Multistep Dump Combustor Design to Reduce Combustion Instabilities

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Based on the understanding of the critical role of large-scale structures as drivers of pressure oscillations, a multistep dump was sucessfully tested to suppress pressure oscillations in a coaxial dump combustor. The multistep concept, which prevents development of large-scale structures, was studied in nonreacting air and water flows and in an annular diffusion flame before it was applied to the dump combustor burning gaseous fuel. The nonreacting tests in water and air showed that there is an optimal geometric configuration of the multisteps to achieve the highest level of turbulence. At this geometry the shear layer that is separated from the upstream step impinges on the next downstream step edge. When this geometry was tested in a dump combustor, the fuel injection pattern was found to be critical to obtain suppression of instabilities. With fuel injection distributed into the small-scale turbulence downstream of each step and not interfering with the flow impingement, the pressure oscillation in the dump combustor was suppressed.

Nomenclature

D	= exit diameter
D_t	= throat diameter
$D_{t,\mathrm{Step}}$	= choked orifice diameter to meter fuel injection from steps 1-3
H	= step height
L/H	= step length-to-height ratio
$\dot{m}_{\mathrm{AIR}}$	= air mass flow
$\dot{m}_{F,0}$	= fuel mass flow injected from step 0
$\dot{m}_{F,1\text{-}3}$	= fuel mass flow injected from steps 1-3
$\dot{m}_{\mathrm{FUEL,TOTAL}}$	= total fuel mass flow
$(N)_{\mathrm{ST}}$	= number of steps
P_A	= air-only combustor pressure
P_{AMB}	= ambient pressure
P_C	= combustor pressure
Re	= Reynolds number
r	= exit radius
U	= velocity
u'	= fluctuating axial velocity component
$\overline{u'v'}$	= Reynolds stress
x	= axial distance from exit
ΔP_{rms}	= root-mean-square pressure amplitude
ϕ	= equivalence ratio

Subscripts

℄	= centerline
max	= maximal value
O	= at exit

Introduction

HIGH-AMPLITUDE pressure oscillations have been observed in various dump combustor configurations. The more troublesome oscillations for modern, compact combustor designs are in the lower-frequency range (500 Hz and lower), which generally correlate with the acoustic properties of the chamber. These oscillations can interfere with the inlet shock system of the ramjet, causing loss of performance due to inlet unstart,[1] and can result in structural damage in the combustor.

The source of energy needed to excite and maintain pressure oscillations is associated with unsteady combustion or periodic heat release. Driving occurs if the periodic heat release is in phase with the pressure oscillations (Rayleigh criterion).[2] Various physical causes for unsteady heat release have been considered, including oscillatory inlet dynamics,[3] pulsating fuel injection, and oscillating pressure interaction with the combustion zone.[4,5] More recently, the role of fluid dynamic processes has been given increased attention in laboratory combustors.[6-11]

Recent research at the Naval Weapons Center (NWC) has addressed the role of flow coherent structures as drivers of the combustion-induced, low-frequency instabilities in an axisymmetric dump combustor.[12,13] Results of nonreacting test in air and water flows, as well as combustion experiments in a diffusion flame and dump combustor, showed that the flow structures, or vortices, are formed by the interaction between shear-flow instabilities and the chamber acoustic resonance. When these vortices dominate the reacting flow, the coherent flow strucutres lead to periodic heat release and may result in the driving of high-amplitude pressure oscillation.

The understanding of the shear-flow dynamics and their role in the combustion process is used in the NWC work to develop methods to control passively the combustion instabilities. Various methods are experimentally investigated to alter passively the structure of the initial shear layer at the dump to prevent or delay the regular sequence of shear-flow instability processes, which lead to the generation of large-scale structures. This passive control to suppress instabilities may be of advantage over active control with "antisound"[14] because of the increased complexity associated with an external driver.

