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Improvement of combustion efficiency and reduction of NO_x emission by external oscillation of reactants in an oil burner

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Abstract−The important requirement for the development of burners is the achievement of low emissions, particularly NO_x, while maintaining high combustion efficiency. In this work, an externally oscillated oil burner was developed which provides both high-efficiency combustion and low NO_x emission simultaneously. To investigate combustion characteristics and NO_x emission, parametric studies were carried out about oscillation frequency, forcing amplitude, and air velocity. Optimum combustion was achieved at frequency of 1,900 Hz, amplitude of 3 V_{pp}, and air velocity of 6.8 m/s. The NO_x and CO emissions were reduced by 47% and 22%, respectively. In particular, the mechanism responsible for the inherently low NO_x emission levels from an externally oscillated oil burner has been shown to be a short residence time at high temperature caused by rapid mixing with cooler residual gases.

Key words: External Oscillation, Low Emission Oil Burner, Combustibility, NO_x

INTRODUCTION

Liquid fuels such as light and heavy oil have been used in many heating facilities. These fuels have characteristically generated a large amount of pollutants of nitric oxides (NO_x) and particles while burning, compared to gaseous fuels. Nitric oxide is generally specified as thermal NO_x and fuel NO_x. Thermal NO_x is generated in a high temperature flame through a wide range of air ratio so that it is examined many times experimentally and theoretically.

In-furnace technology and after technology have been known as the reduction methods of nitric oxide. Many studies have been performed on nitric oxide emission control through after-treatments such as selective catalytic reduction and so on [1-3]. However, these methods have a demerit of low NO_x reduction, high maintenance price, and so on. Therefore, improving the In-furnace technology such as combustion method can be more fundamental and effective than after-treatment from the economic point of view.

Among the techniques of controlling nitric oxide through improving combustion technology, the low NO_x burner is one of the most popular techniques. However, combustion efficiency decreases along with an increasing generation of unburned hydrocarbon (UHC) and carbon monoxide (CO) when the NO_x reduction increases. The UHC and CO affect flame stability [4] and combustion efficiency. Thus, it is necessary to develop a technique to control the generation of UHC and NO_x simultaneously.

To solve this problem, we applied external oscillation technology in this study. Most previous studies on oscillation were on combustion stability [5] based on the Rayleigh's criterion [6] and sound wave in the flow field. And the external oscillation for flame stability and NO_x control were mainly examined in gas burners. Therefore, it needs to be applied to external oscillation in liquid fuels such as light oil.

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We developed a low NO_x oil burner applying external oscillation, which enables high combustibility and NO_x reduction. Also, to have optimal operating conditions, parametric screening studies were done by oscillation frequency, amplitude, and air velocity.

EXPERIMENTAL EQUIPMENT AND METHOD

1. Experimental Equipment

Fig. 1 shows the experimental apparatus used in this study. It consisted of an externally oscillated burner, a chimney, a fuel supply line, and a measurement and analysis system.

The externally oscillated burner topped with a fuel nozzle was a non-premixed burner which is fed oil fuel and combustion air, separately. This consisted of a fuel nozzle to inject oil, burner controller to control the feeding of fuel and combustion air and the ignition time of the igniter, and a loud speaker in the lower portion of the burner to oscillate combustion air. To minimize sound wave loss from the speaker, a conical cap was attached to the burner. External oscillation was supplied through the function generation (Agilent Technology-33250A) and power amplifier (JEIL Power Amplifier-JPA120). The chimney was designed in a cylindrical shape to prevent the influx of external air, and was lined with refractory to conserve heat and prevent heat loss. The sampling ports were installed at 10 places with the distance between each port being 5 cm to measure the combustion gas and temperature.

The fuel supply line consisted of the tank and fuel pump with which the fuel pump pressure was set at 3 kg_f/cm^2 to optimize fuel atomization.

