

**A STUDY OF APPROPRIATE SCENARIOS FOR MERCURY
EMISSION CONTROL FROM COAL-FIRED POWER PLANT
USING IPOG AND CALPUFF MODEL**




VASITA TUNLATHORNTHAM

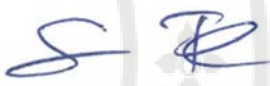
**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
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EMISSION CONTROL FROM COAL-FIRED POWER PLANT
USING IPOG AND CALPUFF MODEL**


.....
Miss Vasita Tunlathorntham
Candidate


.....
Assoc. Prof. Sarawut Thepanondh,
Ph.D. (Atmospheric Science)
Major advisor


.....
Assoc. Prof. Sopa Chinwetkitvanich,
Ph.D. (Environmental Engineering)
Co-advisor



.....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University

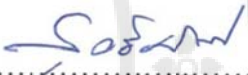

.....
Assoc. Prof. Naowarut Charoenca,
Dr.P.H. (Environmental Health)
Program Director
Master of Science Program in
Environmental Technology
Faculty of Public Health
Mahidol University


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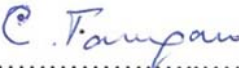

.....
Miss Vasita Tunlathorntham
Candidate


.....
Asst. Prof. Suttida Pliankarom
Thanasupsin,
Ph.D. (Environmental Engineering)
Chair


.....
Assoc. Prof. Sarawut Thepanondh,
Ph.D. (Atmospheric Science)
Member


.....
Assoc. Prof. Sopa Chinwetkitvanich,
Ph.D. (Environmental Engineering)
Member


.....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University


.....
Assoc. Prof. Chanuantong Tanasugarn,
Dr.P.H. (Behavioral Science and Patient
Education)
Dean
Faculty of Public Health
Mahidol University

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Vasita Tunlathorntham

A STUDY OF APPROPRIATE SCENARIOS FOR MERCURY EMISSION CONTROL
FROM COAL-FIRED POWER PLANT USING IPOG AND CALPUFF MODEL

VASITA TUNLATHORNTHAM 6036123 PHET/M

M.Sc. (ENVIRONMENTAL TECHNOLOGY)

THESIS ADVISORY COMMITTEE: SARAWUT THEPANONDH,
Ph.D. (ATMOSPHERIC SCIENCE), SOPA CHINWETKITVANICH,
Ph.D. (ENVIRONMENTAL ENGINEERING)

ABSTRACT

Burning coal in a power plant is one of the important anthropogenic sources that release mercury into the atmosphere. However, it is expected to decrease due to control strategies. This research presents analysis of appropriate scenarios to controlling mercury emissions from coal-fired power plants. Those scenarios include controlling by gas cleaning systems, coal properties, furnace conditions and co-benefit of air pollution control devices toward reduction of mercury emissions. In this study, mercury emissions under several scenarios were estimated using the iPOG model. It was found that mercury emissions could be different from 0.00 - 9.15 times of the emission under base line scenarios accounted for 4.48 - 374 g/hr. In the absence of existing air pollution control devices equipped at the power plant, mercury emissions could increase up to 89.04% from their current emissions. The findings revealed the co-benefit of the air pollution control devices towards controlling of mercury emission. The appropriate scenario for this research was ESPc+WFGD+Brominated ACI before ESPc or APH installations that could reduce the mercury emission by 9.15 times from its existing emission and could cause the change of mercury concentration in the atmosphere from the current situation up to 92.8%.

KEY WORDS: iPOG MODEL / CALPUFF MODEL / COAL-FIRED POWER
PLANT / MERCURY EMISSION

82 pages

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การศึกษาทางเลือกที่เหมาะสมสำหรับการควบคุมการระบายของปรอทจากโรงไฟฟ้าถ่านหินโดยใช้แบบจำลอง iPOG และ CALPUFF

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วาสิตา ตูลธรธรรม 6036123 PHET/M

วท.ม. (เทคโนโลยีสิ่งแวดล้อม)

คณะกรรมการที่ปรึกษาวิทยานิพนธ์: สราวุธ เทพานนท์, Ph.D. (ATMOSPHERIC SCIENCE),
โสภา ชินเวชกิจวานิชย์, Ph.D. (ENVIRONMENTAL ENGINEERING)

บทคัดย่อ

การเผาไหม้ถ่านหินในโรงไฟฟ้าเป็นหนึ่งในแหล่งกำเนิดที่สำคัญจากกิจกรรมของมนุษย์ที่ปล่อยสารปรอทออกสู่บรรยากาศแต่อย่างไรก็ตามมันถูกคาดหวังว่าจะลดลงเนื่องจากกลยุทธ์ในการควบคุม งานวิจัยนี้นำเสนอทางเลือกที่เหมาะสมในควบคุมการปล่อยสารปรอทจากโรงไฟฟ้าถ่านหิน สถานการณ์เหล่านั้นรวมถึงการควบคุมโดยระบบทำความสะอาดก๊าซ คุณสมบัติของถ่านหินเงื่อนไขของเตาเผาและผลประโยชน์ร่วมของอุปกรณ์ควบคุมมลพิษเพื่อลดการปลดปล่อยสารปรอท ในการศึกษาครั้งนี้ใช้แบบจำลอง iPOG ในการประเมินการระบายสารปรอทภายใต้สถานการณ์ต่างๆ พบว่าการการระบายสารปรอทอาจแตกต่างจาก 0.00 - 9.15 เท่าของการระบายภายใต้สถานการณ์พื้นฐานคิดเป็น 4.48 - 374 กรัม / ชั่วโมง ในกรณีที่ไม่มีอุปกรณ์ควบคุมมลพิษทางอากาศที่ติดตั้งอยู่ที่โรงไฟฟ้าการระบายสารปรอทอาจเพิ่มขึ้นเป็น 89.04% จากการระบายปรอทในปัจจุบัน การค้นพบนี้แสดงให้เห็นถึงประโยชน์ร่วมของอุปกรณ์ควบคุมมลพิษทางอากาศที่มีต่อการควบคุมการปล่อยสารปรอท สถานการณ์ที่เหมาะสมสำหรับการวิจัยนี้คือ ESPc+WFGD+Brominated ACI ก่อนการติดตั้ง ESPc หรือ APH ซึ่งสามารถลดการระบายปรอทได้ 9.15 เท่าจากการระบายที่มีอยู่เดิมและสามารถทำให้เกิดการเปลี่ยนความเข้มข้นของปรอทในบรรยากาศจากสถานการณ์ปัจจุบันสูงถึง 92.8%

82 หน้า

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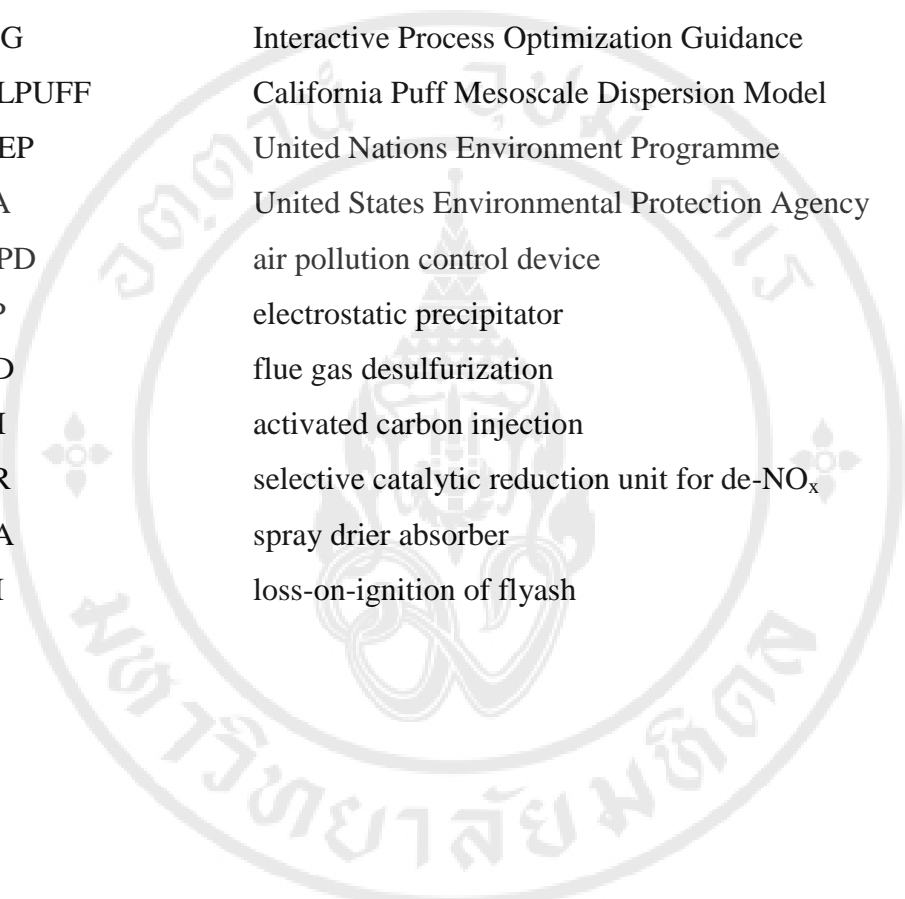
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LIST OF ABBREVIATIONS



iPOG	Interactive Process Optimization Guidance
CALPUFF	California Puff Mesoscale Dispersion Model
UNEP	United Nations Environment Programme
EPA	United States Environmental Protection Agency
ACPD	air pollution control device
ESP	electrostatic precipitator
FGD	flue gas desulfurization
ACI	activated carbon injection
SCR	selective catalytic reduction unit for de-NO _x
SDA	spray drier absorber
LOI	loss-on-ignition of flyash

CHAPTER I

INTRODUCTION

1.1 Rationales and Justifications

Mercury and mercury compounds are toxic to humans and the environment. Mercury is simply transferred by water and air. In the form of mercury gaseous has a long atmospheric lifetime and persistence in the environment, so it shows that it can be around the globe, from such a characteristic makes it as a global pollutant. Mercury is emitted from both the natural sources, weathering of rocks, forest fires, soil erosion and the anthropogenic sources, about 18% for Artisanal/small-scale gold mining, 5%-6% for industrial gold production. (UNEP,2009)

For the atmosphere, especially coal combustion processes which is the main source of anthropogenic mercury emissions in atmosphere, accounting about 45% of the total mercury emission (Dziok, Strugała, Rozwadowski and Macherzyński, 2015; UNEP, 2009). The mercury in the coal which is released during combustion into the atmosphere has three species are particle-bound mercury (Hg_p), vapor-phase oxidized mercury (Hg^{2+}) and vapor-phase elemental mercury (Hg^0) which is normally can be converted into Hg^{2+} or Hg_p (Lopez-Anton, Yuan, Perry, & Maroto-Valer, 2010; USEPA, 2002).

In general, there are two main methods to reduce emissions of mercury, pre-combustion and post-combustion (Dziok, Strugała, Rozwadowski and Macherzyński, 2015). In case of pre-combustion (coal washing, fuel switching) (Hu and Cheng, 2016), the main factor that results in the discharge is the amount of mercury in the coal while post combustion used to decrease emission between coal burned and air pollution control devices are an effective way to eliminate mercury (Wang *et al.*, 2014).

Controlling of the mercury emitted from coal-fired power plants are considered to be as co-benefit removal from the installation of a pollution treatment systems. Oxidize mercury is water-soluble and can be removed in wet scrubber such

as wet flue gas desulfurization systems (WFGD) and particle-bound mercury (Hg_p) is almost completely capture in PM control equipment such as ESPs and fabric filters (FFs) while elemental mercury is not usually trapped by emission control equipment and is emitted into the atmosphere. Therefore, the transformation of the mercury form is important by electing the suitable technology to reduce mercury (Burmistrz, Kogut, Marczak and Zwoździak, 2016; Naik, Krishnakumar and Niksa, 2010; USEPA, 2002).

Model studies are an alternative to reducing the effect of mercury on the environment. As the application of the model, iPOG is a software package that predicts Hg emissions rates from full-scale utility gas cleaning systems fired. The reduction of emissions of mercury involves the use of coal or coal blends which affects the characteristics of coal, the gas cleaning configuration, furnace conditions firing and gas cleaning conditions, and a classification of Hg control technologies. The approximation Hg emissions are based on engineering correlations of the Hg field test database from American utilities which supported by NEA's detailed Hg transformation mechanisms (NEA, 2011). For the CALPUFF model, it examines the dispersion of gases and determines pollutant concentrations in the environment (Holnicki, Kałuszko and Trapp, 2016).

The main objective of this research is to find the methodology and experimental results from the application of the iPOG to evaluate the mercury emission of each scenario and used the CALPUFF model to evaluate the concentration of mercury in the environment by selecting of appropriate alternative to reduce the mercury emissions from coal-fired power plant.

1.2 Research Objectives

1.2.1 To predict the mercury emission of each alternative from Mae Moh coal-fired power plant using the iPOG model

1.2.2 To investigate the concentration of mercury (Hg) of each scenario by using CALPUFF model

1.2.3 To evaluate appropriate scenarios to reduce mercury emissions from Mae Moh coal-fired power plant

1.3 Scope of Study

The Scope of this study covers on the following:

1.4.1 Determine the concentration of mercury in the environment at 30 km radius from Mae Moh coal-fired power plant.

1.4.2 Air Dispersion Modeling: CALPUFF (California Puff Model) Version 5.8.5 developed by Lake Environment.

1.4.3 Air Modeling: iPOG developed by Niksa Energy Associates (NEA) for the United Nations Environment Program (UNEP).

1.4.4 Mercury emission of the Mae Moh coal fired power plant is determined by the alternative of installation of air pollution control system and the mercury control option within the iPOG model.

1.4.5 Meteorological data were simulated from WRF pre-processed meteorological data.

1.4 Expected Outcome

This research will assist to select the optimal scenarios of the installation of the pollution control system and options for mercury control in order to reduce the mercury emission and the mercury concentration in the environment in Mae Moh coal-fired power plant.

1.5 Conceptual Framework

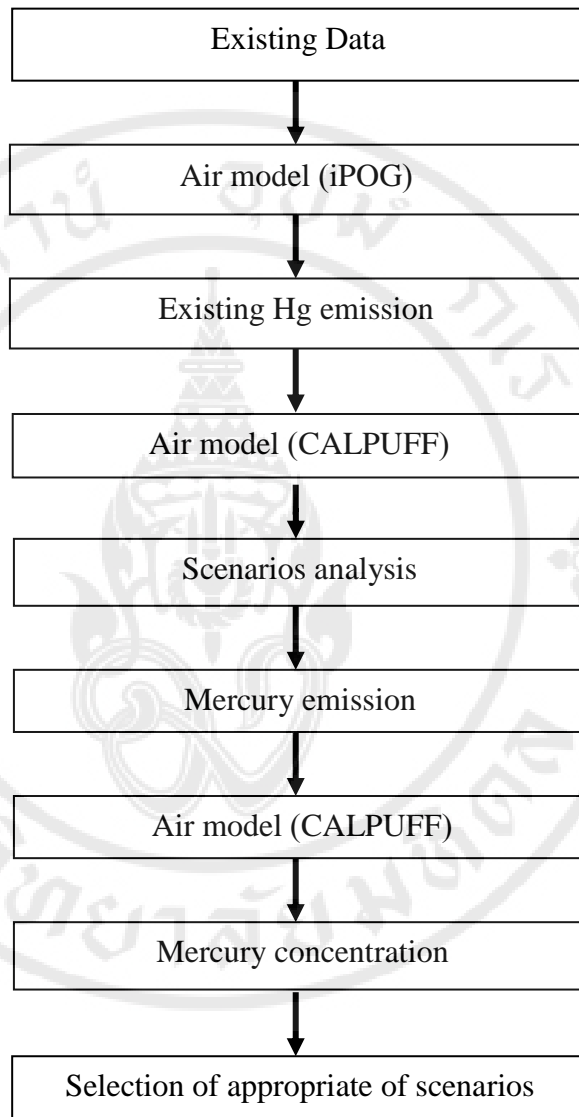


Figure 1.1 Conceptual Frameworks

1.6 Definition of Keywords

CALPUFF model (California Puff Model) is a multi-layer, multi-species, non-steady-state Lagrangian puff dispersion model. The distribution of the puffs is Gaussian, and concentrations are based on the contribution of each puff. It consists of CALMET, CALPUFF and CALPOST.

iPOG model (Interaction Process Optimization Guidance) was developed by Niksa Energy Associates LLC (NEA) for the United Nations Environment Program to evaluate the mercury emission rate and type of mercury from the full-scale gas cleaning system. Estimates based on engineering relationships based on mercury test data from US uses.

CHAPTER II

LITERATURE REVIEWS

2.1 Mercury

Mercury is naturally occurring in the environment and there are many forms. At room temperature, mercury is a liquid metal, most of which combine with other substances as inorganic salts or compounds. Most of the oxidized mercury (Hg^{2+}) is transformed into an inorganic and organic compound of mercury. Inorganic mercury compounds are known as mercury salts, for example, sulphide mercury (HgS) (Holmes and Morawska, 2006) and mercuric oxide (HgO), as well as mercuric chloride (HgCl_2) found in the atmosphere. Although Mercury is found in elemental mercury most atmospheres, it can change the form of mercury. But the water solubility and chemical reactivity of this inorganic mercury is rapidly accumulating in the atmosphere over elemental mercury. The organic mercury is formed by mercury combined with carbon such as dimethylmercury, phenylmercury, ethylmercury and methylmercury, which is common form in the environment (UNEP, 2002).

2.1.1 Sources of atmospheric mercury

2.1.1.1 Primary natural sources

Mercury can be released from the earth's crust by geothermal, which is difficult to quantify. Predictions from some models suggest that mercury contains only one-third to one half of Mercury emissions to the atmosphere (UNEP, 2002).

2.1.1.2 Primary anthropogenic sources

The main source of mercury emission into the atmosphere are coal, mining or cement production. In coal, there is not much mercury, but when the coal is burned in large quantities, mercury in the coal can be released into the atmosphere significantly. One problem for estimating mercury emission is the lack of

specific measurement data for each type of coal since each type of coal has different mercury content.

2.1.1.3 Secondary anthropogenic sources

Mercury is used in many products such as batteries, energy-saving lamps, pesticides or even cosmetics. Even in some countries, the use of mercury is reduced, but the policy of saving energy is more mercury emission (UNEP, 2002).

2.1.1.4 Re-mobilization and re-emission

Mercury emission from various sources can also be re-mobilized and re-emitted in the air. Re-mobilization occurs had been taken out of atmospheric circulation causing mercury to be released again., like rain, can release mercury in the soil or sediment into the atmosphere from aquatic system. Re-emission occurs is a common process, such as the conversion of mercury to elemental mercury. It is likely to return to the air in the form of gas (UNEP, 2002).

The source of mercury is shown in Fig 2.1



Source: UNEP 2008b

Figure 2.1 Mercury emission sources

(Source: UNEP, 2008)

2.1.2 Chemistry of Mercury in the Air

Elemental mercury is common mercury found in the atmosphere. It has a long-distance motion and is found around the world. It can stay in the atmosphere for up to 6-18 months (UNEP, 2008). For oxidized mercury and mercury particles caused by the transformation of elemental mercury. Oxidized mercury is released into the atmosphere quickly within an hour or a day. However, its persistence is shorter than that of primary mercury, making global mercury problems more likely to be due to primary mercury or elemental mercury. The action of mercury may be related to bromine, ozone or hydroxyl radical, which leads to the reaction of mercury in the gas state or total particulate mercury that cause accumulation in the atmosphere. Mercury can be converted to methylmercury, which makes it more toxic by the action of bacteria (UNEP, 2002).

