Noise Mitigation by Manipulating Combustion using Porous Inert Media

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Hearing loss from noise induced by machines, engines, and flow systems is a major concern in industry. In gas turbine engines, a major source of direct noise is the turbulent heat release process in the combustor. In this study, the combustion process is manipulated passively using high-strength, oxidation-resistant porous inert materials (PIM) rings located within the reaction zone. Effectiveness of this approach is demonstrated from noise measurements acquired in a swirl-stabilized combustor replicating typical features of a gas turbine combustor. Atmospheric pressure experiments using methane fuel were conducted for a fixed air flow rate and equivalence ratios of 0.7 and 0.8. Several PIM configurations were investigated by varying the number of PIM rings, pore density or pores per cm, and PIM ring inner diameter. Results show that the PIM geometry has a significant effect on combustion noise. Diffuser shaped ring configuration of high pore density PIM was most effective in reducing the combustion noise.

Introduction

Noise-induced hearing loss is uncommon in the home or office, but it is a major concern in industry. Accessories such as ear-plugs and noise cancelling head phones are often mandatory in certain areas; however, anyone can be negligent to these devices. Typically, sound absorbing materials are placed in the workspace to protect from the noise generated by machines, engines, flow systems, turbines, etc. While this approach minimizes the adverse effects of the noise already created, an alternative approach is to mitigate the generation of the noise itself by improving the system design. In this study, this approach was implemented to reduce combustion generated noise in systems replicating gas turbine engines. The combustion process is manipulated passively using porous inert materials (PIM), designed to resist oxidation at temperatures above 1800 K, while retaining structural strength needed to sustain the reactions.

Sound consists of pressure waves propagating through a medium, and it is quantified by the sound pressure level (SPL) measured in decibels or dB [1]. The human auditory canal concentrates pressure waves. Then small, rigid structures, called hair cells, convert the sound energy into electrical signals recorded by the brain. Long duration exposure to SPL's of 100 dB or greater can be permanently damaging to hair cells. Single bursts of 140 dB or greater can temporarily damage hair cells [1]. Mechanical devices and support structures are also subject to noise-induced fatigue, particularly when resonance occurs; structures can unexpectedly collapse, causing catastrophic failure [2].

The focus of this study was on the gas turbine engine, which is the most popular method for powering not only aircrafts, but also plants that supply electricity to homes and factories. Many sources contribute to the noise in a gas turbine engine. Examples include noise created by airflow through guide vanes, mechanical noise, jet noise, and combustion noise. Although the relative importance of each noise source varies, the combustion noise alone can be significant in many cases. The combustion noise itself is composed of direct and indirect noise. Direct combustion noise is generated by pressure fluctuations resulting from the unsteady heat release process in the turbulent flow of the reactants [4]. Indirect combustion noise is produced as the imperfectly mixed combustion products flow through the downstream components such as turbine blades. Our focus, direct combustion noise, is often the primary source of combustion noise.

Figure 1 illustrates the flow structure in a swirl-stabilized combustor, typically used in gas turbines. Reactants enter the combustor through an annular swirler. The resulting annular jet undergoes sudden expansion in the combustor, where an outer recirculation zone (ORZ) and an inner recirculation zone (IRZ) are formed on either side of the jet. These recirculation zones trap hot products, which ignite fresh reactants in the annular jet to sustain the combustion process. The swirling motion imparted to the annular jet also helps to stabilize the flame. While recirculation zones supply the ignition energy necessary to sustain combustion, they also create vortical structures with a wide range of length and time scales. The turbulent fluctuations of vortical structures are a major source of combustion noise [5]. Thus, a method to ignite and stabilize the flame without the turbulent vortical structures can be effective in reducing the combustion noise.

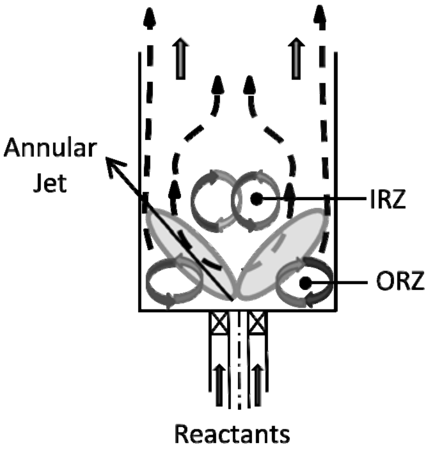


Figure 1. Flow field in a swirl stabilized combustor.

