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ACTIVELY CONTROLLED AFTERBURNER FOR COMPACT WASTE INCINERATOR

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ABSTRACT

In a continuing research program directed at developing technology for compact shipboard incinerators, active control of fluid dynamics has been used to enhance mixing in incinerator afterburner (AB) experiments and increase the DRE for a waste surrogate. Experiments were conducted at power levels between 50 kW and 700 kW. This highest level is essentially full scale. The open loop active control system is based on the concept of combustion in periodic axi-symmetric vortices. Acoustic excitation was used to stabilize coherent vortices in the central air flow of a dump combustor configuration and waste gases injected annularly at the dump. This leads to good mixing, a controlled yet lifted partially premixed flame, high DRE and low emissions.

Tests with more realistic waste surrogate gases were undertaken. Nitrogen was used to dilute the ethylene and reduce the BTU content and an electric heater brought the waste surrogate gas temperature to more realistic levels (up to 1000 F). Even at BTU contents as low as 152 BTU/ft^3 the active combustion control worked well with a strong vortex, a stable lifted blue flame, and low emissions (CO and NOx below 10 ppm at a residence time of 104 msec). Then realistic waste off-gas chemistry was addressed using 640F mixtures of CO, H_2, H_2O, and N_2. Despite the low energy content (115 BTU/ft^3) the active control was still successful and emissions low (CO 9 ppm, NOx < 2 ppm).

Simplified, and more practical, configurations were developed. At full scale the high flow rate of the secondary air creates undesirable back pressure (0.25 PSI) which can prevent the secondary air speakers from operating. The relatively high waste injection velocity also creates expensive back pressure. This was addressed in three ways. First a 500 kW burner was built with variable secondary air area. The back pressure could be reduced and the secondary air forcing made effective. Then afterburners at the 50 kW scale were constructed, without secondary air flow or acoustic forcing at all, based on the use of the modulated central air flow in an ejector configuration. This geometry was optimized and good performance obtained (CO ~ 5 ppm, NOx 2 ppm). Finally, a design based on the use of the secondary air in many individual tapered elliptical waste ejectors was designed at full scale and tested in the enclosed dump configuration. The fuel was 20% ethylene and 80% N_2. This AB worked remarkably well even without any active forcing as the system self excited at the quarter wave mode. Emission were quite low (CO 15 ppm, NOx < 15 ppm for 340 kW) given the very short residence time of 84 msec. This afterburner was operated up to 700 kW, essentially full scale, and remained stable with the same low emissions (CO 35 ppm, NOx < 15 ppm at residence time of 46 msec). This is actually better performance than any of the 50 kW simulators when the residence time is taken into consideration. The ejectors were successful and the back pressure actually negative. They used less than 6% of the total AB air flow.

INTRODUCTION

Fluid dynamics control performance in many practical combustion applications such as airbreathing propulsion, energy conversion power plants, waste incinerators and other industrial burners. The importance of organized coherent large-scale vortical structures in large scale fluid mixing has been illustrated (1-3). Active manipulation of these vortical structures can lead to enhancement of the mixing process via an increase of the natural spreading rate of the shear layer. This can be realized using acoustic driving of the initial shear layer (4, 5). Through the use of advanced laser diagnostic techniques (6), the importance of controlling large and small scale mixing in combustion was determined (7). Active control by shear layer excitation has been used to enhance energy release (8-11) and to reduce emissions (12) and enhance hazardous waste incineration (13, 14).

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Tests with more realistic waste surrogate gases were undertaken. Nitrogen was used to dilute the ethylene and reduce the BTU content and an electric heater brought the waste surrogate gas temperature to more realistic levels. Even at BTU contents as low as 152 BTU/ft3 the active combustion control worked well with a strong vortex, a stable lifted blue flame, and low emissions. Then realistic waste off-gas chemistry was addressed using 640F mixtures of CO, H2, H2O, and N2. Despite the low energy content the active control was still successful and emissions low.

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At the Naval Air Warfare Center (NAWC), China Lake, work on active combustion control included open and closed loop control of small scale (~10kW) and large scale (~1MW) combustors to enhance their performance by increasing energy release, extending the lean flammability limit, and stabilizing the combustion (15). The focus of the investigations shifted recently to emphasize practical applications such as the investigation of techniques for the development of compact waste incinerators for use aboard Navy ships. The common underlying concept of the combustion processes discussed in the present paper is vortex combustion. The combustion in many practical burners is partially diffusion controlled and this means localized regions have fuel to air ratios not conducive to low emission performance. The vortex combustion technique ensures that the combustion is confined to regions (i.e., vortices) within the combustor where optimal local conditions can be maintained. The vortex provides intense mixing and long residence time necessary for a complete combustion process. The high strain rate in the vortex roll-up region also delays ignition until partial premixing is obtained. Thus vortex control, via acoustic excitation, can turn a sooty yellow benzene diffusion flame into a perfectly blue clean flame.

Since this is the last year of this SERDP funded program, we have directed our focus on the practical aspects of implementing this active control vortex technology afterburner (AB) on a real incinerator. These include evaluating performance on more realistic waste surrogates, evaluating self excited (passive) configurations, looking at simplified designs, reducing back pressure, and quantifying performance at full scale.

EXPERIMENTAL

Since many different experimental configurations, including combustor geometry and firing gases, were studied, only a general description will be given here. For DRE measurements, the waste surrogate contained benzene, which is third on the EPA list of thermally stable, difficult to destroy hazardous compounds, as reported by Lee et. al. (16). The pyrolysis surrogate was a mixture of nitrogen, ethylene, and benzene at 62%, 31%, and 7% by weight. It has been found previously (17-19) that CO emission inversely tracked benzene DRE: low CO emissions were directly correlated with high benzene DRE. In the DRE tests benzene constituted a very large fraction of the combustible content for sensitivity reasons; therefore it actually unrealistically affected the combustion properties (no real incinerator, outside of a hazardous waste incinerator, would be burning so much benzene). Therefore, for most other tests (and all those reported here) the benzene was left out of the waste mix and CO emissions tracked as a performance monitor. (Unburned hydrocarbons were not found to be a good tracking parameter as they are destroyed to unmeasureable levels long before the CO levels drop and benzene DRE rise to reasonable values.)

