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Transport Enhancement in Acoustically Excited Cavity Flows, Part 2: Reactive Flow Diagnostics

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Planar laser-induced fluorescence is used to study the unsteady temperature field associated with reactive flows in a two-dimensional dump combustor. These studies are performed alternately under steady, naturally resonant, and externally driven conditions. Fluorescence from an inert seed (nitric oxide) is used to determine the temperature field. Images of the temperature field taken under naturally resonant acoustical conditions show evidence of strong perturbations of the flame, similar to perturbations seen in images taken during on-resonance, externally forced conditions. If the device is externally forced at the same amplitude but at an arbitrary (off-resonance) frequency, however, the temperature field remains unperturbed, very nearly as if there were no acoustic excitation at all. Hence, the reactive cavity flow appeared to be preferentially responsive to external acoustic forcing at frequencies at which the flow could potentially resonate anyway, given a sufficient level of energy input by the reaction. External acoustical forcing using the loudspeaker provided such energy input at the specific resonant modes, resulting in increased thermal transport within the cavity.

I. Introduction

THE dump combustor configuration, in which premixed flames are stabilized at a rearward-facing step, has been studied extensively for its applications to aerospace propulsion systems, in particular, for ramjet engines. Acoustically driven combustion instabilities are known to occur naturally in such devices when pressure oscillations and periodic heat release associated with the combustion are in phase.[1,2] Transverse[3] as well as longitudinal[4,5] acoustic modes are associated with vortex shedding (coincident with the premixed flames) in such combustors. These acoustic instabilities are generally undesirable for aerospace applications, and for many years researchers have sought to dampen such instabilities through active flow control strategies.[6–11]

Over the past few years, a two-dimensional dump combustor has been studied by our group as a suitable configuration for a small, transportable, highly efficient hazardous waste incinerator.[12–19] This configuration, shown in Fig. 1, actually consists of a reactive cavity flow, thus demonstrating the potential for natural acoustical excitation similar to that of the traditional dump combustor,[3,5–7] as well as that of a nonreactive, driven cavity.[20–24] In the present context, wastes are injected into hot, stable recirculating regions formed within the combustor, where they can be destroyed at high levels.

In the course of these investigations, it has been noted that incineration performance (measured in terms of the degree of destruction of the hazardous waste surrogate) is strongly enhanced if the device is externally forced acoustically at frequencies corresponding to certain longitudinal modes of the system.[18,19] This type of acoustic excitation appears to change the structure of the premixed flame substantially, producing a broader and, on average, a less-lifted flame, which tends to lie closer to the sudden expansion or dump plane. These observations, considered together with the findings of other researchers,[7,9] suggest that acoustic excitation might provide a simple and robust means of controlling combustion instabilities in dump combustor configurations. Whereas for the ramjet engine the aim of such control would be to dampen the instabilities, for the incineration application explored by our group, enhancement of the instability is desirable.

The accompanying study,[25] conducted in a larger-scale version of the present dump combustor, explores the effect of acoustic forcing on the velocity field in the absence of chemical reaction, i.e., in cold flow. External acoustic forcing at frequencies corresponding to natural longitudinal modes of the system is seen to result in increased jet spreading and an enhancement of the mass exchange between the core jet and the recirculation regions as compared with behavior during operation at unforced or off-resonance excitation conditions. The current work seeks to investigate the effect of natural as well as externally generated acoustic forcing on the reactive flowfield by studying the evolution of the temperature field using planar laser-induced fluorescence (PLIF) imaging.

II. PLIF for Temperature Measurement

PLIF is a nonintrusive method for making simultaneous, multipoint measurements of temperature or chemical species concentration in a plane. In the technique, a sheet of laser light excites a molecule from its ground electronic state to a higher electronic state. After a very short time (of the order 10^{-12} s), the molecule collapses back to its ground state and in so doing emits the absorbed energy as fluorescence. Because the molecule may also change vibrational and rotational states during and between its excitation and collapse, the frequency of the emitted energy is different from that of the exciting energy. The intensity (photon flux) of the emitted radiation depends on the number of molecules in the ground state that are excited and the number of molecules in the excited state that collapse by fluorescing.

The strength of the fluorescence signal S_{fl} for the excitation of an arbitrary molecular species may be determined, for example, as described by Cattolica and Vosen[26]:

$$\frac{dS_{fl}}{dt} = \eta\epsilon\frac{\Omega}{4\pi}VA_{21}n_2 \tag{1}$$

where η is the light collection efficiency of the optics, ϵ is the quantum efficiency of the detector, Ω is the solid angle of light collection, V is the volume of fluorescence, n_2 is the number density of the excited state, and A_{21} is the Einstein coefficient for spontaneous emission from the excited to the ground state. In the present study, we use a two-level model to represent the laser excitation of the molecular species, described in detail in Cadou.[27]

For weak laser excitation by a spectrally broad source (a laser linewidth much greater than the absorption linewidth of the transition), it is assumed that the perturbations to the equilibrium energy distribution and the ground state population are small. Further, it is

