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Thermally-Choked Combustor Technology

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A program is underway to demonstrate the practical feasibility of thermally-choked combustor technology with particular emphasis on rocket propulsion applications. Rather than induce subsonic to supersonic flow transition in a geometric throat, the goal is to create a thermal throat by adding combustion heat in a diverging nozzle. Such a device would have certain advantages over conventional flow accelerators assuming that the pressure loss due to heat addition does not severely curtail propulsive efficiency. As an aide to evaluation, a generalized one-dimensional compressible flow analysis tool was constructed. Simplified calculations indicate that the process is fluid dynamically and thermodynamically feasible. Experimental work is also being carried out in an attempt to develop, assuming an array of practical issues are surmountable, a practical bench-scale demonstrator using high flame speed H_2/O_2 combustibles.

Introduction

In chemical rocket propulsion, thrust is generated by converting high-pressure gases at low subsonic velocities to low-pressure gases at supersonic velocities. Traditionally, hot high-pressure gases are formed in an enclosed combustion chamber in which raw propellants are injected at the head and the exit flow is choked through a converging-diverging nozzle. Options for subsonic-to-supersonic flow transitioning other than a geometrical throat are conceivable, however.

For instance, one could utilize Rayleigh flow for heat addition in a constant area duct such that thermal choking back-pressures the system inducing a sonic point. Then, the flow could be transitioned to supersonic conditions in a diverging nozzle. This idea can be pushed even further by requiring that heat addition and thermal choking occur only within the diverging nozzle section. Indeed, this feature forms a central element of the Dual-Mode Ramjet cycle contemplated for hypersonic flight [1-2]; Fig. 1 shows an idealized sketch of the flow field in the ramjet mode. Clearly, the analogy to rocket combustion is direct in that an injector would become the source for gaseous subsonic propellant flow. Although heat addition (Rayleigh) losses are higher for a thermally-choked combustor, the simplicity inherent in the design may offset minor performance concerns.

The thermally-choked combustor concept is ideally suited for the Full Flow Staged Combustion (FFSC) rocket engine cycle, shown in Fig. 2, because the main chamber is fed with fully gaseous propellants. By eliminating the main chamber and converging nozzle section and developing an injector for the diverging nozzle section, one could arrive at a simpler, smaller, lighter, and less expensive thrust chamber design as conceptualized in Fig. 3. Such a gas-fed thruster would have an effectively low L^* chamber, yet it could still achieve rapid combustion and good c^* efficiency.

The basic concept of a thermally-choked combustor is, from a theoretical standpoint, completely valid; however, there are numerous practical issues which make actual construction and operation problematic. Issues such as starting, heat release profile, flame stablization, detonability, and flashback may have an inimical influence on idealized behavior. Ultimately, the practical feasibility of thermally-choked combustors must be determined in the laboratory.

This paper presents our current thinking with respect to this technology and outlines an active program for developing a bench-scale demonstrator. We discuss operational issues using simplified but relevant analysis techniques and summarize progress in developing the demonstrator combustor.

Theoretical

Physical Concept

Fundamentally, there are two alternative injection schemes, premixed or non-premixed, on which to base a thermally-choked combustor design. The dual-mode ramjet cycle is non-premixed by necessity, but rocket engine applications permit a choice. One's instinctive inclination is toward a relatively safe non-premixed design; however, premixed injection offers

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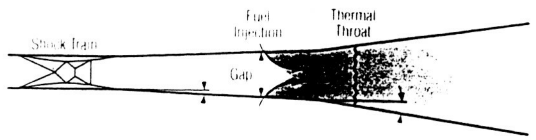

Figure 1: Idealized flow field for the Dual-Mode Ramjet cycle when operating in the ramjet mode (adapted from Edelman et al. [1]).

the best opportunity for collapsing the combustion zone into the smallest region possible. This feature would allow the thermal throat to be very near the injector so that an exaggerated nozzle length would not be necessary. Unfortunately, premixed injection poses significant safety threats which cannot be carelessly dismissed. The practical construction and operation of a thermally-choked combustor will probably hinge on such enabling combustion technology issues.

