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Cavity Flame-Holders for Ignition and Flame Stabilization in Scramjets: An Overview

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This paper describes ongoing research efforts in the scramjet community on cavity flame holders, a concept for flame holding and stabilization in supersonic combustors. During the last few years, cavities have gained the attention of the scramjet community as a promising flame-holding device, owing to results obtained in flight tests and to feasibility demonstrations in laboratory-scale supersonic combustors. However, comprehensive studies are needed to determine the optimal configuration that will yield the most effective flame-holding capability with minimum losses. The flowfield characteristics of cavities and research efforts related to cavities employed in low- and high-speed flows are summarized. Open questions impacting the effectiveness of the cavities as flame holders in supersonic combustors are discussed.

I. Introduction

SUPERSONIC airbreathing engines are key components of future high-speed transportation vehicles. At flight speeds beyond Mach 6, air entering the combustor must be supersonic to avoid excessive dissociation of both nitrogen and oxygen gases. Consequently, the time available for fuel injection, fuel–air mixing, and combustion is very short, of the order of 1 ms.

Different injection strategies have been proposed[1–7] with particular concern for rapid near-field mixing. These injection strategies, both flush-mounted injectors and intrusive injectors, typically rely on the generation of strong streamwise counter-rotating vortices. As a result, mixing is enhanced both in macroscale by entrainment of large quantities of air into the fuel and in microscale due to stretching of the fuel–air interface. Stretching increases the interfacial area and simultaneously steepens the local concentration gradients thereby enhancing the diffusive micromixing. Microscale mixing is required for combustion because chemical reactions occur at the molecular level. However, efficient mixing of fuel and air does not directly initiate the combustion process.

Ignition and flame holding[8–11] are two other important factors that have to be addressed in the design of an injection system. Once ignition is established, the efficiency of combustion depends directly on the efficiency of the mixing. For self-ignition (and, therefore, combustion) to be accomplished in a flowing combustible mixture, it is necessary that four quantities have suitable values: static temperature, static pressure, fuel–air mixture, and residence time at these conditions. The ignition is considered accomplished when sufficient free radicals are formed to initiate the reaction system, even though no appreciable heat has yet been released. When the conditions of spontaneous ignition exist, the distance l_i at which it occurs in a medium flowing at a velocity U is: $l_i = U\tau_i$, where τ_i is the ignition delay time. As the combustor velocity U becomes larger, ignition requires longer distances. The primary objective of a flame holder in supersonic combustion, therefore, is to reduce the ignition delay time and to provide a continuous source of radicals for the chemical reaction to be established in the shortest distance possible.

In general, flame holding is achieved by three techniques: 1) organization of a recirculation area where the fuel and air can be mixed partially at low velocities, 2) interaction of a shock wave with partially or fully mixed fuel and oxidizer, and 3) formation of coherent structures containing unmixed fuel and air, wherein a diffusion flame occurs as the gases are convected downstream.

These three stabilization techniques can be applied in a supersonic combustor in different ways. One of the simplest approaches is the transverse (normal) injection of fuel from a wall orifice (see Fig. 1a). As the fuel jet interacts with the supersonic crossflow, a bow shock is produced. As a result, the upstream wall boundary layer separates, providing a region where the boundary layer and jet fluids mix subsonically upstream of the jet exit. This region is important in transverse injection flowfields because of its flame-holding capability in combusting situations, as has been shown in previous publications.[10–12] However, this injection configuration has stagnation pressure losses due to the strong three-dimensional bow-shock formed by the normal jet penetration, particularly at high flight velocities.

Another way of achieving flame stabilization is by means of a step,[13,14] followed by transverse injection (see Fig. 1b). The step creates a larger recirculation area with the hot gases serving as a continuous ignition source. This approach can provide sustained combustion but, like the previously described method, has the disadvantage of stagnation pressure losses and increase in drag due to the low flow pressure base behind the step.

On the other hand, it is possible to reduce the pressure losses associated with the injection process by performing angled injection (e.g., 60 or 30 deg rather than 90 deg) so that the resulting bow shock is weaker (see Fig. 1c). In this approach, jet axial momentum can also contribute to the net engine thrust. Riggens et al.[5] studied the thrust potential of a supersonic combustor at Mach 13.5 and Mach 17 flight conditions with 30-deg flush wall injection of hydrogen and concluded that the major component of thrust potential gain is due to the jet momentum. In previous work,[11,12] autoignition of a hydrogen jet transversely injected into Mach 10–13 flight enthalpy flow conditions was observed in the upstream recirculation region of the jet and behind the bow shock. However, different experiments[15] performed for similar geometry but at much lower total-enthalpy flow conditions showed that ignition occurred only far downstream of the jet. Based on those observations, angled injection is likely to reduce or eliminate these forms of autoignition and stabilization especially at flight speeds lower than Mach 10. Therefore, it is likely that a new technique will be required to obtain autoignition and downstream combustion stabilization.

In recent years, cavity flame holders, an integrated fuel injection/flame-holding approach, have been proposed as a new concept for flame holding and stabilization in supersonic combustors.[2] Cavity flame holders, designed by the Central Institution of Aviation Motors (CIAM) in Moscow, were used for the first time in a joint

