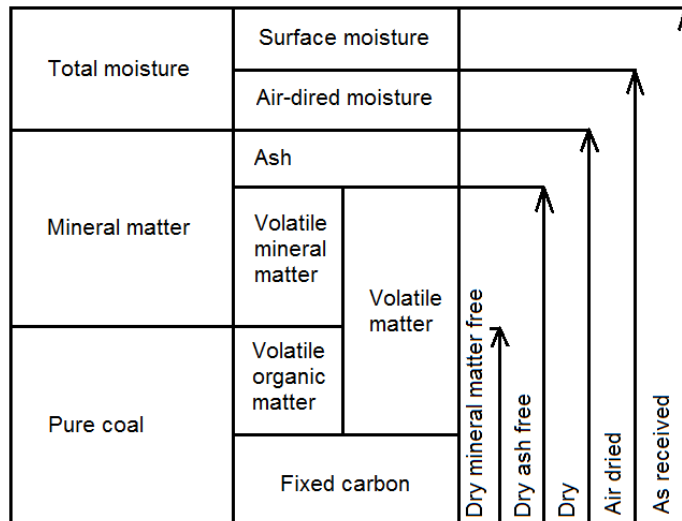
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Total moisture	Surface moisture		Dry mineral matter free	Dry ash free	Dry	Air dried	As received
Total moisture	Air-dired moisture						
Mineral matter	Ash						
Mineral matter	Volatile mineral matter	Volatile matter					
Pure coal	Volatile organic matter	Volatile matter					
Pure coal	Fixed carbon						

Figure 1.2 Coal components in the different bases (Thomas, 1992)

The data in "as received (a.r.)" basis, also "as sampled", used to explain the percentages of the coal including the total moisture content. The percentages of the air dried coal includes the air dired moisture but excludes the surface moisture are used "air dired (a.d.)" basis. The "dry (d.)" basis was expressed as percentages of the coal after all the moisture has been eliminated. The "dry ash free (d.a.f.)" means the coal include of volatile matter and fixed carbon without total moisture and ash. This basis is easiest to compare organic fractions of coals. The last basis is "Dry mineral matter free (d.m.m.f.)" that is necessary determined the total mineral matter rather than ash. The required formula for calculation of results basis are shown in appendix.
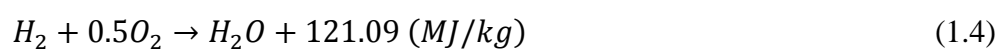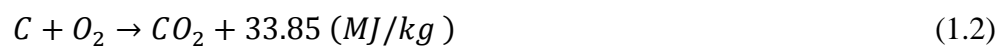
1.2.1 Coal as Fuel

Although the usage of coal is less than the use of oil, the World coal reserves are greater than the estimated World oil reserves (approximately 2.5 times) (Miller and Tillman, 2008). Therefore, coal is used as fuel to get attention to the present. For several decades, coal has been used as a main energy resource. Coal is used in the industrial sector for producing steam and electricity, and produced some chemicals. The technologies used for coal utilization are combustion, carbonization, gasification, and liquefaction (Miller, 2011). The pulverised coal combustion is widely used throughout

the world for power generation and it currently provides about 41% of the global electricity, and is likely to remain as a major source of power generation (Gubba, 2012) for many years to come.

Coal combustion is the most direct way to use coal. Currently, the coal usage for direct residential heating and industrial processes represents a small percentage of total coal consumption, while the primary coal usage is for burning in boilers to generate electricity. Combustion is the conversion of fuel into chemical compounds as products of combustion by combination with an oxidizer. The process is an exothermic chemical reaction, based on the heating value of fuel. Eq. (1.1) represented the combustion that releases energy by-product.

