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Fuel Processing Technology 87 (2006) 1085–1094

FUEL PROCESSING TECHNOLOGY

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Minimizing fuel and environmental costs for a variable-load power plant (co-)firing fuel oil and natural gas Part 1. Modeling of gaseous emissions from boiler units

W. Kaewboonsong, V.I. Kuprianov *, N. Chovichien

School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, P.O. Box 22, Thammasat Rangsit Post Office, Pathum Thani 12121, Thailand

Received 10 May 2006; received in revised form 29 July 2006; accepted 8 August 2006

Abstract

This work was aimed at modeling of major gaseous emissions (NO_x, SO_3, SO_2, CO_2) from boiler units of a power plant firing (or co-firing) fuel oil and natural gas for variable operating conditions (load and load-related variables: excess air, flue gas recirculation, etc.). The emission rate of the pollutants for the co-firing was estimated for a particular boiler using these characteristics for the burning of each fuel in the boiler on its own and taking into account energy fractions (contributions) of fuel oil and natural gas to the boiler heat input. The gaseous emissions (in terms of emission concentrations, emission rates and specific emissions) from a 200-MW boiler unit firing low-S fuel oil and from a 310-MW boiler unit firing (or co-firing) medium-S fuel oil and natural gas were estimated and compared for 50–100% unit loads based on actual fuel properties and load-related operating variables of these units. Upper limit for the energy fraction of medium-S fuel oil was determined for the 310-MW boiler unit co-firing the two fuels with the aim to meet the national emission standard for SO_2.

Keywords: Boiler units; NO_x; SO_3; SO_2 and CO_2 emissions; Emission models; Emission rates

1. Introduction

Over the last 20 years, natural gas has been the major fuel for power generation in Thailand, while the share of fuel oil in the national energy balance has dramatically reduced [1]. Presently, more than 70% of the electricity production in this country is based on natural gas, whereas only about 2% of electricity is generated from fuel oil [2]. Since the year 2001, a number of boiler units at domestic thermal power plants, originally designed for firing fuel oil, have been switched to co-firing of fuel oil and natural gas with the aim of reducing environmental impacts by the power plants. This fuel switching became possible due to construction of a gas pipeline supplying natural gas from the Gulf of Thailand (also known as the Gulf of Siam) to the utilities.

In Thailand, the boiler units of thermal power plants (co-) firing fuel oil and natural gas are conventionally involved in power–frequency (*P-f*) control and, therefore, operated with time-variable load. Accordingly, major gaseous emissions from the boiler units, such as NO_x, SO_2, SO_3 and CO_2 (generally formed in fuel oil/gas combustion), are represented by time-domain characteristics responding to changes in fuel analysis and operating conditions (unit load, excess air and flue gas recirculation) [3,4]. As revealed by experimental data obtained on utility boilers firing fuel oil and natural gas, NO_x and SO_3 formations are strongly influenced by combustion conditions in the boiler furnace (temperature and O_2 concentration at the post-flame region, both following changes in the unit load), while SO_2 and CO_2 emission concentrations (corrected to reference excess air) are almost independent of the boiler load and air supply [5–7]. Furthermore, with variation in unit loading, the thermal efficiency of a boiler may deviate from the rated value to some extent, affecting the fuel consumption by the boiler and, consequently, the emission rate of the gaseous pollutants [4].

In some engineering practices, e.g. in optimization of the boiler design (geometry) and operating conditions (when a numerous number of feasible cases must be considered), computational emission models can be used as an effective tool for the

* Corresponding author. Tel.: +66 2 986 9009x2208; fax: +66 2 986 9112.
E-mail address: ivlaanov@siit.tu.ac.th (V.I. Kuprianov).

0378-3820/$ - see front matter
doi:10.1016/j.fuproc.2006.08.003

assessment of environmental performance of individual boiler units. Reliable computational data on the emissions are also needed when boiler retrofitting and/or selecting of gas-cleaning facilities (type, capacity, etc.) to a boiler unit. Limited studies have addressed the environmental (or "external") boiler costs, associated with damage done by the emissions to the environment and human health, which are commonly coupled with the fuel costs (dependent on the fuel consumption) in different optimization models related to individual boiler units or entire power plant [8,9]. Rather than emission factors, the results from computational modeling secure an accurate environmental risk assessment for areas surrounding the power plant.

The emission models, postulating the boiler furnace as a control volume and including the effects of fuel properties, operating conditions and furnace geometry (the latter being used for estimating NO_x and SO_3 emissions), have been developed and applied for firing distinct fossil fuels in large industrial and utility boilers [10,11]. However, there is a lack of studies for determining the emission characteristics for a boiler co-fired with different fuels.

This work deals with the modeling of emission concentrations, emission rates and specific emissions for the major pollutants discharged from 200-MW and 310-MW boiler units (co-) firing fuel oil and natural gas for variable operating conditions. A comparison of these emission characteristics for different fuel options and boiler loads was the focus of this study as well.

2. Computational models

It appears that the emission rate of the gaseous pollutants discharged from a boiler unit depends on the fuel consumption by the boiler as well as on the concentration of these pollutants in the flue gas leaving the unit, or emission concentrations. Computational methodology below includes only key models (equations) for determining the boiler fuel consumption and major emissions, while some supporting relationships are provided in Appendices. In all computations, the volume of gaseous compounds (m^3) is related to the standard conditions (1 atm, 0 °C) [12,13].

2.1. Determining the fuel consumption

For a particular boiler firing a single fuel at a given unit load, the fuel consumption is determined by taking into account the available heat, or heat input to the boiler (Appendix A), the rate of heat transfer to working fluid circulating in different boiler components (Appendix B), and thermal efficiency of the boiler (Appendix C) to be [12,13]:

- for firing fuel oil (kg/s):

$$\dot{m}_{\mathrm{FO}} = \frac{100\dot{Q}_1}{(\eta_\mathrm{b})_{\mathrm{FO}}(Q_{\mathrm{av}})_{\mathrm{FO}}}, \tag{1}$$

- for firing natural gas (m^3/s):

$$Q_{\mathrm{NG}} = \frac{100\dot{Q}_1}{(\eta_\mathrm{b})_{\mathrm{NG}}(Q_{\mathrm{av}})_{\mathrm{NG}}}. \tag{2}$$

However, for this boiler co-firing fuel oil and natural gas, supplied with flow rates $(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}}$ and $(Q_{\mathrm{NG}})_{\mathrm{cf}}$, respectively, the energy balance equation can be written by taking into account the contributions of the fuels to the boiler heat input and thermal efficiency of the co-fired boiler:

$$(\eta_\mathrm{b})_{\mathrm{cf}}[(Q_{\mathrm{av}})_{\mathrm{FO}}(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}} + (Q_{\mathrm{av}})_{\mathrm{NG}}(Q_{\mathrm{NG}})_{\mathrm{cf}}] = 100\dot{Q}_1. \tag{3}$$

In the co-firing practices, the fuel feed rate ratio is typically adjusted at constant value:

$$(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}}/(Q_{\mathrm{NG}})_{\mathrm{cf}} = \mathrm{FRR}. \tag{4}$$

Hence, $(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}}$ and $(Q_{\mathrm{NG}})_{\mathrm{cf}}$ corresponding to current unit load (or boiler thermal power output $\dot{Q}_1$) can be determined by coupling Eqs. (3) and (4).