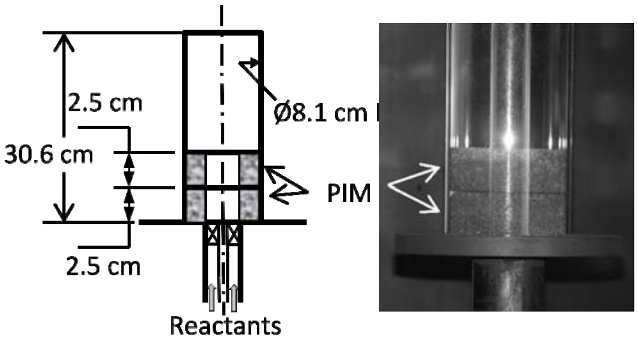
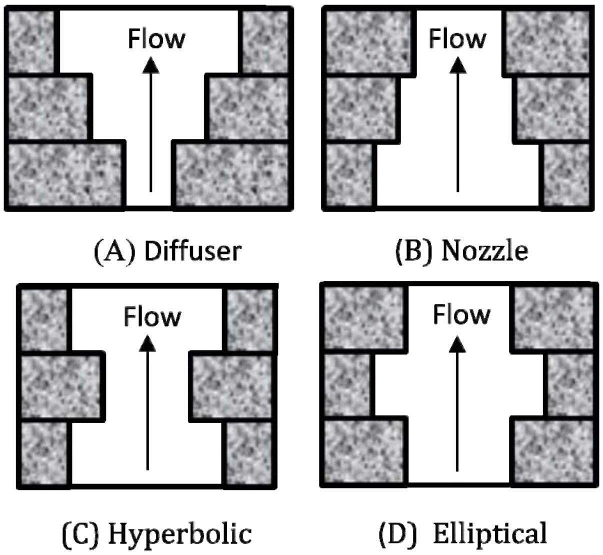


Figure 2. Placement of porous inert materials (PIM) in the combustor.

In this study, a PIM ring was placed inside the combustor as illustrated in Figure 2. The resistance to the flow caused by the PIM ring is hypothesized to intensify the swirling jet and constrain it to the core region. The PIM is also expected to eliminate the ORZ (and associated vortical structures) and to reduce the size of the IRZ [3]. Finally, a more uniform flow field is likely to emerge downstream of the PIM.

The photograph in Figure 2 shows the quartz combustor with two stacked PIM rings. The porous material is made of silicon-carbide coated carbon foam, and it offers high structural strength as well as oxidation resistance in the combustion environment. The PIM has porosity of about 0.85, i.e., the solid matrix occupies only about 15% of the flow area. The flow resistance of the PIM is affected by the pore density given in pores per cm or ppcm. Porous rings can be stacked to form different PIM configurations illustrated in Figure 3. The flow area decreases in the flow direction in a nozzle and increases in a diffuser configuration.

The flow area first decreases and then increases in the hyperbolic configuration, and it increases and then decreases in the elliptic configuration. In this study, only discrete changes in the flow area were considered since PIM rings of only fixed diameters were available. The objective of this study was to characterize combustion noise with and without the PIM placed inside the combustor. Experiments were conducted to understand how PIM geometry (configuration and pore density) affects combustion noise, so that an optimum PIM geometry with the minimum noise could be identified.



(A) Diffuser (B) Nozzle

(C) Hyperbolic (D) Elliptical

Figure 3. PIM configurations.

Experimental Setup

Figure 4 shows a schematic diagram of the experimental setup with a quartz combustor located downstream of the swirl injector. Combustion air supplied from a compressed storage tank was heated by an electrical heater, and then supplied to the mixing chamber through a plenum section to break down the turbulent flow structures. Gaseous methane from a storage tank was injected into the mixing chamber, where methane and air mixed to form homogeneous reactants at the inlet of the swirl injector. The inner and outer diameters of the swirl injector were 1.79 cm and 4.14 cm, respectively. Reactants were discharged into 8.1 cm ID, 30 cm long quart tube to complete the combustion. The combustion products from the quartz tube discharged into the ambient through a laboratory chimney and exhaust hood.

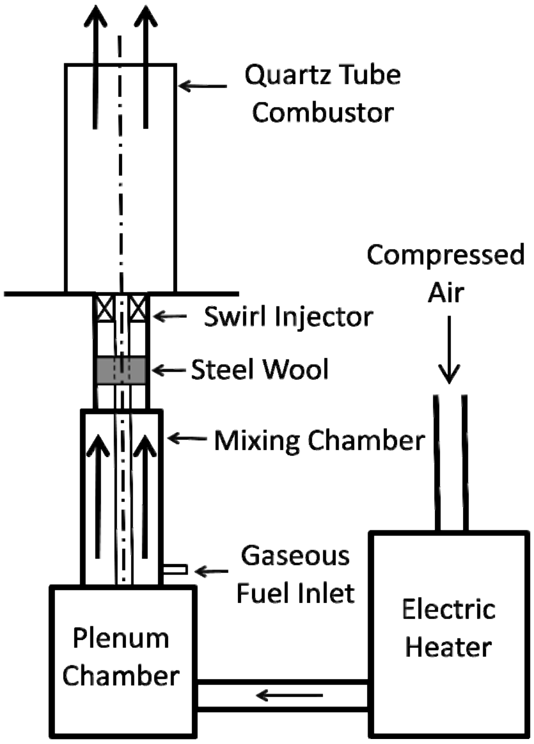


Figure 4. Experimental setup.

