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Flashback Arrestor for LPP, Low NO_x Combustors

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ABSTRACT

Lean premixed, prevaporized (LPP) high temperature combustor designs as explored for the Advanced Subsonic Transport (AST) and High Speed Civil Transport (HSCT) combustors can achieve low NO_x emission levels. An enabling device is needed to arrest flashback and inhibit preignition at high power conditions and during transients (surge and rapid spool down). A novel flashback arrestor design has demonstrated the ability to arrest flashback and inhibit preignition in a 4.6 cm diameter tubular reactor at full power inlet temperatures (725 C) using Jet-A fuel at $0.4 \leq \phi \leq 3.5$. Several low pressure loss (0.2 to 0.4% at 30 m/s) flashback arrestor designs were developed which arrested flashback at all of the test conditions. Flame holding was also inhibited off the flash arrestor face or within the downstream tube even velocities (≤ 3 to 6 m/s), thus protecting the flashback arrestor and combustor components. Upstream flow conditions influence the specific configuration based on using either a 45% or 76% upstream geometric blockage. Stationary, lean premixed dry low NO_x gas turbine combustors would also benefit from this low pressure drop flashback arrestor design which can be easily integrated into new and existing designs.

INTRODUCTION

Aircraft and stationary gas turbines are being required to meet more stringent emission requirements, especially NO_x emissions. To achieve low NO_x emissions, stationary gas turbine combustors operating on natural gas have been switching to lean, premixed combustor designs. With the planned introduction of high altitude supersonic commercial aircraft, lean premixed, prevaporized aircraft combustors are being designed to achieve the low NO_x emissions required to minimize the damage to the earth's protective ozone layer in the stratosphere. These lean premixed combustor designs can experience damage by flame holding in the premixing region as a result of preignition, combustion chamber instability or flashback. A short, low pressure loss

flashback arrestor would assist in the acceptance and safety of lean, premixed combustion systems for stationary and aircraft gas turbines to achieve low NO_x emissions. Ideally, the flashback arrestor system would also assist in inhibiting flame stabilization downstream before the combustion chamber as a result of preignition or flame reversal (unstable operation).

Low NO_x emissions have been demonstrated for both aircraft and stationary power generation using various fuel-lean combustor designs, however a means to arrest flames from flashback and combustor dynamic instabilities may be required in some designs to prevent damage to the engine. Lean, premixed combustion zones can result in lower NO_x production than a typical diffusion flame gas turbine combustor by avoiding the local rich regions associated with prompt NO_x formation and by producing lower primary zone temperature to give lower thermal NO_x [Lefebvre, 1983]. Complete premixing before the combustion chamber must be achieved with a low pressure drop premixer to maintain high engine cycle efficiency and within a short residence time to prevent autoignition upstream of the combustion chamber. Typically, complete mixing is not achieved within a practical system given the tradeoffs between cost, pressure loss, autoignition delay time and combustor dynamic stability. This tradeoff is made even more complex if the combustor designer must ensure the premixer system cannot act as a flame holder before the combustion chamber.

In general, NO_x emissions from commercial aviation affect the global environment differently in the troposphere than in the stratosphere. In the upper stratosphere, ozone is catalytically destroyed by NO_x in an analogous manner to ozone destruction by CFCs. Typically, subsonic commercial aircraft fly in the troposphere to lower stratosphere (9 - 14 km altitude) where the ozone concentration is relatively low, however, these subsonic aircraft do have a significant impact on the stratospheric ozone concentration [Johnson, 1992]. The ozone concentration distribution with altitude forms a bell shaped curve with the peak concentration near the middle of the anticipated supersonic cruise range for the High Speed Civil Transport (HSCT). Commercial supersonic aircraft are expected to cruise through the upper stratosphere for best fuel economy. Minimizing the NO_x production is especially important during the upper stratosphere (18 - 27 km altitude) HSCT supersonic cruise operation to protect the region richest in high altitude ozone needed to block UV radiation. Without ultra-low NO_x engines, the HSCT would become a prime source of NO_x in the heart of the upper stratosphere's protective ozone layer which could make operation both environmentally and politically unacceptable (Wilhite and Shaw, 1997). Both fuel-rich and fuel-lean combustor designs are being developed with the goal of achieving NO_x emission index (EI) below 5 g of NO_x / kg of fuel burned at supersonic cruise conditions. Lean premixed, prevaporized jet fuel combustor designs may benefit from the addition of a short, low pressure loss, flashback arrestor given the short autoignition delay time for Jet-A of less than a few milliseconds at the elevated inlet temperature and pressure typical of aircraft gas turbines [Spadaccini, 1977, 1983 and Poeschl, 1994] as shown in Figure 1.

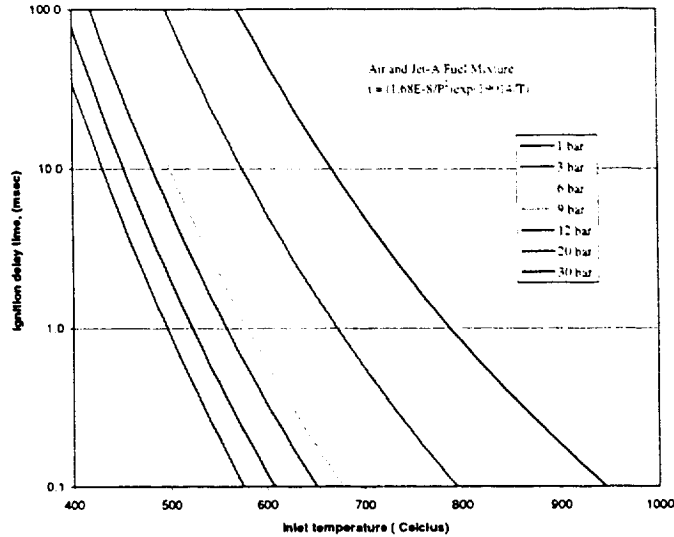


Fig. 1 Autoignition delay time for Jet-A fuel [Spadaccini, 1982]

Ground based gas turbines also face significant emissions challenges for both stationary power generation applications and for hybrid electric vehicle (HEV) applications. In the troposphere, NO_x emissions react with non-methane hydrocarbons to form photochemical smog and with ammonia to form ammonium nitrate particulates [Wallerstein, 1997]. Southern California's Air Quality Management District (SCAQMD) Rule 1134 has set strict emission requirements of 25 ppmV NO_x for 0.3 to 2.9 MW gas turbines and 9 to 15 ppmV NO_x for larger gas turbines. Other impacted areas in the USA are expected to adopt a 9 ppmV NO_x requirement for future gas turbine engine installations based on DOE projections. Equivalent zero emission vehicle (EZEV) standards proposed by California Air Resource Board (CARB) are anticipated to require the on board power generating units to produce NO_x emissions below 0.029 g/mile (~ 1.8 ppmV NO_x for steady state operation at an efficiency of 0.25 kW/mile). Clearly, the direction in such impacted areas is to achieve emissions at least equal to a modern electric power generating station with after-treatment. To achieve the less than 25 ppmV NO_x emission goals, most new stationary gas turbines combustor designs operate also lean, premixed (LP) with natural gas fuels.