In this paper, large-scale structure development at the dump is minimized and fine-scale turbulence maximized using a dump with a series of downstream facing steps that act as a source for turbulence production. The idea is based on the theoretically proven relation between the number of unstable modes for turbulence production and the number of inflection points in the velocity profile.[15] The same concept of multiple steps was used to enhance fine-scale mixing and flame stability for a fuel-rich plume combustion process in air.[16]

The multistep dump concept, to minimize combustion instabilities, was investigated in nonreacting flows (air and water) and annular diffusion flames before it was applied to a coaxial dump combustor.

Presented as Paper 88-2854 at the AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, Boston, MA, July 11-13, 1988; received July 25, 1988; revision received March 1, 1989.

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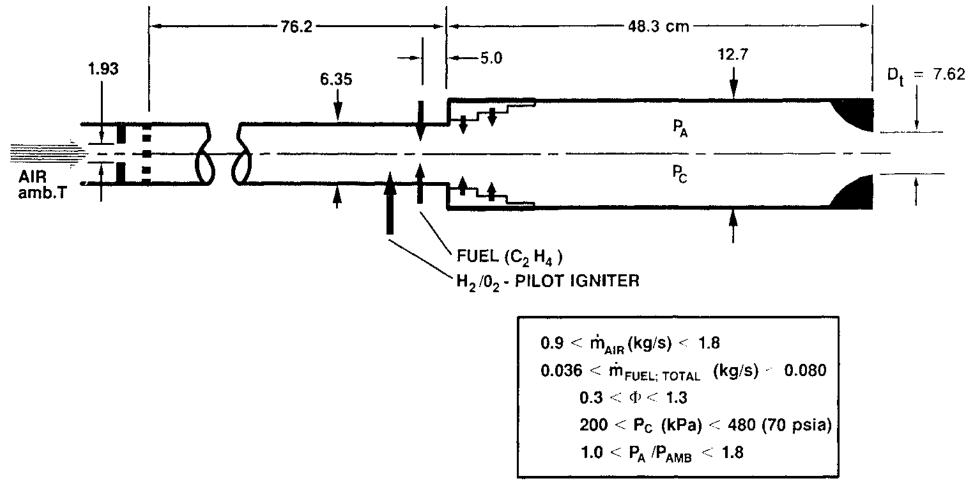

Fig. 1 Combustor with fuel injection from multistep dump.

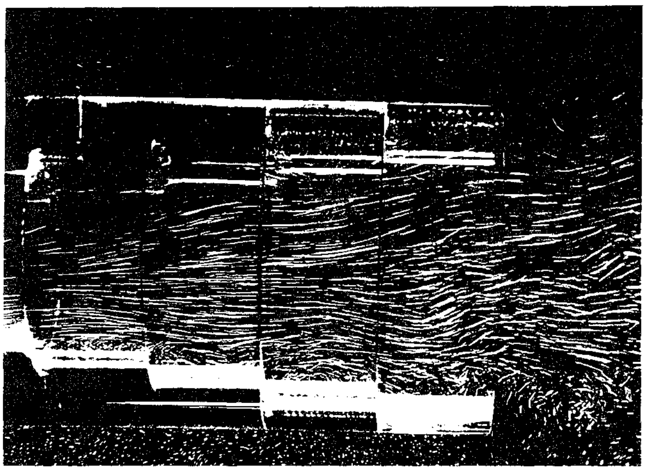

Fig. 2 Water flow visualization—multiple steps; $L/H=7$.

Experimental Set

Four different experimental methods were used to study shear flows of multistep arrangement and its effect on combustion.

Hot-wire anemometry was employed to compare fluctuating velocities and Reynolds stress for a circular jet issued from a pipe with an exit diameter of $D=63.5$ mm and a jet issued from the same facility, at exactly the same conditions with the addition of a multistep nozzle with $D=101.6$ m, having three equal downstream facing steps $[(N)_{ST}=3]$. The step height was $H=6.4$ mm, and the length-to-step height ratio was varied from $L/H=3.5$ to 7.0 and 10. The jet exit velocity at the centerline was held constant at $U_O=50$ m/s, corresponding to a Reynolds number of $Re=2\times10^5$ based on the jet nozzle diameter, $D=63.5$ mm. The DISA hotwire was mounted on a computer-controlled traverse mechanism. Calibration, data acquisition, and data reduction were done on a VAX 11/750 computer.

