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Transport Enhancement in Acoustically Excited Cavity Flows, Part 1: Nonreactive Flow Diagnostics

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Acoustically driven, nonreactive flow processes in a two-dimensional dump combustor cavity were explored experimentally. Particle image velocimetry in the device was used to quantify the time-dependent, phase-locked velocity field in the cavity. Cavity operation during external acoustic excitation and during natural (undriven) operating conditions was explored. Interrogation of this flowfield showed quantifiable increases in inlet core/jet width, enhanced rates of entrainment between jet and recirculation regions, and increased jet rms velocity fluctuations during external forcing at frequencies corresponding to resonant longitudinal modes of the device. No such enhancement was observed during off-resonance external excitation. These results suggest that external acoustic excitation at resonant modes can result in enhanced mass and momentum transport within the cavity flow, providing a potentially powerful method for active flow control.

I. Introduction

THE flow adjacent to and within a cavity in the absence of combustion has attracted attention over the years because of its relevance to many practical flow systems. Early experimental studies examined the effects of geometry and flow conditions on recirculating regions that can dominate the cavity flow.[1-4] The shear layer bounding the cavity was postulated early on to influence momentum transport between the external flow and the flow within the cavity.[5] Shear layer instability in such flows has been seen to cause the flow to be susceptible to self-sustained oscillations. These oscillations can be undesirable if they induce structural vibration and fatigue, noise, and drastic increases in drag on the body enclosing the cavity.

More recent experiments[6-9] indicate that the impingement of the shear layer on the sharp corner bounding the downstream end of the cavity can produce pressure perturbations, resulting in acoustic tones, which amplify the shear layer instability into an acoustically driven cavity excited at discrete frequencies. Rockwell and Naudascher[10] found that the feedback of downstream impingement data back upstream can amplify vorticity perturbations generated by the cavity's free shear layer, resulting in a globally organized shear layer oscillation. This feedback mechanism is seen to result in increases in the shear layer growth rate[11] and in the organization and phase coherence of turbulent eddy structures within the layer.[12,13] Externally forced cavity shear layers have been studied experimentally by Gharib.[14] Above a certain amplitude of acoustic forcing, the driving frequency becomes the dominant frequency of the shear layer oscillations, overwhelming any natural oscillations that may have occurred in the absence of external forcing.

The present study focuses on details of the physical processes present in an acoustically driven, nonreactive cavity flow. A general schematic of the two-dimensional device under examination is shown in Fig. 1. This configuration has been studied by our research group at the University of California, Los Angeles, for a number of years in a reactive context as a potential hazardous waste incinerator/afterburner device.[15-22] Under reactive conditions, fuel and air at room temperature are introduced into the plenum section of the combustor and then are mixed and accelerated through an inlet section before entering the combustion cavity and forming premixed flames at the sudden expansion or dump plane. As shown in Fig. 1, vortex shedding coincident with the flames may occur under conditions of either natural or externally driven acoustic excitation, as has been observed in more conventional dump combustor systems.[23-25]

As a thermal waste destruction device, gaseous or liquid waste surrogate is introduced through injectors embedded in the ceramic plugs into the combustion cavity recirculation zones, allowing the surrogates to be trapped for relatively long residence times under potentially high-temperature and/or relatively oxygen-rich conditions so that they may be destroyed more efficiently. In the course of these investigations, it was found that waste destruction rates are strongly enhanced, by several orders of magnitude, if the device is acoustically forced at frequencies corresponding to certain longitudinal modes of the system.[21,22]