For illustrative purposes, it is instructive to examine the thermally-choked combustor concept on the basis of premixed injection. Fig. 4 depicts the basic idealized concept. The combustibles enter the nozzle at a subsonic velocity greater than the flame speed and diffuse to higher pressures and lower velocities as the flow area increases. At some point, the flow velocity reaches the burning velocity where a stablized flame front is formed. In the practical case, flame stablization will depend on boundary layer processes and may even reqire the insertion of a coarse mesh bluff body to hold the flame. As combustion proceeds, heat addition dominates over the area change effect, and the flow is forced to accelerate. If the quantity of heat is sufficient, the flow velocity will reach a sonic condition somewhere in the combustion region and a thermal throat will form. Because the area continues to increase, transition to supersonic flow will occur and expansion to lower pressures and higher Mach numbers is possible. In this concept, inertial pressure confinement is provided by a collapsed combustion region rather than a geometrical throat.

To minimize heat addition losses and nozzle size, it is desirable to minimize the size of the combustion region. This implies that one should utilize fuels possessing the fastest chemical reaction rates possible. Furthermore, the classical thermal burning velocity relationship

$$\text{flame speed} \propto \sqrt{(\text{diffusivity})\ (\text{reaction rate})} \quad (1)$$

implies that seeking fast reaction rates corresponds to seeking high flame speeds. There is a bit of good luck in this result since hydrogen gas, a common high-performance rocket propellant, has the highest flame

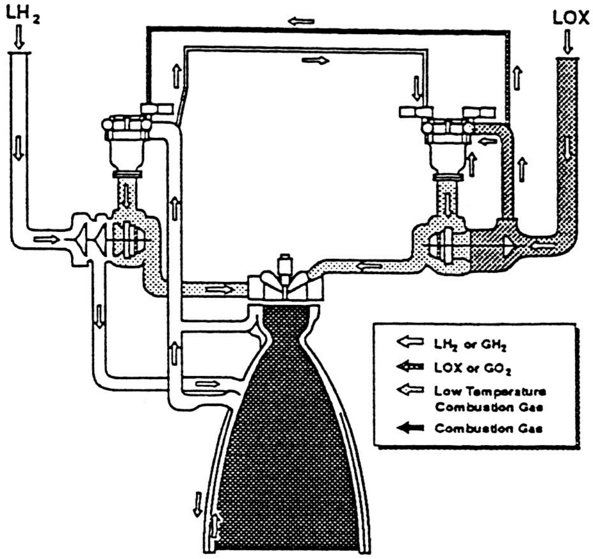

Figure 2: Full Flow Staged Combustion (FFSC) cycle rocket engine schematic (courtesy of Aerotherm Corporation).

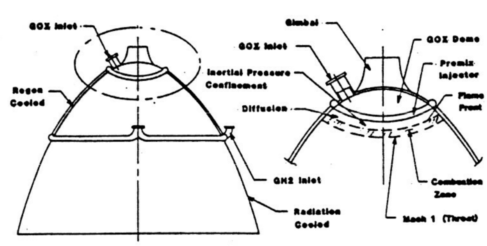

Figure 3: Gas-fed thermally-choked combustor concept for a FFSC cycle rocket engine.

speed of any fuel. High flame temperature acetylene can achieve burning velocities roughly one-half of that attained with hydrogen, but all other hydrocarbons produce burning velocities less than one-half that attained by acetylene.

Measured laminar flame speeds for hydrogen gas burning in air are shown in Fig. 5 as a function of mixture ratio [3]. The maximum flame speed occurs well into the fuel-rich regime (O/F $\approx$ 0.45) because the increased thermal diffusivity associated with excess hydrogen tends to increase the flame speed more strongly than the drop in flame temperature tends to decrease it. Fig. 6 shows the additional effect of oxygenation mole fraction on the laminar flame speed of hydrogen [4]. Increased burning speed with increased oxygen concentration may be attributed, in general, to the influence of flame temperature on reaction rates and diffusivities. For hydrogen burning in pure oxygen, the laminar flame speed is 3.4 times that for combustion with air.