2.1.3 Effect of mercury

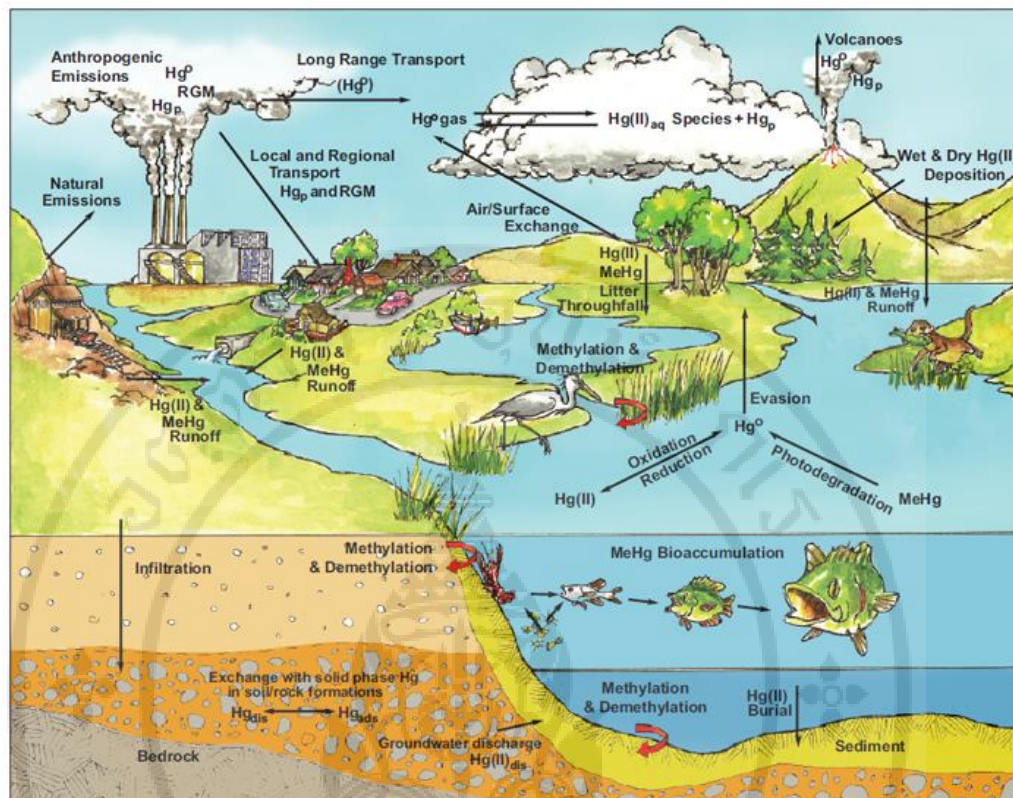
2.1.3.1 Mercury occurs in the food chain

The important factor in the impact of environmental mercury is its presence in the food chain. Although all forms of mercury can accumulate to some degree, some forms can be absorbed more quickly and accumulate at a higher level than other forms, such as methylmercury. The toxicity of methylmercury is well explained by the accumulation of fish tissue. As a result, it can move from one trophic level to the next higher trophic level due to the consumption of the next level in the food chain (UNEP, 2002).

2.1.3.2 Toxicity of mercury compounds to wildlife

Methylmercury can accumulate in the central nervous system and kidneys, as well as in abnormal behavior, reproduction and development of the fetus.

Elemental mercury does not disintegrate into the environment. When it is released it can remain and can circulate between air, water, soil, plants and animals for a long time, which is shown in Fig 2.2. For example, mercury emission into the atmosphere can accumulate on the soil surface and surface by precipitation and can also flow into the water such as the outflow of soil or through groundwater.



Source: Tetra Tech, Inc. 2010

Figure 2.2 Mercury cycle
(Source: Tetra Tech, Inc. 2010)

2.2 iPOG Model

The Interactive Process Optimization Guidance (iPOG) was developed by Niksa Energy Associates LLC (NEA) for the United Nations Environment Program to evaluate the mercury emission rate and type of mercury from the full-scale gas cleaning system. iPOG is a software suite that uses the "tree decision" concept in a POG document, designed as a model for which users can change the parameters. That would be a coal blend, coal properties, coal conditioning selection of gas cleaning and conditioning systems including the use of common technologies of other gas cleaning systems such as existing pollution control devices for NO_x , PM and SO_2 or mercury-specific control technologies such as halogenation agent, injection carbon sorbents to

find effective mercury control and reduce the emission rate of mercury into the atmosphere.

2.2.1 Input Data Requirements

For the parameters to be used in the iPOG, specify the cleaning conditions to calculate. The basic data requirements are collected in Table 2.1 by the following groups:

1) The properties of coal or coal blend must be used to evaluate the composition of the gas. There is no method to properly calibrate mercury or chlorine components in coal. Coal properties should be checked daily with the field test data.

Table 2.1 Input Data Requirements (Source: NEA, 2011).

Coal Properties	Rank, Moisture, Ash, S, HHV, Cl, Hg, Blend Percentages
Furnace Conditions	Rating, Load, Gross Efficiency, Firing Configuration, LOI, Economizer O ₂ & Bottom Ash (% total ash)
Gas Cleaning Configuration	Flow diagram from furnace exit to stack, including all APCDs& Hg Controls
SCR	Economizer NO Concentration & NO Reduction Efficiency
ESP, FF, Wet PM	PM Collection Efficiency
WFGD, SDA	SO ₂ Capture Efficiency
Sorbent Injection	Injection Position & Concentration

2) Furnace condition must be evaluated gas components and gas flow rates determined. By rating the furnace, load data during testing, higher heating value of the fuel and the oxygen concentration on economizer. The flow rate and gas composition can be estimated based on the total efficiency, which has a default value of 32 %. By

separating the amount of ash in the coal into fly ash and bottom ash are important because of loss-on-ignition by displayed as percentage of fly ash only.

3) Determining the composition of fuel for air pollution control devices is essential.

4) SCR conditions by measuring the NO concentration on the economizer while SCR works to effectively reduce NO.

5) Particle collection device: Total PM collection efficiency requires more than 98% efficiency.

6) SO₂ Scrubber conditions: All sulfur dioxide capture efficiency should be identified.

7) Sorbents and Halogenation Agents must be identified the chemical elements, injection rates and injection position.

2.2.2 Steps to Estimating Hg Emissions

First, the user must provide information about the configuration of the furnace and the gas cleaning system, along with the selection of operating conditions. By the properties of the fuel, type of coal and the efficiency of air pollution control systems, such as particle collection device, wet flue gas desulfurization system, SCR are significant to mercury conversion. In addition, if users are interested in the use of mercury-specific control technology with combination with NO_x, SO_x and PM control technologies, the mercury removal evaluation is based on the order of the equipment installed. Then the properties of the fuel, furnace type and configuration of furnace, the hierarchy of installation, gas cleaning systems and mercury control technologies are based on the POG concept in iPOG.

2.2.3 Limitation of Hg Emission Evaluation

1) Research on the emission of mercury from utility power plants is mainly in the Netherlands and the United States. Given several factors that affects the percentage of mercury in coal emitted by the stack in the large population of power plants, utilities. Field test results use the basic knowledge of environmental control testing. Tested and synthesized as a reaction mechanism that can predict mercury emissions for power plants with specific coal samples within useful quantitative

tolerances. But these assessments do not have information about fuel, furnace and gas cleaning system is enough. It is not suitable for those who do not have experience controlling the release. However, at present, POG and iPOG have developed for another user base and have no direct experience in controlling the emission of mercury. But doing this will make calculations not use the current data, which may not be the most accurate.

IPOG's general limitation is that there is more regression of field tests than the detection of chemical reaction mechanisms. Most field tests come from the US Department of Energy Technology Laboratory. In general, field testing is designed to cover every cleaning step, fuel and technology are the most popular mercury control systems. It's not like a typical corporate test. While the NETL project is more detailed, it identifies the properties of the fuel, test conditions and uncertainty in the measurement of mercury forms data. In addition, NEA has independent features as well. This has led to uncertainty in the measurement of the database. By testing all data from NETL, about 15 percent were rejected and these tests were exempted from the statistical regression developed for iPOG. Despite these precautions, iPOG users must recognize that the iPOG rating. It is less accurate than the measured value, approximately 10 to 15% of all mercury emissions in each test.

Another important limitation is that in projection is the requirement to ignore all, but the process requires input. Therefore, the assessment of iPOG cannot explain gas characteristics in the gas cleaning system. First of all, the user does not specify the temperature of the PM control device. Although mercury particles are relatively sensitive to the temperature of an ESP or FF. All iPOG assessments are evaluated under the operating temperature of the device in the United States. For use of ACI, the difference in performance of each type of activated carbon was not differentiated because of the different preparation methods, loading and surface area. The most important is to evaluate the capture of mercury on the unburned carbon in LOI and carbon sorption. Not influenced by SO_3 interference because SO_3 usually occurs at cold gases below dew point in the air preheater (APH) and most power plant operators in the United States try to control the temperature of the PM control systems above this dew point.

2) Ignoring the mercury vapor oxidation (Hg^0) associated with SCR monoliths. The iPOG account has changed the halogen concentration in the gas and the concentrations of HCl and HBr but does not specify the difference between the SCR design requirements, catalyst performance and lifetimes in service of the manufacturers. The designation of SCR influences the halogen concentration in the gas, but these designs are ignored by the iPOG, because it is technically and often proprietary to many utility companies. The evaluation is under the design. If the application is used, the data will be different from the actual.

3) The ignition of mercury oxidation (Hg^{2+}) in wet flue gas desulfurization system. In most of wet flue gas desulfurization system, most of the mercury is oxidized in the gases stored in the wastewater of scrubber or gypsum. The dissolved oxidized mercury in the form of Hg^0 . Therefore, it is necessary to identify factors related to the emissions again. So, for that unusual situation that re-emission, the value is quite high.

The limitations of iPOG interrupt mercury control data, which NEA's MercuRator™ is one of the tools that makes mercury control more effective. Use specific system specifications and use field test data to compare basic forecasts. Sample detailed input requirements for a particular simulation system in MercuRator™ appear in Table 2.2

Table 2.2 Input Data Requirements for NEA's MercuRator™ software package

	Essential	Helpful
Coal Properties	Moisture, Ash, S, HHV, Cl, Hg, blend percentages and properties	C, H, O, N
Furnace Conditions	Rating, Load, Economizer O ₂ & NO Bottom ash (% total ash)	Coal feed rate or gross thermal efficiency, economizer SO ₂ , HCl
Gas Cleaning Configuration	Flow diagram from furnace exit to stack, including all heat exchangers and	

Table 2.2 Input Data Requirements for NEA's MercuRator™ software package (cont.)

	Essential	Helpful
	APCDs	
Thermal History	FEGT, Economizer T, SCR T, Air Preheater Inlet T, ESP or FF T,FGD T	Nominal residence times for all heat exchangers and APCDs
SCR	GHSV at 32°F, inlet and outlet NO or molar NH ₃ /NO, T, pitch, channel shape, configuration, and vendor	Inlet and outlet T, monolith length, catalyst composition, pore size distribution
ESP	Fly ash LOI, ESP temperature	Ash collection efficiency, residence time, SCA
FF	Fly ash LOI, Air-to-Cloth, Cell number	Fabric material, cleaning interval and method
Wet FGD	Limestone slurry or Mg/Lime, inlet O ₂ , SO ₂ capture efficiency, T	Molar Ca/S, solid product, inlet SO ₂ and HCl
SDA	Slurry injection rate and composition, inlet O ₂ , SO ₂ capture efficiency, T	Molar Ca/S, spray injector layout
Sorbent Injection	Type, total surface area, injection rate, location, temperature, and stream composition	Sorbent PSD

Table 2.2 Input Data Requirements for NEA's MercuRator™ software package (cont.)

	Essential	Helpful
Agent Injection	Chemical composition, injection rate, location, temperature, and stream composition	

2.3 CALPUFF Model

2.3.1 History of CALPUFF

CALPUFF was developed by Sigma Research Corporation, which is now part of Earth Tech consulting scientists and engineers, as well as the development of the CALMET meteorological model. The System application (SAI) as a subcontractor to Sigma Research is responsible for developing the modeling component of the original wind field in the CALMET model, both CALPUFF and CALMET, are supported by the California Air Research Board (CARB). Air dispersion modeling (ADM) uses the mathematical estimation of the effect of origin. It involves with transport of pollutants in atmosphere, meteorological conditions, emission characteristics, surrounding terrain. CALPUFF is called a puff model that can be computed in hours-by-hour and the spatial variations of the wind. In addition, CALPUFF has been evaluated the distribution of pollution from few kilometers to several kilometers (Scire *et al*, 2000).

2.3.2 CALPUFF modeling system

CALPUFF is a form of gas and particle diffusion using spatial data, time and meteorological data that can explain a variety of effects (Holmes and Morawska, 2006) such as multi-layer, multi-species, non-steady-state puff dispersion model, movement of pollution transformation and elimination involve time, complex terrain, land use, conditions of meteorological change in the spatial, distribution of pollutants

in low wind speed and plume fumigation are as follows (Holmes and Morawska, 2006).

1) It is possible to assess both sources as a source of pollution, spatial, volume and line sources.

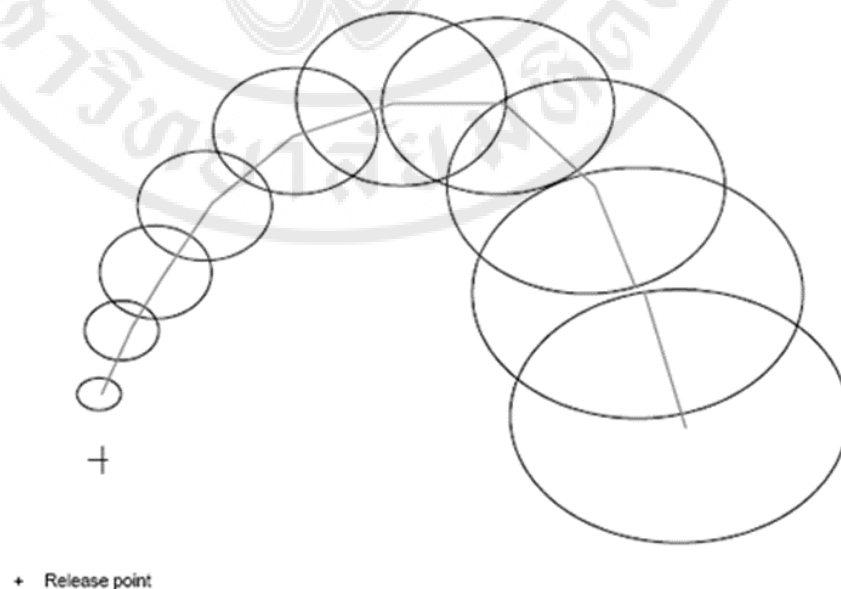
2) The model can be modeled from the tenth in meters to the hundreds in kilometers, both from a source and source complex.

3) Predict the average time from one hour to one year.

4) Applied to inert substances including the removal and chemical conversion mechanisms.

5) Used in rough or complex terrain until overwater scenarios.

Advanced models were grouped into three categories: puff, particles and grid points. All of these assessments do not need all three types, depending on the presentation of the pollution. Figure 2.3 shows a graphic representation of the puff model method.



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Figure 2.3 Graphic of the puff model method

(Source: New Zealand National Institute of Water and Atmospheric Research, 2004)

The model system was developed to answer the objectives of the impact assessment. There are 3 components.

- 1) CALMET is a meteorological and weather forecasting series.
- 2) CALPUFF is a Gaussian diffusion model that involves the removal of chemicals, wet and dry deposition, complex terrain, downwash and plume fumigation.
- 3) CALPOST is post processing programs for displaying meteorological information of concentration and deposit. CALPUFF concentrations are used for evaluation and present by selecting the average time and place.

In addition to CALMET, CALPUFF and CALPOST, the modeling system is also interconnected with other models by changing processors and utilities. An overview of the modeling system is shown in Figure 2.4.

There are four types of images in this model that are not included in the CALPUFF system, but can be connected to CALPUFF (Scire *et al*, 2000).

- 1) MM5 / MM4 (Penn State / NCAR Mesoscale Model) is a predictive model of four-dimensional wind (Scire *et al.*, 2000b). CALMET has the option to allow the data of the wind field produced by MM5 or MM4 to be used as an initial guess field and shared with other resources as part of the CALMET objective analysis process.
- 2) CSUMM (a version of the Colorado State University Mesoscale Model) is a model of the wind model (Kessler, 1989), which simulates mesoscale airflow resulting from different surfaces and the effects of the terrain.
- 3) CALGRID is an Eulerian photochemical transport model and dispersion model, including vertical and horizontal diffusion, dry deposition and mechanism photochemical
- 4) KSP is a multi-species model of Lagrangian, which has multi-layer that can be used to produce CALMET.

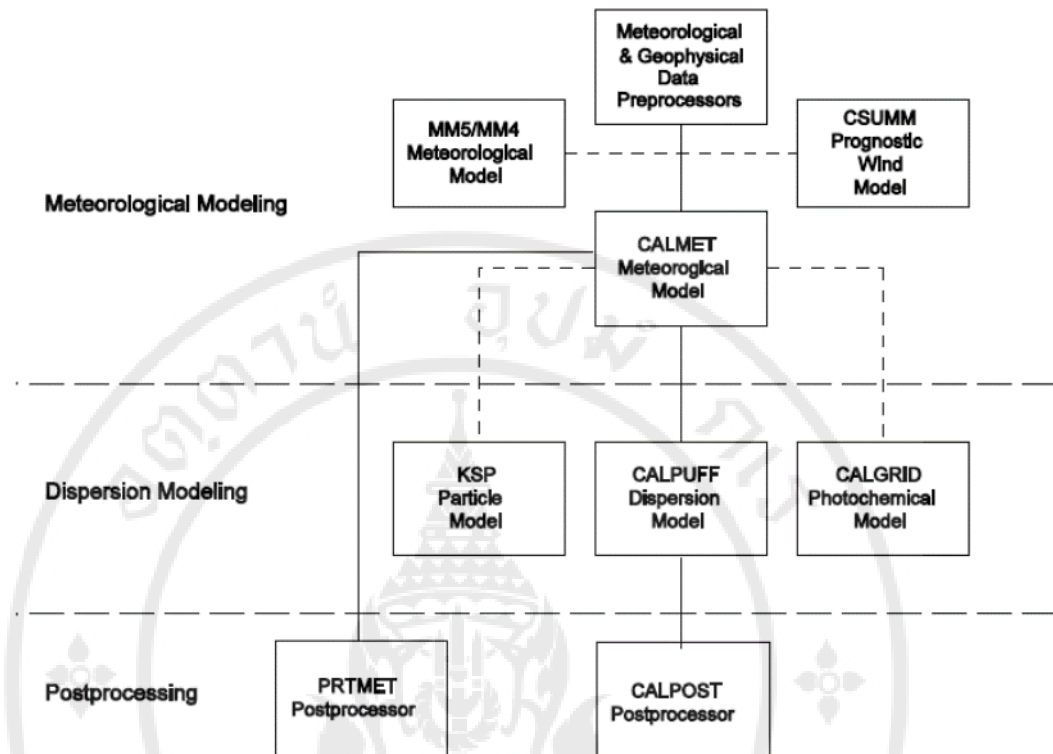


Figure 2.4 Overview of the program components in the CALMET / CALPUFF modeling system. It also shows the relevant CALGRID chemical models, the KSP particle model, and the meteorological model of MM5 / MM4 and CSUMM.

(Source: Scire et al., 2000)

CALMET is a model that analyzes the meteorological data, wind, slopes, impacts and blocks of terrain, a divergence minimization procedure and a micro-meteorological model for the boundaries of the overland and overwater or a meteorological model that develops hourly wind and temperature fields on a three-dimensional grided, involving two-dimensional simulation such as mixing height, surface characteristics and dispersion properties. The criteria for wind analysis are two steps (Scire *et al*, 2000).

1) The initial wind field was analyzed by altering the kinematic effects of the terrain, slope floes and impact of terrain blocking. This procedure does not use observation data. The wind data generated by this process depends on the reduction of

obstacles and the difference in information leading to the creation of the final wind field.

2. Observation data was used to analyze for final wind field.

For missing precipitation values are replaced by the values of the closest stations. Included are the available data. However, one valid values for each parameter must be available from one or more stations per hour for analysis or use of data from CSUMM and MM5 / MM4 are required for initial wind analysis.

CALMET data is the output of hourly winds and other meteorological variables on gridded modeling domain. It is divided into three-dimensional data and two-dimensional data. Three-dimensional data: wind speed, wind direction, and surface air temperature. For two-dimensional data: Surface friction velocity (u^*), Convective velocity scale (w^*), Mixing height (z_i), Monin-Obukhov length (L), PGT stability class, and Precipitation rate, including hourly data at the surface: air density (ρ_a), air temperature, short-wave solar radiation, relative humidity, and precipitation type (Scire *et al*, 2000b) The required data for CALMET are shown in Table 2.3.

Table 2.3 Summary of Input Data Required from CALMET

(Source: Scire *et al*, 2000b)

Surface Meteorological Data	
Hourly observation of :	Hourly precipitation data :
<ul style="list-style-type: none"> - wind speed - wind direction - temperature - cloud coverage - ceiling height - surface pressure - relative humidity 	<ul style="list-style-type: none"> - precipitation rates - precipitation type code
Upper Air Data	
Twice-daily observed vertical profiles of	Hourly gridded wind fields (optional) :

Table 2.3 Summary of Input Data Required from CALMET (cont.)

- wind speed - wind direction - temperature - pressure - elevation	- MM4/MM5 output - CSUMM output
Overwater Observations (optional)	
- air-sea temperature difference - air temperature - relative humidity - overwater mixing height - wind speed - wind direction - overwater temperature gradients above and below mixing height	
Geophysical Data	
- terrain elevations - land use categories - surface roughness length (optional) - albedo (optional) - Bowen ratio (optional) - soil heat flux constant (optional) - anthropogenic heat flux (optional) - vegetative leaf area index	

Main features and options of the CALPUFF model. Some technical steps are described below. (Scire *et al.*, 2000a).

- Dry Deposition: A full-scale model of resistance, which uses a multi-layer approach by increasing the resistance to deposition for each layer. This is intended for calculating the dry deposition rates of gases and particles in the form of geophysical parameters, meteorological conditions and species of pollutants. It has the

option to allow users to specify multiple deposition rates on a daily for at least one pollutant, rather than a resistance model or to avoid the deposition of chemicals completely.

- Wet Deposition: The empirical scavenging coefficient approach is used to calculate the wet deposition fluxes since precipitation scavenging. The coefficients are defined as the function of the pollutant and the type of precipitation.

