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EMISSIONS OF MAJOR POLLUTANTS FROM LIGNITE-BASED POWER GENERATION IN THAILAND: PART 1. EFFECTS OF SEASONAL FLUCTUATIONS IN THE FUEL QUALITY

Vladimir I. Kuprianov [1] and Vicharn Tanetsakunvatana [2]

[1] School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology,
Thammasat University, P.O. Box 22, Thammasat Rangsit Post Office, Pathumthani, 12121, Thailand
[2] Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi,
91 Pracha-uthit Road, Tungkru, Bangkok, 10140, Thailand

ABSTRACT

In Thailand, about 15% of the total power supply is secured by domestic lignite. The quality of Thai lignite is quite low and rather variable showing apparent seasonal fluctuations. Effects of the fuel quality on the emissions of major pollutants (CO_2, NO_x, SO_2 and PM) from a selected 300-MW boiler unit were the focus of this study. Emission models for the pollutants of interest are discussed in this paper. The SO_2 and PM emission models include the effect of SO_2 absorption by fly ash in the boiler flue gas ducts as well as the efficiency of the flue-gas cleaning systems. An ultimate fuel analysis is provided for twelve months of the fiscal year 2003. For this time period, the specific (per MWh) CO_2, NO_x, SO_2 and PM emissions are presented for this boiler unit. While the CO_2 specific emission was apparently affected by the fuel lower heating value, the specific SO_2 and PM emissions were found to follow the fluctuations in fuel-S and fuel-ash in different months. However, the specific NO_x emissions showed the lowering trend for the months of the rainy season when the fuel-moisture was at an elevated level. Contribution of the boiler unit to the "greenhouse" gas (CO_2) and acid rain gas (NO_x) emissions in the region was found to be substantial.

Keywords: Boiler Unit, CO_2, NO_x, SO_2 and PM, Specific Emissions.

1. INTRODUCTION

Presently, low-rank lignite remains to be one of the major fossil fuels used for power generation in Thailand because of shortage in domestic high-quality energy sources. A Mae Moh power plant located in Northern Thailand is the only lignite-based electrical power producer in the country. However, the power plant provides about 15% of the national electricity production. Due to low quality of Thai lignite, 150-MW and 300-MW boiler units of the power plant are strong contributors to the air pollution in the region.

The major gaseous pollutants (CO_2, NO_x and SO_2) as well as particulate matter (PM) emitted from the power plant units are dispersed over the large territory in the surrounding area. Moreover, some trace elements, such as arsenic and other heavy metals contained in the fly ash of Thai lignite, propagate into the ecosystems via PM [1,2]. Continuous emission monitoring of the boiler units of this power plant is therefore required.

Environmental (or emission) performance of the power plant boiler units is reported to be quite variable following seasonal and random fluctuations in the lignite quality, basically caused by strong changes in fuel-moisture and fuel-ash [1]. In order to provide an accurate environmental risk assessment for the surrounding areas, it is, therefore, necessary to quantify the environmental (or emission) characteristics of distinct boiler units installed at this power plant taking into account the time-variable fuel properties and the actual boiler operating conditions.

The specific (per MWh) emissions of major pollutants seem to be the most appropriate characterization of the environmental performance of a boiler unit because these characteristics include effects of the fuel properties as well as the thermal efficiency of the entire unit, i.e., thermodynamically, the thermal efficiency of a power producing cycle.

In the first part of this work, the effects of seasonal fluctuations in the fuel properties on the emission characteristics of a single boiler unit firing Thai lignite were the focus of the study. Because of the major contribution of the 300-MW boiler units to the lignite-based power generation, the work was aimed at modeling, quantifying and analysis of the specific CO_2, NO_x, SO_2 and PM emissions for an individual 300-MW boiler unit for distinct months of a year.

