利用燃燒調整技術降低燃油鍋爐氮氧化物之排放

Reduction of NOx emission from an oil-fired boiler via combustion tuning technology

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摘要

本研究之目的在於探討燃燒調整技術對降低燃油鍋爐氮氧化物排放的影響。燃燒調整技術之原理為利用降低燃燒場中的空燃比，以減少氧和氮在高溫反應結合成氮氧化物的機會，進而降低氮氧化物的排放。其優點為不需增加額外的設備，且同時可以提升鍋爐的整體效率。燃燒調整技術的操作方法為在固定空氣或燃料供給量兩者其中一的情況下，改變另一個供給量，以達到低過剩氧(low excess oxygen)燃燒的操作條件。實驗中將觀察火焰穩定性、火焰型態、火焰顏色變化和煙囪排放黑煙的情形，同時量測煙道氣中 CO，CO_2，O_2和 NOx 的排放濃度，並利用熱損失法計算鍋爐效率。研究結果顯示，藉由調整空氣或燃料供給量，進而提供適當的過剩氧量進行燃燒過程，NOx 排放的減量最高可達 30%以上而鍋爐效率最高亦可提升 8%以上。因此，燃燒調整法為一有效的 NOx 減量技術，不僅降低了 NOx 的排放，同時亦提升鍋爐效率，進一步達到節省能源和促進溫室氣體(CO_2) 的減量。

關鍵字：氮氧化物、燃燒調整、鍋爐效率、過剩空氣

Abstract

The objective of this study was to demonstrate a case study of NOx reduction from an industrial fuel oil boiler by using combustion tuning technique. The effect of low excess oxygen supply on NOx emission as well as boiler efficiency was examined under various conditions of boiler operation. It was found that at a fixed boiler load, a decrease in excess air (oxygen) leads to a reduction in NOx emission and an increase in boiler efficiency. In comparison with the original operating conditions, the demo boiler can perform the reduction of NOx emission up to 30% and the improvement of boiler efficiency reaching 8% or above. Once excess air supply is limited, CO_2 emission from the boiler can be diminished. Meanwhile, the thermal efficiency of the boiler is enhanced and the fuel consumption of the boiler is reduced. Therefore, it is essential but important to limit excess air supply of the boiler unit for achieving the satisfactory performance on environmental aspects.

Keywords: NOx; Combustion tuning; Boiler efficiency; Excess air

1. Introduction

Fossil fuels are widely used as energy source for many combustion processes. During combustion these fuels are primarily converted to water and carbon dioxide while releasing heat. Beside of this expected conversion, a secondary reaction often takes place between oxygen and nitrogen from the air or fuel. Oxides of nitrogen (NOx) play an important role in atmospheric chemistry and are largely responsible for the acidification of the environment. NOx emissions are generated by combustion systems where nitrogen and oxygen are present within a locally high temperature region of the flame. The abbreviation NOx is chemical shorthand for the combined species of NO and NO_2. These species of emissions pose a significant health hazard in ambient air. Other detrimental environmental effects of NOx emissions are photochemical smog and acid rain, both found in industrial areas around the world. Because the stricter regulations for pollutant emission from industrial plants are imposed, the concerns of NOx reduction from the industrial boilers or furnaces via optimum combustion tuning have drawn much attention [1-12].

Nitrogen oxide is an important minor species in combustion because of its contribution to air pollution. NOx production from combustion sources depends strongly on four primary variables: temperature, concentrations of oxygen and nitrogen, C-N bonds with the chosen of fuel, and residence time [13]. If any one or more of variables are properly controlled, NOx production will be decreased. During the combustion of fuels without nitrogen-containing, nitric oxide can be formed by three chemical mechanisms or routes that include the thermal or Zeldovich mechanism, the Fenimore or prompt mechanism, and the N_2O-intermediate mechanism [14]. The thermal mechanism dominates in high-temperature combustion over a wide range of equivalence ratios, while the prompt mechanism is particularly important in rich combustion. It appears that the N_2O-intermediate mechanism plays an important role in the production of NO in very lean and low-temperature combustion processes.

Based on economical considerations, it is advantageous to reduce NO_x emission by controlling combustion conditions. In addition to advanced burner technologies, different methods, such as air staged, low excess air (LEA), overfire air (OFA) and flue gas recirculation (FGR), are successfully applied on furnaces or boilers to reduce peak flame temperatures and/or local concentrations of oxygen, which are requisite to cutback thermal NO formulation. The formation of nitric oxide is unavoidable in many industrial processes because of both the required high operating temperatures and the preheating of combustion air for an economical furnace operation.