An improved solution to lowering flashback and pre-ignition risks, such as the technology to be discussed herein, is an important step in permitting the widespread use of clean power engines enjoying Advanced Turbine System (ATS) efficiencies and low NO_x combustion. The use of low NO_x ATS gas turbines will provide sustainable competitive advantage for a strong U.S. export industry in a market now totaling \$5 billion annually.

Like Jet-A, natural gas has a short autoignition delay time which varies with combustor inlet temperature, pressure, equivalence ratio and fuel composition [Spadaccini, 1994]. Most high efficiency, natural gas LP gas turbines can experience preignition since they operate above the autoignition temperature for methane [Prade, 1996]. Determination of the autoignition delay time for natural gas is more complex than for jet fuel due to the wide variability of non methane combustible compounds [Spadaccini, 1994]. Thus, the premixer design must provide rapid

mixing within a conservative ignition delay time based on some predefined natural gas composition.

Unless protected from flashback, the premixer design should not allow flame holding and be resilient to damage from flashback or preignition events [Smith, 1997]. Flashback events can occur during a compressor surge or rapid deceleration event. The resulting detonation or deflagration wave ignites the fuel at the fuel injectors which can result in flame holding upstream of the combustion chamber by the premixer or fuel injector or both. If flame holding occurs, the hot flame streak can quickly produce severe damage to the premixer, downstream combustor aerodynamic flame stabilizer (if present), and turbine. Preignition upstream of the combustion chamber can result in similar damage. LP combustors are known to be more sensitive to combustion driven oscillations than diffusion flame combustor designs [Prade, 1996, Richards, 1997]. If the combustor is not dynamically stable, these oscillations can result in flame propagation upstream into the premixing region which can result in flame holding off the premixer or fuel injector or both. Lean, premixed combustors could benefit from a flashback arrestor placed between the premixing region and entrance into the combustor to prevent damage resulting from flashback or dynamic instabilities. The results of a Jet-A fuel demonstration program for a short, inexpensive, low pressure loss flashback arrestor suitable for new or retrofit aircraft and stationary gas turbines is described herein. Figure 2 illustrates some examples of typical lean premixed combustor designs with an integrated flashback arrestor.

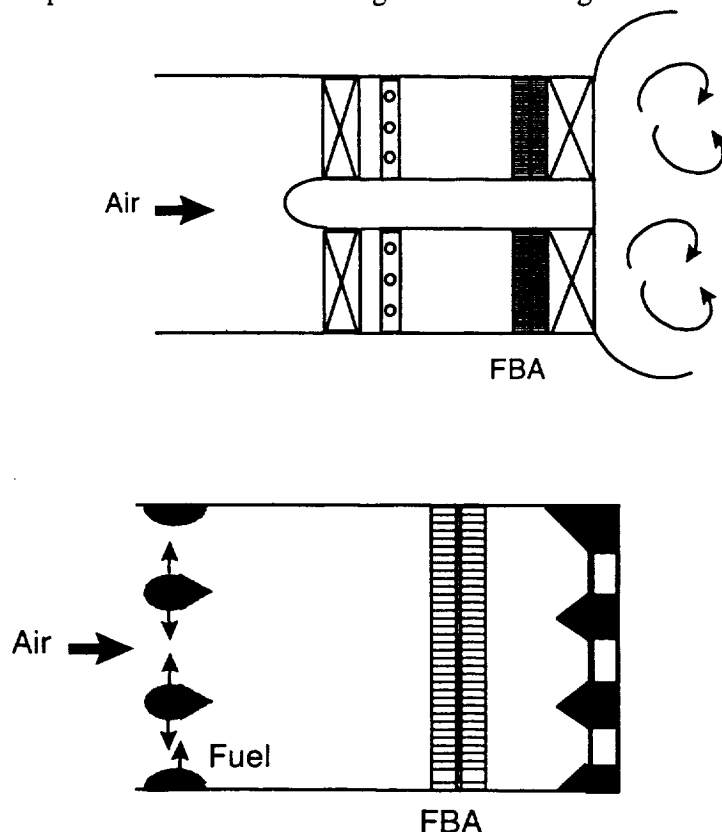


Fig. 2 Examples of a flashback arrestor integrated into various lean premixed combustor designs.

Flashback Arrestor Design

One classic approach to arresting flashback is with a monolith whose channels are smaller than the critical quenching diameter. This critical diameter is the minimum diameter required to quench the flame front for a given set of conditions. For thin wall monoliths, the primary route to flame arresting is usually by quenching the flame front by relatively cooler gases formed through wall collisional quenching of reactive species in the flame. Thick wall monoliths can also supply a significant thermal reservoir to aid in quenching the flame, especially when the initial gas temperature is low. Classical single channel flashback arrestors have long channels (typically $L/D > 40$) which can produce turbulent self preserved jet structure at the monolith exit as a result of the fully developed channel flow formed within the long channels [Wilson, 1978, Vosen, 1984]. For long channel, thin wall metal monoliths, the primary pressure loss is channel drag with a relatively small contribution from the frontal area. Long monoliths have several disadvantages for aircraft gas turbine flash arrestor design due to the desire for shortness, lowering pressure drop, and a requirement to reduce downstream turbulence (to inhibit pre-ignition). Fibrous metal pad type flashback arrestor provides the short length with severe pressure loss penalty.

Various means of enhancing quenching within the monolith channels have been suggested to reduce the pressure loss and size. The NACA 1300 report suggests that through the insertion of a small center body down the centerline of a channel, the wall quenching can be enhanced, allowing the use of larger diameter channels with the same flame arresting effectiveness (reducing pressure drop and weight). Adding a center body quenches the flame front within the high velocity channel core region simultaneously with quenching on the channel wall. Thus a small cross sectional area center body provides a light weight, low pressure drop approach to increase the critical quenching diameter of the monolith channels.

A new flashback arrestor design was conceived to provide a device to enable lean, premixed combustor designs for aircraft and ground power applications [Kraemer, 1997]. This approach is a practical alternative to the concept of addition of a center body surface to quench the core region. In our structure, the core region is quenched sequentially rather than simultaneously by placing surfaces within the core flow immediately downstream of the upstream monolith. Non-aligned monoliths can produce a complex flow field with a large surface area within the central region of the upstream monolith's core flow. The first monolith would be used to quench the near wall region and the downstream monolith would quench the hot core region exhausting from the upstream monolith. Essentially, an exchange process occurs resulting in the quenched upstream flow becoming the downstream flow's core region and the hot core being quenched on the downstream surfaces which translate across the channel, as illustrated in Figure 3 [Kraemer, 1997].

