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Hazardous Waste Destruction and Nitric Oxide Reduction with Externally Forced Oscillation

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Abstract−The research described here focuses on the enhancement of hazardous waste destruction and the reduction in nitric oxide and unburned emissions in a cavity incinerator, which has externally forced acoustic oscillation. The specific configuration of the incinerator was manufactured to consist of two opposing jets and a rearward facing step [Chun, 1999]. The cavity-type incinerator warrants a sufficient residence time and effective turbulent mixing by the formation of a strong recirculation region in a combustion cavity. The experiments were carried out about combustion characteristics in a 3.2 kW laboratory scale, transportable, cavity incinerator without external oscillation. These showed that hazardous waste was destructed effectively, but unfortunately NO was increased by high gas temperature. To solve this problem, we developed an externally oscillated auxiliary burner embedded on the incinerator furnace. The external oscillation was effective to reduce NO which is produced at high temperature incineration and to destruct hazardous waste, simultaneously. Emissions of NO are seen to be decreased by nearly 60%, and DRE (destruction and removal efficiency) is above 99.99%, all with external forcing at a specific optimum conditions.

Key words: Hazardous Waste, Cavity Incinerator, External Oscillation, Nitric Oxide, CCl_4

INTRODUCTION

Incineration is an attractive alternative for the treatment of several classes of toxic hazardous wastes. In particular, a cavity-type incinerator, located on the same site where the waste is generated usually, has been considered as an attractive incinerator for less public opposition. A cavity incinerator [Chun, 2002] is generally characterized by the sudden expansion of a fuel-air mixture into a combustion cavity formed by a rearward facing step. This gives higher residence time in the recirculation zone which is formed in the combustion cavity. Therefore, it has a long reaction time enough for hazardous waste to be destroyed at high temperature.

Dump incinerators, which are similar to cavity-type incinerators in this study, have been studied extensively because of their ability to burn fuel and contain heat in a relatively compact configuration. Acoustically driven combustion instabilities are known to occur in such devices when pressure oscillations and periodic heat release associated with the combustion are in phase [McManus et al., 1993]. Over the past few years research has focused on the development and investigation of a small-scale, two-dimensional dump combustor which has been found to be capable of destroying hazardous waste surrogates to a high degree [Willis et al., 1994]. The degree of waste surrogate destruction in the device has been found to correlate with naturally occurring acoustic conditions [Marchant et al., 1992]. Destruction and removal efficiency (DRE) for the temperature-sensitive waste surrogate sulfur hexafluoride (SF_6), for example, are observed to be as high as 99.999999% (“8 nines”) under quiet conditions and occasionally under acoustically resonant conditions [Oppelt, 1987].

The DRE is defined as

$$\mathrm{DRE} = \frac{(m_{in} - m_{out})100\%}{m_{in}} \tag{1}$$

where, m_{in} and m_{out} are the mass flow rates of the principal organic hazardous constituent entering and leaving the system, respectively.

However, the results, which have already been done under unforced oscillation, have had the problem of increased NO_x emission, due to high temperature in combustion cavity. Therefore, what is needed is a hazardous incinerator which can simultaneously reduce NO_x and destruct hazardous waste.

The purpose of the present study is to further quantify and understand the benefits of externally forced acoustic oscillation on cavity incinerator performance for the destruction of hazardous waste and the reduction of NO, simultaneously. Therefore, a series of experimental studies have been made to figure out the physics of design process and thereby determine the operating conditions in the cavity incinerator, which was proposed in the numerical simulation [Chun, 2002].

EXPERIMENTAL APPARATUS AND PROCEDURE

A cavity incinerator and auxiliary burner embedded loud speaker for the externally forced oscillation are shown in Fig. 1. The insulated, 3.2 kW laboratory scale incinerator was constructed to show the attainment of the desired DRE, before application to a full-scale plant. The externally forced auxiliary burner consists of premixed burner, loudspeaker and control unit which is function generator (HP-33250A), oscilloscope (Tektronik TDS3052) and power amplifier (JPA-120). The control range of frequency and power voltage is 1 μHz-80 MHz and 10 mV_{pp}-10^2 V_{pp}, respectively.

