IMPROVEMENT OF COAL-FIRED GENERATION UNITS AT LAMMA POWER STATION FOR NOx EMISSION CONTROL

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ABSTRACT

Combustion of coal for electricity generation inevitably leads to emission of Nitrogen Oxides (NOx) and other air pollutants. To improve the air quality of Hong Kong, the HK Special Administrative Region (SAR) Government has been tightening emission allowances from the power plants. Facing this challenge, Lamma Power Station has retrofitted advanced pollutant abatement facilities in some of its older electricity generation units. Two coal-fired generation units were retrofitted with Alstom low NOx combustion system. Through modifications to the burners and addition of over-fire air nozzles, NOx emission has been significantly reduced by 30 % – 60 % at different unit loads. At the same time, modifications have been made to the coal pulverizers and boiler control system to improve the fuel flexibility. By inputting the fuel properties and calorific values of different ranks of coal being burnt into the control system, the boiler is capable of burning both bituminous and sub-bituminous coal at optimal conditions. After completion of the modification, boiler tuning was performed to ensure an efficient and safe operation of the boilers. Function curves for excess O_2 in flue gas and openings of over-fire air dampers at different unit loads were obtained through the boiler tuning. Finally, performance tests were carried out to confirm the emission levels of NOx and carbon monoxide, and unburnt carbon in fly ash. The low NOx combustion system retrofit project not only significantly reduced the NOx emissions level of the two generation units, but also enhanced their combustion efficiency when burning coal of different grades.

KEY WORDS

NOx Emission, Low NOx Burner, Concentric Firing System, Staged Combustion

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BACKGROUND INFORMATION OF LAMMA POWER STATION

Lamma Power Station (LPS) is one of the major power plants in Hong Kong. LPS supplies electricity to Hong Kong Island, Apleichau and Lamma Island; and serves more than 550,000 customers. Currently, LPS has a total installed capacity of 3,737 MW with eight coal-fired generation units, five oil-fired open-cycle gas turbines, two gas-fired combined-cycle gas turbines (CCGT), one wind turbine and one solar power system. Since its commissioning in 1982, LPS has maintained efficient and reliable operations, contributing to Hongkong Electric's world-class electricity supply reliability of over 99.999 %.

NECESSITY FOR EMISSION CONTROL IN POWER PLANT

Nitrogen oxides (NOx), sulphur dioxide (SO_2) and respirable suspended particulates (RSP) have been and continue to be the three major air pollutants in Hong Kong. According to the latest Hong Kong Air Pollutant Emission Inventory, the pollutant emission sources are categorized into six major sectors, which are public electricity generation, road transport, navigation, civil aviation, other fuel combustion and non-combustion sources. In 2012, emission of NOx, SO_2 and RSP from public electricity generation sector contributed to 28 %, 47 % and 16 %, respectively, of the total annual emissions in Hong Kong. In order to enhance the air quality, the HK SAR Government Environmental Protection Department has implemented measures to reduce pollutant emissions from the public electricity generation sector. Starting from 2008, Environmental Protection Department has made use of "Technical Memorandum for Allocation of Emission Allowances in Respect of Specific Licences" to control the quantities of NOx, SO_2 and RSP emissions from electricity works in Hong Kong. A total of four technical memoranda have been issued to set out the quantity of annual emission allowances of power stations for each and every emission year from 2010, 2015, 2017 and 2019 respectively. The approximate emission allowance of each type of pollutants allocated to Lamma Power Station including Lamma Power Station Extension are given in Table 1.

Year / Pollutants	2010 and thereafter (Base)	2015 and thereafter	2017 and thereafter	2019 and thereafter
Nitrogen oxides (NOx)	15,890 (100 %)	10,020 (63.1 %)	9,450 (59.5 %)	8,980 (56.5 %)
Sulphur dioxide (SO_2)	9,370 (100 %)	6,780 (72.4 %)	5,200 (55.5 %)	4,250 (45.4 %)
Respirable suspended particulates (RSP)	470 (100 %)	300 (63.8 %)	250 (53.2 %)	200 (42.6 %)

Table 1: Allocated annual emission allowances to Lamma Power Station (in tonne)