For the co-firing, the boiler thermal efficiency $(\eta_\mathrm{b})_{\mathrm{cf}}$ in Eq. (3) is likely ranged between $(\eta_\mathrm{b})_{\mathrm{FO}}$ and $(\eta_\mathrm{b})_{\mathrm{NG}}$, depending upon the contributions of the co-fired fuels to boiler heat input. The energy balance equation [Eq. (3)] can be then rewritten satisfying the boundary conditions:

$$(\eta_\mathrm{b})_{\mathrm{FO}}(Q_{\mathrm{av}})_{\mathrm{FO}}(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}} + (\eta_\mathrm{b})_{\mathrm{NG}}(Q_{\mathrm{av}})_{\mathrm{NG}}(Q_{\mathrm{NG}})_{\mathrm{cf}} = 100\dot{Q}_1. \tag{5}$$

Comparison of Eq. (3) with Eq. (5) results in:

$$(\eta_\mathrm{b})_{\mathrm{cf}} = (1-0.01\mathrm{EF}_{\mathrm{NG}})(\eta_\mathrm{b})_{\mathrm{FO}} + 0.01\mathrm{EF}_{\mathrm{NG}}(\eta_\mathrm{b})_{\mathrm{NG}}, \tag{6}$$

where the energy fraction of natural gas in the total heat input to the boiler (%) is given by:

$$\mathrm{EF}_{\mathrm{NG}} = \frac{100}{1 + \frac{(Q_{\mathrm{av}})_{\mathrm{FO}}}{(Q_{\mathrm{av}})_{\mathrm{NG}}} \times \frac{(\dot{m}_{\mathrm{FO}})_{\mathrm{cf}}}{(Q_{\mathrm{NG}})_{\mathrm{cf}}}}. \tag{7}$$

As the ratio of the available heats in Eq. (7) is (almost) regardless of boiler operating conditions, the $\mathrm{EF}_{\mathrm{NG}}$ is adequately correlated with the specified (or applied) value of FRR [see Eq. (4)] and, thus, independent of the unit load and other operating variables.

2.2. Emission models

Like the boiler thermal efficiency, the emission rate of an "em-th" pollutant (em = NO_x, SO_3, SO_2 and CO_2) from a boiler unit co-fired with fuel oil and natural gas at the particular unit load is determined in this work based on the $\mathrm{EF}_{\mathrm{NG}}$ and corresponding "boundary" emission rates, i.e. those found for firing pure fuel oil and pure natural gas in this boiler at the same unit load:

$$(\dot{m}_{\mathrm{em}})_{\mathrm{cf}} = (1-0.01\mathrm{EF}_{\mathrm{NG}})(\dot{m}_{\mathrm{em}})_{\mathrm{FO}} + 0.01\mathrm{EF}_{\mathrm{NG}}(\dot{m}_{\mathrm{em}})_{\mathrm{NG}} \tag{8}$$

The load-related emission models for the major pollutants discharged from large industrial and utility boilers fired with pure fuel oil or pure natural gas are as follows.

2.2.1. Nitrogen oxides

For NO_x emissions from conventional combustion of fossil fuels in boiler units, the model includes contributions by thermal and fuel-and-prompt NO_x, as proposed in Ref. [11].

The concentration of thermal NO_x (as NO_2) in wet flue gas at the furnace outlet (g/m^3) of a fully-loaded boiler firing fuel oil or natural gas is found for the actual excess air ratio at the burner zone and flue gas recirculation factor to be:

$$C_{NO_2^{th}} = 7.03 \times 10^3 C_{O_2}^{0.5}\, \bar{t} \exp(-10,860/T_m) \tag{9}$$

The computational procedures for the (residual) oxygen concentration (C_{O_2}), relative time factor ($\bar{t}$) and maximum temperature at the burner zone (T_m) are given in details in Ref. [11]. For an accurate estimation of the time factor, the temperature of flue gas at the furnace outlet (predicted by a normative method [12,13]) is required along with T_m. Thus, the model for estimating $C_{NO_2^{th}}$ includes the effects of combustion conditions (temperature, excess air ratio, flue gas recirculation factor) as well as the furnace geometry and thermal efficiency.

For a boiler firing fuel oil at 100% load, the total concentration of fuel-and-prompt NO_x (as NO_2) in wet flue gas at the furnace outlet (g/m^3) is determined for the actual excess air ratio and flue gas recirculation factor to be:

- for $2100 > T_m \geq 1850$ K:

$$C_{NO_2^{f+p}} = (0.4{-}0.1\mathrm{N})\mathrm{N}[(\alpha_{bz} + r) / (1 + r)]^2 [(2100{-}T_m)/125]^{0.33}, \tag{10}$$

- for $1850 > T_m \geq 800$ K:

$$C_{NO_2^{f+p}} = 1.25(0.4{-}0.1\mathrm{N})\mathrm{N}[(\alpha_{bz} + r) / (1 + r)]^2 [(T_m{-}800)/1000]^{0.33}. \tag{11}$$

As seen in Eqs. (10) and (11), NO_x emissions are substantially affected by the fuel-N content (in formation of fuel NO) and, also, by the excess air ratio at the burner zone, whereas the influences of flue gas recirculation and (maximum) flame temperature are rather weak.

When firing natural gas, the contribution of fuel NO_x is zero, and nitrogen oxides are formed in the boiler furnace due to thermal and prompt mechanisms only. However, in the prediction of NO_x emissions from the combustion of natural gas, one has to assume the maximum temperature in the burner zone, T_{max}, as that by 1% higher than T_m (i.e. $T_{max} = 1.01 T_m$), according to a recommendation in Ref. [11]. Hence, for a fully-loaded boiler firing natural gas, the thermal NO_x emissions can be estimated by Eq. (9) replacing T_m by T_{max}, while the concentration of prompt NO_x (as NO_2) in wet flue gas at the furnace outlet (g/m^3) is estimated taking into account the actual excess air ratio and flue gas recirculation factor to be:

$$C_{NO_2^p} = 0.16[(\alpha_{bz} + r)/(1 + r)]^2 [(T_{max}{-}800)/1000]^{0.33}. \tag{12}$$

Thus, for a boiler operated at full load, the total yield of NO_x is found by summing $C_{NO_2^{th}}$ with $C_{NO_2^{f+p}}$ (for firing fuel oil), or with $C_{NO_2^p}$ (for firing natural gas).