$$Fuel + Oxidizer \rightarrow Products\ of\ combustion + Energy \qquad (1.1)$$

In commercial combustion processes, the oxidizer is usually air. The combination of oxidizer and fuel has been at stoichiometric air-fuel ratio which the fuel is completely burned with a minimum of oxidizer. Air is a mixture of nitrogen 78%, oxygen 21%, and other constituents by volume. The combustion calculations are usually satisfactory to represent air as nitrogen 79%, and oxygen 21% by volume (Culp, 1979). The coal compounds and elements are burned to CO_2, H_2O, and other less desirable species (SO_2, CO, hydrocarbons, etc.). The main combustion equations are shown in Eq. (1.2) - (1.5) (Culp, 1979).

$$C + O_2 \rightarrow CO_2 + 33.85\ (MJ/kg) \qquad (1.2)$$

$$C + 0.5O_2 \rightarrow CO + 10.17\ (MJ/kg) \qquad (1.3)$$

$$H_2 + 0.5O_2 \rightarrow H_2O + 121.09\ (MJ/kg) \qquad (1.4)$$

$$S + O_2 \rightarrow SO_2 + 9.31 \ (MJ/kg) \tag{1.5}$$

The coal combustion process would occur with the exact proportions of oxygen and a combustible heat. However, the theoretical level of zero percent excess oxygen (stoichiometric) is impracticable in boiler operation. The condition is approached by providing an excess of oxygen in the form of excess air of atmosphere and varies with the fuel, boiler load, and type of firing equipment (Singer, 1981). The excess air is defined by Eq. (1.6).

$$Excess \ air \ (\%) = 100 \left[\left(\left(\frac{Air}{Fuel} \right)_{act} - \left(\frac{Air}{Fuel} \right)_{theo} \right) / \left(\frac{Air}{Fuel} \right)_{theo} \right] \tag{1.6}$$

1.2.2 Thai coal

Thailand is the second largest coal producing country in Southeast Asia (Ewart, 2004). Coal has been used mainly for energy. According to Mineral Resources of Thailand (2001), coal production began with an open-pit mine in Mae Moh, Lampang in 1955 (Wongyai et al., 2013). The production grew little by little and then was found in other parts of the country as shown in Table 1.2. Most coal resources are lignite to subbituminus occurring in the Tertiary Era. The majority of macerals in Mae Moh coal are densinite and gelinite with an abundance of alginate, sporinite, liptodetrinite. The framboidal pyrite is abundant in mineral matter (Ratanasthien et al., 2008). The Mae Moh basin of Lampang is the most well-known in Thailand Stratigraphy is shown in Fig. 1.3. The Mae Moh basin has been divided by formations into 3 groups (Jitapunkul, 1980; Ratanasthien et al., 2008; Shibata et al., 2013).

1) Huai Luang formation consists of red to brownish red, semi-consolidated and unconsolidated claystone, siltstone, mudstone, and sandstone and coal of "I-Zone". There is abundant gypsum and pyrite, rare roots and flame structures. The thickness varies from 5 to 400 meters with soft lignite.

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2)　　Na Khaem formation consists of semi-consolidated mudrock and is the major coal in Mae Moh basin. There are 5 coal zones with varying thickness of 300 to 420 meters. S-Zone and R-Zone are lignite or carbonaceous mudstone with brown to brownish black. Q-Zone is black to brownish black, brittle, interbedded with soft lignite, claystone/silty claystone. K-Zone is black to brownish black, brittle, with calcareous white spot, interbedded with soft lignite and silty claystone. The last is J-Zone, that is soft fragmented and abundant of gastropod, fish remains, ostracod, plant remains, reptile skeletal.

3)　　Huai King formation is the lowest formation of the Tertiary succession, the Lampang group. There are mudstone, siltstone, sandstone, conglomerate, common calcrets, semiconsolidated, slightly calcareous cement, fining upward sequence grading from conglomerate to mudstone or claystone in this zone.

