Emissions Reduction and Pyrolysis Gas Destruction in an Acoustically Driven Dump Combustor

G. PONT, C. P. CADOU, A. R. KARAGOZIAN,* AND O. I. SMITH
Department of Mechanical and Aerospace Engineering, University of California,
Los Angeles, CA 90095-1597, USA

The research described here focuses on the enhancement of hazardous waste and pyrolysis gas surrogate destruction and the reduction in nitric oxide and unburned hydrocarbon emissions in an acoustically resonant dump combustor. While several prior studies have focused on flowfield interrogation and hazardous waste surrogate destruction under conditions of natural acoustic excitation, the present study focuses on the device's behavior under externally forced acoustic excitation. The effect of external forcing on hazardous waste surrogate destruction in the device was recently found to be significant, yielding destruction rates for the surrogate SF₆ that increased by as much as four orders of magnitude with acoustic forcing at specific resonant modes [1]. The present study also indicates a significant improvement in performance with external forcing at the same acoustic modes as those explored earlier. Emissions of NO are seen to decrease by nearly 60%, unburned hydrocarbons are seen to drop by over two orders of magnitude, and waste and pyrolysis gas surrogate destruction is seen to increase by nearly three orders of magnitude, all with external forcing at a specific acoustic mode of the device. The present observations further support the idea that acoustically resonant conditions can render the dump combustor device extremely efficient as well as highly controllable as a small-scale thermal treatment system. © 1998 by The Combustion Institute

INTRODUCTION

Dump combustors 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 [2–4]. Acoustically excited combustion processes are also generated in pulse combustor systems [5–8]. Local extinction by flame stretch is observed to delay ignition; later relaxation of strain allows thermal ignition to take place in a volumetric fashion, significantly increasing heat and mass transfer rates. Emissions of NO are also seen to drop during optimal pulse combustion performance [7, 9]; this is largely attributed to short gas residence times at high temperatures caused by rapid mixing with cooler residual gases.

Over the past few years our 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 [10–15]. The degree of waste surrogate destruction in the device has been found to correlate with naturally occurring acoustic conditions [11, 13, 15]. Destruction and removal efficiencies (DREs) for the temperature-sensitive waste surrogate sulfur hexafluoride (SF₆), for example, are observed to be as high as 99.9999999% ("8 nines") under quiet conditions and occasionally under acoustically resonant conditions [15]. The DRE is defined as

\[
DRE = \frac{m_{in} - m_{out}}{m_{in}} \times 100\%
\]

where \(m_{in}\) and \(m_{out}\) are the mass flow rates of the principal organic hazardous constituent entering and leaving the system, respectively. SF₆ destruction of eight nines is thus four orders of magnitude above the EPA requirement of 99.99% DRE for hazardous waste incinerators [16].

More recent experiments have focused on the ability of the resonant combustor to destroy waste surrogates under externally forced acoustic conditions using a loud speaker [1]. DREs for SF₆ under fixed flow conditions are found to

*Corresponding author. Current address: Department of Mechanical and Aerospace Engineering, 45-147D Engineering IV, UCLA, Los Angeles, CA 90095-1597 U.S.A. Phone: (310) 825-5653; FAX: (310) 206-4830, E-mail: ark@seas.ucla.edu.

© 1998 by The Combustion Institute
Published by Elsevier Science Inc.

0010-2180/98/$19.00
PII S0010-2180(97)00172-7
increase by four orders of magnitude or more, to 8 nines DRE, when acoustical forcing is imposed at system characteristic frequencies of 295 and 550–600 Hz. With external forcing at these natural modes of the system, OH* chemiluminescence images indicate that periodically excited flame structures become more compact and somewhat broadened, likely due to flame deformation by vortex shedding from the entrance to the combustion cavity. In addition, average flame liftoff distances appear to decrease with external acoustical forcing at desirable modes, suggesting that higher recirculation zone temperatures may be associated with on-resonance forcing.