One approach to form this labyrinth-like structure would be to assemble two or more non-aligned monoliths into a single structure. The labyrinth mixes and quenches the flow from the upstream monolith's channels with the objective of greatly increasing the minimum channel diameter required to arrest the flame. This series of shorter length channels enhances mass transfer of radicals to the surface for quenching, since the mass transfer coefficient decreases as the channel length increases especially for a L/D of greater than ten [Ullah, 1992]. Replacing a single long monolith with a series of shorter monoliths results in a much higher effective mass transfer for an

equivalent length device. The non-aligned, short multiple monoliths have provided a highly effective approach to produce a lower pressure drop flash arrestor while providing improved turbulence reduction (for inhibiting pre-ignition and flame holding downstream) and lowering manufacturing costs.

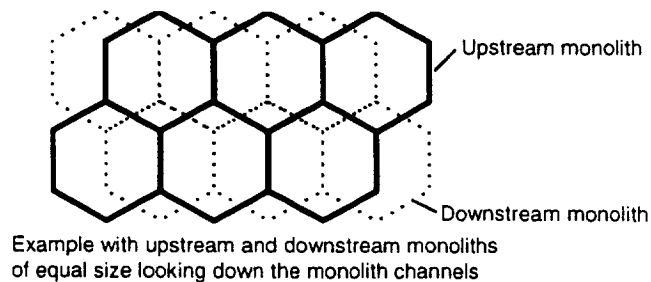


Fig. 3a. Offset inlet and exit monolith configuration to improve surface quenching.

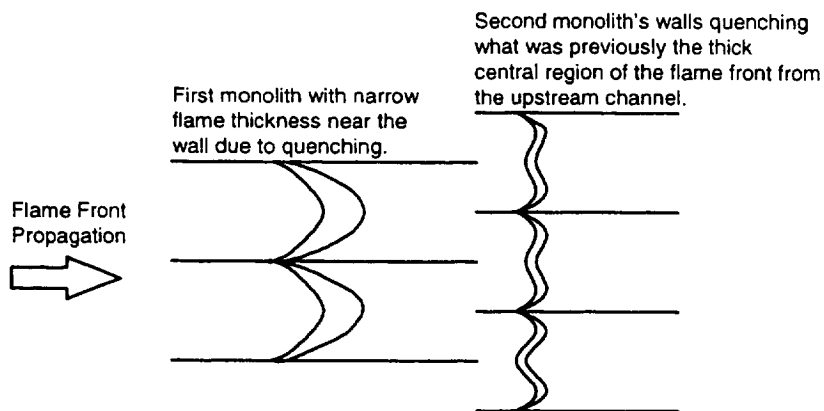


Fig. 3 b. Shape of flame front propagating down a channel with reduced thickness due to wall quenching, patent number 5,628,181.

Reduced turbulence and flame speed: Over most of the combustor operating range, turbulence is the primary factor contributing to high flame speed. Our approach to inhibit propagation of flame kernel formed by pre-ignition of the fuel and air mixture (and potentially quench the flame kernel) is to maintain the local gas velocity above the local flame speed throughout the flow field, minimize the turbulent eddy size and minimize the residence time before the combustion zone. Often the laminar flame speed (S_L) contribution to the flame speed is relatively low compared to the contribution from turbulence (based on the turbulence intensity, u_{rms}) in many practical combustion system ($S \approx S_L + u_{rms}$) [Kuo, 1986]. Typically, the laminar flame speed varies between 0.4 to 3 m/s for hydrocarbon fuels depending on the local conditions; however, the contribution from turbulence can be many times higher (for example $u_{rms} = 10$ m/s for a mean velocity of 30 m/s and turbulence intensity of 33 percent).

After the diffuser, the flow entering a typical combustor is highly turbulent. A key to avoiding pre-ignition is to reduce turbulence in the region upstream of the combustor and closely couple the fuel injection/mixing with the desired combustion region (to reduce residence time). The pre-combustion region should also be clear of turbulence-inducing structures and flows to inhibit

preignition and flashback [Plee, 1978], however, a device to reduce the upstream turbulence from the diffuser and mixer is not usually incorporated into the lean premixed combustor design. Reducing the upstream turbulent eddy size to approach the size of the Kolmogorov scale results in rapid dissipation of turbulent kinetic energy [Linan, 1993] and as a result potentially extinguish an undesired flame. For this reason, small channel diameter monoliths are employed to reduce the upstream eddy size. A properly designed monolith structure can transform the turbulent flow to essentially laminar flow downstream of the monolith. By reducing the turbulence intensity throughout the flow, the turbulent flame speed is reduced below the local velocity for a well designed premixing region to inhibit flame propagation at typical combustor flame tube velocities.

Potentially hazardous conditions can also exist during transient operation of a gas turbine. During a surge or rapid spool down the combustor inlet pressure and temperature decrease rapidly [Schaffer, 1994] creating a potential for low air velocities, high turbulence and higher than desired air temperatures and fuel flow rates. Reducing the downstream turbulence is also important to prevent flame holding off the flashback arrestor face after arresting the flame front. If no downstream turbulence existed, the flame would blow off the face once the gas velocity exceeded the laminar flame speed. Minimizing the downstream turbulence is desirable to protect the downstream structures results.

EXPERIMENTAL

The primary objective of this work is to demonstrate the feasibility of a short, light weight, low pressure loss flashback arrestor which could inhibit preignition over a range of conditions suitable for HSCT and AST aircraft gas turbine combustors. A secondary objective was to develop a flashback arrestor which does not act as a flame holder after arresting flashback. The downstream turbulence generated by many flashback arrestors designs supports flame holding off the flashback arrestor face. Ambient pressure results of three different flashback arrestor designs are presented in this paper. A high pressure facility has been built to provide tests at inlet temperatures up to 700 °C at 10 atmospheres.

Ambient pressure, bench scale testing of various flashback arrestor designs was conducted with Jet-A fuel to examine their ability to arrest flashback and inhibit or quench downstream flame kernels. Figure 4 illustrates the important features of the test rig. Downstream of the fuel injector, three rows of 0.63 cm o.d. rods provide both additional mixing and turbulence generation. The final row of horizontal rods provides a 45 percent geometric blockage of the 5.6 cm square premixing section. The flashback arrestors were positioned at the entrance of a 4.6 cm diameter stainless steel of 30.5 cm in length. A 5.6 cm square upstream mask with a 4.6 cm diameter opening held the 5.6 cm square shaped flashback arrestors in place. Regions of recirculation are created around the upstream periphery of the opening in the mask. If the flashback arrestor did not extinguish the downstream flame front, 0.2 mm exposed bead Type K thermocouple (TC_{FB}) measured the temperature rise generated by flames held by recirculation zones created by the upstream rods or mask.