- Chemical Transformation: CALPUFF consists of 5 transformational options: SO_2 , SO_4 , NO_x , HNO_3 and NO_3 used in the MESOPUFF II model which is the pseudo first order chemical reaction or user-specified change rate

- Subgrid Scale Complex Terrain: The complex terrain module in CALPUFF is based on the Complex Terrain Dispersion Model (CTDMPLUS), plume impingement on sub grid scale hill is assessed using a dividing streamline (H_d) to determine which pollutant material diverted around the hills sides (below the H_d) and any material passing through the hills (above the H_d). By calculating each section of the puff, it is divided into three parts if the material is polluting. Any deviation around the hills (below the H_d) and any material advected over the hills (above H_d) is calculated by dividing the individual parts of the puff into three parts.

- Puff Sampling Functions: for solving calculation problems using the puff model. CALPUFF has a set of accuracy and efficiency in puff sampling with the application of a meteorological environment similar to the one used, the puff sampling function is used. Integrated puffs are used in less demanding conditions to reduce the computational burden.

- Wind Shear Effects: The puffing algorithm allows the vertical wind shear in each puff to be calculated. By varying the rate of dispersion and transport occurring on the puff created from the original puff. Some conditions can increase the rate of horizontal growth of the plume.

- The Downwash (Building Downwash) has the option to use a model for all the stack or select parts of the stack-by-stack and wind sector basin. This allows the dimension of wind direction to be specified.

- Overwater and Coastal Interaction Effects: Because of CALMET's meteorological pattern, there are both overwater and overland boundary layer algorithms. CALPUFF can simulate the effect of water bodies on plume transport,

dispersion and deposition is designed to support geographic and air-distribution changes, including most sudden changes occurring at the coastline.

The main features of the CALPUFF model are shown in Table 2.4

Table 2.4 Major Features of the CALPUFF Model

(Source: Scire *et al.* 2000a, Table 1-1)

Source type (constant or variable emissions)
<ul style="list-style-type: none"> - Point source - Line sources - Volume sources - Area sources
Non-steady-state emissions and meteorological conditions
<ul style="list-style-type: none"> - Gridded 3-D fields of meteorological Variables (winds, temperature) - Spatially-variable fields of mixing height, friction velocity, convective velocity scale, - Monin-Obuknov length, precipitation rate - Vertically and horizontally-varying turbulence and dispersion rates - Time-dependent source and emissions data
Efficient sampling functions
<ul style="list-style-type: none"> - Integrated puff formulation - Elongated puff (slug) formulation
Dispersion coefficient (σ_y, σ_z) options
<ul style="list-style-type: none"> - Direct measurements of σ_v and σ_w - Estimated values of σ_v and σ_w based on similarity theory - Pasquill-Gifford (PG) dispersion coefficients (rural areas) - McElroy-Pooler (MP) dispersion coefficients (urban areas) - CTDM dispersion coefficients (neutral/stable)
Vertical wind shear
<ul style="list-style-type: none"> - Puff splitting

Table 2.4 Major Features of the CALPUFF Model (cont.)

Plume rise
<ul style="list-style-type: none"> - Partial penetration - Buoyant and momentum rise - Stack tip effects - Vertical wind shear - Building downwash effects
Building downwash
<ul style="list-style-type: none"> - Huber-Snyder method - Schulman-Scire method
Subgrid scale complex terrain
<ul style="list-style-type: none"> - Dividing streamline, H_d: <ul style="list-style-type: none"> - Above H_d, puff flows over the hill and experiences altered diffusion rates - Below H_d, puff deflects around the hill, splits, and wraps around the hill
Interface to the Emissions Production Model (EPM)
<ul style="list-style-type: none"> - Time-varying heat flux and emissions from controlled burns and wildfires
Dry Deposition
<ul style="list-style-type: none"> - Gases and particulate matter <ul style="list-style-type: none"> Three options: <ul style="list-style-type: none"> - Full treatment of space and time variations of deposition with a resistance model - User-specified diurnal cycles for each pollutant - No dry deposition
Overwater and coastal interaction effects
<ul style="list-style-type: none"> - Overwater boundary layer parameters - Abrupt change in meteorological conditions, plume dispersion at coastal boundary - Plume fumigation
<ul style="list-style-type: none"> - Option to introduce subgrid scale Thermal Internal Boundary Layers (TIBLs) into coastal grid cells

Table 2.4 Major Features of the CALPUFF Model (cont.)

Chemical transformation options
<ul style="list-style-type: none"> - Pseudo-first-order chemical mechanism for SO₂, SO₄²⁻, NO_x, HNO₃, and NO₃⁻ (MESOPUFF II method) - User-specified diurnal cycles of transformation rates - No chemical conversion
Wet Removal
<ul style="list-style-type: none"> - Scavenging coefficient approach - Removal rate a function of precipitation intensity and precipitation type

Meteorological information consists of fields that are arranged hourly by meteorological parameters, three-dimensional wind field, temperature and geophysical data such as terrain elevation and land use are required, including CALMET and CALPUFF models. Import data can be identified by points, lines, areas, and volumes. The CALPUFF receiver data includes options for grid and none-grid receivers.

In CALPUFF and CALMET, the input data set is wide that allowed the CALPUFF system to be more accurate and more realistic in the simulation of emissions. The basic information for CALPUFF is summarized in Table 2.5

Table 2.5 Summary of Input Data Required by CALPUFF

(Source: Scire *et al.* 2000a, Table 1-3)

Geophysical Data (CALMET.DAT)
<ul style="list-style-type: none"> - surface roughness lengths (z_0) - land use categories - terrain elevations - leaf area indices
Meteorological Data (CALMET.DAT)
<ul style="list-style-type: none"> - u, v, w wind components (3-D)

Table 2.5 Summary of Input Data Required by CALPUFF (cont.)

<ul style="list-style-type: none"> - air temperature (3-D) - surface friction velocity (u^*) - convective velocity scale (w^*) - mixing height (z_i) - Monin-Obukhov length (L) -PGT stability class - Precipitation rate - Hourly values of the following parameters at surface met. stations: <ul style="list-style-type: none"> - air density (ρ_a) - air temperature - short-wave solar radiation - relative humidity - precipitation type 	
<p>Meteorological Data (ISCMET.DAT)</p>	
<p>Hourly values (standard records)</p>	<p>Hourly values (extended records)</p>
<ul style="list-style-type: none"> - wind speed, flow direction - temperature, stability class - mixing height (z_i) for rural/urban 	<ul style="list-style-type: none"> - surface friction velocity (u^*), Monin-Obukhov length (L) - surface roughness (z_o) - precipitation code and rate - potential temperature gradient - wind speed profile power-law exponent - short-wave solar radiation relative humidity
<p>Meteorological Data (PLMMET.DAT)</p>	
<p>Hourly values (standard records)</p>	
<ul style="list-style-type: none"> - wind speed, wind direction 	

Table 2.5 Summary of Input Data Required by CALPUFF (cont.)

<ul style="list-style-type: none"> - temperature, stability class - mixing height (z_i) - turbulence (σ_θ) - wind speed profile power-law exponent - potential temperature gradient
Hourly values (extended records)
<ul style="list-style-type: none"> - precipitation code and rate - short-wave solar radiation - relative humidity
Meteorological Date (SURFACE.DAT, PROFILE.DAT)
Hourly values (SURFACE.DAT - standard records)
<ul style="list-style-type: none"> - mixing height (z_i) - surface friction velocity (u^*), Monin-Obukhov length (L) - surface roughness (z_o)
Hourly values (SURFACE.DAT - extended records)
<ul style="list-style-type: none"> - precipitation code and rate - short-wave solar radiation - relative humidity
Hourly values at multiple levels (PROFILE.DAT)
<ul style="list-style-type: none"> - height - wind speed (scalar, vector) - wind direction - temperature - turbulence (σ_v/σ_θ, σ_w)
Restart Data (RESTARTB.DAT)
<ul style="list-style-type: none"> - Model puff data generated from a previous run (allows continuation of a previous model run)

Table 2.5 Summary of Input Data Required by CALPUFF (cont.)

Emissions Data (CALPUFF.INP, PTEMARB.DAT, BAEMARB.DAT, VOLEM.DAT, LNEMARB.DAT)
<ul style="list-style-type: none"> • Point source emissions: <ul style="list-style-type: none"> - Source and emissions data for point sources with constant or cyclical emission parameters (CALPUFF.INP) - Source and emissions data for point sources with arbitrarily-varying emission parameters (PTEMARB.DAT)
<ul style="list-style-type: none"> • Area source emissions <ul style="list-style-type: none"> - Emissions and initial size, height, and location for area sources with constant or cyclical emission parameters (CALPUFF.INP) - Gridded emissions data for buoyant area sources with arbitrarily-varying emission parameters (BAEMARB.DAT)
<ul style="list-style-type: none"> • Volume source emissions <ul style="list-style-type: none"> - Emissions, height, size, and location of volume sources with constant or cyclical emission parameters (CALPUFF.INP) - Emissions data for volume sources with arbitrarily-varying emission parameters (VOLEM.DAT) • Line source emissions <ul style="list-style-type: none"> - Source and emissions data, height, length, location, spacing, and orientation of buoyant line sources with constant or cyclical emission parameters (CALPUFF.INP) - Emissions data for buoyant line sources with arbitrarily-varying emission parameters (LNEMARB.DAT)
Deposition Velocity Data (VD.DAT)
<ul style="list-style-type: none"> • Deposition velocity for each user-specified species for each hour of a diurnal cycle
Ozone Monitoring Data (OZONE.DAT)
<ul style="list-style-type: none"> • Hourly ozone measurements at one or more monitoring stations
Chemical Transformation Data (CHEM.DAT)
Species-dependent chemical transformation rates for each hour of a diurnal

Table 2.5 Summary of Input Data Required by CALPUFF (cont.)

<ul style="list-style-type: none"> • cycle
Hill Data (HILL.DAT)
<ul style="list-style-type: none"> • Hill shape and height parameters in CTDMPLUS format for use in the subgrid-scale complex terrain module (CTSG)
CTSG Receptors (HILLRCT.DAT)
<ul style="list-style-type: none"> • Receptor locations and associated hill ID in CTDMPLUS format
Subgrid Scale Coastal Boundary Data (COASTLN.DAT)
<ul style="list-style-type: none"> • File containing X,Y coordinates of subgrid scale coastlines to be treated by CALPUFF
Boundary Data for Diagnostic Mass Flux Option (FLUXBDY.DAT)
<ul style="list-style-type: none"> • File containing X,Y coordinates of boundaries used to evaluate hourly mass transport

After that, CALPUFF will display the information that is summarized in Table 2.6.

Table 2.6 Summary of CALPUFF Output Files

(Source: Scire *et al.* 2000a, Table 1-4)

Default File Name	Contents	Unit*Number	Type
RESTARTE.DAT	Output restart file containing a dump of all puff parameters sufficient to allow a model run to continue (optional)	IO4	Unformatted
CALPUFF.LST	List file produced by CALPUFF	IO6	Formatted
CONC.DAT	One-hour averaged concentrations (g/m^3) at the gridded and discrete receptors for species selected by the user in the control file (optional)	IO8	Unformatted
DFLX.DAT	One-hour averaged dry deposition fluxes ($\text{g}/\text{m}^2/\text{s}$) at the gridded and	IO9	Unformatted

Table 2.6 Summary of CALPUFF Output Files (cont.)

Default File Name	Contents	Unit*N umber	Type
	discrete receptors for species selected by the user in the control file (optional)		
WFLX.DAT	One-hour averaged wet deposition fluxes (g/m ² /s) at the gridded and discrete receptors for species selected by the user in the control file (optional)	IO10	Unformatted
VISB.DAT	Relative humidity data required for visibility-related post processing (optional)	IO11	Unformatted
DEBUG.DA	Tables of detailed puff/slug data useful for debugging (optional)	IO30	Formatted
MASSFLX.DA	Hourly report of mass flux into and out of regions defined	IO36	Formatted

2.4 Related Research

Ancord *et al.*, 2015 studied of mercury removal using air pollution control technology and economic analysis of mercury at coal-fired power plants in China, as well as cost-effectiveness analysis at enterprise and industry levels in China. In 2020 and 2030, the most cost-effective control technology has been evaluated for the 600 MW was the installation of the fabric filter system (FF), followed by the installation of the wet flue gas desulfurization system (WFGD) that removed up to 86 percent of mercury emissions at a cost of 8696 CNY/kg of mercury was removed. For a power plant installed SCR+ESP+WFGD can replace ESP and FF and increase the efficiency of mercury removal by 21%. Halogen injection (HI) is an effective mercury control strategy. SCR+ESP+WFGD was able to remove 26 percent of mercury with costs

3657 CNY/kg. China's coal-fired power sector was releasing 193 tons of mercury, with an annual mercury emission control cost of 2.7 billion CNY. The increase in selective catalytic reductions system (SCR) and the use of HI can remove mercury 39 tons, with a cost of 3.8 billion CNY. It is expected that the total cost of remove of mercury in the years 2020 to 2030, compared with 2010 to 2020, reflects the higher costs for reducing emissions by specific controls.

Burmistrz *et al.*, 2016 studied content in coal and mercury emission to the atmosphere. A total of 121 samples of mercury in subbituminous was collected from 30 Polish coal mines and 29 lignite samples from 5 deposits in Poland. Used as an example for the use of coal as an energy source in power plants and heat in Poland. Analyzes of sulfur, chlorine and bromine were also carried out. The mercury was emitted from three sources. The study indicated that Mercury content in subbituminous was 104 $\mu\text{g}/\text{kg}$. The average was 18-518 $\mu\text{g}/\text{kg}$. Mercury in lignite is 197 $\mu\text{g}/\text{kg}$. The average was 60-665 $\mu\text{g}/\text{kg}$. The amount of mercury in gypsum ash and suspended limestone was between 5 and 1200 $\mu\text{g}/\text{kg}$. For the control system, the air pollution control system mercury was removed ranged from 72%-84%, with 65 percent was removed by electrostatic precipitators and 36% was removed by Flue-gas desulfurization (FGD). The amount of mercury in the gases emitted from coal-fired boilers in bituminous and lignite coals values were between 8.7 and 10.9 $\mu\text{g Hg}/\text{m}^3$ and 70.0 $\mu\text{g Hg}/\text{m}^3$, respectively. The particles mercury emitted for subbituminous was about 40% and oxidized mercury between 16%-46%. Mercury emission into the atmosphere for subbituminous and lignite was between 2 to 5 $\mu\text{g Hg}/\text{m}^3$ and 15.1 $\mu\text{g Hg}/\text{m}^3$. Hg^0 is more than 90 percent, Hg^{2+} to 5-9% and Hg_p was less than 2.1%

Gao *et al.*, 2016 studied the pollution characteristics of mercury dust in an atmosphere near a coal power plant located on the southeastern coast of China. For example, $\text{PM}_{2.5}$ and PM_{10} were collected in rural areas from December 2014 to August 2015. The total mercury concentrations in $\text{PM}_{2.5}$ ranged from 116.2 and 1070.9 pg/m^3 . The average values were $309.5 \pm 94.9 \text{ pg}/\text{m}^3$ and the PM_{10} ranged from 173.4 to 1456.8 pg/m^3 . The average concentration of mercury in $\text{PM}_{2.5}$ and PM_{10} was $387.5 \pm 133.5 \text{ pg}/\text{m}^3$, respectively. It has the highest average concentrations during winter than in spring and summer. This is due to the seasonal variability of the meteorological conditions and the concentration of dust at that time. In addition, the high amount of

HCl-soluble particulate mercury (HPM) and elemental particulate mercury (EPM) in PM_{2.5} compared to PM₁₀ indicates that the accumulation of PM_{2.5} results in greater harm.

Glodek *et al.*, 2009 presented knowledge about the origin of mercury emissions in Poland. The current volume of coal is about the same as the reserves. These coals are the main energy sources of energy in Poland. This is related to the amount of mercury that is present in the coal. The use of coal in Poland in the past present and future coal combustion for electricity and heat is a major source of human mercury emissions in Poland. It is expected that current emissions will decline in the future because of more effective control measures. The release of mercury I fuel gases was assessed by a coal-fired power plant located in Upper Silesia, Poland. Using coal Lignite and anthracite and the system is electrostatic precipitators (ESPs). The average mercury content of anthracite and lignite was 0.100 and 0.250 mg/kg, respectively. The concentration of mercury in the fuel gases after the electrostatic precipitators was less than 0.011 mg/m³. While the efficiency of the electrostatic precipitators is only 10 percent, this coal-fired power plant releases mercury per year for the first and second units of 52.985 and 57.544 kg. It also forecasts the release of mercury in the next 20 years compared with the emission of mercury gas in 2000, it is expected that the change in energy from coal to other energy sources. It was found that 74% of the mercury in the power plant could reduce the emission of mercury by 2020.

Hu *et al.*, present the current data and recommendations for controlling mercury in China, as the use of coal for use as a source of energy in the country is increasing. The study found that mercury was burned at high temperatures (over 800° C), almost all mercury in the burned coal is converted to elemental mercury and released into the flue gas. Oxidized Mercury can be absorbed in carbon particles. So, the temperature in the flue gas, contents in carbon particles and contents in coal have a significant effect on mercury emission. The remaining mercury in the ash, generally less than 2% and about 4% of all mercury. While reducing the temperature of the flue gas, vapors of elemental and oxidized mercury including unburnt carbon particles can condense and absorb on fly ash. The oxidation of mercury is strongly influenced by natural chlorine in coal. By oxidation, mercury can be adsorbed by activated carbon or reacted with sulfide to be in the form of hydrogen sulfide and captured by particle

control devices. Wet flue gas desulfurization systems highly soluble mercury removal significantly. Nonetheless, elemental mercury is not effectively removed by this type of treatment due to its low water solubility and chemical inertness except for selective catalytic reduction, which found that the elemental mercury becomes oxidized mercury by wet flue gas desulfurization. In addition, it is found that controlling emissions from the source is an effective means of reducing mercury emissions and can control air pollution. Therefore, the most cost-effective mercury control option for combustion is considered. Considering the characteristics of coal, combustion conditions and pollution control equipment installed.

Krishnakumar *et al.*, 2010 studies the influence of sulfur trioxide on the effect of inhibition on the unburned carbon efficiency and the adsorption of activated carbon from the coal-fired power plant. This mechanism was examined against the measurements in 14 power plants based on the gas cleaning system including a range of coal-S, furnace stoichiometry, gas cleaning conditions, and comparison between actual measurement and prediction data. Mechanism of sulfur trioxide describes the inhibition of mercury oxidation and elimination due to the condensation of sulfur trioxide in unburned carbon, fly ash and activated carbon. This analysis was used to indicate a negative effect on mercury removal by testing at the Daniel and Mercury Research Center. These tests included blending different types of coal, concentration of Activated Carbon, brominated activated carbons, and sulfur trioxide concentrations. The results showed that in addition to the increased amount of sulfur trioxide, the removal of mercury was reduced. Concentration of moisture, ammonia, nitrogen monoxide is an inhibitor of the oxidation of sulfur dioxide. The amount of sulfur trioxide can reduce the absorption of mercury vapor and oxidized mercury and increasing in temperature contributes to the increase in sulfur trioxide content also until the temperature is 1400 °C, the amount of sulfuric oxide is constant. However, the presence of sulfur trioxides less than 35 ppmv did not affect the removal of mercury by activated carbon.

Lee *et al.*, 2014 studied the concentration distribution of air pollution (PM₁₀, SO₂) and calculated the statistics for model capability using WRF-CALPUFF (Weather Research and Forecasting-California PUFF) model of the Ulsan metropolitan City includes two national industries are the Ulsan Petrochemical

Industrial Complex (UPIC) and the On-San Industrial Complex (OSIC). The results were shown that CALMET simulation coefficients are reliable enough to predict CALPUFF. The Index of Agreement (IOA) of PM₁₀ and SO₂ were found to be 0.284 to 0.850 and 0.412 to 0.895, respectively. The Fractional Bias (FB) of PM₁₀ and SO₂ were 0.043 to 0.821 and -0.393 to 0.638 respectively. The highest concentrations of PM₁₀ and SO₂ were around the OSIC and UPIC respectively. By comparing the observed values at the 14 monitoring stations, it was found that the predicted SO₂ model tended to be more consistent with the observed values than the PM₁₀ model. The steel, machinery and electronic industry close to OSIC had an influence on the air quality of PM₁₀ and SO₂ at 35.1% and the chemical industry close to UPIC has an influence on the air quality of PM₁₀ and SO₂ at 40.6%. The correlation between PM₁₀ and SO₂ concentrations and the different emission amounts were 0.663 and 0.528, respectively.