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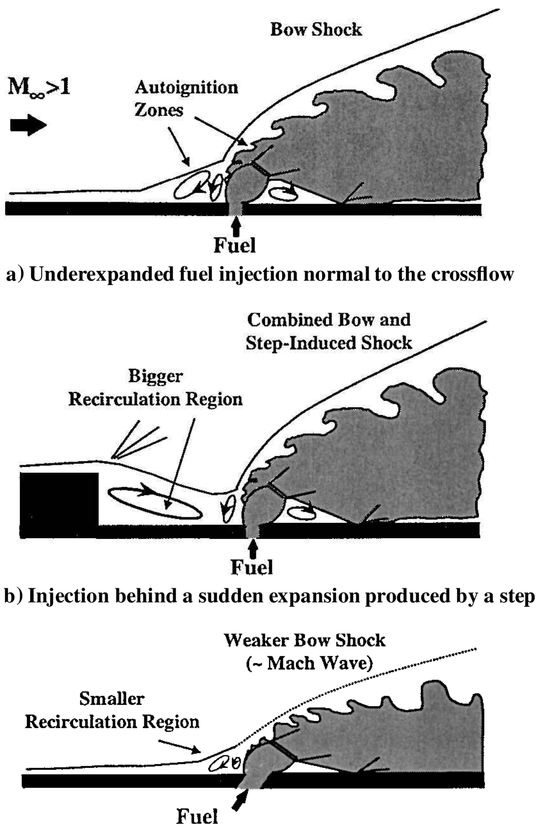
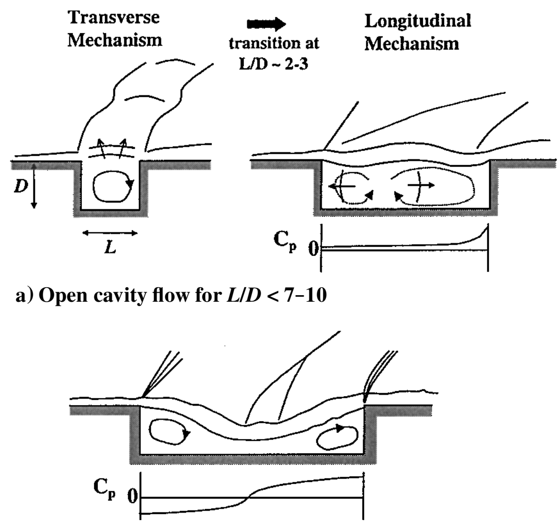


a) Underexpanded fuel injection normal to the crossflow

b) Injection behind a sudden expansion produced by a step

c) Fuel injection at angle

Fig. 1 Flowfield schematics of traditional injection/flame-holding schemes for supersonic combustors.



a) Open cavity flow for $L/D < 7$–10

b) Closed cavity flow for $L/D > 10$–13

Fig. 2 Flowfield schematics of cavities with different L/D in a supersonic flow.

Russian/French dual-mode scramjet flight test (hydrogen fueled).[16] Further experiments[17–19] showed that the use of a cavity after the ramp injector significantly improved the hydrocarbon combustion efficiency in a supersonic flow. Similar flame stabilization zones, investigated by Ben-Yakar et al.,[20] have been employed within a solid-fuel supersonic combustor, demonstrating self-ignition and sustained combustion of PMMA (Plexiglas®) under supersonic flow conditions.

In November 1994, NASA contracted CIAM[21,22] to continue exploring the scramjet operating envelope from dual-mode operation below Mach 6 to the full supersonic combustion mode at Mach 6.5. The proposed combustor design also included two cavity flame holders (20 mm in depth × 40 mm in axial length and 30 × 53 mm). The performance predictions obtained by analytical solutions indicated that these cavities would be quite effective as autoignition and flame-holding devices. Indeed, the recent flight test of this combustor has been successfully completed, encouraging further investigation of cavity flame holders.

Note that, although there is recent interest in cavity flame holders for supersonic combustors, their application in subsonic combustors dates back to the 1950s. Probably, the first published investigation of cavity flame holders is due to Huellmantel et al.,[23] who studied various shapes of cavities to sustain combustion in low-speed propane–air flames.

The main purpose of the present paper is to summarize relevant known characteristics of cavities in supersonic flows and research efforts related particularly to cavities employed in low- and high-speed combustors.

II. Review of Previous Research

A. Cavity Flowfield Characteristics

Supersonic flow over cavities has been extensively studied for many years because of their relevance to aerodynamic configurations.[24–35] A cavity, exposed to a flow, experiences self-sustained oscillations, which can induce fluctuating pressures, densities, and velocities in and around the cavity, resulting in drag penalties. This problem motivated many experimental and computational studies, which have been directed toward improving the understanding of the physics of cavity flows and the means to control their nature.

Cavity Flow Regimes

In general, cavity flow can be categorized into two basic flow regimes depending primarily on the length-to-depth ratio, L/D (see Fig. 2). In all cases, a shear layer separates from the upstream lip and reattaches downstream. For $L/D < 7$–10, the cavity flow is termed "open" because the upper shear layer reattaches to the back face. Small aspect ratio cavities ($L/D < 2$–3) are controlled by transverse oscillation mechanism, whereas in larger aspect ratio cavities, longitudinal oscillation becomes the dominant machanism. The high pressure at the rear face as a result of the shear layer impingement, increases the drag of the cavity. For $L/D > 10$–13 the cavity flow is termed "closed" because the free shear layer reattaches to the lower wall. The pressure increase in the back wall vicinity and the pressure decrease in the front wall results in large drag losses (see Fig. 2b). The critical length-to-depth ratio, at which a transition between different cavity flow regimes occurs, depends also on the boundary-layer thickness at the leading edge of the cavity, the flow Mach number, and the cavity width.

Cavity Oscillations

The cavity pressure fluctuations consist of both broadband small-amplitude pressure fluctuations typical of turbulent shear layers as well as discrete resonances whose frequency, amplitude, and harmonic properties depend on the cavity geometry and external flow conditions.

Experimental results reviewed by Zhang and Edwards[25] found open cavities to be dominated either by longitudinal or transverse pressure oscillations (Fig. 2a) depending on L/D and the Mach number M_∞. In the short cavity filled by a single large vortex, the oscillation is controlled by a transverse mechanism, whereas in the long cavity filled by vortices, the oscillation is controlled by a longitudinal mechanism. The transition from transverse oscillation to longitudinal oscillation has been found to occur near $L/D = 2$ at Mach 1.5 and between $L/D = 2$ and 3 at Mach 2.5.

