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Minimizing fuel and "external" costs for a variable-load utility boiler firing fuel oil

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Abstract

The results of experimental study on excess-air-dependent heat losses and gaseous emissions (NO_x, SO_2 and CO) for a 310 MW fuel oil-fired boiler operating at full and reduced (75 and 50%) loads, are discussed. For the 100% boiler load, data on NO_x emissions indicate the formation of thermal NO along with the fuel and prompt NO. The material balance for SO_x points out the minor formation of SO_3 in fuel oil combustion. The CO emission from the boiler is detected when firing the fuel at excess air of less than 4%.

A cost-based method for excess air optimization is presented. The boiler fuel consumption is incorporated into "internal" (or fuel) costs whereas the experimentally found gaseous emissions are associated with "external" costs (or costs of damage done by the boiler to the environment and humans). The minimum total sum of "internal" and "external" costs for the fully loaded boiler was found to correspond to the (residual) oxygen concentration of 0.73% O_2 in flue gas at the economizer outlet. However, the "compromise" value of 1.1% O_2 was selected as the recommended O_2 set point in boiler operation taking into account the desired diminishing of the total costs as well as the constraints concerning minimized soot formation at extremely low excess air values. Switching the boiler to firing the fuel at the "compromise" excess air ensures a substantial saving of the total costs per unit boiler per year.

Keywords: Excess air; Heat losses; Gaseous emissions; Cost-based optimization

1. Introduction

In the Thai power sector, power plants fired with fuel oil are frequently involved in power-frequency control in response to fluctuations in the electric power demand [1,2]. The boilers at these power plants are subjected to variable loads over a 24 hr period. Accordingly, operating conditions of the boilers (associated with excess of combustion air, flue gas recirculation, etc.) are time-varied as well, following the respective load-related programs.

Excess air, or the excess air ratio, is one of the key operating variables affecting the thermal efficiency of a boiler [3]. Conventionally, optimum excess air, i.e., the one ensuring the highest boiler efficiency, is determined for the 100% boiler load based on minimizing the total sum of excess-air-dependent heat losses, $(q_2 + q_3 + q_4)$, and taking into account operating constraints [3,4].

At the same time, excess air and boiler load affect in a varying degree the major emissions from a particular fuel oil-fired boiler. As known, the rate of NO_x formation in the furnace of a fully loaded boiler is basically reduced with the diminishing of excess air [5,6]. However, under certain operating conditions (e.g., with shortage or absence of gas recirculation) the relationship between the NO_x emissions and excess air becomes more complicated owing to formation of thermal NO [2].

Reduced excess air also promotes lower sulfur trioxide, SO_3, formation [5]. A quasi-linear proportional effect of the excess oxygen concentration (or excess air) on the SO_3 emission from utility boilers fired with high sulfur fuel oil is confirmed experimentally [7]. Since the SO_3 is formed owing to oxidation of a small amount of SO_2, the emission rate of SO_2 is weakly affected by excess air.

Meanwhile, firing fuel oils at extremely low excess air ratios (less than the so-called "critical" excess air ratio, α_{cr}) leads to incomplete combustion associated with the presence of gaseous compounds (CO, H_2, CH_4, etc.) as well as carbonaceous particles in flue gas leaving the boiler [3–5].

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Nomenclature

N/N_0	relative boiler load	
LHV	lower heating value	$MJ \cdot kg^{-1}$
V^0	theoretical volume of air	$m^3 \cdot kg^{-1}$
V_{dg}	volume of dry flue gas	$m^3 \cdot kg^{-1}$
$\dot{m}$	mass flow rate, emission rate	$kg \cdot s^{-1}$
P	price, specific costs	$US\$ \cdot kg^{-1}$
C	costs, cost rate	$US\$ \cdot s^{-1}$
SD	standard deviation	%
q_2	heat loss with waste gas	%
q_3	heat loss by incomplete combustion	%
q_4	heat loss owing to unburned carbon	%
q_5	heat loss owing to surface radiation and convection	%
α	excess air ratio	
η_b	boiler (gross) efficiency	%

Subscripts

cr	critical
ext	"external"
f	fuel
int	"internal"
sp	sampling point
PM	particulate matter

Superscript

r	fuel mass "as-received"

Basically, in well adjusted combustion of fuel oils in utility boilers at $1.0 < \alpha < \alpha_{cr}$, methane and other hydrocarbons are not present in the flue gas. For the particular α in this region, the H_2 concentration in flue gas is found to be about ten times less than the CO concentration which rapidly increases whilst excess air diminishes [7]. Thus, the contribution of hydrogen to the heat loss q_3 as well as to air pollution can be neglected.