Excess air is one of the important operating parameters affecting both thermal and environmental performances of a boiler. Low excess air involves operating at the lowest possible excess air level without compromising good combustion. Typical NOx reductions of 20% can be obtained simply by good combustion or low excess air firing. It has been reported by van der Lans et al. [1] and Kouprianov and Tanetsakunvatana [2] that with the reduction of the excess air ratio, the rate of NOx emissions in the boiler furnace is decreased. Therefore, the lowering in the excess air can result in an improvement on the environmental performance of the boiler unit. However, firing fuel oil at extremely low excess air ratios leads to incomplete combustion and unburned carbon in a flame. Consequently, combustible gaseous compound and carbonaceous particles (cenospheres and soot particles) are emitted from a boiler via the flue gas [2].

As is known, the flue gas emitted from an industrial boiler is one of the primary air pollution, therefore the methodology of NOx reduction should be employed. Well adjusted combustion of fuel oil in industrial boilers at low excess air (oxygen) supplies affect simultaneously the thermal efficiency and NOx emission [13]. Clearly, the boiler operation at a proper range of excess air, which ensures a low NOx emission and a high boiler efficiency, is extremely important. This work is aimed at reducing NOx emission from an industrial boiler fired with fuel oil via combustion tuning technology. The results obtained herein will be of great importance to provide a good guidance for achieving an improvement on environmental performance (the reduction of NOx emission) of the boiler unit.

2. Combustion tuning technology

NOx reduction techniques developed over the last two decades fall into four basic categories [14]:

(1) Modification of operating conditions, e.g. low excess air, burners-out-of-service (BOOS), and biased firing (BF).
(2) Modification of combustion system, e.g., flue gas recirculation, overfire air, and reburning.
(3) Modification of burner internals, e.g. air-staged or fuel-staged combustion.
(4) Post combustion cleanup, e.g. SCR (selective catalytic reduction) and SNCR (selective noncatalytic reduction).

Theoretically, the conventional method of excess air optimization is based on the approach that the total sum of excess-air-dependent heat losses has a minimal value, which ensures the maximum boiler efficiency. In real boiler furnaces, however, the oxygen concentration in the flue gas may be elevated due to air leakage. Therefore, whether the combustion efficiency is high or low can not be determined only by the measured oxygen concentration in the flue gas. In addition to oxygen concentration, CO emission should be detected as well in the flue gas. Fig. 1 shows the CO and NOx emissions as a function of excess air. It is found that with a progressive decrease in excess air, the CO emission first increases very slowly, and then increases rapidly when the excess air is smaller than the critical (normal) operating point. As a consequent, smoke occurs at extremely low excess air (oxygen). On the other hand, with the decrease in the excess air (oxygen), the rate of NOx emissions is diminished.

By adjusting fuel supply pressure or excess air, the boiler furnace can operate at the lowest possible excess air level without interfering with good combustion and, then, achieve safety, high efficiency and low emissions. Variations in the burning process require minor changes of the fuel/air mixture to maintain the correct ratio and efficient boiler operation. The process of adjusting the fuel or air is called combustion tuning or boiler trim. Combustion tuning technology, which is based on the measured CO and O_2 concentration in the flue gas, is a simple, economic and effective method to reduce NOx. Technically, this technology does not require any capital investments and can be realized by simply changing the set point of the combustion air controller or fuel supply. Methods of boiler trim vary by boiler manufacturer, fuel type, boiler load and control scheme. Some methods control the amount of air injected into the system, others control the amount of fuel, and still others control both. However, in any scheme, it is critical, for safety and efficiency, to know the amount of oxygen in the process. Apparently, Combustion tuning optimization (excess air optimization) depends on the boiler manufacturer, boiler load, burner type, fuel type, and control system. For the same boiler fired with the same fuel, excess air optimization is dependent on the boiler load.

Following the previous studies [16, 17], the combustion tuning steps for industrial boilers are listed as follows:

(1) First, it should be confirmed that the fuel flow rate is kept within the operating range for the combustion appliances. Then, automatic combustion control is replaced by manual combustion control.
(2) At a fixed boiler load, flue gas temperature, ambient temperature, CO, O_2, CO_2, and NOx emissions in the flue gas should be measured after the

combustion is stable. Here, “the combustion is stable” means that the combustion phenomena including flow pattern, flame shape, flame length and flame color are not changed. Whether the O_2 concentration in the flue gas is suitable for the boiler should be identified. If the O_2 concentration is detected within the acceptable operating range, as shown in Table 1, and, meanwhile, both the CO emission and smoke are acceptable, then this boiler operates at the condition near the optimum condition. We proceed with the following steps.