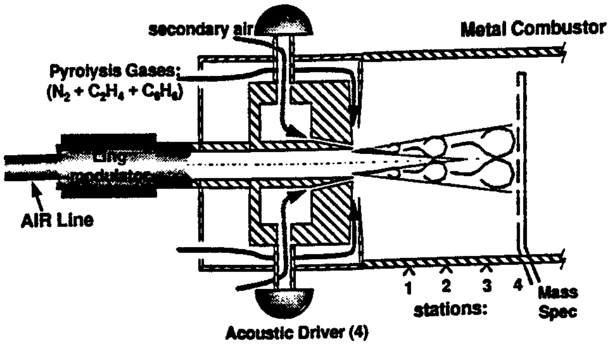

Fig. 1 Schematic diagram of the version 3F 50 kW actively controlled dump combustor incinerator afterburner concept. The probe fed a mass spectrometer for benzene DRE measurements as well as a continuous emissions monitor for CO, NO, NO_2, and unburned hydrocarbons (UHC).

The baseline medium scale incinerator (Version 3F, Fig. 1) generated 35-51 kW of heat release, depending on operating conditions. The inlet diameter was 38.4 mm and the dump 178 mm. The velocity of the inlet jet was 15.3 m/s for a Reynolds number of 39,000 based on the jet diameter. The measured preferred mode of the jet at 15 m/s was 190 Hz. The inlet flow was forced using a high speed acoustic valve (from Ling Electronics™); it was easy to generate coherent vortices using less than 5 Watts. The acoustical output power of the Ling™ valve increases sharply with increasing flow rate, even at constant electrical power input, so it was also easy to generate coherent vortices at full scale (700 kW).

In the baseline afterburner configuration ethylene, benzene, and nitrogen, used to simulate the output of a primary pyrolysis chamber such as a kiln or plasma unit, were introduced circumferentially via an "entrainment" plate to enter the main air shear layer at the incipient vortex roll-up point. This region is not directly forced, but PIV results reported previously (17) showed the entrainment is periodic due to the periodic roll-up of the central air vortices. Secondary air was then introduced through 38 holes of 2.3 mm diameter fed from an acoustically forced plenum. The plenum is forced with four 75 Watt acoustic compression drivers. This extra forced flow helps indirectly modulate the waste surrogate. In a real system, and in some tests reported here, the waste surrogate is hot and difficult to modulate directly.

One variation on this configuration, referred to here as version 5, was nearly identical to the baseline with the exception that the waste surrogate was introduced through the holes and the secondary air entered from the "entrainment" region. In addition, the waste surrogate plenum was not acoustically forced but the secondary air entrainment region was. In this configuration the waste surrogate is sandwiched between the main air shear layer and the secondary air flow. This testing was done at the 350 kW level.

A water cooled probe was directly attached to a continuous emission monitor which measured O_2, CO, NO, and NO_2. The probe has been redesigned to enter via the tail pipe so that any measurements could be made at any axial location within the combustor. The probe were mounted vertically to minimize sampling error caused by buoyancy, i.e. the multiple orifices of the probes averaged over a vertical radial profile across the duct. The probe reaches entirely across the diameter of the 50 kW scale dump but only across the radius of the 500 kW scale combustor. In the 500 kW scale experiments no difference was seen between the lower and upper radii (i.e. no effect of buoyancy). Because the flow in these combustors is neither plug nor even fully developed, there is no benefit from using a particular orifice spacing rule.

RESULTS AND DISCUSSION

Realistic Waste Surrogates

Previous work on the 50 kW afterburner had been done with a mixture of nitrogen, ethylene, and benzene as a waste surrogate. Benzene is a good tracer for DRE as it is number three on the EPA list of hard to destroy hazardous compounds. However, the waste surrogate mixture used falls very short of emulating real pyrolysis chamber off-gases in three areas. First the mixture wasn't hot. Hot gases might impact the operational characteristics of the vortex afterburner as it depends on rapid mixing and a brief hold off of combustion (lifted flame) so that reaction occurs mostly in a clean partially premixed manner versus a dirtier diffusion flame manner. The delay, i.e. lift off, of the flame is caused by the high strain rate in the vortex roll-up region. If the pyrolysis gas surrogate were hot this may have caused earlier ignition and flame attachment leading to higher emissions. Secondly, the BTU content of the ethylene benzene mixture (about 1580 BTU/ft^3) was much higher than the typical output of pyrolysis chambers. Finally the chemistry of the gas, mostly ethylene with up to 17% benzene, is not representative of pyrolysis chambers.

Therefore two sets of experiments were undertaken with heated gases. First, in an attempt to get down to realistic BTU content the ethylene was diluted with large quantities of nitrogen. A 6 kW electric heater was used to raise the mixture up to 810 K (most test were run at 644 K). The nitrogen level was varied to reduce BTU content. The experiments were done in a modified version 3F geometry: the gap for pyrolysis gas introduction was widened to maintain the same injection velocity at the higher temperature (lower density). Even at BTU contents as low as 152 BTU/ft^3 the active combustion control worked well with a strong vortex, a stable lifted blue flame, and low emissions. The power level was 43 kW.