The purpose of the present study is to further quantify and understand the benefits of external acoustical excitation on dump combustor performance for an incinerator/afterburner application. Two additional surrogate species were examined here, methyl chloride (CH₃Cl) and a mixture of ethylene (C₂H₄), benzene (C₆H₆), and nitrogen (N₂), each of which has different destruction characteristics from surrogates previously examined. Nitric oxide (NO) and unburned hydrocarbon (HC) emissions were also measured under resonant and nonresonant operating conditions. In order to understand and further quantify transport processes associated with acoustical excitation, thermocouple measurements were made in the present study to examine the temperature distributions within the flowfield.

EXPERIMENTAL APPARATUS AND PROCEDURE

The two-dimensional dump combustor used in the present experiments is shown schematically in Fig. 1, with an expanded view of flow/reaction processes in the combustion cavity. The combustor’s basic features have been described previously, and will only be summarized here. The reader is referred to [13, 15] for additional details.

In general in these dump combustor experiments, propane (C₃H₈) and air at room temperature were introduced into the plenum/mixing section of the combustor, then were accelerated through an inlet section before entering the combustion cavity at the sudden expansion or “dump plane”. Premixed flames can be stabilized due to the formation of high-temperature recirculation regions downstream of the dump plane [17], but as noted above, vortex shedding coincident with the flames may occur under conditions of natural acoustic excitation [10–15]. The spanwise depth of the inlet, combustion cavity, outlet and exit sections (30.5 cm) was usually sufficient to produce a visually two-dimensional flame over the entire span, although under certain experimental conditions the flow in the cavity became turbulent and the flame/flow structures became three-dimensional. Quartz windows bounded each end of the system in the spanwise direction, allowing appropriate optical access; additional quartz window slits were installed in the side walls to allow the introduction of a sheet of laser light for optical diagnostics [12].

A set of movable ceramic plugs defined the outlet section of this combustor. Waste or pyrolysis gas surrogate was introduced through injectors embedded in these plugs as indicated in Fig. 1. Injection into the recirculation zones allowed waste surrogates to be trapped for relatively long residence times under potentially high temperature and/or relatively oxygen-rich conditions so that they could be destroyed more efficiently. For the pyrolysis gas experiments described below, no auxiliary fuel was required in the inlet and only air was injected into the plenum. Water-cooled stainless steel injectors were used in all cases here to introduce gaseous surrogates into the cavity [11, 13]; there were 40 0.3-mm-diameter holes in the spanwise direction along each injector. Acoustic data were taken using pressure transducers located in the plenum and inlet.

External acoustical forcing was accomplished in the present experiment using a loudspeaker situated at the bottom of the plenum section of the device. Using a signal generator it was possible to produce a sine wave of varying frequency, then to amplify the signal and pass it to the speaker. This enabled a sweep through a range of input forcing frequencies from 0 to 1000 Hz to be performed, with forcing amplitude variation up to 150 dB, although frequencies below 200 Hz were difficult to attain consistently with the present speaker. Thus it
became possible to force the loudspeaker at frequencies corresponding to the natural ("resonant") modes of the device as well as other ("nonresonant") frequencies.

To continue to evaluate the performance of this dump combustor as a potential incinerator or pyrolysis gas afterburner, the gas phase surrogates methyl chloride and a mixture of ethylene, benzene, and nitrogen (EBN) were used in the present study. CH$_3$Cl is a gas which has been ranked as one of the 30 Resource Conservation and Recovery Act (RCRA) Appendix VIII compounds which are most difficult to destroy [18]. The difficulty in incinerating CH$_3$Cl results from the fact that chlorine scavenges hydrogen in the flame, thus reducing the radical pool and acting as a flame inhibitor. Hence CH$_3$Cl is a surrogate whose destruction is sensitive to the presence of radical species formed at high temperatures, so that hot recirculation zones created by premixed flames at the dump plane are required for adequate destruction. The EBN mixture has been identified by the Naval Air Warfare Center (NAWC) China Lake as a suitable surrogate for pyrolysis off gases from a plasma arc pyrolysis system. The proportions of ethylene:benzene:nitrogen used in the mixture were 12:1:20 by volume. In contrast to CH$_3$Cl,
the EBN mixture required the presence of high concentrations of oxygen for complete burning; this mixture burned as a diffusion flame in the recirculation zones, again, requiring no auxiliary fuel in the core flow at all.