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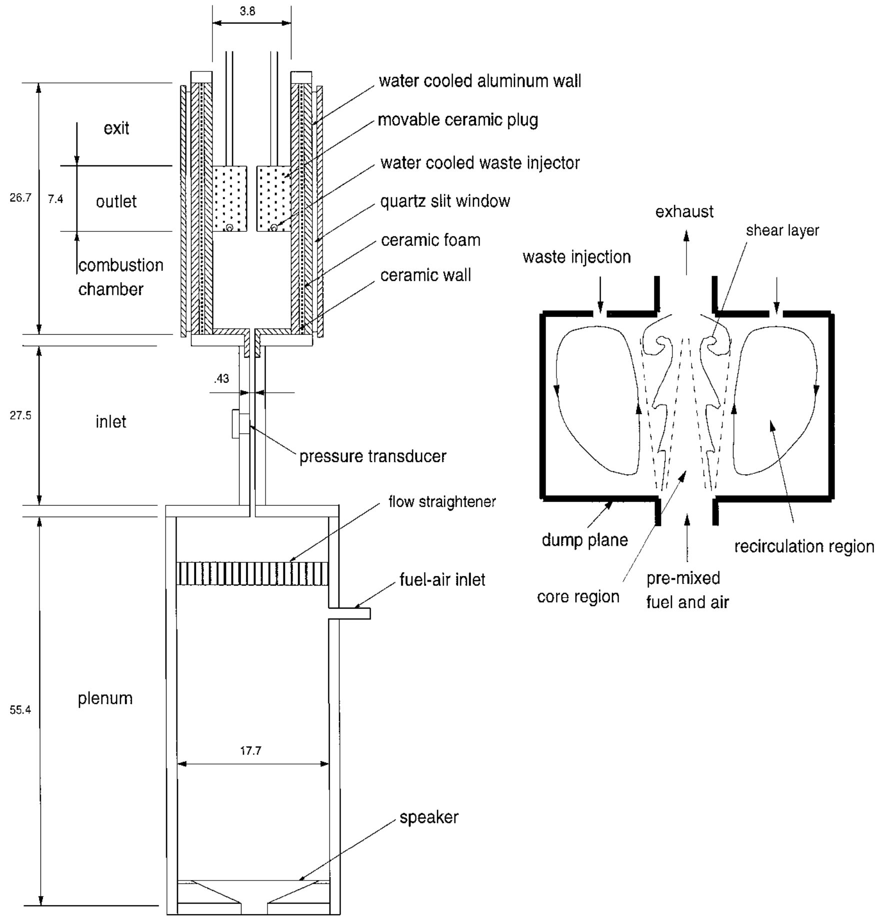


Fig. 1 Schematic of the dump combustor, with dimensions in centimeters; loudspeaker in the plenum is used only during the externally driven sets of experiments.

assumed that collisional quenching cross sections for NO with other chemical species are constant throughout the flowfield. Based on these assumptions, one obtains the final expression for the strength of the fluorescence signal:

$$S_{\mathrm{fl}} = C\frac{A_{21}B_{21}}{Q_{21}(T_{\mathrm{ref}}, P_{\mathrm{ref}})}\frac{P_{\mathrm{ref}}}{R\sqrt{T_{\mathrm{ref}}}}E_{12}\frac{N_F(T)}{\sqrt{T}}x_s \tag{2}$$

where E_{12} is the energy supplied by the laser pulse

$$E_{12} = \int_0^{\tau} \rho_v \,\mathrm{d}t \tag{3}$$

C is a constant containing parameters of the collection optics and detection system, Q_{21} is the collisional quench rate, and B_{21} is the Einstein probability for transitions from the excited state. Note that the strength of the fluorescence signal is, thus, a function of species mole fraction x_s and temperature through the function $N_F(T)/T^{1/2}$.

PLIF as a temperature diagnostic has been used to a limited extent in the past.[28] The flow is seeded with an inert molecule (in the present case, nitric oxide, NO) in such a way that its mole fraction remains constant throughout the flowfield; this is justified subsequently. With the mole fraction held constant, the intensity of the fluorescence signal at each point in the laser sheet depends only on the local temperature of the flowfield through $N_F(T)/T^{1/2}$ in Eq. (2). Thus, the temperature field may be computed from an image of fluorescence in the plane of the laser sheet. In this work, we pump the $Q(12)(J=12)$ line of the NO $A^2\Sigma(v=0) \leftarrow X^2\Pi_{1/2}(v=0)$ transition (at about 226.13 nm) and collect the broadband fluorescence. This line is chosen for its sensitivity and monotonic temperature dependence over the expected range of combustion temperatures.[27]

NO is relatively inert in this system. Although some NO is undoubtedly produced from molecular nitrogen in the flame, the NO seeding level is high enough (4000 ppm) so that the effect on the postflame mole fraction is negligible. Detailed modeling predicts significant conversion of NO to NO_2, due to reaction with HO_2 within a very narrow region (three to four pixels) just on the upstream side of the flame front. Yet NO_2 undergoes rapid thermal dissociation back to NO within the flame front, which results in the NO mole fraction being restored to within 1% of the original seed level. Thus, except for a very thin region immediately upstream of the flame front, the NO concentration is essentially constant at the seeded level, 4000 ppm.

III. Apparatus and Data Processing

Figure 1 is a schematic of the dump combustor used in this work; the device was roughly one-quarter the size of the device considered in the accompanying cold-flow study.[25] The smaller size of the present device enabled laser illumination of a larger relative area within the combustion cavity. Fuel (methane CH_4) and air entered and mixed in a large plenum chamber and passed upward through honeycomb flow straighteners into the combustion cavity via a narrow inlet section. The flame was stabilized at the sudden expansion where the reactants entered the combustion cavity, in general forming an inverted V-shaped reaction zone within the combustion cavity. The downstream end of the combustion cavity was formed by two movable ceramic plugs, which permitted adjustment of the combustion cavity length and through which hazardous waste could be injected in an incineration context. In the present experiments, however, no such waste injection occurred. Two large quartz windows forming the front and rear walls of the combustion cavity and two small slit windows in the side walls provided two-dimensional optical access to the reacting flow.

Referring to the inset of Fig. 1, note that the flowfield in the combustion cavity breaks into three regions: 1) a core flow associated with the introduction of premixed reactants, 2) recirculation zones on either side of the flame associated with hot products, and 3) a shear layer in which chemical reaction occurred, separating the core flow from the recirculation zones. As vortices shed from the inlet propagated downstream through the combustion cavity, they wrinkled the reaction zone or flame. Previous work[12,16] has shown that under certain operating conditions, i.e., for certain combinations of inlet velocity, equivalence ratio, and combustion cavity length, the chemical reaction can excite a variety of longitudinal acoustic modes ranging from low-frequency oscillations near 50 Hz to intermediate- and high-frequency oscillations in the range 300–600 Hz. Whereas one-dimensional acoustical modeling of the device[12,16] suggests the potential for a variety of possible modes to be excited under given operating conditions, the mode that is actually excited is nonlinearly dependent on the amount of energy contributed to the flow by the chemical reaction. The large velocity perturbations associated with naturally excited acoustic resonances have been shown to result in large-scale wrinkling and even extinguishment of the flame.[14,17,18]

One of the aims of the present study is to examine the reactive temperature field during nonexcited, naturally driven, and externally driven acoustic excitation. External acoustic forcing was accomplished here via a loudspeaker situated in the bottom of the plenum chamber. In theory, forcing frequencies could be varied from 0 to 1000 Hz with amplitudes up to 150 dB. In practice, however, frequencies below 200 Hz were difficult to obtain reliably, and this study focuses on the relatively high-frequency instabilities.