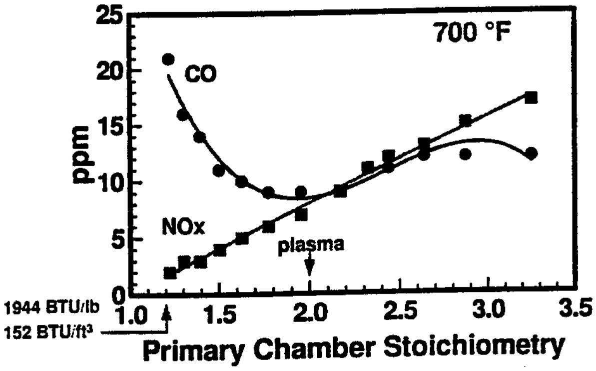

Fig. 2 CO and NOx emissions for actively controlled 43 kW vortex afterburner combusting mixtures of ethylene and nitrogen. The abscissa is equivalent primary chamber stoichiometry where infinity means 100% ethylene and 1.0 means 100% N_2. The label "plasma" refers to a proposed Navy plasma primary chamber.

Figure 2 shows the performance of the afterburner as a function of nitrogen dilution measured at x/D of 3.0 (D = dump diameter, 178 mm). The data is plotted in terms of equivalent primary chamber phi, where phi = infinity means 100% fuel and 0% nitrogen and phi = 1.0 means no fuel at all, i.e. 100% nitrogen. The fuel to air stoichiometry operating point of the *afterburner* for these tests was 0.61. Notice that the CO is below 25 ppm at all primary phi's and actually optimizes at a primary phi of 2.0. Note also that the NOx linearly decreases at lower primary phi's. This is an obvious effect of dilution: the higher the nitrogen the lower the exhaust gas temperature and, therefore, lower the NOx. DRE was not measured but previous tests have shown DRE to inversely track CO, i.e. low CO means high DRE. In fact, CO has been found to be the most sensitive indicator for performance. The CO rises at very low primary stoichiometry for three reasons. First the flame stability decreases at very high nitrogen dilutions. Second the actual residence time for the constant x/D = 3.0 downstream sampling position decreases as nitrogen is added. Finally, the waste injection geometry is designed for medium flow levels so at high nitrogen content the waste injection flow speed is considerably above design point (the AB air and stoichiometry are kept constant, so the total ethylene flow rate is constant and as nitrogen flow is added the total waste flow increases). This effect may also be the cause for the decrease in performance at higher primary phi's: the waste injection velocity becomes too low for optimum operation. In a real incinerator application if the primary pyrolysis phi got below a certain level, say 1.4, the controller would automatically add auxiliary fuel, so the AB would not have to handle such a wide range of flow rates.

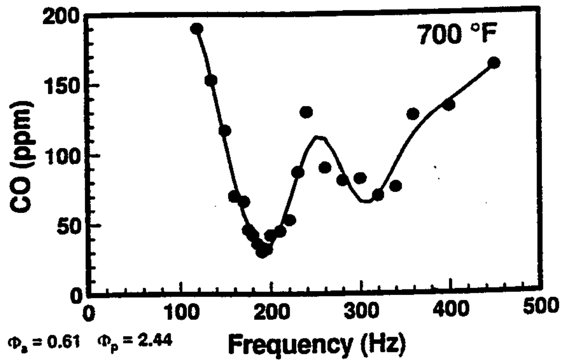

Fig. 3 CO emissions as a function of forcing frequency in hot waste afterburner tests. The afterburner fuel to air stoichiometry was 0.61 and the input gas simulated a primary chamber phi of 2.44 at 700 F.

Figure 3 shows the performance of the system, at primary phi of 2.44, as a function of forcing frequency. It is clear that coherent vortices are still the controlling mechanism: the minimum in CO comes at the preferred mode of the air jet, i.e. the frequency at which the most coherent vortex is generated. Comparison of controller off to controller on as a function of downstream distance x/D (Fig. 4) showed that at 2/3 power the controller goes below the 100 ppm CO limit at an x/D of 2.5 which is essentially as compact as previous tests with pure ethylene. The active control is still viable with hot low BTU content gases:

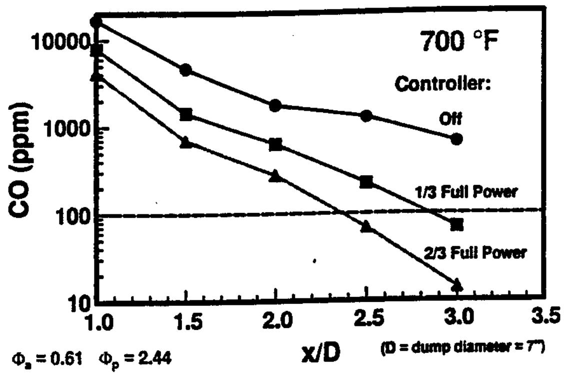

Fig. 4 CO emission as a function of downstream distance and controller power. Same conditions as Fig. 3.

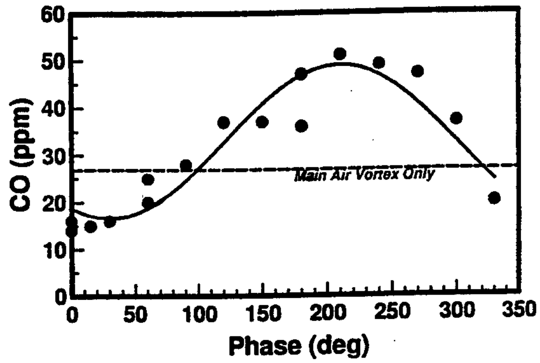

Fig. 5 Effect of relative phase angle between main air forcing and secondary air forcing.

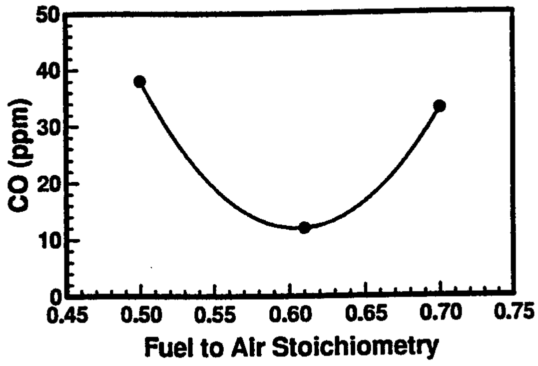

Fig. 6 Effect of afterburner fuel to air stoichiometry on performance.