The measurement and analysis system was divided into the lines for combustion gas analysis and for gas temperature measurement. The line analyzing combustion gas was composed of the sampling probe, sampling line, non-dispersive infrared analyzer (California Analytical Instrument-ZRFEHDE1) and gas chromatography (Shimazu-14B). The line for temperature measurement was composed of thermocouple (K-Type) and data analyzer (Fluke-Hydra Data

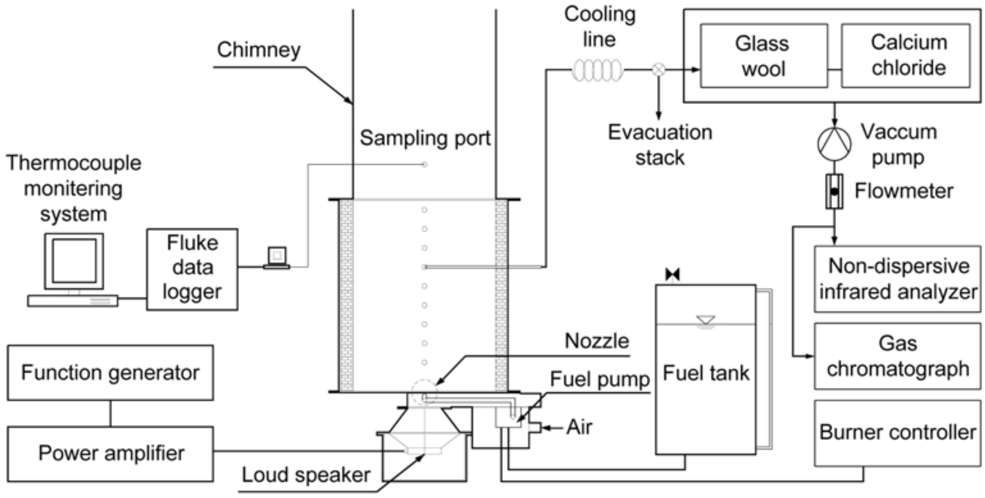


Fig. 1. Experimental apparatus for external oscillation burner.

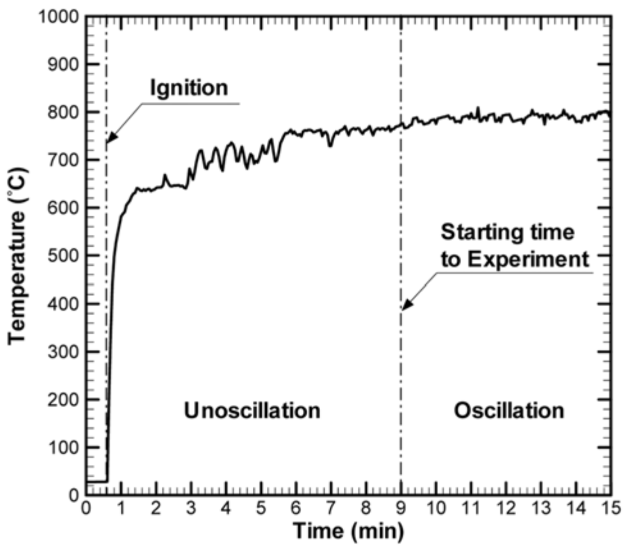


Fig. 2. Initial operating characteristics of the externally oscillated oil burner.

Logger 2625A).

2. Experimental Method

In order to confirm flame stability, the combustion temperature was continually monitored at a 30 cm distance from the burner tip in the flame downstream direction. Fig. 2 shows temperature characteristics at the initial operation of the burner. The experiment was started after 9 minutes when the flame stabilized as around 800 °C when oscillation was not applied.

External oscillation in the burner was supplied by function generator which adjusted the frequency (Hz) and amplitude (V_{pp}). This sound was amplified by a power amplifier, and it was supplied to a loud speaker and finally into the burner.