With lower boiler load, the maximum temperature of flue gas and residence time of reactants at the burner zone change with opposite trends, affecting formation of thermal, fuel-and-prompt NO_x with different extents. However, at reduced boiler loads, all these contributions to the NO_x emissions are basically lowered [3].

In accordance with the model proposed in Ref. [11], for a boiler operated with the relative load P/P_0 ($P \leq P_0$), the total NO_x (as NO_2) concentration in wet flue gas at the outlet of the furnace (g/m^3) can be estimated by:

- for firing fuel oil:

$$(C_{NO_2})_{FO} = C_{NO_2^{th}}(P/P_0) + C_{NO_2^{f+p}}(P/P_0)^{0.5}, \tag{13}$$

- for firing natural gas:

$$(C_{NO_2})_{NG} = C_{NO_2^{th}}(P/P_0) + C_{NO_2^p}(P/P_0)^{0.5}. \tag{14}$$

For comparison with experimental data or emission standards, the predicted concentrations of nitrogen oxides are corrected from 'wet gas basis' to 'dry gas basis' by standard methodology [13] and may be represented in ppm (in 6% O_2 dry flue gas).

For a boiler unit operated at any arbitrary load, the emission rate of uncontrolled NO_x as NO_2 (kg/s) is given by:

- for firing fuel oil:

$$(\dot{m}_{NO_x})_{FO} = 10^{-3}(C_{NO_2})_{FO}(V_g)_{FO}\dot{m}_{FO}, \tag{15}$$

- for firing natural gas:

$$(\dot{m}_{NO_x})_{NG} = 10^{-3}(C_{NO_2})_{NG}(V_g)_{NG}Q_{NG}, \tag{16}$$

where $(V_g)_{FO}$ and $(V_g)_{NG}$ are found by Refs. [11,12] for firing fuel oil and natural gas, respectively, taking into account actual characteristics of excess air and flue gas recirculation at the furnace.

2.2.2. Sulphur oxides

Since natural gas does not produce sulphur oxides on combustion, the models below are only related to SO_3 and SO_2 formation in fuel oil firing boilers.

The SO_3 concentration in wet flue gas at the furnace exit (g/m^3) of a fuel oil-fired boiler operated at an arbitrary load ($P \leq P_0$) is predicted to be:

$$(C_{SO_3})_{FO} = 0.01514 x_{SO_2} (O_2)_{bz}^{0.5} q_f (P/P_0)^2. \tag{17}$$

As may be seen in this model, the SO_3 concentration in flue gas is proportional to the fuel-S content and affected by the boiler load, excess oxygen at the burner zone and furnace geometry. With higher SO_3 formation, the SO_2 concentration in the wet flue gas at the furnace exit (g/m^3) becomes, accordingly, somewhat lower:

$$(C_{SO_2})_{FO} = 2.86(1000 x_{SO_2} {-} 0.28 C_{SO_3}). \tag{18}$$

Like for NO_x, the predicted concentrations of sulphur oxides may be corrected from 'wet gas basis' to 'dry gas basis' and represented in ppm (in 6% O_2 dry flue gas).

The rates of uncontrolled SO_3 and SO_2 emissions (kg/s) from a boiler firing fuel oil are determined, respectively, by:

$$(\dot{m}_{SO_3})_{FO} = 10^{-3}(C_{SO_3})_{FO}(V_g)_{FO}\dot{m}_{FO}, \tag{19}$$

$$(\dot{m}_{SO_2})_{FO} = 10^{-3}(C_{SO_2})_{FO}(V_g)_{FO}\dot{m}_{FO}. \tag{20}$$

2.2.3. Carbon dioxide

In this work, the CO_2 emission rate (kg/s) is estimated based on the fuel analysis and fuel consumption by a boiler, neglecting products of incomplete combustion, to be [4,11,14]:

- for firing fuel oil:

$$(\dot{m}_{CO_2})_{FO} = 0.03667\mathrm{C}\dot{m}_{FO}, \tag{21}$$

- for firing natural gas:

$$(\dot{m}_{CO_2})_{NG} = 0.0198(CO_2 + CO + CH_4 + 2C_2H_6 + 3C_3H_8 + 4C_4H_{10} + 5C_5H_{12} + 6C_6H_{14})Q_{NG}. \tag{22}$$

2.2.4. Specific emissions

For a boiler co-fired with fuel oil and natural gas, the specific emission (kg/MW h) for the pollutants of interest (em = NO_x, SO_3, SO_2 and CO_2) is determined based on the predicted [by Eq. (8)] emission rate (kg/s) and taking into account the electrical power output of the unit, P (MW), to be:

$$(m_{em})_{cf} = 3600(\dot{m}_{em})_{cf}/P \tag{23}$$

Apparently, Eq. (23) can be also used for quantifying $(m_{em})_{FO}$ and $(m_{em})_{NG}$, by assuming $EF_{NG}=0$ and $EF_{NG}=1$, respectively, in Eq. (8).

3. Case study and essential input

3.1. The boiler units and fuels

The South Bangkok Power Plant (SBPP) located in the suburb of the capital of Thailand is a typical utility with multi-fuel options. Generally, two 200-MW boiler units of this power plant are fired with low-S fuel oil (no. 5, by domestic classification), while three 310-MW boilers are co-fired with medium-S fuel oil (no. 2) and natural gas. Table 1 shows ultimate analyses of the fuel oils and volumetric analysis of the natural gas (co-)fired in the power plant units. The LHV of these fuels are found (using correlations from Appendix A) to be 42.5 MJ/kg for low-S fuel oil, 40.5 MJ/kg for medium-S fuel oil and 33.9 MJ/m^3 for natural gas.

For the 100% load, an individual 200-MW boiler unit is designed to supply 180 kg/s of superheated steam at 540 °C and 129 bar to a high-pressure turbine. About 150 kg/s of steam at 35 bar is returned into the boiler for reheating to 540 °C. A tangentially-fired furnace of this boiler of 10.38 × 11.45 m cross-sectional dimensions and 21.5 m height is equipped with the straight-flow type burners arranged at four furnace corners. Meanwhile, a single 310-MW boiler unit produces about 280 kg/s of superheated steam at 540 °C and 155 bar and 250 kg/s of reheated steam 540 °C and 37 bar at the full unit load. The furnace with 10.21 × 12.53 m cross-sectional dimensions and 22.4 m height is similar (by type) to that of the 200-MW unit.

