Low NOx Combustion of Pulverized Petroleum Cokes

Sewon Kim, Minjun Kwon, Changyeop Lee

Abstract**—**This paper is aimed to study combustion characteristics of low NOx burner using petroleum cokes as fuel. The petroleum coke, which is produced through the oil refining process, is an attractive fuel in terms of its high heating value and low price. But petroleum coke is a challenging fuel because of its low volatile content, high sulfur and nitrogen content, which give rise to undesirable emission characteristics and low ignitability. Therefore, the research and development regarding the petroleum coke burner is needed for applying this industrial system. In this study, combustion and emission characteristics of petroleum cokes burner are experimentally investigated in an industrial steam boiler. The low NOx burner is designed to control fuel and air mixing to achieve staged combustion, which, in turn reduces both flame temperature and oxygen. Air distribution ratio of triple staged air is optimized experimentally. The result showed that NOx concentration is lowest when overfire air is used, and the burner function at a fuel rich condition. That is, the burner is operated at the equivalence ratio of 1.67 and overall equivalence ratio including overfire air is kept 0.87.

Keywords**—**Petroleum cokes, Staged combustion, Low NOx, Equivalence ratio.

I. Introduction

PETROLEUM coke is a byproduct of the oil refining industry. It has high heating value and low price. Owing to the increasing demand for heavy oil processing, the production of petroleum coke is increasing. The high availability and low price of petroleum coke make its combustion for steam generation increasingly attractive [1]–[4]. To overcome the low ignitability and high emission characteristics of petroleum cokes fuel, a special combustion modification method should be applied to reduce high potential of NOx and SO_2 emission in burning petroleum coke. Moreover, sulfur emission control for petroleum coke combustion is also challenging because of the high sulfur content [5], [6].

A number of options exist for combustion and post-combustion modifications that lead to a decrease in NOx emissions. The most common method is to install low-NOx burners. These control fuel and air mixing to achieve staged combustion, which, in turn reduces both flame temperature and oxygen concentration during some phases of combustion. In turn, this reduces both lower thermal NOx and fuel NOx production. Overfire air is often used in conjunction with low-NOx burners to complete the combustion process at a lower temperature. Air is injected into the furnace above the normal combustion zone. When overfire air is used, the burners function at a lower-than-normal air-to-fuel ratio, which reduces NOx formation.

An additional combustion process known as reburning injects some part of fuel into a separate reburn zone. The fuel-rich reducing conditions in this zone lead to a reduction of NOx formed in the normal combustion zone. Flue gas recirculation (FGR), in which part of the flue gas is recirculated to the furnace, can also be used to alter conditions in the combustion zone by lowering the temperature and reducing the oxygen concentration. Additionally, FGR is used as a carrier to inject fuel into a reburn zone to increase penetration and mixing.

In this study, low NOx petroleum cokes burner is designed and tested in the industrial steam boiler.

II. Experimental Setup & Method

A. Analysis of Fuel Characteristics

Typical fuel analysis of petroleum coke is shown in Table I. As shown in Table I, petroleum cokes contain very high levels of fixed carbon, about 87 percent. Petroleum cokes contain less volatile matter and ash than bituminous coal. The sulfur content of petroleum cokes can vary considerably depending on the coking process and the particular crude oil being refined. Thus, low volatile fuels such as petroleum cokes have poor ignition and burnout characteristics and if such fuels are to be fired in an industrial boiler it is necessary to cofire with a substantial fraction of oil, gas, or coal. Therefore, in this study, 10% of refined oil is cofired with 90% of petroleum cokes in the furnace.