Fig. 5 shows that the CO emission optimized at a particular phase angle between main air vortex roll up and secondary air acoustic forcing (which indirectly modulates the hot waste products). This indirect modulation feature of the 3F configuration was originally designed to remove the acoustic drivers from direct contact with hot gases and worked very well in the actual hot tests. No speakers were damaged in several days of running. Figure 6 shows that the AB optimized at a stoichiometry of about 0.6. Leaner lead to decreasing stability and higher CO. Richer also lead to higher CO as is always seen. It is important not to confuse the primary stoichiometry (which sets the chemistry and BTU content of the waste gases entering the AB) and the AB phi, which is the stoichiometry at which combustion occurs in the AB.

The second set of tests undertaken with the 50 kW combustor involved not only hot gases of low BTU value, but accurate chemistry as well. Equilibrium calculations were done by Jerry Cole of EER Corporation for typical Navy waste streams and the off-gas composition was determined as a function of primary chamber fuel to air stoichiometry. The major constituents of these mixtures were N_2, CO, H_2, and water (CO_2 and hydrocarbons were low and left out). Tests were run for a primary chamber equivalent phi of 2.5 with a mixture of 18% CO, 10% water, 20% H_2, and 52% N_2 (by volume). The BTU content was 115 BTU/ft^3. The temperature for these tests was 640 F. The actively controlled vortex afterburner (again version 3F) worked very well with this realistic chemistry mixture. There was again a strong vortex and stable blue flame.

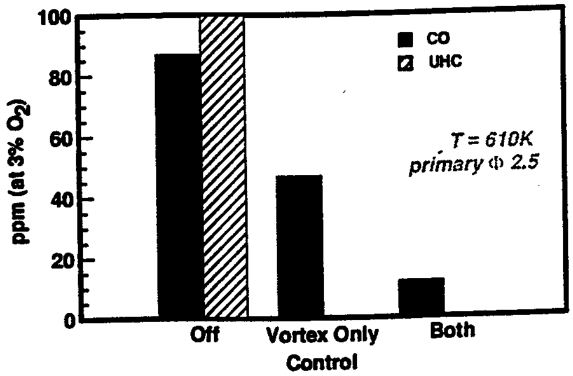

Fig. 7 Actively controlled vortex afterburner performance using realistic waste chemistry at 610K.

Figure 7 shows that the controller brought the CO from about 70 ppm (7% O_2 basis, controller off) down to about 9 ppm (both main vortex actuator and secondary air acoustic forcing on). Unburned hydrocarbons dropped to below our measurement capability (100 ppm). The NOx was very low: never above 1-2 ppm (detection limit of 1 ppm). Active control was still viable and the optimum phase angle for injection of waste into the vortex the same (Fig. 8). Figure 9 shows that the CO emissions fell below 100 ppm for a downstream distance corresponding to a combustor volume of 0.0095 cubic meters.

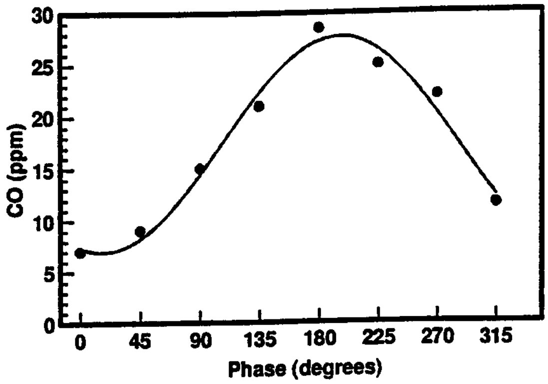

Fig. 8 Effect of relative phase between main vortex and waste injection for realistic waste chemistry case.

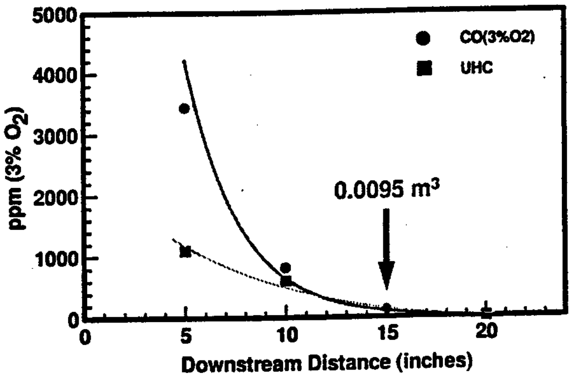

Fig. 9 Emissions versus down stream distance for realistic waste chemistry case.

Simplified Designs

Simplified, and more practical, configurations were developed to aid in transition to real incinerator use and overcome some limitations to full scale implementation. Some of these limitations include back pressure, narrow channels, and the complexity (and longevity) of the secondary air acoustic forcing.

At full scale the high flow rate of the secondary air creates undesirable back pressure (0.25 PSI) which can prevent the secondary air speakers from operating by pinning the diaphragms against the stop. The relatively high waste injection velocity also creates expensive back pressure. This was addressed in three ways. First a 500 kW burner was built with variable secondary air injection area. The back pressure could be reduced by adjusting the gap, and therefore area, larger. Although this reduces the secondary air velocity the secondary air forcing made effective. The relative phase angle between the main air vortex and secondary air forcing was able to change the performance of the AB. These tests were done at the MW level with an open flame. (The power level of an open flame is always higher due to entrainment of surrounding air which forces the use of higher fuel rates.) The geometric configuration was version 5 (where the waste is sandwiched between the main and secondary air flows). The effect of the forcing was judged by the appearance, or absence, of yellow in the flame (soot). At the proper phase angle the flame was blue. At improper phase angles some yellow formed.