Wang *et al.*, 2014 studied on the emit of mercury from five coal-fired power plants in China using the Ontario Hydro Method (OHM) for the collection of mercury before and after fabric filter (FF) and electrostatic precipitator (ESP) and mercury forms for example, Hg⁰, Hg²⁺ and Hg_P in flue gas were analyzed by EPA. The mercury content in the coal was between 0.01 to 0.25 mg/kg. For Hg²⁺, Hg⁰ and Hg_P concentrations before fabric filter and electrostatic precipitator were in the range of 0.11 to 14.76 µg/Nm³, 1.18 to 33.63 µg/N m³ and 0 to 12.11 µg/Nm³, respectively and after the fabric filter and electrostatic precipitator were the range of 0.02 to 21.20 µg/Nm³, 0.77 to 13.57 µg/Nm³ and 0 to 0.54 µg/Nm³, the proportion of Hg²⁺, Hg⁰ and Hg_P before the fabric filter and electrostatic precipitator were in the range of 4.87% to 50.93%, 13.81% to 94.79% and 0% to 45.13 %, respectively and after the fabric filter and electrostatic precipitator were in the range of 2.02% to 75.55%, 15.69 % to 98% and 0% to 11.03%, respectively. Most of the flue gas is in the form of Hg⁰ and Hg²⁺. Mercury is in the form of elemental mercury between 13% and 98% and in the form of oxidized mercury 2% to 80%, where the concentration of chlorine, sulfur in coal and flue gas affects the form of mercury that occurs before entering the air pollution control device. By increasing the NO_x, SO₂, HCl, Cl₂ in the flue gas, the proportion of mercury oxidation increased. Efficiency of mercury removal by fabric filter and

electrostatic precipitator is related to absorption of mercury by fly ash particles, carbon content of fly ash, gas composition and chlorine and sulfur content in coal.

Xu *et al.*, 2017 studied the local effects of coal power plants on inorganic mercury and the distribution of methylmercury in rice and the amount of mercury accumulated in the soil. This study shows that the emission of mercury from a coal-fired power plant can increase the amount of mercury (Hg^{2+}) and methylmercury of rice. Mercury in the form of methylmercury found in rice was found to be 1.7 to 3.8 $\mu\text{g}/\text{kg}$, and for mercury oxidation, mercury contained in rice was 2 to 22 $\mu\text{g}/\text{kg}$. The mercury content of soil was 68 to 220 $\mu\text{g}/\text{kg}$.

Zhang *et al.*, 2008 studied mercury emissions from 6 coal power plants in China found that power plants with Electrostatic Precipitator systems emitted elemental mercury rather than oxidized mercury. For power plants equipped with Fabric Filters, elemental mercury is less than oxidized mercury. While particle-bound mercury is removed in both electrostatic precipitator and fabric filters. The fabric filters system is more effective in the removal of elemental mercury and the oxidation of mercury than the electrostatic precipitator. Elemental mercury and oxidized mercury were removed in the flue gas by wet flue gas desulfurization systems were 78.0% and 3.14% respectively. While the original mercury in the coal was removed 8.94% by wet flue gas desulfurization systems. The mercury removal efficiency of electrostatic precipitator, fabric filters systems and electrostatic precipitator combined wet flue gas desulfurization systems were 11.5%, 52.3% and 13.7%. During the combustion process, mercury is first released in the form of elemental mercury. Then when the temperature drops, some of the elemental mercury is converted into oxidized mercury. If the concentration of oxygen in the fabric filter is increased from 7.1% to 8.8%, the oxygen concentration is excessive. This may promote direct or indirect mercury oxidation on other reactors. For elemental mercury and oxidized mercury, mercury is adsorbed by fly ash, where the adsorption is correlated with unburned carbon. In the study of mercury in coal, the mercury was found in coal from 0.01 ppm to 0.28 ppm and mercury is present in bottom ash, about 0.02% to 1.2%.

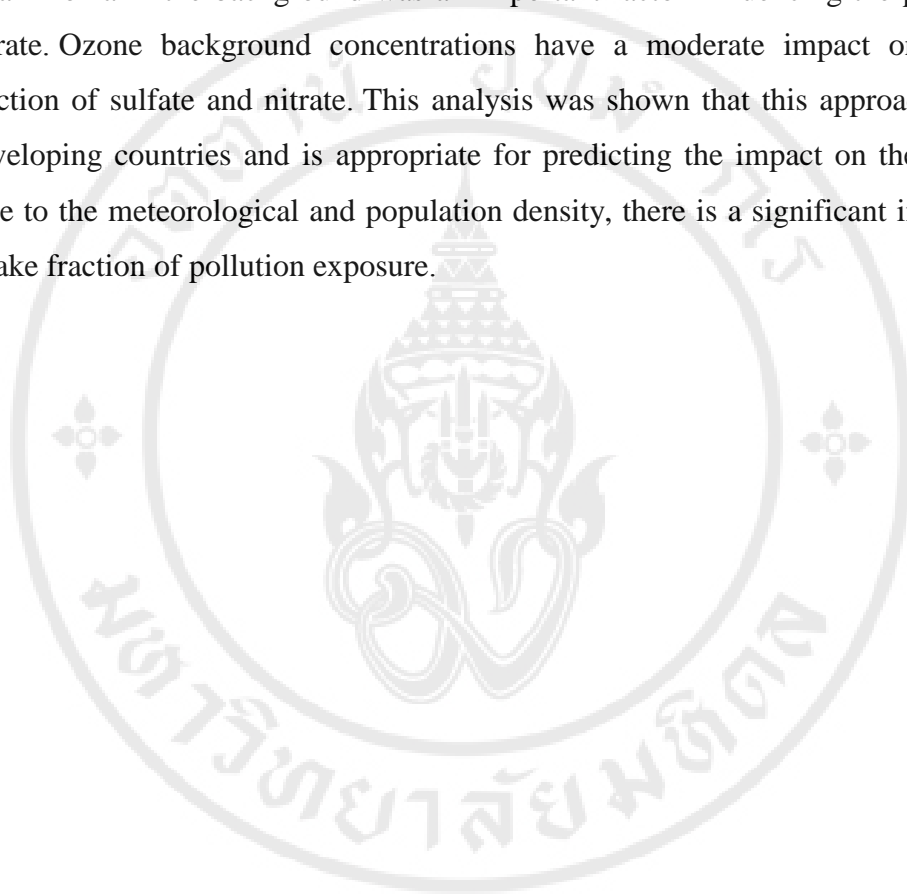
Zhao *et al.*, 2017 studied the release of mercury in coal-fired fuels by field tests of 100%, 85% and 68%. In the combustion of 350 MW of coal, various types of coal are used, and there are selective catalytic reduction (SCR), electrostatic

precipitator and fabric filter (ESP + FF) and wet flue gas desulfurization (WFGD) by using Ontario Hydro Method for mercury samples at the entrance and exit of each air pollution control unit. The results show that the mercury content of the system or each of the control devices is in the range of 70 % to 130 %. SCR can eliminate mercury vapor (Hg^0), an element of effective oxidation, of 50.13 % to 67.68 %. For ESP + FF, 99.95% to 99.99% of mercury (Hg_p) was removed by adding halogen or oxidant to change the form of mercury vapor (Hg^0) and inhibitor Mercury vapor release the wet electrostatic precipitator (WESP) was introduced.

Zhuang *et al.*, 2011 studied the relationship of mercury, sulfur oxide and injection of activated carbon in coal fuel gas. Effect of mercury capture of activated carbon in coal gas. The level of sulfur trioxide can be changed by varied the humidity from 8.5% to 21%, the temperature from 177 °C to 121 °C and the amount of sodium flume injected into the fuel gas. Simultaneously, the release of mercury emission in the activated carbon before entering the electrostatic precipitator was evaluated under the change of sulfur trioxide concentration. This concentration of Sulfur trioxide is used to condense. The experiments showed that sodium fume injections prove that the amount of sulfur trioxide generated can effectively prevent the removal of mercury from activated carbon in coal fuel gas. While aerosol of sulfur trioxide, such as mist of sulfuric acid, has less effect on the efficiency of activated carbon. The low concentration of sulfur trioxide in the fuel gases is a decrease in temperature. Adding humidity or increase the absorption of Sulfur trioxide, such as sodium injection. It can increase the efficiency of mercury capture with activated carbon. It was found that the activated carbon was 0.08 g/m³ and vapor of sulfur trioxide was 28 ppm. The mercury was removed by only 20% while the sulfur trioxide decreased by 3.2 ppm and the amount of activated carbon is the same. The mercury removal was increased to 40 percent as a result of reducing the gas temperature to 121 °C, and reducing the vapor concentration of sulfur trioxide to 1.6 ppm was reduced the efficiency of mercury up to 80%.

Zhou *et al.*, 2014 studied the risk assessment for exposure to various pollutants. This case study was shown that the proportion of emission from power plants in China can be calculated using a detailed long-range atmospheric dispersion model (CALPUFF). They found that the primary particle size was about 10⁻⁵ while the

fraction of sulfur dioxide and sulfate was in the order of 10^{-6} . These estimates are a higher priority than those of the US and tested how important the test results are to the key assumptions within the model. The distribution of primary particles had a significant impact on the intake fraction for primary particles, while the concentration of ammonia in the background was an important factor influencing the proportion of nitrate. Ozone background concentrations have a moderate impact on the intake fraction of sulfate and nitrate. This analysis was shown that this approach applies to developing countries and is appropriate for predicting the impact on the population. Due to the meteorological and population density, there is a significant impact on the intake fraction of pollution exposure.



CHAPTER III

METHODOLOGY

3.1 Location

3.1.1 Mae Moh coal-fired power plant, Lampang

Mae Moh coal-fired power plant is a heat power plant and base load plant with the use of lignite as fuel. About away 616 km from Bangkok, located at Mae Moh subdistrict, Mae Moh district, Lampang province. The area is approximately 1.66 km² which is divided into 0.34 km² of electricity and transport, 0.39 km² of the building area, 0.55 km² of the green area and the other area is 0.38 km². Electricity production capacity of 10 power plants totaling 2,400 MW including of production units 4-7 units, 150 MWs and production units 8-13 units, 300 MWs. The Mae Moh coal-fired power plant has a total of 13 power plants, with unit 1-3 has been discharged from the system since 1 October 2003 and has been demolished since July 2011.

This study evaluated mercury concentrations from ten sources and seventeen sources using the 7th generation electricity unit, which has UTM (X,Y) at 579.413 km and 2023.124 km as the center. The locations of source and receptor are as shown in Figure 3.1, Table 3.1 and Table 3.2.

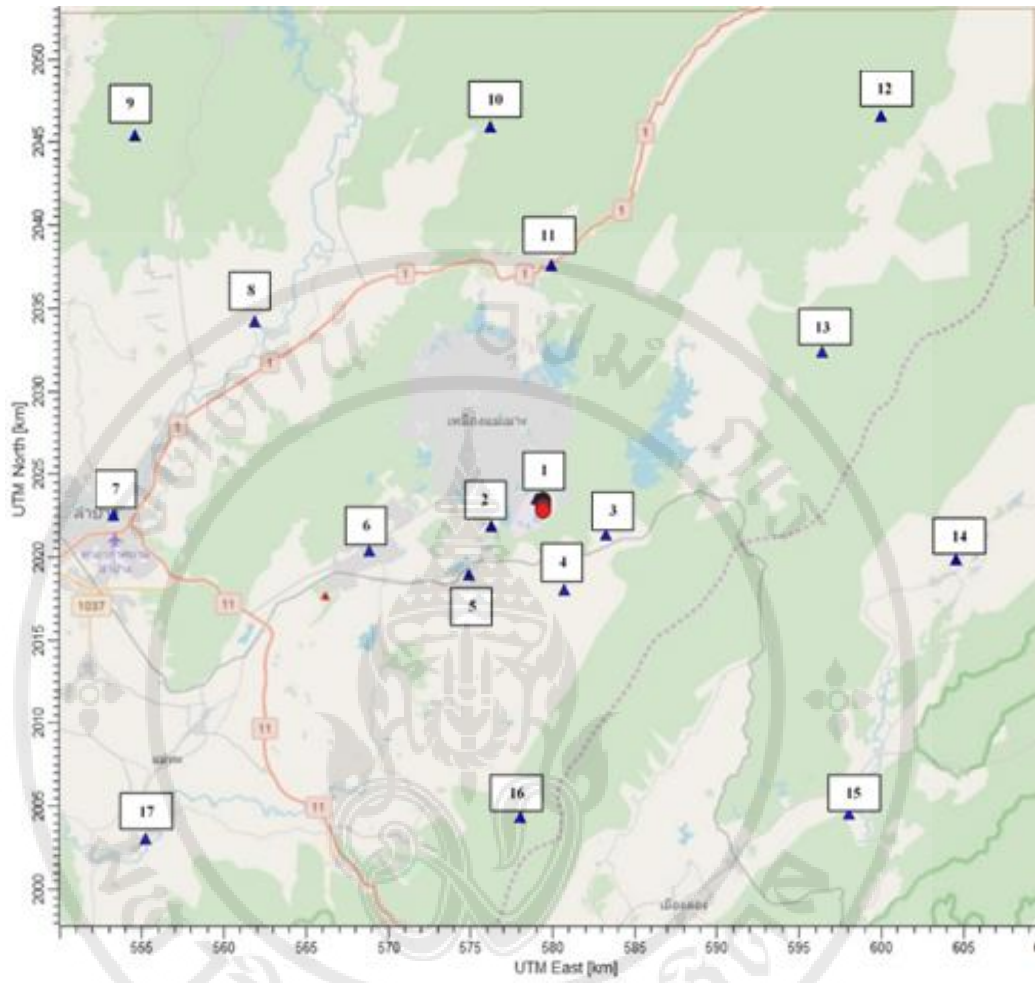


Figure 3.1 Location of source and receptors

Table 3.1 Emission of sources characteristic

Emission Source	Geographical location (UTM:km)		Stack			
	X	Y	height (m)	temperature (°C)	velocity (m/s ²)	diameter (m)
Unit 1	579.391	2023.469	155	103.78	20.81	5.9
Unit 2	579.394	2023.411	155	103.78	20.81	5.9
Unit 3	579.388	2023.351	155	106.49	20.91	5.9
Unit 4	579.419	2023.289	155	106.49	20.91	5.9
Unit 5	579.245	2023.216	150	92.22	22.16	5.75
Unit 6	579.413	2023.124	150	61.98	20.28	5.75
Unit 7	579.416	2023.035	150	85.8	21.59	5.75
Unit 8	579.420	2022.946	150	83.86	21.42	5.75
Unit 9	579.413	2022.815	155	78.63	18.6	5.9
Unit 10	579.421	2022.807	155	77.7	18.72	5.9

Table 3.2 List of receptors

Receptor	Geographical location (UTM:km)		Distance from Reference (km)	Direct from power plant
	X	Y		
Mae Moh Office	579.052	2023.538	0.65	N
Hang Hung SatthaTham temple	576.314	2021.882	3.63	W
Ban Mae Jang school	583.289	2021.343	4.30	E
Ban Sop Pat Health Center	580.692	2018.013	5.44	SE
Sob MohWittaya school	574.947	2018.985	5.94	SW
Maemoh hospital	568.862	2020.422	10.92	SW
Muang Lampang District office	553.277	2022.531	26.06	W

Table 3.2 List of receptors (cont.)

Receptor	Geographical location (UTM:km)		Distance from Reference (km)	Direct from power plant
	X	Y		
Mountain area	561.896	2034.193	20.78	NW
Mountain area	554.561	2045.438	33.51	NW
Mountain area	576.235	2045.927	23.22	N
Ban Tha Si Health Center	579.944	2037.595	14.64	N
Mountain area	600.028	2046.579	31.36	NE
Mountain area	596.443	2032.401	19.44	NE
Ban Lao school	604.544	2019.886	25.43	E
Mountain area	598.072	2004.535	26.31	SE
Mountain area	578.028	2004.372	18.81	S
Mountain area	552.134	2003.068	34.41	SW
Mae Moh Power Plant	579.413	2023.124	0.00	-

3.2 Data Collection

Data collection is an important to emission data and dispersion calculation, including pollutant in the air.

3.2.1 Emission Data

Mercury emission data from coal-fired power plant were obtained from analysis of alternative options for the installation of pollution control systems and mercury control options in each of scenario of the iPOG models and the data required for the CALPUFF model is mercury emission which shown in Appendix.

3.2.2 Meteorological Data

The WRF meteorological model were used to simulate surface data, including hourly wind speed, wind direction, elevation, cell height, temperature, cloud cover, surface pressure and relative humidity.

3.3 Treatment of data

3.3.1 iPOG model

Mercury emission is obtained from the scenarios of the iPOG model, where the emission of mercury depends on the characteristic of the coal, power plant capacity, method to reduce mercury content in coal pollution control system is installed and efficiency. The basic information of Mae Moh coal-fired power plant is shown in the Appendix. An example of scenarios analysis is shown in the table 3.3

Table 3.3 Example of scenarios analysis

Scenarios	Changing of emission (%)	Changing of ambient concentration (%)
1. No ESP + WFGD	+94	+48
2. No ESP	+69.2	+30
Base data (ESP + WFGD)		
3. ESP + WFGD + Washing	-2.8	-1
4. ESP + WFGD + ACI	-30.8	-10
5. ESP + WFGD + ACI + Cl addition	-41	-12

3.3.2 CALPUFF Model

The mercury emission of the coal-fired power plant was analyzed for the most appropriate scenarios. The amount of mercury emission into the environment is compared with the Ambient Air Quality Criteria (AAQCSs) of harmful air pollutants

for the purpose of reducing the risk to human health of mercury (mercury vapor), which gives an average of 24 hours for health effect less than $2 \times 10^3 \text{ ng/m}^3$, $30 \times 10^3 \text{ ng/m}^3$ of mercury emissions from stack and guideline value of hazardous air pollutant in ambient air for the purpose of reduction of human health risk: Mercury (Mercury vapor) is not exceeding 40 ng/m^3 (annual average value).

3.4 Model Configuration

3.4.1 iPOG Configuration

The iPOG model was used to assess the emission of the stack in two types.

- 1) Unit 4-7 Furnace Rating (MW_e) 150
- 2) Unit 8-13 Furnace Rating (MW_e) 300

The economizer O_2 3.5%, LOI 1%, ESP efficiency 98%, Limestone wet FGD efficiency 90% and the use of lignite. The basis and characteristics of the coal are shown in the Appendix.

3.4.2 CALPUFF Configuration

The CALPUFF model is used in this research. The CALMET and CALPUFF models use the EPA approved version (version 5.8.5) and the CALPOST model uses the EPA approved version (version 6.221) to determine the mercury concentration in the environment. The creation of the CALPUFF model system consists of three main parts: CALMET, CALPUFF, and the post-processing and graphical display format. Information of the model configuration were set as follows;

Grid Center Coordinate

- Latitude $18^{\circ}29'N$
- Longitude $99^{\circ}75'E$

Grid Parameters

- Number of grid points ($n_x=60, n_y=60$)
- Grid resolution ($x=1 \text{ km}, y=1 \text{ km}$)
- Outer grid spacing ($x=60 \text{ km}, y=60 \text{ km}$)

Source Options: There were 10 point source are unit 4-13. The mercury emission rate is in grams per hour (g/hr) and concentration unit is in nanogram per cubic meter (ng/m³).

Receptor Options: Table 3.2 shows the data of 17 receptors.

Meteorology Options: Meteorological data used data from the WRF-processed meteorological data

Dispersion Options: The dispersion coefficient of mercury pollution was calculated as an average of 24 hours and 1 year.

Terrain Options: the gridded data required by CALMET was selected based on the Data Elevation Model (DEM) data and topographic elevations terrain data during the Shuttle radar topography Mission (SRTM₃ 90 m).

Land Use Categories (LUC): The land use data provided by CALMET was used in the Global Land Cover Characterization data set in Eurasia (optimized for Asia). For the grid-averaged land use category that are calculated as a default values of surface characteristics using the 1 km resolution.