The particulate matter emitted from boilers includes two kinds of particles: (1) cenospheres, or coke particles, of 10–50 µm size with a rigid skeleton (surface) and (2) soot particles of 1–10 µm size with a smooth surface [8,9]. Cenospheres mainly consist of unburned carbon (coke) and include compounds of vanadium, nickel, sulfur (as the result of SO_x absorption from flue gas), sodium, etc. The formation of these particles is primarily dependent on the initial fuel properties and weakly affected by operating conditions (temperature and oxygen concentration) as well as fuel droplet size [10]. It is therefore the soot formation that mainly causes a black smoke over a stack when firing fuel oil at extremely low excess air ratios.

Under actual operating conditions of a particular boiler, the formation of CO_2 (per unit fuel mass) is in effect independent of the excess air ratio; however, the emission rate of this greenhouse gas depends on the fuel flow rate, or eventually, on the excess-air-dependent boiler efficiency.

In Ref. [11], a cost-based approach for the optimization of excess air for a fuel oil/gas-fired boiler is considered conceptually. The heat losses affecting the boiler fuel flow rate (or fuel consumption) are incorporated into "internal" boiler costs, i.e., associated with the boiler operation. Meanwhile, the environmental impacts of the pollutants emitted from the particular boiler are also estimated in terms of cost variables and included into "external" boiler costs, inevitably paying for the damage done by the boiler unit to the environment and humans [12,13]. For a given boiler load, the excess-air-dependent total costs comprising both "internal" and "external" costs, are expected to have a minimum which corresponds to optimum excess air.

This research was focused on the practical implementation of the cost-based optimization of the excess air using an experimental approach solely. The paper discusses the effects of excess air and unit loading on the boiler performance and major emissions from the selected utility boiler firing fuel oil. The paper was also aimed at determining the potential saving of the total costs which could be achieved from switching the boiler to firing fuel at the optimized excess air.

2. Optimization model

For a fuel oil/gas-fired steam boiler, the total sum of the excess-air-dependent "internal costs", C_{int}, and "external costs", C_{ext}, is required to be a minimum:

$$C_{int} + C_{ext} \to \min \tag{1}$$

The "internal" costs, unlike in [8], are determined as the total fuel expenditures, i.e., comprising the boiler fuel consumption, to be:

$$C_{int} = P_f \dot{m}_f \tag{2}$$

The "external" costs are found regardless of the energy consumption by forced- and induced-draft fans (actually, weakly varied with air excess changes) to be:

$$C_{ext} = P_{NO_x}\dot{m}_{NO_x} + P_{SO_2}\dot{m}_{SO_2} + P_{SO_3}\dot{m}_{SO_3} + P_{CO}\dot{m}_{CO} + P_{CO_2}\dot{m}_{CO_2} + P_{PM}\dot{m}_{PM} \tag{3}$$

The particulate emission from fuel oil-fired utility boilers is reported to be much lower compared with that from small industrial boilers because of an effect of the furnace residence time [8]. For $1.0 < \alpha < \alpha_{cr}$, the heat loss q_4 associated with unburned carbon accounts for 15–20% of the q_3 level, i.e., less than 0.15% of the fuel LHV [7], and therefore is negligible in the boiler heat balance. Moreover, taking into account a relatively low value of P_{PM} [12], the last term in Eq. (3) can be omitted.