Measurements were done by using a probe at the sampling port to obtain gas samples and temperature. Gas samples were taken at the seventh port, which was 55 cm away from the burner top by probe. And this was passed through cooling line, glass wool to remove soot, calcium chloride to remove water, and supplied to the

Table 1. Experimental conditions of reference flame and parameter studies

Conditions	Flame type	Frequency (Hz)	Amplitude (V_{pp})*	Air velocity (m/s)
Reference flame	Case R	1,900	3	6.8
Variation of frequency	Case 1	100-3,000	3	6.8
Variation of amplitude	Case 2	1,900	1-10	6.8
Variation of air velocity	Case 3	1,900	3	5.1-9.2

$^*_{pp}$: peak to peak.

flowmeter where a constant flow rate of 0.5 *l*/min was set, and introduced into the gas analysis equipment. The NO and CO were measured by using a non-dispersive infrared analyzer. The O_2 was measured with a gas chromatograph. Temperature was measured with a thermocouple and was monitored in real time by using a Fluke data logger. The thermocouple was inserted at the sixth port, which is 30 cm away from the burner top.

The condition of reference flame (Case R), which is the best flame, was decided by trial and error method experimentally. Parametric studies were achieved according to the variation of oscillation frequency (Case 1), forcing amplitude (Case 2), and air velocity (Case 3). For each case, the experimental conditions are shown in Table 1.

RESULTS AND DISCUSSION

1. Characteristics of Reference Flame

Fig. 3 shows the results of comparing the concentrations of NO and CO at the exit for oscillation and without oscillation.

The NO reduction rate in external oscillation was 31%, compared to without oscillation. This is why peak temperature in the flame is reduced due to the good mixing. CO concentration was lower overall at oscillation because combustion was improved due to improved mixing by oscillating. The fluctuations of CO concentration at the near burner tip can be explained because sheet twist flames were formed due to local partial mixing by oscillation.

As a result, when external oscillation was applied to the flame in the burner, heat, mass and momentum were promoted, compared

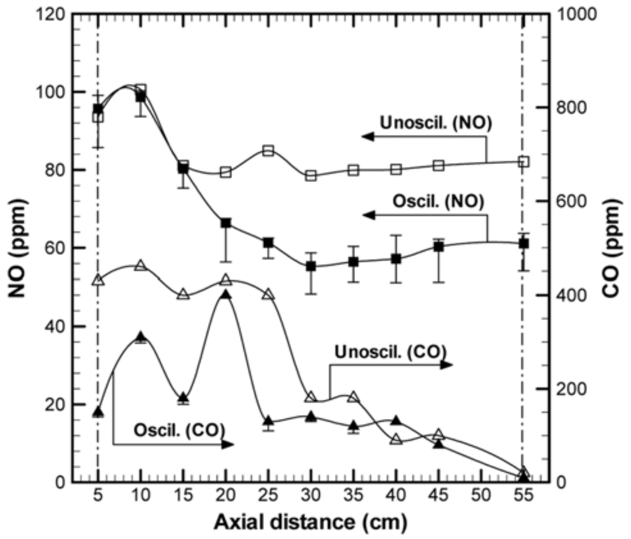


Fig. 3. Generating characteristics of NO and CO in reference flame.

to without oscillation, improving combustibility. Furthermore, the local area of maximum temperature within the flame region was decreased and the time of combustion gas retention at maximum temperature decreased, reducing thermal NO_x. Thus, NO_x reduction and high combustibility could be maintained with external oscillation.