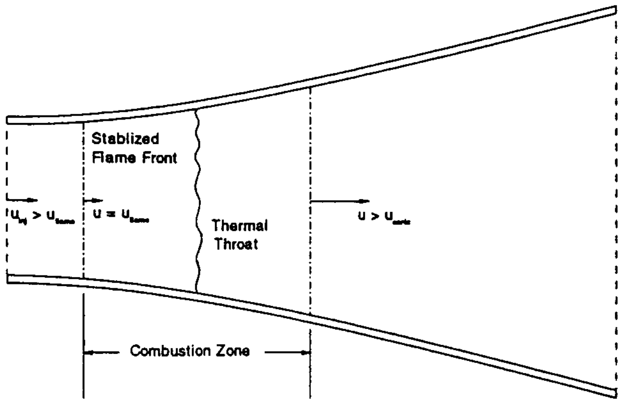

Figure 4: Idealized flow field in a premixed thermally-choked combustor with a stablized flame.

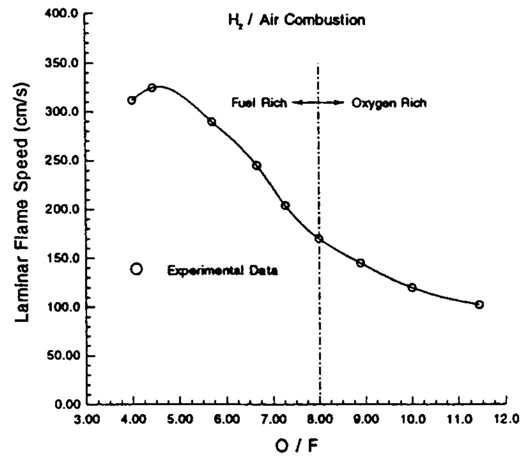

Figure 5: Measured laminar flame speeds as a function of mixture ratio for hydrogen/air combustion (after Gibbs and Calcote [3]).

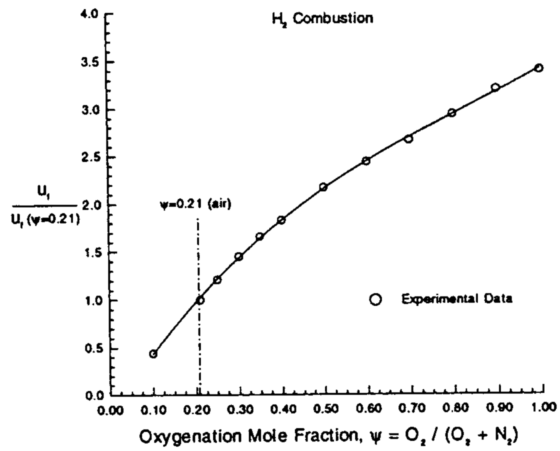

Figure 6: Effect of oxygen concentration, with nitrogen dilution, on the measured laminar flame speed of hydrogen fuel (after Zebatakis [4]).

The effect of turbulence on flame speed is an additional consideration of importance. Turbulent velocity fluctuations produce an apparent flame speed greater than the laminar burning velocity. Indeed, it is not unusual to find apparent turbulent flame speeds 5 to 10 times larger than the laminar value. Unfortunately, turbulence induced amplification effects are configuration dependent, and predictive capabilities for turbulent combustion lack precision. The effectively higher flame speeds for turbulent flow can be used to advantage in the thermally-choked combustor concept, but utilization requires hardware specific development work.

Generalized 1-D Compressible Flow Formulation

In pursuing the development of a demonstrator combustor, it seemed sensible to acquire an analytical support tool. Our immediate needs centered on a simple physical verification of the basic idealized concept and an ability to approximate the expected variation in flow parameters. Clearly, results from simplified one-dimensional gas dynamics theory were not adequate since they do not allow for simultaneous variation in flow area and heat transfer. In contrast, CFD analyses appeared too elaborate and complex for our immediate needs. As a compromise, we settled for a generalized one-dimensional compressible flow analysis of a thermally and calorically perfect gas in conjunction with a very simple combustion model for the heat release profile.

In generalized one-dimensional compressible flows, multiple effects such as area change, heat or mass addition/rejection, and friction can be imposed simultaneously. This generality negates the development of closed-form solutions so that numerical evaluation becomes necessary. The governing system of ordinary differential equations under the above imposed driving potentials are generally presented in terms of influence coefficients for the dependent variable differentials [5]. However, a direct construction by matrix inversion was recently accomplished by Hodge using the symbolic manipulation language MACSYMA [6].