Detection of waste destruction in the present device was made using a gas chromatograph (GC) equipped with an electron capture detector to measure CH$_2$Cl$_2$ destruction (sensitive to 100 ppb), yielding a maximum detectable DRE of approximately 5.6 nines. A flame ionization detector was used to detect ethylene (to 100 ppb or 7 nines DRE) and benzene (to 0.1 ppb or 5.5 nines DRE). In addition to DREs, unburned hydrocarbons were measured for the EBN mixture.

A chemiluminescence NO – NO$_2$ analyzer (Thermo Environmental 10AR Chemiluminescence NO – NO$_2$ Gas Analyzer) was used to measure the NO emissions from the combustor. The analyzer measured NO by reacting ozone O$_3$ with the sampled gases and measuring the resulting chemiluminescence. After being generated in the analyzer, O$_3$ was mixed to react with the sampled gases in a reaction chamber. The resulting chemiluminescence signal resulted from the decay of electronically excited NO$_2$ molecules produced in the reaction,

$$\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2$$

and was monitored through a filter by a high-sensitivity photomultiplier. The output of the photomultiplier was linearly proportional to the NO concentration. For this reason, a one point calibration with a sample of known concentration suffices as a calibration. For the present experiments, a gas cylinder of 19.2 ppm NO in N$_2$ from Matheson Gas Products was used as the calibrating gas.

**RESULTS AND DISCUSSION**

Results for the destruction of the two surrogates examined here, methyl chloride and the ethylene/benzene/nitrogen mixture, are quantified in terms of the DRE. CH$_3$Cl DREs are shown in Fig. 2 as a function of the equivalence ratio in the inlet core flow, with overall equivalence ratios (based on both the C$_3$H$_8$ in the inlet flow and the CH$_3$Cl surrogate) also shown. As one would expect, with increasing equivalence ratio (accomplished here by increasing the propane fuel flow rate) in the absence of external acoustical forcing, the primary reaction at the dump plane produced a hotter reaction, closer to stoichiometric, resulting in an increase in the rate of destruction of methyl chloride in the recirculation zones. Interestingly, at a relatively low overall equivalence ratio which nominally produced low DREs without forcing (overall $\phi = 0.75$), acoustic excitation via the loudspeaker at the 295 Hz mode showed a dramatic improvement in DREs, by nearly three orders of magnitude, to 5.6 nines. Since this was the detection limit of the GC for CH$_3$Cl, it is quite possible that acoustic excitation produced even higher destruction under these conditions. These observations suggest that the effect of acoustical excitation on CH$_3$Cl destruction was to cause the device to behave as if it were actually operating as if in a richer (closer to stoichiometric) combustion environment. Based on the destruction mechanism for CH$_3$Cl, Fig. 2 suggests that external acoustical excitation at
this natural mode enhanced the transfer of heat and radicals from the flames to the recirculation zones, which in turn became better able to destroy CH₃Cl. Acoustical forcing thus had the benefit of requiring less auxiliary fuel for very high surrogate destruction, as similarly seen for SF₆ destruction in prior experiments [1].

 Destruction and removal efficiencies for the EBN mixture are shown in Fig. 3a, b. As noted previously, this mixture did not require any auxiliary propane fuel in the inlet core flow. Its combustion was dependent on the transport of oxygen from the core to the region of surrogate injection, in this case, to the recirculation zones. In all cases, diffusion flame structures were observed in the recirculation zones. Here again it was found that acoustic excitation at the 295 Hz natural mode produced much higher DREs than without excitation for both benzene and ethylene. With the air flow rate fixed in the inlet, increases in the surrogate injection rate (to increase \( \phi \)) without external forcing produced somewhat degraded destruction (Fig. 3a), indicating that higher rates of injection of the fuel source required a greater degree of entrainment of oxidizer to the recirculation zones for more complete combustion. Yet under the same flow conditions but with external acoustical forcing, substantial increases in DREs for both benzene and ethylene were seen; in fact, the percentage increase in DREs with acoustic forcing was generally higher for the higher equivalence ratios. This suggested that not only was the transport of oxygen from the core to the recirculation zones increased with acoustic forcing, but that entrainment of oxidizer into the jet of surrogate within these zones was enhanced as well. This improvement in DREs was observed until a critical equivalence ratio was reached (\( \phi = 0.45 \)), above which the DREs dropped, eventually to unforced levels. Clearly, this critical equivalence ratio reflected a need for entrainment of oxygen into the recirculation zones and into the surrogate jet that even acoustical forcing could not accomplish.