For NO_x (as NO_2), SO_2, SO_3, CO, the emission rates are determined taking into account the fuel flow rate (i.e., boiler fuel consumption) as well as the measured emission concentrations in dry flue gas (in ppm) and its volume at sampling point:

$$\dot{m}_{NO_x} = 2.05 \times 10^{-6} \dot{m}_f NO_x V_{dg} \quad (4)$$

$$\dot{m}_{SO_2} = 2.93 \times 10^{-6} \dot{m}_f SO_2 V_{dg} \quad (5)$$

$$\dot{m}_{SO_3} = 3.57 \times 10^{-6} \dot{m}_f SO_3 V_{dg} \quad (6)$$

$$\dot{m}_{CO} = 1.25 \times 10^{-6} \dot{m}_f CO V_{dg} \quad (7)$$

In the experimental approach, the volume of dry flue gas at sampling point can be approximated taking into account the theoretical volume of air as well as the actual excess air ratio found with the use of the oxygen content in flue gas [4]:

$$V_{dg} \approx \alpha_{sp} V^0 \quad (8)$$

For fuel oil-fired boilers, the emission rate of carbon dioxide can be predicted without determining the CO_2 concentration in flue gas, but accounting for the fuel-carbon content, C^r (%), and fuel flow rate [2]:

$$\dot{m}_{CO_2} = 0.03667 \dot{m}_f C^r \quad (9)$$

Basically, the fuel flow rate is determined using the boiler load and thermal efficiency, the latter being found with the use of the heat-loss method. The method includes all the above heat losses as well as the heat loss owing to the boiler's external surface radiation and convection, q_5. The q_2 and q_5 are estimated by [3]. For a fuel oil-fired boiler of high capacity (> 200 MW_e), "combustion" heat losses, $(q_3 + q_4)$, are quite small ($< 0.1\%$) and normally neglected when excess air is sufficient, i.e., for $\alpha > \alpha_{cr}$ [7].

3. Case study and essential input

The fuel oil-fired utility boiler of a 310 MW capacity has been selected for this study. At the design capacity (100% load), the boiler produces about 280 $kg \cdot s^{-1}$ of superheated steam at 540 °C and 160 bar. The reheated steam of 240 $kg \cdot s^{-1}$ at 40 bar is returned into the boiler to increase its temperature to 540 °C.

Medium-sulfur fuel oil with LHV = 40.9 $MJ \cdot kg^{-1}$ was fired in the boiler during experimental tests. The fuel oil was preheated up to some 100 °C prior to burning, and this was taken into account in the estimation of the boiler available heat [3,4].

The pressurized tangentially-fired boiler furnace (12.53×10.21 m^2), with the burners arranged at four corners, ensures conventional combustion of fuel oil. The rated heat release rate (per unit cross-sectional area) is about 6.27 $MW \cdot m^{-2}$.

Recirculation of some 10% of the total flue gas volume, extracted from the flue gas flow between the boiler economizer and air heater, was used in order to maintain the temperatures of the superheated and/or reheated steam as well as for NO_x reduction. The recirculating gas was injected into the furnace through the nozzles arranged very close to the furnace bottom, on the front and rear water walls.

Required thermal and other operating characteristics used in estimations of the thermal efficiency and fuel consumption were collected from the boiler monitoring system. For measuring the gas concentrations (of major pollutants and O_2) at sampling point, the "Testo-350" gas analyzer was employed.

During the last few years, fuel oil has been supplying to the power plant from local refineries was characterized by a rather stable values of the LHV and fuel carbon: LHV = 40.6–41.5 $MJ \cdot kg^{-1}$, $C^r = 84$–87%, respectively. Therefore, C^r and V^0 included in Eqs. (8) and (9) can be approximated with the use of the respective "resolved" (or per unit LHV) variables [4]:

$$C^r = 2.11 LHV \quad (10)$$

$$V^0 = 0.261 LHV \quad (11)$$

By introduction of Eqs. (10) and (11), the method used in this study becomes independent of the elemental fuel analysis. The only required fuel property, the lower heating value, is thus sufficient to provide excess air optimization based on the experimental approach.

4. Results and discussion

The experimental tests of the selected boiler were conducted at boiler loads of 100, 75 and 50%. In these tests, excess air was however adjusted in different ranges in accordance with the needs of steam temperature control.

The most important results on the gaseous emissions and boiler performance are discussed below. The gaseous emissions (CO, NO_x, SO_2) as well as excess oxygen (O_2), required for determining excess air, are represented as volume concentrations in dry flue gas for actual O_2 measured at sampling point (at the economizer outlet).

For each test run, the operating variables, including O_2, were maintained at the desirable constant values by the boiler control system. However, the variables were subject to macro-fluctuations during the tests because of disturbances of various types. In particular, the O_2 concentrations at the economizer were fluctuated around the O_2 set point with standard deviations SD = $\pm$(0.1–0.25)% O_2 in different tests. In Fig. 1 the O_2 fluctuations are shown for the two particular O_2 set points which are considered to be the averaged values (mean O_2) for both these dependencies.

