MODELING EMISSIONS FROM THE BOILER UNITS OF A FUEL OIL/GAS-FIRED POWER PLANT

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ABSTRACT

The 1330-MW Southern Bangkok power plant (co-) firing fuel oil and natural gas is situated in the suburb of the capital of Thailand. This variable-load power plant consists of two 200-MW units firing low-S fuel oil and three 310-MW units co-fired with the medium-S fuel oil and natural gas. This work was aimed at the modeling of major gaseous emissions taking into account the applied fuel options and variability of the boiler operating conditions (load, excess air ratio and others). The emission concentrations for the co-firing of the above two fuels were estimated with the use of the corresponding emission characteristics for firing each fuel on its own taking into account actual contributions (energy fractions) of fuel oil and natural gas to the boiler heat input. For characterizing the environmental impacts by the units, emission rates for the major gaseous pollutants (NO_x, SO_3, SO_2, CO_2) discharged from the units were estimated for different fuel options operated at different unit loads, taking into account actual changes in the load-related operating conditions.

Keywords: Utility boilers, Co-firing, Emission models, Emission rates.

1. INTRODUCTION

Since the mid-80s, natural gas has been the major fuel for power generation in Thailand, whereas the fuel oil share in the national energy balance has dramatically reduced [1]. By the fiscal year 2003, the government power generation sector managed by Electricity Generating Authority of Thailand (EGAT) supplied annually some 60,000 GWh (or about 50% of the national electricity production), and about 30,000 GWh were generated from natural gas and only 2,000 GWh from fuel oil [2].

During the past recent years, most of the boiler units, originally designed for firing fuel oil and installed at the EGAT power plants, have been switched to co-firing of fuel oil and natural gas with the aim of reduction of the power plants' environmental impacts. Meantime, the fuel oil/gas (co-) fired boilers at these power plants have been involved in power-frequency (*P-f*) control and therefore operated with time-variable loads.

The emission rates of major pollutants, such as NO_x (as NO_2), SO_x (as SO_2 and SO_3) and CO_2, discharged from boiler units firing fuel oil or natural gas on its own are known to depend on fuel analysis, unit load, excess air ratio and operating conditions [3,4]. The models for assessment the major emissions from boiler units have been developed for firing pure fuels [4,5]. However, there is an apparent lack of models for estimating the emission characteristics of boiler units co-fired with different fuels.

The work was aimed at the assessment of emission concentrations and emission rates of the major pollutants discharged from distinct boiler units of a 1330-MW power plant (co-) firing fuel oil/gas under variable operating conditions.

2. METHODS AND MATERIALS
2.1 Emission Models

An emission rate, kg/s, of uncontrolled gaseous pollutants (NO_x, SO_3, SO_2 and CO_2) discharged from a boiler unit firing fuel oil or natural gas is found to be [5]:

$$\dot{m}_{em} = 10^{-3} C_{em} \cdot V_g \cdot B \qquad (1)$$

where C_{em} is the mass concentration (g/m^3) of the particular pollutant at reference point in the boiler flue gas duct found for the particular operating conditions, V_g is the volume of wet flue gas (m^3/kg, for firing fuel oil, or m^3/m^3, for firing fuel gas) at this point, and B is the boiler fuel consumption ($\dot{m}_{fo}$, kg/s, or Q_{ng}, m^3/s, respectively) determined by Ref.[6].

For firing pure fuel oil, C_{NOx}, C_{SO3} and C_{SO2} are predicted by Refs.[4,5], whereas for the case of firing natural fuel gas with no sulfur-based compounds ($C_{SO3} = C_{SO2} = 0$), C_{NOx} is estimated by Refs.[5,7].

In analysis of the CO_2 emission from complete combustion of fuel oil, one can predict the emission rate of CO_2, kg/s, avoiding the determination of this pollutant in the flue gas [4,5]:

$$\dot{m}_{CO_2} = 0.03667C^r \cdot \dot{m}_{fo} \qquad (2)$$

where C^r = carbon content (wt.%) in "as-received" fuel.