Table 1
Typical analyses of the fuel oils and natural gas fired in boiler units of the South Bangkok Power Plant

Low-S fuel oil		Medium-S fuel oil		Natural gas	
Ultimate analysis	(wt.%, ash-free)	Ultimate analysis	(wt.%, ash-free)	Volumetric analysis	(vol.%, db)
C	85.40	C	86.21	CH_4	76.46
H	13.10	H	10.74	C_2H_6	6.56
O	0.00	O	0.00	C_3H_8	1.18
N	0.92	N	0.99	C_4H_{10}	0.42
S	0.28	S	1.76	C_5H_{12}	0.17
W	0.30	W	0.30	C_6H_{14}	0.06
				CO_2	13.5
				N_2	1.65

The excess air ratio at the furnace outlet in these 200-MW and 300-MW boiler units with the pressurized draft system is controlled at values of 1.08 and 1.07, respectively, for the full unit load. At these excess air ratios, the CO emission from high-capacity utility boilers is reported to be (almost) zero, as revealed by the experimental results obtained on one of the 310-MW boiler units at SBPP and elsewhere [4–6]. The effects of the CO emission on both thermal and environmental performances of the boilers are therefore ignored in this work.

Recirculating flue gas of about 10% (by vol.), extracted from gas flow between the boiler economizer and air heater and injected through nozzles into the furnace bottom region, is used in both boilers for adjusting the temperature of superheated and reheated steam as well as for NO_x reduction. However, no gas-cleaning facilities are installed at the power plant; hence, all pollutants are entirely emitted from these boiler units into the atmosphere through stacks, 76 m height of the 200-MW units (unit nos. 1 and 2), 84 m height of the 310-MW unit (unit no. 3), and 110 m height of another two 310-MW units (unit nos. 4 and 5).

3.2. Operating conditions

In accordance with the proposed computational methodology, the thermal and environmental characteristics for a particular 310-MW boiler unit co-fired with medium-S fuel oil and natural gas at different loads were predicted using these characteristics for firing each fuel on its own. Meanwhile, the computations for the 200-MW boiler unit were limited by one fuel only (low-S fuel oil). The fuel properties given in Table 1 were used in these computations.

For the 100% unit load, the required input data included the design parameters of steam, flue gas and combustion air. However, in computations for the reduced boiler loads, some parameters (steam flow rate, temperature and pressure of

Table 2
Major operating variables for the 200-MW boiler unit firing low-S fuel oil at different unit loads

Variable	Symbol	Unit	Relative load					
			100%	90%	80%	70%	60%	50%
Excess air ratio at the furnace	α_f [a]	–	1.07	1.07	1.09	1.11	1.12	1.14
Temperature of air pre-reheated in the auxiliary air pre-heater	t_{aex}	°C	76	77	78	80	85	90
Flow rate of superheated steam	$\dot{m}_{sh}$	kg/s	180	163	144	126	108	91
Temperature of superheated steam	t_{sh}	°C	540	540	540	540	540	540
Pressure of superheated steam	p_{sh}	bar	129	129	129	129	129	129
Flow rate of reheated steam	$\dot{m}_{rh}$	kg/s	153	138	122	107	92	79
Temperature of steam at the reheater inlet	$t_{rh,1}$	°C	362	354	347	342	332	322
Pressure of steam at the reheater inlet	$p_{rh,1}$	bar	35	31	29	26	22	17
Temperature of steam at the reheater outlet	$t_{rh,2}$	°C	542	540	539	537	532	527
Pressure of steam at the reheater outlet	$p_{rh,2}$	bar	33	29	27	24	21	16
Temperature of feedwater	t_{fw}	°C	243	238	232	229	219	209
Pressure of feedwater	p_{fw}	bar	155	152	150	148	146	145
Temperature of the waste gas	ϑ_{wg}	°C	168	163	159	155	148	141
Fraction of flue gas recirculation	r	–	0.10	0.11	0.13	0.15	0.17	0.20
Temperature of recirculating flue gas	ϑ_r	°C	350	346	341	334	325	310
Temperature of hot air	t_{ha}	°C	274	270	268	263	256	245

[a] Estimated based on excess oxygen at the boiler economizer outlet.

reheated steam and feedwater, temperature of the waste gas, excess oxygen at the economizer outlet, etc.) were assumed in accordance with load-related programs obtained from boiler monitoring at 50–100% unit loads.

As an illustration, Table 2 provides the key input variables, important for predicting the fuel consumption and emissions, for the 200-MW boiler unit firing low-S fuel oil at different relative loads. Similar load-related input data were generated for the 310-MW boiler unit fired with pure medium-S fuel oil and pure natural gas.

3.3. Experimental tests for validating the emission models

Prior to the computational study, one of the 310-MW boiler units of the SBPP was tested with the aim of validation of the emission models for NO_x and SO_2 for two fuel options: (1) firing medium-S fuel oil (C=86.35%, H=11.19%, O=0%, N=0.86%, S=1.30%, W=0.30%, ash-free basis), and (2) firing natural gas whose volumetric analysis turned out to be quite close to that provided in Table 1.

When firing fuel oil, performance tests were conducted at three unit loads, 100, 75 and 50%, whereas the boiler was run at two loads only, 50% and 72%, when operated on natural gas. The performance test on this boiler was not manageable in the case of firing natural gas at the full load, because of the constraints associated with steam temperature control.

During the tests, NO_x and SO_2 emission concentrations were measured together with O_2 concentrations, at the boiler economizer outlet using a portable "Testo-350" gas analyzer, which secured measurements of the above concentrations with the errors ±5% for NO_x (as NO), ±2.5% for SO_2, and ±0.2% (by vol.) for O_2. The concentrations were measured every 3 min during the testing period (30 min) for boiler steady state.

The O_2 concentrations were used for determining the excess air ratio and also for correcting the emission concentrations to the 6% O_2 dry flue gas for each test run.

Besides the gas concentrations, actual variables (same as in Table 2) were collected in the test runs for firing each fuel on its own in order to accomplish an accurate prediction of the NO_x and SO_2 emissions. However, for firing pure natural gas at the 100% load, these variables were generated by extrapolation, using respective experimental data acquired for the 50% and 72% unit loads and also relevant statistical data.

