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Technical Notes

Fluidic Flame Stabilization in a Planar Combustor Using a Transverse Slot Jet

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I. Introduction

THE stabilization of a premixed flame in a high-speed internal environment has received a considerable amount of interest from many researchers, for example, [1–3]. Flame stabilization behind a bluff body represents the most common strategy for flame anchoring [4–8]. Bluff bodies and rearward-facing step flows stabilize the flame by introducing a low-velocity recirculation zone containing combustion products that act as a continuous ignition source. Although these flame-holding devices provide an environment suitable for flame holding, a drag penalty is incurred. An alternative fluidic-based approach using a transverse slot jet to generate a "virtual bluff body" would reduce the thrust penalties through the removal of form drag while producing a flowfield with flame-holding potential. Figure 1 shows two schematics for combustors employing bluff body and fluidic methods for flame holding. The dashed box in the figure represents the control volume that will be used to demonstrate that form drag imposes a penalty. A momentum balance in the streamwise direction for the two situations, employing the assumption of negligible viscous shear, indicates that the drag force on the bluff body F_D will result in a loss in either streamwise momentum or an increased pressure drop across the burner. For the fluidic case, a balance will be maintained between pressure drop and an increase in streamwise momentum. A simple one-dimensional analysis of the systems, shown in Fig. 1, using a drag coefficient based on the inlet flow properties was conducted to determine the additional total pressure losses due to flame-holder drag. The calculation employs constant specific heats, models the fluid as air, and employs conservation of mass, momentum, the ideal gas equation, Mach number definition, and stagnation relations. Figure 2 shows the additional total pressure loss due to form drag on the flame holder as a function of inlet Mach number and drag coefficient.

In addition to thrust penalty reduction, the fluidic flame holder allows active control of the recirculation zone size, providing dynamic control of the stabilization characteristics that will allow a broader operating envelope and improved off-design performance. Dynamic control would allow for optimization of the tradeoff between combustion efficiency and flame stability. The cost of the fluidic actuation is considered in terms of the required mass flow rate to achieve the necessary recirculation zone. For the present experiments, the fluidic flow rate was nominally 7% of the main flow rate.

The objective of the current note is to document the operating characteristics of a fluidic flame holder consisting of a planar transverse jet issuing into a channel flow. The influence of the test chamber initial conditions on the scaling of the induced recirculation zone will be shown. It will also be shown that the jet equivalence ratio can be used to manipulate the rich and lean blowout limits.

II. Experimental Setup

The experiments were conducted in the Combustion Laboratory in the Mechanical and Aerospace Engineering Department at the University at Buffalo, State University of New York. The schematic of the ramjet model is shown in Fig. 3. The figure shows three sections of the experiment: the nozzle, the diffuser, and the combustion section. The diffuser is present in the experiment to produce combustor initial conditions that would be present for a ramjet engine, for which the diffuser is required for thrust production due to the projected area in the streamwise direction. The analogous sudden expansion burner would have the same area ratio as the diffuser, but would also incur higher total pressure losses due to the flowpath geometry.

The air for the main channel flow is generated using a blowdown-type facility, in which pressurized air is regulated and metered before delivery to the plenum of the ramjet model facility. The plenum of the test rig contains flow conditioning in the form of two coarse screens, a 1 in. section of a 1/8 in. aluminum honeycomb, followed by a fine mesh screen. The Reynolds number based on the mean velocity at the combustor inlet U_o and the combustor height H was varied up to approximately 32,000. The combustion section has a short dimension height H of 45 mm and a cross-sectional aspect ratio of 2.8:1. The diffuser has an expansion ratio of 3:1, with a total angle of 7.5 deg and a length of 229 mm that produces a quasi-parabolic exit mean streamwise velocity as shown in Fig. 4a. Note that the diffuser did not have separated flow although the fluctuation levels were quite high, as indicated in Fig. 4b. An additional flow conditioning section, consisting of three axially spaced fine mesh screens, was employed for some measurements to investigate the role of the combustor inlet conditions. The additional screens resulted in nominally uniform flow with low turbulence levels, as shown in Figs. 4c and 4d. Measurements have been made with both initial conditions.