There are currently two primary models used to explain the longitudinal cavity oscillation process (Fig. 3). The unsteady motion of the shear layer above the cavity is the paramount mechanism for cavity oscillations and results in mass addition and removal at the cavity trailing edge (rear wall). The shear layer impinging on the rear wall causes freestream flow to enter the cavity. As a result of the impingement, the cavity pressure increases and creates an acoustic

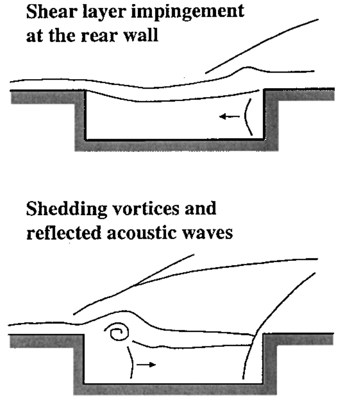


Fig. 3 Typical longitudinal cavity oscillations caused by the impingement of the free shear layer on the rear wall, which generates traveling shocks inside the cavity.

wave (compression wave), which propagates upstream at the local sound speed and impacts the front wall. The first model proposes that this acoustic wave induces small vortices at the leading edge of the front wall, which grow as they are convected downstream. Because of the instabilities, the shear layer deflects upward and downward resulting in a shock/impingement event on the rear wall of the cavity. The second model, on the other hand, assumes that the acoustic wave reflection from the front wall, rather than the shedding vortices, is the cause of the shear layer deflection and, therefore, the impingement event on the rear wall. The oscillation loop is closed when the instability (caused either by vortex shedding or a reflected acoustic wave) propagates downstream and the mass added in the beginning of the loop is ejected at the trailing edge again.

Typically, the frequency of the longitudinal oscillations is expressed in terms of the Strouhal number based on the cavity length (impingement length L):

$$Sr_L = f_m L / U_\infty$$

Multiple peaks of comparable strength in unsteady pressure spectra were observed in compressible flow-induced cavity oscillations. These resonant frequencies can be predicted using Rossiter's semi-empirical formula,[26] developed based on the coupling between the acoustic radiation and the vortex shedding (model 1):

$$f_m = \frac{m - \alpha}{M_\infty + 1/k} \cdot \frac{U_\infty}{L}$$

L is the cavity length; M_∞ and U_∞ are the freestream Mach number and flow speed, respectively; f_m is the resonant frequency corresponding to the mth mode; and α and k are empirical constants. Whereas k is the ratio of the speed of the convection of the shear layer vortices to the freestream flow speed U_∞, α is the phase shift between the acoustic waves and the shear layer instability. This equation was modified by Heller and Bliss[27] for compressible flows by taking into account the effect of the higher sound speed within the cavity, which is approximately equal to the freestream stagnation sound speed. Their model assumes that the pressure fluctuations are a result of the interaction of the shear layer with the reflected acoustic waves (model 2):

$$f_m = \frac{m - \alpha}{\left\{M_\infty \big/ \sqrt{1 + [(\gamma_\infty - 1)/2]M_\infty^2} + 1/k\right\}} \cdot \frac{U_\infty}{L}$$

where γ_∞ is the ratio of specific heats. Heller and Delfs[28] determined from their experiments that $\alpha = 0.25$ and $k = 0.57$ for cavities with $L/D = 4$ or more, and estimated the difference between the formula and experiments as $\pm 10\%$.

Therefore, the oscillatory frequency of a particular mode in a shallow cavity decreases with increasing length or L/D of the cavity.

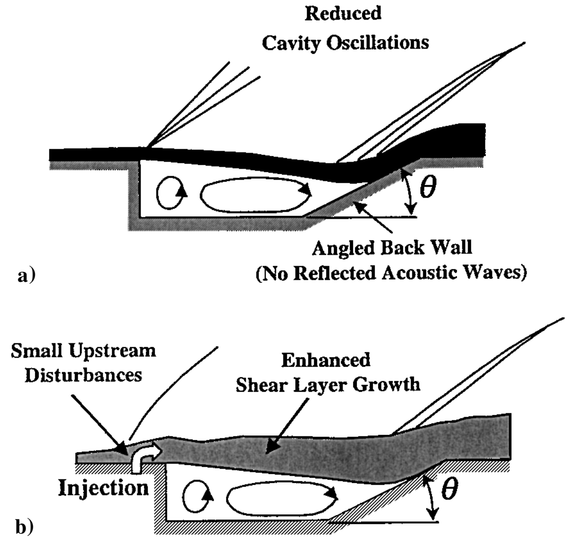


Fig. 4 Concepts to suppress the cavity oscillations: a) angled back wall to suppress unsteady nature of the free shear layer by eliminating the generation of the traveling shocks inside the cavity due to the free shear layer impingement and b) small disturbances produced by spoilers or by the secondary jet injection upstream of the cavity to enhance free shear layer growth rate.

However, the dominant oscillatory mode (the mode with the largest amplitude) jumps from a lower mode to a higher mode as the L/D increases.

Stabilization Techniques for Cavity Oscillations

Several passive[31,32] and active[33–35] control methods have been proposed and developed to suppress the cavity oscillations (Fig. 4). Because the shear layer interaction with the rear cavity wall is the main factor for fluctuations as already discussed, the stabilization or control of the shear layer can ultimately suppress the cavity oscillations. Passive control methods, which are usually inexpensive and simple, utilize mounted devices such as vortex generators and spoilers upstream of the cavity or a slanted trailing edge that modifies the shear layer so that the reattachment process does not reflect pressure waves into the cavity. These methods are found to be very effective in suppressing the cavity oscillations. However, because these devices are permanent features, the performance of a cavity at different conditions may actually be worse than the performance of a cavity without passive control.