4. Results and discussion

4.1. Validating the NO_x and SO_2 emission models

Fig. 1 compares predicted and experimental NO_x emission concentrations, all corrected to the 6% O_2 dry flue gas, for firing "experimental" medium-S fuel oil (with N=0.86% and S=1.3%) and pure natural gas. For the particular unit load, the experimental data in Fig. 1 are scattered within a 15% band, mainly because of fluctuations in operating variables (in response to various external and internal boiler disturbances). The comparison shows that the prediction of NO_x emissions

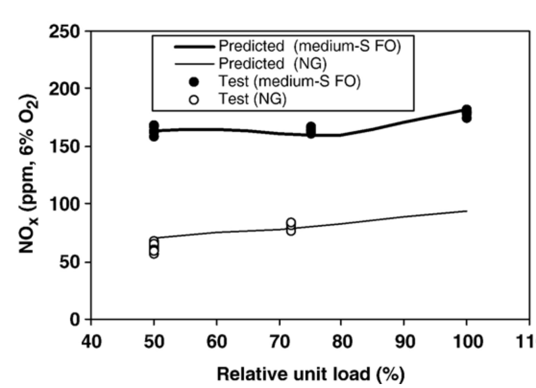

Fig. 1. Predicted and experimental NO_x emissions from the 310-MW boiler unit for firing medium-S fuel oil and natural gas at different loads.

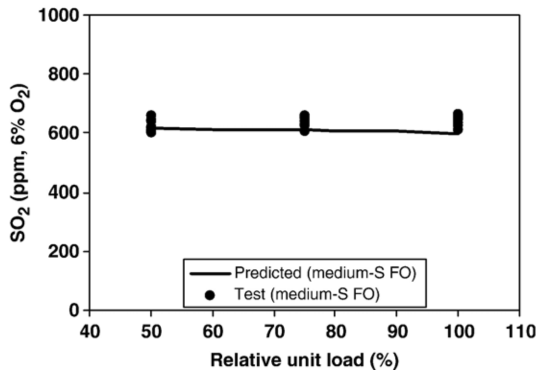

Fig. 2. Predicted and experimental SO_2 emissions from the 310-MW boiler unit for firing medium-S fuel oil at different loads.

from this boiler unit can be done with sufficient computational accuracy, of about 15% for the case of firing fuel oil and 25% for the case of firing natural gas.

For the 100% load, the contributions of thermal NO_x to the total yield of nitrogen oxides were found to be about 20% for firing the fuel oil and 15% for firing the natural gas. Elevated formation of thermal NO_x indicated a quite weak effect of the flue gas recirculation applied on this boiler (when the flue gas was injected into the furnace at the bottom region of the furnace). As seen in Fig. 1, for the 50–100% unit loads, the NO_x emissions from the fuel oil combustion were 2.2–2.5 times greater than those from firing natural gas.

For the full unit load, the (maximum) NO_x emissions for the two fuels were somewhat lower than the corresponding national emission standards for NO_x, 195 ppm (on 6% O_2 dry gas basis) for fuel oil and 130 ppm (on 6% O_2 dry gas basis) for natural gas, for utility boilers.

In Fig. 2, the predicted dependence of SO_2 on the unit load is shown for the case of firing medium-S fuel oil in this boiler unit. As seen in Fig. 2, the predicted and experimental SO_2 emission concentrations were in good agreement, since the difference between them did not exceed 15% for the 50–100% unit loads. However, the experimental concentrations, 600–660 ppm (in 6% O_2 dry gas), were substantially higher than the national SO_2 emission standard, 480 ppm (in 6% O_2 dry gas), for 300–500 MW units. That is why the utility boilers at SBPP are not operated on pure medium-S fuel oil any longer.

4.2. Model results for the 200-MW boiler unit firing low-S fuel oil

Table 3 shows the heat losses, gross thermal efficiency and fuel consumption determined for the 200-MW boiler unit firing low-S fuel oil at different unit loads using input data in Table 2. The "combustion heat losses" for this boiler were assumed to be q_3 = 0.15% and q_4 = 0% based on the boiler design characteristics and recommendations in Refs. [12,13].

As the incremental rate of q_5 for this 200-MW utility boiler was quite low (0.3% over the 50–100% load range), the gross thermal efficiency turned out to slightly improve with the lowering in the unit load due to 0.54% reduction in q_2. Owing to quasi-uniformity in the thermal efficiency and smooth dependencies of the steam/water properties on the unit load, the fuel consumption by this boiler was, in effect, in linear correlation with the load, diminishing from 12.2 kg/s (at full load) to 6.55 kg/s (at 50% load). However, the specific (per 1 MW h electricity produced) fuel consumption increased from 220 to 236 kg/MW h, respectively, because of the deterioration in the efficiency of the power cycle.

Table 4 shows predicted NO_x (as NO_2), SO_3, SO_2 and CO_2 emission concentrations, emission rates and specific emissions for this boiler unit for different loads. As seen in Table 4, with reducing unit load from 100 to 50%, the NO_x emission concentration diminished from 184 to 141 ppm (in 6% O_2 dry gas), or by about 23%; however, the specific NO_x emissions reduced by 10% only, from 1.22 to 1.10 kg/MW h, because of the effect of the specific fuel consumption (see Table 3). Like in the 310-MW boiler unit, the contribution of thermal NO_x to the total nitrogen oxides formation in this 200-MW boiler unit firing low-S fuel oil was substantial (17%, at full unit load) showing quite low effectiveness of the flue gas recirculation technique applied.

The SO_3 emission from this boiler fired with low-S fuel oil (S = 0.28%) is found to be negligible (about 3 ppm, at the 100% unit load). The effects of SO_3 can be therefore ignored in the assessment of the emission performance of the utilities operated on low-S fuel oil.

The SO_2 emission concentrations for the 50–100% unit loads were at almost constant value, 127–129 ppm (in 6% O_2 dry gas), whereas the specific SO_2 emission increased from 1.17 to 1.27 kg/MW h with reducing unit load from 100 to 50%. Similar effects were found in analysis of CO_2

Table 3
Heat losses, thermal efficiency and fuel consumption for the 200-MW boiler firing low-S fuel oil at different unit loads

Variable	Symbol	Unit	Relative load					
			100%	90%	80%	70%	60%	50%
Heat loss with the waste gas[a]	q_2	%	6.63	6.47	6.46	6.43	6.23	6.09
Heat loss by incomplete combustion	q_3	%	0.15	0.15	0.15	0.15	0.15	0.15
Heat loss owing to unburned carbon	q_4	%	~0	~0	~0	~0	~0	~0
Heat loss due to surface radiation and convection	q_5	%	0.30	0.34	0.39	0.43	0.51	0.60
Gross thermal efficiency	η_b	%	92.92	93.04	93.00	92.99	93.11	93.16
Fuel consumption	$\dot{m}_{FO}$	kg/s	12.2	11.1	9.95	8.78	7.63	6.55
Specific fuel consumption	m_{FO}	kg/MW h	220	222	224	226	229	236

[a] For the excess air ratio at the boiler outlet.