The Mae Moh mine is the largest open-pit lignite mine in Thailand and one of the largest mines in South East Asia. In 2011, the pit area covered 4 km by 7.5 km at various depths up to 290 m. The coal production is about 15-16 million tons per year. The total geological lignite reserves are approximately 1140 million tons and the total economical lignite reserves are approximately 825 million tons. Up till now, lignite of nearly 350 MT has been used, and the remaining future reserves are approximately 478 MT (Zarlin et al., 2012; Wongyai et al., 2013). Due to the large size of Mae Moh mine, each region of the mine has produces lignite of different properties. The typical properties of coal in Mae Moh mine are shown in Table 1.3.

The coal from Mae Moh mine is supplied to the Mae Moh power plant. For 2,400 MW of plant capacity, the lignite is supplied at more than 1,440 million ton a year (Wongyai et al., 2013). Lignite coal generated the net energy about 19% of total energy sources for electricity generation in 2012 (EGAT annual report, 2012).

Table 1.2 Thailand coal reserves (Mineral Fuels, 2000)

| Basin name	Location	Produced (Mtones)	Remaining (Mtones)	Coal rank	Age
Mae Moh	Mae Moh, Lampang	178.862	1,226.75	Lignite to Sub-bituminous	Tertiary
Li	Li, Lamphun	34.315	1,037.00	Lignite to Bituminous	Tertiary
Mae Than	Sop Prap, Lampang	15.451	20.398	Lignite to Bituminous	Tertiary
Chiang Muan	Chiang Muan, Phayao	1.872	NA	Lignite to Bituminous	Tertiary
Na Hong	Mae Chaem, Chiang Mai	2.487	NA	Lignite to Sub-bituminous	Tertiary
Bo Luang	Hod, Chiang Mai	1.378	NA	Lignite to Sub-bituminous	Tertiary
Mae Lamao	Mae Sod, Tak	1.053	0.576	Lignite to Bituminous	Tertiary
Mae Teep	Ngao, Lampang	0.885	10.115	Lignite to Bituminous	Tertiary
Mae Tum	Mae Ramat, Tak	0.32	0.9	Lignite to Bituminous	Tertiary
Nong Ya Plong	Nong Ya Plong, Phetchaburi	1.091	0.63	Lignite to Bituminous	Tertiary
Krabi	Muang, Krabi	0	112.38	Lignite to Sub-bituminous	Tertiary
Kantang	Kantang, Trang	0.01	NA	Lignite	Tertiary
Na Duang	Na Duang, Loei	0.154	NA	Anthracite	Pre-tertiary
Na Klang	Na Klang, Udon Thani	0.006	NA	Anthracite	Pre-tertiary
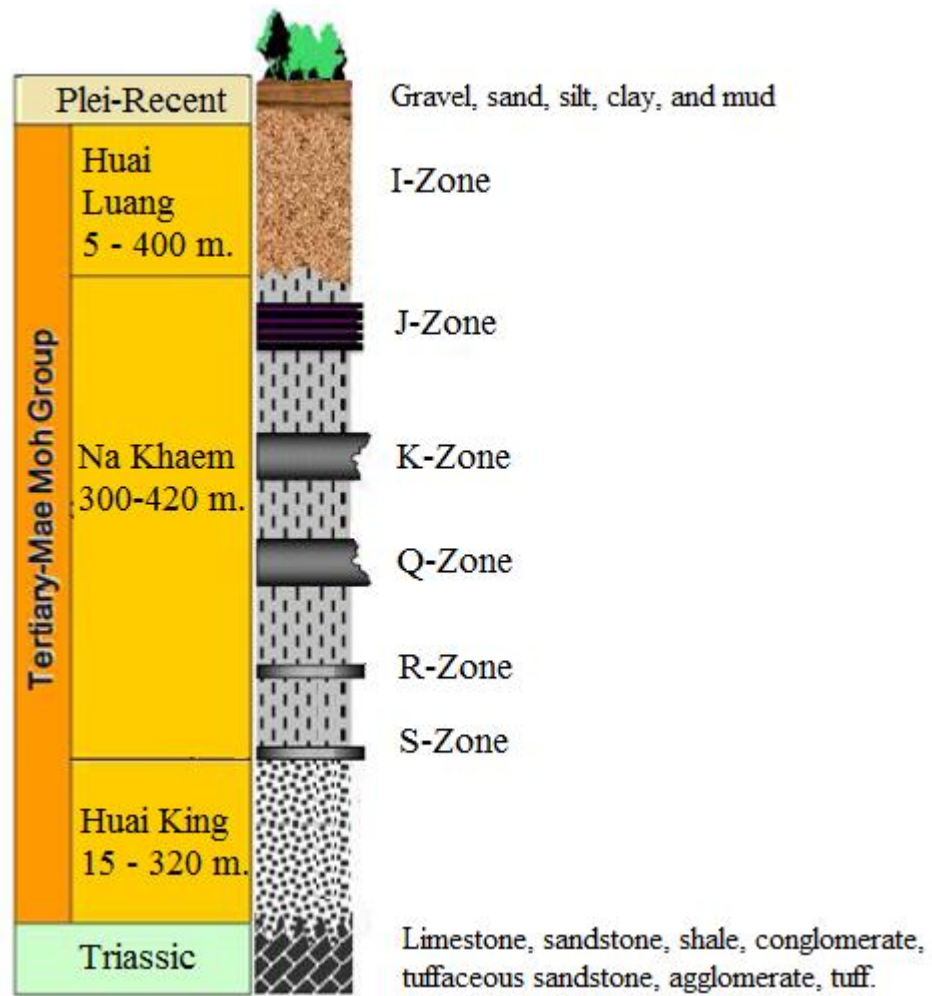
Figure 1.3 The stratigraphy of Mae Moh mine (Ratanasthien et al., 2008;

