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Technical Notes

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Characteristics of Cavity-Stabilized Flames in a Supersonic Flow

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I. Introduction

TWO characteristics of flames that are stabilized in a directly fueled rectangular cavity are reported in this Note. They are 1) the flame location within the cavity at different fueling rates and 2) the qualitative effect of heat release in the cavity on flow oscillations.

Dual-mode scramjet engines require flameholders that can sustain stable combustion over a wide range of operating conditions. Wall cavities have proven to be a viable option for combined fuel injection and flameholding in such environments.[1] A stable flame in the cavity acts as an ignition source for the core flow, which is fueled separately and provides the bulk of the heat release for producing thrust in a scramjet engine. Several methods of fueling cavity-stabilized flames have been investigated.[2,3] Direct fueling of the cavity offers several advantages over passive injection schemes, and a wide range of stability has been observed for a variety of conditions.[4] Most notably, directly fueled flames have maintained stability during the ignition transient, where the flowfield evolves from purely supersonic to dual mode as a result of the combustion heat release in the core flow.[2]

The theory of flame stabilization in streams of premixed fuel and air is based on the fact that the temperature is nearly uniform in the recirculation zone and the reaction occurs in the shear layer.[5] Because the cavity volume is nonpremixed when direct fueling is used, new information pertaining to flame structure and location is needed for development of new models. It is hypothesized that the flame stabilizes in different regions of the cavity depending on strength of the recirculation zone, the local stoichiometry, and the flow pattern.

Supersonic flow over a cavity causes pressure oscillations, which result in unsteady wave patterns in the surrounding freestream. A significant amount of research has been done toward understanding the process through which the oscillations are generated and how they can be accurately modeled and abated.[6,7] A review of pertinent concepts is found in Ref. 8. Recently, interest in the unsteady shear layer has resurfaced because of its role in enhancing mass exchange between a supersonic freestream and a cavity flameholder. Heller and Bliss outline the process by which fluid is exchanged as a result of these oscillations in a high-speed, nonreacting flow[7]; however, numerical simulations suggest that heat release in the cavity will affect the strength of the oscillations.[9,10] Other studies have shown that the injection of fluid into the cavity can have the effect of suppressing oscillations.[11,12]

Experiments reported here were performed at Wright–Patterson Air Force Base (U.S. Air Force Research Laboratory). Detailed information on the test rig can be obtained from Ref. 13. The cavity used was the same as the rectangular geometry reported in the previous blowout research in Ref. 4. The cavity geometry is defined by $L/D = 4$, where the depth D was 16.5 mm, the length L was 66.0 mm, and the width W of the test section was 152 mm. Two sets of injectors were used. The wall injectors consist of 10, 1.6-mm-diam injectors spaced 1.3 cm apart on the aft wall of the cavity. They are located 5.1 mm above the cavity floor and direct the fuel upstream, in a direction opposite that of the core flow. The four floor injectors are 2.3 mm in diameter and spaced 2.5 cm apart. They inject fuel from the bottom of the cavity upward toward the shear layer and are located 5.1 mm downstream of the cavity leading edge. A pulsed xenon light source, with 20-ns broadband light pulses, was used to illuminate the flow for acquiring instantaneous shadowgraph images. A Kodak ES 4.0 digital camera was used to capture both the shadowgraph and chemiluminescence images. The freestream Mach number was 2 for all conditions with a total pressure of 5.44 atm and a total temperature of 590 K. The characteristic air mass flow rate, which is defined as $m_A^* = \rho_A U_A L W$, was 5.4 kg/s. Chemiluminescence images were captured over a 1-ms exposure time.

II. Results and Discussion

A. Flame Location

Chemiluminescence emissions from the flame were measured to identify where the flame is located within the cavity. Images were obtained for a variety of local fuel–air mixtures by varying the fuel flow rate between the lean blowout (LBO) and rich blowout (RBO) limits. For the given freestream conditions and cavity geometry, Rasmussen et al.[4] report that LBO occurred at a mean fuel flow rate of 0.6 g/s with both injection schemes, whereas RBO took place at a mean fuel flow rate of 5.2 g/s with wall injection and at $m_f > 5.8$ g/s with floor injection. The freestream flows from left to right in Figs. 1–3, shown by the arrow marked U_0 in Fig. 1a. White lines denote the outline of the cavity, which is on the bottom wall of the duct, and arrows show the location of fuel injection.