4.1. Carbon monoxide

Despite a relatively small value, the CO emission plays an essential role in the performance assessment as well as in the excess air optimization, affecting both the "internal" and "external" costs at low excess air ratios. The measured CO concentrations versus excess oxygen for the 310 MW boiler

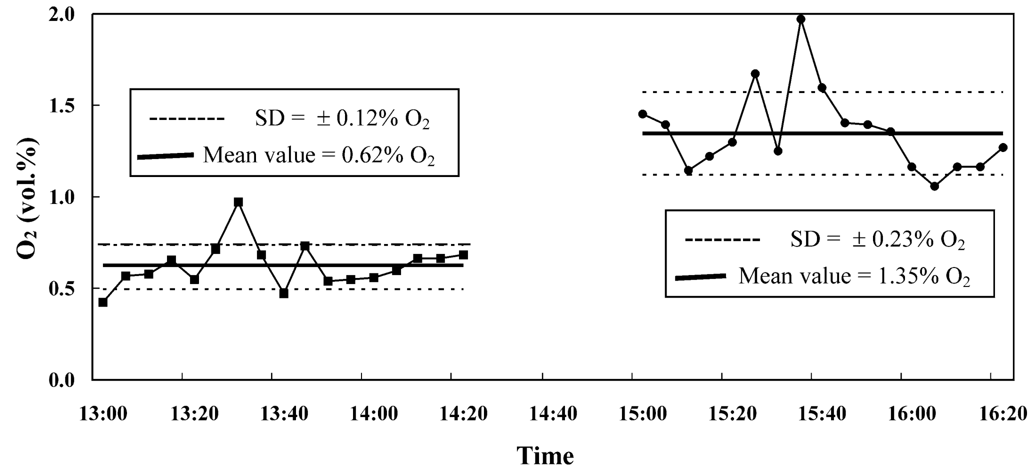


Fig. 1. Fluctuations of the oxygen concentration in dry flue gas at sampling point during the tests.

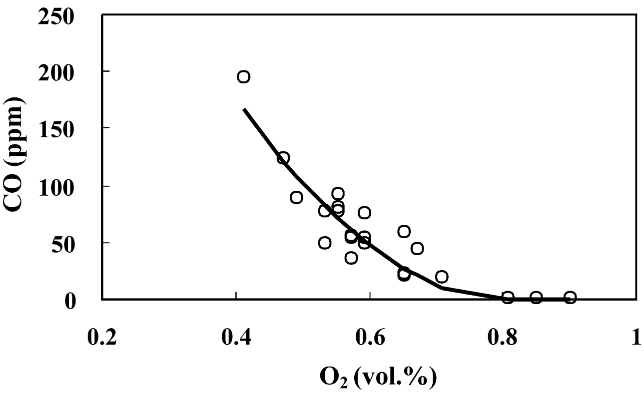


Fig. 2. Measured CO concentrations in dry flue gas at various excess air for the 310 MW fuel oil-fired boiler operating at 100% load.

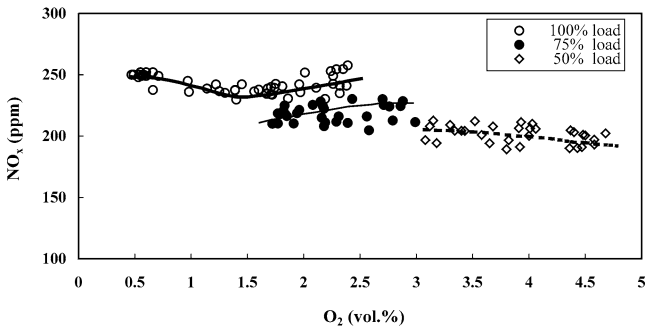


Fig. 3. Effect of excess air on the actual NO_x concentrations in dry flue gas for the 310 MW fuel oil-fired boiler operating at three different loads.

operating at 100% load are shown in Fig. 2. For the excess air ratios of $\alpha < \alpha_{cr}$, experimental data on CO emission (in vol.%) can be approximated by the square-order fit:

$$CO = 50 \cdot (\alpha_{cr} - \alpha)^2 \tag{12}$$

where $\alpha = \alpha_{sp} = 21/(21 - O_2)$ [4].