Zarlin et al., 2012; Shibata et al., 2013)

Table 1.3 The properties of Mae Moh lignite

Properties		Pipatmanomai et al., 2009	Rattanakawin and Tara, 2012	Pintana and Tippayawong, 2013
Proximate analysis	Moisture (%)	32.40	40.96	35.10-39.60
(As-received basis)	Volatile matter (%)	42.00	21.18	27.60-28.20
	Fixed carbon (%)	NA	28.67	20.90-25.80
	Ash (%)	32.30	9.18	10.90-11.80
Heating value	HHV (MJ/kg)	NA	15.12	22.6-23.7
(Dry basis)	LHV (MJ/kg)	NA		22.0-23.10
Ultimate analysis	Carbon (%)	46.70	NA	58.40-58.50
(Dry basis)	Hydrogen (%)	2.80	NA	2.40-3.00
	Hitrogen (%)	1.70	NA	1.80-1.90
	Oxygen (%)	NA	NA	12.60-12.90
	Sulfur (%)	4.00	NA	3.30-5.50

1.3 Mae Moh Coal Fired Power Plant

Mae Moh power plant is a pulverized-coal-fired power plant, with four 150 MW units and six 300 MW units, totaling 2,400 MW. Mae Moh power plant is located in Mae Moh sub-district, Mae Moh district, Lampang province, Thailand, approximately 630 kilometers north of Bangkok.

When Mae Moh lignite coal was found, the project to construct Mae Moh lignite power plant started. At first, two 75 MW generators were installed, but as the electricity demand has grown, EGAT has installed more generating units. At present, Mae Moh power plant consists of 13 generators with the total generating capacity of 2,625 MW that can totally provide an average annual energy output of 15,450 million kWh. However, the generating units 1, 2, and 3 have already retired (Teparut and Sthiannopkao, 2011).

The lignite of about 40,000 tons per day from different mining pits are crushed and transported by belt conveyors to lignite stockpiles. At the stockyard, further blending with lignite quality as shown in Table 1.4 is achieved by stacking technique prior to being reclaimed by bucket wheel reclaimers, then conveyed to the distribution bunkers of the power plants (Sompong and Teparut, 2004, Teparut and Sthiannopkao, 2011). Typically, the Mae Moh power plants are designed to burn low quality lignite. The sulfur and heating values are the primary controlled parameter for blending with carefully monitored in operation condition. The ash content is important for management without environment problem. While moisture in coal and CaO content in ash are monitored during operation without handing and slagging problem.