It is the aim of the present study and the accompanying investigation[26] to use detailed laser diagnostic techniques to quantify flow processes occurring in the dump combustor cavity under different conditions of acoustical excitation and nonexcitation. The present experiments are focused on the behavior of the inlet core and shear layer regions of the cavity under cold (nonreactive) conditions, in which only air is introduced into device through the plenum. Although there are obvious differences between flowfields associated with reactive and nonreactive gas conditions, several comparative studies[27-29] have indicated that the main flowfield differences consist of higher turbulence intensities downstream of the flame due to increased vorticity generation and higher velocity gradients. Both effects should actually augment mixing and reaction processes for the present experiment with reaction, although the actual magnitudes of entrainment to/from the recirculation zones may be reduced.[30] Nevertheless, cold-flow results can provide a quantification of the comparative alteration in transport that occurs with and without acoustic excitation. Thus, nonforced and externally forced acoustic conditions were examined to distinguish physical phenomena related to mass and momentum transport that could explain differences in dump combustor/incinerator performance.[21,22]

II. Experimental Apparatus

The two-dimensional dump combustor cavity examined in the present experiments is shown schematically in Fig. 1, with an expanded view of flow processes. Quartz windows bounded each end of the device 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. In these nonreactive experiments, air at room temperature and pressure was passed from the plenum into the inlet and then through the cavity and outlet of the device to the exhaust.

External acoustical forcing was accomplished in this 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

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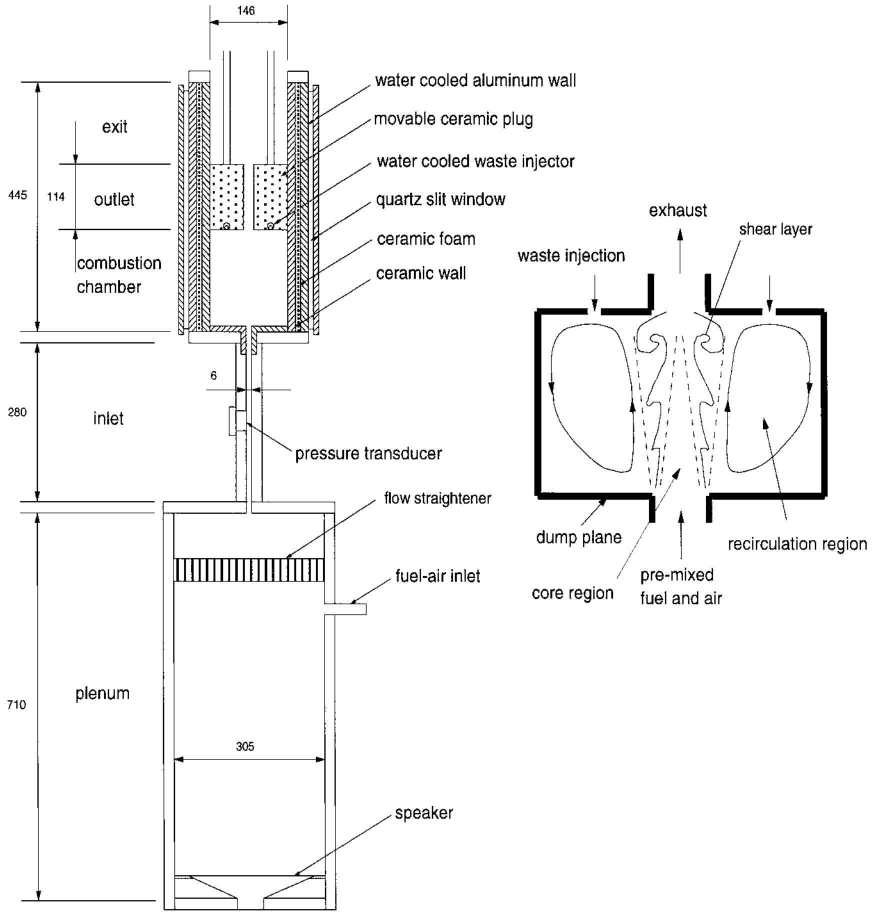


Fig. 1 Schematic of the dump combustor facility, with dimensions in millimeters: Only air is injected into the plenum in the present experiments.