A flame was located in the shear layer at moderate fueling conditions for both injection schemes. Figure 1 shows representative images of the flame emissions for moderate fueling cases. Wall injection is used in Fig. 1a, where $m_f = 1.6$ g/s, which falls between the LBO and RBO points.[4] Strong emissions were detected in the shear layer and the cavity volume near the point of injection. Little

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image-to-image variation was noted in the series of images collected at this condition. When floor injection was used, the most intense reaction was in the shear layer, whereas only weak emissions were collected from the cavity volume, as shown in Fig. 1b. A fuel flow rate of $m_f = 1.9$ g/s resulted in a stable flame between the LBO and RBO limits for this condition. More variation in the emissions pattern between images was observed with floor injection than with wall injection.

At the extremes of flame stability, near the rich and lean limits, the location and appearance of the flame was significantly different than for the moderate fueling rates of Fig. 1. Near the lean limit, the flame migrated into the cavity volume on the same side of the cavity where fuel was being injected. Figures 2a and 2b show images from this case for wall and floor injection schemes, where the fuel flow rates were $m_f = 0.8$ g/s and $m_f = 0.6$ g/s, respectively. When wall injectors were used, sudden changes in the appearance and location of the flame were observed near LBO. In the majority of the images recorded at this condition, the flame was located in the downstream-half of the cavity volume and shear layer, away from the aft wall, as shown in Fig. 2a. The flame resembled that of Fig. 1a in the rest of the images, where it extended farther upstream in the shear layer and a distinct reaction zone was apparent along the floor of the cavity. These two distinct flame structures were also apparent in video recordings. The unsteadiness evidenced by these sudden changes in flame appearance near the lean limit suggests that two different flameholding mechanisms are competing. Detailed investigation of the reacting flowfield may give insight into this phenomenon.

A representative image for the near LBO flame with floor injection is shown in Fig. 2b. Arrows indicate the direction and location of fuel injection. Reaction was occurring in the shear layer and throughout the upstream portion of the cavity. The emissions pattern in this case is similar in character to that of Fig. 1b, but the length of the flame in the shear layer is shorter. Fluctuations in the length of the reaction zone in the shear layer were observed, but the general emissions pattern did not vary drastically between images.

Some changes in the location and shape of the reaction also occurred for the near RBO fueling condition. A fueling rate of $m_f = 4.7$ g/s was used with both wall and floor injection schemes for the near rich condition. Figure 2c shows a typical image near RBO when the wall injection scheme was used. The flame has receded toward the aft wall of the cavity and curves into the cavity volume. In contrast, the flame fueled by floor injectors extends across the entire shear layer and down into the cavity, as shown in Fig. 2d.

In general, these results indicate that the location of the flame is highly dependent on the fuel flow rate into the cavity. At near LBO conditions, more reaction is apparent in the volume of the cavity. This indicates that air, fuel, and products are all present somewhere within the cavity. A better understanding of how the flowfield associated with the flameholding recirculation zone changes with heat release and direct injection would give greater insight into the stabilization mechanism. Furthermore, because flame emissions measurements average over the depth of field, planar measurements are desirable inasmuch as they allow discernment of the three-dimensional structure in the scalar field and its relation to the flowfield.

Previous work indicated that flames were hard to blow out at the rich limit when floor injection is used because fuel is directed from the cavity floor toward the shear layer.[4] Because the flame is primarily in the shear layer, plenty of air is available for combustion. In contrast, when the wall injection scheme is used, fuel is directed into the cavity volume, and RBO can be easily achieved. As the fuel flow rate is increased toward RBO, the flame moves into the downstream portion of the shear layer and cavity. It is likely that the upstream volume of the cavity can no longer act as a flameholder due to the abundance of unburned fuel. Therefore, the flame is forced to move to a different region of the cavity, where a steady ignition source and appropriate fuel–air mixture can be found.