Fuel (C_3H_8) and air were mixed and introduced into the auxiliary burner. And the hazardous waste (CCl_4) was injected through the waste injector only. The CCl_4 was transported with the aid of a

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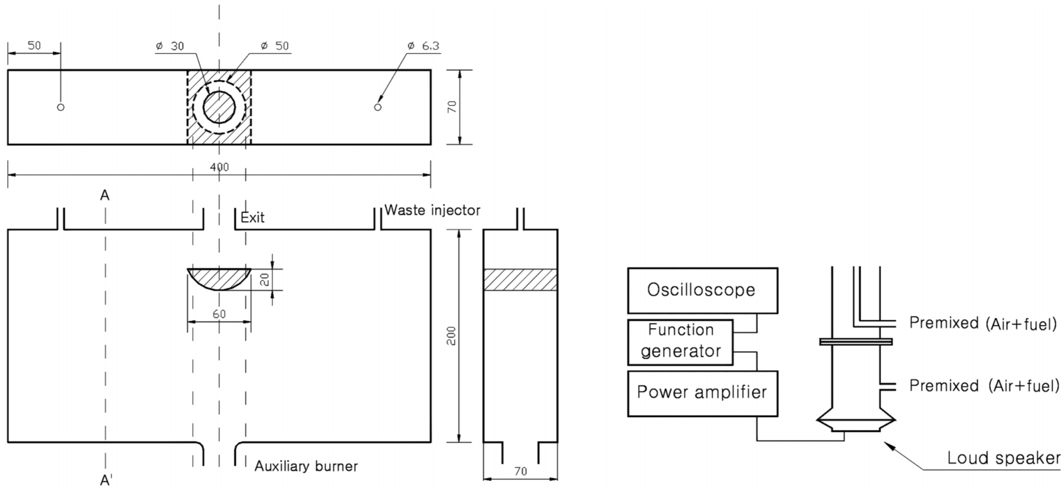


(a) Cavity incinerator (b) Auxiliary burner

Fig. 1. Schematic of a cavity incinerator and externally forced auxiliary burner.

pumpless "blow-case" system, consisting of a pressurized liquid reservoir tank, by high-pressure nitrogen gas, a high precision flow regulation valve, and corresponding gauges for the monitoring of pressure and temperature. The CCl_4 was injected into the heated gas at a heating unit. All the lines, after the liquid injection, were heated to prevent condensation of the CCl_4.

Temperature was measured by 5 points thermocouple probe inserted at section A-A' (see Fig. 1) in the combustion cavity. Gas sampling was achieved by the sampling probe placed at the exit. The combustion gases were withdrawn from the cavity incinerator by using a vacuum pump, through glass wool (to remove soot) and electric gas cooler (to condense vapor), and sampled, at time intervals, through a sampling loop in a gas chromatograph system (Shmadzu 14B).

The analysis of CO and CO_2 gases was accomplished by gas chromatography using Porapak Q columns with thermal conductivity detector. Detection of waste destruction in the device was made by using DB 5 capillary columns with flame ionization detector to measure CCl_4 destruction (sensitive to 100 ppm), yielding a maximum detectable DRE of approximately 5.7 nines. NO gas was continuously monitored by using an NDIR (Non-dispersive infrared) analyzer (CAI-ZRF). Temperature measurements are taken with 0.3 mm Pt/Pt-13% Rh thermocouples with Data Logger (Fluke 2625A).

Experimental flow condition is shown in Table 1.

Table 1. Experimental flow condition

Auxiliary burner				Waste injector				
Q_{fm}	Q_{am}	λ_m	V_m	Q_{fw}	Q_{cw}	Q_{aw}	R	λ_w
3.5	92	1.0	0.8	0	1.4	0	0.4	0

List of symbols

Q_f : fuel flow rate (*l*/min)

Q_a : air flow rate (*l*/min)

λ : air ratio

Q_c : hazardous waste flow rate (*l*/min)

R : molar concentration ratio of CCl_4 to CH_4

V : inlet mixture velocity (m/s)