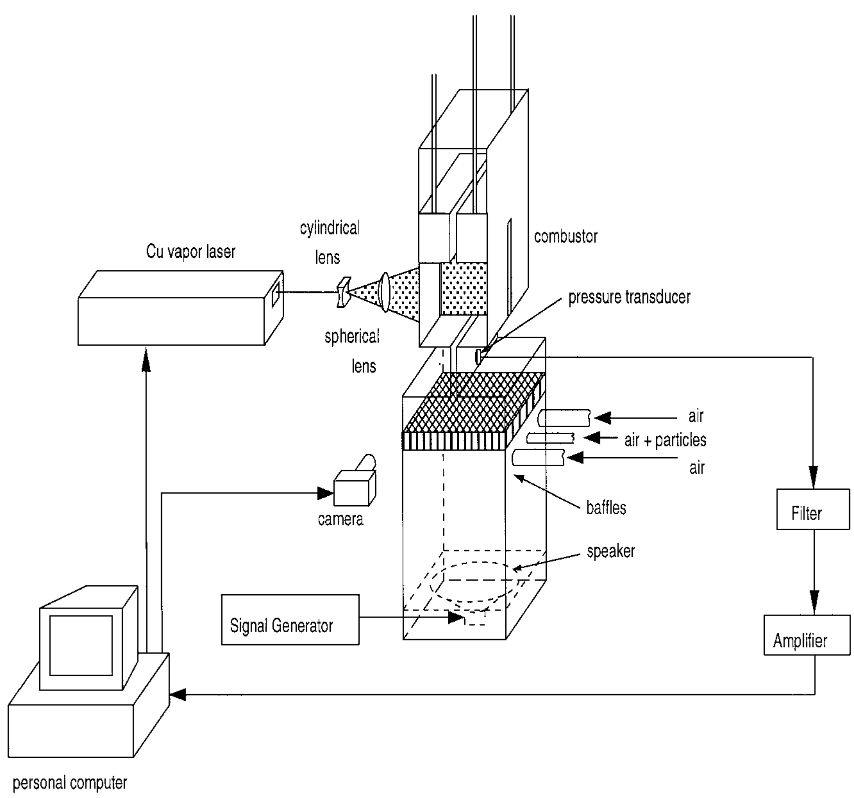


Fig. 2 Schematic of the optical setup used to collect particle images under nonreactive conditions in the cavity of the dump combustor.

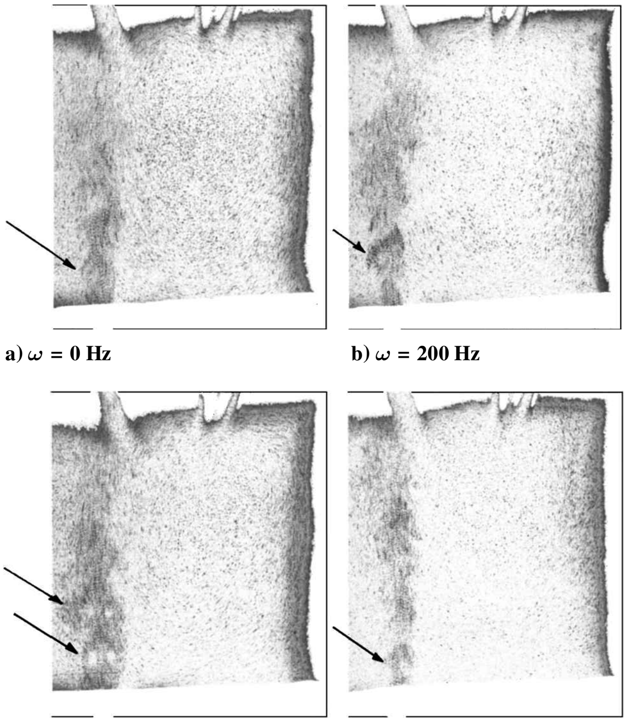
wave of varying frequency and then to amplify the signal and pass it to the speaker. This enabled a sweep through a range of input forcing frequencies from 0 to 1000 Hz to be performed, with forcing amplitude variation up to 150 dB, although frequencies below 200 Hz were difficult to attain consistently with the present speaker. Thus, it became possible to force the loudspeaker at conditions corresponding to the possible resonant longitudinal modes of the device (above 200 Hz) as well as other nonresonant frequencies.