2. Experiments Using Different Parameters

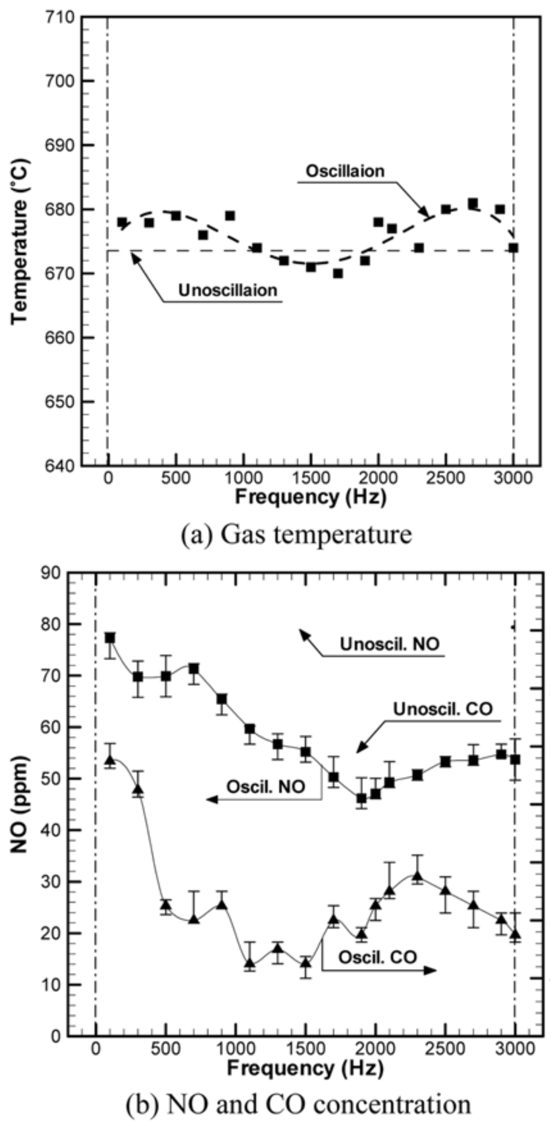
The factors expected to affect combustibility and NO_x reduction at external oscillation, i.e., oscillation frequency, forcing amplitude, and air velocity, were examined. Table 1 shows the experimental conditions for Cases 1-3.

3. Oscillation Frequency

Fig. 4 shows the temperature and NO and CO concentrations when the oscillation frequency was changed from 100 to 3,000 Hz at the forcing voltage of 3 V_{pp}.

Fig. 4(a) shows the results of comparing gas temperature with oscillation and without oscillation. Gas temperature with oscillation was than without oscillation.

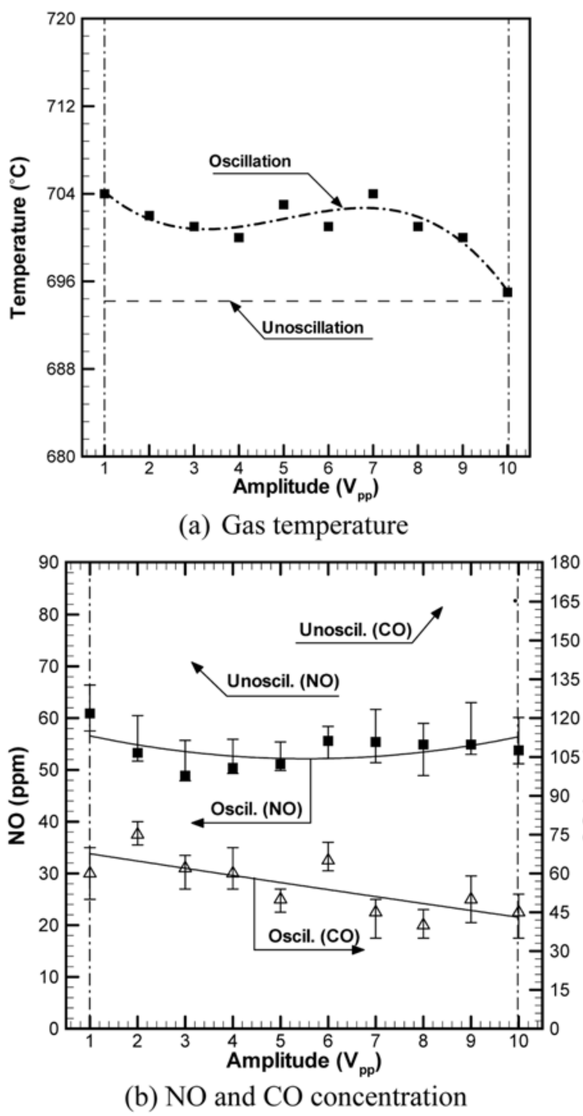
Fig. 4(b) shows the NO and CO concentrations with changes in oscillation frequency. NO concentration changed significantly with



(a) Gas temperature

(b) NO and CO concentration

Fig. 4. Effect of the variation of oscillation frequency.