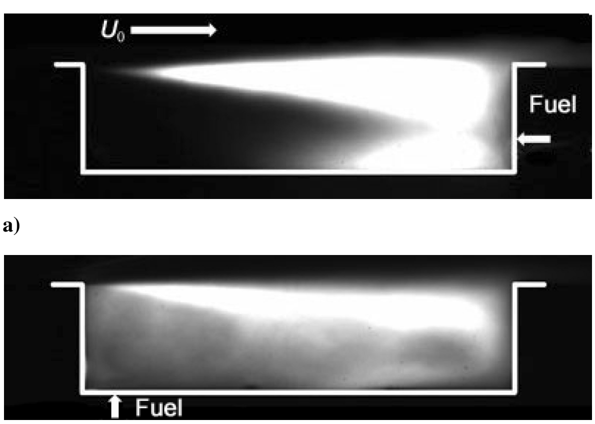

Fig. 1 Moderate fueling case, reaction anchored in shear layer for both a) wall and b) floor injection methods.

B. Pressure Oscillations in the Cavity

Instantaneous shadowgraph images were obtained for Mach 2 flow over the cavity flameholder with and without reaction. Figure 3a shows a representative image of the complex wave pattern above the cavity in a nonreacting flow. The curvature of the shock emanating from the leading edge of the cavity exemplifies its unsteady nature. A number of other waves, including a strong shock near the downstream edge and weaker compressions in the freestream, are visible above the cavity and are similar to those discussed by other researchers.[7,14,15] These waves are evidence that pressure oscillations are occurring.

To examine the extent of the spatial variation due to the oscillations, the standard deviation of 79 shadowgraph images was computed and is shown in Fig. 3b. Brighter regions have a relatively higher degree of variation than the darker regions. The standard deviation of the background is greater than zero because of the pulse-to-pulse intensity variation of the light source. The unsteadiness

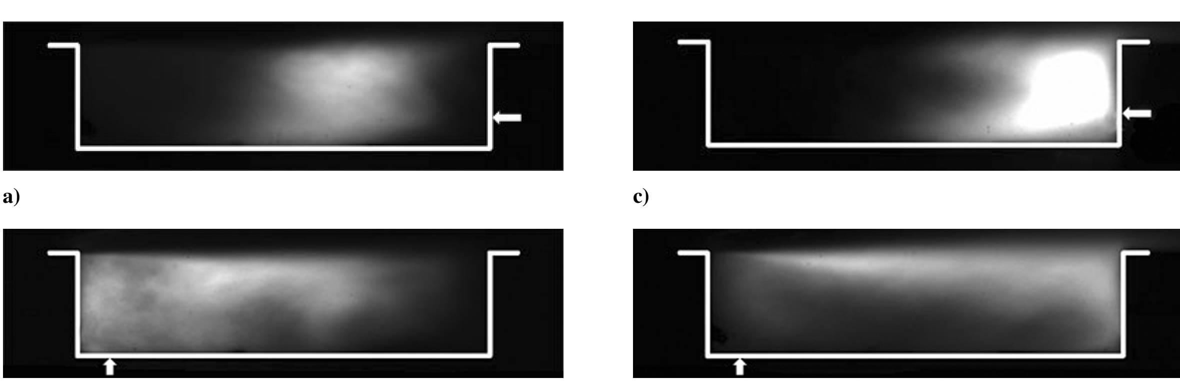

Fig. 2 Near lean blowout, reaction zone moves into cavity volume for both a) wall injection b) and floor injection; at high fueling rates approaching RBO, wall fueled flame c) moves to rear of cavity and floor fueled flame d) extends to length of cavity.