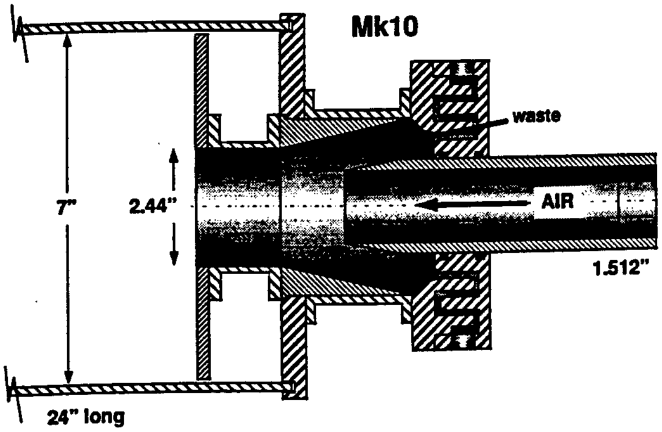

Fig. 10 Apparatus diagram for optimum configuration of version 10 of the afterburner.

Tests were also done, on afterburners at the 42 kW scale, without secondary air flow or acoustic forcing at all, based on the use of the modulated central air flow in an ejector configuration. This geometry was extensively studied (eleven configurations, collectively referred to as version 10) and the performance characterized under varying forcing levels and frequencies. Because there were so many tests to do with the wide range of geometries, they were not done with realistic waste temperature or chemistry. The waste surrogate was 18% ethylene and 82% nitrogen, at room temperature, so the BTU content was low (280 BTU/ft^3). Figure 10 shows the optimum geometry: note that the waste injection channel is much wider than previous designs (17-19) and less likely to clog. (The serpentine path at the rear of the waste channel is there to distribute the flow evenly around the circumference. Under no circumstance would a real design use such a large pressure drop method. In a real system some form of scroll with flow straighteners would be used.) The main air exit diameter was fixed at 38.4 mm as was the velocity (15 m/s), but most other dimensions were varied. These include the limiting exit diameter of the waste channel, as well as its convergence angle, the distance from the main air exit to the limit of the waste channel convergence, and the length of the final straight section before the dump plane. Note that the optimum geometry resembles an ejector, where the main AB air is the fluid that would pull the waste into the AB.

The system was found to work best when forced heavily at the preferred mode as defined by the dump plane exit diameter and velocity (not the main air exit diameter and velocity). Again, as in the past, this shows the importance of the large scale vortex combustion within the dump region. The optimum forcing frequency of each geometry tracked the dump plane preferred mode, so that the best geometric configuration, which has a much larger dump exit plane diameter and lower velocity, optimized at a much lower frequency (~100 Hz) than previous systems, such as version 3F (~190 Hz). The acoustic resonance of the chamber was found to be near 215 Hz so the wide separation between this acoustic mode and the preferred mode of the jet (100 Hz) allowed active forcing control without the interference of self excitation.

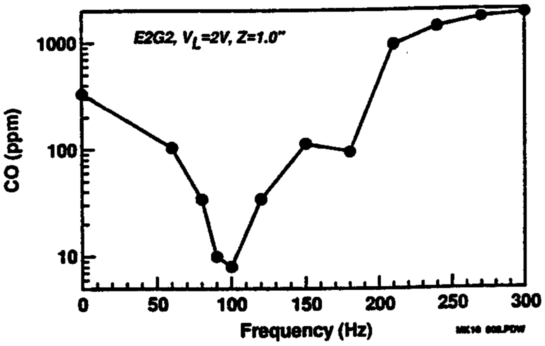

Fig. 11 Performance of afterburner configuration of Fig. 10 as a function of driving frequency. The preferred mode of the jet is about 100 Hz. Note the log scale.

Figure 11 shows the CO emissions versus forcing frequency for the optimum geometry (for space reasons, only the performance of the best configuration will be shown). The performance obviously optimizes at the preferred mode of the dump plane exit. At higher forcing levels on the main air actuator the CO performance was as low as 3 ppm (Fig. 12) and the NOx as low as 2 ppm, both at an AB phi of 0.575. Notice that the design gives considerable mixing time before the dump plane. At low forcing levels, or no forcing at all, the flame would sometimes move upstream of the dump plane into the waste/air premixing region. This always lead to very bad performance (left side of Fig. 12). The forcing probably keeps it out of this region by strain rate quenching. It also considerably hastens the premixing process. Forcing at high frequencies, however, creates small vortices and this actually pulled the flame inside the premixing region and again lead to poor performance (right hand side of Fig. 11).

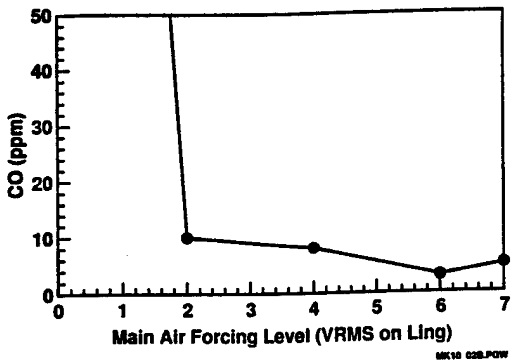

Fig. 12 Performance as a function of forcing level (vortex coherence).

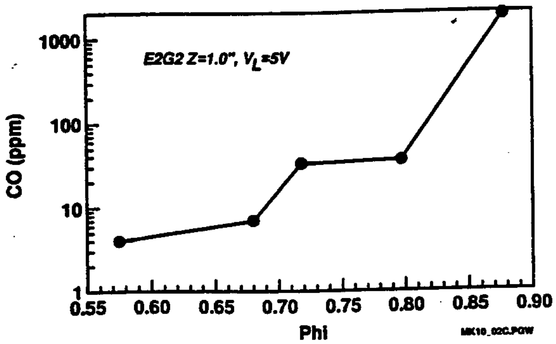

Fig. 13 Performance as a function of fuel to air stoichiometry, phi.

Figure 13 shows the performance, in terms of CO emissions, as a function of AB phi. As always, performance worsened as excess air dropped towards stoichiometric. The lower limit on phi (upper limit on excess air) is governed by infrequent flameout.