Figure 2 is a schematic of the optical setup for the PLIF experiment. A Questek 2640 Excimer laser operating on XeCl (308 nm) was used to pump a Lambda Physik Scanmate 2E dye laser running Coumarin 46 dye. The output of the dye laser was frequency-doubled using a BBO crystal to 226 nm. A Tylan flow controller metered the NO seed into the combustion cavity. In both experiments, an ITT™-gated, intensified charge-coupled device camera collected the fluorescence from molecules in the plane of the laser sheet. A pressure transducer in the plenum provided a signal for phase-locking image acquisition to oscillations in the combustion cavity.

NO PLIF data were calibrated as follows. A thermocouple inserted at a known location in the imaged plane permitted the association of a temperature with a specific pixel value. From this information, the lumped value of the constant parameters in Eq. (2) were computed. Assuming that this lumped value remained constant throughout the flowfield, the temperatures at other points in the image plane were computed from an image of the NO fluorescence distribution. Shot-to-shot variations in laser intensity were accounted for by recording the energy in the undoubled beam and using this to rescale each image to constant power. The standard deviation was also computed on a pixel-by-pixel basis during the averaging process. Pixels with $2\sigma/\bar{x} \geq 0.08$ were considered unreliable and were discarded. Spatial variations in the energy distribution in the laser sheet were accounted for by normalizing each image by an image of NO fluorescence at constant temperature. Each image was corrected for the effects of scattering by subtracting an image of the scattering only, made by tuning the laser slightly off the NO transition. Finally, the effects of noise were reduced by computing the temperature field from the averages of at least 10 images.

IV. Results

A. Nonresonant Flow

Figure 3 is an image of the two-dimensional temperature distribution in the combustion cavity with the combustor operating in an acoustically nonresonant or quiet mode. In this image, the temperature increases linearly as the colors proceed from violet to red. The image was generated by computing the temperature field from an average of 10 individual fluorescence images and then averaging spatially using a 2 × 2 pixel kernel. Information was lost near the walls when scattering was subtracted from the raw image. More information was lost in regions where the energy distribution normalization factor was smaller than a somewhat arbitrary threshold value (about 0.12).

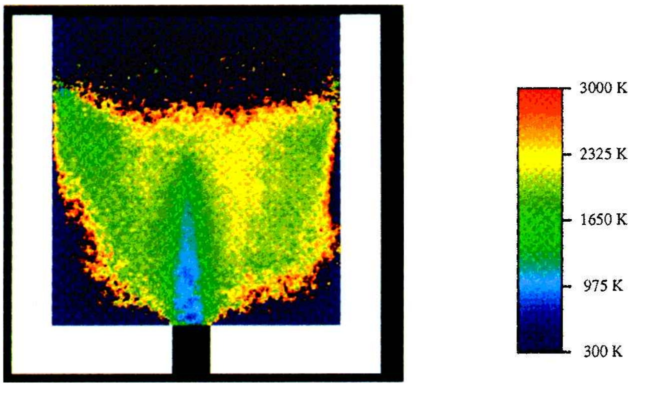


Fig. 3 Time-averaged, two-dimensional temperature distribution in the dump combustor during quiet mode operation with core equivalence ratio $\phi = 0.75$, inlet velocity 2.7 m/s, and cavity length $l_c = 5.08$ cm.

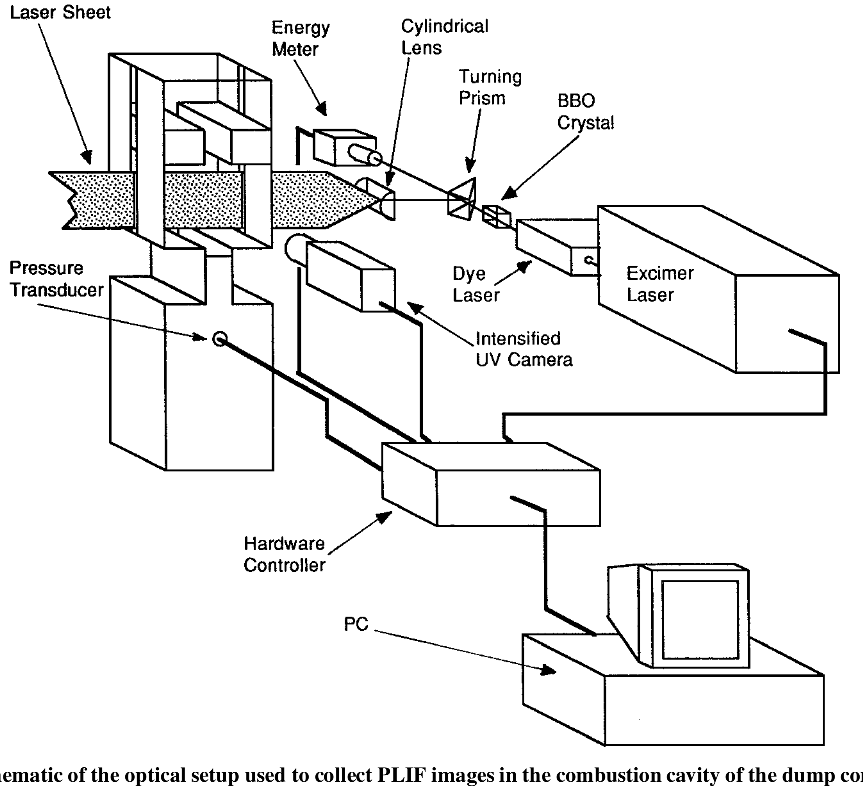


Fig. 2 Schematic of the optical setup used to collect PLIF images in the combustion cavity of the dump combustor.