For complete combustion of natural gas, the CO_2 emission rate, kg/s, can be determined by [5]:

$$\dot{m}_{CO_2} = 0.0198(CO_2 + CO + CH_4 + 2C_2H_6 + 3C_3H_8 + 4C_4H_{10} + 5C_5H_{12}) \cdot Q_{ng} \qquad (3)$$

where the fuel gas components (CO_2, CO and C_xH_y) are represented in vol.%.

For co-firing of fuel oil in certain proportion with natural gas under particular operating conditions (load, excess air ratio, etc.), the emission rate of each pollutant is expected to correlate with the energy fractions of the fuel oil of natural gas. Technically, the emission rate can be expressed as the function of the natural energy fraction, EF_{ng} (%), i.e. contribution of the natural gas to the boiler heat input.

2.2 Case Study and Research Objectives

The 310- and 200-MW boiler units at the Southern Bangkok power plant of the 1330-MW installed capacity were the focus of this study. At a nominal (100%) load, a 310-MW unit produced 1088.4 t/h of superheated steam at 15.5 MPa and 540°C, whereas a fully-loaded 200-MW unit generated 650 t/h of superheated steam at 12.4 MPa and 540 °C for. The thermal cycle of both boiler units included steam reheating with corresponding steam properties at the inlet and exit of boiler reheaters.

For validating the emission models for NO_x and SO_2, one of the 310-MW power plant units of the power plant was tested for three fuel options, prior to the computational study on emission assessment.

For the Fuel Option 1, the boiler unit was fired with medium-S fuel oil whose fuel analysis is provided in Ref. [4]. In the test of the second option (Fuel Option 2), the boiler unit was fired with pure natural gas of the fuel analysis shown in Table 1. For the last option (Fuel Option 3), the boiler was co-fired with medium-S fuel oil and natural gas, at about $EF_{ng} = 80\%$, and the properties of these fuels are provided in Table 1 as well (in the part related to the 310-MW boiler unit).

For the Fuel Options 1 and 3, the boiler was tested at three loads, of about 100, 75 and 50% nominal boiler capacity (load), whereas for the Fuel Option 2, the boiler was run at two loads only, of 50% and 72% loads. The 100% load test of the boiler was not manageable when firing fuel gas because of the constraints associated with the steam temperature control.

Table 1: Analyses of fuel oil and natural gas used in the experimental tests and for predicting the emission rates of major pollutants discharged from the 200- and 310-MW boiler units (W = fuel moisture)

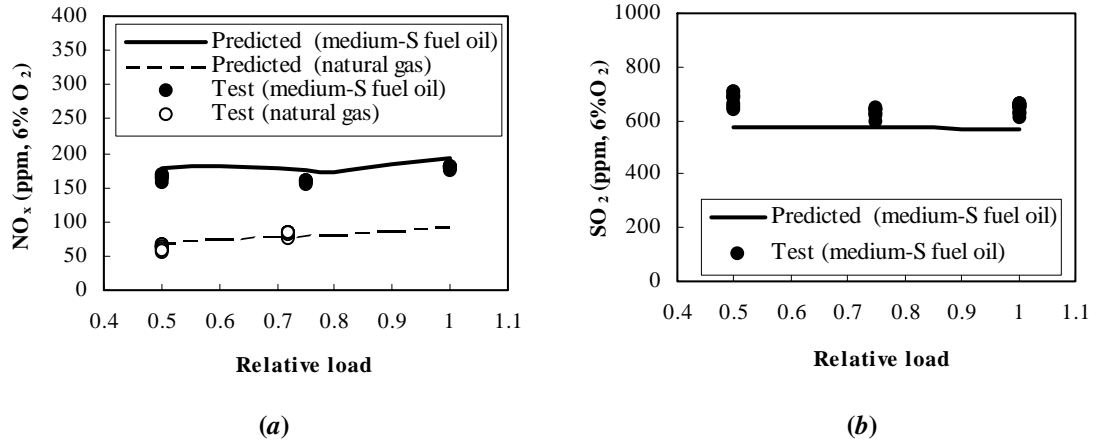| Fuel properties				
200-MW boiler unit		310-MW boiler unit		
Analysis	Low-S fuel oil (wt.%, on "as-received" basis)	Medium-S fuel oil (wt.%, on "as-received" basis)	Natural Gas	
			Analysis	(vol.%, on dry basis)
C	85.40	86.21	CH_4	76.46
H	13.09	10.74	C_2H_6	6.56
O	0.00	0.00	C_3H_8	1.18
N	0.92	0.99	C_4H_{10}	0.42
S	0.28	1.76	C_5H_{12}	0.17
W	0.30	0.30	C_6H_{14}	0.06
			CO_2	13.5
			N_2	1.65