Comparing 2019 to 2010, the emission allowances of NOx, SO_2 and RSP allocated to LPS will be reduced by 43.5 %, 54.6 %, and 57.4 % respectively. In order to comply with the emission allowances, all the coal-fired generation units in LPS are installed with emission abatement facilities. Wet scrubbing-type Flue Gas Desulphurization (FGD) plants have been installed in six coal-fired generation units to reduce SO_2 emission. After passing through the FGD plant, approximately 90-95 % of SO_2 in the flue gas is converted to calcium sulphite slurry, which is further oxidized to gypsum for use in building industry. Other than reducing SO_2 emission, FGD plant also helps remove particulates in flue gas. Regarding RSP control, all coal-fired generation units in LPS are equipped with Electrostatic Precipitators, which collect and remove about 99 % of particulates in the flue gas. To meet the tight emission allowance, LPS also maximizes the use of its only two natural gas-fired generation units, prioritizes uses of the coal-fired generation units according to their environmental performances, uses coal with low sulphur content and phased out heavy fuel oil by ultra low sulphur diesel, etc.

In addition to the control of SO_2 and RSP emission, reduction of NOx is also a major challenge to LPS. In all combustion process, NOx can be formed from three mechanisms, which are thermal NOx, fuel NOx and prompt NOx. In coal-fired generation units, major sources of NOx emission are thermal NOx and fuel NOx. Thermal NOx are formed from the reaction of nitrogen and oxygen molecules in the combustion air. Formation of thermal NOx is strongly dependent on combustion temperature and oxygen availability. When combustion temperature exceeds 1,300 ^{o}C and oxygen is readily available, formation rate of thermal NOx will increase significantly. On the other hand, fuel NOx is formed from the combustion of nitrogen-bound fuel e.g. coal. During the combustion, nitrogen in fuel will be ionized and oxidized to form fuel NOx. Formation of fuel NOx is sensitive to nitrogen content in fuel and oxygen availability. Thermal NOx and fuel NOx respectively contribute to 20 – 40 % and 60 – 80 % of total NOx emission of coal-fired generation units. Different abatement technologies have been developed for reduction of NOx emission, such as reducing peak combustion temperature, reducing residence time at peak temperature, chemical reduction of NOx and removal of nitrogen in flue gas, etc.

IMPROVEMENT OF COAL-FIRED GENERATION UNITS FOR NOx CONTROL

In 2009 and 2010, two 350MW coal-fired generation units L4 and L5 in Lamma Power Station were retrofitted with low NOx combustion system. In addition to reducing NOx emission level of the generation units, the retrofit also aimed to increase the boiler capability of burning coal with different calorific values. The low NOx retrofit project was divided into (1) In-furnace modification, (2) Modification to coal pulverizers and (3) Modification to boiler control.

In-Furnace Modification

A "Low NOx Concentric Firing System (LNCFS)^{TM} Level 2" was adopted for the in-furnace modification to the two generation units. The in-furnace modification included upgrade of burners and addition of Secondary Over-Fire Air (SOFA) System. A schematic diagram of the in-furnace modification and the layout of the post-retrofit boiler are given in Figures 1 and 2, respectively.