Flow visualization was obtained in a water tunnel to compare the flow characteristics in a 101.6 i.d. pipe and in a multistep nozzle with the same dimensions as the air tests. The length-to-step height was varied as in the air tests. Air bubbles illuminated with a slot lamp were used for flow visualization in tests with and without forcing. Forcing was obtained with a butterfly valve in the inlet duct. The forcing tests were conducted in order to simulate the conditions of combustion instability when large-amplitude oscillations are forcing the flow in the combustor.

The effect of a multistep arrangement on combustion was studied in an annular diffusion flame. The fuel (propane) was injected from the lip of the circular nozzle ($D=22$ mm) and a multistep nozzle ($D=36$ mm, $H=3.5$ mm, $N_{ST}=2$, and $L/H=5$) into the developing shear flows to achieve annular diffusion flames. The air issued at a velocity of $U_O=5$ m/s, yielding a Reynolds number of 7000 based on $D=22$ mm. The fluid dynamic/combustion interaction was visualized by planar laser-induced fluorescence (PLIF) imaging of in situ OH radicals[17,18] in experiments with and without acoustic forcing via a loudspeaker in the plenum chamber.

A laboratory coaxial dump combustor with a perforated orifice plate at the air inlet side was used to determine the amplitude of combustion-induced pressure oscillations. A sudden dump configuration, for which the oscillating pressure amplitude and phase distribution had been determined,[19] was compared to a combustor with a multistep dump (Fig. 1). The comparison was done for the operational mass flow and pressure conditions shown in the figure with one Kistler high-frequency response pressure transducer located near the exit nozzle. Ethylene entered the combustor through a choked orifice ($D=4.8$ mm) to determine the total fuel mass flow, $m_{FUEL,TOTAL}$, and eight feed lines. The fuel was injected through eight orifices mounted in the inlet duct wall, and additional orifices were mounted in the steps 1-3. Fuel injection from the steps was possible in radial and axial directions. Tests were made with 100% of the fuel injected through the eight choked orifices in step 0, and with 85% from step 0 and 15% from steps 1-3. The fuel mass flow from steps 1-3 was metered with a choked orifice. The step height was $H=6.4$ mm with $L/H=7$ in all of the arrangements tested.

Results

Water Flow Experiments

In the water-tunnel tests the turbulent intensity of the circular duct flow was significantly enhanced in the multistep flows. The turbulence enhancement was maximized for $L/H=7$ (Fig. 2), at which reattachment of the separated boundary layers occurred near the downstream end of the steps. The tests indicated that the critical L/H required for flow reattachment was longest for the first step and decreased for the downstream located steps because of increasing turbulence intensity. The flow did not develop large-scale flow structures, even when it was forced at a velocity fluctuation amplitude of 3% of the mean velocity, which was $U_O=0.5$ m/s. The excitation frequency was $f_F=2.5$ Hz. For shorter steps of $L/H=3$, the flow separated without reattachment at the first step. The turbulence intensity in the jet core at the nozzle exit was reduced relative to $L/H=7$ and became similar

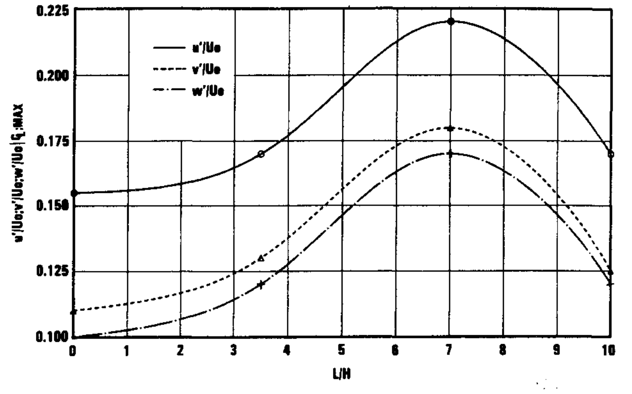

Fig. 3 Dependence of the maximal centerline turbulence intensity on the step length-to-height ratio (L/H).