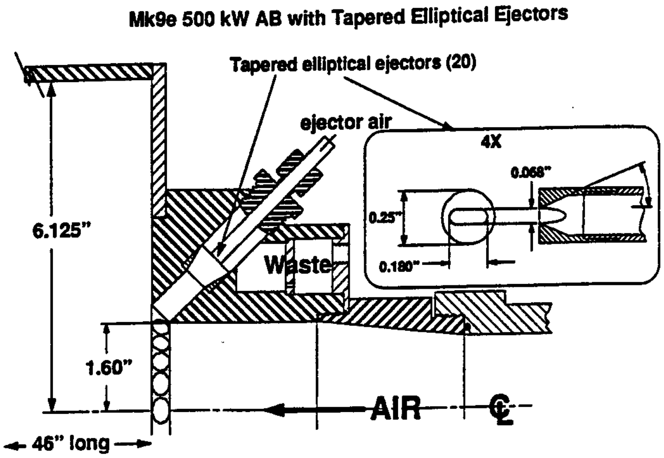

Fig. 14 Schematic cross section of the 500 kW version 9 afterburner. Only one side of the symmetric design is shown; there is cylindrical symmetry about the center line. The inset shows an enlarged cross section of the tapered elliptical ejector nozzles (of which there are 20).

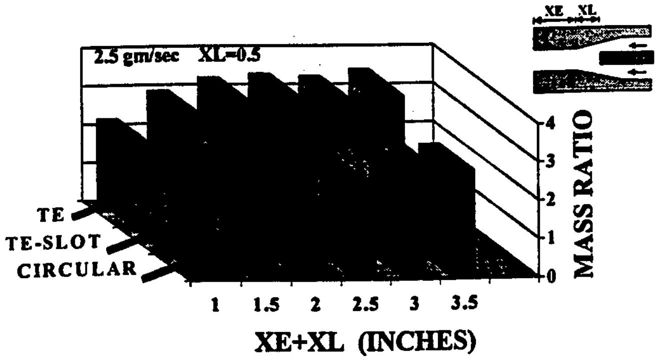

Fig. 15 Performance, in terms of mass pumping ratio, of the tapered elliptical nozzle ejectors comared with circular nozzle ejectors. The geometry is shown.

The final design presented was directed at reducing the waste injection back pressure to zero or below zero. It is based on the use of a small amount of secondary air in many individual tapered elliptical waste ejectors, and was designed at full scale and tested in an enclosed dump configuration. The tapered elliptical ejector was developed in Dr. Schadow's group at NAWC China Lake (20). It has much faster mixing rate than a circular nozzle and therefore a higher pumping rate for short ejectors. Since the design would be mixing air, albeit small amounts, with what would be hot combustible gases in a real system, it was important to keep the ejectors as short as possible to minimize the occurrence of pre-ignition. The inset of Fig. 14 shows the design of the ejectors, of which there were 20 situated around the circumference of the main AB air exit. Each ejector nozzle is at the end of a 6.4 mm diameter tube and has an approximately elliptical exit of 4.6 mm by 1.7 mm. This elliptical slot is machined into a conical back angle and the edges act as delta wings leading to stream wise vorticity on top of the normal spanwise exit plane shedded vortices. These greatly enhance the mixing rate.

The performance of the individual ejectors is shown in Fig. 15 as a function of the length of the ejector. It is clear that the mass pumping ratio of the tapered elliptical (TE) ejectors is higher for short ejectors than the circular. (The configuration labeled slot is for a 2D ejector plenum rather than a circular one.) The nominal operating conditions for the TE ejectors is a mass ratio of 3.0 (3 times as much waste is pumped as air used) and a back pressure of essentially zero. Under these conditions the ejectors are only using about 6% of the total AB air flow, or 12 gm/s for all 20 ejectors. Negative back pressures can be generated with higher ejector air flow. The nominal waste injection velocity was 20 m/s. These numbers are for a firing rate of 340 kW (1.1M BTU/hr). Although the combustor experiments were done with cold waste surrogate, the individual ejector design was tested with hot off gases of a rich burner at 480 C. There was no ignition of the combustible off gases when the ejector air was turned on.

The fuel was 20% ethylene and 80% N_2 at room temperature. The AB was operated at a phi of 0.575. The total ethylene flow rate was 7.15 gm/s for the 340 kW case (1350 lb/day) and 14.3 gm/s at 680 kW (1.35 ton/day). The main air inlet diameter was 81 mm and the nominal operating velocity 30 m/s (at 340 kW). Tests were also run at AB air velocities of 45 and 60 m/s (680 kW). The probe locations (0.91m for 30 m/s and 1.02 m for 45 and 60 m/s) lead to average residence times (plug flow) of 84, 62, and 46 ms respectively. The combustor dump region was 311 mm diameter by 1.17 m long and it is insulated with ceramic blankets between the inner and outer stainless steel tube walls. the outer tube is 508 mm diameter so the ceramic blanket insulation is about 86 mm thick. During operation the inner wall glows bright yellow-orange; these are the first tests we have done with hot walls. The measured chamber temperature was between about 1030 C at startup (cold walls) and 1180 C (hot walls).

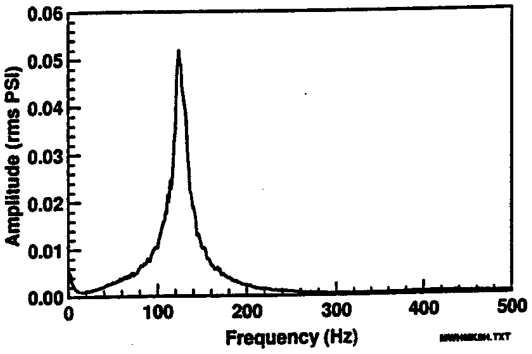

Fig. 16 Unforced power spectrum of version 9 of the afterburner operating self excited at 340 kW. The peak corresponds to the quarter wave acoustic mode of the chamber (123 Hz for the temperature of this measurement).