Operation diagram of the power plant is shown in Fig. 1.4. Each plant consists of steam turbine and boiler. The boilers were design for basic parameters shown in Table 1.5 and the details are in appendix C. The processes of Mae Moh power plant are as follow:

1.3.1 Lignite from bunker is transported to Pulverizer. The lignite must be pulverized until particles are less than 74 μm (200 mesh) and sort

contamination out. Meanwhile hot air with 300°C (Primary air) required for dries the lignite in the pulverizer. After that the air is used to transport the lignite about 60°C to the burner for 4 corners.

1.3.2 Secondary air with more than 500°C is used to mix with pulverized lignite and primary air for stoichiometric combustion in furnace.

1.3.3 The pulverized lignite is burn with tangential fired furnace and transfer the heat to Waterwalls and Superheater&Reheater. The steam go to turbine for generate electricity.

1.3.4 Ash from combustion lignite consists of Fly ash, bottom ash, Crinkle, and Slag, is transport to an ash dumping area by Submerged Scraper Conveyor (SSC). A waste ash water disposal system is supplied, transporting ash water to the ash water lake. Water from the ash water lake is reused as make-up for the scraper convayors.

1.3.5 The flue gas is treated by a Flue Gas Desulfurization (FGD) plant.

Table 1.4 Mae Moh lignite quality data for supplied to Mae Moh power plant
(Wongyai et al., 2013)

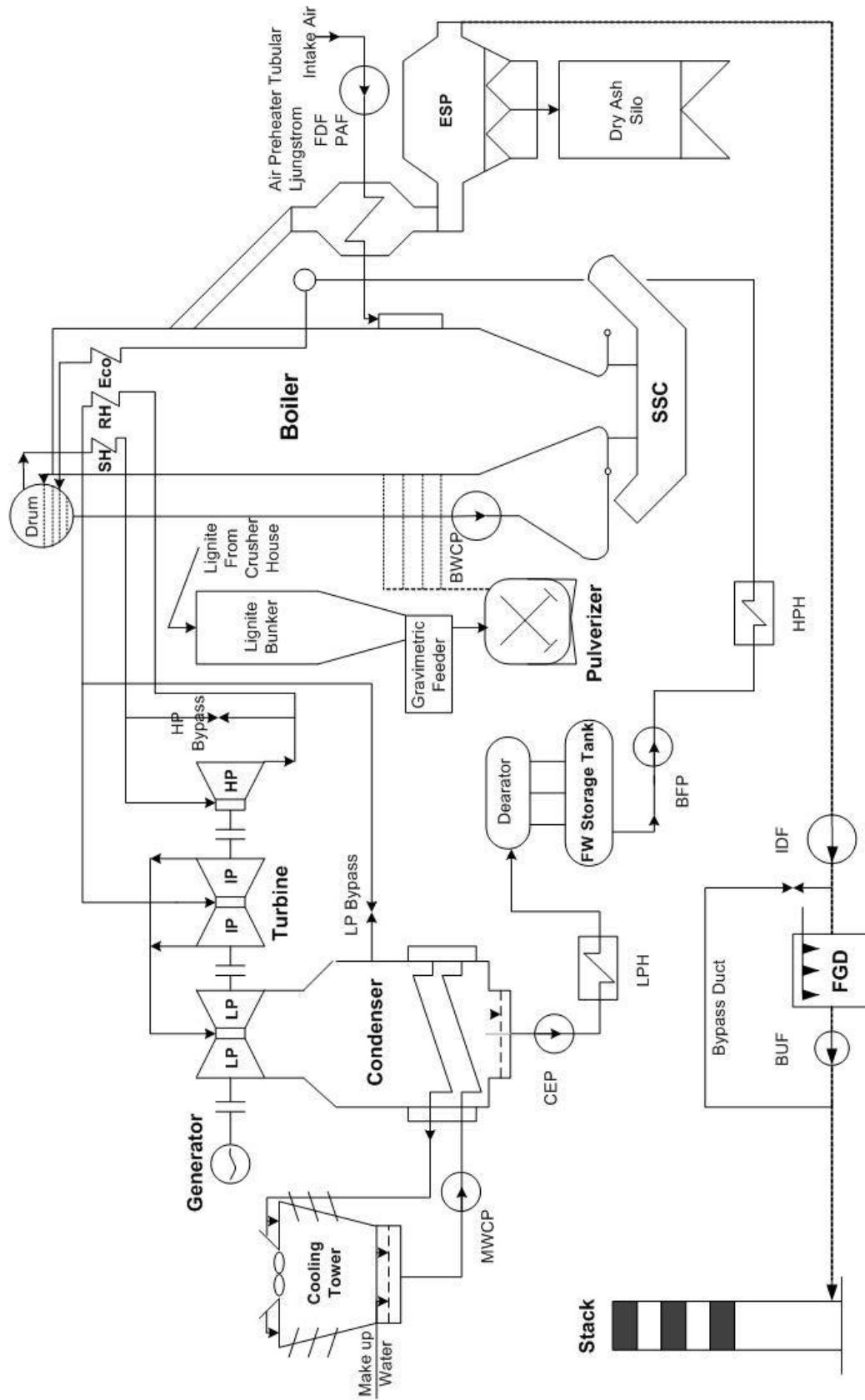| Parameter (As-received basis)	Preferred limited	Acceptable limited	Remark
Sulfur (%)	< 2.00	3.0	Critical for control of SO_2 emission
Ash (%)	< 23.3	36	Increases disposal requirement
Heating values (kcal/kg)	< 2,600	2,000	Energy available
Moisture (%)	< 31.8	36	Handing/grinding problems
CaO (% free SO_3)	< 23	23	Slagging