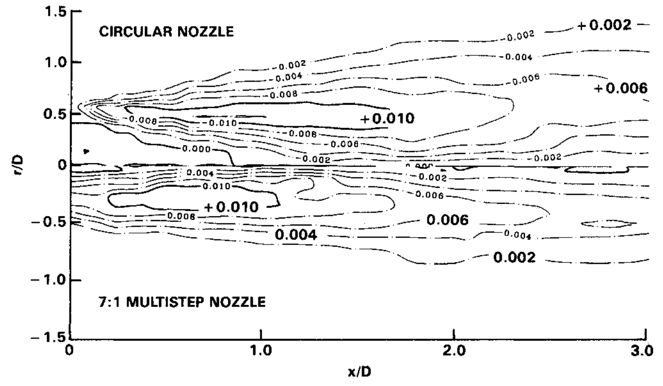

Fig. 5 Reynolds stress ($\overline{u'v'}/U_O^2$) contours for circular and 7:1 multistep nozzles.

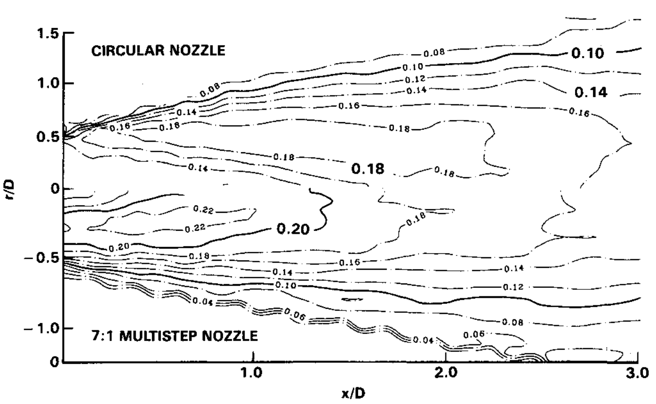

Fig. 4 Turbulent axial mean velocity (u_∞/U_O) contours for circular and 7:1 multistep nozzles.

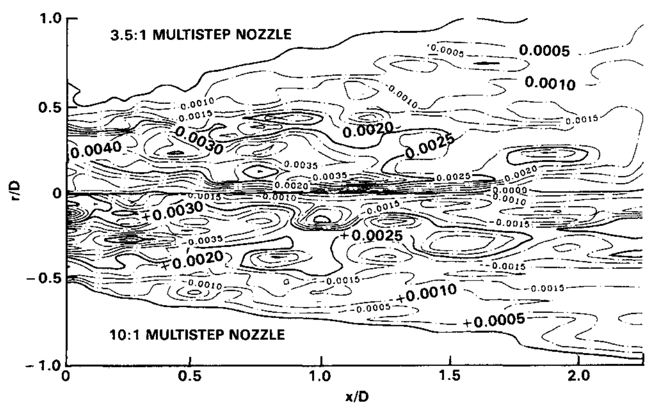

Fig. 6 Reynolds stress ($\overline{u'v'}/U_O^2$) contours for 3.5:1 and 10:1 multistep nozzles.

to the pipe flow without steps. For longer steps of $L/H = 10$, the flow was restabilized after flow reattachment, and the turbulence intensity was again lower than that for $L/H = 7$.

Airflow Experiments

The water-tunnel results were confirmed in the airflow experiments. The maximum centerline turbulence intensity for the circular jet and the three step configurations ($L/H = 3.5$, 7, and 10) are compared in Fig. 3. The highest increase of the turbulence intensity for all three velocity components was obtained for $L/H = 7$. Both other step configurations were lower but still larger than the circular jet. In the following, circular and multistep nozzles will be compared based on turbulent axial mean velocity contours (Fig. 4) and Reynolds stress contours (Figs. 5 and 6), both determined from the nozzle exit ($x = 0$) to $x/D = 8$ (circular nozzle) and up to $x/D = 4$ (multistep nozzles).