Subscripts

m : auxiliary burner

w : waste injector

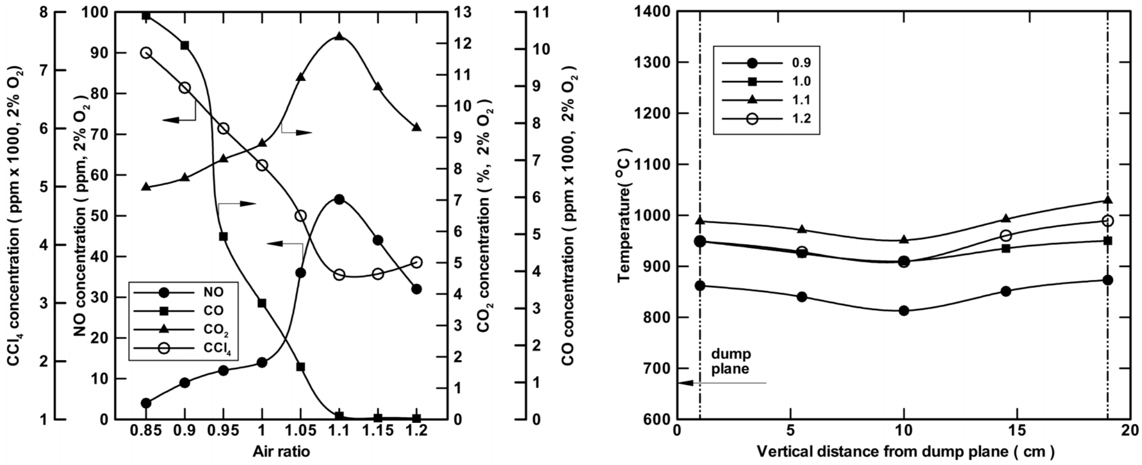
RESULTS AND DISCUSSION

1. Characteristics of the Flame in Cavity Incinerator

Results for flame characteristics are the data of the absence of external acoustic forcing, to know the characteristics of a cavity incinerator only and to compare with the results of externally forced oscillation. Selected species concentrations and gas temperatures are shown in Fig. 2 as a function of the air ratio at the auxiliary burner and through the combustion cavity at the center of section A-A' (see Fig. 1), respectively.

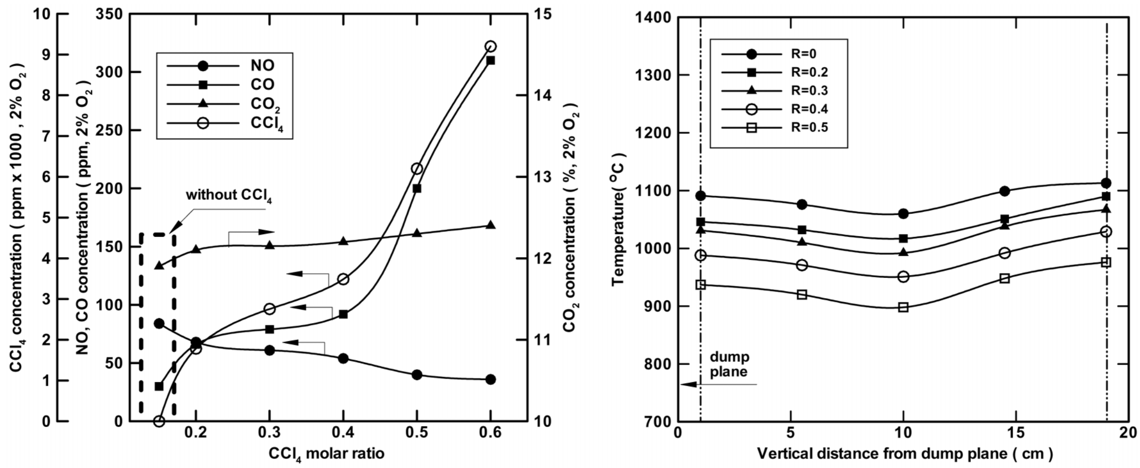
As one would expect, with increasing air ratio (accomplished here by increasing the air flow rate), the primary reaction at the cavity plane produced a hotter reaction, resulting in an increase in the destruction of CCl_4, which is the surrogate of hazardous waste, in the recirculation zones. Maximum destruction of CCl_4 showed around the air ratio of 1.1, showing that the concentration of CCl_4 was about 3,400 ppm. This means our cavity incinerator with optimal condition could achieve destruction above the EPA requirement of 99.99% ("4 nines") DRE for hazardous waste incinerators [Oppelt, 1987]. Good combustion (as can be known by the minimum concentration of CO) was also achieved with the air ratio of 1.1, which showed the maximum concentration of CO_2. However, unfortunately, the concentration of NO showed a similar pattern to that of CO_2, indicating good combustion. It means that the concentration of NO, produced by high gas temperature, was highest value at which hazardous waste was destructed effectively and good combustion was achieved. These observations suggest that thermal NO_x must be controlled by other technology, for example, an externally forced oscillation as applied in this study.