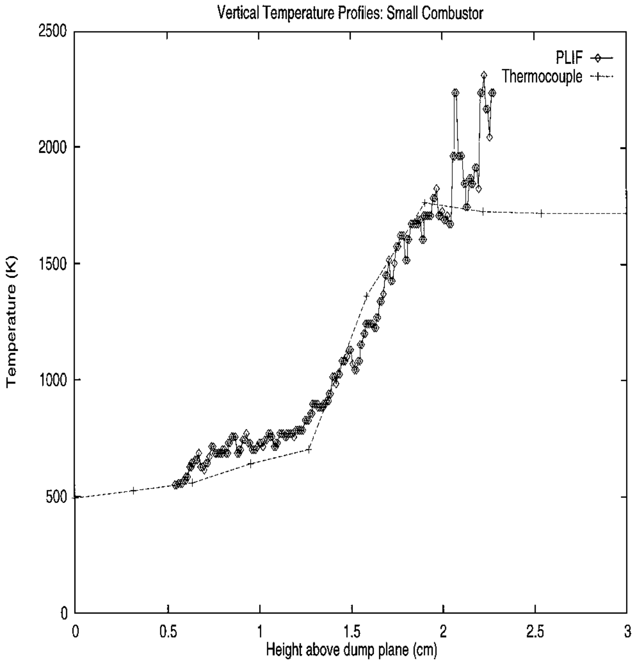
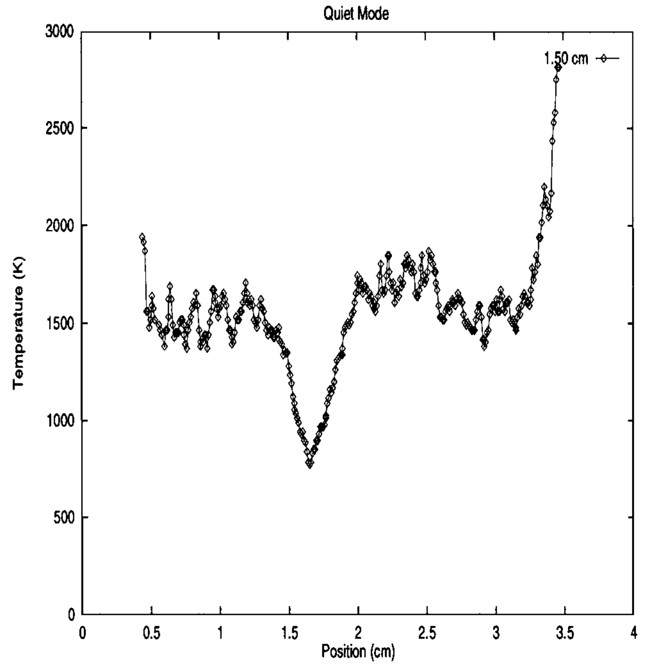


Fig. 4 Comparison of thermocouple measurements taken along the small dump combustor's line of symmetry with temperatures computed from the NO PLIF image corresponding to Fig. 3; downstream position measured from the dump plane.

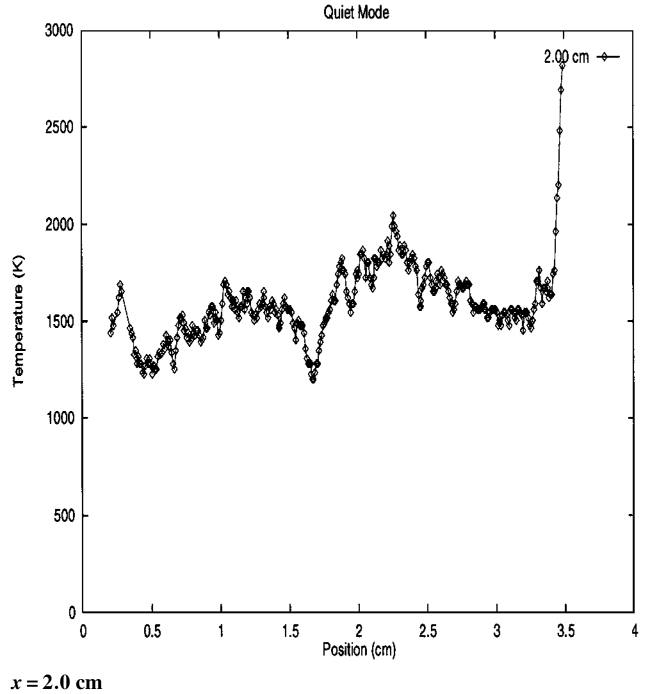
The image in Fig. 3 clearly shows a relatively cool central core region composed of unreacted gases and a region of strong temperature gradient indicating the presence of the flame front and heated recirculation zones. Figure 4 is a plot of the temperature profile through this flame along the combustor's axis of symmetry, computed from the PLIF image in Fig. 3. Note the good agreement between the PLIF data and the thermocouple measurements shown in Fig. 4. The vertical temperature profile in Fig. 4 and the horizontal temperature profiles in Fig. 5 show that the temperature remained at about 1500 K downstream of the flame and within the recirculation regions of the cavity, respectively. The presence of the large and apparently stable regions of high-temperature gas within the recirculation zones explains why previous work has shown that this quiet mode is effective for thermal waste destruction. The high-temperature tails on the ends of the profiles in Figs. 4 and 5 are artifacts of the scattering subtraction process near the plugs and walls, respectively.

Figure 6 shows temperature fields for quiet combustor operation at five different combustion cavity lengths, with averaging as done in Fig. 3. Quiet operation was again observed for these flow and geometrical conditions. Note that the inlet velocity here was lower than in Fig. 3. These images show that temperatures increased in all areas of the combustion cavity as the cavity length was decreased, in some cases reaching the adiabatic flame temperature. This observation is consistent with destruction characteristics for a temperature-sensitive waste surrogate,[17] which improve significantly for shorter cavity lengths because the waste is injected from the ceramic plugs into the (hotter) cavity recirculation zones. Figure 7 shows this trend by plotting average temperatures computed for different areas of the right half of the combustion cavity as a function of cavity length. Data from the right side of the cavity are provided because the laser sheet entered the cavity from the right and the effects of laser sheet absorption on this side were not as great as on the left. Note also that, as the cavity length decreased, the flame length also slightly decreased.

The increase in temperature of the recirculating gases with decreasing cavity length, seen in Figs. 6 and 7, resulted in flame structures that were more closely attached to the dump plane, according to recent OH* chemiluminescence imaging.[18] These observations are consistent with Marble and Adamson's[29] classical analysis of ignition and combustion in a laminar shear layer between parallel streams of reactants and hot products.