TABLE I
The Results of Proximate Analysis of Petroleum Cokes

Analysis contents	results
Total Moisture(As Received Basis) [%, Wt]	0.51
Proximate Analysis(Air Dry Basis)	
Inherent Moisture [%, Wt]	0.51
Ash [%, Wt]	0.48
Volatile Matter [%, Wt]	11.96
Fixed Carbon [%, Wt]	87.05
Total Sulfur(Air Dry Basis) [%]	5.57
Higher Heating Value	
Gross Calorific Value(Air Dry Basis) [kcal/kg]	8,480
Gross Calorific Value(Dry Basis) [kcal/kg]	8,520

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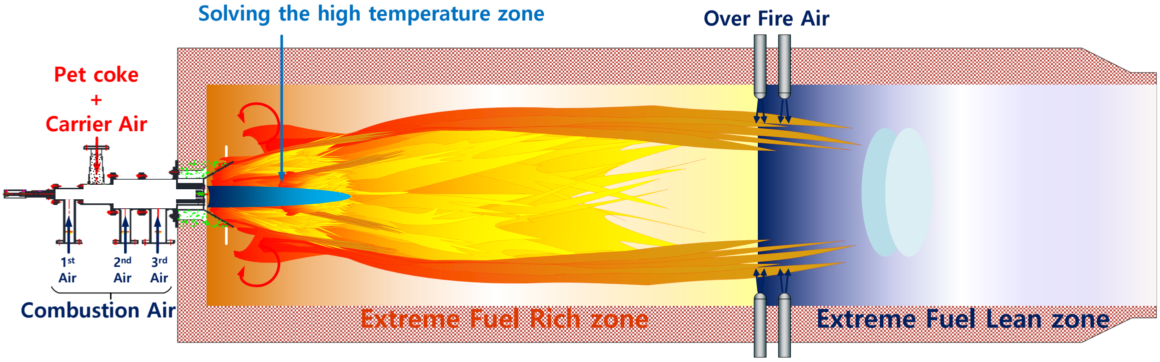

Fig. 1 Schematic diagram of the Petroleum cokes combustion system

Fuel analysis of refined oil used in this study is shown in Table II.

TABLE II
THE ANALYSIS RESULTS OF REFINED OIL

Analysis contents	Results
Viscosity [mPa.s @ 20℃]	3
Viscosity [mPa.s @ 50℃]	1.7
Viscosity [mPa.s @ 70℃]	1.52
Viscosity [mPa.s @ 40℃ - light oil]	1.9~5.5
Ultimate analysis	
N [mass fraction, %]	0.5
C [mass fraction, %]	88.21
H [mass fraction, %]	8.475
S [mass fraction, %]	0.01
O [mass fraction, %]	2.08
Higher Heating Value	
Gross Calorific Value [kcal/kg]	9501.92

B. Design of Petroleum Cokes Combustion System

The petroleum cokes burner is designed as an air-staged burner. The oil nozzle is installed at the center of the burner. The primary air is supplied around the oil nozzle, which is non-swirling axial flow. This primary air flow acts to avoid high flame temperature near the flame front region. Then petroleum cokes are supplied with a carrier air through the second annulus in a cyclone motion. The secondary and tertiary airs are supplied through third and fourth annulus, respectively. This secondary and tertiary air is supplied by passing through swirlers with different swirl number. Heat capacity of this burner is designed at 700,000 kcal/hr maximum. This low NOx petroleum cokes burner is designed to control fuel and air mixing to achieve staged combustion, which, in turn reduces both flame temperature and oxygen. Air distribution ratio of triple staged air is optimized experimentally.

A horizontal cylindrical type furnace is used for this experiment. The volumetric heat release rate of this combustion chamber is 500 kW/m3. On the top of the furnace, temperature measuring probes are installed axially to measure the temperature profile of the flame. Overfire air are supplied through the ports at the sides of the furnace. The schematics of experimental petroleum cokes combustion system is shown in Fig. 1. Schematic diagram of petroleum cokes burner is shown in Fig. 2, and detailed diagram of petroleum cokes injection nozzle is shown in Fig. 3. The actual photograph of this petroleum cokes burner is shown in Fig. 4 [7].