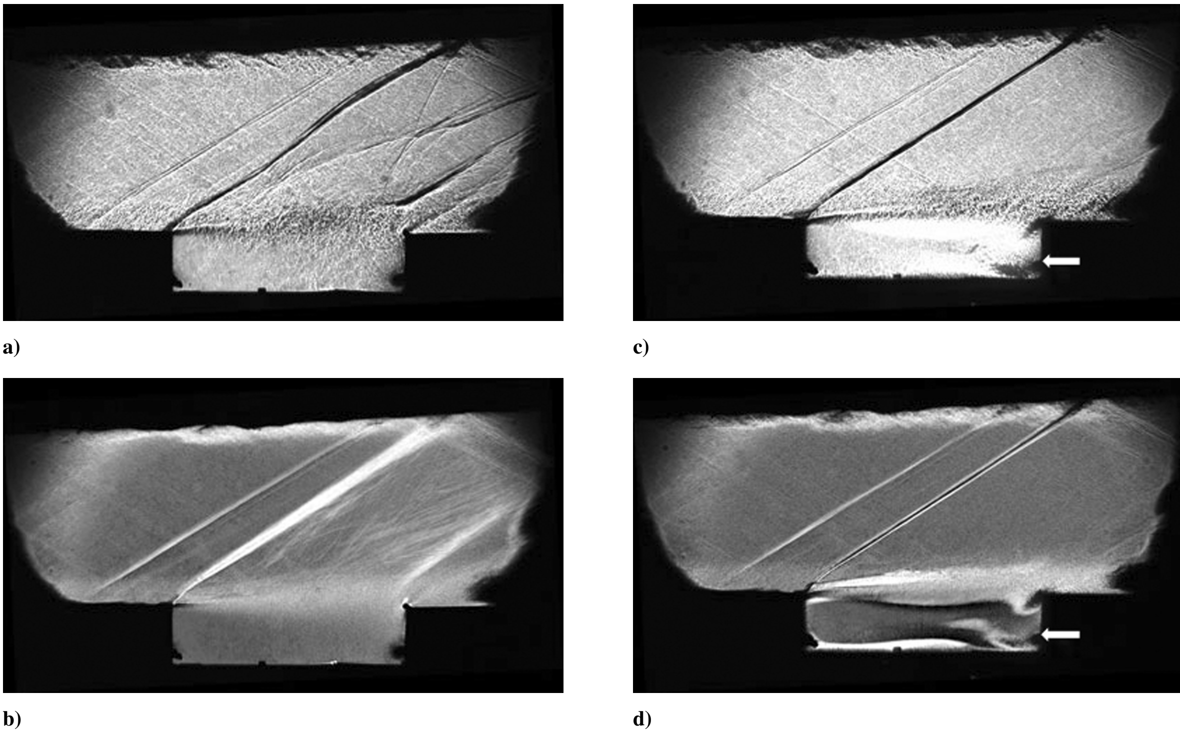

Fig. 3 Unsteady oscillations in nonreacting flow over cavity: a) an instantaneous image, and b) the standard deviation of a series of images; with reaction in the cavity, c) instantaneous image and d) standard deviation do not show marked unsteadiness.

of the weak compressions over the cavity is apparent in the standard deviation. Some image-to-image variation in the position of the strong disturbances is also evidenced by Fig. 3b because regions of high standard deviation exist where the shock emanates from the leading edge of the cavity and at the point of shear layer reattachment.

In contrast to the nonreacting flow case, an instantaneous shadowgraph image of the flow with reaction occurring in the cavity looks steady, as shown in Fig. 3c. In Figs. 3c and 3d, location and direction of fuel injection are marked with an arrow. A flame was stabilized in the cavity by injecting ethylene through the wall injectors at a flow rate of $m_f = 1.7$ g/s. This is a comparable situation to that shown in Fig. 1a. The standard deviation of a series of images for the reacting case is shown in Fig. 3d and indicates that the central portion of the leading-edge shock wave is steady because the standard deviation is very low at that location. Weak compression waves over the cavity and at the point of shear layer reattachment, which are apparent in Figs. 3a and 3b, were not observed with a flame present. Thus, combustion in the cavity suppresses large-amplitude pressure oscillations. Nonuniform heating of the quartz windows produced the unusual wavy patterns in the cavity in Fig. 3d.

The fact that combined direct injection and heat release steady the flowfield over a cavity is not surprising because they both act to raise the shear layer above the downstream edge of the cavity. As a result, the impingement of the shear layer does not occur or is not sufficiently strong to create pressure oscillations. This has been predicted by numerical simulations,[9] but never clearly demonstrated for this geometry.

Confirmation that heat release at moderate fueling conditions, that is, significantly greater than the LBO condition, leads to a steady flowfield, suggests that simple, first-order models of mass exchange may be appropriate. Contributions of shear layer oscillations of mass exchange between the cavity and the core flow may no longer need consideration when sufficient heat release is taking place in the cavity. Further research is needed to identify the range of heat release required to steady the flow for cavities of varying L/D. Oscillations mays still play a role in LBO because some unsteadiness was captured in the flame emissions patterns near LBO with both wall and floor injection.

III. Conclusions

Several results from this study are pertinent to modeling of directly fueled, cavity-based flameholders for scramjet engines.