A slot jet is situated one channel height H downstream of the diffuser exit on the bottom wall of the combustion channel. The slot spans the full channel spanwise depth. The slot jet has a short dimension of 0.254 mm. Compressed air is first passed through a Laskin nozzle for seeding the airstream with nominally 1-μm-diam olive oil droplets before delivery to the plenum for the nonreacting

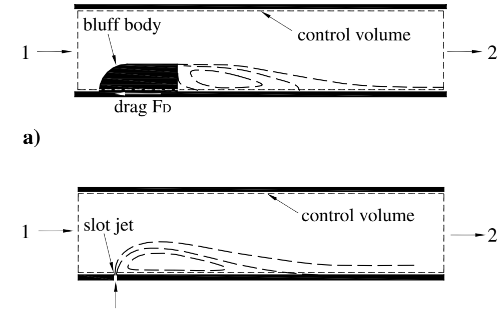

Fig. 1 Schematic of the channel flow: a) geometrical flame holder, and b) fluidic flame holder.

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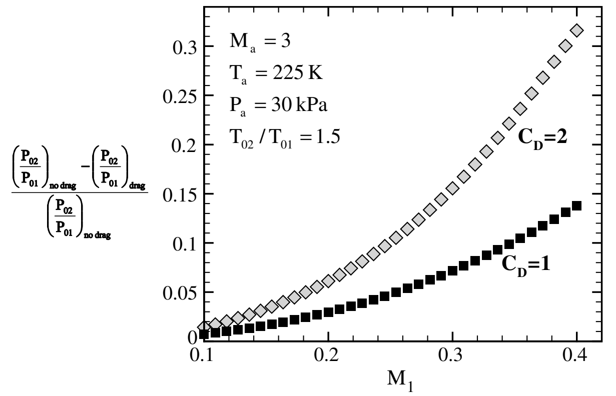


Fig. 2 Influence of form drag on the total pressure loss across a constant area combustion chamber.

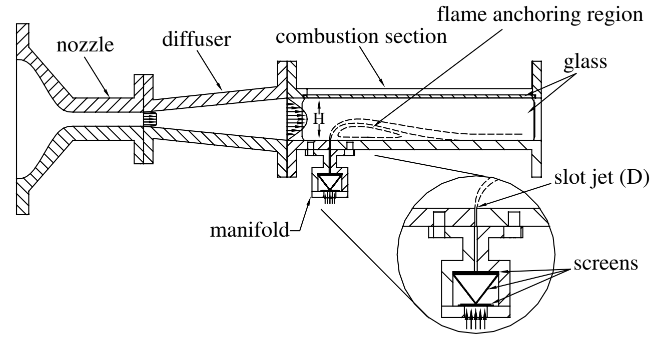


Fig. 3 Schematic of the experiment.

tests. Aluminum oxide particles of 0.5 μm in diameter were used for combustion cases using a cyclone-type seeder. The spanwise uniformity of the slot jet velocity was verified with a pitot rake. The velocity profile of the injection jet is expected to play a role in the transverse slot jet flowfield. Studies on round jets in crossflow have shown that top-hat profiles produce a stronger vortex structure and bend earlier than a fully developed jet profile [9–11]. The jet passage has a normalized streamwise length L/D of 50 and, for $Re_D = 1500$, which is typical for many of the operating conditions, the velocity profile is expected to be fully developed as predicted numerically using ANSYS/CFX-10. The injection air was metered using Dwyer rotameters employing corrections for deviations from the standard density. The channel flow rate was set using particle image velocimetry (PIV) before each experiment. A flush-mounted igniter was placed at $0.84H$ downstream of the slot jet.