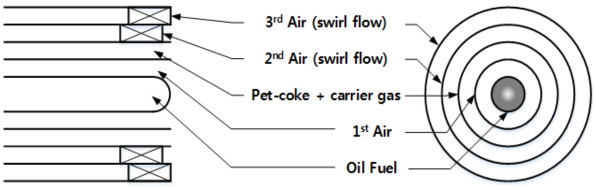

Fig. 2 Schematic diagram of burner

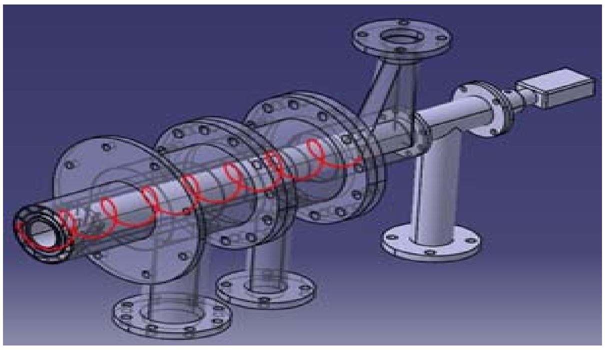

Fig. 3 The cyclone motion of pet-coke and carrier air

Fig. 4 Picture of the Pet-coke burner

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C. Experimental Conditions

In this study, overfire air is used in conjunction with low-NOx burners to complete the combustion process at a lower temperature. When overfire air is used, the burners function at a fuel rich condition, which reduces NOx formation. Thus, the ratio of overfire air is an important factor for this study. The overfire air ratio, Q_r, are defined as the ratio of OFA flow rate to the total air flow rate are varied along with air distribution ratio of staged burner.

$$Q_r = \frac{Q_{OFA}}{Q_{total}} \tag{1}$$

where, Q_r: OFA ratio; Q_{OFA}: OFA flow rate; Q_{total}: Total air flow rate.

By varying the amount of air supplied to burner and overfire air, the equivalence ratio of burner, Φ_b, and the overall system equivalence ratio, Φ, are carefully controlled. For a given equivalence of burner, air distribution ratio of primary, secondary, and tertiary air are varied.

TABLE II
EXPERIMENTAL CONDITION (AIR DISTRIBUTION RATIO)

Case	Air distribution ratio (1st:2nd:3rd), (Overall Equivalence ratio, Φ)
Case 1	10 : 70 : 20 (Φ=0.85)
Case 2	10 : 40 : 50 (Φ=0.85)
Case 3	10 : 10 : 80 (Φ=0.85)
Case 4	10 : 10 : 80 (Φ=0.87)

TABLE III
EXPERIMENTAL CONDITION (Q_R, Φ_B)

Variable	-
Air distribution ratio condition	30 : 40 : 30
OFA ratio	0 ~ 50%
Burner equivalence ratio (Φ_b)	Φ_b =1.67
	Φ_b =1.25
	Φ_b =1.83

The experimental conditions of this study are shown in Tables II and III.

The exhaust gas concentrations of NOx and CO are measured at 5 second interval throughout the experiment.

III. RESULTS AND DISCUSSIONS

For this study, 90% petroleum cokes and 10% refined oil are cofired in the furnace. Experiments are carried out for wide ranges of equivalence ratio of burner and overfire air ratios.

The burner are operated at fuel rich to lower thermal and fuel NOx formation and also to promote the NOx reduction reaction, while the overfire air is supplied to complete combustion.

Figs. 6 and 7 show the NOx emission characteristics during initial stages of combustion. That is, oil flame is used to heat up the furnace, then petroleum cokes are supplied until it reaches maximum load. The refined oil is reduced accordingly until it reaches 10% of total fuel supplied. As mentioned earlier, by controlling the equivalence ratio of burner and overfire air ratio NOx emissions are significantly reduced. It is believed that fuel rich operation of burner lower thermal and fuel NOx formation.

The amount of air supplied to overfire air is varied at three different burner equivalence ratios. Fig. 8 shows that NOx concentration is lowers at burner equivalence ratio, Φ_b, is 1.67 and overfire air ratio, Q_r, is 30%.