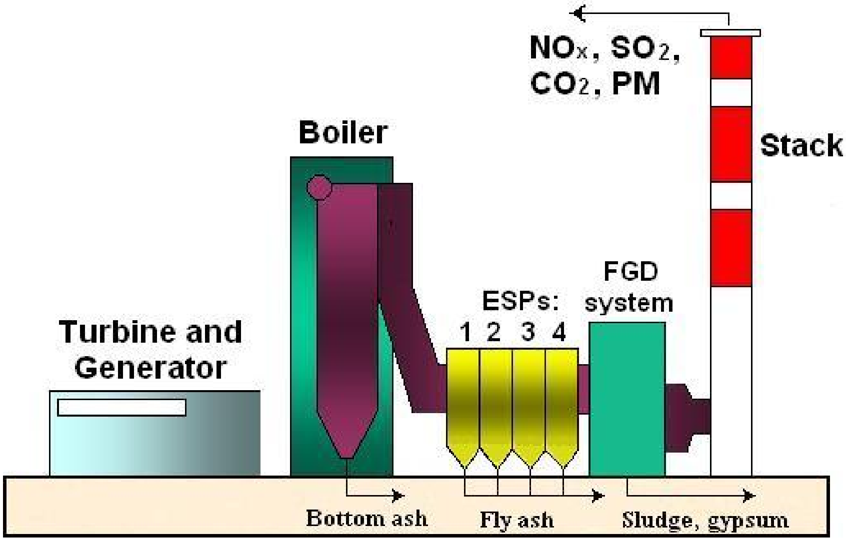

Fig 1. Schematic diagram of a 300-MW power generation unit with flue-gas cleaning facilities.

2. MATERIALS AND METHOD

2.1 The Boiler

Figure 1 shows the schematic diagram of the 300-MW boiler unit with flue-gas cleaning facilities. The boiler is designed for generating 255 kg/s of superheated steam at 540 ^{0}C and 160 bar when operating at full (100%) unit loading. About 220 kg/s of steam is returned from the turbine into the boiler for reheating to 540 ^{0}C at 38 bar. A tangentially-fired dry-bottom furnace of 13.8 × 15.3 m in sizes with the burners arranged at four corners ensures the rated heat release rate (per unit cross-sectional area) of about 3.8 MW/m^2 at the full boiler load.

In order to avoid severe environmental impacts by SO_2 and PM emissions, the boiler unit is equipped with the wet flue gas desulphurization (FGD) system and cascade electrostatic precipitator (ESP) consisting of four units, ESP-1, ESP-2, ESP-3 and ESP-4 (see Fig. 1). The ash-collecting efficiency of the ESP system is high, of about 99.5%, as secured by the manufacturer.

Meanwhile, the wet FGD system installed downstream from the ESPs contributes significantly to collecting fine ash particles, thus, reducing the PM concentration in the flue gas by 70–90% and eventually increasing the overall ash-collecting efficiency to 99.85–99.95%.

However, nitrogen oxides are not mitigated in the boiler (e.g. with the use of flue gas recirculation or selective non-catalytic reduction system); no technique is used for removal of NO_x from the flue gas leaving the boiler unit. Hence, the NO_x emissions formed in the boiler furnace are expected to entirely penetrate into the environment.

The excess air ratio, a key operating variable affecting the boiler thermal efficiency [3], is specified for this boiler at the value of 1.2 (related to the furnace exit); however, because of operational constraints for the FGD system, the boiler has been operated at slightly lower excess air ratios, of 1.16–1.19.

2.2 Emission Models

In this work, the emission rate of NO_x discharged from the boiler unit was predicted to be:

$$\dot{m}_{\mathrm{NOx}} = 10^{-3}\,\dot{m}_{\mathrm{f}}\,V_{\mathrm{g}}\,[\mathrm{NO_x}] \qquad (1)$$

where $\dot{m}_{\mathrm{f}}$, and V_g, were found by Ref. [3]. In the calculation of $\dot{m}_{\mathrm{f}}$, the above boiler characteristics as well as fuel properties, in particular, the lower heating value (*LHV*), were used together with the estimated thermal efficiency of the boiler. The boiler heat losses were therefore determined prior to the emissions assessment for each computational case.