In any case, for a thermally and calorically perfect gas with constant mass flow rate in a duct, the solution of the entire flow field is characterized by a single differential equation for the Mach number squared

$$\frac{dM^2}{dx} = \frac{G(x)}{1 - M^2} \tag{2}$$

where

$$G = M^2\Psi\left[-\frac{4}{D_h}\frac{dD_h}{dx} + \gamma M^2\frac{f}{D_h} + \frac{1+\gamma M^2}{T_0}\frac{dT_0}{dx}\right] \tag{3}$$

with

$$\Psi = 1 + \frac{\gamma - 1}{2} M^2 \tag{4}$$

In the above equations, M is the Mach number, γ is the specific heat ratio, D_h is the duct hydraulic diameter, f is the Moody friction factor, T_0 is the total temperature, and x is the streamwise coordinate.

When $M = 1$ in Eq. (2), the denominator vanishes. Therefore, to insure that the gradient in Mach number remains bounded, $G^* = 0$ at the sonic point where the $*$ superscript indicates that the Mach number has been set to unity. Because dM^2/dx becomes 0/0 indeterminate there, it is further necessary to apply L'Hospital's Rule such that

$$\left(\frac{dM^2}{dx}\right)^* = \frac{\left[G'(x)\right]^*}{-(dM^2/dx)^*} \tag{5}$$

implying

$$\left(\frac{dM^2}{dx}\right)^* = \pm\sqrt{-\left[G'(x)\right]^*} \tag{6}$$

where $\left[G'(x)\right]^*$ has been evaluated by Shapiro [5].

The computational procedure follows that delineated by Beans [7]. First, the total temperature is specified at the inlet. Then, based on an imposed variation in area, total temperature, and friction, the sonic point, if one exists, is located where $G^* = 0$. From the sonic point, Eq. (2) is solved back to the inlet and forward to the exit using a fourth-order Runge-Kutta solver. Once the Mach number distribution is known, the remaining flow properties are obtained by specifying reference conditions and applying the following integral relations.

<u>Integral Relations</u>:

$$\frac{T}{T_i} = \frac{T_0}{T_{0i}} \frac{\Psi_i}{\Psi} \tag{7}$$

$$\frac{P}{P_i} = \frac{A_i}{A} \frac{M_i}{M} \sqrt{\frac{T}{T_i}} \tag{8}$$

$$\frac{u}{u_i} = \frac{M}{M_i} \sqrt{\frac{T}{T_i}} \tag{9}$$

$$\frac{P_0}{P_{0i}} = \frac{P}{P_i} \left(\frac{\Psi}{\Psi_i}\right)^{\frac{\gamma}{\gamma-1}} \tag{10}$$

$$\frac{F}{F_i} = \frac{P}{P_i} \frac{A}{A_i} \left(\frac{1 + \gamma M^2}{1 + \gamma M_i^2}\right) \tag{11}$$

$$\frac{\Delta s}{C_p} = \ln \frac{T}{T_i} - \frac{\gamma - 1}{\gamma} \ln \frac{P}{P_i} \tag{12}$$

where T is the static temperature, P is the static pressure, P_0 is the total pressure, A is the duct cross-sectional area, u is the streamwise velocity, F is the impulse function, s is the entropy, and C_p is the constant pressure specific heat of the gas. The subscript i has been introduced to denote the inlet conditions.

The reference for these integral relations are the inlet conditions which become fully defined when the total temperature, pressure, and Mach number (obtained by marching back from the sonic point) are simultaneously specified. Here, the additional symbols ρ and $\dot{m}$ have been introduced for the density and mass flow rate, respectively.

<u>Inlet Condition Relations</u>:

$$T_i = \frac{T_{0i}}{\Psi_i} \tag{13}$$

$$u_i = M_i \sqrt{\gamma R T_i} \tag{14}$$

$$\rho_i = \frac{\dot{m}}{u_i A_i} \tag{15}$$

$$P_i = \frac{\rho_i}{R T_i} \tag{16}$$

$$P_{0i} = P_i \Psi_i^{\frac{\gamma}{\gamma-1}} \tag{17}$$

$$F_i = P_i A_i + \rho_i A_i u_i^2 \tag{18}$$

Combustion Model

A simple combustion model has been constructed to define the heat release profile. In this model, the flame front is located where the flow velocity just equals the specified flame holding speed. The heat release profile is then represented by a one-parameter shape function over a designated burning length. The streamwise variation in total temperature can then be deduced for the combustor.