At the exit of the circular duct ($x/D = 0$; Fig. 4), the shear layers developed on both sides of the potential core. The initial turbulence intensity was amplified in the shear layers to a maximum of 18% of the mean velocity. For the multistep nozzle with $L/H = 7$ (Fig. 4), the highest turbulence intensity ($u'/U_O = 0.22$) was obtained near the nozzle exit for $0 < x/D < 1.0$. The exit flow did not develop shear layers as in the circular nozzle because of the high initial turbulence activity, thus preventing the growth of large-scale coherent structures. The maximum turbulence intensity of u'/U_O was lower for $L/H = 3.5$ and 10 compared to $L/H = 7$. The flow regime with $u'/U_O \geq 0.20$ was the smallest for $L/H = 3.5$, making this nozzle the least desirable for obtaining highly turbulent flow and thus avoiding large-scale structure development.

The turbulence enhancement with the multistep concept was also demonstrated in the Reynolds-stress results. For the circular pipe, highest Reynolds stress ($\overline{u'v'}/U_O^2 = \pm 0.010$) developed in the shear flow surrounding the jet core region (Fig. 5) with zero Reynolds stress near the nozzle exit. For the multistep nozzle with $L/H = 7$, the Reynolds stress was larger than zero also near the jet centerline and increased to a maximum of ± 0.010 at $r/D = \pm 0.3$ (Fig. 5). The range of this maximum stress value was much larger than in the circular jets. This high Reynolds stress throughout the jet prevents orderly growth of large-scale coherent structures. Lower and randomly distributed Reynolds stress was measured for the multistep nozzle with $L/H = 3.5$ and 10 (Fig. 6). For both nozzles, the maximum Reynolds stress was $\overline{u'v'}/U_O^2 \approx 0.04$, significantly lower than the maximum Reynolds stress of 0.010 for the $L/H = 7$ multistep nozzle.

Annular Diffusion Flame Experiments

The fine-scale turbulence augmentation of prevention of large-scale structure development with multiple steps had a strong effect on the flame stability and intensity of the diffusion-flame burner (Fig. 7). With forcing, combustion in the circular burner occurred in distinct vortices (Fig. 7a), which resulted in periodic heat release and possible driving of pressure oscillations. In the multistep burner with forcing (Fig. 7b), the flame was rich of fine-scale activity, and development of large-scale structures was avoided.