In lignite furnace flame, the formation of thermal NO_x is negligible because of relatively low combustion temperature (less than 1500^{o}C). For this reason, the NO_x emission model involved in this work included the fuel and prompt NO_x only [4]. For the boiler operated at the full load, the emission concentration of these nitrogen oxides in the wet flue gas at the furnace outlet was calculated by Ref. [5]:

$$[\mathrm{NO_x}] = 1.25(0.4 - 0.1\mathrm{N})\mathrm{N}\cdot\alpha_{bz}^{\;2} \times [(T_{\max} - 800)/1000]^{0.33} \qquad (2)$$

When predicting $T_{\max}$ (dependent on the fuel properties, furnace geometry and operating conditions), the burner zone in the furnace was considered as the control volume.

The emission rate of sulfur dioxide was calculated taking into consideration that some part of SO_2 was absorbed by calcium oxide contained in the fly ash ($\mathrm{CaO_{fa}}$) during the ash transportation through the boiler gas ducts [6]. This effect was included in the model by using a dimensionless factor K_{SO2} [1] whose value was dependent on the CaO/S ratio ($\mathrm{CaO} = 0.01\mathrm{A}\cdot\mathrm{CaO_{fa}}$):

$$K_{\mathrm{SO2}} = 0.21(a_{\mathrm{c}}\,\mathrm{CaO/S})^{0.5} \qquad (3)$$

Table 1: Ultimate analysis (%wt.) and *LHV* (MJ/kg) of Thai lignite fired in the 300-MW boiler unit in the validating test runs at different fuel qualities

Run No.	**C**	**H**	**O**	**N**	**S**	**W**	**A**	***LHV***
1	24.54	1.04	8.63	0.94	3.06	27.80	33.99	8.08
2	24.24	1.13	8.04	0.97	2.88	27.60	35.14	8.13
3	29.13	0.90	6.66	1.14	2.70	33.50	25.97	9.53
4	30.21	1.67	9.25	1.07	3.31	30.90	23.59	10.54
5	32.76	1.85	7.08	1.26	3.14	29.30	24.61	11.85

where a_c = 0.95 was assumed for this boiler with the dry-bottom furnace [3].

Thus, for the boiler unit equipped with the FGD system, the SO_2 emission rate could be determined based on S, $\dot{m}_f$ and K_{SO2} [1]:

$$\dot{m}_{SO2} = 0.02(1 - K_{SO2})(1 - \eta_{FGD})\,\dot{m}_f\,\mathrm{S}. \qquad (4)$$

The PM emission rate was apparently affected by A, $\dot{m}_f$, as well as by the overall ash-collecting efficiency of ESP and FGD systems (η_{ash}). Taking into account the above effect of the SO_2 absorption by the fly ash, the mass flow rate of PM penetrating into the atmosphere from the boiler unit was estimated by Ref. [6]:

$$\dot{m}_{PM} = a_c(\mathrm{A} + 2.5\mathrm{S} \times K_{SO2})(1 - \eta_{ash})\dot{m}_f \qquad (5)$$

The CO_2 emission rate was predicted using C and $\dot{m}_f$ to be [1]:

$$\dot{m}_{CO2} = 0.03667\,\dot{m}_f\,\mathrm{C} \qquad (6)$$

Based on the above emission rates and taking into account the electrical power output by the particular boiler unit, distinct specific (i.e. per MWh of the electrical power produced) emissions, m_{em} (em = CO_2, NO_x, SO_2 and PM), for this unit could be then readily determined by:

$$m_{em} = 3600\,\dot{m}_{em} / \dot{W}_e \qquad (7)$$

3. RESULTS AND DISCUSSION

3.1 Validation of NO_x and SO_2 Emission Models

A series of experimental tests has been carried out on a selected 300-MW boiler unit operated at the full load with the aim of validating the above NO_x and SO_2 emission models. The test runs were conducted for different qualities of the fuel whose properties are shown in Table 1 for each test run. As seen in Table 1, during these tests, it was managed to change the *LHV* from some 8 to about 12 MJ/kg, thus, providing a rather wide range of the fuel quality.