$x = 1.5$ cm



$x = 2.0$ cm

Fig. 5 Plots of the horizontal temperature distribution calculated from the PLIF image of Fig. 3, measured from the dump plane.

B. Naturally Resonant Flow

Figure 8 is a sequence of 15 images representing the time evolution of the temperature field over one acoustic period when the combustor excited a natural acoustic resonance. Here the equivalence ratio and inlet velocity were roughly the same as in Fig. 3, but a longer combustor cavity produced conditions leading to acoustic excitation. The collection of the images was phase locked to the high-frequency (328-Hz) acoustic oscillations formed naturally here by a standing wave in the plenum. Phase is thus defined with respect to the temporal pressure variation. As before, each frame was computed from an average of 10 individual images and was subsequently averaged spatially over a 2×2 pixel kernel and filtered to reject pixels with $2\sigma \geq 0.08\bar{x}$.

The images in Fig. 8 show a periodically pinched-off core region, with a somewhat broader shear layer than in the quiet mode (Fig. 3). There appeared to be regions of high temperature that periodically

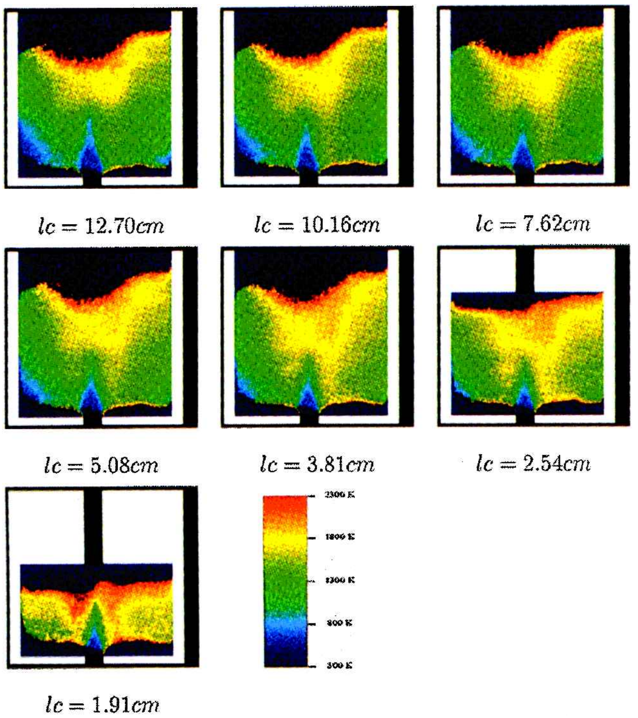


Fig. 6 Images of the temperature field in the dump combustor for various combustion cavity lengths l_c; equivalence ratio $\phi = 0.78$ and inlet velocity 1.88 m/s.

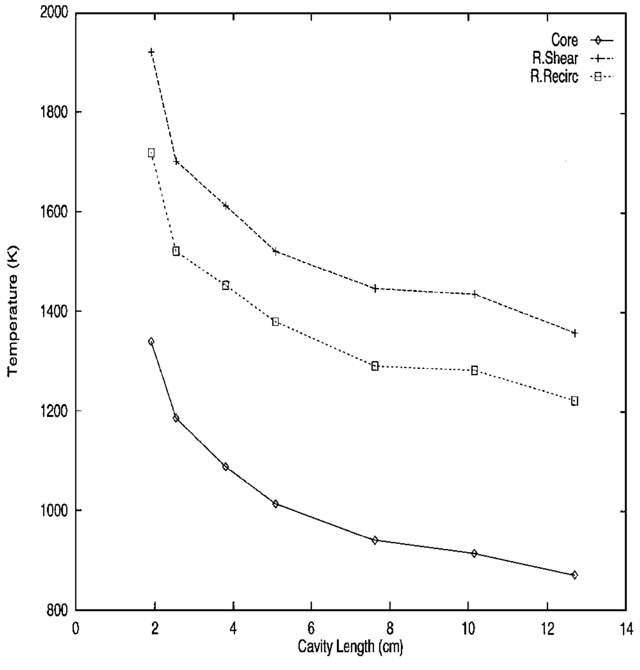


Fig. 7 Average temperatures in various areas of the combustion cavity (core, right shear layer, and right recirculation zone) as a function of combustion cavity length l_c; equivalence ratio $\phi = 0.78$ and inlet velocity 1.88 m/s.

propagated upward through the combustion cavity. These high-temperature regions were generally coincident with vortices shed from the dump plane, as seen in schlieren images taken in acoustically resonant ramjet combustors.[5] Figure 9 is a plot of the position of the local maximum in temperature gradient present along the combustor's axis of symmetry as a function of the phase of the pressure oscillation. Note that the motion of this gradient was in phase with the oscillating pressure field, indicating that the flame and core flow followed the pressure (and presumably velocity) oscillations during natural excitation. Again, this was consistent with other dump combustor experiments,[4] as well as with Rayleigh's criterion.[1,2] These

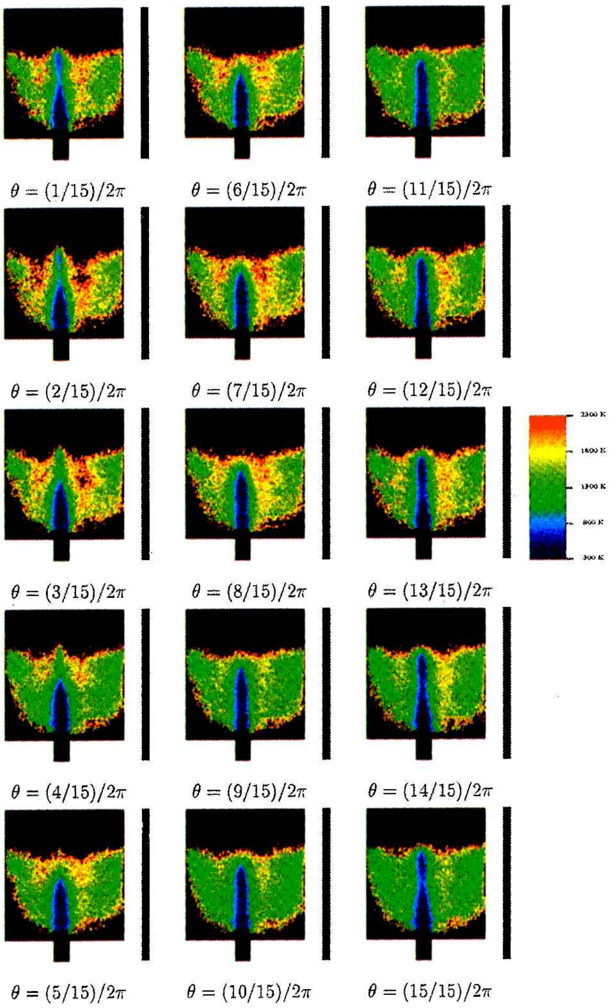


Fig. 8 Two-dimensional temperature field at various phases in the naturally driven acoustic resonance at 328 Hz, with equivalence ratio $\phi = 0.70$, inlet velocity 2.7 m/s, and cavity length $l_c = 10.16$ cm. Note that core pinchoff appears near $\theta = [(3 - 5)/15]$.