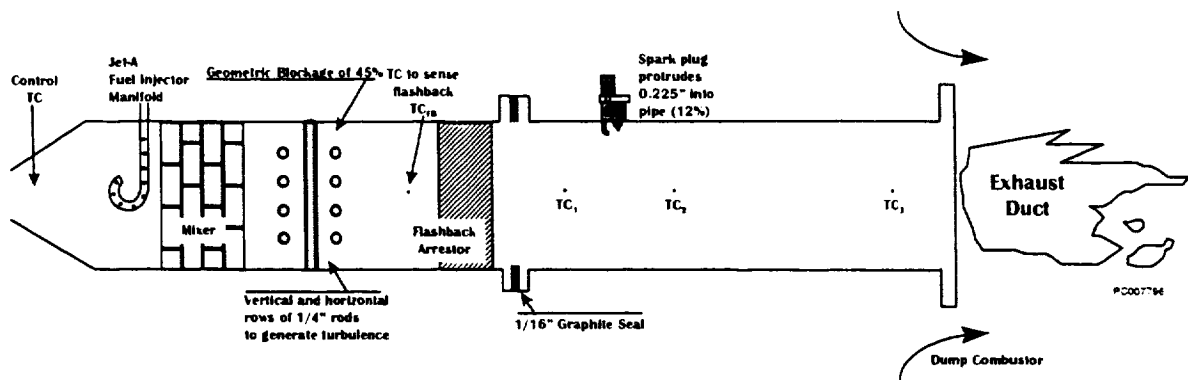


Fig. 4 Flashback arrester test rig

Upstream turbulence produced by the rods were added to emulate flow disturbances produced by the diffuser, fuel injector and other structures in the flow path upstream of the flame stabilization region. A highly turbulent flow is desired to test the preignition prevention characteristics of the flashback arrester design. To prevent preignition, the concept is to reduce the turbulent flame speed to less than five percent of the mean velocity such that a flame kernel would be extinguished due to its low flame speed (laminar + turbulent). Thus the flashback arrester design is configured ideally to eliminate the upstream turbulence intensity to inhibit downstream flame holding and propagation. Downstream of the rods is an exposed junction Type K thermocouple to measure if flames flashback through the flash arrester. In initial screening tests of various designs if the flame was not arrested, flame holding off the turbulence generator often resulted in catastrophic failure of the Hastelloy X flame arrester. Short duration preignition or non arrested flashback events did not harm the monoliths. Higher temperature metal monolith materials are readily available for more demanding environments.

If the flame front was not arrested, several downstream 0.2 mm exposed bead Type K thermocouples located near the wall would indicate the source of flame holding. One thermocouple (TC_1) was located 2.79 cm downstream of the flashback arrester exit and before the protruding spark plug at 5.94 cm to determine if a holding occurred off flashback arrester face. Two additional downstream thermocouples were located at 11.3 cm (TC_2) and 25.9 cm (TC_3) downstream of the flashback arrester exit. These thermocouples were used to examine spread of a flame held off the spark plug whose center electrode protruded 0.57 cm into the flow. Ignition of the air and Jet-A mixture was provided by either the downstream spark plug or a butane torch located near the exit 10 cm flame holding plate. This square plate forms a bluff body flame holder to burn up the fuel before entering the 25 cm exhaust duct.

Inlet temperature always refers to the main air temperature ($TC_{Control}$) measured mid-stream and 8 cm before the fuel injector, which was within 5 K of the temperature measured before the flash arrestors (TC_{FB}). Fuel was provided by two Zenith gear fuel pumps. The pumps were weight flow calibrated with Jet-A prior to testing. Air flow rate was measured by a vane meter upstream of the electrical heaters. Inlet air temperature ranged from 200 °C to 650 °C and inlet air velocities ranged from 2.4 to 43 m/s. Most of the data was obtained for an inlet temperature of 400 °C, 500°C, and 600 °C. The minimum velocity was chosen to prevent damage to the electrical heaters unless preignition occurred. Above 500 °C, the minimum velocity was limited by preignition of the fuel which varied with inlet temperature and fuel stoichiometry. At each

inlet temperature and velocity, data was collected typically between equivalence ratios (ϕ) of 0.5 to 4.0 in increments of 0.5. Ignition by the spark ignitor or butane torch was provided for steady-state conditions and for transient fuel flow conditions.

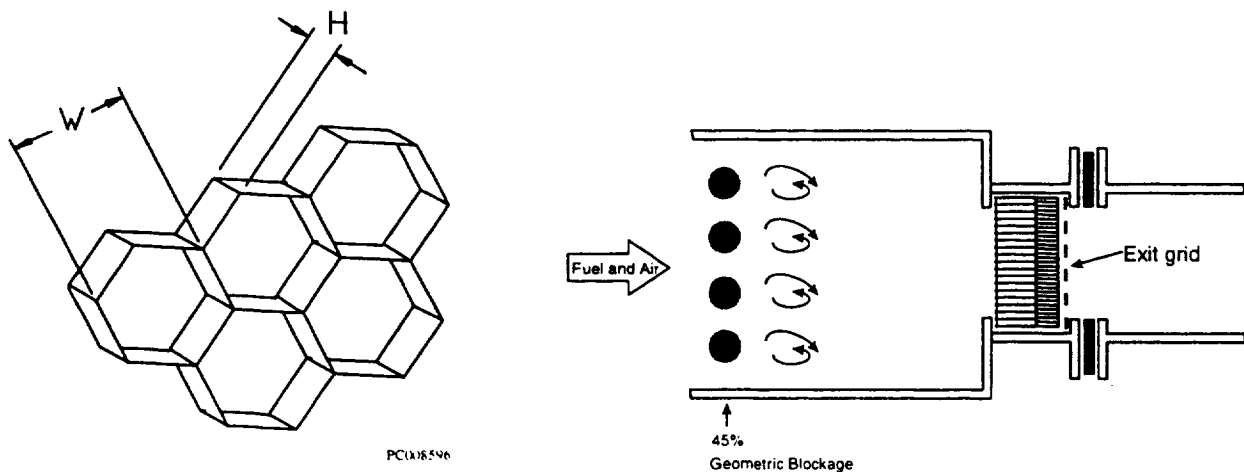
Three tests were conducted at each condition to examine the ability to quench a flame kernel formed by preignition, to arrest flashback from a detonation wave and to arrest flashback from a combustion (deflagration) wave. Ignition for the flame quenching and detonation flashback tests was provided by a spark plug which protruded 0.6 cm into the 4.6 cm diameter pipe creating a small flame holding region. The long pipe length (L/D of 6) resulted in detonations for the more turbulent downstream flow fields. Ignition for the deflagration wave testing was initiated by the ~ 7 cm flame from a propane torch at the exit of the test rig, as shown in Figure 4. Note the flange and graphite seal downstream of the flashback arrestor have jagged edges to emulate a non optimal installation with a combustor. The rig is designed with the intention of providing a rigorous test for the potential of each design to operate successfully in a gas turbine.