With the surrogate injection rate fixed at the
maximum shown in Fig. 3a, air flow rate in the core was then increased to verify this conjecture. As shown in Fig. 3b, even without acoustical excitation, an increased inlet velocity increased the oxygen available for combustion in the recirculation zones, and surrogate DREs increased. With external forcing at 295 Hz, the improvements in destruction rates were dramatic, bringing both benzene and ethylene DREs to their detection limits. Augmentation of transport of oxygen to the recirculation zones and into the surrogate jet in particular appeared to result from the acoustic forcing. Hence from this set of results it became apparent that the effect of acoustical forcing for EBN destruction was to cause the device to behave effectively as if combustion were occurring under leaner conditions overall.

The effect of acoustical forcing on jet entrainment within the recirculation zones was observed visually as well. As indicated in the photograph in Fig. 4a, without acoustical forcing the sooting diffusion flames were long, circulating within the recirculation zones and filling the entire combustion cavity. Under the same flow conditions but with acoustical forcing at the 295 Hz natural mode (Fig. 4b), the diffusion flame was dramatically shortened, indicating substantial augmentation of transport of oxygen to the recirculation zones and in turn into the vicinity of the “waste” jet, where the reaction was completed and the flame ended in a much shorter distance. There was a clear visual augmentation of transport of gases from the inlet core to the recirculation zones during on-resonance acoustic excitation.

Emissions of unburned hydrocarbons during combustion of the EBN mixture further confirmed this effect of external forcing. As shown in Fig. 5a, b, under conditions corresponding to those in Fig. 3a, b, respectively, HCs were substantially reduced with acoustic excitation at 295 Hz, bringing levels nearly to 0 ppm. Again, this forcing appeared to have the effect of causing the combustor to behave as if operating under leaner conditions.

NO emissions from the combustor, with a propane–air mixture in the inlet core and no surrogate injection into the recirculation zones, further demonstrated the desirability of external acoustic driving. Figure 6a shows a plot of NO

Fig. 4. Photograph of sooting flame structure in the right half of the combustion cavity during destruction of the EBN mixture, for overall equivalence ratio 0.23 and cavity length 10.2 cm. Photos shown are for cases: (a) in the absence of external acoustical forcing, and (b) with external forcing at 295 Hz.
emissions from the combustor (corrected to 3% oxygen) as a function of forcing frequency, for flow conditions given in the caption. These conditions were the same baseline conditions (equivalence ratio, inlet velocity, cavity length) that produced extremely high DREs for SF$_6$.

---

**Fig. 5.** (a) Unburned hydrocarbon emissions from the EBN injection case during unforced and 295 Hz externally forced acoustical excitation as a function of equivalence ratio based on EBN as the sole fuel source. Only air is injected in the core flow, so that equivalence ratio is increased by increasing the EBN injection rate. Cavity length = 10.2 cm. (b) Unburned HC emissions as a function of air flow rate in the core. The EBN injection rate is fixed at that yielding the maximum equivalence ratio in (a). Cavity length = 10.2 cm.