Table 2 shows the key operating variables required for estimating the boiler efficiency and fuel consumption. As seen in Table 2, excess oxygen at the boiler economizer outlet was maintained at (nearly) the same value, corresponding to the excess air ratio (coefficient) of 1.18–1.19.

For the required (100%) power output, the mass flow rates of superheated and reheated steam as well as the feed water temperature were maintained at the values securing that power output. Meanwhile, the temperature of superheated steam and that of reheated steam at the boiler reheater's exit were controlled at the design "set points". Small deviations in the above controlled boiler parameters were caused by the fluctuations in the fuel quality ("internal" factor) and electricity demand ("external" factor). Due to these fluctuations, the power output varied in the range of 295–301 MW in the tests. The waste flue gas temperature, one of the important thermal characteristics of the boiler affecting the corresponding boiler heat loss, was slightly increased with higher fuel quality, following the increase in the flame temperature in the burner zone

Table 2: Key operating variables for the validating tests on the 300-MW boiler unit firing Thai lignite of different qualities at the 100% unit load

Variable	**Unit**	**Run No.**				
		1	**2**	**3**	**4**	**5**
O_2^a	%vol.	3.30	3.35	3.33	3.32	3.13
$\dot{m}_{sh}$	kg/s	258	252	251	255	251
t_{sh}	°C	540	541	541	541	542
$\dot{m}_{rh}$	kg/s	219	215	215	218	215
t_{rh}	°C	535	538	540	526	535
t_{fw}	°C	242	241	240	240	239
ϑ_{wg}	°C	172	175	175	178	178

[a] At the boiler economizer exit.

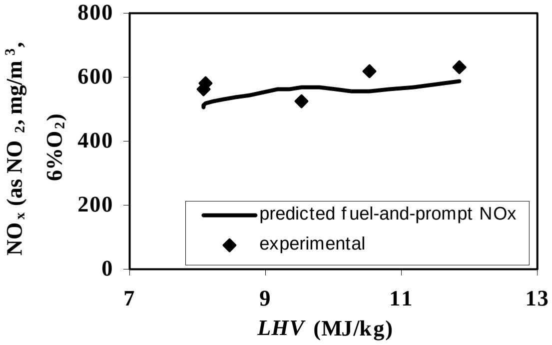

Fig 2. Predicted and experimental NO$_x$ emissions from the 300-MW boiler unit for different fuel qualities.

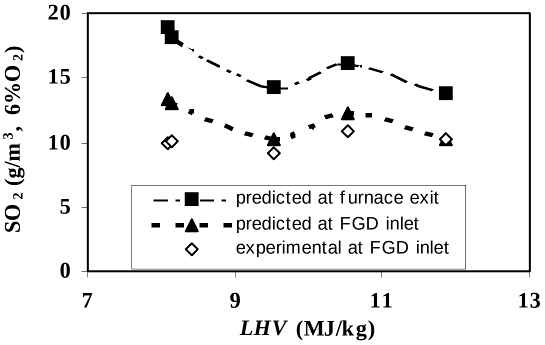

Fig 3. Predicted and experimental SO$_2$ concentrations for different qualities of fuel fired in the 300-MW unit.

In all the test runs, the CO concentration in the waste flue gas was found to be at a very low level (5–8 ppm) and, therefore, was neglected in the assessment of the heat loss owing to incomplete combustion. Like CO, unburned carbon in the fly ash was found to be at rather low level, of about 0.04–0.09% (in an inverse relationship with the fuel *LHV*), leading to small values of the associated heat loss when firing this high-volatile pulverized coal. For the validating test runs (Runs No. 1–5), all boiler heat losses were quantified. Based on these heat losses, the (gross) boiler efficiency (as *LHV* percent) was found to be in the range of 90.3 to 91.1%, showing the improvement with higher *LHV*. Dual effect of the *LHV* resulted in the diminishing of the fuel consumption by the boiler unit from 96.0 to 64.24 kg/s when *LHV* varied from the lowest to the highest value.