As seen in Fig. 2, the critical excess oxygen for 100% boiler load is about 0.8% O_2 which corresponds to critical excess air ratio $\alpha_{cr} = 1.04$, or 4% in terms of excess air. However, with the boiler load reduction, one can expect the increase in α_{cr} followed by the increase in CO for any fixed excess air ratio lower than α_{cr} [4].

In the test runs for the 75 and 50% boiler loads, the CO emissions were found to be negligible, since even starting (or lowest) values of excess air were sufficient to suppress CO emission.

4.2. Nitrogen oxides

The measured emission concentrations of NO_x are shown in Fig. 3. As may be seen, the effects of excess air and boiler load on NO_x emissions are rather noticeable.

The test data for 100% boiler load indicated formation of thermal nitric oxide along with fuel and prompt NO. Thus, when excess air was relatively low (at excess oxygen less than 1.5–1.7% O_2), the NO_x emissions increased with lowered excess air, consequently followed by an increase in the flame temperature. The latter is the major factor responsible for thermal NO formation [6]. On the other hand, for the excess oxygen greater than 1.7% O_2, NO_x emissions were, as expected, intensified with the increase in excess air. Despite the diminishing of the temperature (followed by the rapid reduction of thermal NO formation), the rate of NO_x formation was increased owing to growing contribution of fuel and prompt NO with the excess air increase.

The obtained data on NO_x emissions for the full boiler load showed a quite weak effect of the flue gas recirculation because of the inappropriate location of the gas injection into the furnace. This effect could be much stronger and useful in NO_x mitigation if the recirculating flue gas was injected into the active combustion zone directly, e.g., as premixed with combustion air.

With the boiler load reduction, the temperature level in the active combustion zone is normally reduced owing to deeper cooling of combustion products and flame dilution by excess air. That is why, in boiler operation at 75 and 50% loads, thermal NO was not formed, and the yield of NO_x emissions depended on the rates of fuel and prompt NO formation only. In the 75% load test, NO_x formation

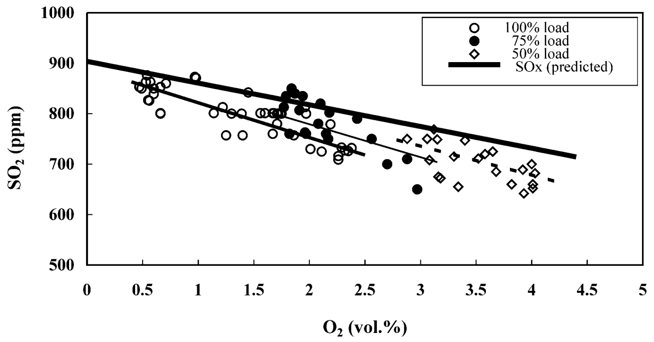


Fig. 4. Effect of excess air on the actual SO_2 concentrations in dry flue gas for the 310 MW fuel oil-fired boiler operating at three different loads: $SO_x = SO_2 + SO_3$.

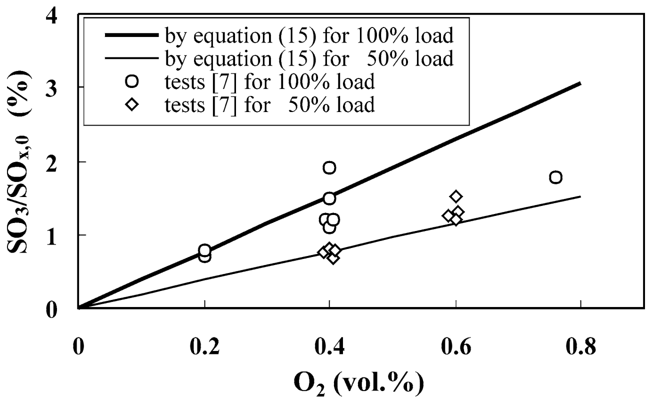


Fig. 5. Comparison of predicted by Eq. (15) and experimental [7] SO_3 emissions, as percentage of $SO_{x,0}$, for 100 and 50% loads of a 308 MW boiler firing high-sulfur fuel oil at different values of excess air.

was found to increase with the growing variation in excess air from 1.7 to 3% O_2, which is typical for the fuel and prompt NO. Meanwhile, for the 50% boiler load, the NO_x emissions were found to diminish with the excess air increase because of the growing dilution effect resulting in significant reduction in the flame temperature.