(3) Increase the excess air until the O_2 concentration in the flue gas is 1~2% higher than the original value. After the combustion is stable, all the required data should be recorded.

(4) Reset the excess air to the original normal operating value, and then gradually decrease the excess air with a small adjustment. At each operating condition, observe the combustion phenomena including flame appearance, flame color, and smoke. Additionally, the ambient and flue gas temperatures, CO, O_2, CO_2, and NOx emissions in the flue gas should be measured.

(5) Continuously decrease the excess air until one of the following conditions takes place.
  (a) Flame instability, flame impingement on the wall, or the flames of different burners overlap.
  (b) The rate of CO emission is too high and, thus, smoke occurs in the flue gas.
  (c) Incomplete combustion occurs seriously for solid fuels, which can be detected by a large amount of combustible substance in the fly ash or carbon in the dust collector.
  (d) Combustion tuning exceeds the limit of furnace pressure or the supply of air (or fuel).

(6) Plot the characteristic curve of the excess O_2 versus CO emission.

(7) Find the minimum excess air operating point according to the characteristic curve of the excess O_2 versus CO emission. However, it is not appropriate to operate boiler at the minimum excess air operating point since rapid increase of CO emission or smoke, or combustion instability often occurs when fuel supply varies at this operating point. In general, an increase in boiler load causes a decrease in the minimum excess air. Compare this minimum excess air with that provided by the boiler producer and we will see the difference between them. If the minimum excess air measured is greater than that provided by the boiler producer, then the combustion air can be reduced by burner adjustment to enhance the mixing of fuel and air.

(8) When the fuel type, combustion load and atmospheric pressure are varied, the determination of the minimum excess air needs to take these variations into consideration.

(9) Repeat steps 1~8 to find the excess air optimization for various boiler loads.

(10) When combustion tuning is complete, it is required to double check whether the excess oxygen in the flue gas is suitable, or CO emission increases rapidly, or smoke appears.

Before undertaking combustion tuning, it is necessary to make a careful check of boiler burner, oil atomizer, combustion air controller, flame shape and flame appearance, flue gas damper and combustion control system. Additionally, it is required to check the measuring apparatus, such as the flow meter, thermocouple, gaseous emission analyzer…etc. In order to be aware of the effect of combustion tuning on boiler performance, we need to develop a set of data as the baseline before undertaking combustion tuning.

3. Case study

An industrial oil-fired boiler of 25

ton/hr (16 kg/cm^2) steam capacity, at the rated capacity (i.e. 100% load), was selected for this study. The schematic diagram of the boiler is shown in Fig. 2. The boiler type is DY-KSK (PD-25KE). The burner type is NFK-CONE: 3MV with a steam atomizing injector. The fuel oil (No. 6 fuel oil produced by Chinese Petroleum Corporation) is preheated to 95 ℃ prior to burning, but the primary air is not preheated. Neither gas recirculation nor other techniques are used to mitigate the NOx formation in the furnace.

Gaseous emissions including CO, O_2, CO_2, and NOx emissions in the flue gas are measured after the combustion is stable. The concentrations of the combustion product components (CO, O_2, CO_2, and NOx) are measured using the commercially available gas pollutant analyzer (Model 9950, Teledyne Analytical Instruments). In addition, flue gas temperature, ambient temperature, and furnace pressure are measured. The original NOx emissions obtained in experimental tests on the studied boiler need to be corrected to be presented as the volume concentrations of NOx in 6% O_2 dry flue gas by using the following equation:

$$\text{NOx (dry, 6\% O}_2\text{)}=\frac{21\%\text{-}6\%}{21\%\text{-[excess O}_2\text{]}}\times[\text{NOx}]$$

(1) where $[\text{NOx}]$ (in ppm) is the measured NOx concentration, [excess O_2] is the excess O_2 concentration (in %) in the flue gas. Additionally, according to CNS 2141-B1025 Standard [18], boiler efficiency is found based on the concentrations of CO, O_2, CO_2, and the flue gas and ambient temperatures by the use of the heat-loss method. Boiler efficiency is calculated by the following equation:

$$\text{Boiler efficiency}=\left(1-\frac{\text{total losses}}{\text{gross input heat}}\right)\times 100\%$$