Apart from the CO concentrations, NO$_x$ and SO$_2$ concentrations in the flue gas at different sample points were measured in these test runs. With the use of the above emission models and relevant parameters and characteristics, the NO$_x$ and SO$_2$ emission concentrations were predicted as well.

Figure 2 shows the predicted and experimental NO$_x$ (as NO$_2$) emission concentrations in the 6% O$_2$ dry flue gas (under standard conditions) for the above fuel properties and operating conditions. As seen in Fig. 2, the theoretical and experimental results were in good agreement; the difference between predicted and experimental NO$_x$ concentrations did not exceed 15% for all *LHV*s. This may prove the validity of the selected computational method. Due to higher temperature in the burner zone, the NO$_x$ emission concentration was slightly increased with higher fuel quality.

Meanwhile, almost all of the experimental dots in Fig. 2 were scattered above the predicted NO$_x$ (shown by the solid line). Hence, through counting the contribution of thermal NO$_x$, the computational accuracy could be somewhat higher.

Figure 3 compares the predicted and experimental SO$_2$ concentrations in the dry flue gas at 6% O$_2$. The computational results were obtained for the two locations, at the boiler furnace and at the FGD inlet, providing an opportunity for the analysis of uncontrolled SO$_2$ emission (i.e. for $\eta_{\mathrm{FGD}} = 0$). As follows from data in Fig. 3, the dependencies responded to the fluctuations in fuel-S (see Table 1). For *LHV*s of 9.53 to 11.85 MJ/kg, the predicted and experimental SO$_2$ concentrations at the FGD inlet seemed to be in good agreement (at about 10% relative error), whereas the computational accuracy was obviously lower for the two cases at $LHV \approx 8$ MJ/kg.

As may be concluded, an apparent difference between the SO$_2$ concentrations (at the boiler furnace and FGD inlet) for the identical operating conditions indicates the significant effect of SO$_2$ absorption by the fly ash along the boiler flue gas ducts, and this effect should be taken into account (via using K_{SO2}) in estimating the PM emission as well.

Table 3 shows the major emission characteristics of the 300-MW boiler unit for the fuel properties in Table 1. The specific NO$_x$ and SO$_2$ emissions in Table 3 were determined based on the corresponding experimental emission concentrations, whereas the specific CO$_2$ and PM emissions were predicted by the emission models (i.e., in effect, by mass balance correlations) using the relevant properties and characteristics.

Table 3: Boiler unit's emission characteristics for the validating tests at different fuel qualities

Variable	Unit	Run No.				
		1	2	3	4	5
m_{CO2}	kg/MWh	1032	1023	1038	975	941
m_{NOx}	kg/MWh	2.064	2.142	1.922	2.225	2.245
m_{SO2}	kg/MWh	0.622	0.722	0.377	0.790	0.271
m_{PM} [a]	kg/MWh	0.397	0.409	0.244	0.214	0.198

[a] Predicted for 99.9% overall ash-collecting efficiency.

Table 4: Ultimate analysis (wt.%) and *LHV* (MJ/kg) of Thai lignite ("as-received" basis) used in the prediction of the specific emissions for the 300-MW boiler unit for different months in the fiscal year 2003

Month'year	W	A	C	H	O	N	S	*LHV*
Oct'02	31.50	27.09	28.47	1.55	7.82	1.13	2.44	9.87
Nov'02	32.38	24.71	30.57	1.43	7.19	1.24	2.48	10.51
Dec'02	31.56	26.68	28.83	1.44	7.72	1.09	2.68	9.92
Jan'03	28.76	31.93	26.43	1.15	7.77	1.05	2.91	8.89
Feb'03	31.45	27.39	28.98	1.07	7.09	1.13	2.89	9.68
Mar'03	30.13	25.71	30.85	1.60	7.30	1.18	3.23	10.09
Apr'03	27.53	29.58	29.95	1.76	7.16	1.11	2.91	10.81
May'03	29.70	27.45	30.14	1.62	6.82	1.19	3.08	10.73
Jun'03	30.96	25.15	30.68	1.51	7.75	1.24	2.71	10.63
Jul'03	32.08	24.95	29.69	1.66	7.96	1.08	2.95	10.04
Aug'03	31.28	26.09	29.92	1.71	7.04	1.02	2.94	10.67
Sep'03	32.03	24.92	30.45	1.66	6.85	1.01	3.08	10.82