The fundamental differential relation which must be satisfied relates the differential heat release dQ to the differential change in total temperature dT_0,

$$dQ = C_P dT_0 \tag{19}$$

where C_P is defined as the constant pressure specific heat. Therefore,

$$\frac{dT_0}{dx} = \frac{1}{C_P} \frac{dQ}{dx} = \frac{Q'(x)}{C_P} \tag{20}$$

Furthermore, we require that

$$\tilde{Q} = \int_{l_p}^{l_p+l_b} dQ = \int_{l_p}^{l_p+l_b} dx\, Q'(x) = \frac{\Delta H_{\text{COMB}}}{O/F+1} \quad (21)$$

where $\tilde{Q}$ is the absolute heat release per kg of total flow, l_p is the preburn length, l_b is the burning length, and ΔH_{COMB} is the fuel heat of combustion.

A suitable one-parameter shape function for $Q'(x)$ which satisfies Eq. (21) is

$$Q'(x) = \frac{\tilde{Q}}{l_b}(\alpha+1)\left(\frac{x-l_p}{l_b}\right)^{\alpha} \quad ; l_p < x \le l_b \quad (22)$$

where α defines the heat release profile shape. The rate of reaction is represented in the value specified for α. Increasingly large negative values simulate increasingly large reaction rates. The uniform heat release profile is recovered when α=0. The general behavior of $Q'(x)$ is shown in Fig. 7 assuming l_p=0 and α = 0, -0.25, -0.5, -0.8.

Analysis

To check the validity of the analysis procedure and the coding, calculated solutions were successfully confirmed against known closed-form solutions for isentropic flow in a converging–diverging nozzle and for Rayleigh flow. The geometry and operating parameters for an idealized combustor similar in size to the proposed demonstrator were then selected for analysis.

The selected geometry consists of a diverging circular duct with an injection diameter of 0.5 cm and an exit diameter of 1.25 cm. The total nozzle length was 8 cm. The shape of the diverging section was defined such that the cross-sectional area varies according to the relationship

$$A = A_i + (A_e - A_i)(x/L)^{\beta} \quad (23)$$

where β is a nozzle shape parameter. A quadratic variation in flow area was chosen by setting β = 2. The resulting streamwise variation in nozzle radius is shown in Fig. 8.

Analysis was based on H_2/O_2 combustion at a mixture ratio of O/F=4.5 at which the maximum flame speed is attained. The heat of combustion for hydrogen was taken as ΔH_{COMB} = 120 MJ/kg. The specific heat ratio was estimated as γ=1.3 while the constant pressure specific heat was taken to be C_P=2000 m^2/s^2 K. An apparent turbulent flame speed 10 times the laminar value was assumed. Combustion was estimated to occur over a burning length of no more than 3 cm, and fast chemical reaction was simulated by specifying α=-0.75. Friction effects were neglected. Inlet reference conditions were T_{0i}=300 K and P_i=14 atm.

Based on the above conditions, iterative calculations revealed that the flame front should be located approximately 1 cm downstream from the inlet. For the assumed heat release profile, computations further indicated that a thermal throat should form roughly 1 cm downstream from the stablized flame

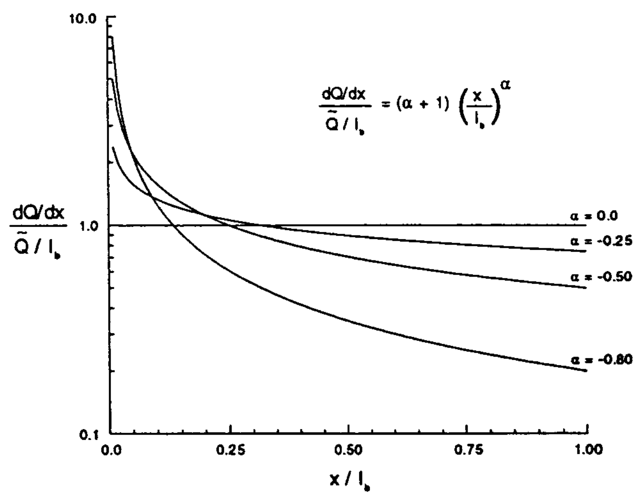

Figure 7: One-parameter reaction rate shape function for various assumed rate profiles. Uniform heat release is achieved when α=0.