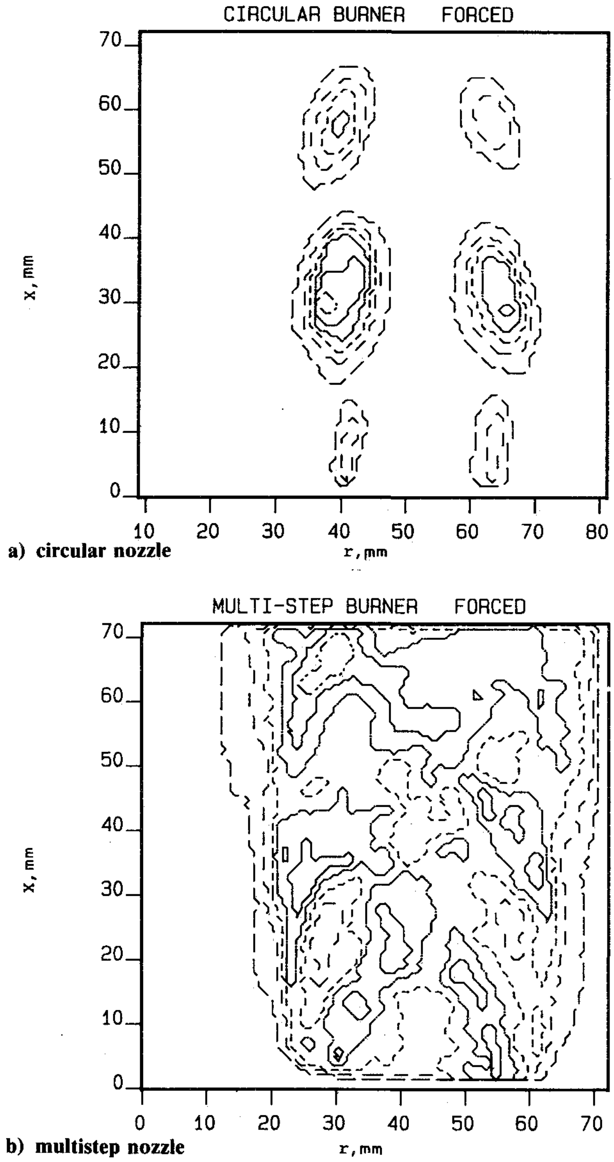

Fig. 7 PLIF imaging in annular diffusion flame. Contour levels: 2, ———; 3, — — — ; 4, - - - - -; 5, — · —; 6, ——; 7, — ·· —.

Dump Combustor Experiments

The multistep dump was investigated in the coaxial dump combustor and compared to the standard sudden dump. For the latter configuration, the rms values of the pressure oscillation amplitudes (ΔP_{rms}) were up to 40% of the mean chamber pressure (P_C) for equivalence ratios of $\phi > 0.65$ and $\phi < 0.55$ (Fig. 8). With the multistep dump pressure oscillations were reduced below $\Delta P_{rms}/P_C = 0.10$. The lean flame blowout limit was slightly extended to lower ϕ with the multistep dump relative to the sudden dump; however, rich flame blowout occurred at a lower equivalence ratio for the multistep dump ($0.8 < \phi < 0.9$) than for the sudden dump ($\phi > 1.3$). The suppression of the pressure amplitude with the multistep dump may also be seen from Fig. 9, which compares the pressure spectra of the multistep with those of the sudden dump for tests at $\phi = 0.75$. Distinct peaks, mainly associated with the harmonics of the bulk mode frequency of the combustor cavity, were determined for the sudden dump, whereas the spectra for the multistep dump were more random with lower amplitudes and a frequency hump at the 200-Hz bulk mode frequency. This behavior of the pressure fluctuations spectrum for the multistep configuration is in agreement with the enhanced small-scale turbulence that was measured in nonreacting tests using this inlet.[12,15]

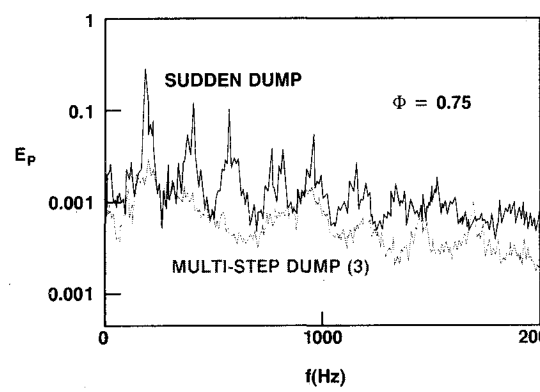

Fig. 9 Spectra of pressure oscillations for sudden dump and multistep dump combustor.