Acoustic data were taken using pressure transducers located in the plenum and inlet; these signals allowed synchronization of optical diagnostic equipment with the acoustic cycle in the combustor. As a consequence, phase-locked particle image velocimetry (PIV), planar laser-induced fluorescence (PLIF) of seeded NO (Ref. 26), OH PLIF,[17] and OH* chemiluminescence[21] were able to capture images of the flowfield at different portions of the acoustic cycle.

III. PIV

PIV is a technique for making simultaneous, multipoint velocity measurements in a plane.[31,32] In this technique, the flow is uniformly seeded with fine particles that follow the fluid and are subsequently illuminated with pulses of light from a laser sheet. Scattered light from particles in the plane of the laser sheet is captured on photographic film or on a charge-coupled device array. The scattering images are broken into small regions, each of which is analyzed (or interrogated) to yield a velocity vector. Collecting the velocity vectors from each interrogation area yields the velocity field corresponding to a particular scattering image. The advantage of this technique is that it provides simultaneous, multipoint velocity measurements, which are essential to the study of two-dimensional unsteady velocity fields. Such measurements are not possible with conventional point measurement techniques such as hot-wire or laser Doppler anemometry.

PIV has been used to a limited extent in the past by our group to study the behavior of the flow in the dump combustor recirculation zones under steady reactive and nonreactive conditions.[17] The experimental setup for the present PIV experiments, focusing on the inlet core and shear layer regions, is shown in Fig. 2. A 20-W copper vapor laser (at 511- and 578-nm modes) was used to form a laser sheet that illuminated Al_2O_3 particles seeded in the flow. Four laser pulses 167 μs apart, i.e., with a 6000-Hz repetition rate, illuminated the particles in the flow. Scattered light was collected by a 35-mm single-lens reflex camera equipped with a 60-mm, $f/2.8$ macrolens and recorded on Kodak T-Max 400 film. With scattered light suppressed by sooted or blackened cavity walls, it was possible to use Al_2O_3 seed particles in the 1–5-μm range with laser illumination at about 2 mJ/pulse. Phase locking the laser and camera to combustor oscillations was achieved via pressure oscillations detected by



a) ω = 0 Hz   b) ω = 200 Hz   c) ω = 300 Hz   d) ω = 400 Hz

Fig. 3 Instantaneous particle images in the center and right side of the combustor cavity under cold-flow conditions for unforced and forced cases at 200, 300, and 400 Hz. For the forced cases, images shown are for comparable portions of the acoustic cycle: inlet velocity U_i = 4.7 m/s and cavity length = 10.2 cm; inlet and exit openings are shown as breaks in the upper and lower walls of the cavity. Vortical structures associated with the jet/core flow are indicated by the arrows.