Table 4
Predicted gaseous emissions[a] from the 200-MW boiler firing low-S fuel oil at different unit loads

Pollutant	Unit	Relative load					
		100%	90%	80%	70%	60%	50%
NO_x	ppm	184	171	166	158	150	141
	kg/s	0.0680	0.0569	0.0506	0.0436	0.0370	0.0306
	kg/MW h	1.22	1.14	1.13	1.12	1.11	1.10
SO_3	ppm	2.7	2.2	1.9	1.6	1.2	0.9
	kg/s	0.0017	0.0013	0.0010	0.0007	0.0005	0.0003
	kg/MW h	0.030	0.026	0.023	0.019	0.015	0.011
SO_2	ppm	127	127	127	128	128	129
	kg/s	0.0650	0.0597	0.0535	0.0474	0.0411	0.0355
	kg/MW h	1.17	1.19	1.20	1.22	1.24	1.27
CO_2	vol.%	10.8	10.8	10.8	10.8	10.8	10.8
	kg/s	38.1	34.8	31.1	27.5	23.8	20.5
	kg/MW h	685	695	701	707	715	738

[a] Emission concentrations are corrected to the 6% O_2 dry flue gas.

emissions: the CO_2 concentration in the waste gas stayed constant, 10.8%, and the specific CO_2 emission increased from 685 kg/MW h to 738 kg/MW h when changing the unit load from 100 to 50%.

As can be concluded, this boiler unit firing low-S fuel oil meets the national emission standards for NO_x and SO_2.

4.3. Model results for the 310-MW boiler unit

4.3.1. Firing medium-S fuel oil and natural gas

Fig. 3 shows the fuel consumption by the boiler for two cases, (1) firing medium-S fuel oil (S = 1.76%), and (2) firing pure natural gas, in the 50–100% load range. Like for the 200-MW boiler unit, these dependencies of fuel consumption on the unit load were quite close to the first-order curves for both fuels. Such patterns could be partly explained by quite stable values of the boiler thermal efficiency over the 50–100% load range, 92.95–93.19% for firing fuel oil and 93.34–94.47% for firing natural gas.

Table 5 shows the same, as in Table 4, load-related emissions from the 310-MW boiler unit for these fuel options. Owing to differences in the fuel-N content and operating conditions, the NO_x emissions, 173–193 ppm (in 6% O_2 dry flue gas), were slightly higher compared to those from the 200-MW unit,

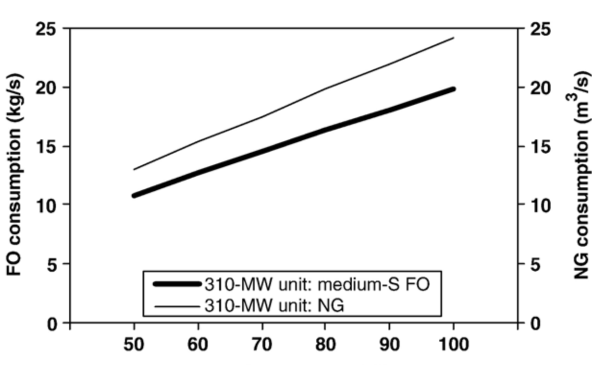

Fig. 3. Fuel consumption by the 310-MW boiler unit for firing medium-S fuel oil and natural gas at different loads.

meeting nevertheless the emission standard for NO_x. For this boiler unit operated at the 50% load, the specific NO_x emissions were at near the same value as for the full load (1.29 kg/MW h), because of the elevated excess air ratio at the furnace (1.21, against 1.08 for the 100% load) and, also, increased specific fuel consumption at this reduced load.

As revealed by the computational results, the SO_3 emission from this boiler unit fired with medium-S fuel oil was rather low. However, it turned out to be 10 times greater (in terms of emission concentration and specific emission) than that from the 200-MW boiler unit firing low-S fuel oil. For the full load and above specified excess air ratio, the predicted SO_3 emission was only 24 ppm, or about 4% (by vol.) of the total SO_x. Taking into account higher toxicity of SO_3 (compared to that of SO_2), the contribution of this gas to the environmental costs may become noticeable.

The SO_2 emission concentrations for this boiler unit firing medium-S fuel oil were found to be high, 766–781 ppm (in 6% O_2 dry flue gas), substantially exceeding the emission standard for SO_2, which corresponded to the 7.64–8.52 kg/MW h specific SO_2 emissions. Hence, medium-S fuel oil can be used as co-fired with the natural gas only.

Despite the CO_2 emission concentration for this boiler (10.6%) was slightly lower than that for firing low-S fuel oil in the 200-MW unit (10.8%), the specific CO_2 emission for the 310-MW unit firing medium-S fuel was about 20% higher compared to this characteristic for the 200-MW boiler unit fired with low-S fuel oil.

As seen in Table 5, the combustion of pure natural gas in the 310-MW boiler unit at 50–100% loads resulted in much better emission performance (NO_x = 0.5–0.6 kg/MW h, CO_2 = 606–653 kg/MW h, SO_x = 0) compared to those for firing medium-S fuel oil in this boiler unit and firing low-S fuel oil in the 200-MW boiler unit.

4.3.2. Co-firing medium-S fuel oil with natural gas

Fig. 4 shows the predicted emission rates for NO_x, SO_3, SO_2 and CO_2 for the 310-MW boiler unit (co-)firing medium-S fuel oil and natural gas. Using these computational data, one can readily estimate the emission rate for the pollutants of interest for any arbitrary EF_{NG} and unit load ranged from 50 to 100%.

Table 5
Predicted gaseous emissions[a] from the 310-MW boiler for firing medium-S fuel oil and natural gas at different unit loads

Fuel option	Pollutant	Unit	Relative load					
			100%	90%	80%	70%	60%	50%
Firing medium-S fuel oil	NO_x	ppm	193	184	173	177	182	178
		kg/s	0.111	0.097	0.082	0.075	0.067	0.056
		kg/MW h	1.29	1.26	1.19	1.24	1.30	1.30
	SO_3	ppm	24	19	16	14	12	9
		kg/s	0.026	0.019	0.014	0.011	0.008	0.005
		kg/MW h	0.30	0.25	0.21	0.18	0.15	0.13
	SO_2	ppm	766	771	774	776	778	781
		kg/s	0.658	0.606	0.549	0.492	0.431	0.367
		kg/MW h	7.64	7.82	7.97	8.16	8.34	8.52
	CO_2	vol.%	10.6	10.6	10.6	10.6	10.6	10.6
		kg/s	62.6	57.1	51.6	46.1	40.3	34.2
		kg/MW h	726	737	749	765	780	794
Firing natural gas	NO_x	ppm	95	89	83	78	76	70
		kg/s	0.052	0.046	0.038	0.032	0.026	0.022
		kg/MW h	0.61	0.59	0.55	0.53	0.51	0.50
	CO_2	vol.%	11.5	11.5	11.5	11.5	11.5	11.5
		kg/s	52.2	47.6	42.8	38.1	33.2	28.1
		kg/MW h	606	614	621	632	642	653

[a] Emission concentrations are corrected to the 6% O_2 dry flue gas.