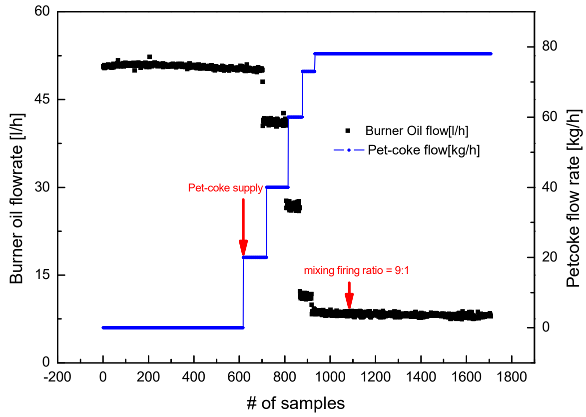


Fig. 5 The flow rate of pet-coke & refined oil

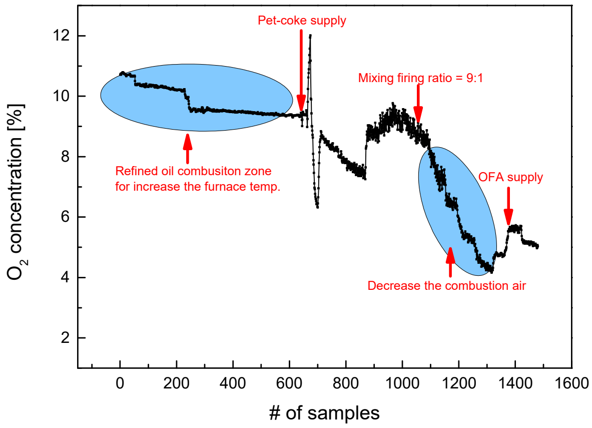


Fig. 6 The O_2 concentration during experiment

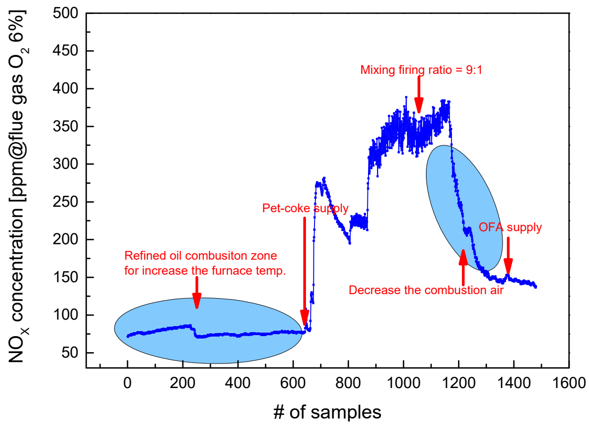
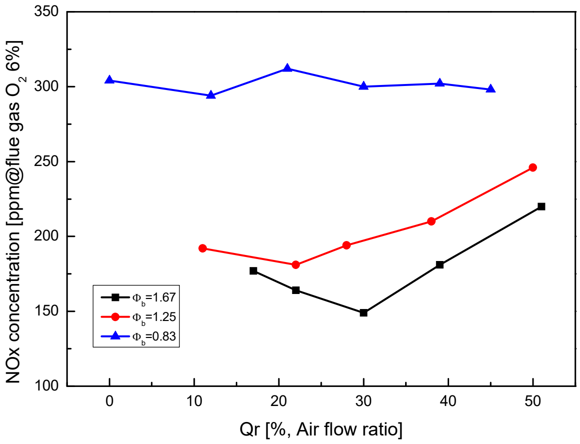


Fig. 7 The NO_X concentration during experiment



Fig, 8 NO_X concentration for Qr

Fig. 9 shows the emission characteristics of case 1 which is 70% of combustion air are supplied to secondary air. The NOx and CO concentrations are 78.4ppm and 162ppm, respectively. Fig. 10 shows the emission characteristics of case 2 which is 40% of combustion air are supplied to secondary air and 50% of combustion air is supplied to tertiary air. The NOx and CO concentrations are 76.2ppm and 162ppm, respectively. Fig. 11 shows the emission characteristics of case 3 which is 80% of combustion air are supplied to tertiary air. The NOx and CO concentrations are 65.5ppm and 125ppm, respectively. Fig. 12 shows the emission characteristics of case 4 which is decrease the burner equivalence ratio, Φ_b, and keep the flow rate of OFA. The NOx and CO concentrations are 52ppm and 141ppm, respectively.

The air distribution ratio of burner is changed to see the effect of these staged air distribution to the emission characteristics of NOx and CO. The results show that as the flow rate of the tertiary air increases the improved performance of the NOx and CO emissions of the burner can be obtained.