(2) Because the industrial oil-fired boiler adopted in this study possesses the features that the excess air is greater than 10%, the flue gas temperature is larger than 170 ℃ and the boiler efficiency is smaller than 80%, combustion tuning technique is expected to be an extremely effective approach to reduce NOx emissions. As is known, the boiler operation at a proper value of excess air for ensuring lower NOx emission and higher boiler efficiency is extremely important. The influence of low excess air by using combustion tuning technology on the NOx emissions and the boiler efficiency is shown in the following text.

4. Results and discussion

For this boiler, firing fuel oil at an extremely low excess O_2, smaller than 2%, leads to incomplete combustion and unburned carbon (smoke) in a flame. Furthermore, when the excess O_2 is larger than 11%, incomplete combustion takes place and then CO emission rises rapidly since a large amount of excess air leads to a considerable decrease of flame temperature. Therefore, when we undertake combustion tuning, the boiler always operates at the range of 2.7~9.8% excess O_2 that ensures a low CO emission. Meanwhile, CO_2 concentration in the flue gas is within the range of 8.4~13.8%.

Fig. 3 shows the NOx emissions as a function of excess O_2 in the flue gas and, meanwhile, Fig. 4 demonstrates the boiler efficiency as a function of excess O_2 in the flue gas. In the figures, the numbers in the brackets denotes the range of boiler load. It is seen that at a fixed boiler load, a decrease in excess O_2 leads to a reduction in NOx emissions (Fig. 3) and an increase in boiler efficiency (Fig. 4). By adding that extra air, more of the combustion energy is consumed just in the combustion, the burner expends energy just to heat air. Therefore, the lower the excess air level, the higher the boiler efficiency becomes.

For a boiler load in the range of 74~76%, the reduction rate of NOx and the elevation rate of boiler efficiency as a function of excess O_2 are shown in Figs. 5 and 6, respectively. In the figures, the symbols “*” designate the original results measured before combustion tuning. In other words, points A, B and C shows the operating conditions via combustion tuning technique, while points D and E represent the original results obtained from the operating conditions before combustion tuning. “A: Oil=6.0, Air=5” denotes the boiler operates at the operating condition (point A) where fuel oil supply pressure is 6 kg/cm^2 and air controller scale is maintained at 5. Similar descriptions hold for the other operating conditions, i.e. points B, C, D and E. In order to achieve an appropriate fuel-air ratio for burning, generally, the fuel-oil supply pressure is increased when the air controller scale is enlarged. The number in the brackets denotes the boiler load, which is the same as the definition in Figs. 3 and 4. It is found that a decrease in excess O_2 leads to an increase in the reduction rate of NOx emissions (Fig. 5) and a rise in the growth rate of boiler efficiency (Fig. 6).

It is clear that point A is the optimized operating condition achieved by using combustion tuning technique for the boiler load in the range of 74~76% since it has the largest reduction rate of NOx emission and the highest promotion rate of boiler efficiency. In comparison with the original operating conditions before combustion tuning (points D and E), the optimized operating condition after combustion tuning (point A, i.e. 2.7% excess O_2) can achieve a maximum reduction rate of 30% or more on NOx emissions (Fig. 5) and, meanwhile, reach a maximum boiler efficiency variation, which is about +8% (Fig. 6).

5. Conclusions

In this study, the influence of main operating variable (low excess air) on NOx emission and boiler efficiency of an oil-fired industrial boiler was investigated by using combustion tuning technique. Concluding remarks are summarized as follows:

(1) Excess air (oxygen) is one of the important operating variables affecting both thermal and environmental performances of a boiler. At a fixed boiler load, a decrease in excess O_2 brings about a reduction in NOx emissions and an increase in boiler efficiency.

(2) In comparison with the original operating conditions, the demo boiler operating at the condition of 2.7% excess O_2 can perform the reduction of NOx emission up to 30% and the improvement of boiler efficiency reaching 8% or above.

(3) Due to the improved thermal efficiency, followed by reduction in the boiler fuel consumption, the rate of CO_2 emission is diminished when the excess air is decreased. Accordingly, the lowering in the excess air can result in an improvement on the environmental performance of the boiler unit.