FLASHBACK ARRESTOR DESCRIPTIONS:

Three different designs of flashback arrestors were tested to determine their ability to arrest flashback, inhibit preignition and minimize static pressure drop. Table 1 lists the various geometries of the flashback arrestors tested and their open area. The long channel monoliths are representative of conventional designs ($L/D > 40$) which are based on diffusional quenching of the flame front on the wall. These designs were expected to produce a turbulent exit velocity profile due to self preserved jet structure resulting from the fully developed channel velocity profile. Previously, this form of downstream turbulence has been found to support flame holding at the monolith exit at high velocities [Wilson, 1995]. These designs serve as a reference for the flashback tests and for examining the effect of long channel monoliths on inhibiting downstream flame holding. Several off-set channel designs were tested with and without an exit grid. Exit grids properly located have been known to reduce the downstream turbulence generated by longer upstream channels as recently studied by Farrell and Youssef. In earlier works, the turbulence and pressure drop produced by monolith and screens has been described primarily at the exit plane [Loehrke, 1996, Scheiman, 1981, and Brundrett, 1993]. One off-set monolith designs was modified to examine the effect of breaking up the channel generated turbulence by adding a 50 mesh exit grid located 0.0 cm and 0.6 cm downstream of the exit monolith, as illustrated in Table 1. Removing most of the upstream turbulence is beneficial for flame quenching, preventing detonation (may only form deflagration waves in the same geometry due to reduced flame speed) and inhibiting downstream preignition and flame holding. Addition of fine exit grids would not be practical for aircraft gas turbine applications due to contaminate ingestion such as birds. Adding a fine exit grid was a simple approach to examine the effects of exit turbulence on downstream flame propagation for the same flashback arrestor configuration. A commercial, packed metal fiber pad type flashback arrestor was obtained. This device is advertised as a means to relaminarize the downstream flow field. This packed metal flashback arrestor was the only uncooled, short, commercial flashback arrestor we found which was designed to relaminarize the downstream flow. This design was chosen to be a base line to compare with our off-set monolith designs for the relative effect of relaminarizing the downstream flow on inhibiting downstream flame propagation.

Table 1. Geometries of the various flashback arrestors tested to date. Multiple monolith designs are listed with downstream monolith first. The monolith dimensions are given by the hexagonal cell width (W or for diameter for circular channels) first and then by cell height (H, or referred to as the length). The upstream geometric blockage to create turbulence was 45 %. NOTE: Sketches below indicate cell geometry and one typical installed configuration. Configuration 4 has a 50 mesh grid located at the exit of the second monolith and Configuration 5 has a 50 mesh grid located 0.6 cm downstream of the second monolith.

| Configuration | First Monolith | Second Monolith | Downstream Distance of Exit Grid from Second Monolith | Percent Open Area (least open monolith if more than one) |
|----------------------|--|----------------------------|---|--|
| 0 | None. baseline | | | 100 % |
| 1. single channel | 0.32 cm (W) by 3.8 cm (H) | none | none | 97 % |
| 2. off-set monolith | 0.32 cm (W) by 0.64 cm (H) | 0.08 cm (W) by 0.32 cm (H) | none | 88 % |
| 3. off-set monolith | 0.32 cm (W) by 0.64 cm (H) | 0.16 cm (W) by 0.32 cm (H) | none | 93 % |
| 4. off-set monolith | 0.32 cm (W) by 0.64 cm (H) | 0.16 cm (W) by 0.32 cm (H) | 0.0 cm | 93 % |
| 5. off-set monolith | 0.32 cm (W) by 0.64 cm (H) | 0.16 cm (W) by 0.32 cm (H) | 0.6 cm | 93 % |
| 6. single channel | 0.08 cm (W) by 2.5 cm (H) | none | none | 88 % |
| 7. single channel | 0.16 cm (W) by 3.8 cm (H) | none | none | 93 % |
| 8. off-set monolith | Configuration 3 but downstream spark plug flush with i.d. wall | | none | 93 % |
| 9. fibrous metal pad | Commercial flashback arrestor | | none | 84 % |
| 10. off-set monolith | 0.08 cm (W) by 0.32 cm (H) | 0.16 cm (W) by 0.32 cm (H) | 0.0 cm from First Monolith | 88 % |



Configuration 4

RESULTS

Ambient pressure, bench scale testing of three different flashback arrestor designs was conducted with Jet-A fuel over a wide range on inlet mixture velocity, temperature and equivalence ratio. The objective of this study was to examine the potential of a flashback arrestor composed of short off-set channels to replace higher pressure drop single, long channel monoliths and fibrous

metal pad type flashback arrestors. A second objective of this study was to determine the potential of a flashback arrestor to inhibit downstream flame holding and flame propagation after arresting a flashback event. Static pressure loss ($\Delta P/P$) data was obtained to examine the impact of the various designs on engine efficiency.

Arresting Flashback

Flashback testing was conducted at steady-state fuel flow conditions and transient fuel flow operation. During steady-state operation, ignition of the fuel and air mixture was provided by an automotive spark plug protruding into the exhaust tube or a butane torch located at the exit of the rig. Transient operation was simulated by turning on the spark plug before the fuel to observe the flame propagation and flame holding. After a stable flame was formed, the spark plug was turned off to examine if the flame would extinguish. Without a flashback arrestor present, detonation waves were usually formed above 300 °C and for $\phi \geq 1$. The detonation waves usually produced an acoustic intensity of over 130 dB and the deflagration waves usually produced a sound intensity of less than 100 dB. Between 200 °C and 400 °C, deflagration waves were formed at all of the test conditions examined. At most conditions, a deflagration wave would be formed after ignition with a flashback arrestor present.