3.5 Model Simulation Frameworks

3.5.1 iPOG Model Simulation Frameworks

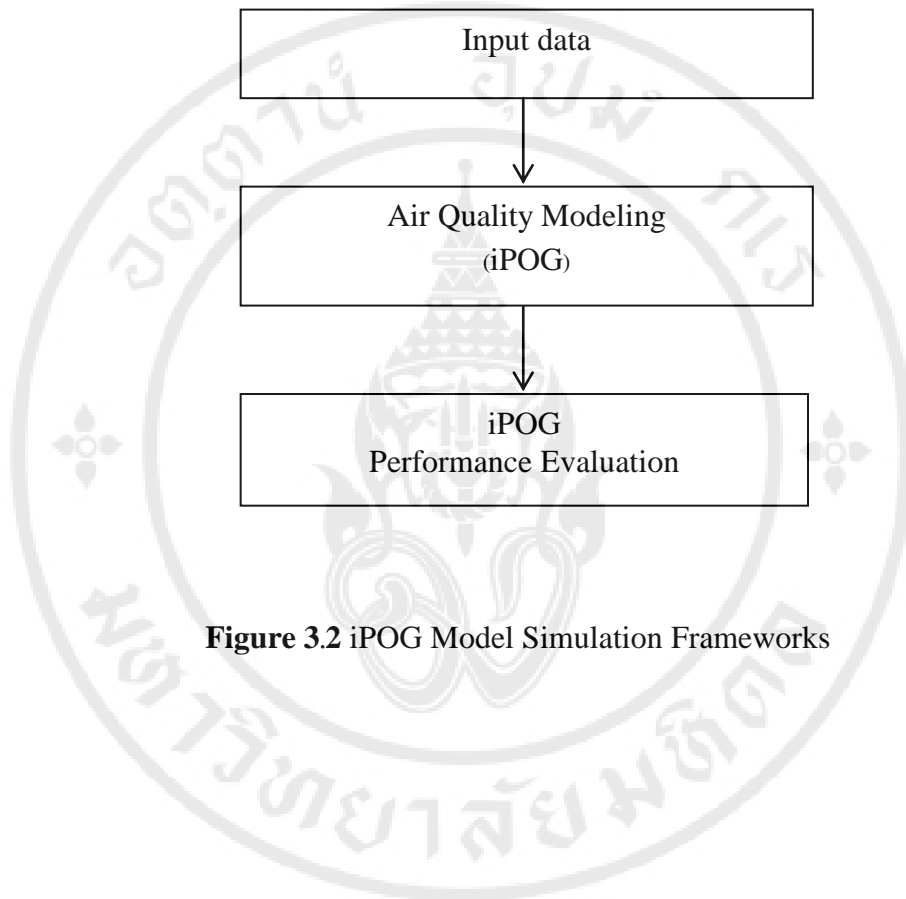


Figure 3.2 iPOG Model Simulation Frameworks

3.5.2 CALPUFF Model Simulation Frameworks

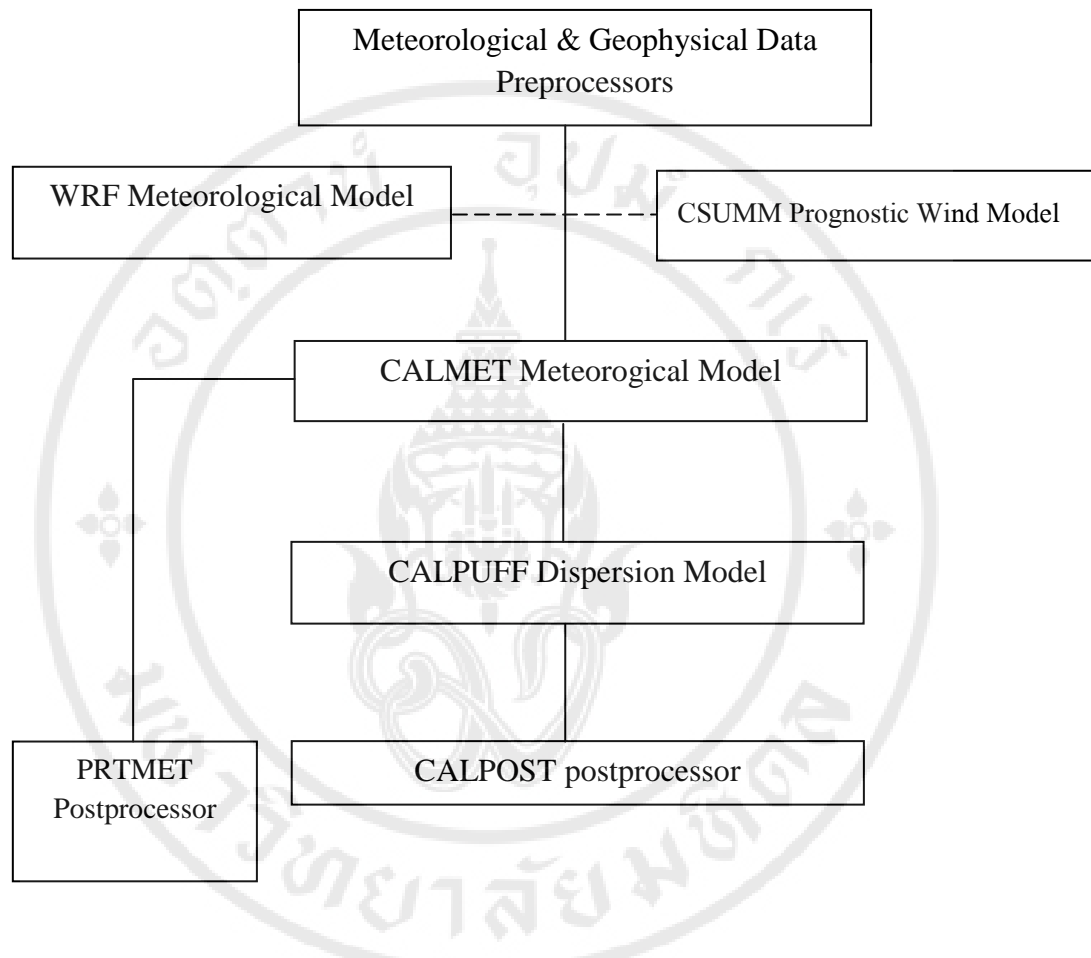


Figure 3.3 CALPUFF Model Simulation Frameworks

CHAPTER IV

RESULTS AND DISCUSSION

In this chapter, mercury release is calculated using the iPOG model, with mercury released from the source at the Mae Moh coal plant in Thailand. The results showed that the efficiency of mercury removal in each situation is expressed as an increase or decrease in the amount by comparing with the amount of mercury released in the current situation by predicting the mercury drainage into the environment from Mae Moh Coal-fired power plant, Lampang.

The results were divided into 4 scenarios.

Scenario 1 Modifications to the installation of pollution control devices and mercury options

Scenario 2 Existing + adding pollution control devices or coal cleaning

Scenario 3 Existing + air pollution control devices (SCR, ESP, ACI installation).

Scenario 4 Without existing air pollution control devices.

Scenario 5 Existing + Furnace condition (LOI, bottom ash, coal blend properties)

The situations were shown in Figures 4.1, 4.2, 4.3, 4.4, 4.5, respectively.

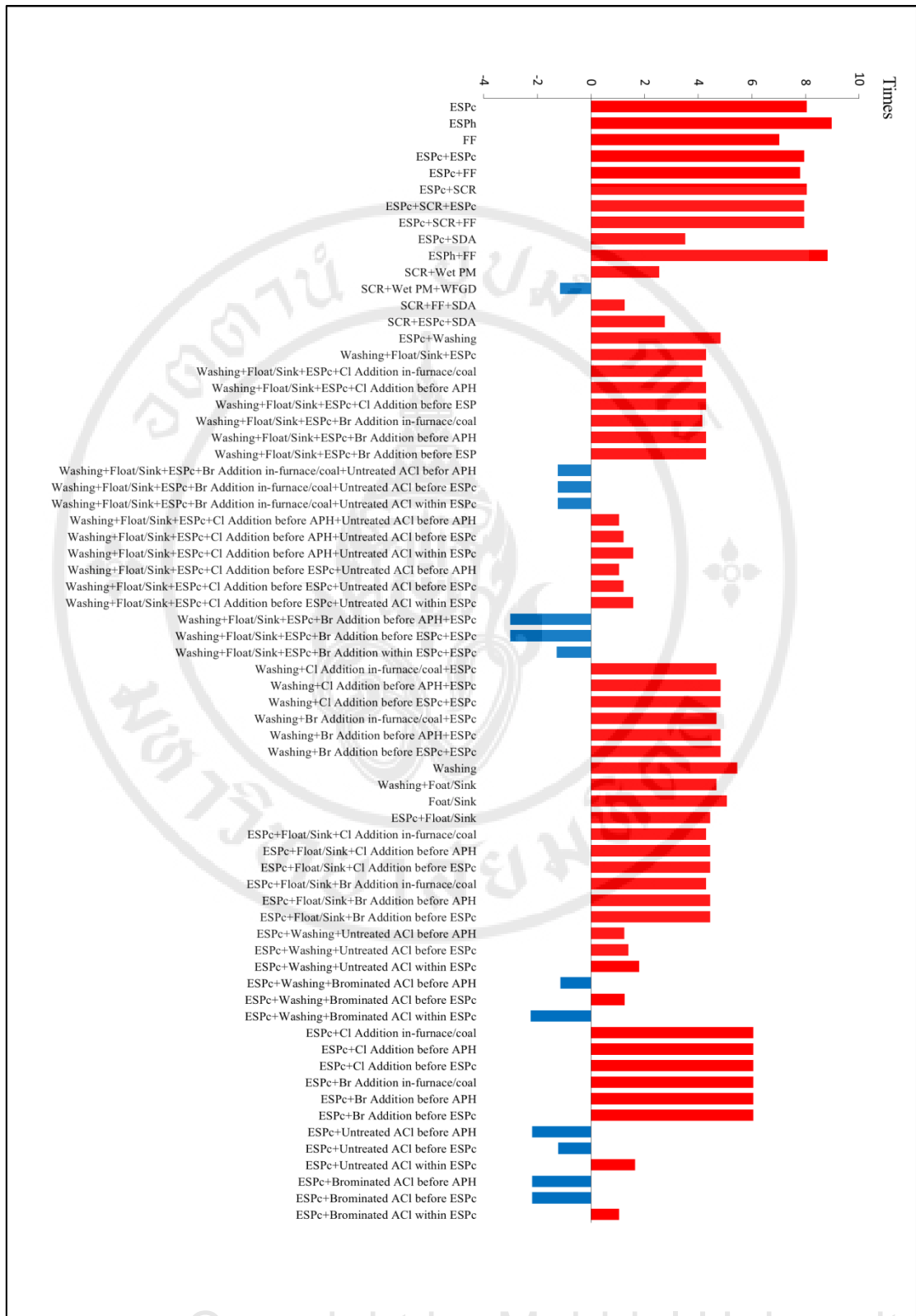


Figure 4.1 Pollution control devices installation and options to reduce mercury.

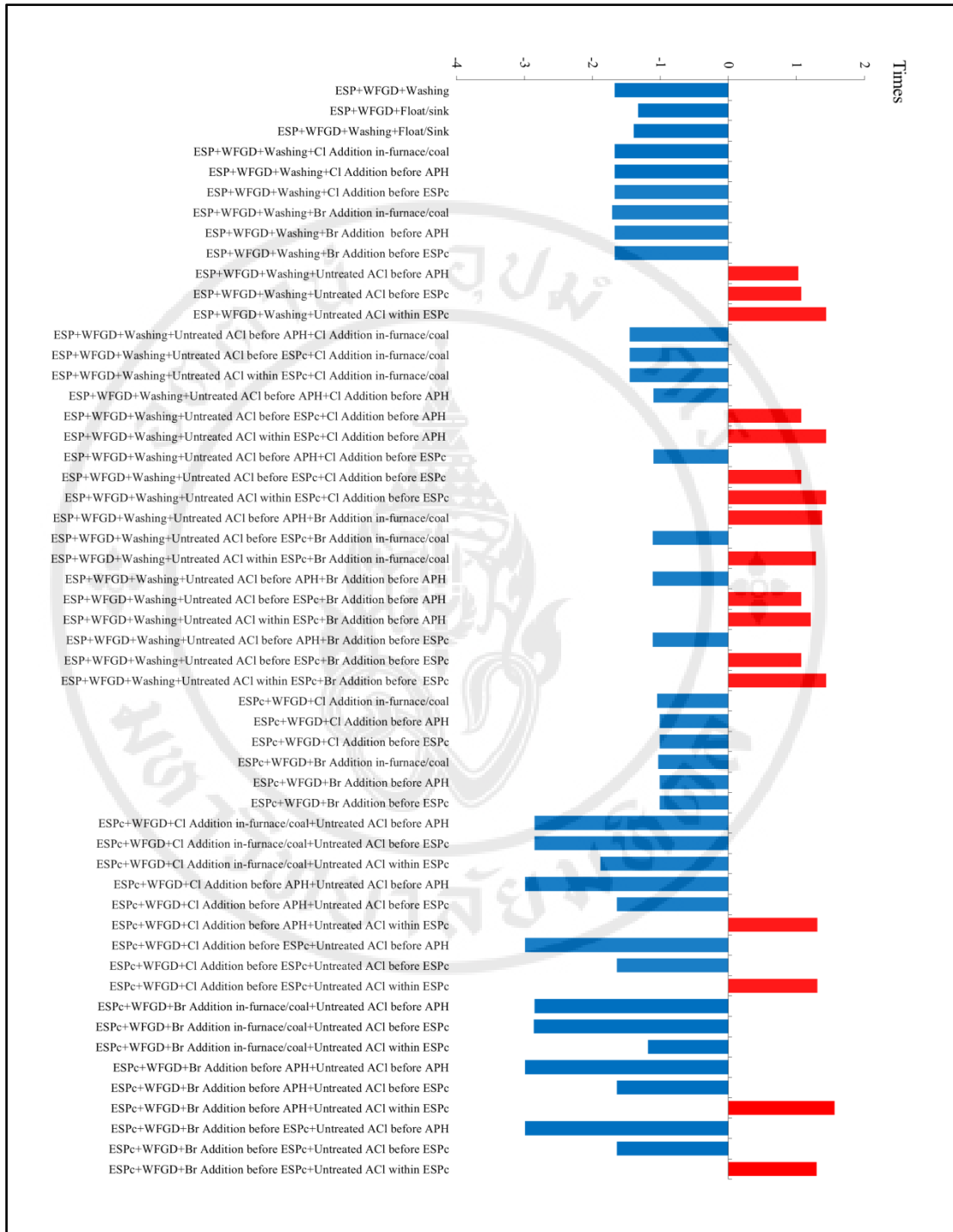


Figure 4.2 Existing + adding pollution control devices or coal cleaning

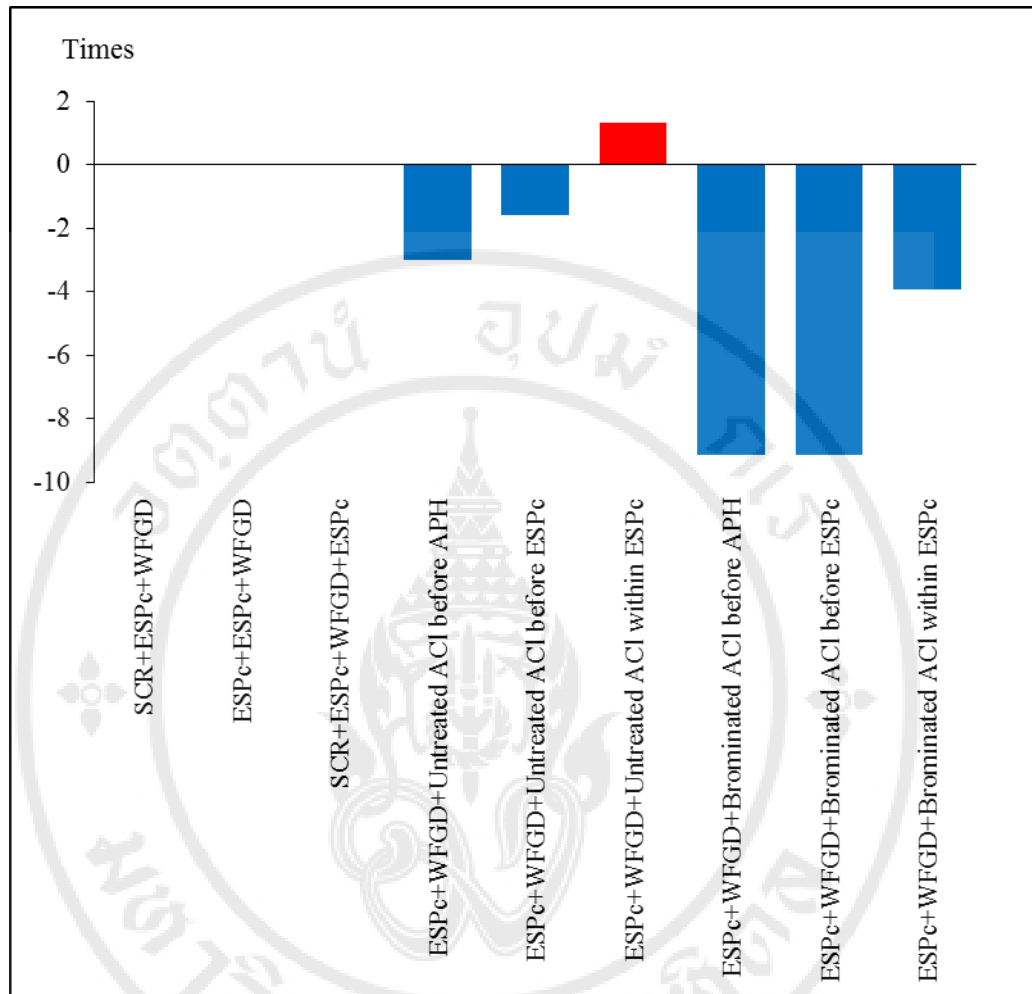


Figure 4.3 Existing + air pollution control devices (SCR, ESP, ACI installation).

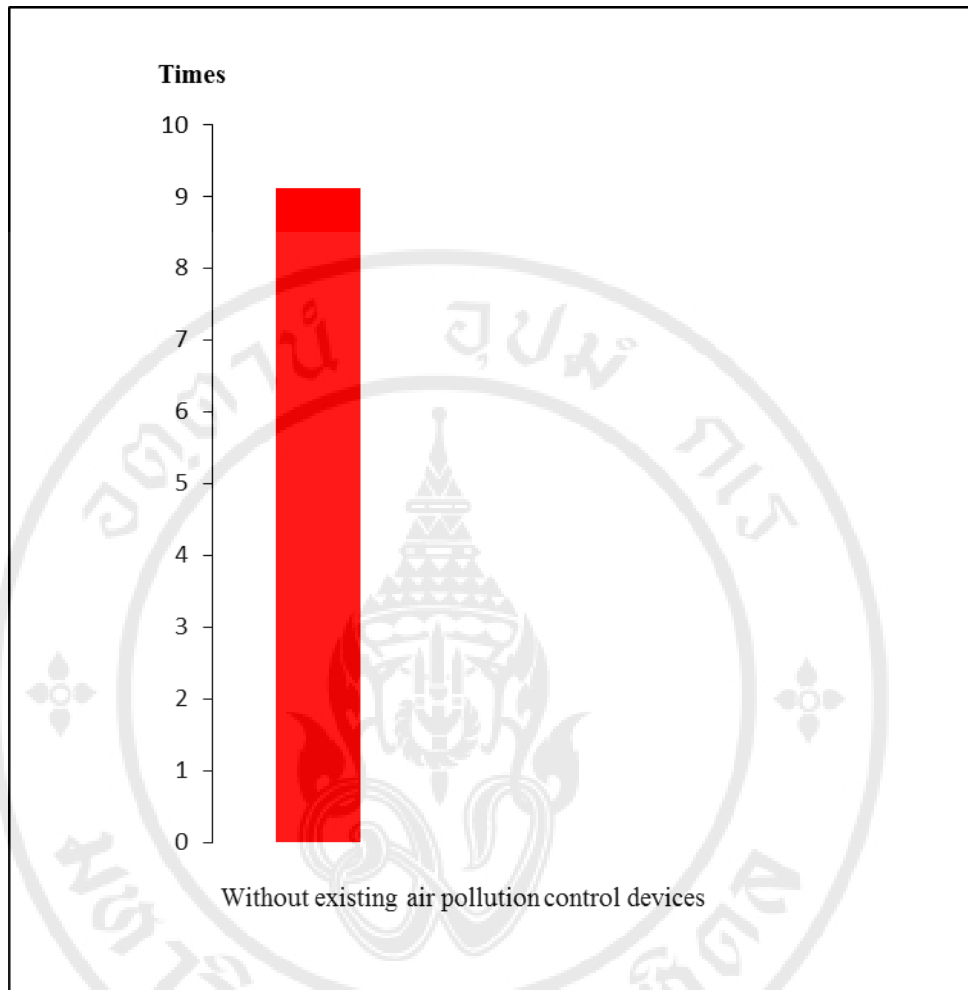


Figure 4.4 Without existing air pollution control devices.