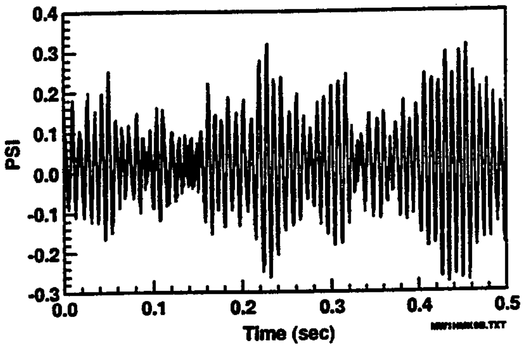

Fig. 17 Time trace of the signal of Fig. 16 showing less than perfect coherence.

The defining feature of this combustor was that it strongly self excited at the quarter wave acoustic mode, which, depending on the chamber temperature, was between 121 and 132 Hz. This was fortuitously close to the preferred mode of the jet (the Strouhal number for 125 Hz is 0.34, right in the middle of the expected preferred mode range). Figure 16 shows the unforced chamber pressure power spectrum under nominal operation. The oscillations are relatively coherent (time trace in Fig. 17). The transfer function of the operating combustor, i.e. the output chamber pressure vs. input driving frequency, is shown in Fig. 18. It too is relatively sharply peaked around the acoustic resonance. If forced exactly at the acoustic resonance frequency, the power spectrum is very narrow (Fig. 19) and pressure oscillations quite coherent (Fig. 20).

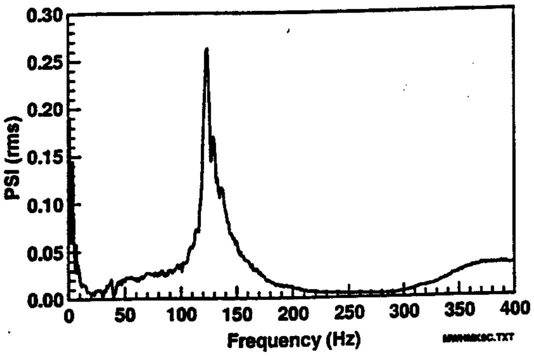

Fig. 18 Transfer function of the combusting version 9 AB. The peak is at 124 Hz.

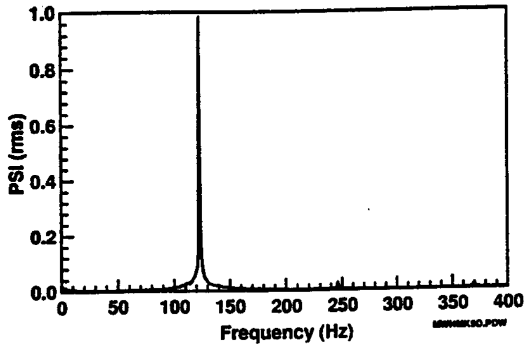

Fig. 19 Power spectrum of the forced afterburner (123 Hz).

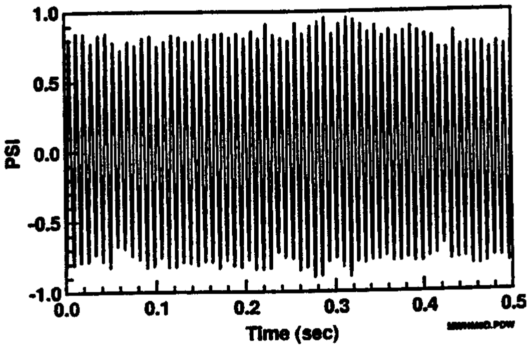

Fig. 20 Time trace for Fig. 19.

With a strong chamber acoustic resonance close to the fluid dynamic mode, it was not possible to show great improvement with forcing as the strong mixing vortex was already present by self forcing and the performance excellent. In fact, it was not possible to force the system coherently at other frequencies without the acoustic resonance showing strongly. Figure 21 shows the chamber pressure power spectrum when attempting to force at 100 Hz. One solution to matching the driving to the acoustic resonance is a closed loop feed back system. The pressure transducer signal was fed, unfiltered, into the phase lock input of the main air modulator driving electronics so that the forcing could track changes in the acoustic resonance frequency, as the chamber heated for example. Being even a few tenths of a Hz off frequency leads to significantly reduced pressure coherence. Figures 22 and 23 show the extremely coherent result of this closed loop control.

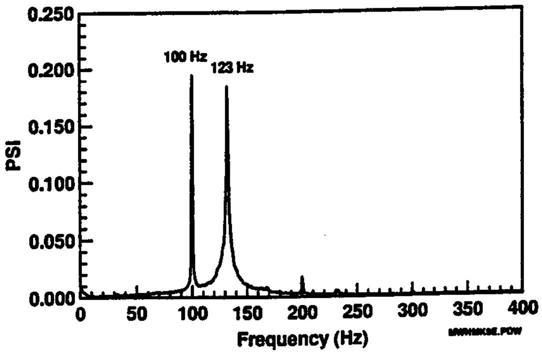

Fig. 21 Power spectrum when trying to force at 100 Hz.

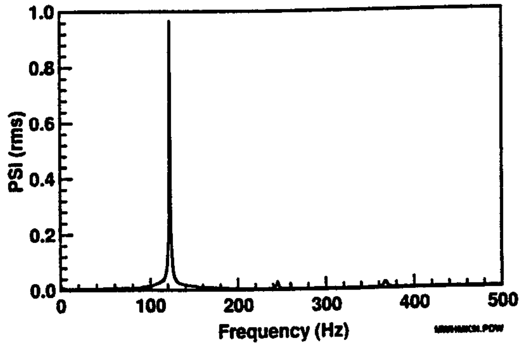

Fig. 22 Chamber pressure power spectrum under closed loop forcing.