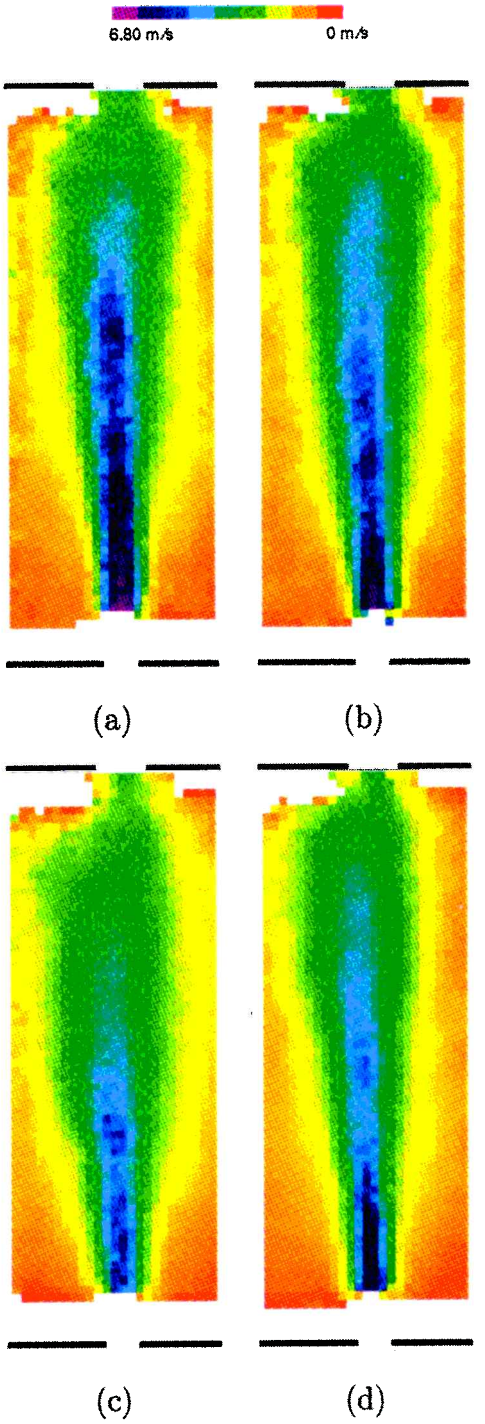


Fig. 4 Comparison of time-averaged streamwise velocity distributions with data averaged over one acoustic cycle (with six images each) and three to four different data sets; inlet velocity U_i = 4.7 m/s and cavity length = 10.2 cm: a) unforced flow, b) 200-Hz forced flow, c) 300-Hz forced flow, and d) 400-Hz forced flow, computed from PIV data.

pressure transducers in the inlet, as done in earlier OH* chemiluminescence experiments.[21] Hence, a series of PIV images over each acoustic cycle was acquired for each set of operating conditions.

The idea behind PIV is that multiple exposures of particle-laden flows leave a trail of particle images corresponding to each particle on the exposed negative. If the time between successive particle images (exposures) is known, the particle's velocity may be determined by measuring the space between particle images. A line drawn through the particle images provides the direction of velocity with a 180-deg ambiguity. In this work, the extraction of velocity information from the exposed negatives was performed by digitizing each negative at 127 pixels/mm (comparable to the spatial resolution of the film) using a Nikon LS-3500 negative scanner and transferring