A visual observation of a cavity flowfield stabilized by an oblique rear wall can be found in Fig. 5. Figure 5 contains two instantaneous schlieren images from our recent experimental efforts[12] demonstrating the stabilizing effect of a slanted back wall on the shear layer reattachment. The freestream was generated in an expansion tube to simulate Mach 10 total enthalpy conditions at the supersonic combustor entry: $M_\infty = 3.5$, $U_\infty = 2420$ m/s, $T_\infty = 1300$ K, and $P_\infty = 32$ kPa. The boundary-layer thickness at the trailing edge of the cavity is approximately 1 mm. In the open cavity with a 90-deg back wall (Fig. 5a) the flow generates shock waves at the cavity trailing edge. As the shear layer reattachment point oscillates about the sharp corner, periodic acoustic waves propagate inside the cavity accompanied with some mass exchange at the cavity trailing edge. The angled back wall shown in Fig. 5b, on the other hand, leads to a steady shear-layer reattachment process.

Active control methods, on the other hand, can continuously change to adapt to different flow conditions. Forcing of the shear layer can be accomplished by various mechanical, acoustical, or fluid injection methods. The use of steady or pulsating mass injection upstream or at the leading edge of the cavity is one of the most commonly studied techniques. Various researchers[33–35] have examined the feasibility of this technique. Vakili and Gauthier[34] observed significant attenuation of cavity oscillations with upstream mass injection. This was attributed to the thickening of the cavity

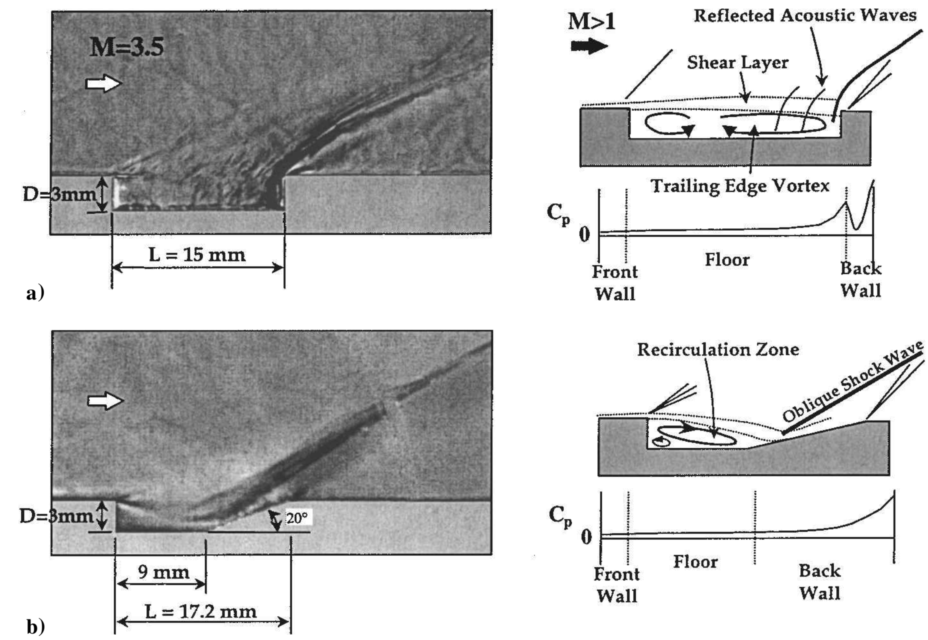


Fig. 5 Instantaneous schlieren images 200-ns exposure time (provided by Ben-Yakar and Hanson, Stanford University[12]) demonstrates effect of the back wall angle to the flowfield structure of a cavity exposed to a supersonic flow: a) cavity with *L/D* = 5 shows unsteady nature of the shear layer at the reattachment with the trailing edge of the back wall and b) cavity with slanted back wall (20-deg) stabilizes the shear layer reattachment process.

shear layer, which altered its instability characteristics, such that its preferred rollup frequency was shifted outside of the natural frequencies of the cavity.

Cavity Drag

Two components produce pressure drag in the cavity. First, the pressure in the backward facing step may be lower than the freestream pressure. This results in a net force in the positive x direction (drag force) acting on the base area (base pressure higher than freestream would result in a thrust force). Second, the reattachment of the shear layer at the back wall produces a region of high pressure that imparts a force in the positive x direction acting on the forward facing area.

In Fig. 6, the magnitude of pressure fluctuations on the floor of the cavity and the drag coefficient for different L/D are given, as adapted from Zhang and Edwards.[25] Their experimental results demonstrate a sharp rise of the oscillatory level and the drag when the oscillatory mode inside the cavity changes from a transverse mode to a longitudinal one. The magnitude of the fluctuations decreases gradually with the increasing L/D of the cavity, while the average drag coefficient, however, rises significantly. As the L/D of the cavity increases, the shear layer thickens at the reattachment point damping the oscillations and simultaneously increasing the pressure on the back wall of the cavity. Subsequently, the time-mean pressure on the upstream wall of the cavity drops as a result of the momentum diffusion across the shear layer. These combined effects of increasing pressure in the back wall of the cavity and decreasing pressure in the upstream wall of the cavity, increase the drag of the cavity. The drag penalties become larger as the cavity L/D ratio reaches a critical value at which the closed cavity flowfield is established.

The drag coefficient of an open cavity is affected greatly by the cavity back wall geometry. Gruber et al.[36] studied the drag penalties of open cavities with $\theta = 16$ and 30 deg angled back wall, where θ is defined as the angle relative to the horizontal wall (Fig. 4). They concluded that the drag coefficient increases for shallower back wall angles. First, the small back wall angles lead to the formation of an expansion wave (rather than a compression wave) at the cavity leading edge that reduces the pressure on the backward facing step adding drag. Second, the shear layer deflects farther into the cavity, which results in a larger area of recompression on the angled back wall, again increasing the drag.