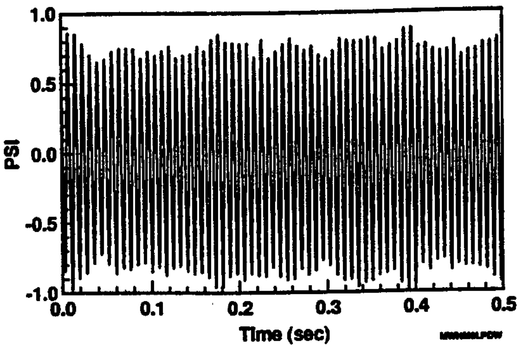

Fig. 23 Pressure time trace for Fig. 22.

This AB worked remarkably well despite the short residence times. The flame was entirely blue and, when the walls started to glow, nearly invisible. Even unforced emissions were quite low: CO 15 ppm, NOx < 15 ppm, UHC below detection, for 340 kW at a residence time of 84 msec. (All the CO and NOx results quoted below are uncorrected for O_2 %, but the measured O_2 is almost always around 7% anyway.) Figure 24 shows that forcing at relatively low levels could even make performance worse as the forcing fought for control over the natural acoustics. At high levels (even beyond the values shown in Fig. 24) the performance reduces back to, or below, the unforced levels.

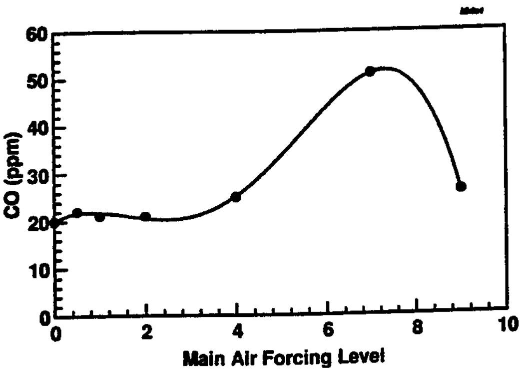

Fig. 24 CO emissions as a function of forcing level when forced at the acoustic resonance.

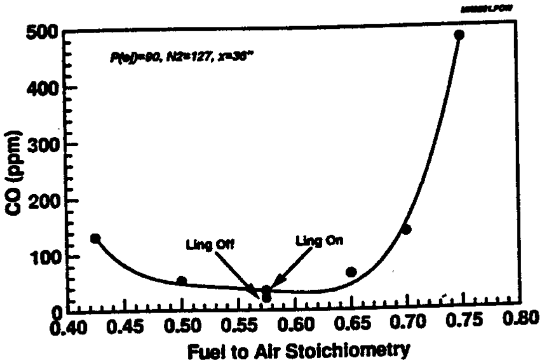

Fig. 25 CO emissions as a function of AB stoichiometry. In this case the forcing level was not high enough to bring performance back to the unforced case.

Figure 25 shows the performance as a function of AB phi; again the CO emissions rise at high phi due to low excess oxygen and at low phi due to lower flame stability. The NOx (Fig. 26) is lowest for the lowest phi due to lower flame temperature (5 ppm at phi = 0.42, 70 ppm at phi = 0.75). The NOx was seen to rise significantly as the chamber walls heated (again a temperature factor). The use of ejector air (to reduce back pressure) had a negligible effect on performance for flows giving zero back pressure. At higher ejector flows (negative back pressure) the performance was adversely affected: the CO rose by about 2.5 at three times the nominal ejector flow. This is somewhat counterintuitive as higher ejector air flow constitutes more premixing.

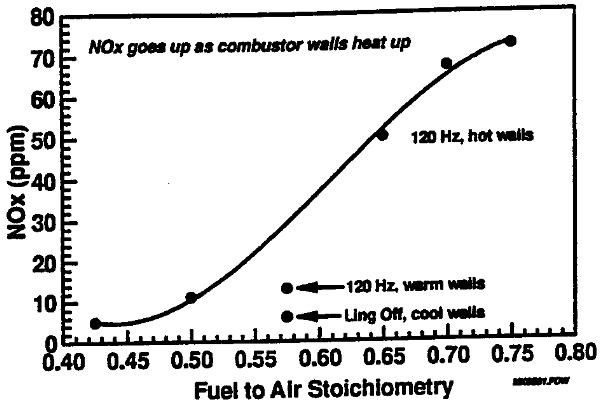

Fig. 26 NOx performance as a function of AB stoichiometry.

This afterburner was operated at firing rates up to 680 kW, essentially full scale for the compact shipboard incinerator application, and remained stable with the same low emissions (CO 35 ppm, NOx < 15 ppm at a residence time of only 46 ms). This is actually better performance than most of the 50 kW AB simulators when the residence time is taken into consideration. At this firing rate the central air velocity was 60 m/s and the flame started to lift off downstream of its normal (lifted) position. In this case, forcing at high levels was able to restabilize the flame at its normal lifted position and the forced performance was actually better than unforced (35 ppm vs. 66 ppm). At a 510 kW firing rate the difference was 17 ppm forced vs. 24 ppm unforced, at a residence time of 62 ms.

SUMMARY AND FUTURE PLANS

The active vortex combustion afterburner technology has been demonstrated under more practical conditions. Hot, low BTU content, realistic chemistry waste surrogates were fired and the control mechanism remained viable and performance remained excellent down to BTU levels as low as 115 BTU/ft^3. The geometric design was simplified and back pressure addressed. Again the control mechanisms remained viable and performance remained excellent. Back pressure could be reduced to zero using tapered elliptic waste ejectors. Closed loop control was demonstrated at full scale matching the chamber acoustic resonance. Performance of the technology was demonstrated at full scale and efficiency was found to be high and emissions remarkably low despite short residence times (down to 46 ms).

In the near future the reaction of the system to high pyrolysis gas soot loading will be evaluated. In addition, talks are ongoing with a commercial marine incinerator manufacturer to test this afterburner technology on a real incinerator with actual solid waste. These tests are planned for this summer or fall.

It is clear that this vortex combustion technology is scalable and has wide applicability for use in afterburners for incinerators as well as low NOx burners and other combustion devices.

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