Table 1 lists the configuration of the various flashback arrestors(FBA) tested extensively and discussed herein. The larger 0.32 cm wide single channel monolith, Configuration 1, did not arrest flashback above 500 °C. The other single channel designs (Configuration 6 and 7) and the fibrous metal pad flashback arrestor did arrest flashback below 650 °C. All of the short, off-set designs arrested flashback at all of the conditions tested. Configuration 3 was the most open (lowest pressure drop) off-set monolith FBA design and should be the off-set monolith design most likely to allow flashback due to the channel width. This design was able to arrest flashback at 735 °C inlet temperature. Damage to the air preheater prevented further testing above 700 °C after completing testing for Configuration 3. Based on these results, Configuration 3 provided the lowest pressure drop flashback arrestor tested capable of arresting flashback at a range of inlet conditions typical for a LPP combustor, even during transient conditions where the air velocity could decrease while the fuel flow increased. Configurations 2, 3, 4, 5, 6, 7 and 9 were able to arrest flashback at the maximum temperature tested; the additional margin for higher temperature operation above 735 °C at ambient pressure is unknown. A high pressure facility has been constructed to provide the required higher pressure data to select the lowest pressure loss design suitable for operation in an aircraft gas turbine.

The primary goal of this program is to demonstrate that the flame arrestor design can be effectively incorporated into a properly modified lean premixed natural gas combustor to prevent flashback and inhibit flame holding within the premixer at conditions similar to those expected for an aircraft gas turbine engine. Using a simple first order approach, the ambient pressure data can be referred to higher pressure conditions. The critical quenching distance is known to vary inversely with the square root of the global reaction rate for most hydrocarbon fuels [Friedman, 1952; Kuo, 1986]. Thus for the same aerodynamic conditions, the flashback arrestor performance at higher pressure conditions could be estimated by matching the global reaction rate at ambient pressure with the reaction rate at some higher pressure. For the same equivalence ratio, the matched global reaction rates would depend only on the inlet temperature and pressure at the two conditions. Ambient pressure is defined as one atmosphere. Then the global rate

equations at ambient pressure and at some referred inlet temperature and referred higher pressure condition can be solved to determine the temperature at ambient pressure required provide the same reaction rate as calculated for the higher pressure condition. The ambient temperature required to match the reaction rate over a range of higher referred pressures at a given referred temperature is shown in Figure 5 using a global reaction rate for hexane [Westbrook, 1981]. For example, the maximum flashback arrestor temperature tested of 735 °C (1008 K) was at one atmosphere. This ambient pressure test result would represent same reaction rate at about 5 atmospheres for an inlet temperature of 550 °C (823 K) and a 46 atmospheres for an inlet temperature of 400 °C (673 K) if hexane fuel was used. The validity of this first order approximation will be established as part of a future high pressure flashback arrestor development test program.

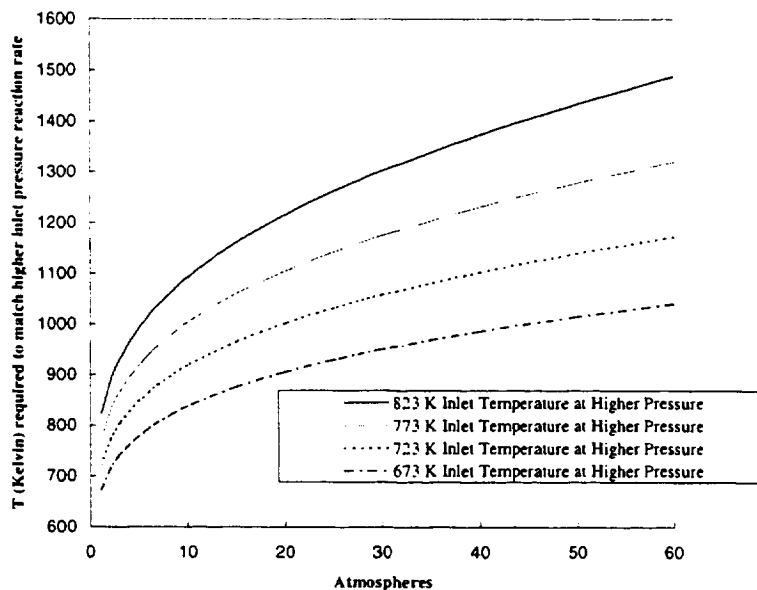


Figure 5 relates the inlet temperature required at ambient pressure to produce the same global reaction rate at some higher pressure. The same hexane equivalence ratio is assumed for each condition. The global rate equation suggested by Westbrook [1981] was used where rate varies as $[\text{Hexane}]^{0.25} [\text{O}_2]^{1.5} \exp(-15097/T)$.

The effect of upstream turbulence on the generation of a detonation wave was examined by increasing the geometric blockage at the location of the last row of turbulence generating rods shown in Figure 6. Note, the almost stagnant low velocity region formed near the bottom of the exhaust tube. If the 45 percent upstream blockage was increased to a 76 percent geometric blockage, detonation waves were formed without a flashback arrestor present at all conditions tested from 150 °C to 650 °C. Most aircraft gas turbine combustor designers would not consider designs with a blockage similar to that generated for this test, however, this configuration provided both detonation waves at all test conditions and a means to examine the influence of higher inlet turbulence and local low velocity regions on the flashback arrestor performance. Configuration 3T (same as Configuration 3 but with 76 % upstream blockage) was not able to arrest flashback above 400 C at low inlet velocities, however, Configuration 3 did arrest flashback at low velocities at 735 °C with a 45 percent upstream geometric blockage. To reduce

the inlet turbulence with the same monolith arrangement, a thin 50 mesh grid was placed upstream for design Configuration S3T. This design did arrest flashback at all conditions tested with a maximum inlet temperature of 650 °C. Similar results were obtained by the addition of another 0.32 cm cell width and a 0.64 cm long monolith upstream to reduce upstream turbulence. One off-set monolith configuration with smaller cell diameters, Configuration 10T, was tested to demonstrate that upstream turbulence could be reduced easily without a fine grid. Configuration 10T also provided a low pressure drop design using only two short off-set monoliths which both arrested flashback and suppressed downstream flame holding and propagation.

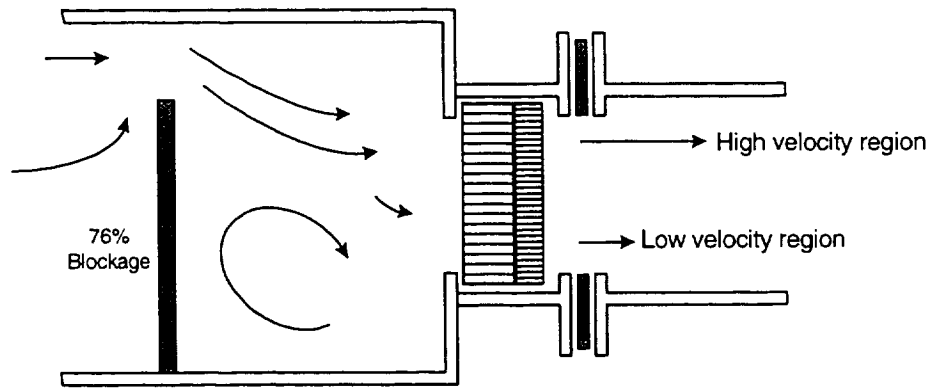


Fig. 6 Sketch of the flow field produced by the large upstream blockage to simulate an extremely adverse inlet flow condition.