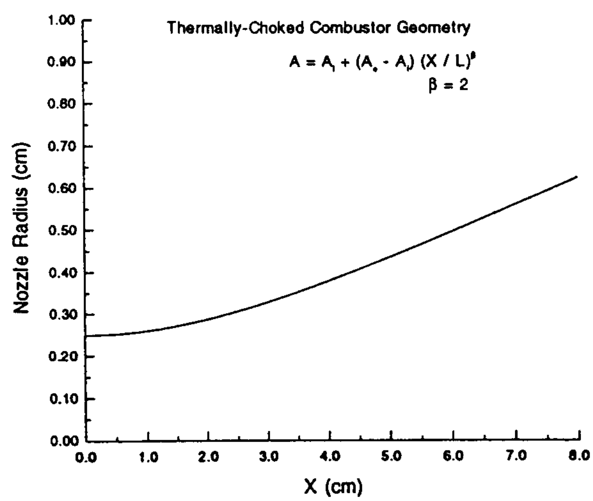

Figure 8: Radial variation in flow area for the analyzed diverging nozzle geometry.

front supporting a mass flow rate of 0.0235 kg/s. The flow was also predicted to accelerate smoothly through the transonic regime with subsequent expansion to high Mach numbers as shown in Fig. 9. There was no violation of the second law of thermodynamics. These results support the contention that thermally-choked combustors are both fluid dynamically and thermodynamically feasible, and they provide useful design estimates for the proposed bench-scale demonstrator.

Experimental

Demonstrator Combustor

Despite favorable theoretical results, practical feasibility must be proven in the laboratory. Thus, the emphasis of our research has been aimed at successfully constructing and operating a bench-scale thermally-choked combustor design. The evolution of our design was driven by a desire for simplicity, flexibility, and limited purpose – that being fundamental demonstration of the technology. Neither heavy diagnostics outfitting nor performance optimization were deemed desirable.

With these goals in mind, a design based on premixed injection appeared to offer the greatest potential for success. Furthermore, we were very interested in adapting high-pressure oxygen/hydrogen torch technology which was readily available for operating pressures up to 200 psi. As a result, our design turned on the idea of mating a commercial oxygen/hydrogen torch with a diverging nozzle combustor section. The configuration which emerged from this exercise is shown in Fig. 10.

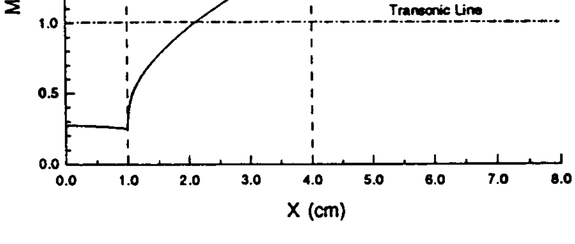

Figure 9: Computed streamwise variation in Mach number demonstrating continuous acceleration through the sonic point in the diverging nozzle combustor.

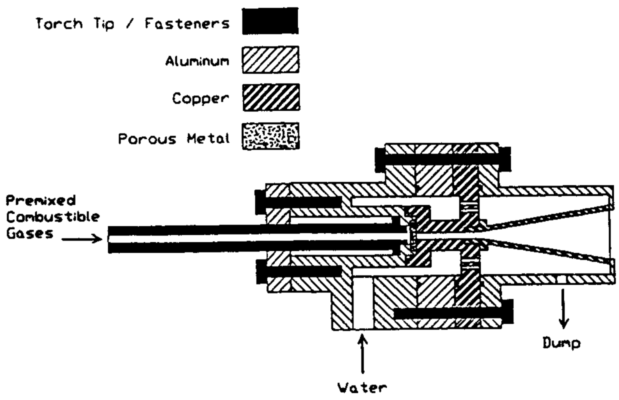

Figure 10: Thermally-choked demonstrator combustor design.