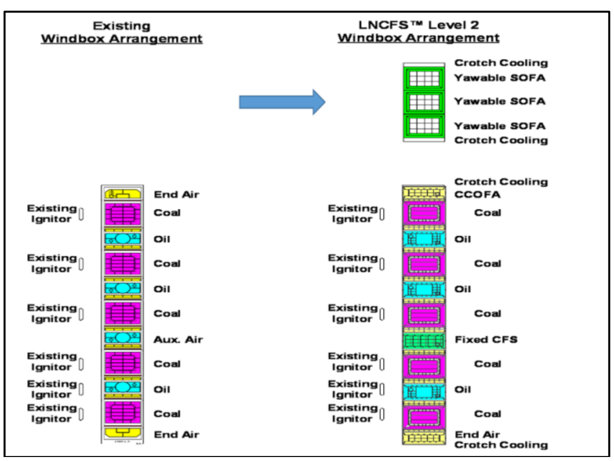

Figure 1: Schematic diagram of In-furnace Modification

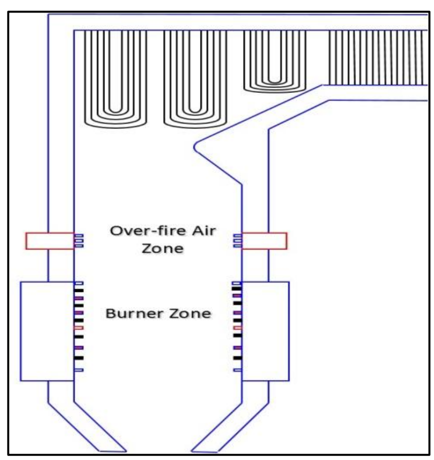

Figure 2: Layout of post-retrofit boiler

The coal burner system used in L4 and L5 is "tangential corner firing burner system". Coal burners, oil burners and auxiliary air nozzles form an integral windbox, and located separately at the four corners of the boiler proper. Twenty coal burners are installed at five different elevation levels. At each elevation level, coal burners are pointing tangentially to an imaginary circle centered at the furnace. The burner nozzles direct the coal and air streams flow into the furnace, forming a "fireball" inside the boiler. This conventional burner system design does not take NOx suppression into consideration. Modifications are necessary to reduce NOx emission.

"LNCFS™ Level 2" burner system adopted vertical and horizontal combustion staging concepts to reduce NOx formation. As shown in Figure 2, vertical combustion staging is achieved by dividing the combustion process sequentially in the burner and over-fire air zones. Only about 75 % of the total required air is injected into the burner zone for the combustion. As a result, a fuel-rich combustion would occur in the burner zone, leading to an incomplete combustion. Due to lack of available oxygen and lowered combustion temperature, formation of fuel NOx and thermal NOx in the burner zone would reduce. Remaining 25 % of the required air is injected into the over-fire air zone to complete the combustion. The unburnt fuel from the burner zone is oxidized in a fuel-lean environment in the over-fire air zone to keep the combustion temperature low, preventing formation of thermal NOx. An illustration of the temperature profiles of the original firing system and the retrofitted firing system is given in Figure 3.

Within the burner zone, horizontal combustion staging is achieved by the Concentric Firing System (CFS). As shown in Figure 1, four fixed CFS air nozzles are located above the Level "B" coal burners which are counted from the bottom of the furnace. About 10 % of total required air is injected through the CFS air nozzles while 65 % of air is injected with the fuel through the coal burners. The CFS air nozzles direct the air stream to form another imaginary circle enveloping the main fireball. The CFS stages the combustion horizontally in the burner zone to reduce the oxygen content in the main fireball. As a result, formation of fuel NOx can be further reduced. A sketch of air distributions of conventional tangential firing system and CFS is given in Figure 4.