As can be seen in Fig. 3(b), gas temperature through the combustion cavity showed highest value at air ratio of 1.1, showing the optimal condition for the highest waste destruction and good com-



(a) Selected species (b) Gas temperature

Fig. 2. Selected species and gas temperature as a function of air ratio.



(a) Selected species (b) Gas temperature

Fig. 3. Selected species and gas temperature as a function of molar concentration ratio of CCl_4 to C_3H_8.

bustion.

Fig. 3 shows selected species concentrations and gas temperatures, according to the variation of the R (molar concentration ratio of CCl_4 to C_3H_8). The air ratio for the auxiliary burner was 1.1.

CCl_4, CO and CO_2 concentrations increased with the increase in the R, while NO and temperature decreased. The increase of CCl_4, CO and the decrease of NO were due to the lower temperature caused by heat release in the recirculation region due to pyrolysis of CCl_4. The increase of CO_2 is due to the increase of carbon, which increased the molar concentration ratio of CCl_4 to CH_4. When the R is more than 0.5, DRE is a failure which is three orders of magnitude below the EPA requirement [McManus et al., 1993]. This is because the temperature is below 1,000 °C in the recirculation region as can be seen in Fig. 3(b). We can see that the choice of an operational parameter such as chlorine to hydrogen loading at the waste injector is an important factor for CCl_4 destruction in a cavity incinerator.

Highest gas temperature showed at R=0, at which is not introduced CCl_4 surrogate in waste injector. And gas temperatures were decreased with increasing the R values. This is because of the inhibiting effect of CCl_4. The inhibiting effect of halogens on the oxidation of hydrocarbon/air flames has been studied and defined by Westbrook and Dryer [1981] as the inhibitor provides competition for radical species, particularly H atoms. Regardless of the inhibiting effect in the waste injector, the flame of the auxiliary burner burns stably. A higher temperature could be maintained (i.e., more than 1,000 °C) in the recirculation region, being particularly effective for the destruction of hazardous waste.

As a result, the cavity incinerator designed in this study guarantees complete destruction with good operation, because most of the wastes burn in the recirculation region.

2. Effect of Externally Forced Oscillation

Figs. 4-6 show a plot of selected species emissions from the combustor (corrected to 2% oxygen) and gas temperature in the combustion cavity as a function of forcing frequency and amplitude, for flow conditions given in the caption. These conditions were the same baseline conditions that produced extremely high CCl_4 destruction with the absence of external acoustic forcing. The air ratio for

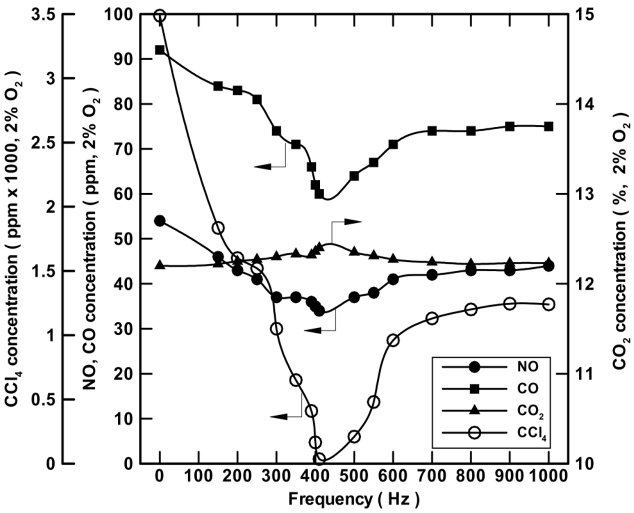


Fig. 4. Selected species as a function of frequency.