4.3. Sulfur oxides

Fig. 4 shows the test data (dots) on SO_2 emission for the three boiler loads in comparison with the theoretical dependence (solid line) for SO_x emissions on excess air. Basically, the SO_x profile coincides with the SO_2 profile obtained for varying excess air with the assumptions of: (1) zero SO_3 formation, and (2) fuel-sulfur stability.

For the 100 and 50% loads, almost all of the experimental dots are located below the theoretical SO_x profile. Indirectly, this fact points out SO_3 formation in the boiler furnace. The test data for the 75% boiler load performs less generality because of probable fluctuations of fuel sulfur during the tests.

As seen in Fig. 4, SO_3 formation is rather weak, accounting for a few percent of the total SO_x and depending on both excess air and boiler load. The following relationship between SO_3 emission (in ppm), on the one hand, and the relative boiler load as well as the oxygen concentration in dry flue gas (%), on the other hand, approximates the test data:

$$SO_3 = 35(N/N_0)O_2 \tag{13}$$

The SO_x concentration in dry flue gas (in ppm) for zero excess air depends on fuel sulfur, S^r (%), and the volume of dry flue gas given by Eq. (8):

$$SO_{x,0} = SO_{2@O_2=0} \approx 7 \times 10^3 (S^r/V^0) \tag{14}$$

Hence, the percentage of “in-furnace” SO_3 formation, related to $SO_{x,0}$ (in our tests $SO_{x,0} \approx 900$ ppm, as seen in Fig. 4), can be determined by:

$$SO_3/SO_{x,0} = 3.89(N/N_0)O_2 \tag{15}$$

In this work, Eq. (15) was also validated for the case of firing high-sulfur fuel oil. Fig. 5 provides the $SO_3/SO_{x,0}$ percentage calculated by Eq. (15) for the 100 and 50% loads in comparison with test data obtained for the same loads of the 308 MW boiler fired with high-sulfur fuel oil ($S^r = 2.3\%$) by direct measurements of SO_3 in flue gas [7].

In effect, the empirically obtained Eq. (15) is regardless of fuel-sulfur and can be applied for the cases of firing medium- and high-sulfur fuel oils; with the preliminary estimated $SO_{x,0}$, one can predict SO_3 emission in the boiler furnace for the desired (N/N_0) and O_2.

For the case of firing low-sulfur fuel oil, the level of SO_3 formation becomes quite negligible and can be omitted in excess air optimization.

4.4. Boiler efficiency and fuel consumption

In this work, the heat loss q_3 was estimated using the above test data on the CO emission. As mentioned above, there is a certain correlation between q_4 and q_3 for utility boilers firing fuel oils at extremely low excess air ratios: the heat loss with unburned carbon is estimated to be 15–20% of the heat loss owing to incomplete combustion [7]. Thus, taking into account quite small level of q_3 for the studied boiler, the q_4 was neglected in further calculations.

The heat losses, as well as the gross thermal efficiency and fuel flow rate to be used in excess air optimization are shown in Table 1 for the boiler of interest operating at 100% load. The independent variable, excess oxygen, was varied in the range of 0.37 to 2.36% corresponding to the excess air ratios of 1.02 to 1.14, respectively. As seen in Table 1, the boiler efficiency attained the maximum at 0.73% O_2; accordingly, for this excess oxygen the fuel flow rate was found to be minimum. Meanwhile, the fuel consumption by the boiler of interest was almost constant in all of the conducted tests.