(4) Due to economical reasons, the use of combustion tuning technique (modification of operating condition) for the reduction of NO_x emission is very advantageous. It has been verified that combustion tuning technique is an effective approach to reduce NOx emissions when the industrial oil-fired boiler possesses the following features: the excess air is greater than 10%, the flue gas temperature is larger than 170 ℃ and the boiler efficiency is smaller than 80%.

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References

1. Van der Lans RP, Glarborg P, Dan-Johansen K. Influence of process parameters on nitrogen oxide formation in pulverized-coal burners. Progress in Energy and Combustion Science 1997; 23(4):349-77.
2. Kouprianov VI, Tanetsakunvatana V. Optimization of excess air for the improvement of environmental performance of a 150 MW boiler fired

with Thai Lignite. Applied Energy 2003;74:445-453.
3. Kouprianov VI, Kaewboonsong W. Modeling the effects of operating conditions on fuel and environmental costs for a 310 MW boiler fired fuel oil. Energy Conversion and Management 2004;45:1-14.
4. Kremer H, May F, Wirtz S. The influence of fuel design on the NO formation in high temperature processes. Energy Conversion and Management 2001;42:1937-52.
5. Hesselmann Gerry J. Optimization of combustion by fuel testing in a NOx reduction test facility. Fuel 1997;76:1269-75.
6. Flamme M. Low NOx combustion technologies for high temperature applications. Energy Conversion and Management 2001;42:1919-35.
7. Van der Drift A, Tjeng, SL, Beckers, GJJ, Beestheheerde J. Low-NOx hydrogen burner. Int. J. Hdrogen Energy 1996;21(6):445-9.
8. Fan JR, Liang XH, Chen LH, Cen KF. Modeling of NOx emissions from an W-shaped Boiler furnace under different operating conditions. Energy 1998;23:1051-55.
9. Takami H, Suzuki T, Itaya Y, Hasatani M. Performance of flammability of kerosene and NOx emission in the porous burner. Fuel 1998; 77(3):165-71.
10. Miller JA, Bowman CT. Mechanism and modeling of nitrogen chemistry in combustion. Progress in Energy and Combustion and Technology 1989; 15:287-338.
11. Fenimore CP. Formation of nitric oxide in premixed hydrocarbon flames. Proc. Combust. Inst. 1970; 13:373-80.
12. Bowman CT. Control of combustion–generated nitrogen oxide emissions: technology driven by regulations. Proc. Combust. Inst. 1992; 24:858-78.
13. Basu P, Cen K F, Jestin L. Boilers and burners. New York: Springer; 2000.
14. North American combustion handbook volume II, 3rd ed., Cleveland Ohio, USA: North American Mfg. Co.; 1986.
15. Turns SR. An introduction to combustion. New York: McGraw-Hill; 1996.
16. Taiwan EPA, Demo Project of Technology Instruction on the Control of Air Pollutant Emission: the Best Available Control Technology of NOx Reduction for Stationary Source (first year), final report EPA-86-FA11-09-84, Taiwan EPA, 1997. (in Chinese).
17. Taiwan EPA, Demo Project of Technology Instruction on the Control of Air Pollutant Emission: the Best Available Control Technology of NOx Reduction for Stationary Source (second year), final report EPA-87-FA13-03-82, Taiwan EPA, 1998. (in Chinese).
18. The Chinese National Standard, CNS 2141-B1025, Calculation method of boiler efficiency for land use, 2004.

Table 1 Typical operating range of low excess air for boiler fired with various types of fuel

Fuel type	The range of low excess oxygen
Natural gas	0.5~3%
Liquid fuel	2~4%
Pulverized coal	3~6%

Figure captions

Figure 1 NOx and CO emissions as a function of excess air (oxygen).
Figure 2 Schematic diagram of the boiler.
Figure 3 NOx emission as a function of excess oxygen in the flue gas at various values of boiler load.
Figure 4 Efficiency as a function of excess oxygen in the flue gas at various values of boiler load.
Figure 5 Reduction rate of NOx emission as a function of excess oxygen in the flue gas at the boiler load near 75%.

Figure 6　Promotion rate of efficiency as a function of excess oxygen in the flue gas at the boiler load near 75%.