Inhibiting Downstream Flame Holding

In addition to arresting a detonation wave, the flashback arrestor should inhibit downstream flame holding and downstream flame propagation. If pressure drop is an important design criteria, typically the flashback arrestor design is based long channel monoliths with cell width below the critical quenching diameter. Long channel monoliths are known to produce downstream turbulence which contributes to the turbulent flame speed. The objective of this test series was to examine the effect of various flashback arrestor designs on the downstream flame holding and downstream flame propagation. The test results would also provide an indication of the potential for flame generated by a preignition event to be quenched or to propagate in the region between the flashback arrestor and combustion chamber. The focus of the downstream flame propagation and quenching data is directed toward the data collected with a 45 percent upstream blockage. The 76 percent blockage produces a highly non uniform velocity distribution entering the various flashback arrestor leading to difficulties in generically interpreting the data.

A Laser Doppler Velocimeter (LDV) was not available during this study to measure the actual turbulence intensity needed to calculate the turbulent flame speed, however, the relative effect of the various designs to reduce the turbulent flame speed can be observed by comparing the maximum flame holding velocity. Configuration 9 was a commercial fibrous metal pad flashback arrestor advertised to relaminarize the downstream flow. Our objective was to create a low turbulence baseline for comparing the relative merit of the various thin wall monolith designs for minimizing the exit turbulence intensity. The fibrous metal pad was not considered

as a practical device for aircraft gas turbine due to the high pressure drop and potential for clogging of the small pores.

Once the flashback event has been extinguished, the flashback arrestor must not hold a flame which could damage downstream combustor components. If the exit turbulence intensity is almost zero, then flame holding would not be expected to occur above the laminar flame speed of 1 to 2 m/s for the range of conditions examined. Flame holding off the flashback arrestor face would be expected above the laminar flame speed if the device generated turbulence or did not fully dissipate the upstream turbulence. As the inlet air velocity increases a maximum velocity is exceeded that results in the flame blowing off the flashback arrestor face. This maximum velocity for sustained flame holding off the face of the flashback arrestor was determined by generating a flashback event in a steady state fuel-air mixture flow with a downstream spark ignitor. Once the combustion wave was generated, the power to the spark plug was discontinued. Results obtained for an inlet temperature of 400 °C are shown in Figure 7. Configuration 2 and 4 did not flame hold at the lowest velocity tested of 3 m/s at any Jet-A equivalence ratio. Generally, the maximum velocity was limited primarily to 15 m/s to minimize damage to the downstream graphite seal from the intense flames at higher velocities. Note, Configurations 1, 7 and 9 flame held at higher velocities greater than 15 m/s. Without a flashback arrestor, the rig (Configuration 0) would not flame hold above inlet velocity of 14 m/s at 400 °C. Configuration 9 apparently did not relaminarize the flow given the flame holding velocity is much higher than the laminar flame speed or several other monolith designs. For an inlet temperature of 650 °C, Configurations 2, 4, 5 and 6 would not flame hold at velocities below the minimum safe operating velocity for the heaters of 6.5 m/s.

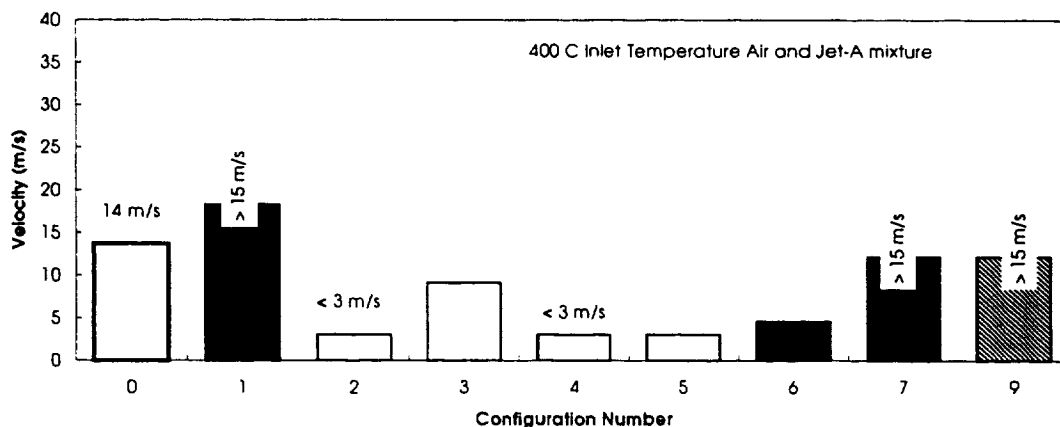


Fig. 7 Maximum recorded velocity for flame holding off the flashback arrestor face after arresting a combustion wave. Inlet temperature was 400 °C.

Flame holding within the exhaust duct was examined after a flashback event generated by a spark source within the duct and a butane torch at the exit of the duct. Configurations 2, 3, 4, 5 and 6 reduced the downstream turbulence sufficiently that only a deflagration wave was generated upon igniting the flow. Configurations 0, 1, 7 and 9 generated loud detonation waves (> 130 dB) especially with the spark ignitor which would blow out the flame without allowing flame holding at certain conditions. Across the range of test equivalence ratios examined, flames

were held off flash arrestor face at higher velocities if the flame was generated by the spark ignitor instead of the exit torch as can be observed by comparing Figs. 8 and 9 at a 600 °C inlet temperature. Typically, the flame was held off the protruding spark plug at the higher velocities and equivalence ratios with only a small flame streak extending some distance down the duct except for Configurations 6, 7 and 9. Based on sound intensity measurements, the spark ignitor produced more intense flashback events than the exit torch. These results would indicate the relative likelihood of a downstream flame holding of after a flashback or preignition event. The torch results would be more indicative of flames propagating upstream after combustor inlet velocity decreased and accompanied by an excess in fuel flow which could occur during compressor stall or rapid deceleration. For this test, the flashback arrestor design has less effect on flame holding within the tube. Although the reason for this observation is not known, transient pitot pressure probe observations indicate the magnitude of the flow oscillations decay further down the exhaust duct for Configurations 6, 7 and 9 to approach the magnitude of the flow oscillations at the exhaust duct exit for Configurations 3 and 6. Overall, the short off-set monolith flashback arrestor designs tend to inhibit downstream flame holding more than the single long channel monolith or fibrous metal pad flashback arrestors tested here.