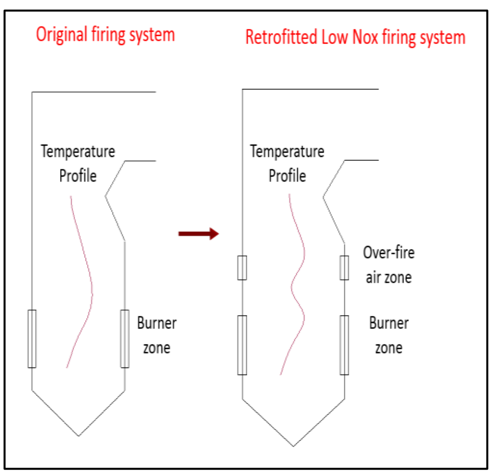

Figure 3: Comparison of temperature profile

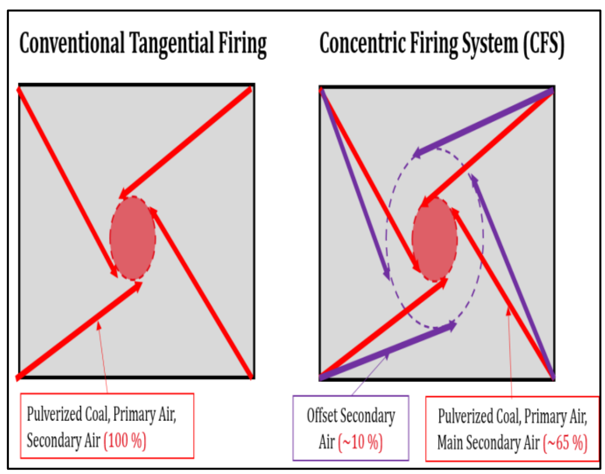

Figure 4: Comparison of air distribution before and after retrofit

In the modification of burners, all existing coal burner nozzles, oil burner nozzles and air nozzles are replaced with new ones of Alstom design. The newly designed AEROTIP™ coal burner nozzle has several advantages comparing to the original one. The nozzle is fabricated with advanced material RA253 MA heat resistant alloy to improve oxidation resistance and strength. In addition, all the leading edges are hard-faced to protect the nozzles from erosion. A recessed inner shroud and splitter plates are installed at the center to protect the coal burner nozzle from furnace heat. These design features help reduce the nozzle overheating and deformation problems encountered in the past. Besides, the new nozzle has round-shaped inner and outer corners which help prevent deposition of coal. Photos of the original coal burner nozzle and AEROTIP^{TM} coal burner nozzle are given in Figure 5. In addition to modification to the burners, three yawable secondary over-fire air (SOFA) nozzles are added on top of the existing windbox at each corner to form the over-fire air zone. A photo of an SOFA nozzle assembly is shown in Figure 6.

Figure 5: Original coal burner nozzle and AEROTIP^{TM} nozzle


Figure 6: SOFA nozzles assembly

Modification to Coal Pulverizers

Each coal-fired generation unit in LPS has five coal pulverizers to pulverize the coal to fine powder for combustion in the boiler. A major drawback from the new low NOx combustion system is the reduction of combustion efficiency of the boiler. Moreover, the conventional coal pulverizers were designed only for burning high calorific-value bituminous coal. In order to recover the combustion efficiency and to enhance the fuel flexibility, the coal pulverizers were modified from the conventional type with static classifier and stationary primary air inlet vanes to dynamic classifier with rotating primary air inlet vanes. With the modification, fineness of the pulverized fuel could be controlled by varying the speed of the dynamic classifier. The original separator deflector plates inside the pulverizers were replaced by deflectors to minimize trapping of residual coal in the pulverizers which might cause fire. Moreover, the fixed air vanes were replaced by a rotary vane wheel. Details of the modification are shown in Figure 7.

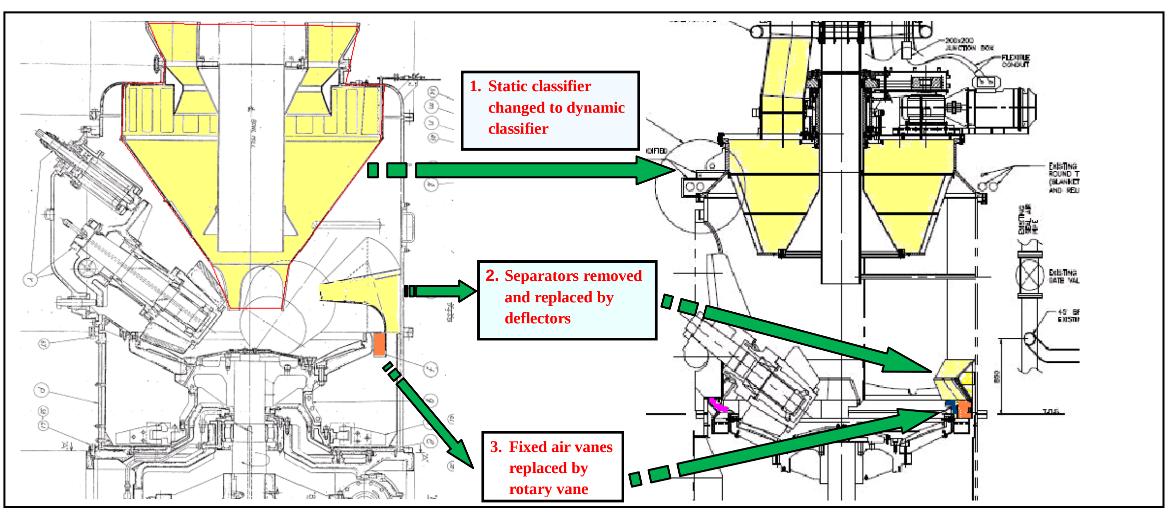

Figure 7: Details of modification to the coal pulverizers

Modification to Boiler Control

For burning a wider range of coal, apart from modifying the pulverizers, the Distributed Control System (DCS) was also modified by HK Electric Engineers. The original control system had only one fixed calorific value (CV) setting and one excess O_2 function curve for all kinds of coal burnt in the boiler as shown in Figure 8.