(a) Gas temperature

(b) NO and CO concentration

Fig. 5. Effect of the variation of forcing amplitude.

frequency change in which oscillation was lower than without oscillation. Especially, the reduction rate was the highest at 41.5% with oscillation when the frequency was 1,900 Hz in the burner used in this study. Even though the frequency for NO reduction could differ according to the burner shape and type, it could be known that the biggest factor affecting NO reduction was frequency. CO concentration for oscillation was also a low value through the whole oscillation frequency. When the oscillation frequency was 1,900 Hz, CO concentration was decreased by 64.1%, compared to without oscillation, suggesting that NO reduction and combustion improvement could be seen at the condition as already mentioned with the reference flame case. However, NO and CO concentrations increased at certain frequency so that it is important to select an appropriate frequency for optimal operations.

4. Forcing Amplitude

Fig. 5 shows the temperature and NO and CO concentrations to externally forcing amplitude change at the oscillation frequency of 1,900 Hz.

Gas temperature in Fig. 5(a) was increased a little with increased forcing amplitude because the vortex structure in the rear flame was crushed with forcing amplitude, accompanying good mixing [5]. However, the gas temperature was decreased gradually when the amplitude was increased to higher than 6 V_{pp} because unstable flame was formulated due to a lift flame [7].

The average NO concentration in Fig. 5(b) was 54 ppm while the values fluctuated regularly through whole range in forcing amplitude. However, the amplitude of 3 V_{pp} was determined to be the optimum in this study since NO reduction was a little effective and CO reduction rate was 14% at this amplitude. The CO concentration generally decreased with increasing forcing amplitude, but changed irregularly with the amplitude since the flame became unstable due to lift flame.

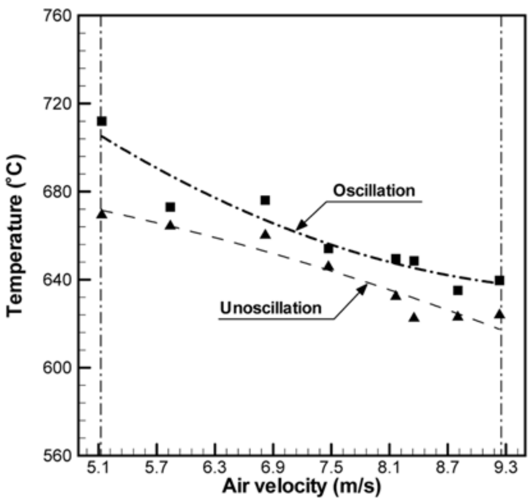
5. Air Velocity

The effects of air velocity were evaluated by changing the air velocity from 5.1 to 9.2 m/s at the oscillation frequency of 1,900 Hz and forcing amplitude of 3 V_{pp}, respectively.

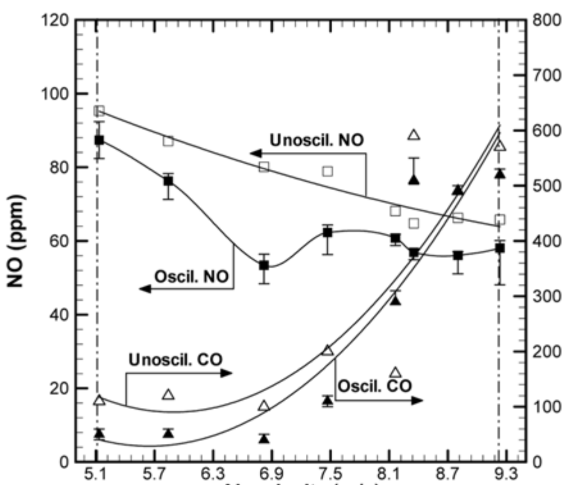
Fig. 6 shows the exhaust gas temperature and NO and CO concentrations.

In Fig. 6(a), gas temperatures for both cases decreased gradually with excess air supply. This is why heat loss increased as the air velocity increased. And the gas temperature of oscillation was higher than non-oscillation through the whole air velocity. The reason is that higher combustibility was maintained overall with oscillation.