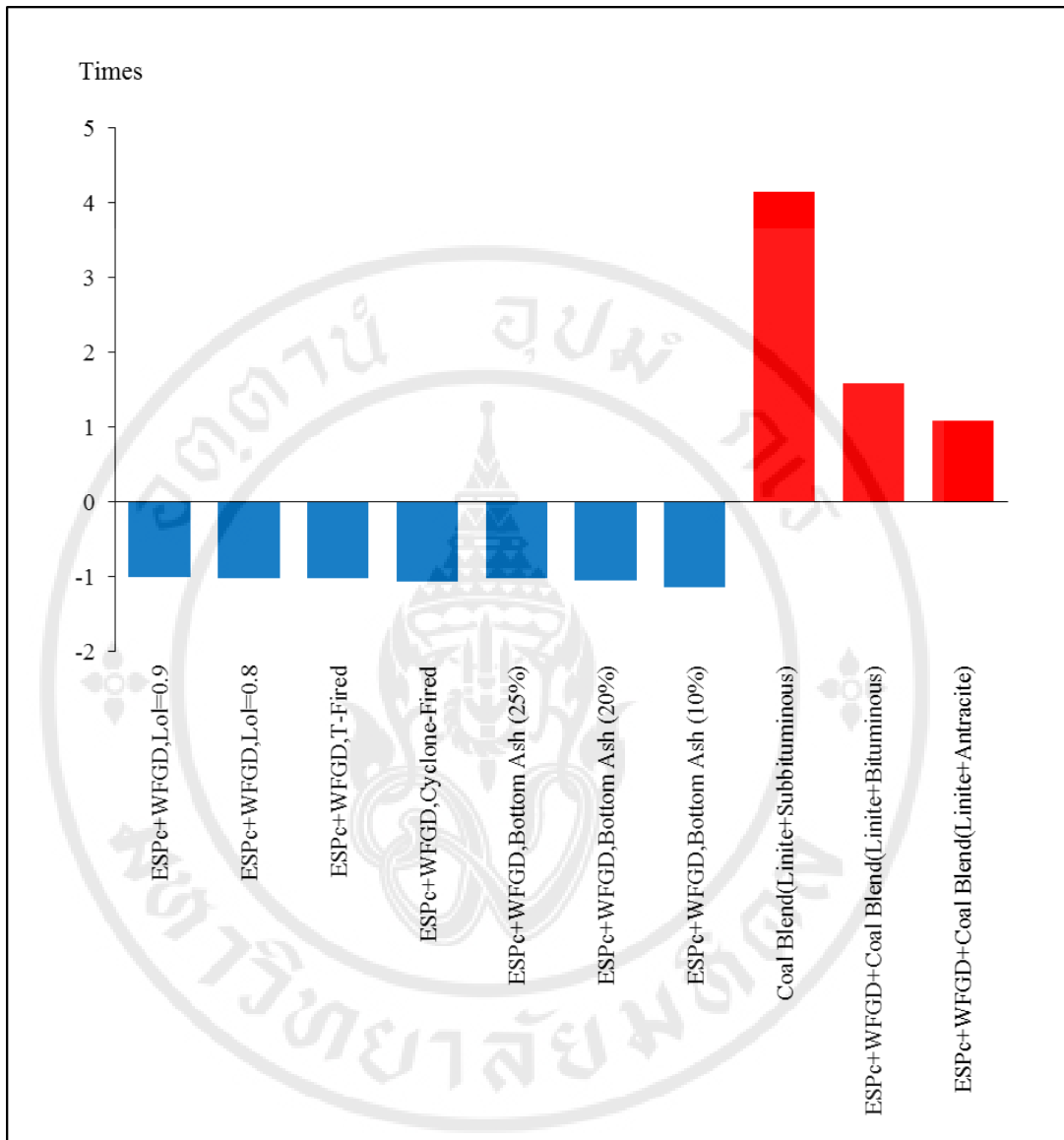


Figure 4.5 Existing + Furnace condition (LOI, bottom ash, coal blend properties)

For the first scenario, most situations result in increased mercury emission from the current situation. For example, the installation of ESPh, ESPh + FF and ESPh only causes mercury emission to increase by 8.98, 8.83 and 8.05 times, according to sequence from the current drainage data, however, there are situations where mercury emission is reduced, such as installing selective catalytic together with wet PM and wet flue gas desulfurization (WFGD), coal washing together with Float/Sink and air pollution control devices (electrostatic precipitator and activated carbon injection) and bromine injection in the furnace or coal, coal washing together with Float/Sink and air

pollution control devices (electrostatic precipitator) and bromine injection before ESPc, coal washing together with air pollution control devices (electrostatic precipitator and activated carbon injection) or adding activated carbon injection to ESPc that reduced mercury drainage from 1.16, 1.24, 3.01, 1.14 and 1.22 times, respectively. The amount of mercury emission that is reduced due to the installation of tools is a device that is commonly used for controlling mercury emission in general.

For the second scenario, the situation has reduced mercury emission than in the case of increasing mercury emission. The most significant change in the situation that caused the increase of mercury drainage was adding activated carbon injection and bromine to air pollution control devices (ESPc and WFGD), which increased the amount of mercury drainage by 1.56 times from the current drainage data. In the case of reducing mercury emission from the current data, increasing the injection of chlorine to air pollution control devices (ESPc, WFGD and untreated activated carbon injection) that reduced mercury emission from 2.99 times due to the use of halogen (Cl_2 , Br_2) can increase the effectiveness of co-benefits of air pollution control devices toward reduction of mercury emission.

For scenario 3, the change in pollutant load has both original and decreased. The situation that caused the most change in the way that was reduced was 9.15 times by adding brominated activated carbon injection to air pollution control devices (ESPc and WFGD) due to ACI technology can reduce mercury in the form of Hg^0 , which results in mercury emission in the form of Hg^{2+} up to 80%. In addition, ACI technology is also a technology that specifically uses mercury removal. In addition, the Mae Moh renewable power plant unit 4-7 has increased the installation of selective catalytic reduction (SCR). However, in this research, the installation of the SCR does not cause changes in mercury emission. For the next situation, in the event that no air pollution control equipment is installed, it is found that mercury drainage has increased to 9.12 times from the current data.

For the final situation, most situations caused the reduction of mercury, which is a situation caused by changing the type of furnace and changing the percentage of bottom ash, but coal blending causes mercury to increase because lignite coal in Mae Moh mine is a high quality coal with high chlorine peroxide, resulting in

more mercury capture which the amount of chloride will be exceeding the speed limit emissions of mercury.

In addition, the results show that the average concentration of mercury in each year of the selected situation shows the different variations of mercury dispersion in the environment by choosing 6 situations were ESPc+WFGD installation situation, ESPc+WFGD and coal washing situation, ESPc+WFGD+Cl addition in-furnace/coal installation situation, ESPc+WFGD+Brominated ACI before ESPc installation situation, ESPc+WFGD+bottom ash 20% and the absence of the installation of air pollution control equipment. The mercury concentration difference of each situation is shown in Figure 4.6-4.17 and the concentration of the grid compared to the international standards shown in Table 4.1.

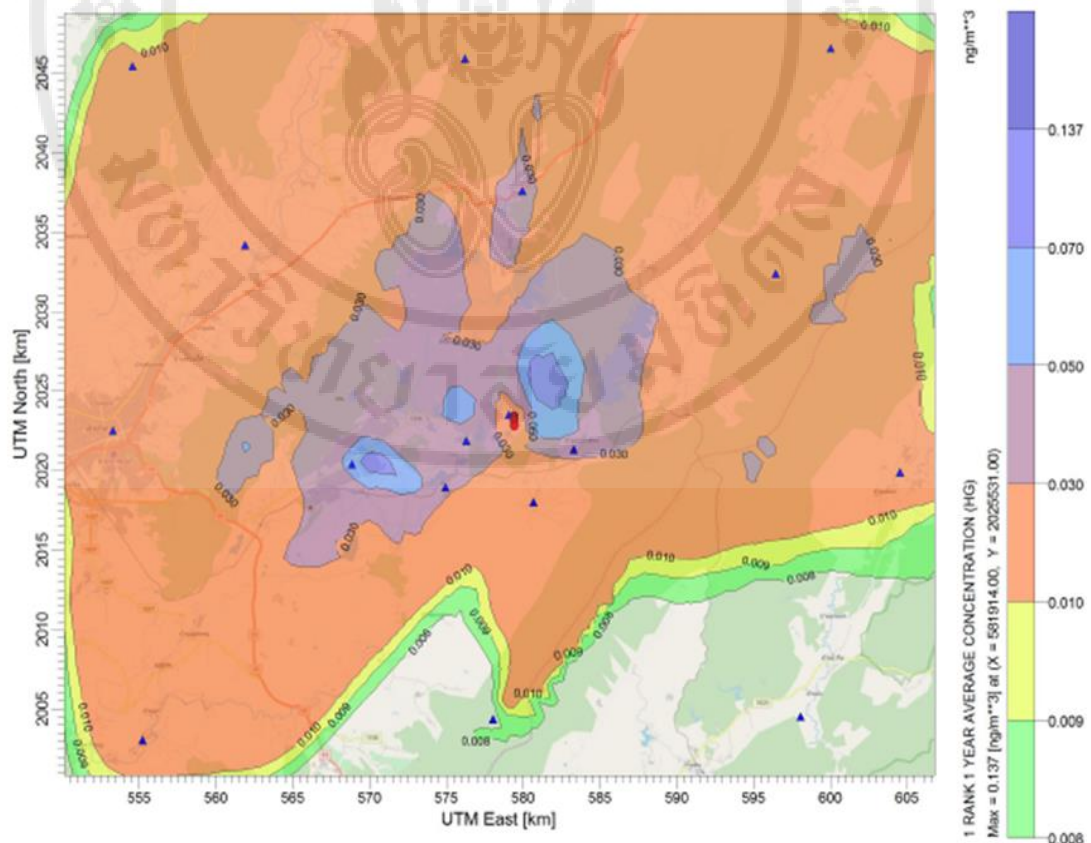


Figure 4.6 Annual average mercury concentration (ng/m^3) of ESPc+WFGD case (baseline scenarios)

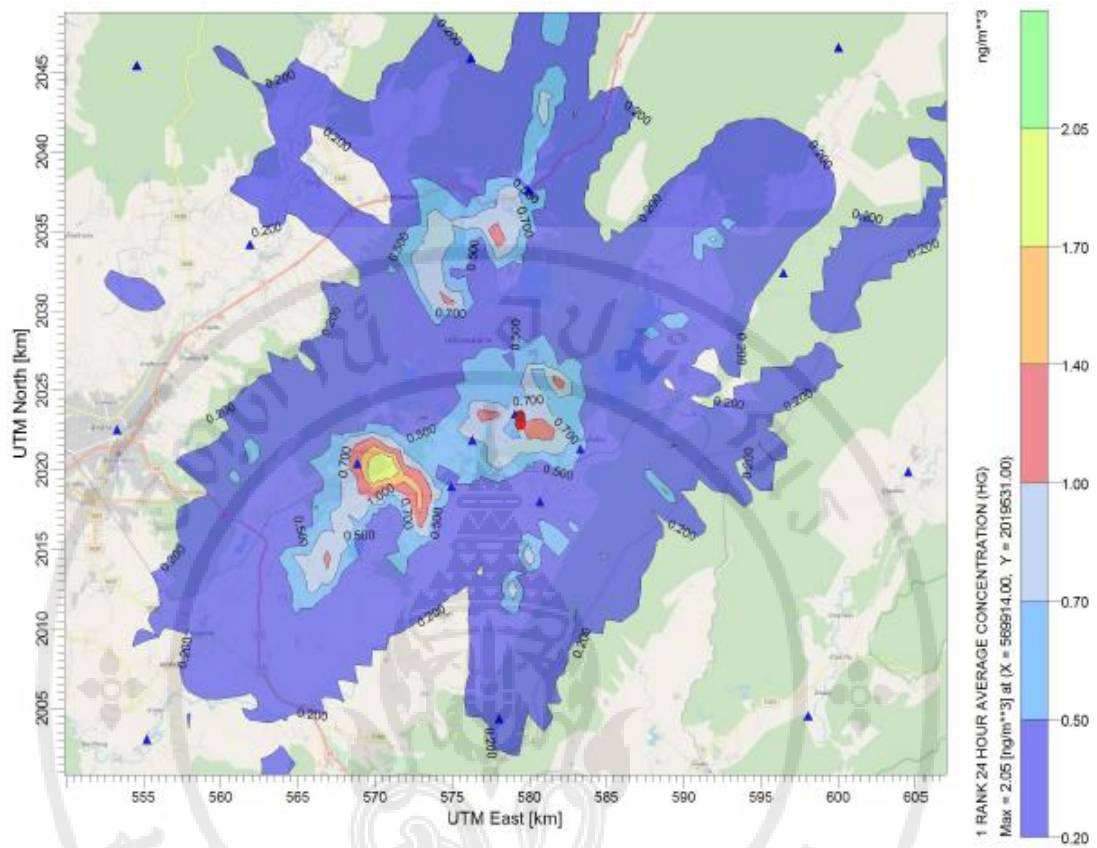


Figure 4.7 24 hours average mercury concentration (ng/m³) of ESPc+WFGD case (baseline scenarios)

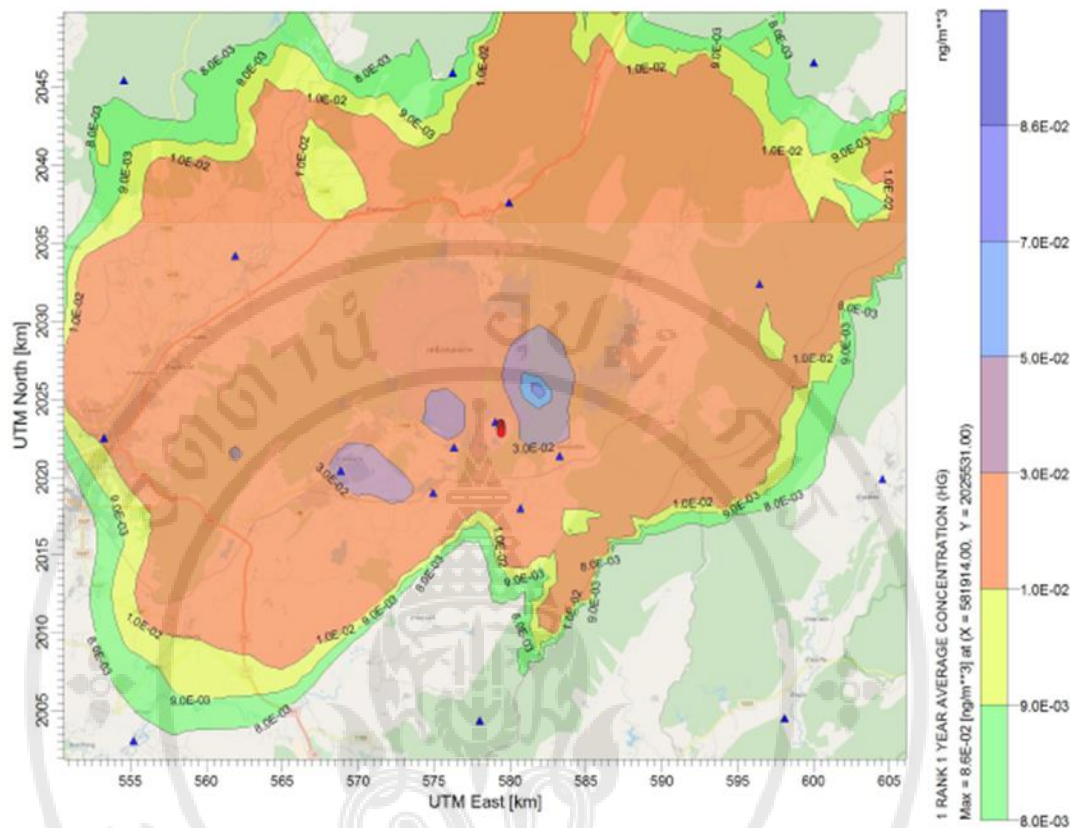


Figure 4.8 Annual average mercury concentration (ng/m^3) (ESPc+WFGD and coal washing scenario)

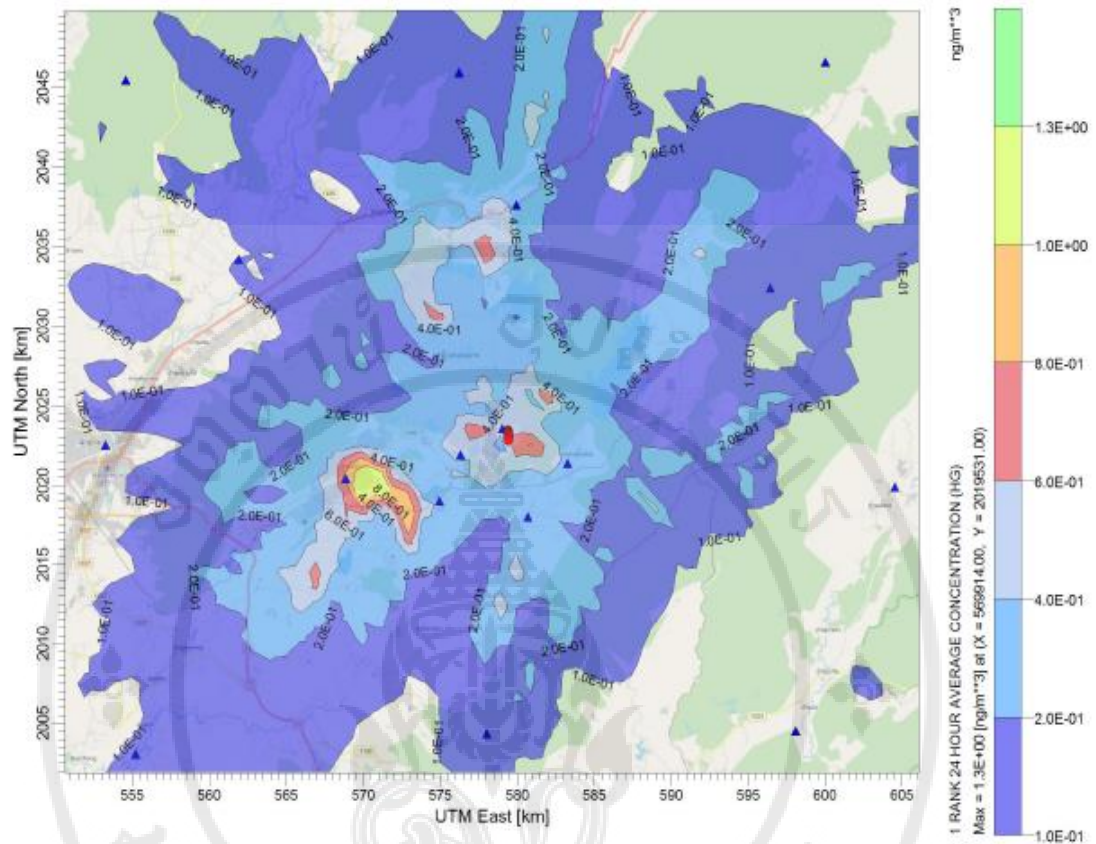


Figure 4.9 24 hours average mercury concentration (ng/m^3) (ESPc+WFGD and coal washing scenario)

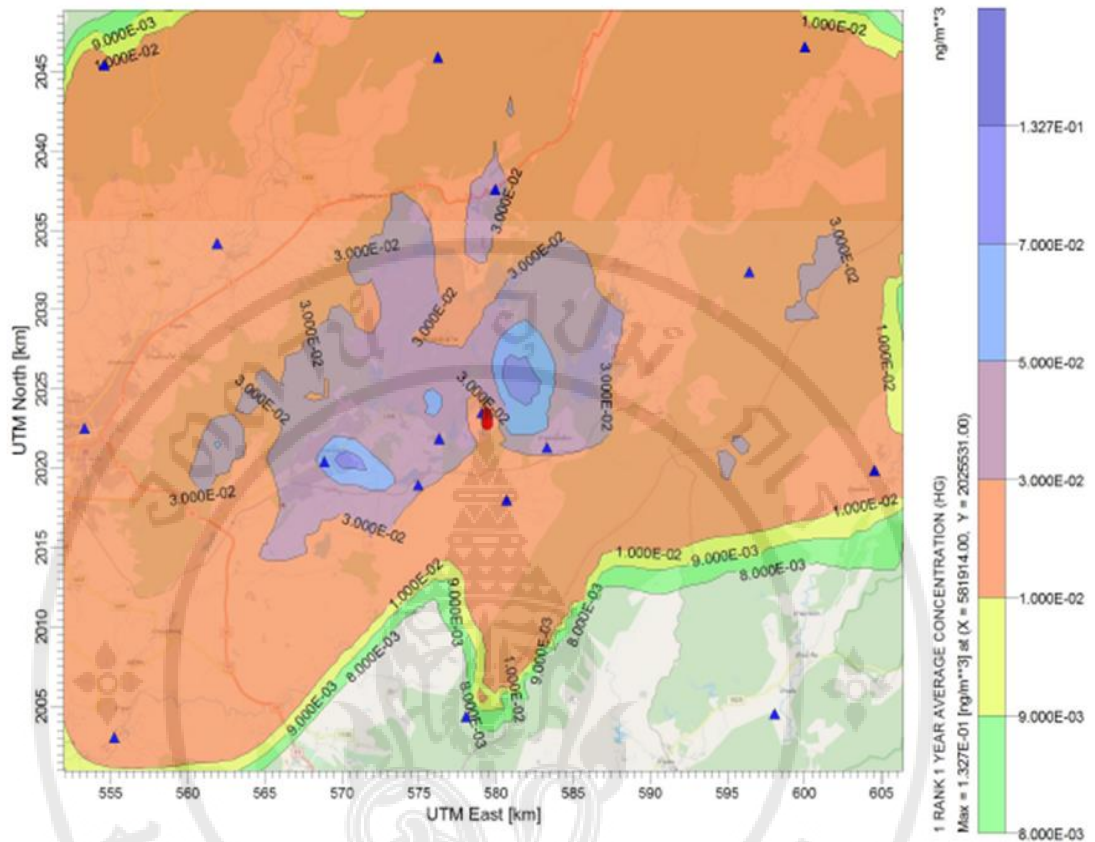


Figure 4.10 Annual average mercury concentration (ng/m^3) (ESPc+WFGD+Cl addition in-furnace/coal scenario)