Calibrated laminar flow elements were used to measure the mass flow rates of air and fuel. A condenser microphone probe (BK type 4189) was used to acquire the sound measurements. The microphone probe converted pressure fluctuations into a voltage signal, which was amplified and recorded in digital form using a LabView based data acquisition system. The voltage data were acquired at 2000 Hz for 5 seconds. A fast Fourier transform algorithm was used to obtain the power spectra, expressed in terms of SPL in dB versus frequency using microphone probe calibration. The total SPL overall recorded frequencies was also computed in dB and dBA.

Experiments were conducted for fixed air flow rate of 300 standard liters per minute (SLPM) and heater exit temperature of 150°C, or combustor inlet temperature of 100˚C. The fuel flow rate was varied to obtain equivalence ratio (Ø) of 0.7 and 0.8. The PIM thickness and outer diameter were kept constant, respectively, at 2.5 cm and 8.1 cm. Experiments were conducted for different PIM configurations, formed by varying the number of PIM rings, pore density (measured in pores per cm or ppcm), and PIM inner diameter (ID). Either 2 or 3 PIM rings with pore density of 4, 8, and 18 ppcm and ID of 3.8, 4.4 or 5.1 cm were used. A nomenclature was developed to describe each configuration. For example, d38p4-d51p8-d51p18 represents a stack of three PIM rings. The first layer consists of a 3.8 cm ID PIM rings of 4 ppcm, the second layer consists of 8 ppcm PIM ring with 5.1 cm ID, and the third layer consists of 14 ppcm PIM ring with 5.1 cm ID. The sequence from left to right corresponds to the flow direction. A baseline combustor with no PIM and twenty different configurations with PIM were examined, each at Ø = 0.7 and 0.8.

Results and Discussion

Figure 5 shows photographs of the flame for the baseline combustor. The blue region in the image represents reaction zones, typically at the interfaces of the annular jet and recirculation zones. The flame structure changed in the presence of the PIM ring as shown by the photographs in Figures 6(a) and 6(b). Specifically, two modes of combustion were observed, depending upon the operating conditions. In the surface combustion mode (Figure 6a), small blue flamelets were formed at the downstream surface of the PIM, while an intense swirl-stabilized flame was established in the core region. In the interior or submerged combustion mode (Figure 6b), an intense flame in the core region was still present, but combustion also occurred inside the PIM as

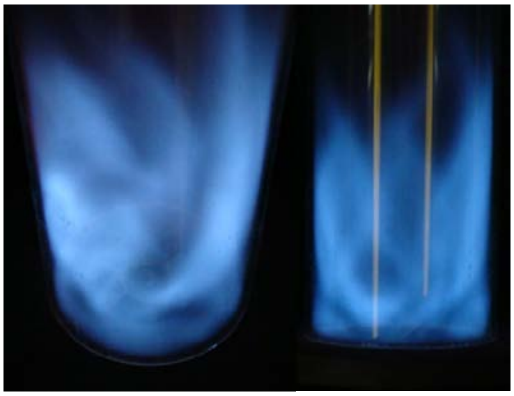


Figure 5. Baseline swirl-stabilized flame.

indicated by the intense glow. Thermal radiation from the PIM can raise combustor surface temperatures to unacceptably high levels and, hence, the interior combustion mode was deemed impractical. Measurements also indicated that the interior combustion mode increased the total SPLs.

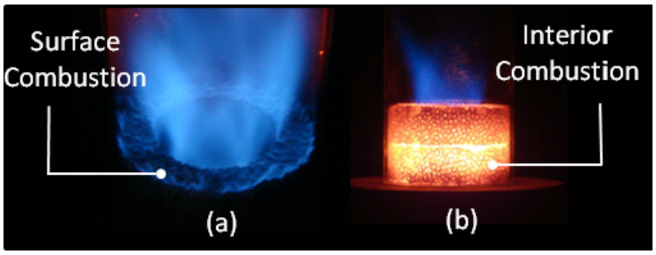


Figure 6. Swirl-stabilized flame with PIM (a) surface combustion, (b) interior combustion.