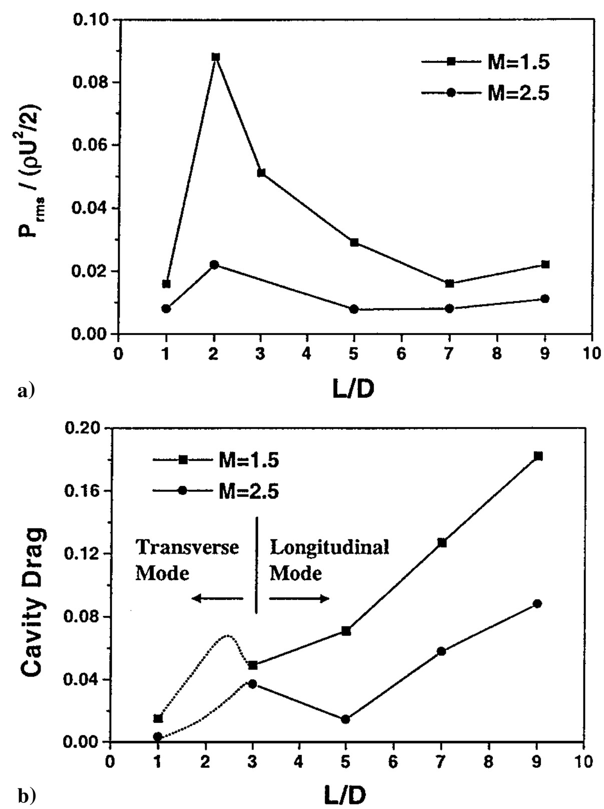


Fig. 6 Effect of *L/D* on a) magnitude (root mean square) of pressure fluctuations on the bottom of the cavity (at *x/D* = 0.33) and b) drag of the cavity at Mach 1.5 and 2.5 flows.[25]

In contrast to Gruber et al.[36] findings, numerical calculations of Zhang et al.[32] resulted in a reduced average drag coefficient as the back wall angle is decreased from $\theta = 90$ to 67.5 and 45 deg. The observations from these two references agree, however, that the pressure on the upstream face of the cavity decreases with decreasing back wall angle. It is possible that, in the 67.5- and 45-deg cases studied by Zhang et al.,[32] the compressive nature of the separation wave at the upstream corner of the cavity actually keeps the shear layer from deflecting into the cavity and could result in lower levels of pressure drag than the 16-deg case that Gruber et al.[36] studied. In a different study, Samimy et al.[37] used a cavity with a 20 deg of back wall angle to create an undisturbed free shear layer. This geometry was chosen such that the wall pressure across the cavity would stay unchanged, thereby minimizing the drag losses associated with the shear layer deflection inside the cavity. These observations suggest that there might be a critical back wall angle (between $\theta = 45$ and 16 deg) at which the drag penalties of a cavity are minimal.

A qualitative description of the pressure distribution along the back wall surface of cavities with and without an angled wall is plotted in Fig. 5 (Refs. 32 and 36). In a rectangular cavity, below the shear layer reattachment point, the trailing edge vortex accelerates the flow and causes a pressure decrease in the middle of the back wall. On the other hand, in the cavity with the angled wall, the high pressure at the corner of the cavity disappears, and a monotonic increase of pressure takes place behind the reattachment point. The drag coefficient depends strongly on the back wall pressure distribution as it is altered by the cavity geometry. Further comprehensive studies are required to complete our understanding of cavity geometry, particularly the effect of the back wall angle on the drag penalty.

Cavity Residence Time

Residence time, τ, of the flow inside a cavity is a direct function of the mass exchange rate in and out of the cavity. In the open cavities, mass and momentum transfer mechanisms are controlled by the longitudinal oscillations and the vortex structure inside the cavity. Computational visualizations of Gruber et al.[36] demonstrate the existence of one large vortex stationed near the trailing edge of the cavity and a secondary vortex near the upstream wall. The mass exchange of the cavity is controlled by the large trailing vortex, which interacts with the unstable shear layer. The mass exchange between the vortices inside the cavity, on the other hand, is relatively small, and, therefore, as the trailing edge vortex occupies larger volume inside the cavity, the mass exchange increases and flow residence time inside the cavity decreases. Consequently, the steady-state numerical calculations showed that the flow residence time in a large cavity ($L/D = 5$) is smaller than the value in a small cavity ($L/D = 3$), in contrast with expectation. Although the volume of the cavity increases (increases τ) with increasing length, the mass exchange rate increases even more (decreases τ), resulting in a decreased residence time. However, it is not yet clear how the flow residence time inside a cavity is affected by the unsteady nature of the cavity. The steady-state computations[36] mentioned earlier, estimated that 1 ms is the order of magnitude of residence time in an $L/D = 5$ cavity with 9 mm depth in a Mach 3 cold flow. This value decreases for slanted wall cavities due to increased mass exchange with the crossflow.

As already summarized, the cavity is a basic fluid dynamic configuration that generates both fundamental and practical interests. A cavity is often characterized by a strong internal oscillation driven by the shear layer instability. These oscillations may be controlled and suppressed by the stabilization of the shear layer. However, stabilizing the oscillations may reduce the effectiveness of a cavity because mass transfer (exchange) and flow residence time inside the cavity are important for flame holding.

B. Cavity in Reacting Flows

In the past few years, the use of cavities has been considered as a tool for performance improvement in a supersonic combustor. Basically there are two main directions in which several research groups have focused their efforts: 1) cavity-actuated mixing enhancement and 2) trapping a vortex within the cavity for flame-holding and stabilization of supersonic combustion. Some recently performed studies investigating these concepts are summarized in the following sections.

Cavity-Actuated Supersonic Mixing Enhancement

It is known that the growth rate of the mixing layer between supersonic air and gaseous fuel in a scramjet combustor decreases as the convective Mach number increases due to compressibility effects.[38] Researchers suggested that cavity flow oscillations can actually be used to provide enhanced mixing in supersonic shear layers. A shear layer develops instability waves in its initial region. This long wavelength Kelvin–Helmholtz (K–H) instability, which leads to large "rollers," is suppressed at high convective Mach numbers. As a method to enhance the K–H instability, Kumar et al.[39] suggested using oblique oscillating shock waves of high frequency, and Yu and Schadow[40] concluded that for the required frequency excitation, transverse acoustic waves emanating from cavities are powerful enough to affect mixing in a significant manner.