---

**Fig. 6.** (a) Nitric oxide emissions in the dump combustor during externally forced acoustical excitation for the case where equivalence ratio $\phi = 0.83$, inlet velocity $U_i = 4.7$ m/s, and cavity length = 10.2 cm. Zero forcing frequency refers to the unforced case. (b) NO emissions as a function of equivalence ratio during unforced and externally forced acoustical excitation at 295 Hz; inlet velocity $U_i = 4.7$ m/s, cavity length = 10.2 cm. No surrogate is injected into the recirculation zones in (a) or (b).
with acoustic forcing at natural modes [1]. Remarkably, at natural frequencies at which SF₆ (as well as CH₃Cl) DREs were very high, nitric oxide production actually dropped compared to the unforced condition, in some cases by more than 50%, below 20 ppm. Even with external excitation at non-natural frequencies (e.g., 400 Hz), NO emissions were reduced compared with the unforced (0 Hz) case. Figure 6b shows NO emissions from the combustor as a function of equivalence ratio, for unforced conditions and forced conditions at 295 Hz. Excitation at this frequency appeared to reduce NO emissions significantly, by nearly 60% in some cases, especially at moderate equivalence ratios \(0.80 \leq \phi \leq 0.85\). Even at stoichiometric conditions the external forcing reduced NO by 40%. These results appear to be consistent with the observations of Keller et al. [7] who suggest that NO reduction during acoustical excitation in general occurs due to shorter gas residence times at higher temperatures. That the present NO emissions drop even further, to a significant degree, at natural frequencies could indicate enhanced residual gas mixing as well as at these frequencies.

The results described above clearly indicate that very efficient combustor operation is achieved during external acoustic excitation at a natural frequency of the system. These extremely high destruction rates and low unburned hydrocarbon and NO emissions suggest that the transport of mass and energy between core/reaction zones and recirculation zones may be strongly enhanced during external forcing. Recent optical diagnostics by our group, described in [1, 19, 20], as well as pointwise temperature measurements within the device, appear to confirm this enhancement of transport.

Figure 7 shows transverse temperature distributions under hot combustion conditions (with propane and air in the inlet core) as measured by a Type B thermocouple introduced into the cavity at a location 2 cm above the dump plane. The frequency response of the thermocouple in its ceramic jacket was considerably slower than the unsteady oscillations in the present flowfield (i.e., slower than 300 Hz), hence only time-averaged temperatures were obtained from the thermocouple. The thermocouple was introduced from the right, and essentially estimated average temperatures in the recirculation zone, flame, and jet core regions for different conditions of forced and unforced operation. Interestingly, the temperature profiles for unforced and 430 Hz externally forced (non-natural mode) cases were nearly identical. In contrast, for 295 Hz excitation (a natural mode in the larger combustor), the temperatures in the recirculation zones, flames, and inner core regions all increased. Actual increases in recirculation zone temperatures during the 295 Hz excitation were of the order 30–50 degrees. According to a simple pyrolysis model [20], this temperature rise could be sufficient to explain the increase in destruction rates experienced by SF₆ [1] during the 295 Hz excitation. The increased temperatures quantified in the recirculation zones are also consistent with prior OH* chemiluminescence images in this device [1] which suggested that average flame liftoff distances decreased during the 295 Hz excitation as well as during excitation at other resonant modes.

That the average temperature in the flame zone increased with the 295 Hz excitation was not necessarily inconsistent with lowered NO production at this condition. Recent phase-locked, planar laser-induced fluorescence (PLIF) imaging of temperature in the combustor [20] indicated that temperature in the cen-
tral (core) region of the combuster oscillated significantly, by as much as 700 degrees during one acoustic cycle at the 295 Hz excitation. Hence the flame could possibly be experiencing high temperatures for relatively short periods of time, too short for significant thermal NO production to occur.

CONCLUSIONS

The present studies continue the evaluation of the acoustically driven dump combustor as a potential hazardous waste incinerator/afterburner, demonstrating remarkable overall performance with external forcing at specific resonant modes. Destruction rates for thermodynamically dissimilar waste/off gas surrogates (SF$_6$, CH$_2$Cl, and an EBN mixture) were found to reach detection limits (of 5.5 to 8 nines) with external acoustic forcing at desirable natural frequencies. Simultaneously, NO emissions as well as unburned hydrocarbons were seen to diminish significantly under these same acoustic conditions. These results suggest the tremendous potential that this device has as a thermal destruction system, in addition to its suitability for active control of combustion performance via external acoustic forcing.

This work has been sponsored by the National Science Foundation under Grant CTS 90-21021 and by the Office of Naval Research under Grant N00014-93-1-1383, with Dr. Klaus Schadow of the Naval Air Warfare Center (China Lake) as grant monitor.

REFERENCES


Received 27 November 1996; accepted 24 April 1997