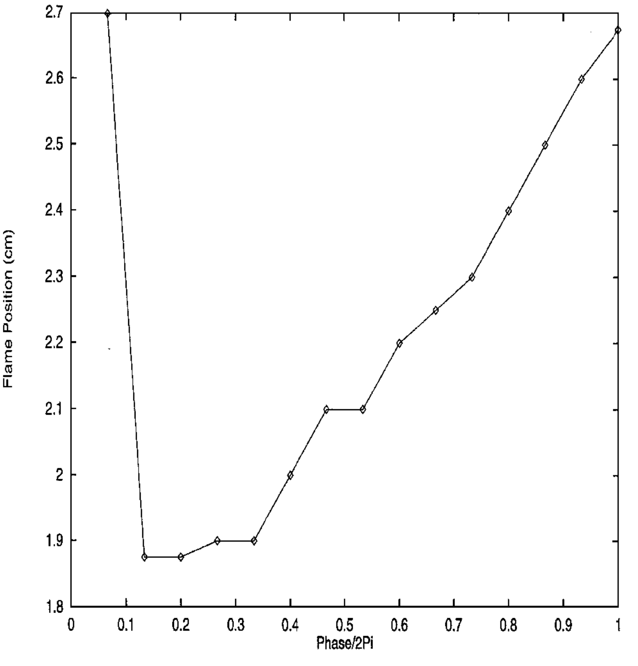


Fig. 9 Position of the temperature inflection point along the combustor's vertical plane of symmetry as a function of the phase of the pressure oscillation, with results extracted from data in Fig. 8.

measurements also indicate that average recirculation zone temperatures during natural acoustic excitation (Fig. 8; 1650 K) actually can be higher than those measured during quiet mode operation (Fig. 3; 1580 K), indicating an improvement in global energy transport from reaction zones to recirculation zones during natural acoustic excitation.

C. Externally Forced Flow

Phase-locked temperature field measurements were also performed in the combustor for flow conditions in which there was no natural acoustic resonance observed but in which forced acoustic excitation was achieved using a loudspeaker in the plenum. The equivalence ratio and cavity length were nearly the same as for naturally excited operation (Fig. 8), but the inlet velocity was different (1.92 m/s with external acoustic forcing vs 2.7 m/s for the naturally resonant case). At the inlet velocity of 1.92 m/s, no acoustic resonances occurred naturally (see also Fig. 6 for the cavity length $l_c = 10.16$ cm), although one-dimensional acoustical modeling indicated that it was possible to excite certain modes with sufficient energy input.[12,16]

Figure 10 is a series of 15 images of the temperature field spanning one acoustic cycle. External acoustic excitation was applied at 360 Hz with an amplitude near 150 dB. The series of images in Fig. 10 each represent averages of 20 individual images, with spatial averaging and filtering as before. Under the operating conditions given, 360 Hz is computed to be a possible resonant mode.[12] In contrast, Fig. 11 shows a corresponding series of temperature images in response to external acoustic excitation at an arbitrary (nonresonant) frequency of 420 Hz and with the same forcing amplitude. These figures demonstrate the structural differences between resonant and nonresonant external acoustic forcing for this reactive flow problem.

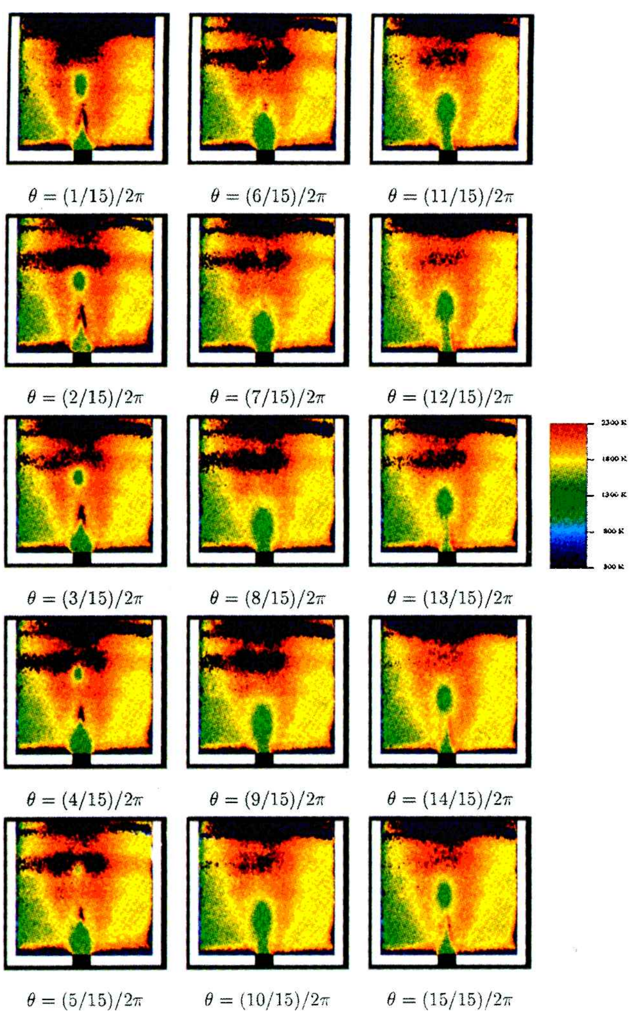


Fig. 10 Time-resolved, phase-locked temperature images in the dump combustor with on-resonance acoustic forcing applied at 360 Hz; equivalence ratio $\phi = 0.76$, inlet velocity 1.92 m/s, and cavity length l_c = 10.16 cm.