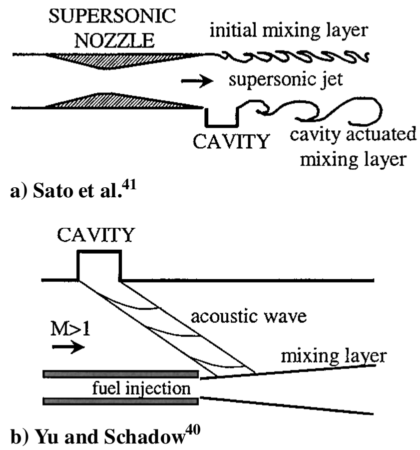


Fig. 7 Cavity-actuated supersonic mixing enhancement concepts.

Yu and Schadow,[40] therefore, suggested using cavities to enhance the mixing of supersonic nonreacting and reacting jets, where the cavity was attached at the exit of the jet circular nozzle (Fig. 7a). When the cavity was tuned for certain frequencies, large-scale highly coherent structures were produced in the shear layer substantially increasing the growth rate. The spreading rate of the initial shear layer with convective Mach number $M_c = 0.85$ increased by a factor of three, and for jets with $M_c = 1.4$ by 50%. Finally, when the cavity-actuated forcing was applied to reacting supersonic jets, 20–30% reduction in the afterburning flame length with modified intensity was observed.

Sato et al.[41] also studied the effect of an acoustic wave, emitted from a cavity and impinging on the initial mixing layer (Fig. 7b). Their results revealed that the mixing was enhanced by the acoustic disturbance and the rate of the enhancement was controlled by the cavity shape while the total pressure losses were negligibly small.

This novel use of cavity-induced oscillations in turbulent compressible shear layers to control the mixing rate encourages the use of unstable cavities in high-speed propulsion applications. However, before implementing such techniques, one must consider and evaluate the potential thrust loss and noise generation associated with the technique.

Cavity as a Flame Holder

Whereas an unstable cavity can provide enhancement in the turbulent mixing and combustion as discussed earlier, a stable cavity can be used for flame-holding applications. In an effort to reduce the combustor length required for efficient high-speed combustion, the scramjet community has proposed the use of wall cavities to stabilize and enhance supersonic combustion. The main idea is to create a recirculation region inside the cavity with a hot pool of radicals, which will reduce the induction time, such that autoignition of the fuel/air mixture can be obtained. However, for a stable combustion process, the cavity recirculation region has to be stable to provide a continuous ignition source (pilot flame). As already discussed, it is possible to control the self-sustained oscillations occurring in cavities either by proper design of the cavity or by a passive/active control system.

In the following sections, we will first discuss the literature for low speed and then the recent advances in high-speed combustors that utilize cavity flame-holders.

Cavity "trapped vortex" (TV) concept in low-speed flows. Recently, cavities have been employed in low-speed flows to stabilize combustion utilizing the so-called "trapped-vortex" (TV) concept.[42] In this concept, a stationary vortex is established inside the cavity by optimal design of the dimensions, namely, by optimal cavity length to depth ratio (L/D). It is known that a vortex will be trapped in the cavity when the stagnation point is located at the downstream end of the cavity, which also corresponds to the minimum drag configuration.[29] Based on this evidence, Hsu et al.[42] designed an experimental cavity to investigate the low-speed flame stability characteristics of a TV combustor, whereas Katta and Roquemore[43,44] performed numerical calculations for this geometry. Their results showed that a vortex is locked in a short cavity ($L/D < 1$).

However, when a vortex is trapped in the cavity, very little fluid is entrained into the cavity, resulting in very little exchange of the main flow and cavity fluid. When flame stabilization is a consideration, a continuous exchange of mass and heat between the cavity and the main flow is required. To overcome this problem, it has been suggested to inject directly both fuel and air into the cavity in a manner that reinforces the vortex and increases mass transfer of the reactive gases with the freestream.

The main conclusions revealed from low-speed cavity flameholder studies can be summarized as follows:

1) In nonreacting flows, a stable cavity flow was observed at an optimal cavity dimension ($L/D = 0.6$) that produces minimum drag, namely, minimum pressure drop. This was also the optimal cavity length that provided the most stable flame.

2) A sufficient amount of fuel and air must be injected directly into the cavity to obtain good performance characteristics of a combustor with a TV cavity.

3) The fluid injection inside the cavity had a strong impact on the stability of the vortex inside the cavity. When jets were injected in such a way that they reinforced the vortex, the flame stabilization capability of the cavity was enhanced.

4) The optimum size (L/D) for steady flow should be larger in the case of cavities with fluid injection than for cavities with no injection.

Cavity flame holders in high-speed flows. In the scramjet community, there is a growing interest in the use of cavity flame holders. In a 1997 U.S. Air Force/NASA workshop,[2] an integrated fuel injector/cavity flame holder was mentioned as one of the new concepts that may provide potential performance gain in a scramjet engine. It was indeed very encouraging to see this new concept employed and flight tested in the scramjet engine by the CIAM in Moscow.[16–19,21,22] The combustor of the axisymmetric scramjet engine, shown in Fig. 8, included three fuel injection stages, two with cavity flame holders ($D = 20$ mm by $L = 40$ mm and $D = 30$ mm by $L = 53$ mm) and one with a step flame holder ($D = 17$ mm). The injection of the fuel (hydrogen) was performed within the cavity flame holders from the front-facing wall at 30 deg to the engine axis and just upstream of the step at 45 deg. With this integrated injection/cavity flame-holder approach, numerical studies[22] showed that autoignition and flame holding within the cavity could be obtained at Mach 6.5 flight, even without the spark ignition plugs. The analysis in Ref. 22 also revealed that, without the cavity, the ignition is unlikely due to the small injector dimension ($d_j = 1.25$–2 mm) and low combustor operation pressure ($p \sim 0.4$ atm) as estimated previously by Huber et al.[10] Finally, the joint Russian/U.S. effort demonstrated in the flight test performed on 12 February 1998 that a positive thrust from the scramjet engine could be successfully achieved.[45]