When burning lower CV coal, the tonnage of coal has to increase for generating the same output. With a fixed CV setting, more air would be introduced to the boiler compared to the actual requirement for the combustion, hence resulting in a restricted boiler output due to limitation of the fans' capacities and high dry flue-gas loss. To improve the situation, a ranking system was introduced to categorize the coal, namely, rank "A" coal with CV of around 6,000 kcal/kg, rank "B" of around 5,400 kcal/kg and rank "C" of around 4,800 kcal/kg. Three different sets of boiler control settings were incorporated in the boiler control system with selection switches. The operators can select a particular coal type with the associated O_2 function curve to suit that coal type. The selection is safe-guarded with "permit" function before the change proceeds. The new design concept is shown in Figure 9.

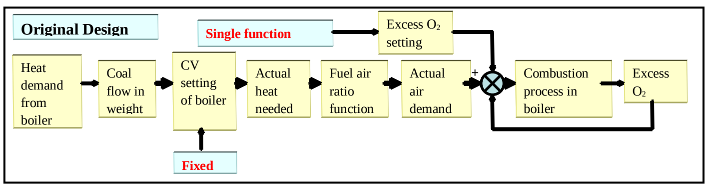

Figure 8: Original design of the boiler combustion control system

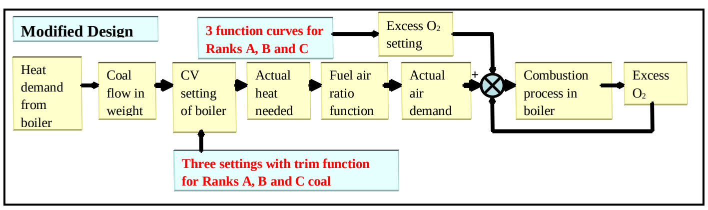

Figure 9: Modified design of the boiler combustion control system

In order to reduce the sudden change in control parameters after selection, a ramp rate was built in the control system to smooth over the transition between different ranks of coal. Sometimes mixed coal is burnt in a boiler, a fixed set of control parameters might not result in an optimal operation. Trimming functions for CV and excess O_2 were built in the control system as shown in Figure 10.

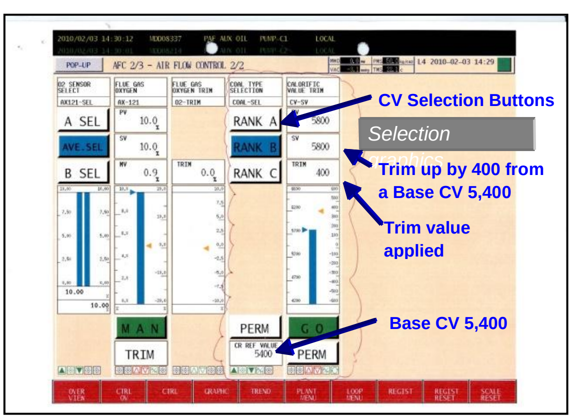

Figure 10: New man-machine interface for incorporating selection of coal type in the boiler control system

By introducing the modified design into the boiler control system, we could achieve (1) introducing selectable function curves to suit three ranks of coals covering a range of gross calorific values from about 4,200 to 6,600 kcal/kg, (2) allowing on-load adjustment of control parameters to suit the particular type of coal being burnt, and (3) preventing excessive air-flow and heat loss when burning low calorific-value coals.

POST-RETROFIT BOILER TUNING AND PERFORMANCE

Boiler Tuning

For efficient and safe operation of the boiler, the combustion system for the three ranks of coal was re-tuned after completion of the low NOx combustion system retrofit. The scope of boiler tuning included (1) fine trimming the excess O_2 in the flue gas to suit the new requirements of different calorific values of the coal being burnt and to enhance the overall boiler efficiency, (2) adjusting the opening of the over-fire air dampers to further reduce the NOx emission, (3) providing selectable settings to facilitate the boiler control for handling different grades of coal, and (4) retuning the mill outlet temperatures for the different grades of coal.