Effect of PIM Configuration

Experiments were conducted using 18 ppcm PIM ring in different configurations. Table 1 summarizes the test results in terms of the total SPL for Ø=0.7 and 0.8. The baseline combustor with no PIM (Case 1) produced total SPL of 95.8 dB at Ø=0.7 and 103.7 dB at Ø=0.8. For the next two cases, two PIM rings of same ID were used. Results show that the total SPL with uniform ID rings increased at Ø=0.7 but decreased at Ø=0.8. Larger ID rings (Case 3) performed better than the smaller ID rings (Case 2), indicating that the flow area occupied by the PIM is an important design parameter. Next, PIM configurations in Figure 3 were examined, each with three PIM rings, a necessity to create the hyperbolic and elliptic shapes. Results show that the nozzle and hyperbolic configurations performed poorly. Elliptic and diffuser configurations produced similar total SPLs, but the diffuser was deemed more promising since it could also be formed with only two PIM rings to limit the flow restriction. Indeed, the diffuser configuration with 2 PIM rings (Case 8) yielded the best performance in this first series of experiments. In comparison with the baseline combustor, Case 8 decreased the total SPL by 2.7 dB at Ø=0.7 and by 7.0 dB at Ø=0.8.

Table 1. Total sound pressure levels for different test configurations.

CASE	Case Config.	Case Design	Total SPL (dB/dBA)	
			Ø= 0.7	**Ø= 0.8**
1	No PIM	Baseline	**95.8/91.4**	**103.7/100.6**
2	Uniform area	d38p18-d38p18	100.4/94.8	101.0/97.3
3	Uniform area	d51p18-d51p18	96.4/91.3	98.9/95.2
4	Nozzle	d51p18-d51p18-d38p18	101.3/97.9	106.3/102.3
5	Hyperbolic	d51p18-d38p18-d51p18	101.7/98.5	103.4/100.1
6	Elliptic	d38p18-d51p18-d38p18	98.3/93.8	98.8/96.1
7	Diffuser	d38p18-d38p18-d51p18	97.8/87.7	99.1/95.5
8	Diffuser-2	d38p18-d51p18	**93.1/86.2**	**96.7/93.3**

Effect of Pore Density

Several diffuser configurations with different pore densities were examined, as shown in Table 2. A change in pore density from 18 ppcm to 8 ppcm (Case 2) deteriorated the performance since the interior combustion mode was readily established in the PIM with large pores (or small pore density). Next, the pore density of one of the rings was kept constant at 18 ppcm, while that of the other ring was varied to obtain a pore density gradient in the flow direction. For 18 ppcm PIM ring in the upstream, the SPL at Ø=0.7 was 93.1, 94.0, and 95.6 dB, respectively, for downstream PIM ring of 18, 8, and 4 ppcm. In contrast, for 18 ppcm PIM in the downstream, the SPL at Ø=0.7 was 93.1, 96.1, and 98.5 dB, respectively, for upstream PIM ring of 18, 8, and 4 ppcm. These results show that a large pore density PIM (18 ppcm in this case) is more desirable, especially in the upstream region. A diffuser configuration with seamless, tapered wall was envisioned; however, PIM is a complex structure requiring specialized manufacturing process to control its thickness and shape. Diffuser-3 (Case 7) with three PIM rings of gradually increasing diameter approximates this idealized configuration. Table 2 shows reduction in the total SPL, especially in terms of dBA, for this diffuser configuration.

Table 2. Total sound pressure levels for different diffuser configurations.

CASE	Case Config.	Case Design	Total SPL (dB/dBA)	
			Ø= 0.7	**Ø = 0.8**
1	Diffuser-2	d38p18-d51p18	**93.1/86.2**	**96.7/93.3**
2	Large pore, LP	d38p8-d51p8	100.9/96.0	101.1/98.9
3	Down-LP-8	d38p18-d51p8	94.0/85.9	97.0/93.1
4	Down-LP-4	d38p18-d51p4	95.6/90.4	97.7/94.8
5	LP-up-8	d38p8-d51p18	96.1/91.9	98.0/95.2
6	LP-up-4	d38p4-d51p18	98.5/94.9	99.5/96.5
7	Diffuser-3	d38p18-d44p18-d51p18	**92.1/82.2**	**97.3/92.4**

Conclusions

This study has shown that direct combustion noise can be reduced by passively manipulating the combustion process using PIM rings. The baseline combustor with no PIM rings produced total SPL of 95.8 dB (91.4 dBA) at Ø=0.7 and 103.7 dB (100.6 dBA) at Ø=0.8. The best performing PIM configuration reduced baseline noise levels by as much as 3.7 dB at Ø=0.7 and about 7.0 dB at Ø=0.8. Experiments revealed that PIM ring of diffuser shape is most effective for combustion noise reduction. In this study, the diffuser was formed with step changes in the flow area, but the ideal diffuser would be a seamless structure with tapered wall. Results show that a high pore density PIM (18 ppcm or higher) ring is necessary, especially in the upstream region, to effectively mitigate the combustion noise. High pore density PIM is also necessary to prevent combustion in interior mode and, hence, to safeguard against excessive heating of combustor surfaces, unexpectedly high sound pressure levels, and mechanical degradation of the PIM by repeated startup and shutdown.

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