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Figure 1.4 Mae Moh power plant system

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Table 1.5 Unit 8-13 boiler technical data and operating parameters

Manufacture	CEMAR (A consortium of ABB and MARUBENI Corporation)
Width	13.83 m.
Depth	15.31 m.
Height	67.97 m.
Type	Control Circulation Radiant Reheater (CCRR), Tangentially fired furnace
Coal feed rate	Approximate 250 Ton/h (at 300 MW, LHV 2,500)
Excess oxygen control	3 % (wet basis)
Main steam flow	245 kg/s
Main steam pressure	161 bar
Main steam temperature	540°C
Reheater steam flow	225 kg/s
Reheater steam pressure	38 bar
Reheater steam temperature	540°C
Feed water temperature	242°C
Flue gas temperature (Economiser outlet)	350°C
Flue gas temperature (Boiler Exit)	170°C
Flue gas temperature (Electrostatic Precipiation outlet)	160°C
Boiler efficiency (at LHV)	Approximate 92%

1.4 Slagging Challenge in Future Operation

Lignite contains high levels of oxygen that can act as bonding sites for various cations such as Ca, Na, Mg, K, Sr, and Ba. The inorganic components influence the interactions and transformations of the primary mineral groups (clay minerals, carbonates, sulfides,

oxides, and quartz). In addition, the chemical and physical transformations of the inorganic components to ash or slag during combustion depend on the system design, operating conditions, and coal composition. Slag is usually dominated by silicate liquid phases but may also contain moderate to high levels of reduced in iron phases such as FeO and FeS. The silicates liquid characteristics are highly dependent on the quentities of Na, Mg, Ca, K, and Fe in ash (Miller and Tillman, 2008).