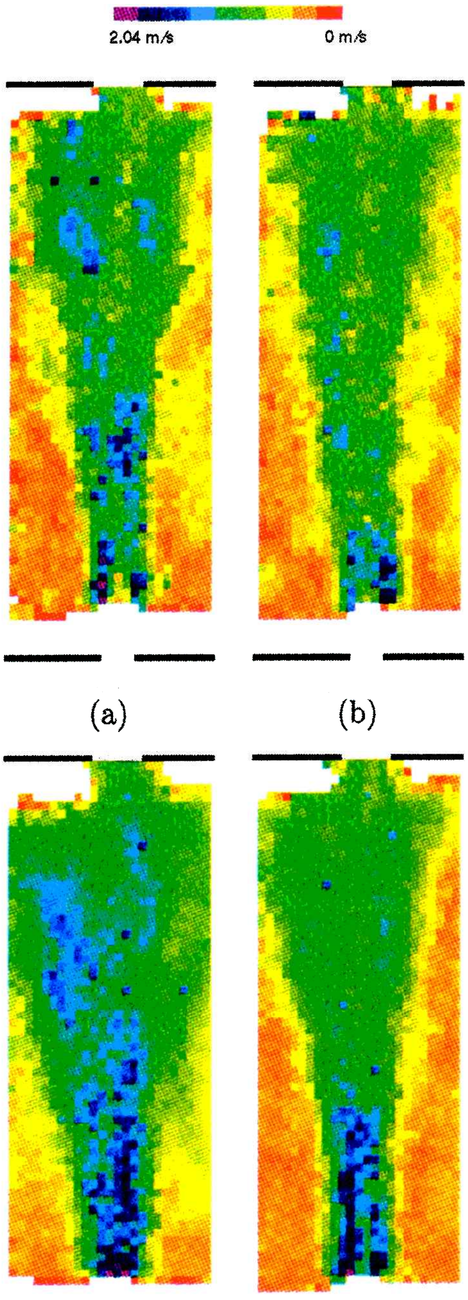


Fig. 5 Comparison of rms streamwise velocity fluctuation distributions with data are averaged over one acoustic cycle (with six images each) and three to four different data sets; inlet velocity U_i = 4.7 m/s and cavity length = 10.2 cm: a) unforced flow, b) 200-Hz forced flow, c) 300-Hz forced flow, and d) 400-Hz forced flow, computed from PIV data.

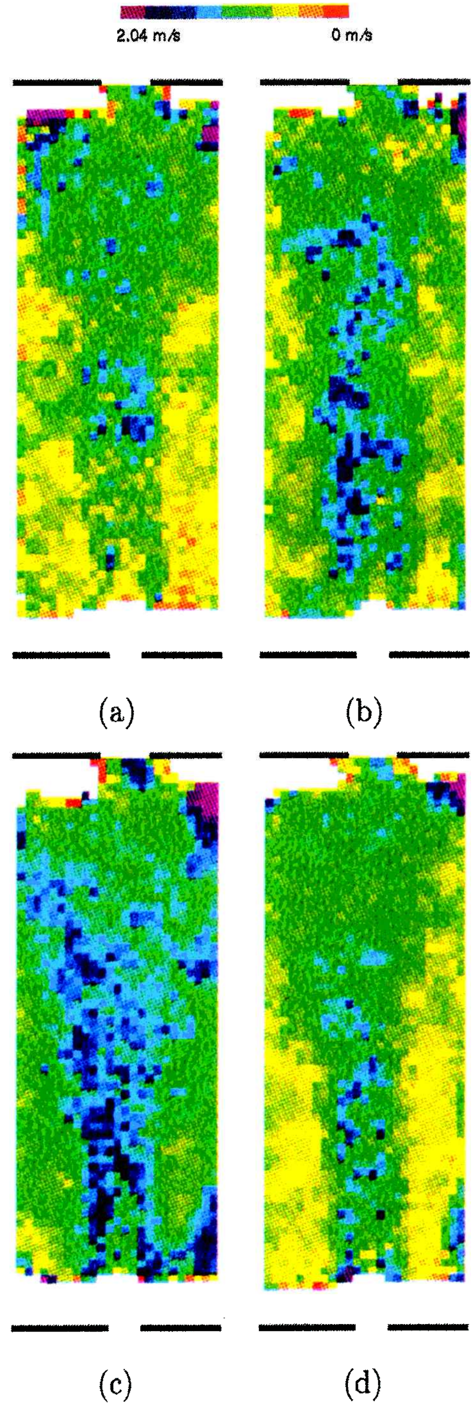


Fig. 6 Comparison of rms transverse velocity fluctuation distributions with data averaged over one acoustic cycle (with six images each) and three to four different data sets; inlet velocity U_i = 4.7 m/s and cavity length = 10.2 cm: a) unforced flow, b) 200-Hz forced flow, c) 300-Hz forced flow, and d) 400-Hz forced flow, computed from PIV data.

the digitized image to an IBM Risc 6000 computer for interrogation. The interrogation spot size was 128 × 128 pixels (corresponding to 3 × 3 mm in the combustion cavity), and interrogation spots were interlaced to enhance spatial resolution. Additional information on the interrogation procedure and the autocorrelation technique used to compute the velocity vectors may be found in Ref. 33.