Particle image velocimetry was used to study the transverse slot jet flowfield. The system is controlled by IDT software ProVISION-XS that employs a PC and an IDT MotionPro X Timing Hub for synchronization. A New Wave Research Solo PIV III Nd:YAG laser capable of 50 mJ/pulse (532 nm) at 15 Hz is used as a light source. An X-Stream VISION camera is used for collecting images for cross-correlation-mode PIV. Sheet forming optics and a 45 deg mirror are used to deliver an approximately 1-mm-thick light sheet to the test section. Images were processed using 64×32 pixel interrogation regions with 50% overlap, resulting in a spatial resolution of 3.136 mm

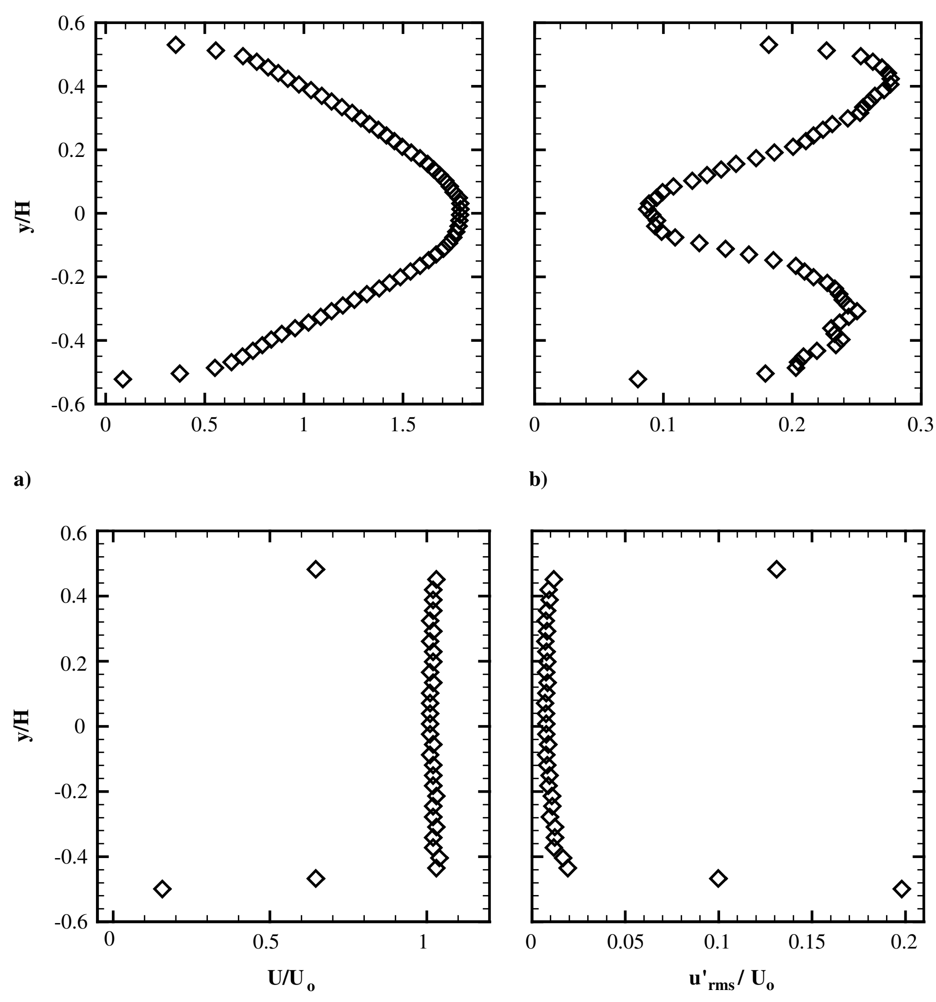


Fig. 4 Profiles of mean and rms fluctuating streamwise velocities: a, b) diffuser without screens, and c, d) diffuser with screens.

in the streamwise direction and 1.568 mm in the cross-stream direction. Generally, 812 image pairs were collected for each case. The precision error of the instantaneous measurements estimated from low-turbulence-intensity benchmark tests was found to be 0.015 pixels for 95% confidence. The peak-locking error was found through analysis of displacement histograms [12] to be approximately 0.02 pixels. The mean velocity in the high-turbulence regions was known to within approximately 5% of the channel flow maximum velocity U_o. Thirty repeat measurements of 812 image pairs for a single case were used to assess the repeatability and uncertainty of the velocity field measurements.

Reacting flow studies were conducted using 99% pure methane fuel premixed with air far upstream of the experiment to ensure complete premixing. The equivalence ratio relative uncertainty based on the bias and precision error of the flow meters for the main flow is $\delta\Phi_m/\Phi_m = 3\%$ and for the jet flow is $\delta\Phi_j/\Phi_j = 7.8\%$.