In a boiler chamber, organic material in coal is combusted under high temperature and high pressure conditions. Fig. 1.5 shows the ash particles adhere to the surface of the slag sinter layer, and then melt into liquid and transform to solid slag on furnace walls or other surfaces exposed predominately to radiant heat or excessively high gas temperatures (Song et al.,2009; Seggiani, 1999). Borio and Levasseur (1984) explained obvious impact of these slags is reduced heat transfer. Slag is caused by many factors, such as coal organic properties, coal mineral matter properties, mineral transformation and decomposition, fluid dynamics, ash transport phenomena, vaporization and condensation of ash species, deposit chemistry-specie migration and reaction and heat transfer to and from the deposit.

As presented previously, the blended coal from Mae Moh mine must have sufficiently high heating value, under limitation of sulfur content, and CaO (free SO_3) in ash must not exceed 23%. Nevertheless, the CaO value of coal found in the remaining areas revealed that coal with up to 40% CaO may be available in the future, that has been estimated to cause melting of ash. It has been proved that more frequent and severe slagging problems such as loss of capacity, loss of heat, boiler equipment damage, loss of time and money in maintenance boiler will occur.

Slag is caused by many factors, such as coal organic properties, coal mineral matter properties, mineral transformation and decomposition, fluid dynamics, ash transport, vaporization and condensation of ash species, deposit chemistry-specie migration and reaction and heat transfer to and from the deposit (Borio and Levasseur, 1984).

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Although EGAT has made every efforts to solve the problem, but the Mae Moh coal is generally worse than others. The issue is still not yet fully resolved. Fig. 1.6 determined the condition with slag problem case. When there is slag in boiler furnace, the efficiency of radiation heat transfer was decreased with the water wall. That is cause of lower boiler efficiency with shoot blowers are required to move the slag from the wall.

The Mae Moh Mine contains geological coal reserves in the total amount of 1,140 Mt. with the economic coal reserves amounting to 895 Mt. (Teparut and Sthiannopkao, 2011) and electricity supply from coal-fired plants is still in the Thailand power development plan for 2011-2030 (EPPO, 2011). Mae Moh power plant will remain in operation for many years for come. So, understanding slag problem, investigation on factors that influence formation and deposition of slag are required, especially for the case of high Ca lignite.
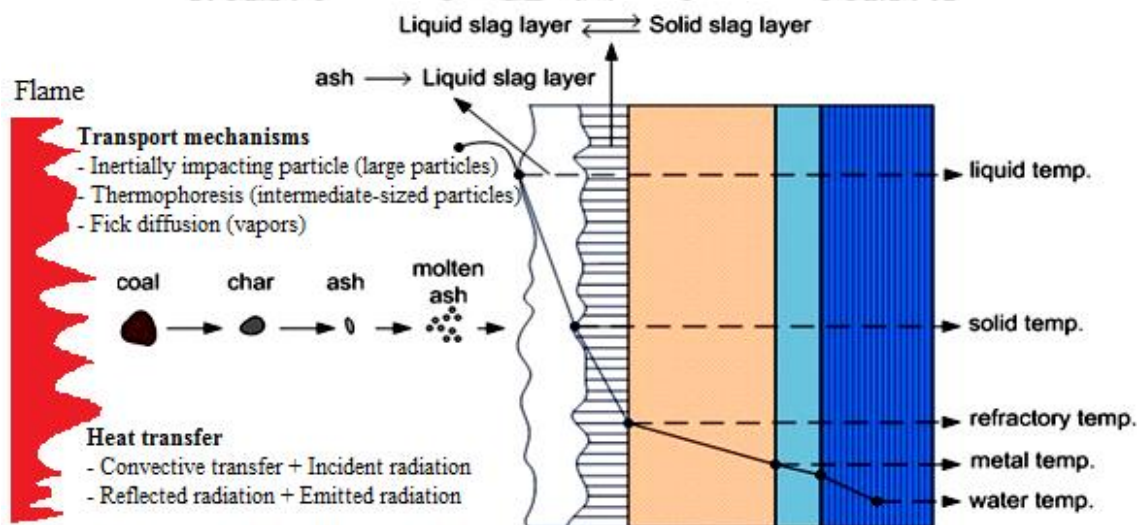