However, this boiler unit has been typically operated with fuel oil/natural gas feed rate ratio FRR = 0.2, corresponding to $EF_{NG} = 0.81$ [as estimated by Eq. (7)]. Hence, for the co-firing with this fuel option, the SO_x emission rate (emission concentration, specific emission) was significantly reduced (by about 80%) compared to that for firing medium-S fuel oil, whereas the NO_x and CO_2 emissions were diminished by 43 and 13%, respectively. Thus, for the 100% unit load, specific emissions of the gaseous pollutants accounted for about $m_{NO_x} =$ 0.74 kg/MW h, $m_{SO_3} = 0.06$ kg/MW h, $m_{SO_2} = 1.5$ kg/MW h and $m_{CO_2} = 630$ kg/MW h.

As can be roughly estimated, in order to meet the SO_2 emission standard, this 310-MW boiler unit must be co-fired with at least 40% EF_{NG}, or, accordingly, at most 60% energy

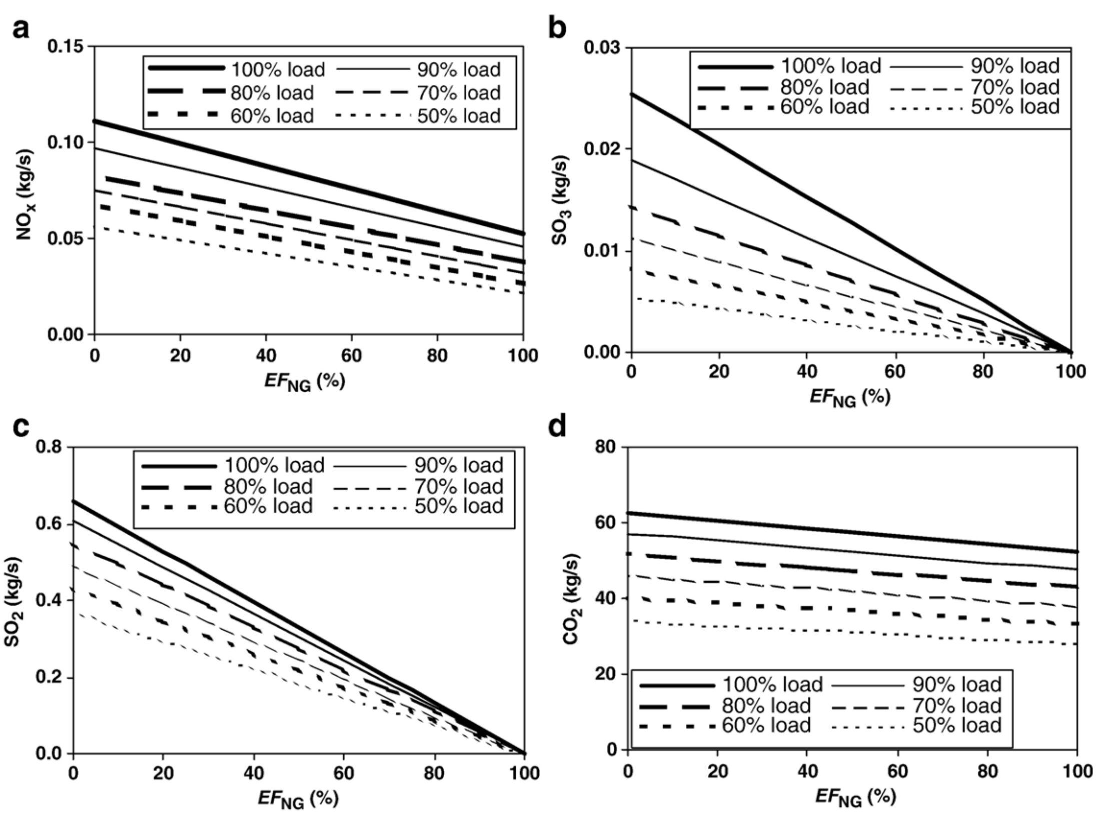

Fig. 4. Effects of EF_{ng} and load on the emission rates of NO_x (a), SO_2 (b), SO_3 (c) and CO_2 (d) for the 310-MW boiler unit (co-)firing medium-S fuel oil and natural gas.

fraction of medium-S fuel oil. For this condition, the NO_x emissions are apparently below the national NO_x emission standard.

5. Conclusions

Computational models were successfully applied for determining emission concentrations, emission rates and specific (per 1 MW h) emissions for the major pollutants (NO_x, SO_3, SO_2, and CO_2) discharged from 200-MW and 310-MW boiler units of the South Bangkok Power Plant for different fuel options and unit loads. The emission models for NO_x and SO_2 were validated by a comparison of the predicted and experimental emission concentrations for the 310-MW boiler unit fired with medium-S fuel oil and pure natural gas at different unit loads.

As revealed by the computational results, the contribution of thermal NO_x to the total nitrogen oxides emissions from these fuel oil/gas-fired boiler units accounts for 15–20%, indicating quite low effectiveness of the flue gas recirculation method applied.

For a typical fuel option (firing low-S fuel oil), a 200-MW boiler unit operated at the full load emits 1.22 kg/MW h of NO_x, 1.17 kg/MW h of SO_2 and 685 kg/MW h of CO_2 and negligible amount of SO_3. With reducing unit load to 50%, the specific NO_x emissions drop by about 10%, while specific SO_2 and CO_2 emissions slightly increase following the change in the specific fuel consumption.

The co-firing of medium-S fuel oil with natural gas at $EF_{NG}=0.81$ (a typical fuel option) in a 310-MW boiler unit operated at full load results in the specific emissions 0.74 kg/MW h for NO_x, 0.06 kg/MW h for SO_3, 1.5 kg/MW h for SO_2, 630 kg/MW h for CO_2.

For the above fuel options, these boiler units meet the emission standards for the NO_x and SO_2. However, at the full load, the NO_x emissions from the 200-MW boiler units firing low-S fuel oil (184 ppm, in 6% O_2 flue gas) are quite close to the emission standard for this pollutant.

The predicted specific emissions can be used for accurate environmental risk assessment for the area surrounding the SBPP, while the fuel feed rates and emission rates are used for quantifying fuel and environmental costs, respectively, for these boiler units.

Acknowledgements

The authors would like to thank the South Bangkok Power Plant (Electricity Generating Authority of Thailand) for allowing the boiler unit testing and for providing relevant data. They also wish to acknowledge the financial support from the Royal Golden Jubilee Ph.D. Program, the Thailand Research Fund (contracts PHD/0118/2544 and BGJ 4580025). The authors thank Ms. C. Wongsaengchan for her contribution to data acquisition.