III. Results

The present study was motivated to explore flame stabilization using a transverse slot jet. The momentum flux ratio is the typical parameter used to characterize an unconfined jet in crossflow [13]. However, due to the confined conditions and the desire to produce recirculation zones that scale with the channel height (independent of the slot jet dimension), a more appropriate parameter is the momentum ratio (MR), defined using global values as

$$\mathrm{MR} = \frac{\rho_j U_j^2 D}{\rho_o U_o^2 H} \tag{1}$$

where ρ is the density of the gas, U is the mean velocity, D is the short dimension of the slot, H is the channel height, and the subscripts j and o represent the jet and channel conditions, respectively. The ratio of the jet to the crossflow momentum for confined conditions presents an appropriate scaling factor for the geometric aspects of the recirculation zone [14–17].

Figure 5 shows the mean flow streamline pattern for three momentum ratio cases (MR = 0.26, 0.42, and 0.76) as measured using PIV under nonreacting and reacting conditions (nonreacting conditions shown in Figs. 5a, 5c, and 5e). The three momentum ratio cases correspond to mass flow rates of 4, 5, and 7% of the main flow rate, respectively. The data presented in Fig. 5 were collected with the additional flow conditioning screens in place. It is clear from the figure that the momentum ratio can be used to dynamically adjust the size of the recirculation zone. The usage of fluidics for inducing a flame-holding recirculation zone will facilitate the optimization of the combustor for different operating conditions. Figure 5 shows that the presence of combustion has a tendency to increase the size of the recirculation zone. A study by Pitz and Daily of the influence of combustion on the flow features downstream of a rearward-facing step found that the recirculation zone length is reduced with combustion [18]. Although the streamline patterns shown in Fig. 5

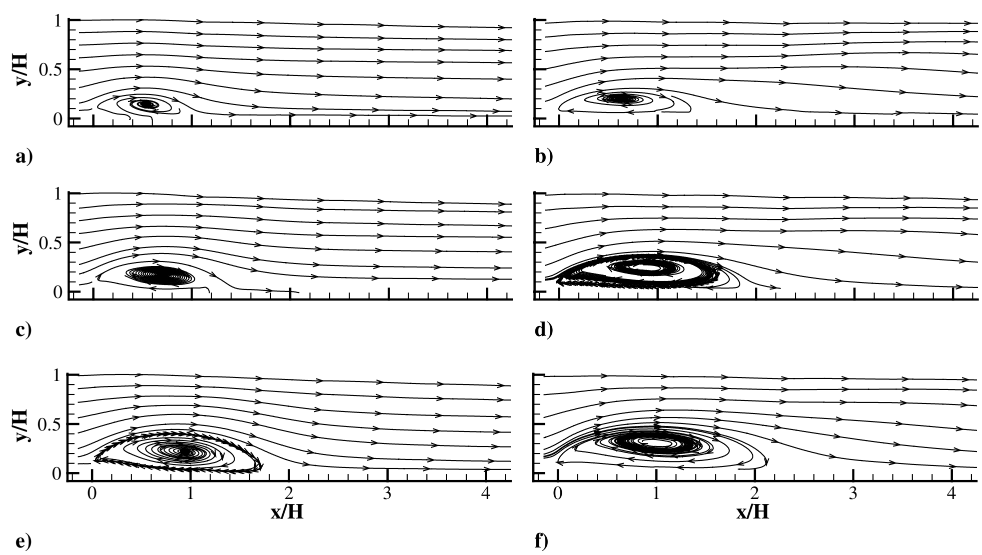


Fig. 5 Mean streamline pattern at MR = 0.26, 0.42, and 0.76: a, c, e) nonreacting flow; and b, d, f) reacting flow.