Fig 1. Effects of the unit load on the NO_x (a) and SO_2 (b) uncontrolled emissions
from the 310-MW boiler fired with distinct fuels.

During the performance tests, NO_x and SO_2 emission concentrations were measured at the exit of the boiler's economizer with the aim of their comparison with the corresponding predicted values. Actual steam properties and flow rates as well as parameters required for estimating the boiler efficiency and fuel consumption were also collected in these tests with the aim of their use in predicting "theoretical" NO_x and SO_2 values.

Meanwhile, the computational part of this work related to the assessments of the emission rates from the boilers was carried out for various operating conditions with the use of the design steam properties and boiler load-related characteristics (for excess air ratio, fraction of flue gas recirculation, feed water temperature, waste gas temperature, etc.). The fuel selection for the particular boiler unit corresponded to the current situation at this power plant: the 310-MW boilers were considered as the ones co-fired with medium-S fuel oil and natural gas, while the 200-MW boilers being fuelled with low-S fuel oil only.

The properties of the fuels involved in this computational study are shown in Table 1. The lower heating values of 42.46 MJ/kg for low-S fuel oil, 40.42 MJ/kg for medium-sulfur fuel oil and 33.9 MJ/m^3 for natural gas used in the study were determined by Ref. [6].

3. RESULTS AND DISCUSSION

Comparison of the predicted and experimental results for NO_x and SO_2 volume concentrations (in the dry 6% O_2 flue gas) for the 310-MW boiler is shown in Fig.1 for the pure firings of medium-S fuel oil (with the analysis provided in Ref. [4]) and natural gas (with the analysis shown in Table 1) in the range of 50–100% boiler loads. As seen in Fig. 1a, the predicted and experimental NO_x emissions were quite close to each other (within the 10% band), whereas the computational accuracy for SO_2 was lower (at the 20% band) as followed from the comparison of data in Fig. 1b. Taking into account the above validation, it was concluded that the emission models provided in Refs. [4,5,7] could be reliably used for estimating the emission concentrations for wide ranges of the boiler operating conditions.

Table 2 shows the emission characteristics predicted

for the boiler units firing the fuels provided in Table 1 for the 50–100% unit loads. A certain non-linearity in the dependencies of fuel consumption on the relative unit load could be explained by the effects of the feed water temperature and boiler efficiency.

As seen in Table 2, $\dot{m}_{NOx}$ and $\dot{m}_{SO3}$ were strongly influenced by the operating conditions, meanwhile, $\dot{m}_{SO_2}$ and $\dot{m}_{CO2}$ were basically correlated with the fuel consumption.

Experimental data on the co-firing showed a proportional correlation of the emission concentrations with EF_{ng}. The NO_x, and SO_2 values for the natural gas energy fractions of 0% (firing pure fuel oil), 80% (co-firing) and 100% (firing pure natural gas) could be fairly fitted by the direct lines plotted versus EF_{ng}. This result was extended to the emission rates; hence, the emission rate of the "i"-th pollutant was determined by:

$$(\dot{m}_{em})_{EF_{ng}} = 0.01(\dot{m}_{em})_{ng}EF_{ng} + (\dot{m}_{em})_{fo} \cdot (1 - 0.01EF_{ng}) \quad (4)$$

where $(\dot{m}_{em})_{EF_{ng}}$, $(\dot{m}_{em})_{ng}$, $(\dot{m}_{em})_{fo}$ represented the emission rates for the co-firing (at the particular energy fraction EF_{ng}), for the firing pure natural gas and the firing pure fuel oil, respectively.