IV. Results

Results from prior experiments indicate that very efficient dump combustor/incinerator operation can be achieved during external acoustic excitation at high-frequency resonances of the system.[21,22] Possible natural resonant frequencies may be determined using a one-dimensional model for the device.[15,19] These observations suggest that the transport of mass (and energy) between core/reaction zones and recirculation zones may be strongly enhanced during specific acoustic excitation. Optical diagnostics within the device confirmed this enhancement of transport.

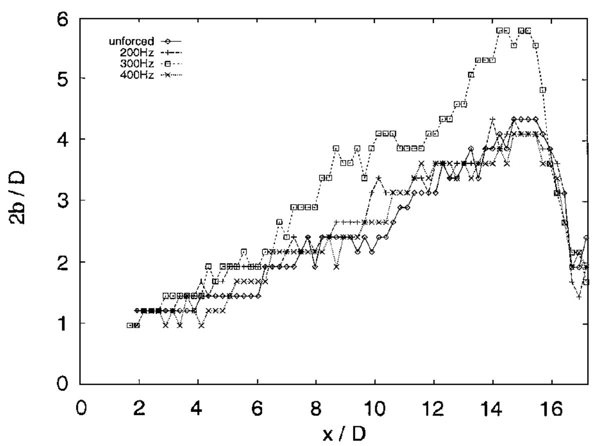
Sample instantaneous particle images obtained by PIV are shown in Figs. 3a–3d for cold (nonreactive) flow in the combustor cavity. In these images the forcing amplitude was 150 dB, which is relatively large. Note that the imaged area includes only the right recirculation region and the core jet so that the imaged area shown for the flowfield is not symmetric; the jet issued upward from the lower edge of the image, near the left boundary of the image. Conditions shown are for the absence of external forcing (Fig. 3a) and for external forcing at 200, 300, and 400 Hz (Figs. 3b, 3c, and 3d, respectively). For cold-flow conditions, 300 Hz was a predicted natural (resonant) frequency of the system,[15] which was virtually the same as that for combusting flow; 200 and 400 Hz were arbitrary (off-resonant) frequencies. As seen by Gharib,[14] for the large-amplitude acoustic forcing imposed here, the driving frequency became the dominant frequency of the jet within the two-dimensional cavity. The instantaneous images in Fig. 3, taken at comparable phases within the acoustic cycles, demonstrated a few fundamental differences in the basic fluid mechanics of the acoustically driven vs nondriven jet in a cavity that play a role in this device's behavior under reactive conditions.

Although vortical structures shed from the combustor's dump plane were observed in the jets with and without acoustic forcing, the broadening and discrete shedding of the vortical structures and the spreading of the jet visually appeared greater for the jet forced at 300 Hz than for that forced at 200 and 400 Hz or for the unforced jet. This broadening was further visible in the time-averaged streamwise velocity distributions shown in Fig. 4, computed over three to four acoustic cycles with six images per cycle. Not only did there appear to be a broadening overall in the average jet structure during forcing at 300 Hz, but there was a reduction in the length of the high-speed core region as well. This suggests that resonant forcing increased the dissipation of the jet and, hence, its mixing with recirculating flow in the cavity. The rms streamwise and transverse velocity fluctuation distributions in the jet region bore this out; these are shown for different forcing conditions in Figs. 5 and 6, respectively. These results not only demonstrated a broadened region over which turbulent velocity fluctuations occurred for on-resonance excitation (compared with no excitation or off-resonance excitation) but also demonstrated an increased magnitude in the fluctuations. Phase-averaged rms vorticity fluctuations in the jet showed generally similar behavior.[33] These results are consistent with the amplification of velocity and vorticity fluctuations in naturally resonant cavity shear layers seen by Rockwell and Naudascher.[10]