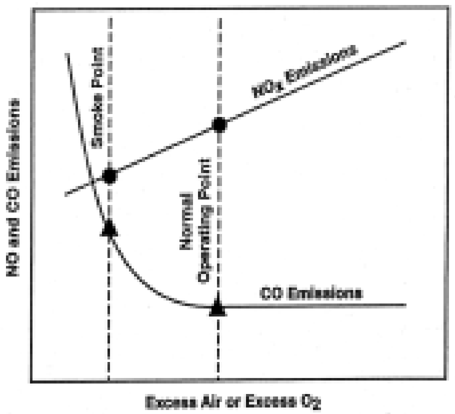

Figure 1

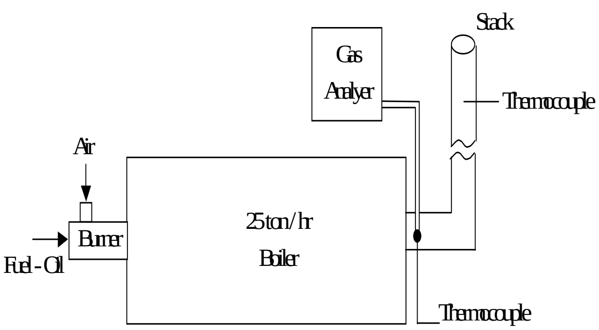

Figure 2

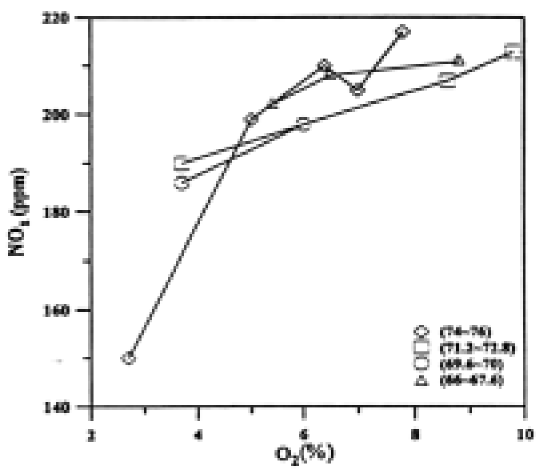

Figure 3

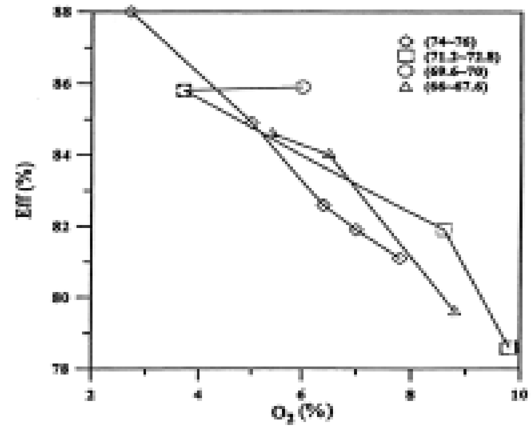

Figure4

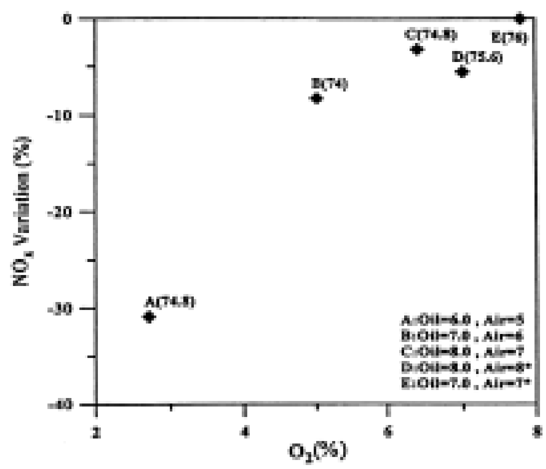

Figure 5

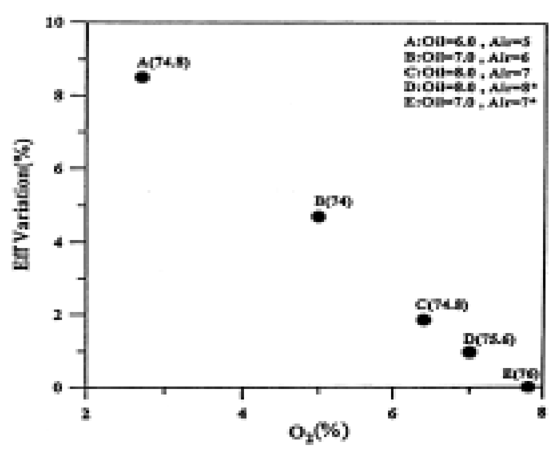

Figure 6