In this design, a large torch tip was cut back and fitted with a mating ring for attachment to the combustor. Premixed combustible gases leaving the torch mixing section and entering through the modified torch tip are forced to pass through a 1/8 inch thick porous metal filter having a 100 μm pore size. This filter is intended to prevent flashback through the delivery system. The gases then pass through a straight section roughly 1 inch long having the same diameter as the torch delivery tube. Then the combustible gases enter a diverging nozzle section where combustion is intended to stablize. The design accomodates interchangable nozzle sections so that different divergence rates and area ratios may be investigated. The entire combustor design is constructed from appropriate materials with adequate sealing between sections, and it is water cooled.

Gases are supplied to the system by two-stage regulators capable of providing 200 psi output. The combustor and gas delivery system are located in an isolated test bay at the UTSI Propulsion Laboratory. Flow control is maintained by control rods which connect to the torch handle valves and pass through the test bay blast wall to a safe control area. The combustor is started by igniting pure hydrogen flow in a diffusion flame. Oxygen and hydrogen flow are then increased to draw the flame into the nozzle section.

Diagnostics

Diagnostics have been intentionally kept to a minimum in keeping with our limited purpose of feasibility demonstration. Currently, we monitor the static pressure and temperature at the wall of the nozzle entrance. The temperature is measured as an indication of the forward location of the flame. The pressure is measured because we expect it to rise when and if thermal choking occurs. In addition, we are using a schlieren imaging system to actively examine the nozzle exit plume. Because a schlieren optical system directly visualizes the density gradient (unlike a shadowgraph method which visualizes the second derivative of density), it offers high sensitivity to weak shock structures. The sensitivity of this technique can be appreciated when one observes the system easily detect natural room convection currents. If thermal choking occurs with subsequent expansion to supersonic Mach numbers, the schlieren technique should permit us to resolve shock structure in the exit plume. The schlieren images are recorded on tape with a video camera so that they can be digitized and processed later as required.

Test Experience

As of this writing, our test experience has primarily involved practical development issues. Initial attempts at operation revealed flaws in our original design requiring some component modifications and alterations. For instance, the original design did not include a porous metal filter. The filter was added after we experienced a burn through in the torch tip immediately downstream from the mixing chamber exit. It was not clear whether the flame flashed back through the system or ignition occured because of contamination. We therefore decided to add the porous metal filter as a flame arrestor. Fortunately, we have not experienced a recurrence since executing this alteration. Another difficulty encountered was inadequate sealing in the original design. We experienced leakage of combustible gases into the coolant flow and were forced to re-design. Subsequent modifications have eliminated this problem.

In all tests to date, we have had no indication of thermal choking. Actually achieving the desired operating conditions depends on a wide range of practical issues which make the entire matter problematic. We continue to pursue the technology by investigating various nozzle divergence rates and area ratios. We have not yet exhausted all conceivable possibilities with regard to the design.

Discussion

This section is dedicated to a discussion of the numerous practical issues encountered in developing a thermally-choked combustor. It is these practical concerns and the developers' ingenuity in addressing them which will determine the success or failure of this technology.

Starting

The issue of starting is immensely important and immensely uncertain. In a conventional flow accelerator, the rise in chamber pressure forces the flow through a fixed geometric throat. The enforced area change variation requires choking at the throat and continuous flow acceleration through the sonic point. In a thermally-choked combustor, however, the thermal throat must be developed by the combusting flow itself.

Before the thermal throat forms, there is no mechanism for sustaining a large injection pressure. Somehow, the flame must choke the flow while the inlet is at a relatively low static pressure. Then the injection system must rapidly respond by increasing the pressure against the throats resistance. Ideally, the flow would stablize with a thermal throat confining a significant injection pressure.

One technique for attempting a start begins by igniting at fuel-rich conditions which creates an external diffusion flame. By increasing both the oxygen and hydrogen flow rates, we approach a mixture ratio having a flame speed sufficiently high to bring the flame into the nozzle. One then relys on a self-induced start of the system in a thermally-choked mode. The feasibility of this approach has yet to be demonstrated. An alternative may be to pre-choke the cold flow upstream of the nozzle prior to ignition. If a thermal throat can then be formed in the nozzle section such that it chokes with a smaller permissible flow rate, the upstream choke point can dissipate allowing the thermal throat to confine the high supply pressure.