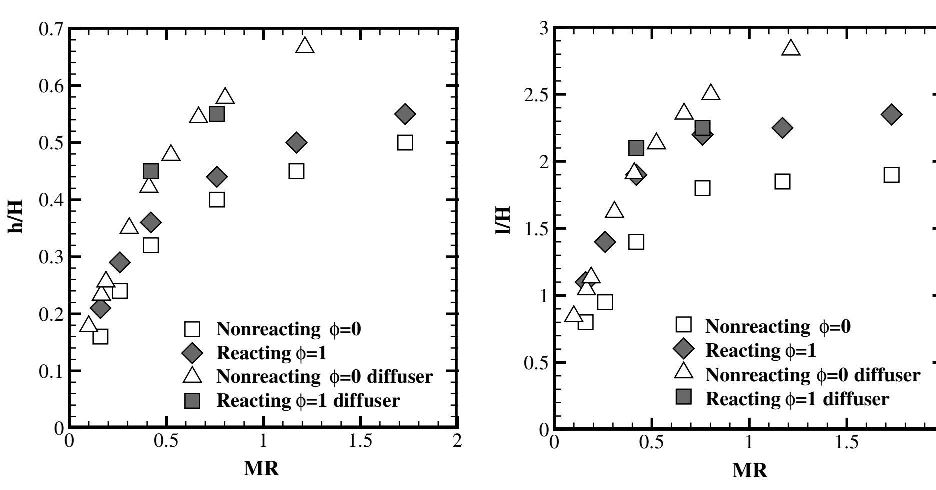


Fig. 6 Recirculation zone in the midspan plane as a function of MR: a) length, and b) height.

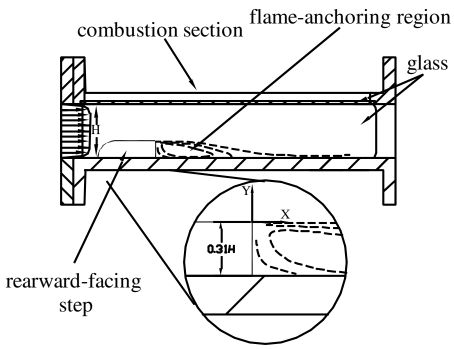
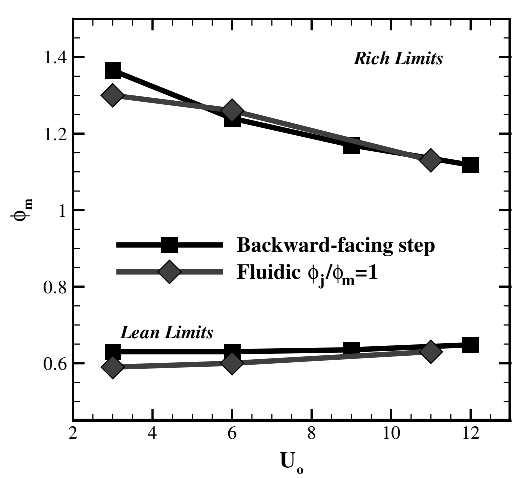


Fig. 7 Rearward-facing step flame-holder configuration.

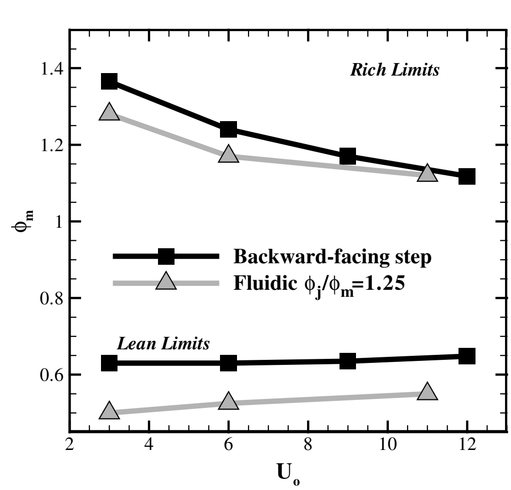
are reminiscent of those observed for rearward-facing step flows, the two flows have some important fundamental differences. The vorticity shed at the trailing edge of a backward-facing step is governed by the boundary layer and will be of a single rotational sense. For the transverse jet, the "shear layer" of the recirculation zone contains vorticity that originates from the jet. Hence, the turbulent mixing region along the boundary of the recirculation zone will have a fundamentally different turbulent structure that is likely responsible for the observed different influence of combustion on this region. For the combustion cases, the streamlines in the region downstream of the recirculation zone show a slight divergence compared with the parallel streamlines under nonreacting conditions. This divergence is cause by volumetric expansion present in the downstream section of the combustor as a consequence of heat release.