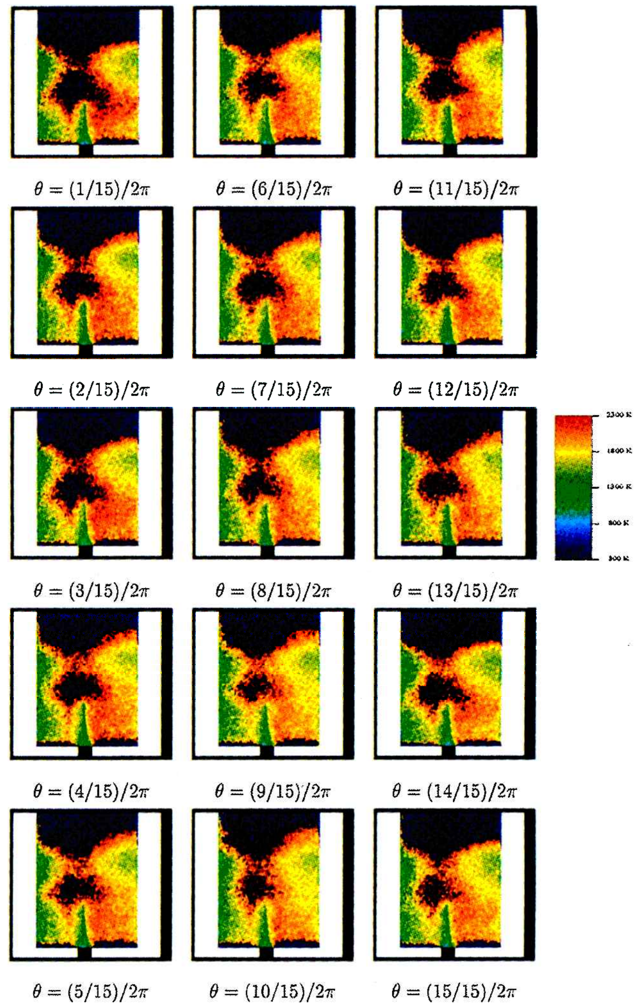


Fig. 11 Time-resolved, phase-locked temperature images in the dump combustor with off-resonance acoustic forcing applied at 420 Hz; equivalence ratio $\phi = 0.76$, inlet velocity 1.92 m/s, and cavity length l_c = 10.16 cm.

In Fig. 10, relatively strong periodic core pinchoff occurred. These periodic temperature disturbances in the core/jet region appeared to be associated with strong velocity fluctuations at the dump plane during on-resonance forcing. Such disturbances have previously been observed[18] under cold flow conditions in hot-wire measurements and in the particle image velocimetry (PIV) results of the accompanying study.[25] In contrast, off-resonance external forcing at 420 Hz (Fig. 11) produced little evidence of perturbation to the temperature field in the core flow, indicating that, in spite of the strong acoustic forcing, the resulting velocity and pressure fluctuations at the dump plane were small and the coupling between the cavity and the reactive jet was significantly reduced. In fact, the flame/core region visibly appeared similar to the unforced, quiet mode image in Fig. 3. Again, this reduced level of core flow perturbation was consistent with the PIV[25] and hot-wire[18] measurements.

Periodic pinchoff in the core region during on-resonance forcing resulted in perturbations to the average temperature in the core.[27] This observation possibly resulted from a combination of phenomena 1) from periodic flame motion in and out of a predefined (average) core region and 2) from periodic variations in the strain rates experienced by the flames, causing periodic alteration in local flame temperature. Such oscillations in temperature were not strongly apparent during off-resonance forcing or for unforced conditions. These core region perturbations appeared to assist with the transport of energy from the flames to the recirculation zones. Temperature measurements with a thermocouple in a larger version of the present dump combustor (described in Ref. 19) also indicated higher average temperatures in the recirculation zones (by about 100 K) during on-resonance excitation vs other operation. Again, the association of higher recirculation zone temperatures with on-resonance excitation was consistent with waste surrogate destruction results.[18,19]

V. Conclusions

PLIF has been used to make measurements of steady and unsteady temperature fields in a resonant dump combustor. The reliability of the technique has been demonstrated in nonresonant flows, where agreement with thermocouple measurements is quite good. The images of the temperature field under naturally resonant conditions show evidence of strong perturbations of the flame, probably due to the passage of strong vortex pairs shed from the dump plane, as seen in other dump combustor experiments, in resonance with the pressure field. The images taken from on-resonant, external acoustic forcing show similarly strong perturbations and demonstrate that low-power external excitation can result in perturbations that are at least as strong as those associated with natural resonance. If the device was forced off resonance, however, the temperature field remained unperturbed, very nearly as if there were no acoustic excitation at all. In other words, the reactive cavity flow appeared to be preferentially responsive to external acoustic forcing at frequencies at which the flow could potentially resonate anyway, given a sufficient level of energy input by the reaction. External acoustical forcing using a loudspeaker provided such energy input at the specific resonant modes, resulting in increased jet spread and perturbed core flow as well as increased energy transport within the cavity.

This study demonstrates the importance of the coupling efficiency between the control actuator for a dump combustor and its reactive flow. Without the efficient coupling offered by the natural resonant properties of the device, effective perturbation of the flow and the associated enhancement of energy transport are not possible.

Acknowledgments

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References

[1] Lord Rayleigh, *The Theory of Sound*, Vol. 2, Dover, New York, 1945, pp. 226, 227.

[2] Putnam, A. A., *Combustion-Driven Oscillations in Industry*, American Elsevier, New York, 1971.

[3] Rogers, D. E., and Marble, F. E., "A Mechanism for High-Frequency Oscillations in Ramjet Combustors and Afterburners," *Jet Propulsion*, Vol. 26, 1956, pp. 456–462.

[4] Poinsot, T. J., Trouve, A. C., Veynante, D. P., Candel, S. M., and Esposito, E. J., "Vortex-Driven Acoustically Coupled Combustion Instabilities," *Journal of Fluid Mechanics*, Vol. 177, 1987, pp. 265–292.