1) Stable flames occupy different positions within a directly fueled cavity. Location of the flame has been shown to vary as the mass flow rate of fuel and the location of the fuel injectors are varied.

2) For moderate rates of fueling, between the LBO and RBO limits, the reaction primarily occurs in the shear layer for both injection schemes. Near LBO, the flame moves into the cavity volume near the point of injection. When the ramp injection scheme is used, the flame moves into the downstream portion of the cavity as the fuel flow rate approaches the RBO condition.

3) Heat release can suppress pressure oscillations in the flowfield surrounding a cavity flameholder. The relation to cavity L/D and the amount of heat release required to dampen the instability has not yet been determined.

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References

[1]Mathur, T., Gruber, M., Jackson, K., Donbar, J., Donaldson, W., Jackson, T., and Billig, F., "Supersonic Combustion Experiments with a Cavity-Based Fuel Injector," *Journal of Propulsion and Power*, Vol. 17, No. 6, 2001, pp. 1305–1312.

[2]Gruber, M. R., Donbar, J. M., Carter, C. D., and Hsu, K.-Y., "Mixing and Combustion Studies Using Cavity-Based Flameholders in Supersonic Flow," *Journal of Propulsion and Power*, Vol. 20, No. 5, 2004, pp. 769–778.

[3]Hsu, K.-Y., Carter, C., Crafton, J., Gruber, M., Donbar, J., Mathur, T., Schommer, D., and Terry, W., "Fuel Distribution About a Cavity Flameholder in Supersonic Flow," AIAA Paper 2000-3585, 2000.

[4]Rasmussen, C. C., Driscoll, J. F., Hsu, K.-Y., Donbar, J. M., Gruber, M. R., and Carter, C. D., "Stability Limits of Cavity-Stabilized Flames in Supersonic Flow," *Proceedings of the Combustion Institute*, Pittsburgh, PA, Vol. 30, 2005, pp. 2825–2833.

[5]Zukoski, E. E., and Marble, F. E., "Experiments Concerning the Mechanism of Flame Blowoff From Bluff Bodies," *Proceedings of the Gas Dynamics Symposium on Aerothermochemistry*, North Western Univ., Evanston, IL, 1956, pp. 205–210.

[6]Rossiter, J. E., "Wind Tunnel Experiment on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds," Aeronautical Research Council, Technical Rept. R&M 3438, Franborough, Hampshire, Oct. 1964.

[7]Heller, H. H., and Bliss, D. B., "The Physical Mechanism of Flow-Induced Pressure Fluctuations in Cavities and Concepts for Their Suppression," AIAA Paper 75-491, March 1975.

[8]Rockwell, D., and Naudascher, E., "Review-Self-Sustaining Oscillations of Flow Past Cavities," *Journal of Fluids Engineering*, Vol. 100, June 1978, pp. 152–165.

[9]Davis, D. L., and Bowersox, R. D. W., "Computational Fluid Dynamics Analysis of Cavity Flame Holders for ScramJets," AIAA Paper 97-3270, July 1997.

[10]Don, W.-S., Gottlieb, D., and Jung, J.-H., "A Multidomain Spectral Method for Supersonic Reactive Flows," *Journal of Computational Physics*, Vol. 192, 2003, pp. 325–354.

[11]Sarohia, V., and Massier, P. F., "Control of Cavity Noise," *Journal of Aircraft*, Vol. 14, No. 9, Nov. 1977, pp. 833–837.

[12]Sarno, R. L., and Franke, M. E., "Suppression of Flow–Induced Pressure Oscillations in Cavities," *Journal of Aircraft*, Vol. 31, No. 1, 1994, pp. 90–96.

[13]Gruber, M. R., and Nejad, A. S., "New Supersonic Combustion Research Facility," *Journal of Propulsion and Power*, Vol. 11, No. 5, 1995, pp. 1080–1083.

[14]Heller, H., and Delfs, J., "Cavity Pressure Oscillations: The Generating Mechanism Visualized," *Journal of Sound and Vibration*, Vol. 196, No. 2, 1996, pp. 248–252.

[15]Zhang, X., and Rona, A., "An Observation of Pressure Waves Around a Shallow Cavity," *Journal of Sound and Vibration*, Vol. 214, No. 4, 1998, pp. 771–778.