After modification of the boiler control system, the original parameters and settings for bituminous coal were put under rank “A” coal. Two additional ranks, rank “B” and rank “C” coal for sub-bituminous coal of lowered calorific values (CVs) were input into the control system. For tuning of the boiler, CVs of the three ranks of coal were input to the control system for accurate calculation of the required air flow for combustion. The tuning was carried out at five operating points of the boiler, i.e. 31 %, 35 %, 45 %, 70 % and 100 % of the boiler maximum continuous rating (BMCR).

At each loading point, the boiler was kept for one hour for stabilization. The NOx emission level, CO emission level, air flow, flue gas excess O_2 at the boiler’s outlet and the steam conditions including temperatures and pressures along the superheaters were recorded. After that, the excess O_2 of the boiler was reduced in steps and the above parameters were reviewed again. The excess O_2 were continually reduced until the CO emission level just started to increase while the unburnt carbon level in ash remained stable. This excess O_2 level would be the optimal operating point of the boiler at that loading. The tuning was repeated for the other operating points. Finally, new sets of flue gas excess O_2 function curve for different coal ranks were obtained for the full range of boiler operation as shown in Figure 11.

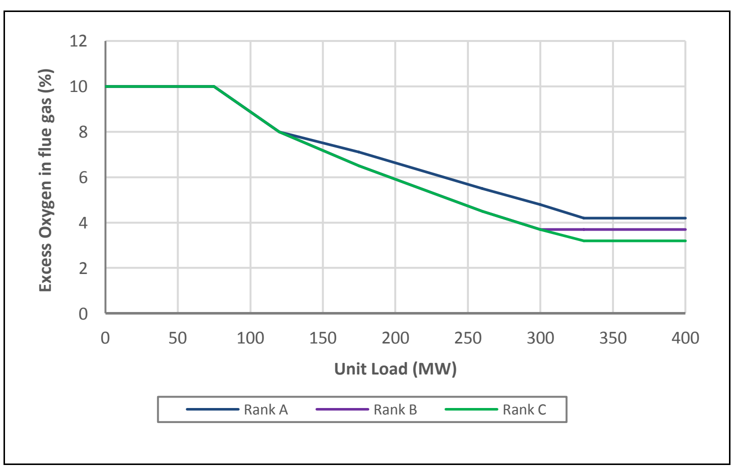

Figure 11: Function curve of excess O_2 in flue gas against unit loads

After completion of tuning of excess O_2 in flue gas, the dynamic response of the boiler at times with transient load changes was checked to ensure (1) its capability and transient response could meet the original design, (2) the NOx emission was reduced over the whole range of boiler operation including periods with rapid load changes, (3) the works power of the unit was reduced, and (4) the originally designed boiler efficiency could be enhanced. With the new flue gas excess O_2 curves, a tuning of transient response of the boiler was carried out. The load-ramp tests were carried out at different rapid changing loadings to ensure the load pick-up and rejection capability of the boiler.

Post-Retrofit Boiler Performance

Performance tests were carried out at four operating points of the boiler, i.e. 35 %, 45 %, 70 % and 100 % of BMCR during the boiler tuning. The first performance test was carried out to compare the NOx emission level at different openings of over-fire air (OFA) dampers. These test data provided information for tuning of the OFA dampers to obtain the optimal opening positions at different unit loads. Results of NOx level before and after OFA tuning are summarized in Table 2 and Figure 12, respectively.