With the use of Eq. (4), the emission rate for NO_x (as NO_2), SO_3, SO_2 and CO_2 were calculated for different unit loads of the 310-MW units co-fired with medium-S fuel oil and natural gas. As an illustration, the emission rates for NO_x and CO_2 are shown in Fig. 2 for some relative unit loads in the range of 50% to 100%.

The emission rates of SO_3 and SO_2 released from fuel oil fired can be determined using the fuel oil compositions and the operating conditions. As known, when firing natural gas, there are no SO_x emissions into the environment. The only source of these pollutants is that from the combustion of fuel oil, in which the fuel-S varies basically, depending on the type (grade) and source of the fuel oil.
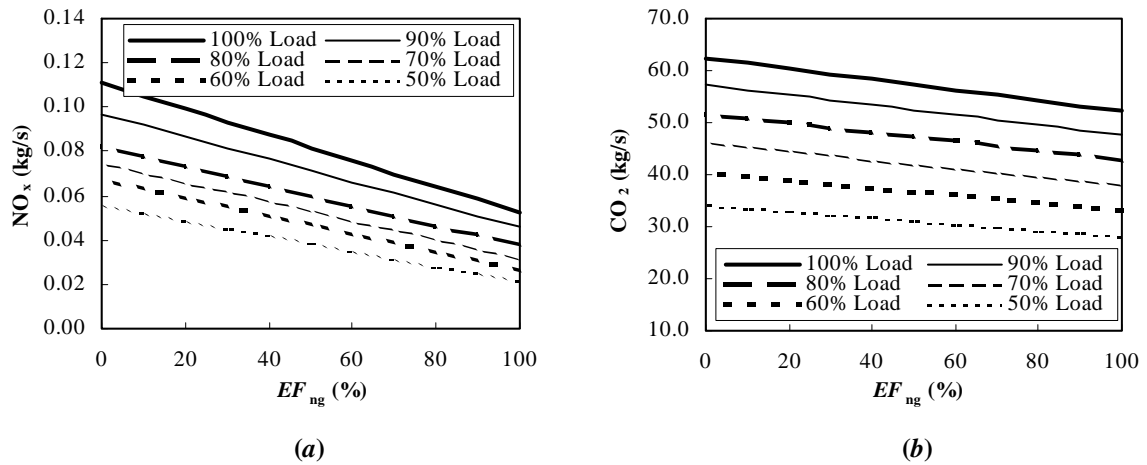
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Fig 2. Effects of the unit loading and EF_{ng} on the NO_x (*a*) CO_2 (*b*) emission rates for the 310-MW unit co-fired with medium-S fuel oil and natural gas.

The SO_2 and SO_3 emission rates (kg/s) for distinct unit loads and various energy fractions can be reasonably determined by the interpolation method, using (like for the NO_x and CO_2 emissions) EF_{ng} as the main entry (parameter). As the result, a graph showing the relationships between the SO_2 and SO_3 emissions (kg/s) and the energy fraction of natural gas for various unit loads can be constructed for the 200- and 310-MW units, as the one shown in Fig. 3

Based on the emission rates of the major pollutants for distinct variable-load boiler units, an accurate assessment of the emission rates over a given time period (e.g. daily emission rates) can be carried out for the whole power plant, taking into account the actual time-domain load dispatching over the power plant units and, when necessary, the changes in fuel options and/or fuel properties.
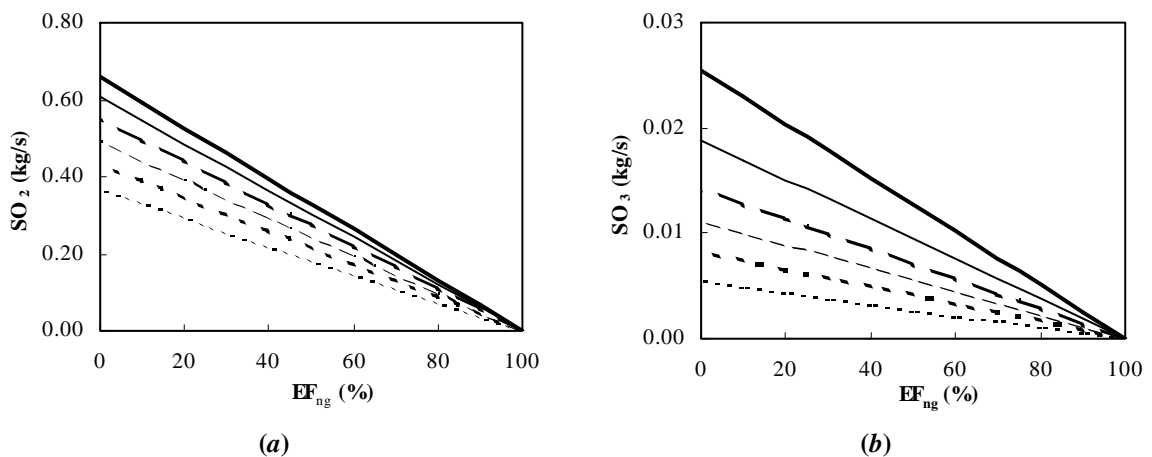