Figure 1.5 Mechanisms of slag deposit formation

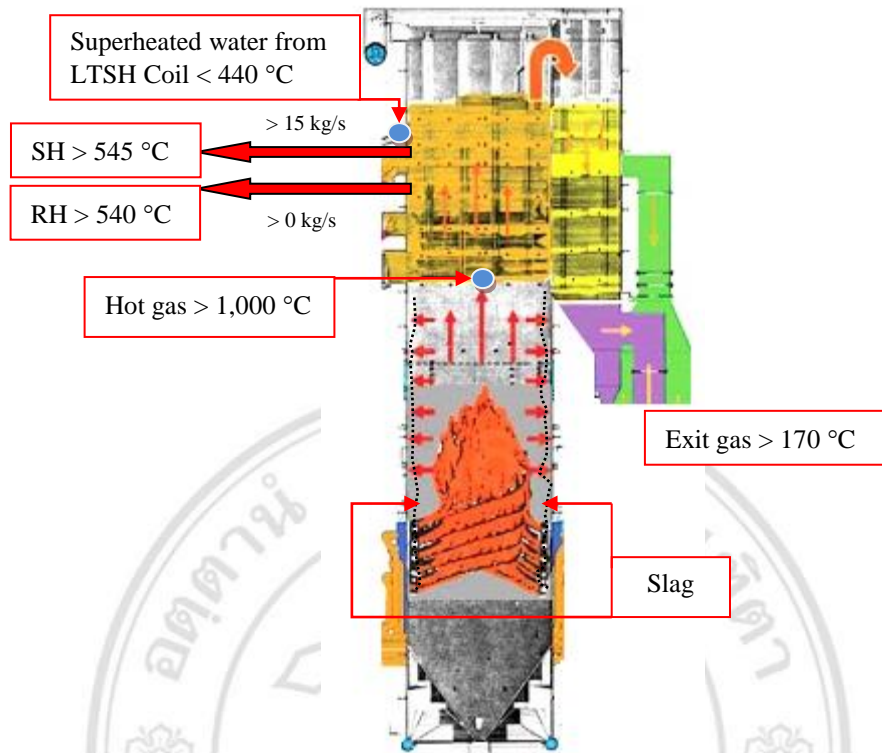(Wang and Harb, 1997; Graham et al., 2011; Pintana et al., 2014 a.)

Figure 1.6 Mae Moh boiler condition with slag problem

1.5 Research Objectives

1.5.1 To investigate composition factors that influence the melting behavior of ash and formation of slag containing high Ca from Mae Moh lignite.

1.5.2 To model fluid dynamics and predict the temperature distribution of the flow in the boiler furnace, and deposition of slag inside the boiler furnace.

1.6 Scope of the Thesis

1.6.1 Lignite coal and ash are from Mae Moh.

1.6.2 Factors considered that are associated with the melting behavior are the composition of coal and ash, melting point of ash, base/acid ratio, iron/calcium ratio, silica/alumina ratio, and iron/dolomite ratio.

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1.6.3 Blending 20-40 % Ca content of coal on the thermal behavior and melting behavior.

1.6.4 Available CFD and particle deposition models are adopted for investigation in Mae Moh power plant boiler.

1.7 Outline of the Thesis

This thesis is divided into six chapters. Chapter 1 introduces the background information related to the slag problem. This includes the objective and scope of the research. Chapter 2 contains a review of coal combustion characteristic, pulverized coal combustion, and slag problem in boilers. Chapter 3 describes the experimentation for coal, ash, and slag analysis. This chapter contains the data processing and analysis. Chapter 4, the numerical simulation, FactSage® modeling and computational fluid dynamic modeling, is briefly described to use for predicting slag potential. Chapter 5 the results of coal, ash, and slag characterization are presented. The effect of Calcium in ash was discussed on slag formation and deposition. Also, the predictions of slag formation and deposition are presented and discussed. Chapter 6 is the final chapter, that contains the conclusions and recommendation for future works.