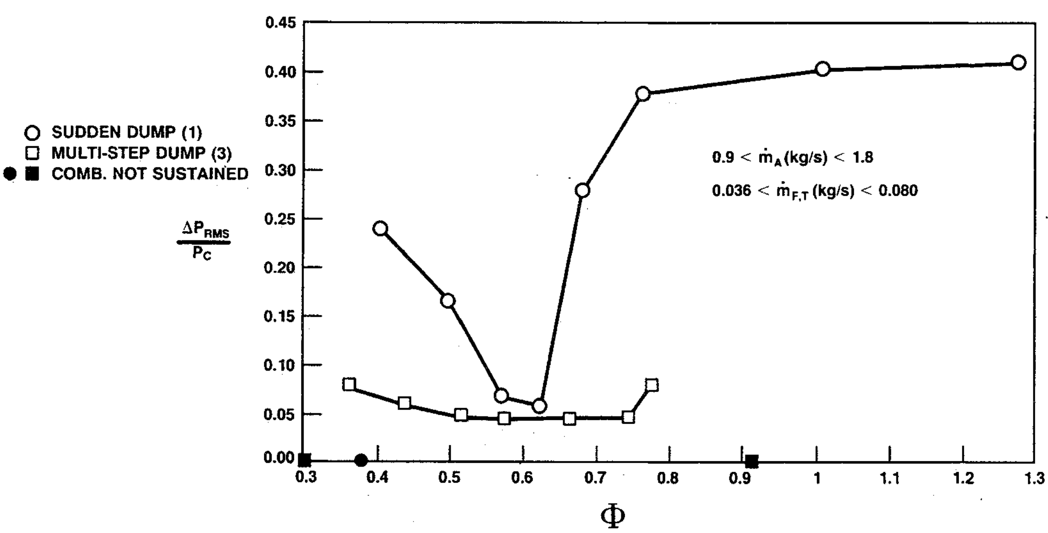

Fig. 8 Pressure amplitude vs equivalence ratio for sudden dump and multistep dump.

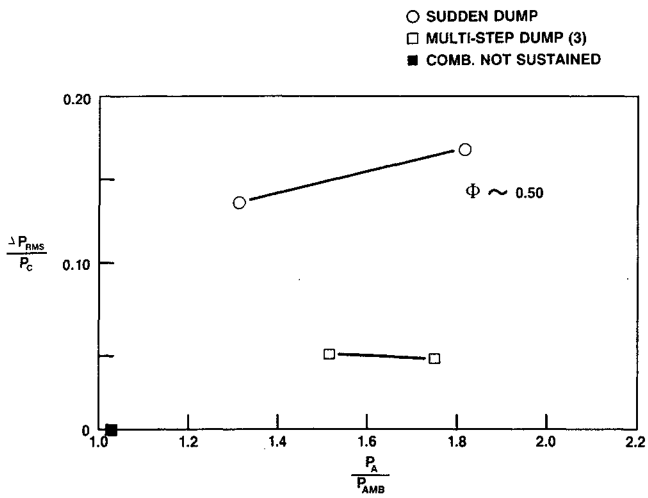

Fig. 10 Pressure amplitude vs air-only chamber pressure for sudden dump and multistep dump.

Significantly reduced pressure amplitudes with the multistep were also obtained when the air-only chamber pressure was reduced from $P_A \approx 1.5\ P_{\rm AMB}$ (ambient pressure) in previously shown tests at $\phi \approx 0.5$ in Fig. 8 to $P_A \approx 1.5\ P_{\rm AMB}$ at a similar ϕ (Fig. 10). With $P_A = 1.02\ P_{\rm AMB}$, combustion was not sustained with multistep dump.

Conclusions

Identification of large-scale structures as drivers of combustion-induced pressure oscillations has opened up the possibility for its passive control. One concept, the multistep dump, which prevents development of large-scale structures, was successfully tested to suppress pressure oscillations in a coaxial dump combustor. The turbulence intensity and Reynolds stress were significantly enhanced in multistep air and water flows, thus preventing development of the large-scale structures. Maximum turbulence intensity and Reynolds stress were obtained for a step length-to-height ratio of seven, at which reattachment of the separated boundary layers occurred near the donwstream end of the steps. In annular diffusion flame experiments, the flame with the multistep exit was rich with fine-scale activity, and development of large-scale structures was avoided. In a coaxial dump, the multistep dump suppressed the pressure amplitude below 10% of the mean pressure from a maximum of 40% for the sudden dump. To obtain the suppression over the entire experimental equivalence ratio range, fuel injection distribution from the steps is critical. The fuel injection has to be distributed along the steps so that it will be introduced into the small-scale turbulence regions downstream of each step. The injection should, preferably, be perpendicular to the flow, such that the fueljet would not interfere with the reattachments of the main airstream. Additional experiments of fuel injection/multistep flow interactions are required, particularly to extend fuel-rich flame blow-off limits.

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