Heat Release Profile

For premixed combustible gases, the rate at which heat is released to the flow depends on the reaction kinetics of the fuel/oxidant system. Furthermore, the ability to achieve high combustion efficiencies at the thermal throat (so that performance losses remain low) requires a very compact combustion zone. Fast chemical reaction rates are therefore necessary, and H_2/O_2 combustibles are optimal in this respect. For a non-premixed injection design, a mixing delay time would also enter consideration.

We have not performed comprehensive calculations based on detailed reaction kinetics to know the probable heat release profile with any degree of certainty. If the combustion zone becomes too enlarged, the entire concept becomes less viable. Prompt combustion and choking near the injector is a critical element for successful and efficient operation.

Flame Stablization

The formation of a stablized flame front near the entrance of the diverging nozzle section is of particular importance. Neither flashback through the delivery system, nor blowout, nor persistent and large flame front oscillations are permissible. By keeping the flow velocity at the nozzle entrance greater than the burning speed, the flame cannot propagate as a deflagration wave into the delivery system. To prevent blowout, velocities equal to the burning speed must occur just downstream of the nozzle entrance. Our current idea is to try and stablize the flame using the boundary layer velocity profile as occurs for Bunsen burners. As the flow diffuses to lower velocities, a speed will be reached near the wall (but far enough away to prevent quenching) which is equal to the flame speed. The flame can then anchor at that location.

This method may not yield a quality combustion front, however, since the flame could be severely stretched downstream. The combustion zone may become too enlarged for practical operation. Introduction of a bluff body flame holder such as a coarse wire mesh may perform better since it would rely on recirculation of hot combustion products to produce a more uniform flame front.

Detonability

With premixed combustibles, the formation of a supersonic combustion wave (detonation) from a subsonic combustion wave (deflagration) is known as a slow-mode deflagration-to-detonation transition (DDT). This occurs when a pre-flame shock front develops having sufficient strength to cause the mixture to explode. The result is a detonation moving into the unburned mixture at high Mach number (typically 5-10). Obviously, such behavior could have disasterous consequences if unquenched.

Experimental detonation limits for H_2/O_2 mixtures have been acquired demonstrating that limits on detonation are only slightly narrower than limits on deflagration. The deflagration lean limit occurs at 4.6 % fuel by volume as compared to a detonation lean limit of 15 %. The deflagration rich limit occurs at 93.9 % fuel by volume as compared to a detonation rich limit of 90 %. Thus, the detonation limits for H_2/O_2 mixtures are too wide to be ignored.

Since the transition length for slow-mode DDT of hydrogen fuel is on the order of one meter, the problem may not be severe for short length premix sections. However, fast-mode self-ignition detonations have also been observed which do not depend on transition from deflagration to detonation. Prudence dictates that any design should include a mechanism for flame quenching near the nozzle entrance.

Flashback / Flame Quenching

Flashback through the premixed delivery system as either a deflagration or detonation wave raises serious safety concerns. A method for quenching any flashback involves forcing the flame through a flow passage having a diameter less than the quenching diameter. With hydrogen, this is not a trivial task since the quenching distance can be extremely small. For example, the deflagration quenching diameter for hydrogen burning with air at 1 atm is 0.6 mm. Combustion with pure oxygen combined with the known inverse relation between quenching diameter and pressure ($d_q \propto P^{-1}$) implies the need for even smaller quenching distances in our application. To address this concern, we have employed a 1/8 inch thick porous metal filter having a 100 μm pore size. We clearly sacrifice pressure loss – and therefore propulsive efficiency – across this flame arrestor to achieve a measure of safety in operation. An opportunity does remain, however, for optimizing the flame arrestor design in later development work.

Concluding Remarks

The CSTAR organization is actively investigating thermally-choked combustor technology for rocket engine applications. Theoretical analyses indicate that the concept is fluid dynamically and thermodynamically feasible. Our immediate aim is to demonstrate the concept in a bench-scale design based on fast reacting premixed H_2/O_2 combustible gases. Current development effort is directed at addressing the numerous practical issues which affect a functionable design.

Acknowledgments

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