Fig. 6(b) shows the concentrations of NO and CO. NO concentration decreased as in the case of gradual decrease in temperature in Fig. 6(a) as the air velocity was increased. The reason is why most of the NO_x was thermal NO_x generated at high temperature, which was closely related to combustion temperature. However, CO showed almost a similar distribution pattern with the air velocity up to 6.8 m/s. On the other hand, it increased drastically when the air velocity was higher than 6.8 m/s because combustibility decreased significantly by flame instability. Thus, the optimal air velocity was determined at 6.8 m/s in order to maintain high combustibility and achieve NO_x reduction.



(a) Gas temperature



(b) NO and CO concentration

Fig. 6. Effect of the variation of air velocity.

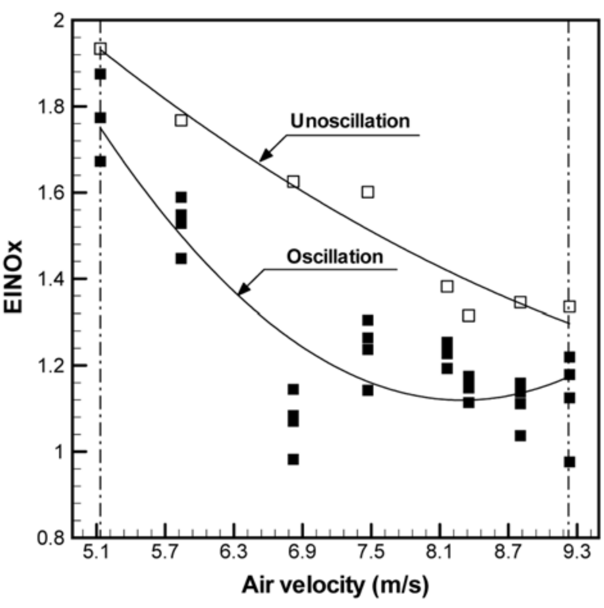


Fig. 7. Characteristics of $EINO_x$ according to the air velocity.

In Fig. 7, $EINO_x$ (emission index of NO_x) [8] was compared with and without oscillation according to changes in air velocity. $EINO_x$ is the number of grams NO_x produced per 1 kg fuel. NO_x concentration was measured in the posterior portion of the flame. The $EINO_x$ was calculated as in Eq. (1) under the assumption that all carbon in the fuel would convert to CO_2.

$$EINO_x\ (g/kg) = \frac{12[NO_x]MW_{NO}\times 1000}{[CO_2]MW_{C_{12}H_{26}}} \quad (1)$$

where MW is the molecular weight of each component, $[NO_x]$ is NO_x concentration (ppm), $[CO_2]$ is CO concentration (%), the coefficient 12 is the mole ratio in which 12 moles of CO_2 would be produced from 1 mole of light oil ($C_{12}H_{26}$), which is the fuel used in this study.

$EINO_x$ was reduced exponentially as air velocity increased, suggesting that $EINO_x$ value could be expressed exponentially with changes in air velocity. Furthermore, $EINO_x$ value decreased in oscillation rather than without oscillation, as known in Fig. 6(b) with NO concentration distribution.

CONCLUSIONS

This study was done to develop an externally oscillated oil burner that could maintain high combustibility and NO_x reduction.

The reference flame test showed that NO_x reduction and high combustibility could be maintained with external oscillation. When external oscillation was applied to the flame in the burner, the heat, mass, and momentum were promoted, improving combustibility. Furthermore, the area of maximum temperature within the local flame region was decreased by rapid mixing so that the time of combustion gas retention was decreased, reducing NO_x.

Parametric screening studies were carried out to determine optimal operating conditions.

1. When the oscillation frequency was 1,900 Hz, the NO_x reduction was the highest at 41.5% and CO was also reduced as 64.1%.

2. Forcing amplitude almost did not affect the rate of NO_x reduction and flame stability significantly, but the rate of CO reduction was 14%.

3. When the air velocity increased, gradual temperature drop resulted in NO reduction. $EINO_x$ showed similar distribution.

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