As seen in Table 3, following the reduction in the fuel consumption, the specific CO_2 emission was apparently reduced when firing lignite with higher *LHV*, thus, diminishing the contribution of the power plant units to the "greenhouse" emissions in the region. Similar conclusion could be formulated with respect to the specific PM emission despite the great uncertainties associated with randomly fluctuated fuel-ash and also the SO_2 absorption by fly ash. Meanwhile, in the vicinity of the 99.9% ESPs efficiency, even small deviations in the operational conditions in the ESP system may lead to significant effects on the amount of PM emitted from the boiler unit.

Although the fuel consumption was diminished with higher fuel quality, the specific NO_x emissions were found to increase following the trends in the NO_x emission concentration (see Fig. 2). However, the specific SO_2 emission in Table 3 pointed at the significant uncertainties, because of strong random fluctuations in the fuel-S as well as in the efficiency of the FGD system.

3.2 Effects of Seasonal Fluctuations in the Fuel Quality

Table 4 provides the properties of Thai lignite fired in the boiler units of the Mae Moh power plant in different months of the fiscal year 2003. For each month, the fuel properties were determined by averaging over the corresponding values for different weeks.

Seasonal changes in the fuel moisture could be apparently seen in Table 4. For the months of the rainy season in Thailand (from May to October) and for one or two months later, the fuel moisture was at an elevated level causing changes in other fuel components. However, this fact did not certainly lead to the deterioration in the fuel *LHV*, which, however, apparently responded to the change in the total fuel ballast, i.e. total moisture and ash, the latter being changed randomly [7]. Meanwhile, fuel-N and fuel-S did not show any correlations with the fuel quality, and these fuel characteristics fluctuated randomly during the period of study.

Table 5 shows the specific CO_2, NO_x (as NO_2), SO_2 and PM (as fly ash) emission predicted for the fuels in Table 4. Predicting the SO_2 emission from the unit, the FGD efficiency was assumed to be η_{FGD} = 97%, typical for the FGD units of the Mae Moh power plant [8]. Meanwhile, the overall ash-collecting efficiency η_{ash} = 99.9% was used in this computations in accordance with the above discussion.

The specific CO_2 emission was found to be in the range of 913 to 1011kg/MWh (965 kg/MWh on average) over the period of study, responding mainly to the changes in *LHV*. All the values are seen to be in good agreement with the specific CO_2 emissions in Table 3 for the *LHV*s of about 9.5 to 10.5 MJ/kg.

As seen in Table 5, the variation in the specific NO_x emissions was found to be in rather narrow range, 1.92–2.34 kg/MWh (2.25 kg/MWh on average), because of contrary effects of the fuel quality on the parameters involved in the NO_x emission model. The predicted data on NO_x (in Table 5) seems to be in good agreement with the specific NO_x emissions (in Table 3) determined with the use of the experimental data.

Table 5: Specific CO_2, NO_x, SO_2 and PM emissions (kg/MWh) for the 300-MW boiler unit predicted for different months in the fiscal year 2003

Month'yr	CO_2	NO_x	SO_2[a]	PM[b]
Oct'02	973	2.147	1.005	0.254
Nov'02	981	2.318	0.981	0.218
Dec'02	982	2.115	1.119	0.250
Jan'03	1004	2.048	1.334	0.333
Feb'03	1011	2.215	1.246	0.264
Mar'03	953	2.325	1.268	0.220
Apr'03	932	2.198	1.108	0.253
May'03	946	2.344	1.208	0.238
Jun'03	972	2.318	1.071	0.221
Jul'03	913	2.095	1.220	0.215
Aug'03	958	1.987	1.161	0.228
Sep'03	948	1.921	1.225	0.215

[a] For 97% FGD efficiency

[b] For 99.9% overall ash-collecting efficiency.