As described above, the burner is designed to form a swirl flame by install a swirler at secondary air supply unit and tertiary air supply unit. In addition, the burner is designed the tertiary air swirl flow is stronger than the strength of the secondary air swirl flow to enhance the turbulence of the flame. Therefore, if the flame has very strong swirl flow, the burner performance is improved. These results show the design of the purpose the flame stabilization and the complete combustion of petroleum cokes acts effectively through the forming the strong swirl flow and the increasing the turbulence degree of the flame.

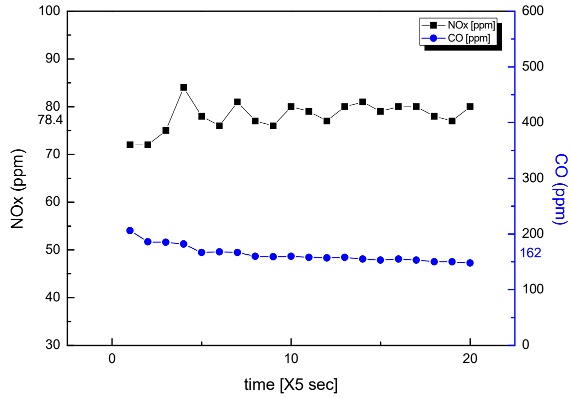


Fig. 9 NO_X & CO concentration at case 1

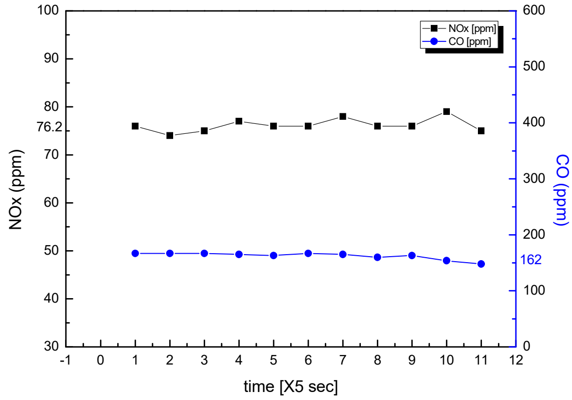


Fig. 10 NO_X & CO concentration at case 2

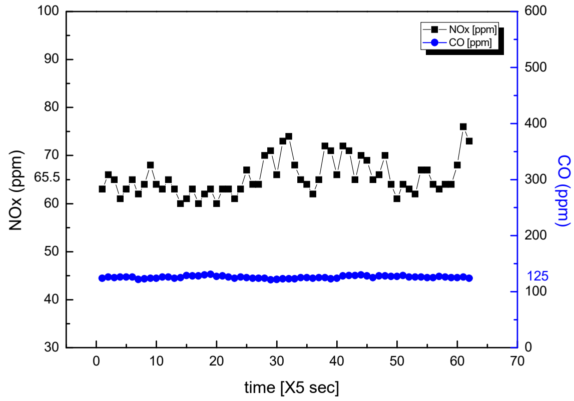


Fig. 11 NO_X & CO concentration at case 3

IV. Conclusion

In this study, detailed experimental studies on combustion and emission characteristics of petroleum cokes burner are conducted. The result showed that NOx concentration is lowest when overall equivalence ratio is 0.87 and burner equivalence ratio is 1.83. In addition, the NOx concentration was lowest when 80% of combustion air is supplied to the tertiary air.

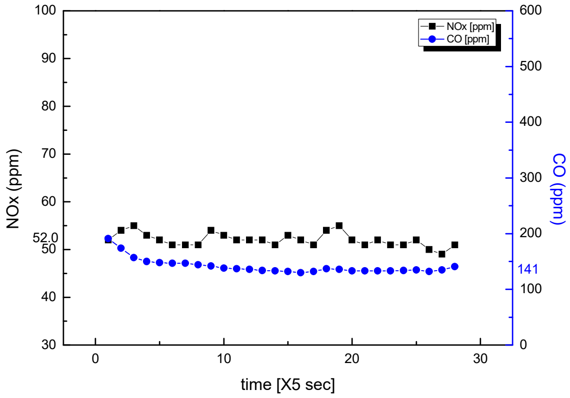


Fig. 12 NO_X & CO concentration at case 4

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