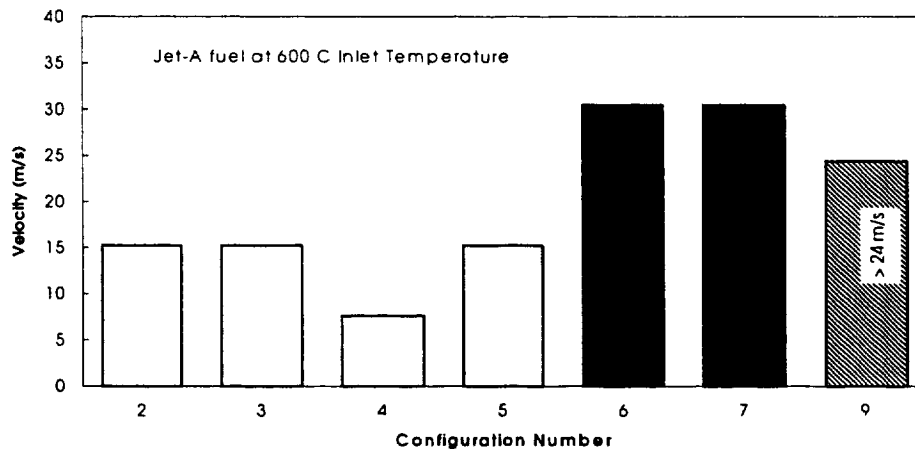


Fig. 8 Maximum recorded velocity for flame holding in the exhaust duct after arresting a combustion wave generated by the spark ignitor near the flashback arrestor. Inlet temperature was 600 °C.

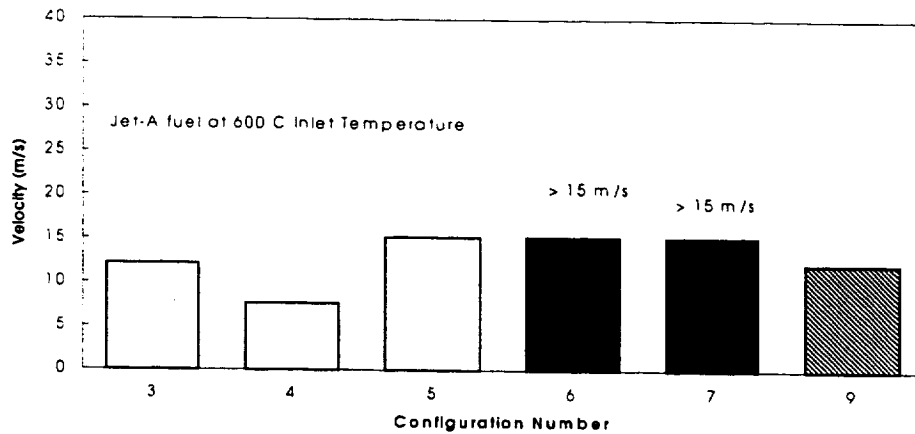


Fig. 9 Maximum recorded velocity for flame holding in the exhaust duct after arresting a combustion wave generated by butane torch near the exhaust duct exit. Inlet temperature was 600 °C.

Static Pressure Loss

The thin, off-set monolith configurations provided a lower pressure loss than similar single channel designs as given in Figure 10. The static pressure loss is the difference between the static pressure with a given flashback arrestor design and without it at the same inlet temperature and velocity flow conditions. All of the monolith based designs provided relatively low pressure loss compared to the fibrous metal pad design, Configuration 9. The static pressure loss is defined as the difference between the static pressure drop with and without a FBA installed into the test rig, normalized by the ambient room pressure. The static pressure loss is indicative of the FBA static pressure drop without rig effects. The pressure drop data were found to be not a function of Reynolds number. The pressure drop data was found to be a function of inlet velocity. A least squares correlation was developed for the flashback arrestor designs to calculate the static pressure drop at 122 m/s in Figure 10. Brundrett [1993] has found similar results for both thin screens and monoliths for isothermal conditions. Pressure drop was primarily a function of frontal area and velocity.

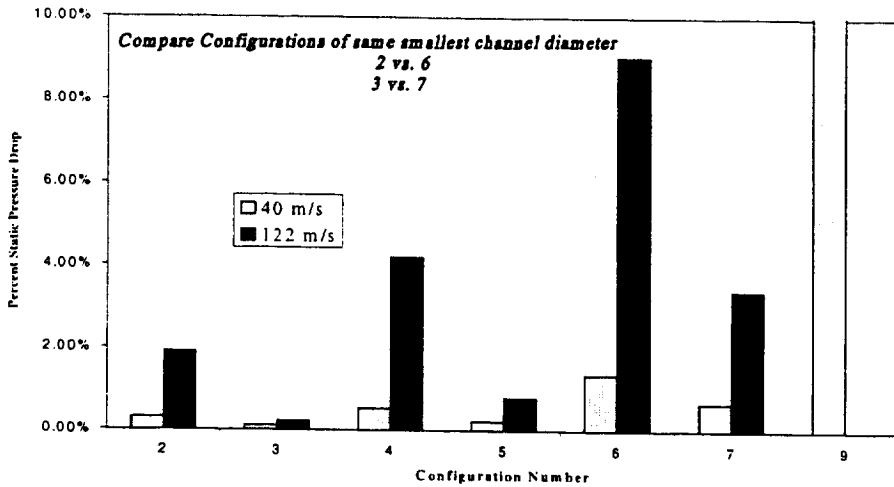


Fig. 10 Predicted static pressure drop from least squares fit of the data at 40 and 122 m/s for the various flashback arrestor designs tested. High static pressure drop of Configuration 9 prevented high velocity measurements with the centrifugal compressor used to supply the inlet air.

SUMMARY OF RESULTS

The proof-of-concept tests demonstrated the potential of a novel, short, low pressure loss, off-set monolith flashback arrestor/preignition inhibition designs especially for LPP combustor designs of current interest for HSCT and AST aircraft gas turbines. Flashback was arrested at all of the conditions tested for inlet temperatures of 200 °C to 735 °C, inlet velocities from 3 to 30 m/s and over the span of lean to rich Jet-A equivalence ratios of 0.5 to 4. This approach is adaptable to other combustor configurations and should be explored for certain LPP being considered for either HSCT or AST. Pressure testing is required to demonstrate the capability of the device to arrest flashback and inhibit preignition at aircraft combustor conditions; tests are planned to begin in 1997. Integrating this flashback arrestor device with an LPP combustor's premixer could prove enabling for safe, low NO_x aircraft and stationary gas turbines. Reducing the potential for stable flame formation in the premixer region could also lead to lower cost premixer designs.

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