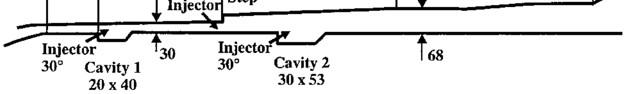


Fig. 8 Axisymmetric combustor of the flight-tested scramjet engine. In this engine two cavities with angled-rear wall were used for flame-holding purposes (dimensions in millimeters).[22]

One can find several recent studies investigating cavities for flame stabilization of a supersonic combustor. Some of these works, performed for different kinds of fuels (liquid, solid and gaseous fuels), are summarized as follows.

The combustion of kerosene in a scramjet requires additional ignition and flame-holding elements because of the long ignition times and reduced reaction rates as compared to hydrogen. Owens et al.[19] tried to determine the flame stability of kerosene injected upstream of a cavity flame holder with Mach 1.8 freestream conditions. Because of the low stagnation temperatures of 1000 K, ignition was provided by pilot hydrogen fuel injected into the cavity. Flame holding could be achieved only when large flow rates of hydrogen were used. In this case, the enlargement of the recirculation region led to entrainment of additional quantities of fresh air contributing to the flame stability. An additional investigation of scramjet combustors operating on kerosene was performed by CIAM.[17] In their configuration, the combustion was sustained by a row of hydrogen fuel injectors placed in front of a cavity.

The use of cavities as flame holders in solid fuel supersonic combustors has been also studied.[20,46] In the experiments of Ben-Yakar et al.,[20] self-ignition and sustained combustion of PMMA (Plexiglas) solid fuel with no external aid (such as reactive gas injection or a pilot flame) was demonstrated under supersonic hot-air flow conditions. This was accomplished by a recirculation region formed inside a cavity, which was positioned at the entrance of the combustor. Typically, in a subsonic solid fuel ramjet, a step is used for flame-holding purposes, and it is known that larger step heights (leading to bigger recirculation zones) can provide better flame stabilization. However, in supersonic flows where a large step is required, the freestream flow velocity would increase as well by the sudden expansion, deteriorating the flame-holding capability. Under those considerations, a cavity consisting of a step followed by an angled wall was chosen as a flame holder in the supersonic solid fuel experiments mentioned earlier. The results revealed that both the cavity length L and the step height D significantly influence combustion sustainment. Although short L caused flameout even for relatively large D, the inverse, namely, small D, did not permit sustained combustion even though L was quite long. Ultimately, cavity length-to-depth ratio between $1.7 < L/D < 2$ showed a regime of sustained combustion.

Besides the use of cavities in liquid and solid fueled supersonic combustors, there are other research groups[47–53] concentrating on characterization of cavity flame holders in gaseous supersonic combustors. Initial experimental efforts were performed by Yu et al.[47,48] They analyzed flow stability and flame-holding characteristics of several wall cavities with various sizes and aspect ratios ($L/D = 0.5$, 1, 2, and 3 and inclined cavity) in a Mach 2 airstream. Pressure oscillations, observed in cold-flow experiments, were diminished in reacting flow, when the thin shear layer above the cavity disappeared by three fuel jets injected at 45 deg upstream of the cavity. Typically, small aspect ratio ($1 < L/D < 3$) cavities appeared to be good flame holders, which is consistent with the TV concept discussed earlier. The narrow cavities ($L/D = 0.5$) provided very steady flame holding; however, they had relatively little effect on the downstream emission characteristics. With the inclined cavity, which was also the longest cavity tested ($L/D = 5$), no flame holding was observed. Additional experiments were conducted by Niioka et al.[49] in Mach 1.5 airflow. They achieved flame stabilization using two struts and by injecting hydrogen gas in the interval between the two parts. They showed that flame stability could be controlled by the cavity length, which controls the competition between the mass transfer rate and the chemical reaction rate, that is, the Damköhler number.

Wright–Patterson Air Force Research Laboratories have also initiated a program[51–53] to examine the effectiveness of cavities in supersonic flows. Experiments on a cavity with upstream ethylene fuel injection were performed in the supersonic combustor facility operating at conditions that simulate flight Mach numbers between 4 and 6. Initial results demonstrate flame holding and large flame spreading in the cavity vicinity. In parallel, Mach 3 cold-flow research is also in progress to study the fundamental aspects of cavities. The results showed the following:

1) The cavity geometry had an effect on mass entrainment rate and residence times. A decrease in cavity residence time was observed in cavities with longer length and slanted walls.

2) In general, the length of the cavity determined the mass entrainment, whereas the cavity depth determined the cavity residence time.

3) Larger cavities ($L/D = 7$) had significantly higher drag coefficients than the smaller cavities ($L/D = 3$). Reduction of the back wall angle below 90 deg resulted in additional drag penalties.

4) Cavities with offset ratios larger than 1 (upstream wall height is larger than the back wall height) caused the cavity base to experience lower pressures and, therefore, larger drag penalties.

In addition, Davis and Bowersox[52,53] used a combined computational fluid dynamics/perfectly stirred reactor methodology as a design guide for sizing of the cavity. They recommend that initial cavity size can be estimated based on the minimum residence time required to obtain ignition by assuming a perfectly stirred reactor cavity flow. Similar to Gruber et al.,[36] Davis and Bowersox[52,53] concluded that cavity depth D, which mainly controls the residence time, can be estimated using their numerically obtained empirical equation: $D = \tau_r \cdot U_\infty/40$, where τ_r is the required residence time for ignition and U_∞ is the freestream velocity.