[5] Sterling, J. D., and Zukoski, E. E., "Nonlinear Dynamics of Laboratory Combustor Pressure Oscillations," *Combustion Science and Technology*, Vol. 77, No. 4–6, 1991, pp. 225–238.

[6] McManus, K. R., and Bowman, C. T., "Effects of Controlling Vortex Dynamics of the Performance of a Dump Combustor," *Twenty-Third Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1990, pp. 1093–1099.

[7] McManus, K. R., Poinsot, T., and Candel, S. M., "A Review of Active Control of Combustion Instabilities," *Progress in Energy and Combustion Science*, Vol. 19, No. 1, 1993, pp. 1–29.

[8] Schadow, K. C., Gutmark, E., and Wilson, K. J., "Active Combustion Control in a Coaxial Dump Combustor," *Combustion Science and Technology*, Vol. 81, No. 1–6, 1992, pp. 285–300.

[9] Gulati, A., and Mani, R., "Active Control of Unsteady Combustion-Induced Oscillations," *Journal of Propulsion and Power*, Vol. 8, No. 5, 1992, pp. 1109–1115.

[10] Knoop, P., Culick, F. E. C., and Zukoski, E. E., "Extension of the Stability of Motions in a Combustion Chamber by Nonlinear Active Control Based on Hysteresis," *Combustion Science and Technology*, Vol. 123, No. 1–6, 1997, pp. 363–376.

[11] Fleifil, M., Annaswamy, A. M., Ghoniem, Z., and Ghoniem, A. F., "Response of a Laminar Premixed Flame to Flow Oscillations: A Kinematic Model and Thermoacoustic Instability Result," *Combustion and Flame*, Vol. 106, No. 4, 1996, pp. 487–510.

[12] Logan, P., Lee, J. W., Lee, L. M., Karagozian, A. R., and Smith, O. I., "Acoustics of a Low Speed Dump Combustor," *Combustion and Flame*, Vol. 84, No. 1/2, 1991, pp. 93–109.

[13] Smith, O. I., Marchant, R., Willis, J., Lee, L. M., Logan, P., and Karagozian, A. R., "Incineration of Surrogate Wastes in a Low Speed Dump Combustor," *Combustion Science and Technology*, Vol. 74, No. 1–6, 1990, pp. 199–210.

[14] Cadou, C., Logan, P., Karagozian, A., Marchant, R., and Smith, O., "Laser Diagnostic Techniques in a Resonant Incinerator," *Environmental Sensing and Combustion Diagnostics, SPIE Proceedings Series*, Vol. 1434, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1991, pp. 67–77.

[15] Marchant, R., Hepler, W., Smith, O. I., Willis, J., Cadou, C., Logan, P., and Karagozian, A. R., "Development of a Two-Dimensional Dump Combustor for the Incineration of Hazardous Wastes," *Combustion Science and Technology*, Vol. 82, No. 1–6, 1992, pp. 1–12.

[16] Willis, J. W., Lee, L.-M., Karagozian, A. R., and Smith, O. I., "Acoustic Mode Alteration in a Dump Combustor Arising from Halon Addition," *Combustion Science and Technology*, Vol. 94, No. 1–6, 1993, pp. 469–481.

[17] Willis, J. W., Cadou, C., Mitchell, M., Karagozian, A. R., and Smith, O. I., "Destruction of Liquid and Gaseous Waste Surrogates in an Acoustically Excited Dump Combustor," *Combustion and Flame*, Vol. 99, No. 2, 1994, pp. 280–287.

[18] Pont, G., Willis, J. W., Karagozian, A. R., and Smith, O. I., "Effects of External Acoustic Excitation on Enhanced Transport in a Resonant Incinerator," *Twenty-Sixth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1996, pp. 2463–2470.

[19] Pont, G., Cadou, C. P., Karagozian, A. R., and Smith, O. I., "Emissions Reduction and Pyrolysis Gas Destruction in an Acoustically Driven Dump Combustor," *Combustion and Flame*, Vol. 113, Nos. 1, 2, 1998, pp. 249–257.

[20] Rockwell, D., and Naudascher, E., "Review-Self-Sustaining Oscillations of Flow Past Cavities," *Journal of Fluids Engineering*, Vol. 100, No. 2, 1978, pp. 152–165.

[21] Sarohia, V., "Experimental Investigation of Oscillations in Flows over Shallow Cavities," *AIAA Journal*, Vol. 15, No. 7, 1977, pp. 984–991.

[22] Rockwell, D., and Knisely, C., "The Organized Nature of Flow Impingement upon a Corner," *Journal of Fluid Mechanics*, Vol. 93, No. 3, 1979, pp. 413–432.

[23] Gharib, M., and Roshko, A., "The Effect of Flow Oscillations on Cavity Drag," *Journal of Fluid Mechanics*, Vol. 177, No. 3, 1987, pp. 501–530.

[24] Gharib, M., "Response of the Cavity Shear Layer Oscillations to External Forcing," *AIAA Journal*, Vol. 25, No. 1, 1987, pp. 43–47.

[25] Kang, Y., Karagozian, A. R., and Smith, O. I., "Transport Enhancement in Acoustically Excited Cavity Flows, Part 1: Nonreactive Flow Diagnostics," *AIAA Journal*, Vol. 36, No. 9, 1998, pp. 1562–1567.

[26] Cattolica, R., and Vosen, S., "Two-Dimensional Measurements of the [OH] in a Constant Volume Combustion Chamber," *20th Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1984, pp. 1273–1282.

[27] Cadou, C. P., "Two-Dimensional Time Resolved Temperature Measurements in a Resonant Incinerator Using Planar Laser-Induced Fluorescence," Ph.D. Thesis, Dept. of Mechanical and Aerospace Engineering, Univ. of California, Los Angeles, CA, Sept. 1996.

[28] McMillin, B. K., Seitzman, J. M., and Hanson, R. K., "Comparison of NO and OH Planar Fluorescence Temperature Measurements in Scramjet Model Flowfields," *AIAA Journal*, Vol. 32, No. 10, 1994, pp. 1945–1952.

[29] Marble, F. E., and Adamson, T. C., "Ignition and Combustion in a Laminar Mixing Zone," *Jet Propulsion*, Vol. 24, No. 2, 1954, pp. 85–94.

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