Fig 3. Effects of the unit loading and EF_{ng} on the SO_2 (a) SO_3 (b) emission rates for the 310-MW unit co-fired with medium-S fuel oil and natural gas (same legends, as in Fig. 2, are applied).

Table 2: Fuel consumption and emission rates for the 310-MW and 200-MW boiler units
firing distinct fuels at different loads in the range of 50–100% nominal loading

Boiler unit	Fuel option	Item (unit)	Relative unit load					
			100%	90%	80%	70%	60%	50%
310-MW unit	Medium-S fuel oil	$\dot{m}_{fo}$ (kg/s)	19.77	18.08	16.33	14.58	12.74	10.82
		$\dot{m}_{NOx}$ (kg/s)	0.1112	0.0929	0.0786	0.0686	0.0591	0.0482
		$\dot{m}_{SO_2}$ (kg/s)	0.6575	0.5966	0.5296	0.4642	0.3988	0.3334
		$\dot{m}_{SO_3}$ (kg/s)	0.0264	0.0193	0.0143	0.0111	0.0078	0.0051
		$\dot{m}_{CO_2}$ (kg/s)	62.50	56.10	49.81	43.54	37.28	31.06
310-MW unit	Natural gas	Q_{ng} (m³/s)	24.10	21.99	19.80	17.59	15.33	12.97
		$\dot{m}_{NOx}$ (kg/s)	0.0523	0.0447	0.0361	0.0301	0.0244	0.0195
		$\dot{m}_{CO_2}$ (kg/s)	52.01	46.59	41.24	35.96	30.70	25.49
200-MW unit	Low-S fuel oil	$\dot{m}_{fo}$ (kg/s)	12.16	11.11	9.95	8.78	7.63	6.55
		$\dot{m}_{NOx}$ (kg/s)	0.0680	0.0569	0.0506	0.0436	0.0370	0.0306
		$\dot{m}_{SO_2}$ (kg/s)	0.0650	0.0597	0.0535	0.0474	0.0412	0.0355
		$\dot{m}_{SO_3}$ (kg/s)	0.0017	0.0013	0.0010	0.0007	0.0005	0.0003

4. CONCLUSIONS

Computational models were successfully applied for predicting the emission rates of the major pollutants (NO_x, SO_3, SO_2, and CO_2) discharged from variable-load boiler units of a fuel oil/gas-fired power plant for different fuel options and unit loads.

The emission models for NO_x and SO_2 were validated by comparison of the predicted and experimental emission concentrations, the latter being obtained on a 310-MW boiler unit for some operating conditions.

As shown in this work, the emission rate of a particular pollutant for the case of co-firing fuel oil and natural gas can be estimated based on the emission rates for firing each fuel on its own as well as the natural gas energy fraction (or contribution by natural gas to the boiler heat input).

By modeling, the emission rates of NO_x, SO_3, SO_2, and CO_2 were quantified for the 310-MW units co-fired with medium-S fuel oil and natural gas, as well as for the 200-MW units fired with low-S fuel oil only, for the 50–100% loads.

5. ACKNOWLEDGEMENT

6. REFERENCES

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