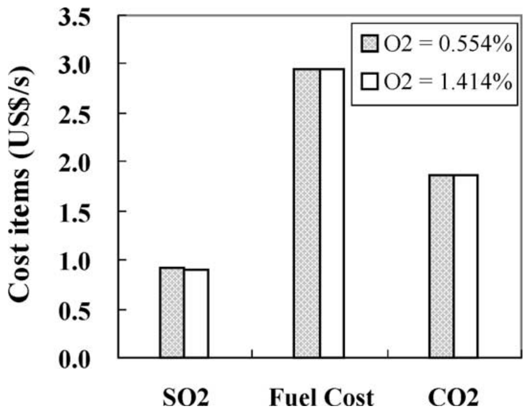
4.5. Total costs

As an illustration, the break-down of the various items of the “external” costs in Eq. (3) along with the fuel costs

Table 1
Heat losses, gross efficiency and fuel flow rate for the 310 MW fuel oil-fired boiler operating at 100% load for various O_2 concentrations measured at sampling point (economizer outlet)

Variable	Unit	Oxygen concentration in dry flue gas (%)						
		0.37	0.73	1.08	1.41	1.74	2.05	2.36
q_2[a]	%	6.536	6.584	6.630	6.674	6.718	6.759	6.800
q_3	%	0.0635	0.0159	negligible	negligible	negligible	negligible	negligible
q_5	%	0.2	0.2	0.2	0.2	0.2	0.2	0.2
η_b	%	93.191	93.216	93.170	93.126	93.082	93.041	93.000
$\dot{m}_f$	$kg \cdot s^{-1}$	19.595	19.584	19.589	19.594	19.599	19.603	19.606

[a] Calculated for the excess air in waste flue gas.



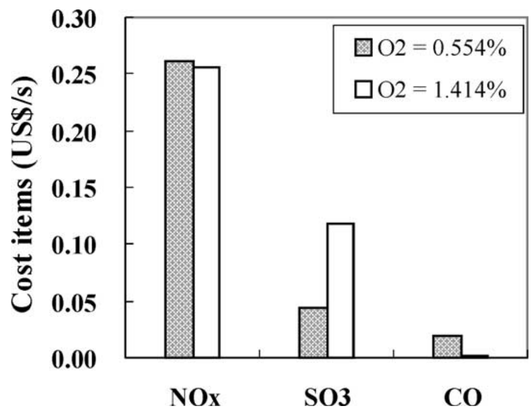


Fig. 6. Break-down of the major (a) and minor (b) costs incorporated into the total costs for the 310 MW fuel oil-fired boiler operating at 100% load for two different values of excess air.

calculated by Eq. (2) are shown in Fig. 6 for the boiler operating at 100% load at two distinct values of excess air. The individual cost items are affected by the fuel oil consumption and the fuel price as well as by the specific (i.e., per unit mass) "external" costs and emission rates for the relevant pollutants. The fuel costs were calculated for $P_f = 0.15$ $US\$ \cdot kg^{-1}$. Meanwhile, the specific "external" costs, or costs of damage done to the environment and humans by 1 kg of a particular airborne pollutant, were assumed by [12,13]: $P_{NO_x} = 2.4$ $US\$ \cdot kg^{-1}$, $P_{SO_3} = 3.0$ $US\$ \cdot kg^{-1}$, $P_{SO_2} = 1.72$ $US\$ \cdot kg^{-1}$, $P_{CO_2} = 0.03$ $US\$ \cdot kg^{-1}$, $P_{CO} = 0.99$ $US\$ \cdot kg^{-1}$ and $P_{PM} = 0.6$ $US\$ \cdot kg^{-1}$.

The major contribution to the total costs is made by fuel costs as well as by CO_2 (despite a relatively low value of P_{CO_2}) and SO_2, as seen in Fig. 6(a). The cost impacts of NO_x, SO_3 and CO can be estimated to be minor (see Fig. 6(b)).

Apparently, varying the furnace excess air results in a change in the cost pattern, and the minor costs (i.e., for NO_x, SO_3 and CO) are noticeably affected by excess air, as seen in Fig. 6(b). However, the cost balance can be changed with fluctuations in fuel properties and boiler load. The effect of the boiler load on the major costs is quasi-linear, whereas the response of the minor costs also depends on the possible changes in combustion conditions followed by the reduction in the boiler load.