The dimensions of the mean recirculation zone were measured through interpretation of the streamline distribution to document the increase in size of the recirculation zone with increasing momentum ratio. Figure 6 shows the change of the normalized recirculation zone length l/H and height h/H with momentum ratio for both sets of initial conditions and with and without combustion. An earlier study of a transverse slot jet established that the momentum ratio is the leading parameter for scaling the size of the recirculation zone, including variable slot jet sizes [17]. The length scales of the mean recirculation zone have a strong dependency on the initial conditions. For nonreacting conditions, the penetration of the transverse jet, which controls the scale of the recirculation zone, is larger for the initial conditions without the additional screens, with the difference being larger at high MRs. The transverse jet is efficient at producing small recirculation zones at low MRs, whereas larger MR values provide diminishing control of the length scale, although the parabolic mean velocity initial condition appears to allow significantly larger recirculation zones at high MRs. Combustion tends to increase the length scales of the recirculation zone for the uniform initial conditions, while having little effect on the parabolic initial conditions.

Having established that a transverse slot jet induces a large-scale recirculation zone, the performance of this approach in terms of flame holding is now discussed. Flame stabilization limits were explored for reacting flow conditions in an analogous manner as for typical geometric flame holders [1,5]. The experiments were performed for a range of combustor velocities ranging from 3 to 12 m/s.



a)



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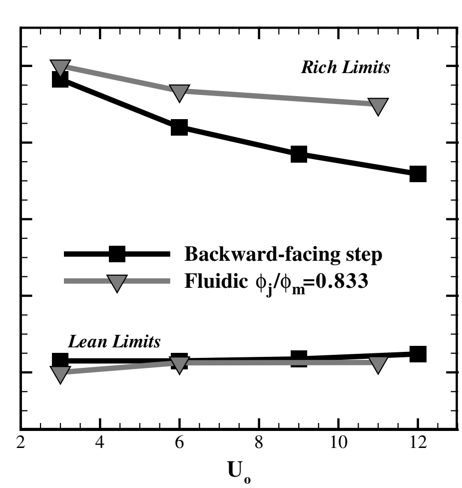

c)

Fig. 8 Flame-stabilization boundaries of a *V* gutter and a fluidic flame holder at $\Phi_j/\Phi_m = 1$, $\Phi_j/\Phi_m = 1.25$, and $\Phi_j/\Phi_m = 0.83$.

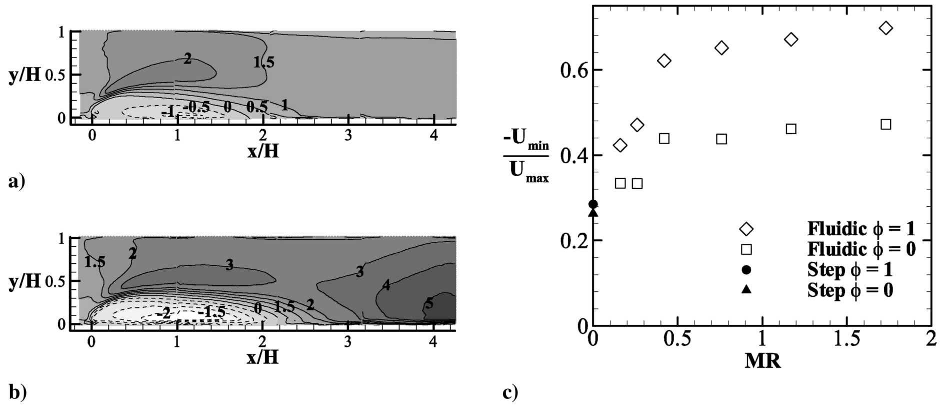

Fig. 9 Mean streamwise velocity for MR = 0.76: a) nonreacting, b) reacting, and c) the velocity ratio at the middle of the recirculation zone as a function of MR.