Nomenclature

α_f	Excess air ratio at the furnace
α_{bz}	Excess air ratio at the burner zone
$C_{NO_2,th}$	Concentration of fuel-and-prompt NO_x (g/m^3)
$C_{NO_2,f+p}$	Concentration of fuel-and-prompt NO_x (g/m^3)
$C_{NO_2,p}$	Concentration of prompt NO_x (g/m^3)
C_{NO_2}	Total NO_x concentration (g/m^3)
C_{O_2}	Residual oxygen concentration at the burner zone (kg/m^3)
C_{SO_2}	Concentration of sulphur dioxide (g/m^3)
C_{SO_3}	Concentration of sulphur trioxide (g/m^3)
η_b	Gross thermal efficiency of a boiler (%)
EF_{NG}	Energy fraction of natural gas (%)
FRR	Fuel feed rate ratio
H_{FO}	Sensible heat of preheated fuel oil (kJ/kg)
h	Specific enthalpy (kJ/kg)
LHV	Lower heating value (kJ/kg or kJ/m^3)
$\dot{m}$	Fuel oil consumption, flow rate, emission rate (kg/s)
m	Specific fuel oil consumption, specific emission (kg/MW h)
q_f	Heat release in the furnace (kW/m^2)
q_2	Heat loss with the waste gas (%)
q_3	Heat loss by incomplete combustion (%)
q_4	Heat loss owing to unburned carbon (%)
q_5	Heat loss owing to radiation and convection (%)
Q_{NG}	Fuel consumption by a boiler firing natural gas (m^3/s)
Q_{av}	Heat input to a boiler (kJ/kg or kJ/m^3)
$\dot{Q}_1$	Total rate of heat transfer to working fluid in boiler components (kW)
Q_{aex}	Heat for external air pre-heating (kJ/kg)
Q_{sb}	Sensible heat of atomizing steam (kJ/kg)
$(O_2)_{bz}$	Residual oxygen concentration at the burner zone (vol.%)
P	Current power output of a unit (MW)
P_0	Nominal power output of a unit (MW)
r	Volume fraction of flue gas recirculation
SBPP	South Bangkok Power Plant
t	Temperature (°C)
$\bar{t}$	Relative time factor
T_m	Maximum temperature at the burner zone for firing fuel oil (K)
T_{max}	Maximum temperature at the burner zone for firing natural gas (K)
ϑ	Temperature of flue gas (°C)
V_g	Volume of wet flue gas (m^3/kg or m^3/m^3)
V_{dg}	Volume of dry flue gas (m^3/kg or m^3/m^3)
W	Moisture content in fuel oil (wt.%)
x_{SO_2}	Fraction (by vol.) of SO_2 in flue gas

Subscripts

aex	External (auxiliary) air (pre-)heater
bz	Burner zone
bw	Blow-down water
cf	Co-firing
f	Furnace
fw	Feedwater
FO	Fuel oil
ha	Hot air
NG	Natural gas
r	Recirculating gas
rh	Reheated (steam)

rh,1	Reheater inlet
rh,1	Reheater outlet
sh	Superheated (steam)
sb	Steam for fuel oil atomization
wg	Waste (flue) gas

Appendix A. Heat input to a boiler

The major constituent of the total heat input to a boiler is the LHV of a fuel burned [12,13]. In this work, the LHV is predicted (within ±1.6% error) based on the fuel analyses (wt.%, as-received basis for fuel oil; vol.%, dry basis for natural gas) to be [11,12]:

- for firing fuel oil (kJ/kg):

$$(\mathrm{LHV})_{\mathrm{FO}} = 339\mathrm{C} + 1030\mathrm{H} - 109(\mathrm{O}-\mathrm{S}) - 25.1\mathrm{W}, \tag{A.1}$$

- for firing natural gas (kJ/m^3):

$$\begin{aligned}(\mathrm{LHV})_{\mathrm{NG}} = {} & 358.18\mathrm{CH_4} + 632.48\mathrm{C_2H_6} \\ & + 912.51\mathrm{C_3H_8} + 1186.46\mathrm{C_4H_{10}} \\ & + 1460.7\mathrm{C_5H_{12}} + 128\mathrm{CO} + 107\mathrm{H_2} \\ & + 234\mathrm{H_2S}.\end{aligned} \tag{A.2}$$

When firing fuel oil, the total heat input may include minor terms, such as sensible heat of fuel (H_{FO}), heat transferred to air in an external air (pre-)heater (Q_{aex}), and heat introduced into the boiler furnace with atomizing steam (Q_{sb}), all being determined by Ref. [13].

The total heat input to a boiler is then predicted to be [12]:

- for firing fuel oil (kJ/kg):

$$(Q_{\mathrm{av}})_{\mathrm{FO}} = (\mathrm{LHV})_{\mathrm{FO}} + H_{\mathrm{FO}} + Q_{\mathrm{sb}} + Q_{\mathrm{aex}}, \tag{A.3}$$

- for firing natural gas (kJ/m^3):

$$(Q_{\mathrm{av}})_{\mathrm{NG}} = (\mathrm{LHV})_{\mathrm{NG}}. \tag{A.4}$$

Appendix B. Heat transfer to working fluid

For a boiler with steam reheating, the rate of heat transferred to working fluid in different boiler's components (or thermal power output of the boiler) is determined by Refs. [12,13] to be:

$$\begin{aligned}\dot{Q}_1 = {} & \dot{m}_{\mathrm{sh}}(h_{\mathrm{sh}} - h_{\mathrm{fw}}) + \dot{m}_{\mathrm{rh}}(h_{\mathrm{rh},2} - h_{\mathrm{rh},1}) \\ & + \dot{m}_{\mathrm{bw}}(h_{\mathrm{bw}} - h_{\mathrm{fw}}).\end{aligned} \tag{B.1}$$

In Eq. (B.1), all enthalpies are found based on temperature and pressure at respective points.

In this work, the flow rate of the blow-down water ($\dot{m}_{\mathrm{bw}}$) was assumed to be 0.5% $\dot{m}_{\mathrm{sh}}$, as specified by the manufacturer.

Appendix C. Thermal efficiency of a boiler

For a boiler firing fuel oil or natural gas, the (gross) thermal efficiency, as percentage of the total heat input, is calculated based on a heat-loss method to be:

$$\eta_{\mathrm{b}} = 100 - (q_2 + q_3 + q_4 + q_5). \tag{C.1}$$

where the heat losses q_2, q_3, q_4 and q_5 are determined by Refs. [12,13]. In the computational study on a boiler firing these fuels at sufficient air supply, the heat loss with unburned carbon q_4 can be neglected [12].

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