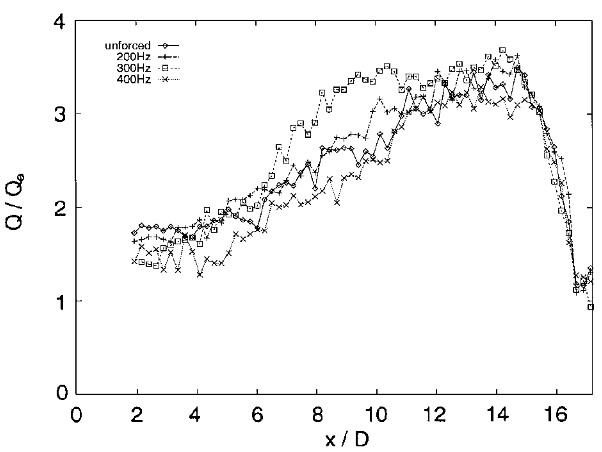
Some of these observations are quantified in Figs. 7a and 7b with data extracted from time-averaged PIV velocity vector fields, as was done for Figs. 4–6. Figure 7a is a plot of the normalized jet width (b/d) as a function of nondimensional downstream distance (x/d) within the cavity, where d is the inlet width. The jet edge is defined as the location at which the axial velocity reaches half its local maximum. Again, on average, the 300-Hz jet diverged more rapidly downstream and continued to be broader than the other jets. Figure 7b is a plot of an effective jet entrainment parameter as a function of nondimensional downstream distance, where nondimensional entrainment is expressed as[34]

$$\frac{Q}{Q_e} = \int_{-b/2}^{b/2} u(y)\,\mathrm{d}y \Big/ U_j d \qquad (1)$$

where y is the transverse coordinate, $u(y)$ is the axial component of velocity, and U_j is the mean jet velocity at the inlet. The data suggest that the rate of entrainment of gas into the jet (from the recirculation zones) was generally higher for the 300-Hz excitation case than for the other cases. Entrainment into the jet was especially high toward the middle of the combustor cavity, which in the reactive experiments was where the primary premixed flame structure tended to reside. This is important because it indicates that the flow is most sensitive to perturbations in the vicinity of the reaction zone, where external forcing may have its greatest effect.



a) Jet width



b) Nondimensional entrainment rate

Fig. 7 Cold flow in the cavity as a function of downstream distance (nondimensionalized by inlet width *d*), extrapolated from PIV data; inlet velocity U_i = 4.7 m/s and cavity length = 10.2 cm.

V. Conclusions

In the present study PIV was used to quantify in two dimensions the temporal evolution of the flowfield under alternative conditions of acoustic excitation and nonexcitation. During external excitation at high-frequency longitudinal modes of the device, enhanced jet core spread and an enhancement of the exchange of mass between jet and recirculation regions were quantified. No significant enhancement over unforced behavior was observed during external excitation at nonresonant frequencies. These observations are consistent with prior nonreactive studies suggesting the correspondence of naturally driven cavity oscillations with increased shear layer growth rate.

These observations are also consistent with recent measurements of waste surrogate destruction in the present combustor in which only air was present in the inlet core flow. Destruction of surrogates (which were injected into the recirculation zones) requiring high levels of entrainment of air was increased by over three orders of magnitude when external acoustic forcing was applied at natural mode frequencies. No such increase was seen during external forcing at nonresonant frequencies. This augmented destruction could only take place due to enhanced transport of air from the core jet to the recirculation zones and is consistent with the present cold-flow observations.

Hence, the nonreactive 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. External acoustical forcing using the loudspeaker provided such energy input at the specific resonant modes, resulting in increased jet spread and perturbed core flow as well as increased mass transport within the cavity. These quantifiable increases in the transport of mass and momentum within reactive cavity flows can be beneficial in a variety of technological systems, including environmental thermal destruction systems.

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