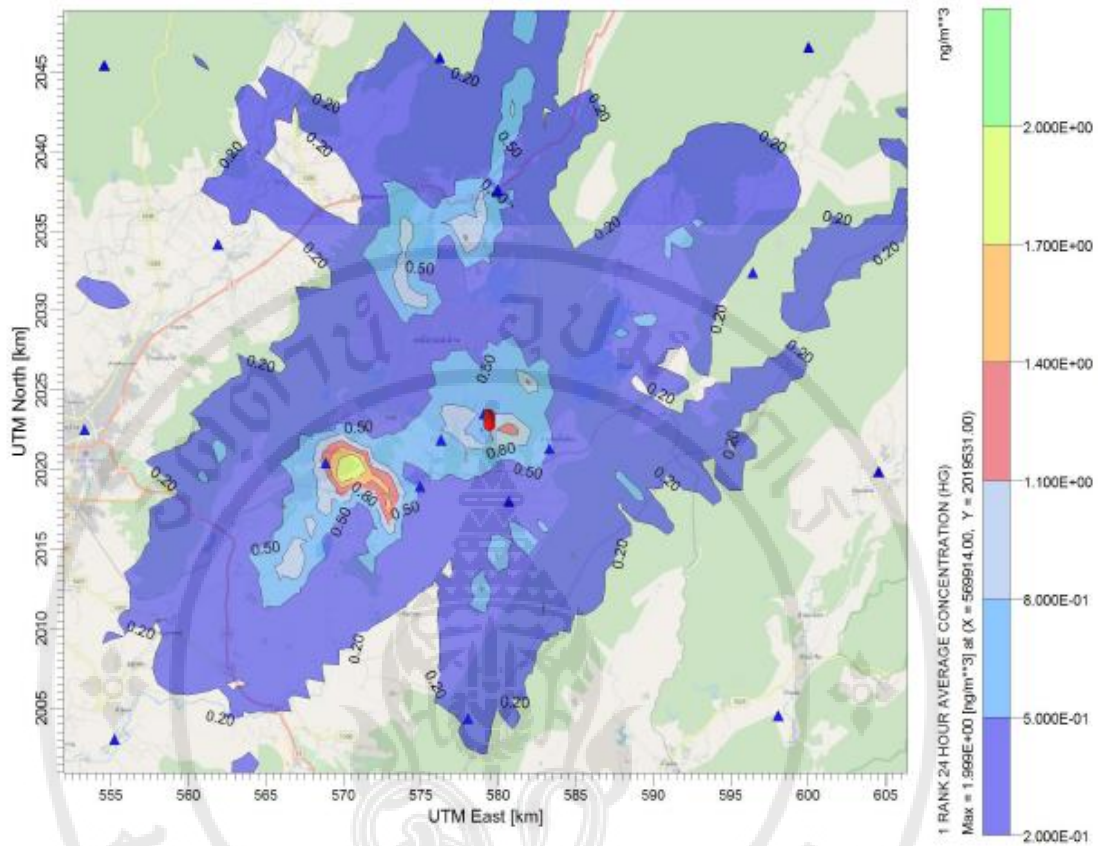


Figure 4.11 24 hours average mercury concentration (ng/m^3) (ESPc+WFGD+Cl addition in-furnace/coal scenario)

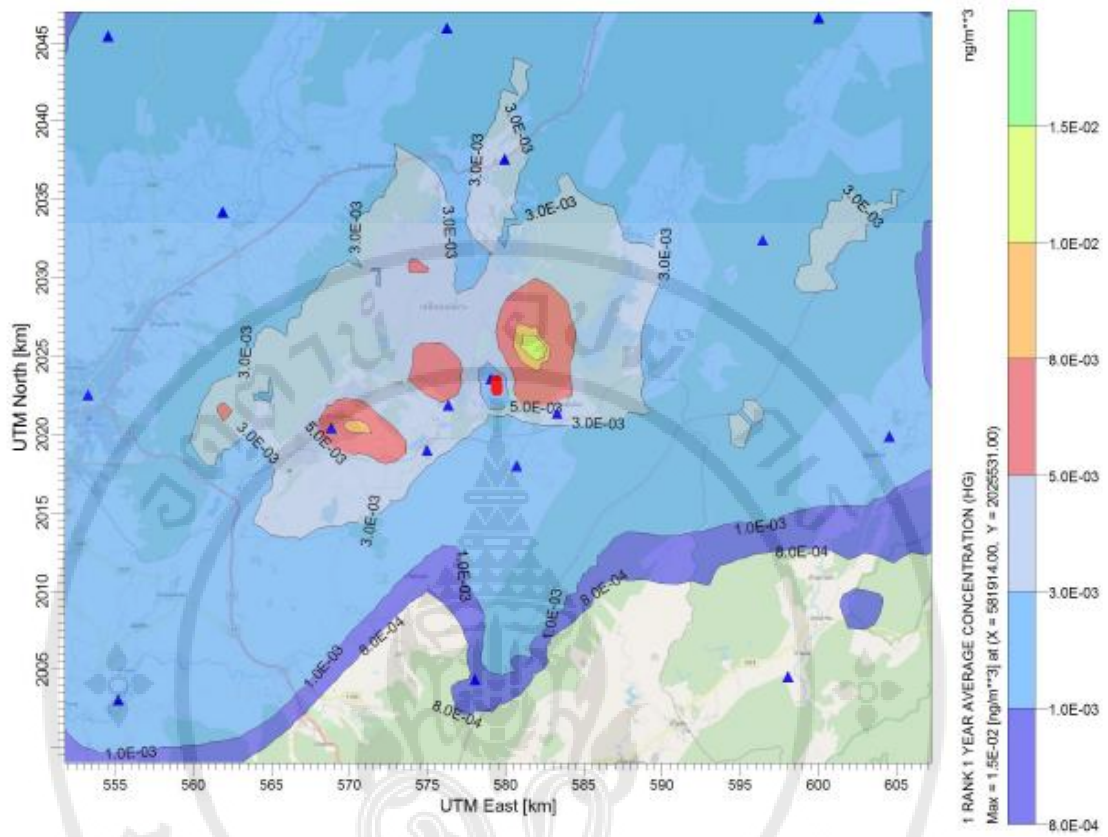


Figure 4.12 Annual average mercury concentration (ng/m^3) (ESPc+WFGD+Brominated ACI before ESP scenario)

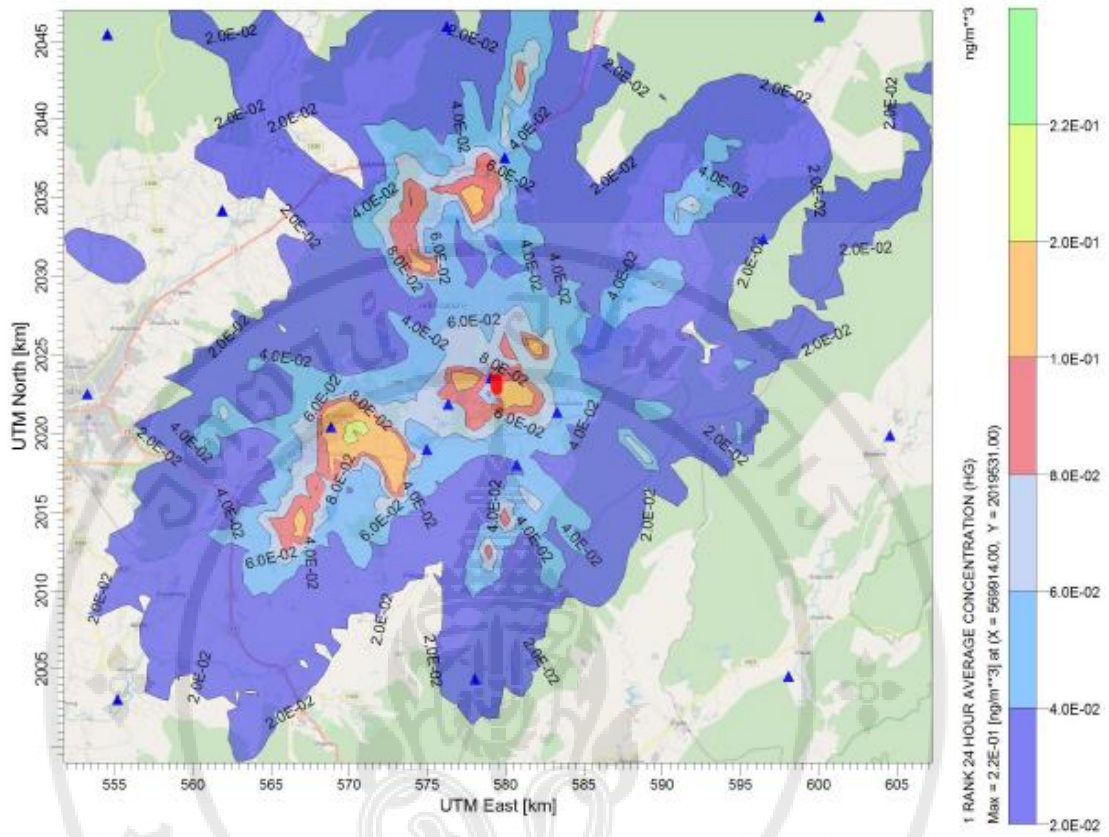


Figure 4.13 24 hours average mercury concentration (ng/m^3) (ESPc+WFGD+Brominated ACI before ESP scenario)

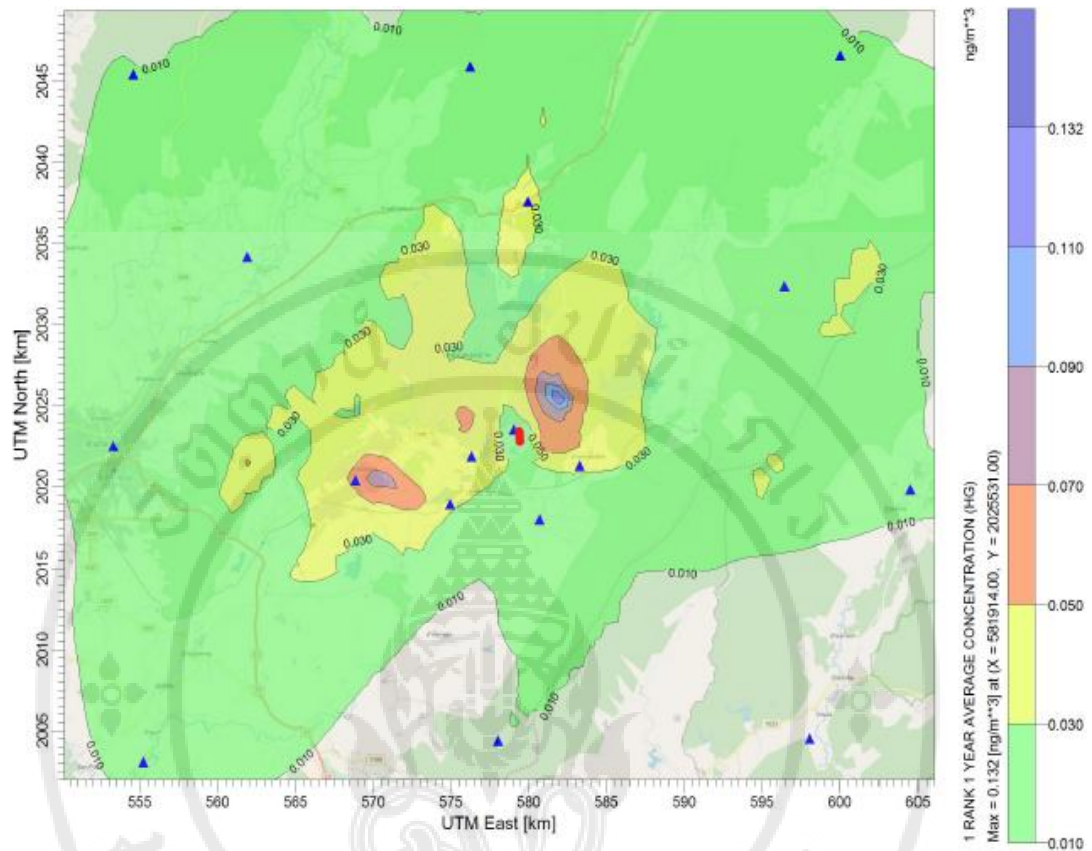


Figure 4.14 Annual average mercury concentration (ng/m^3) (ESPc+WFGD+bottom ash 20% scenario)

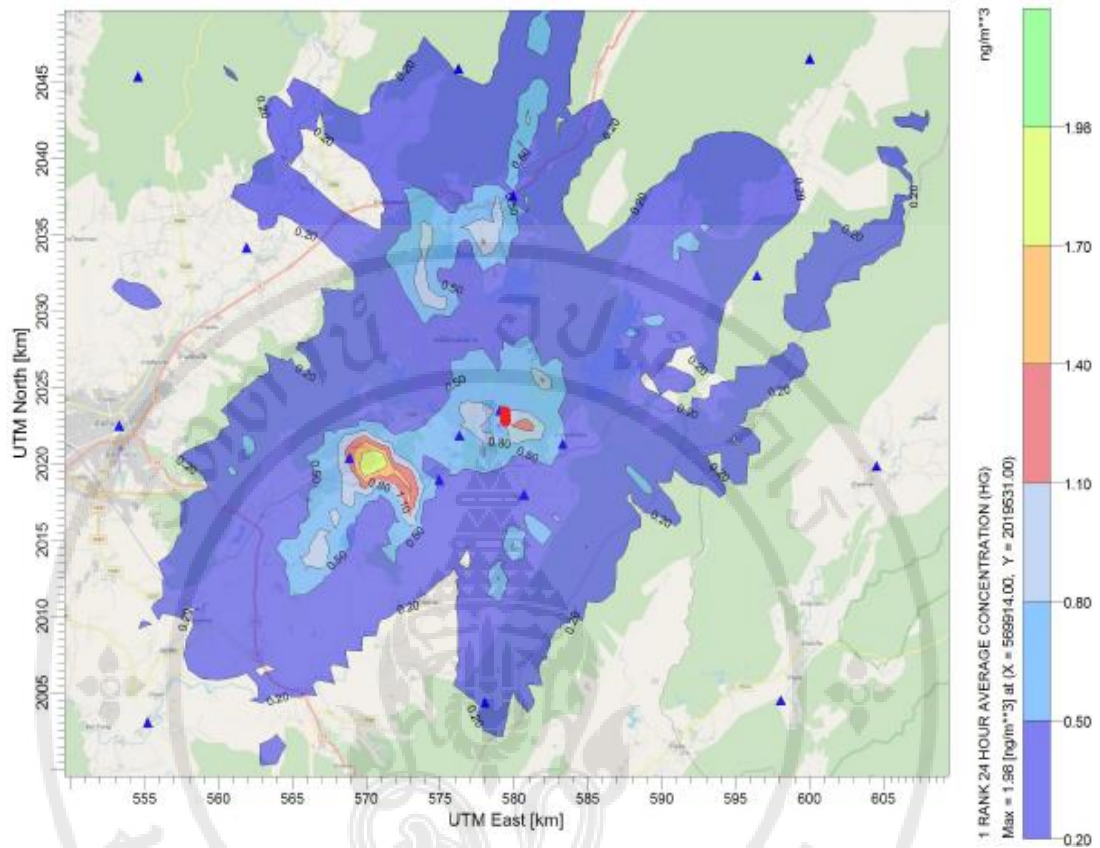


Figure 4.15 24 hours average mercury concentration (ng/m^3) (ESPc+WFGD+bottom ash 20% scenarios)

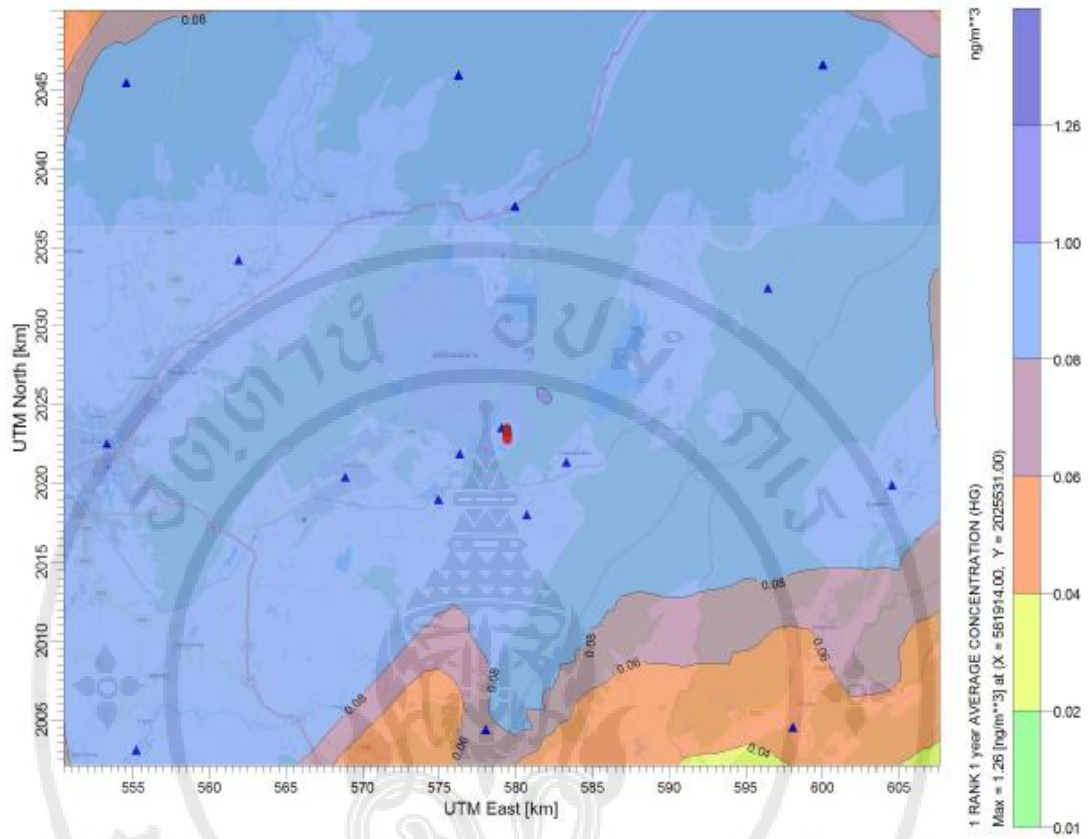


Figure 4.16 Annual average mercury concentration (ng/m³) (without existing air pollution control devices)

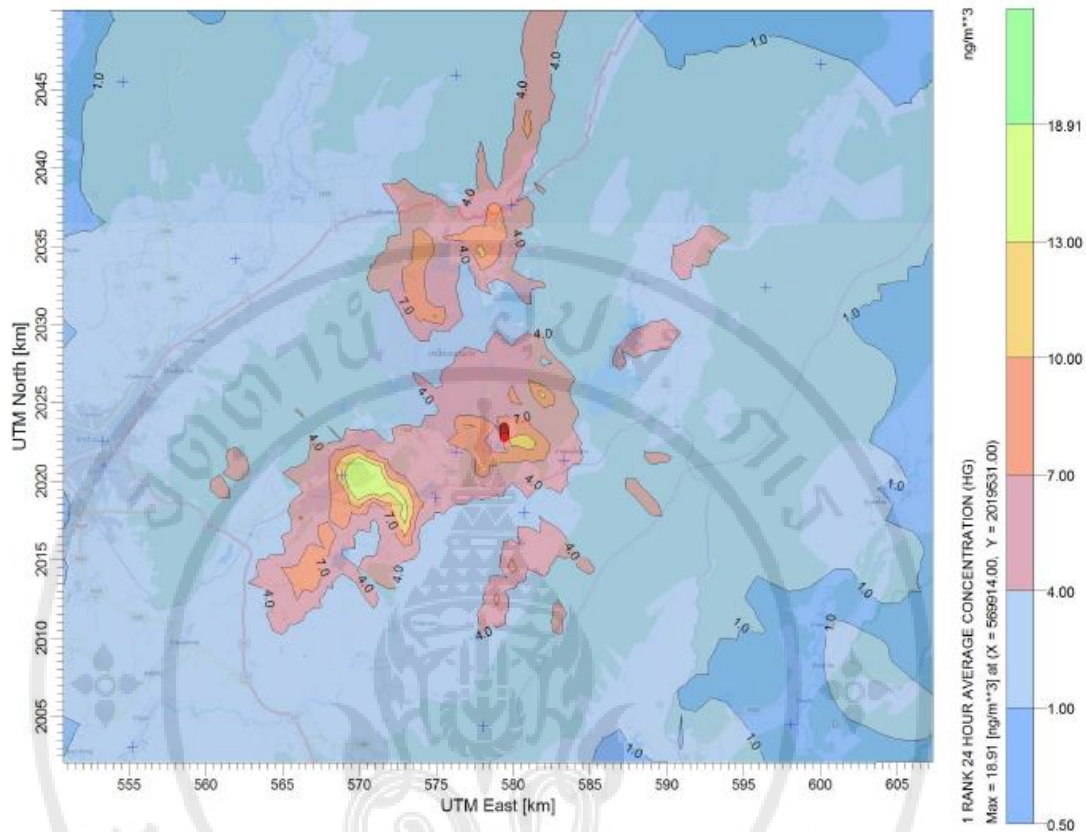


Figure 4.17 24 hours average mercury concentration (ng/m^3) (without existing air pollution control devices)

Table 4.1 Comparison of mercury concentration with different standards.