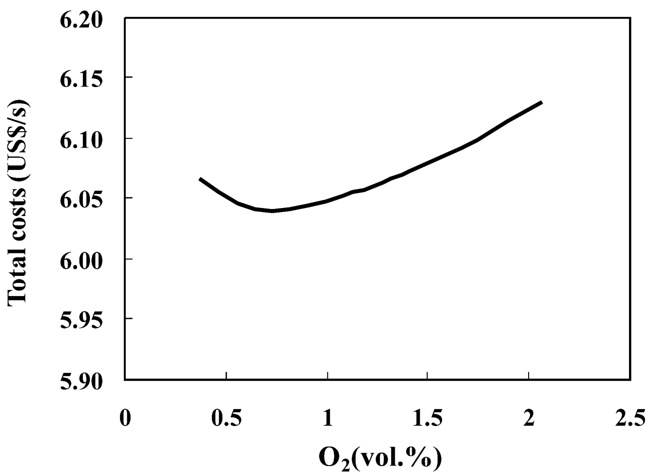


Fig. 7. Total costs versus excess air for the 310 MW boiler firing fuel oil at 100% load.

4.6. *Optimum and "compromise" excess air*

In Fig. 7 the dependence of the total costs on excess air is shown for the boiler of interest operating at 100% load. The minimum of the total costs corresponds to the optimum excess oxygen of 0.7–0.75% O_2. However, these values are in the vicinity of the critical excess oxygen and, taking into account the O_2 fluctuations (see Fig. 1), cannot be recommended as an actual operating variable because of possible elevated soot formation. An increase in the above optimum O_2 by at least 1.5*SD* (or approximately 0.35% O_2) up to "compromise" excess oxygen of 1.1% O_2, seems to provide the desired reduction in the fuel and "external" costs with minimized soot formation in the boiler furnace. Indeed, switching the excess oxygen from the currently employed value of 1.5% O_2 to the "compromise" set point, may ensure a saving of some 0.025 US$\cdot$kg^{-1} per boiler unit, as seen in Fig. 7. This result is equivalent to the potential saving of fuel and "external" costs of about 630 000 US$ per unit boiler per year assuming that the boiler is operated at the full load during 7 000 hrs in a year.

Basically, the excess air optimization can be carried out for any arbitrary boiler load, and respective corrections might be done in the load-related program for the O_2 set point of a variable-load boiler.

5. Conclusions

An experimental approach has been successfully applied in minimizing fuel and "external" (i.e., associated with the boiler's environmental impact) costs for the 310 MW fuel oil-fired boiler. The selected cost-based optimization method included experimental data on the boiler thermal and environmental performance. The only fuel property, the lower heating value, was used in the optimization technique.

Prior to the optimization, the effects of excess air on the boiler performance and gaseous emissions were studied for 100, 75 and 50% boiler loads.

The CO emissions were found in the low-excess-air tests of the 100% loaded boiler, when excess oxygen at sampling point was lower than 0.8% O_2 which corresponded to the critical excess air ratio of 1.04 at the economizer outlet.

The noticeable effects of excess air as well as the boiler load on NO_x emissions were found in this research. The test data indicated the formation of thermal nitric oxide along with fuel and prompt NO in the boiler operating at full load. Lower excess air (when excess oxygen values were less than 1.5–1.7% O_2) led to increased NO_x emissions which were associated with the increased flame temperature. Thus, the data indicated a quite weak effect of the flue gas recirculation because of the inappropriate location of the gas injection into the furnace.

Meanwhile, for 75 and 50% boiler loads, NO_x emissions depended on the rates of fuel and prompt NO formation only, because of reduction in the temperature level in the furnace. In the 75% load test, NO_x formation was found to increase with the growing variation in excess oxygen from 1.7 to 3% O_2, which is typical for the prompt and fuel NO. In the boiler tests at 50% load, even with the excess air increase, NO_x emissions reduced because of dilution effect by the relatively high excess air in these tests.

The experimental results indicated minor SO_3 formation, the rate of which was found from comparison of the theoretical dependence of SO_x on excess air with the test data on SO_2. The empirical equation including effects of excess air as well as boiler load was developed for estimating SO_3 formation for the boiler fired with medium-sulfur fuel oil.

The total fuel and "external" costs for the fully loaded boiler were found to have a minimum corresponding to 0.7–0.75% O_2 at the economizer outlet. However, the "compromise" value of 1.1% O_2 was selected as the recommended O_2 set point in boiler operation taking into account the desired diminishing of the total costs as well as the constraints concerning minimized soot formation at extremely low excess air values. Switching excess oxygen at the economizer outlet from the current set point of 1.5% O_2 to the "compromise" value ensures a significant saving, of about 630 000 US$, in the total costs per boiler unit per year.

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