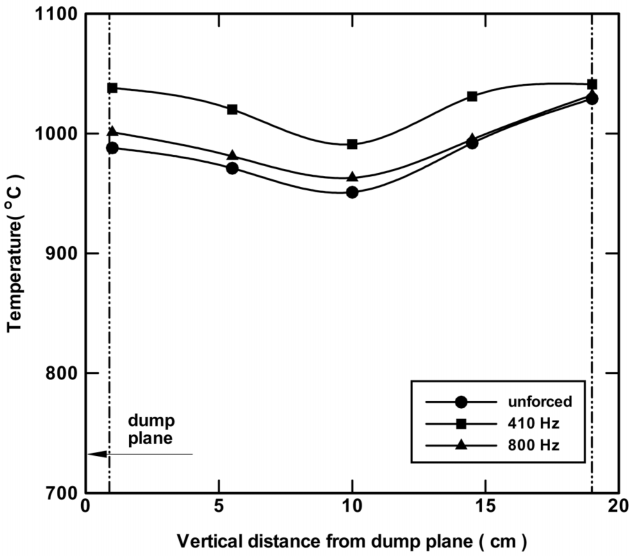


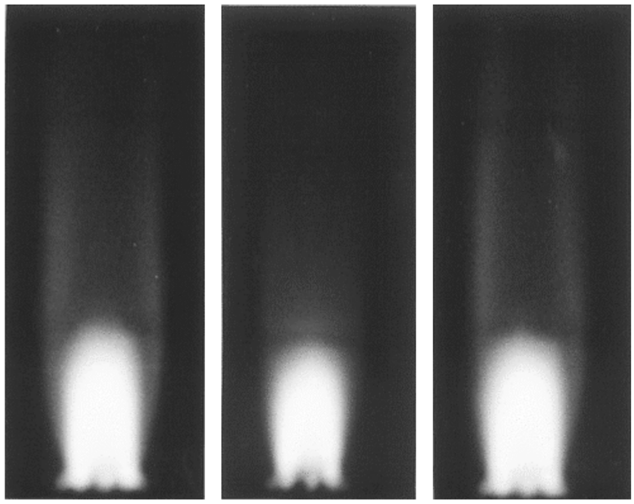
Fig. 5. Gas temperature as a function of frequency.

the auxiliary burner and the molar concentration ratio of CCl_4 to C_3H_8 were both 1.1 and 0.4, respectively.

2-1. Variation of Frequency

Fig. 4 shows a plot of selected species emissions from combustor (corrected to 2% oxygen) as a function of forcing frequency.

NO production actually dropped as compared to the unforced condition, in some cases by more than 61%, below 33 ppm. Even with external excitation at non-natural frequencies (e.g., 900 Hz), NO emissions were reduced compared with the unforced (0 Hz) case. These results appear to be consistent with the observations of Keller et al. [1994] who suggest that NO reduction during acoustical excitation in general occurs due to shorter gas residence times at higher temperature. Therefore, it is clear that averaged temperature can be reduced by the imposition of a single frequency upon a random signal when a maximum value is limited, so that it is possible that the time spent at the maximum temperature can be reduced for a given local air-fuel ratio. Thus this approach may lead



(a) Unforced (b) Forced at 410 Hz (c) Forced at 800 Hz

Fig. 6. Photograph of flames as a function of forced frequency.

to reducing the concentrations of NO_x in premixed systems. CCl_4 and CO concentrations were also reduced compared with the unforced case, while CO_2 increased. The minimum value of CCl_4 and CO was 100 ppm and 60 ppm, respectively.

The results described above clearly indicate that very efficient combustor operation is achieved during external acoustic excitation at the unforced condition. This extremely high CCl_4 destruction and low carbon monoxide and NO emissions suggest that the transport of mass and energy between core/reaction zones and recirculations zones may be strongly enhanced during external forcing.