Unit Loads (% BMCR)	NOx emission level (ppm, corrected to 12 % CO_2)		
	Pre-OFA tuning (Base)	Post-tuning (higher elevation level burners in operation)	Post-tuning (lower elevation level burners in operation)
35 %	310 (100 %)	195 (62.9 %)	187 (60.3 %)
50 %	220 (100 %)	195 (88.6 %)	153 (69.5 %)
75 %	213 (100 %)	192 (90.1 %)	118 (55.4 %)
100 %	221 (100 %)	188 (85.1 %)	142 (64.3 %)

Table 2: NOx emission level before and after OFA tuning

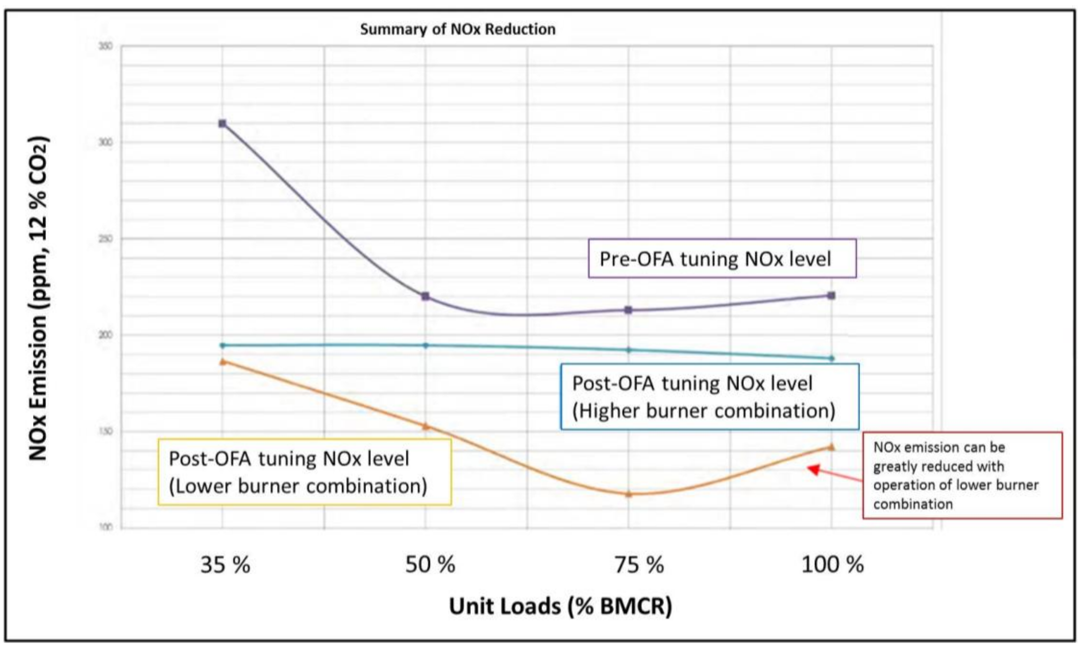

Figure 12: Comparison of NOx emission level before and after OFA tuning

From the results of the performance test, it showed that without proper tuning of openings of the OFA dampers, the NOx emission level of the retrofitted combustion system remained at a relatively high level. The OFA tuning effectively reduced the NOx emission level under different unit loads by 9.9 % to 44.6 % through a proper phasing of air injection. The test results also indicated that maintaining the main combustion zone at lower elevation level can yield a lower NOx emission level than that at higher elevation level at the same unit load.

After completion of OFA tuning, the performance test was performed again to check the post-retrofit emission levels of the generation unit. Results of reduction in NOx after the modification are summarized in Table 3 and Figure 13.

Unit loads (% BMCR)	NOx emission level (ppm, corrected to 12 % CO_2)		
	Pre-retrofit (Base)	Post-retrofit (higher elevation level burners in operation)	Post-retrofit (lower elevation level burners in operation)
35 %	306 (100 %)	195 (63.7 %)	187 (61.1 %)
50 %	292 (100 %)	195 (66.8 %)	153 (52.4 %)
75 %	311 (100 %)	182 (58.5 %)	118 (37.9 %)
100 %	284 (100 %)	188 (66.2 %)	142 (50 %)