Scenarios	Japan 40 ng/m ³ (annual average)	Ontario 2×10 ³ ng/m ³ (24 hours average)	China (30×10 ³ ng/m ³)
No control Technology (24 hr,1 year = 18.91 ng/m ³ ,1.26 ng/m ³)	×	×	×
ESPC+WFGD (baseline) (24 hr,1 year = 2.05 ng/m ³ ,0.14 ng/m ³)	×	×	×
ESPC+WFGD and coal washing (24 hr,1 year = 1.29 ng/m ³ ,0.09 ng/m ³)	×	×	×
ESPC+WFGD+CI addition in-furnace/coal (24 hr,1 year = 2.0 ng/m ³ ,0.13 ng/m ³)	×	×	×
ESPC+WFGD+ Brominated ACI before ESP or APH (24 hr,1 year = 0.22 ng/m ³ ,0.01 ng/m ³)	×	×	×
ESPC+WFGD+bottom ash 20% (24 hr,1 year = 1.98 ng/m ³ ,0.13ng/m ³)	×	×	×

Note: × = Not exceeding the standard value

✓ = Beyond the standard value

The study found that the situation of adding brominated ACI before air pollution control devices (ESPc+WFGD) and adding coal washing to air pollution control devices (ESPc+WFGD) could reduce the concentration of mercury in the atmosphere to a similar level, almost 50% from the current situation. The situation that reduces mercury concentrations in atmospheres is most likely in the situation where adding ACI to air pollution control devices (ESPc+WFGD), but considering the cost side, the situation where the ESPc+WFGD and coal washing and ESPc+WFGD+Cl addition in-furnace/coal installation is suitable for the Mae-Moh coal-fired power plant because is cheaper and can reduce the mercury emission and concentration in the atmosphere. In addition, in the future, Mae-Moh coal-fired power plant has planned to install SCR additions from current pollution control equipment to help increase control of other pollutants. However, such situations for research do not help to reduce the amount of mercury emission from existing data. For the analysis of the results of all 6 situations, it was found that the concentration in the atmosphere, both the average concentration of 24 hours and yearly, does not exceed the standard value for the concentration in foreign countries.

For evaluate the appropriate scenarios to reduce mercury emissions from Mae Moh coal-fired power plant can be summarized as a change in emission and concentration in the Table 4.2

Table 4.2 Scenarios analysis

scenarios	Changing of emission (times)	Changing of ambient concentrations (%)
No control technology	+ 9.12	821.2
Compared with Base data (ESP + WFGD)		
ESPc + WFGD+ bottom ash 20%	-1.05	3.7
ESP + WFGD + Cl addition in furnace/coal	-1.05	2.9
ESP + WFGD + washing	-1.67	37.2

Table 4.2 Scenarios analysis (cont.)

scenarios	Changing of emission (times)	Changing of ambient concentrations (%)
ESP + WFGD + Brominated ACI before ESPc or APH	-9.15	89.1

This table shows changes in emission compared to changing the concentration of mercury from the selected situation to be evaluated. For example, changing the bottom ash (20%) to air pollution control devices (ESPc+WFGD) or adding Cl to air pollution control devices (ESPc+WFGD), although evenly reducing mercury emissions, but with different mercury concentrations or in the case of ESP+WFGD+ Brominated ACI can reduce concentration of mercury up to 89.05%. In addition, if compared with the cost of installing pollution equipment, which by conducting Ancora's research in 2015 to analyze the economy. Which found that even though the installation of specific mercury control devices, such as ACI, could reduce the amount of mercury as much as possible, however the installation has a high cost compared to other methods that can reduce mercury concentrations similarly like in the case of using halogens injection. However, every situation that is used to determine the concentration of mercury, including the current situation, does not exceed the set standard value, therefore, can use the existing pollution control equipment, but there is a policy to reduce mercury from the original situation. Which increases the washing of coal is another option, besides reducing the mercury concentration in the atmosphere and also having a low cost as well.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Mae Moh Coal Plant, Lampang Province is Thailand's largest power generating plant. The power plants are aware of the pollution that comes from many types of power plants, such as sulfur dioxide (SO₂), Nitrogen dioxide (NO₂), including the mercury vapor produced by the process. Mercury, even when it is low in volume compared to other pollutants, is more likely to have a positive effect on health and the environment. Although the methods of pollution control and effective pollution control equipment, the selection of appropriate pollution control methods and equipment is essential. Due to the availability of appropriate air pollution control equipment, it will help reduce the pollution that will be released into the power plant and can reduce the costs of coal-fired power plant operations. In this study, mercury content was calculated using the iPOG model and mercury dispersion was predicted using the CALPUFF

The iPOG model is used to estimate the amount of mercury released from the Mae Moh coal plant compared to the current emission data of the current situation. The situation of the installation of pollution control equipment, change of installation of pollution control equipment, reduction of mercury in coal or option to reduce mercury.

The CALPUFF model was used to predict the spread of mercury in the Mae Moh coal-fired power plant area in Thailand. The assessment capability of the model was calculated as a mean of 24 hours and annually using the meteorological data in 2017 at the site. In this study, mercury vapor discharge data consisted of 10 sources and 17 receptors

Mercury concentrations were predicted by different scenarios using the CALPUFF model. In this study, six scenarios were set for predicting mercury dispersion.

Scenario 1 ESPc+WFGD installation

Scenario 2 ESPc+WFGD and coal washing installation

Scenario 3 ESPc+WFGD+Cl addition in-furnace/coal
installation

Scenario 4 ESPc+WFGD+Brominated ACI before ESPc
installation

Scenario 5 ESPc+WFGD+bottom ash 20%

Scenario 6 without existing air pollution control devices

5.1 Application of iPOG for simulation of mercury concentration in the study area

iPOG model was evaluated the mercury emission rate and type of mercury from the full-scale gas cleaning system which designed as a model for which users can change the parameters of coal properties, gas cleaning selection, coal blending and cleaning systems including the use of common technologies of gas cleaning systems such as existing pollution control devices for NO_x, PM and SO₂ or mercury-specific control technologies such as halogenation agent, injection carbon sorbents to find effective mercury control and reduce the emission rate of mercury into the air

Prediction of mercury drainage from coal-fired power plants from different situations when compared with existing data, resulting in different amounts of mercury in both incremental and decreasing directions. The method of reducing mercury drainage from the current drainage data is the most, increasing the brominated activated carbon injection to air pollution control device (ESPc and WFGD) which causes the mercury drainage to decrease by 9.15 times from the current emission. In addition, additional ACI installations will help increase mercury removal efficiency. Therefore, this situation is the best option to reduce mercury emissions from coal-fired power plants.

5.2 Application of CALPUFF for simulation of Hg concentration in the study area

CALPUFF is a multi-layer, multi-species, non-steady-state puff dispersion model. CALPUFF is a form of gas and particle diffusion using spatial data, time and meteorological data that can explain a variety of effects (Holmes and Morawska, 2006) and calculates atmospheric distribution from a few kilometers to miles, which can be calculated in hours per hour and wind spatial variations (Scire *et al.*, 2000)

The mercury concentration in the atmosphere predicted by the CALPUFF model shows that the mercury concentration is the highest at the second receiving point of every situation, with a distance of 3.63 km from the Mae Moh thermal power plant. Adding installation brominated ACI to air pollution control devices (ESPc+WFGD) is a situation where mercury concentrations can be reduced as much as possible with the average 24-hour and annual average of the receiver is 0.14 ng/m³ and 0.006 ng/m³, respectively, that is different from the current situation (ESPc+WFGD installation), which has an average concentration of mercury in the atmosphere 24 hours and yearly equal 1.27 ng/m³ and 0.06 ng/m³, respectively. In addition, considering mercury removal along with price considerations, the most appropriate situation for mercury removal in this study is adding coal washing to air pollution control device (ESPc and WFGD), which has an average mercury concentration of 24 hours and annuals, is 0.79 ng/m³ and 0.04 ng/m³, respectively. This method not only reduces the concentration of mercury in the atmosphere but also helps reduce installation costs in order to increase pollution treatment equipment as well.

5.3 Recommendations for further study

Since research does not study economics, if there are further studies in the future, studies should be conducted to analyze the cost-effectiveness of the installation of air pollution control equipment.

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APPENDIX A

DETAIL OF EMISSION SOURCES

Table A-1 Proximate analysis of feed coal (Watchalayann *et al.*, 2018)

% Content (Mean ± SD)		
	Unit 4-7	Unit 8-13
Inherent moisture	15.83±0.44	19.06±1.42
Total moisture	30.57±1.52	32.49±1.47
Volatile Matter	42.58±1.44	43.06±2.06
Ash	32.18±2.57	31.45±4.97
Fixed Carbon	25.24±2.37	25.49±3.47
Carbon (C)	47.55±2.31	1.77±0.10
Hydrogen (H)	48.86±3.27	4.70±1.03
Nitrogen (N)	5.67±0.09	4.46±1.51
Sulfur (S)	6.28±0.41	8.12±1.21
Oxygen (O)	1.78±0.08	7.17±2.34

Table A-2 Chemical analysis of coal (Watchalayann *et al.*, 2018)

Concentration (Mean ± SD)		
	Unit 4-7	Unit 8-13
Chlorine (g/kg)	0.09±0.02	0.15±0.03
Bromine (mg/kg)	ND < 1.00	ND < 1.00
Mercury (µg/kg)	198.78±25.43	132.31±36.33
Arsenic (mg/kg)	411.63±47.43	290.12±46.05
Selenium (mg/kg)	0.76±47.43	1.29±0.20
Barium (g/kg)	0.10±0.03	0.26±0.04

Table A-3 Mercury concentrations in solid/liquid samples and flue gas at each sampling Location (Watchalayann *et al.*, 2018)

Type of sample	Mercury concentrations as dry weight (Mean \pm SD)		
	Unit 4-7	Unit 8-11	Unit 12-13
Pulverized coal ($\mu\text{g}/\text{kg}$)	132.5 \pm 28.46	114.97 \pm 14.28	124.43 \pm 10.09
Sea water-In ($\mu\text{g}/\text{L}$)	NA	NA	NA
Limestone ($\mu\text{g}/\text{kg}$)	75.19 \pm 30.45	48.9 \pm 58.40	54.65 \pm 10.45
Bottom ash ($\mu\text{g}/\text{kg}$)	8.27 \pm 11.18	18.43 \pm 23.62	7.505.66
Fly ash ($\mu\text{g}/\text{kg}$)	22.37 \pm 3.60	18.39 \pm 5.16	34.74 \pm 12.00
Sea water-Out ($\mu\text{g}/\text{kg}$) ^a	NA	NA	NA
Gypsum ($\mu\text{g}/\text{kg}$) ^b	168.92 \pm 38.92	140.69 \pm 8.79	165.98 \pm 45.91
Stack gas ($\mu\text{g}/\text{m}^3$)	7.99 \pm 3.94	9.90 \pm 1.98	5.22 \pm 2.62
-particulate ($\mu\text{g}/\text{m}^3$)	0.01 \pm 0.01	0.03 \pm 0.05	0.02 \pm 0.02
-oxidized Hg ($\mu\text{g}/\text{m}^3$)	0.40 \pm 0.30	0.18 \pm 0.20	0.13 \pm 0.15
-Vapor Hg ($\mu\text{g}/\text{m}^3$)	6.65 \pm 3.88	9.14 \pm 2.04	4.57 \pm 2.54

Note: ^a represents the power plant being installed with the sea water-FGD

^b represents the power plant being installed with the wet-FGD

APPENDIX B

MODEL CONFIGURATIONS

CALMET Parameters

INPUT GROUP: 0 -- Input and Output File Names		
Parameter	Description	Value
GEO DAT	Input file of geophysical data (GEO.DAT)	GEO.DAT
METLST	Output file name of CALMET list file (CALMET.LST)	CALMET.LST
METDAT	Output file name of generated gridded met files (CALMET.DAT)	CALMET.DAT
LCFILES	Lower case file names (T = lower case, F = upper case)	F
NUSTA	Number of upper air stations	0
NOWSTA	Number of overwater stations	0
NM3D	Number of prognostic meteorological data files (3D.DAT)	12
NIGF	Number of IGF-CALMET.DAT files used as initial guess	0

INPUT GROUP: 1 -- General Run Control Parameters		
Parameter	Description	Value
IBYR	Starting year	2017
IBMO	Starting month	1
IBDY	Starting day	1
IBHR	Starting hour	0
IBTZ	Base time zone	-7
IRTYPE	Output run type (0 = wind fields only, 1 = CALPUFF/CALGRID)	1
LCALGRD	Compute CALGRID data fields (T = true, F = false)	T
ITEST	Flag to stop run after setup phase (1 = stop, 2 = run)	2
MREG	Regulatory checks (0 = no checks, 1 = US EPA LRT checks)	0

INPUT GROUP: 2 -- Map Projection and Grid Control Parameters		
Parameter	Description	Value
PMAP	Map projection system	UTM
FEAST	False easting at projection origin (km)	0.0
FNORTH	False northing at projection origin (km)	0.0
IUTMZN	UTM zone (1 to 60)	47
UTMHEM	Hemisphere of UTM projection (N = northern, S = southern)	N
XLAT1	1st standard parallel latitude (decimal degrees)	30N
XLAT2	2nd standard parallel latitude (decimal degrees)	60N
DATUM	Datum-Region for the coordinates	WGS-84
NX	Meteorological grid - number of X grid cells	60
NY	Meteorological grid - number of Y grid cells	60
DGRIDKM	Meteorological grid spacing (km)	1
XORIGKM	Meteorological grid - X coordinate for SW corner (km)	549.4135
YORIGKM	Meteorological grid - Y coordinate for SW corner (km)	1993.0314

INPUT GROUP: 2 – Map Projection and Grid Control Parameters		
Parameter	Description	Value
NZ	Meteorological grid - number of vertical layers	10
ZFACE	Meteorological grid - vertical cell face heights (m)	0.00,20.00,40.00,80.00,160.00,320.00,640.00,1200.00,2000.00,3000.00,4000.00

INPUT GROUP: 3 – Output Options		
Parameter	Description	Value
LSAVE	Save met fields in unformatted output file (T = true, F = false)	T
IFORMO	Type of output file (1 = CALPUFF/CALGRID, 2 = MESOPUFF II)	1
LPRINT	Print met fields (F = false, T = true)	F
IPRINF	Print interval for output wind fields (hours)	1
STABILITY	Print gridded PGT stability classes? (0 = no, 1 = yes)	0
USTAR	Print gridded friction velocities? (0 = no, 1 = yes)	0
MONIN	Print gridded Monin-Obukhov lengths? (0 = no, 1 = yes)	0
MIXHT	Print gridded mixing heights? (0 = no, 1 = yes)	0
WSTAR	Print gridded convective velocity scales? (0 = no, 1 = yes)	0
PRECIP	Print gridded hourly precipitation rates? (0 = no, 1 = yes)	0
SENSHEAT	Print gridded sensible heat fluxes? (0 = no, 1 = yes)	0
CONVZI	Print gridded convective mixing heights? (0 = no, 1 = yes)	0
LDB	Test/debug option: print input met data and internal variables (F = false, T = true)	F
NN1	Test/debug option: first time step to print	1
NN2	Test/debug option: last time step to print	1
LDBCST	Test/debug option: print distance to land internal variables (F = false, T = true)	F
IOUTD	Test/debug option: print control variables for writing winds? (0 = no, 1 = yes)	0
NZPRN2	Test/debug option: number of levels to print starting at the surface	1
IPR0	Test/debug option: print interpolated winds? (0 = no, 1 = yes)	0
IPR1	Test/debug option: print terrain adjusted surface wind? (0 = no, 1 = yes)	0
IPR2	Test/debug option: print smoothed wind and initial divergence fields? (0 = no, 1 = yes)	0
IPR3	Test/debug option: print final wind speed and direction? (0 = no, 1 = yes)	0
IPR4	Test/debug option: print final divergence fields? (0 = no, 1 = yes)	0
IPR5	Test/debug option: print winds after kinematic effects? (0 = no, 1 = yes)	0
IPR6	Test/debug option: print winds after Froude number adjustment? (0 = no, 1 = yes)	0
IPR7	Test/debug option: print winds after slope flow? (0 = no, 1 = yes)	0
IPR8	Test/debug option: print final winds? (0 = no, 1 = yes)	0

INPUT GROUP: 5 – Wind Field Options and Parameters		
Parameter	Description	Value
NINTR2	Maximum number of stations used in each layer for interpolation (NZ values)	10*99
CRITFN	Critical Froude number	1
ALPHA	Empirical factor triggering kinematic effects	0.1
NBAR	Number of barriers to interpolation of the wind fields	0
KBAR	Barrier - level up to which barriers apply (1 to NZ)	10
IDIOPT1	Surface temperature (0 = compute from obs/prognostic, 1 = read from DIAG.DAT)	0
IDIOPT2	Temperature lapse rate used in the computation of terrain-induced circulations (0 = compute from obs/prognostic, 1 = read from DIAG.DAT)	0
ZUPT	Depth through which the domain-scale lapse rate is computed (m)	200
IDIOPT3	Initial guess field winds (0 = compute from obs/prognostic, 1 = read from DIAG.DAT)	0
IUPWND	Upper air station to use for domain-scale winds	-1
ZUPWND	Bottom and top of layer through which the domain-scale winds are computed (m)	1.0, 1.00
IDIOPT4	Read observed surface wind components (0 = from SURF.DAT, 1 = from DIAG.DAT)	0
IDIOPT5	Read observed upper wind components (0 = from UPn.DAT, 1 = from DIAG.DAT)	0
LLBREZE	Use Lake Breeze module (T = true, F = false)	F
NBOX	Lake Breeze - number of regions	0

INPUT GROUP: 6 – Mixing Height, Temperature and Precipitation Parameters		
Parameter	Description	Value
CONSTB	Mixing height constant: neutral, mechanical equation	1.41
CONSTE	Mixing height constant: convective equation	0.15
CONSTN	Mixing height constant: stable equation	2400
CONSTW	Mixing height constant: overwater equation	0.16
FCORIOL	Absolute value of Coriolis parameter (1/s)	0.0001
IAVEZI	Spatial mixing height averaging? (0 = no, 1 = yes)	1
MNMDAV	Maximum search radius in averaging process (grid cells)	1
HAFANG	Half-angle of upwind looking cone for averaging (degrees)	30
ILEVZI	Layer of winds used in upwind averaging (between 1 and NZ)	1
IMIXH	Convective mixing height method (1 = Maul-Carson, 2 = Batchvarova-Grvning, - for land cells only, + for land and water cells)	1
THRESHL	Overland threshold boundary flux (W/m**3)	0.05
THRESHW	Overwater threshold boundary flux (W/m**3)	0.05
ITWPROG	Overwater lapse rate and deltaT options (0 = from SEA.DAT, 1 = use prognostic lapse rates and SEA.DAT deltaT, 2 = from prognostic)	0
ILUOC3D	Land use category in 3D.DAT	16
DPTMIN	Minimum potential temperature lapse rate (K/m)	0.001
DZZI	Depth of computing capping lapse rate (m)	200

INPUT GROUP: 6 -- Mixing Height, Temperature and Precipitation Parameters		
Parameter	Description	Value
ZIMIN	Minimum overland mixing height (m)	50
ZIMAX	Maximum overland mixing height (m)	3000
ZIMINW	Minimum overwater mixing height (m)	50
ZIMAXW	Maximum overwater mixing height (m)	3000
ICOARE	Overwater surface fluxes method	10
DSHELF	Coastal/shallow water length scale (km)	0
IWARM	COARE warm layer computation (0 = off, 1 = on)	0
ICOOL	COARE cool skin layer computation (0 = off, 1 = on)	0
ITPROG	3D temperature read option (0 = stations, 1 = surface from station and upper air from prognostic, 2 = prognostic)	2
IRAD	Temperature interpolation type (1 = 1/R, 2 = 1/R**2)	1
TRADKM	Temperature interpolation radius of influence (km)	500
NUMTS	Maximum number of stations to include in temperature interpolation	5
IAVET	Conduct spatial averaging of temperatures? (0 = no, 1 = yes)	1
TGDEFB	Default overwater mixed layer lapse rate (K/m)	-0.0098
TGDEFA	Default overwater capping lapse rate (K/m)	-0.0045
JWAT1	Beginning land use category for temperature interpolation over water	999
JWAT2	Ending land use category for temperature interpolation over water	999
NFLAGP	Precipitation interpolation method (1 = 1/R, 2 = 1/R**2, 3 = EXP/R**2)	2
SIGMAP	Precipitation interpolation radius of influence (km)	100.
CUTP	Minimum precipitation rate cutoff (mm/hr)	0.01

BIOGRAPHY

NAME	Miss Vasita Tunlathorntham
DATE OF BIRTH	September 14, 1994
PLACE OF BIRTH	Bangkok, Thailand
INSTITUTIONS ATTENDED	Thammasat University, 2013-2016 Bachelor of Science (Environmental Science) Mahidol University, 2017-2019
HOME ADDRESS	29/10 moo 9 Bang Hua Suea, Puchao Saming Phrai Rd., Phra Pradaeng Samut Prakan, Thailand 10130. Tel. 081-110-6416 E-mail: vasita.prang@gmail.com