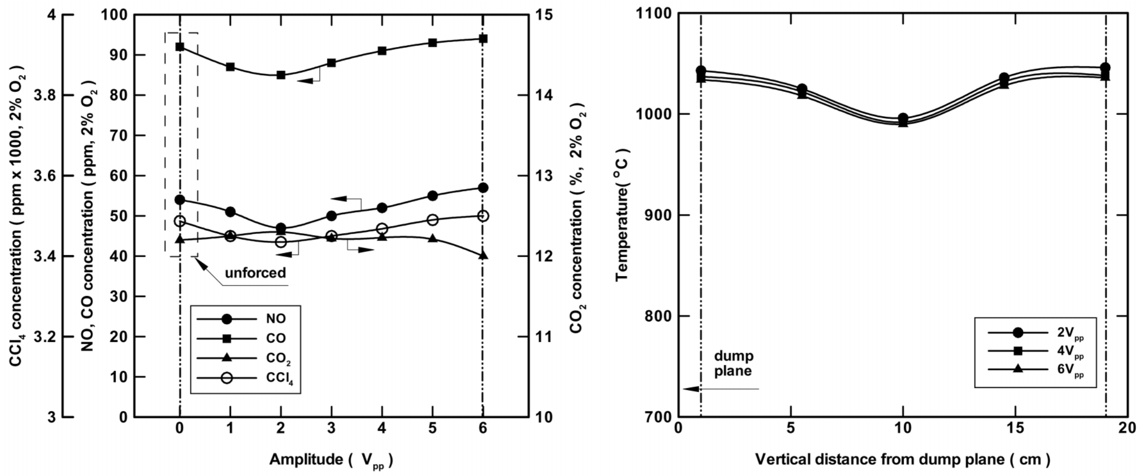
Fig. 5 shows transverse gas temperature distribution in the combustion cavity.

Interestingly, the gas temperature profiles for unforced and 800 Hz externally forced cases were nearly identical. In contrast, for 410 Hz excitation, the temperature in the recirculation zone increased. Actual increases in recirculation zone temperatures during the 410 Hz excitation were of the order 12-49 degrees. According to a simple pyrolysis model, this temperature rise could be sufficient to explain the increase in destruction rates experienced by CCl_4 during the 410 Hz excitation. That the average temperature increased with the 410 Hz excitation was not necessarily inconsistent with lowered NO production at this condition. Hence, the flame could possibly be experiencing high temperatures for relatively short periods of time, too short for significant thermal NO production to occur.

Fig. 6 shows a photograph of open flames as a function of forced frequency.

As indicated in the photograph, the acoustical forcing premixed flame was shortened in comparison with the unforced case. Particularly, the forced case at 410 Hz was shorter than 800 Hz excitation. The reason is that acoustically excited combustion was generated by rapid mixing and increasing heat and mass transfer rates, caused by externally forced oscillation.

Geometrically, the flame at the auxiliary burner is affected by entrained flow through cavity plan, coming from waste injector. This gives the instability of auxiliary burner flame, due to the increase of flame strain rate. And as already mentioned, the CCl_4 using the surrogate of hazardous waste has inhibiting characteristics,



(a) Selected species (b) Gas temperature

Fig. 7. Selected species and gas temperature as a function of amplitude.

like most halogens. Therefore, a long circulating flame forms within the recirculation regions, filling the entire combustion cavity. This means that the stabilization of auxiliary burner flame is very important for maintaining the high temperature circulating flame (i.e., above 1,000 °C), high DRE and NO reduction by externally forced oscillation. Also, forced frequency is an important factor for flame stabilization.

2-2. Variation of Amplitude

Fig. 7 presents the concentration of NO, CCl_4, CO, CO_2 and transverse temperature distribution in the combustion cavity.

Generally, the increase of amplitude shortens flame length by a larger mixing rate, causing an increase of turbulent fluctuation. However, in this study, amplitude was a minor effect because good mixing was already achieved by forced frequency. The concentration of NO, CCl_4, CO was somewhat decreased at amplitude of 2 V_{pp}. But, all the gas concentrations were almost not changed by the variation of amplitude.

CONCLUSIONS

The present study continues the evaluation of the acoustically driven cavity incinerator as a potential hazardous waste incinerator, demonstrating remarkable overall performance with external forcing. Destruction rate for hazardous waste was found to reach detection limits with external acoustic forcing. Simultaneously, NO emissions as well as carbon monoxide were seen to be diminished significantly under these same acoustic conditions. These results suggest that this cavity incinerator has a tremendous potential as a thermal destruction system, in addition to its suitability for active control of combustion performance via external acoustic forcing.

Selected results, studied for the effect of frequency and amplitude, are follows. First, optimal frequency was 410 Hz for the CCl_4 destruction and NO reduction. Therefore, it is possible to treat the CCl_4 and NO simultaneously with externally forced oscillation. Second, flame stability was good for the case which is applied the external oscillation. The optimal condition in this study was also 410 Hz. Lastly, the concentration of NO, CCl_4, CO was somewhat decreased at amplitude of 2 V_{pp}. The amplitude was a minor effect in the developed cavity incinerator.

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