Both CO_2 and NO_x are of great concern because of the significant contributions to the "greenhouse" and "acid rain" gas emissions, respectively.

The data in Table 5 performed quite strong effects of the fluctuating fuel properties (fuel-S and fuel-ash) as well as the efficiencies of the flue-gas cleaning facilities on the specific SO_2 and PM emissions. The predicted specific SO_2 emissions were generally greater than those obtained with the use of the experimental SO_2 emissions. Hence, a higher value of the FGD efficiency, say η_{FGD} = 97.5%, could be used in the assessment.

Summarizing all above data, it could be suggested to use the specific emissions of about $m_{CO2} = 1000$ kg/MWh and $m_{NOx} = 2.3$ kg/MWh in estimations of the amounts of CO_2 and NO_x, respectively, emitted from the fully loaded 300-MW boiler units based on the units' power output for the time period of interest. However, SO_2 and PM are quite sensitive to the efficiency of the flue-gas cleaning facilities; hence, accurate results could be obtained using the reliable values of η_{FGD} and η_{ash} (to be determined in special tests). Meanwhile, for rough assessments of the SO_2 and PM effluents, $m_{SO2} \approx 1$ kg/MWh and $m_{PM} \approx 0.25$ kg/MWh could be recommended for the practical use.

4. CONCLUSIONS

Experimental and theoretical study has been carried out on the effects of the seasonal fluctuations in the fuel quality on the emission characteristics of the 300-MW boiler unit firing Thai lignite.

The thermal efficiency and specific emissions (except for NO_x) of the boiler unit were improved when firing fuels with higher *LHV*. Despite the reduction in the fuel consumption, the specific NO_x emissions were found to increase with higher fuel quality.

Through distinct months of the selected 1-yr time period, the emission characteristics were changed, mainly because of fluctuations in the fuel quality.

The specific emissions of $m_{CO2} = 1000$ kg/MWh and $m_{NOx} = 2.25$ kg/MWh could be used in estimations of the CO_2 and NO_x effluents from the boiler unit. However, in assessment of the same characteristics for SO_2 and PM, accurate results could be obtained using reliable values of η_{FGD} and $\eta_{ash.}$

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

Symbol	**Meaning**	**Unit**
A	Ash content in "as-received" fuel	%wt.
a_c	Fraction of fly ash in total ash	(-)
C	Carbon content in "a.-r." fuel	%wt.
C_{fa}	Carbon content in fly ash	%wt.
CaO	CaO content in "as-received" fuel	%wt.
CaO_{fa}	CaO content in fly ash	%wt.
H	Hydrogen content in "a.-r." fuel	%wt.
LHV	Lower heating value of the fuel	MJ/kg
m	Specific mass flow rate	kg/MWh
$\dot{m}$	Mass flow rate	kg/s
N	Nitrogen content in "a.-r." fuel	%wt.
$[NO_x]$	NO_x concentration in the flue gas	g/m^3
O	Oxygen content in "a.-r." fuel	%wt.
S	Sulphur content in "a.-r." fuel	%wt.
T_{max}	Max. temperature in burner zone	K
V_g	Volume of (wet) flue gas	m^3/kg
W	Moisture content in "a.-r." fuel	%wt.
$\dot{W}_e$	Electrical power output	MW
K_{SO2}	"In-boiler" reduction rate of SO_2	(-)
t	Steam (water) temperature	°C
α	Excess air ratio	(-)
η_{FGD}	Efficiency of the FGD unit	(-)
η_{ash}	Overall ash-collecting efficiency	(-)
ϑ_{wg}	Temperature of the waste flue gas	°C

Subscripts

bz	burner (or flame) zone
f	fuel
fw	feed water
sh	superheated steam
rh,1	steam at the reheator inlet
rh,2	steam at the reheator outlet