C. Outstanding Questions

As already discussed, during the last few years, cavities have gained attention as promising flame-holding devices. However, comprehensive studies still need to be performed to determine optimal configurations that yield the most effective flame-holding capability with minimum loses.

We can pose the following questions concerning the effectiveness of the cavities as stable flame-holders in supersonic combustors.

Can the TV Concept Be Used in Supersonic Combustors?

Several investigators have recognized the aerodynamic advantages of trapping vortices inside small aspect ratio cavities ($L/D < 1$) both as a means of reducing the drag penalties of cavities and also obtaining stable flame holding in a low-speed combustor. Stable, small aspect ratio cavities may possibly be adapted to provide sustained combustion in supersonic flows. However, the cavity flow residence time associated with high-speed flows will be smaller than in low-speed flows and might eliminate its flame-holding capability. Therefore, stable cavities may possibly be adapted to provide sustained combustion in supersonic flows as long as the Damköhler number is larger than unity, namely, the residence time inside the cavity is sufficient to initiate the ignition process. For example, in the flight-tested scramjet engine designed by CIAM and NASA, fuel was injected within the cavity flame holder to provide autoignition and flame holding.[22] Otherwise, autoignition was unlikely due to the low total enthalpies of the Mach 6 flight condition, and small injector dimensions and the low combustor pressures of the design point.

What Are the Cavity Dimensions and Its Geometry?

Open cavities with $L/D < 7$–10 are good candidates for flame holding because of their reduced drag coefficients relative to the closed cavities. The dimensions of an open cavity have to be derived from ignition and flame-holding considerations. The cavity depth can be determined according to the required residence time to initiate ignition. The cavity length, on the other hand, has to be chosen to provide sufficient volume of radicals to sustain the combustion farther downstream.

Can an Unstable Cavity Be Used to Establish Flame-Holding?

Whereas a stable cavity is preferable to sustain continuous and stable combustion, an unstable cavity can be used to enhance mixing and ignition by the shock waves emitted as a result of strong cavity oscillations. However, unstable cavities are unlikely to provide a continuous flame-holding region inside the cavity, as was also shown in our preliminary ignition experiments.[12]

How Does Fuel Injection Affect the Cavity Flowfield?

Jet injection upstream or inside the cavity can alter the shear layer characteristics (its thickness and stability) directly, and therefore, the cavity performance. Raman et al.,[54] for example, have found that jet interaction with a cavity can produce different oscillation frequencies.

How Does the Cavity Flowfield Affect a Fuel Jet Injected Upstream?

Shock waves emanating from a cavity can enhance the mixing of fuel jets injected upstream of the cavity. As shown by several researchers, the acoustic waves of an unstable cavity can be used to actuate mixing. On the other hand, a stable cavity can also enhance mixing. As the jet reaches to the back wall it interacts with the strong trailing-edge shock wave of the cavity. It is known that an oblique shock wave–jet interaction enhances the molecular mixing between supersonic air and gaseous fuel by the vorticity generated due to the baroclinic torque. This might have immediate significance to the spreading rate of the jet and mixing enhancement of the fuel/air, resulting in enhanced combustion efficiency.

Is Local Wall Heating Inside the Cavity a Problem?

High total temperatures of air stagnating inside the cavity can result in excessive heat transfer to the walls. However, the transpiration technique of mass addition from a porous surface can be used as a way to cool the cavity surfaces. This method can, furthermore, decrease the skin-friction losses on the cavity floor surface and reduce the drag losses associated with the shock wave structure of the cavity.[55] Fuel mass bleeding inside the cavity can alter the shear layer bending toward the cavity by increasing the cavity pressure distribution. In this way, the strong trailing-edge reattachment shock wave can be eliminated or reduced in strength. Therefore, an optimized transpiration cooled cavity may also be designed to improve the pressure losses and the drag penalties.

At Which Flight Conditions Can a Cavity Flame Holder Be Effective?

At high flight Mach numbers, beyond Mach 8, the velocity and the total enthalpy of air entering the combustor is high. In this hypersonic flight regime, hydrogen fuel is preferred because of its reduced combustion characteristic times. Ignition of the hydrogen/air system can be purely characterized by radical runaway without the need for thermal feedback (substantiated by direct numerical analysis of Im et al.[8]). Therefore, for a hydrogen/air system, a cavity flame holder, in which the high-stagnation temperatures will initiate ignition by radical runaway, can be designed even though no appreciable heat has yet been released. As we move into lower flight speeds, below Mach 8, application of a flame holder becomes crucial. In this supersonic flight regime, the selection of a cavity flame holder is required to achieve longer flow residence times inside the cavity because of the reduced total enthalpies and longer ignition delay times associated with hydrocarbon fuels, which are the candidate fuels for supersonic flight below Mach 8. Consequently, cavities can be utilized in a wide range of flow conditions, in both supersonic and hypersonic airbreathing propulsion systems.

III. Concluding Remarks

We have provided a review of cavities in supersonic flows and their use for flame holding in supersonic combustors. On-going investigation of cavity flame holders both in laboratories and in real flight tests encourages their further investigation.

In the first part of the review, the basic flowfield features of cavities studied by various researchers are summarized, including different flow regimes of cavities based on the length-to-depth ratio (open and closed), oscillations, techniques to suppress these oscillations, drag penalties for different cavity geometries, and flow residence time inside a cavity, which is crucial to initiate the ignition. Both experimental and numerical studies still need to be performed to answer some of the contradictory results that have been observed by different investigators (drag penalties of angled back wall cavities, amplitude of pressure fluctuations, and flow residence time inside an unsteady cavity).

In the second part of the paper, studies demonstrating the feasibility of cavities to achieve ignition and to enhance flame holding in subsonic and supersonic combustors are described. Finally, we have introduced several questions followed by comments that need to be addressed in the development of cavities for practical combustors.

Further investigation is required to design an optimal cavity for supersonic flame holding. Future work should include a systematic study of cavities both in nonreacting and reacting flows and their interaction with fuel jets.

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