Table 3: NOx emission level before and after retrofit

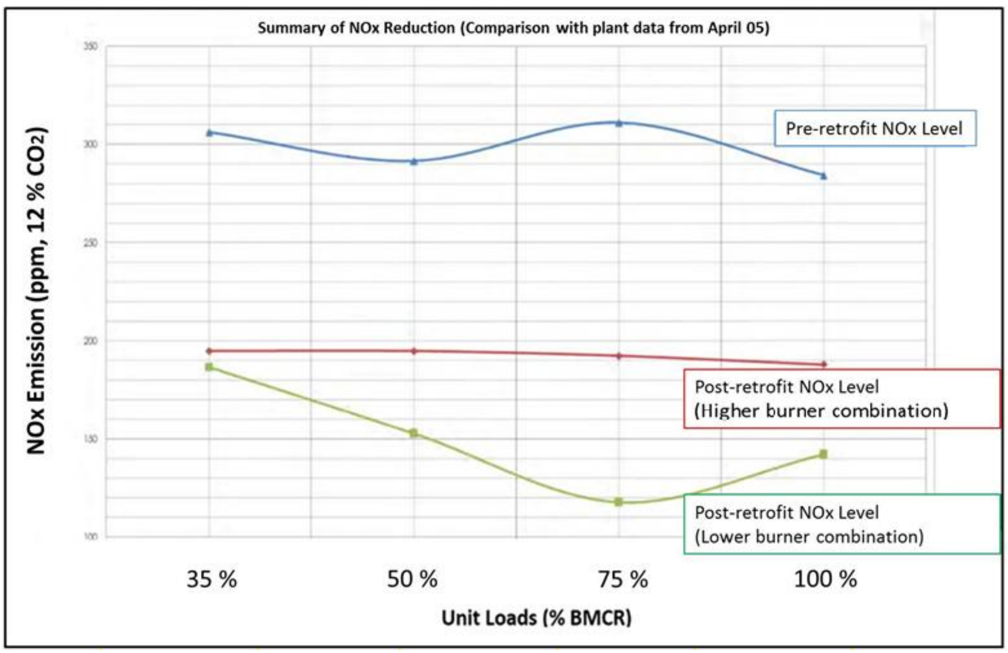

Figure 13: Comparison of NOx emission level before and after retrofit

From the results of the performance test, the retrofitted combustion system significantly reduced the NOx emission level by 33.2 % to 62.1 % at different unit loads.

In addition to the NOx emission level, the CO emission level and unburnt carbon level in fly ash were checked in the performance tests and were confirmed within the guaranteed level. The test results are summarized in Tables 4 and 5, respectively.

Nominal loading (MW)	122 MW	158 MW	245 MW	350 MW
Loading in percentage of BMCR (%)	35	45	70	100
Guarantee (ppm)	150	150	150	150
As-tested (ppm)	6.4	6.3	7.9	18.3

Table 4: Results of carbon monoxide in flue gas at different unit loads

Nominal loading (MW)	122 MW	158 MW	245 MW	350 MW
Loading in percentage of BMCR (%)	35	45	70	100
Guarantee after correction for coal/ash properties (%)	5.07 %	5.07 %	5.07 %	5.07 %
As-tested (%)	0.83 %	1.06 %	0.97 %	1.07 %

Table 5: Results of unburnt carbon in ash at different unit loads

SUMMARY

Facing the challenge of tightening emission control, Lamma Power Station has adopted a number of pollution abatement measures to reduce its emissions. LPS has successfully upgraded two 350 MW coal-fired generation units to meet the tightened NOx emission allowance and enhance the fuel flexibility of the units without sacrificing the boiler efficiency or reliability. The low NOx combustion system continues to show a promising performance.

Through retrofitting the units with the low NOx combustion system, the NOx emission level has been significantly reduced without sacrificing the boiler efficiency. Besides, the generation units are made capable of handling both bituminous and sub-bituminous coals after the modifications to pulverizers and boiler control. The flue gas excess O_2 level was fine-tuned and different control parameter settings were incorporated into the boiler control system to improve the capability of the boiler to burn different ranks of coal at optimal condition. Smooth transition of the control parameters from one rank of coal to another is also important to ensure the safe and effective operation of the boiler when the coal type burnt in the boiler changed. After modifications to the boiler control, operators can adjust the settings of calorific value and excess O_2 in flue gas in the control system to suit the types of coal being burnt.

From the performance test results under different unit loads, it was found that the modification of the boilers could improve the NOx emission by 30 % – 60 % while maintaining a low level of carbon monoxide emission and unburnt carbon in ash. Tuning of over-fire air dampers' opening is an important factor affecting the NOx reduction.

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