A wall-mounted component, shown in Fig. 7, was used to provide a rearward-facing step flame holder that served as a reference case. The fluidic case with $\mathrm{MR} = 0.76$ has a mean recirculation zone length of approximately $2.2H$ under combustion conditions, which matches that achieved using this reference configuration.

A mixture of fuel and air was used for the fluidic stream of the transverse jet, as experimentation using pure air or fuel was generally unsuccessful in stabilizing a flame. The momentum ratio was fixed at $\mathrm{MR} = 0.76$ due to the observed insensitivity of the flame-holding performance with respect to the momentum ratio, although it is anticipated that the momentum ratio will have a strong influence on the flame stabilization limits at higher combustor velocities. The influence of the momentum ratio on the flame stabilization boundary at high velocities will be explored in future studies. The flame stabilization performance of the fluidic flame holder was explored at three different relative fluidic stream mixtures. Initially, a fluidic stream mixture with an equivalence ratio matching that of the main combustor flow, $\Phi_j/\Phi_m = 1$, was considered. Figure 8a indicates that both flame-holding methods, having matched recirculation zone lengths, have nominally the same flame-holding capability. Experiments beyond $U_o = 12$ m/s were not conducted due to fuel flow rate limitations.

The fluidic flame stabilization approach has the added feature that the equivalence ratio of the transverse jet fluid can be altered relative to the main flow. Figures 8b and 8c show the flame stabilization boundaries with the jet equivalence ratio richer/leaner than the main flow. These figures indicate that the flame stabilization boundaries are manipulated through the alteration of the relative equivalence ratio of the transverse jet. The availability of controlling the fluidic mixture equivalence ratio as well as the momentum ratio provides the possibility of expanding the operational domain over traditional flame holders. An additional benefit for the fluidic flame holder is the possibility of introducing a different fuel with a shorter chemical timescale in the fluidic stream while maintaining a more traditional fuel in the main stream, an approach that is expected to improve the flame-holding performance of the fluidic flame holder.

Figures 9a and 9b show the distribution of the normalized mean streamwise velocity for the nonreacting and reacting cases at a momentum ratio of 0.76. These data are for the uniform mean velocity initial condition. The recirculation zone is seen to contain high levels of reverse flow, which intensified under combustion conditions. For the nonreacting case shown in Fig. 9a, the velocity gradients smooth out in the downstream region due to turbulent momentum diffusion, whereas the combustion case shows the emergence of a downstream shear region. This downstream shear region is driven by the baroclinic torque mechanism that is caused by the misalignment between the density gradients associated with the flame and the mean axial pressure gradient caused by the expanding combustion products [8,19]. A detailed study of the turbulent structure in the different regions of this flow, including the role of baroclinic torque, is currently underway. Figure 9c shows the velocity ratio (the peak reverse velocity normalized by the peak forward velocity at $x/l = 1/2$) as a function of the momentum ratio for nonreacting and reacting conditions. The solid symbols represent the rearward-facing step flow. The figure indicates that the velocity ratio saturates at a high momentum ratio, and the velocity ratio is significantly higher than that of the step flow. The increase in the velocity ratio represents the increased shear present for the fluidic case. Additionally, the strong reverse flow for the fluidic configuration suggests that this flame holder is potentially more likely to contain global instabilities due to a large region of absolutely unstable flow [7,20]. The presence of global instabilities that do not overlap with acoustic modes is likely to interfere with the coupling between the acoustics and combustion that drives thermoacoustic combustion oscillations.

IV. Conclusions

This Technical Note introduces a new planar fluidic flame-holding methodology for inducing main flow separation and recirculation with the intent of employing these flowfield features for stabilizing premixed flames. The scaling of the recirculation zone depends on the momentum ratio and the initial conditions. The fluidic flame-holding method is found to have similar flame stabilization characteristics compared with the flow downstream of a rearward-facing step. The ability to separately control the equivalence ratio (and fuel type) of the fluidic jet provides for additional control of the lean and rich flame-holding limits. This method has the potential to provide ultralean operation of premixed combustion systems to reduce emission of nitrogen oxide. Fluidic flame holding also provides for enhanced performance in terms of flame-holder drag and dynamic control of the virtual flame-holder size to allow optimization at different operating conditions.

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