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Investigation of Thermoacoustic Instability for Swirling Flames in a Dual Annular Stratified Burner

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ABSTRACT

Stratified flames have gained prominence in recent years due to the improved flame stability with reduced NOx and CO emissions and resilience to high turbulence. In the present study, the thermoacoustic instability in a stratified swirl dual annular burner was investigated for swirling flames varying the equivalence ratio at constant Reynolds number. The stratification ratio was varied from premixed condition (SR=1) to rich inner stream (SR=3) to study the effect of stratification on the suppression of thermoacoustic instabilities. The premixed swirling flames indicated the onset, coupling and amplification of thermoacoustic instability in the range of equivalence ratios from 0.8 to stoichiometry (1.0). This was followed by the subsequent decoupling of the oscillations at rich equivalence ratio conditions (Φ_g = 1.1). Under stratified conditions (SR=2 and SR=3), thermoacoustic instability was triggered across the same range of equivalence ratio as well. However, stratification helped to reduce the peak amplitudes in the sound pressure by 72% at SR=2 and 64% at SR=3. The heat release amplitude was also damped by approximately 70% in both cases. This shows that stratification can be deployed, within certain range, to suppress and control the thermoacoustic instabilities. The absence of thermoacoustic instability under very lean conditions near blowoff also allows the stratified burner for lean operation thus reducing the CO emissions.

Keywords: thermoacoustic instability, stratified flames, swirling flames, dual annular combustor.

NONMENCLATURE

Abbreviations	
FFT	Fast Fourier Transform
NI	National Instruments
PMT	Photomultiplier Tube
SR	Stratification Ratio
Symbols	
A	Volume of air
F	Volume of fuel
Φ	Equivalence ratio

1. INTRODUCTION

Lean-premixed combustion is deployed as a means to meet up with the stringent emission regulations for NO_x while increasing combustion efficiencies by reducing CO emissions [1]. However, lean-premixed combustion systems are prone to challenges associated with flame stabilization (static instabilities) and thermoacoustic instabilities (dynamic instabilities). The static instabilities include flame flashback and blowout – a consequence of the competition between chemical reaction rates and species diffusion rates- influenced strongly by lean mixtures [2]. The use of swirl to stabilize lean-premixed flames is very common. Swirl-stabilized flames, however, present their unique instability challenges, which are hydrodynamic in nature, mainly due to features of swirling flows like vortex breakdown and precessing vortex core (PVC). These flow features are associated with unique static instability like the vortex-breakdown-

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induced flashback as well as thermo-acoustic instabilities [3][4]. Scenarios where heat release rate and acoustic pressure fluctuations couple together to generate undesirable pressure waves inside the combustor are categorized as dynamic instabilities, also known as thermoacoustic instability [2]. These thermoacoustic instabilities are problematic because they can create excess noise, reduce operation capability, and can lead to significantly increased vibrations and heat transfer in the combustor resulting in possible damage and destruction to the combustor structure. Hence, it is essential to study these thermoacoustic instabilities and how they can be suppressed and controlled.

One of the means of improving the static stability of lean-premixed flames is by employing stratified combustion. Generally, stratified flames display greater static stability with lower NOx emissions compared to their conventional lean-premixed flames counterparts [5]. Stratified burners use two separate pre-mixed fuel and oxidizer mixtures to enhance static stability of lean-premixed combustion. One of the mixtures, usually the inner mixture, is non-lean and is used to sustain the main flame from the outer mixture, which is leaner[6] [7] [8]. The most important parameters in stratified combustion is the stratification ratio (SR) defined as the ratio of the equivalence ratio of the inner mixture to that of the outer mixture. This parameter affects stability and the emissions from stratified flames as they affect the flames propagation speed and the entire flame-flow interactions [9] [10]. It is reported that for stratified burners, the SR directly controls the flame macrostructure, which affects the dynamics within such burners [11]. Stratified burners have been designed and studied by different research groups such as the those by Sweeney et al. [12] and BASIS burner by Han et.al. [13]. The changes to chemistry and flame-flow interaction introduced from the use of stratification necessitate studying the thermoacoustic stability of such combustion systems. While thermoacoustic stability studies are relatively available for non-swirling stratified flames, there is a limited literature on stratified swirling flames [13].

Some of the studies on swirl-stabilized stratified burners include Kim and Hochgreb [14], who investigated methane-air flames subjected to forced excitation. At a constant global equivalence ratio of 0.6 and varying stratification ratio, the flame stabilization response showed different behaviours. Kim and Hochgreb [11] conducted another research on the impact of non-uniform reactant stoichiometry on thermoacoustic instability. A broad variety of stratification ratios was tested, including inner stream enrichment and outer stream enrichment. Han and Hochgreb [15] showed that the gradient in local equivalence ratio had a significant effect on structure of swirl-stabilized, stratified flames as well as their subsequent response to sound velocity fluctuations.

Han et al. [13] investigated the thermoacoustic instabilities from swirl-stabilized, stratified, and non-stratified flames and the effect of the flame macrostructures on the instabilities. Stronger dependence of flames structures with SR over equivalence ratio was reported. Furthermore, the stratified flames were found to exhibit more thermo-acoustic stability having out-of-phase heat release oscillations with the pressure field [13]. Han et al. [16] also studied the relations between the pilot and main flames using the same burner by examining each flame (pilot, main flame, and stratified flame) independently. The oscillation observed for the stratified flame is unique (two frequencies that are closely spaced) compared to the pilot flame and the un-stratified main flame [16]. The influence of stratification on stabilization of the flame and self-excited thermoacoustic oscillations was studied for a dual swirl stratified burner designed by Arndt et al. [17]. Stratification ratio was varied and at different frequencies, major self-induced fluctuations were observed for all flames with the peak frequency appearing at 700 Hz. By examining the velocity fluctuations, chemiluminescence intensities, and the pressure spectra these different modes were observed and identified.

This study aimed to build on these and other works by researchers that studied thermoacoustic instability of stratified flames in a swirl-stabilized combustors. For this purpose, a novel, dual-annular, swirl-stabilized burner was designed and developed. The thermoacoustic instability of methane-air flames in this burner is investigated experimentally. Using the sound pressure and heat release data acquired at varying equivalence and stratification ratios, the stability window of this novel burner is established. Furthermore, the influence of stratification towards the suppression and control of thermoacoustic instabilities was investigated in this study.

2. EXPERIMENTAL METHODOLOGY

2.1 Experimental Setup

The schematic diagram of the experimental setup is shown in Fig. 1. A compressor is used to supply air to the combustor. The air passes through a moisture removal device to remove the water vapor present in the air. Methane with a purity of 99.99% is used as fuel and is supplied from a compressed gas cylinder. ALICAT mass flow controllers are used to control the supply of the reactants to the combustor from their respective sources. The mass flow controllers have an accuracy of ±0.8% reading and ± 0.2% full scale. Air and methane are supplied to plenum of the combustor through stainless steel pipes of diameter 12.7 mm where it is premixed upstream of the combustion chamber. A Photo Multiplier Tube along with a CH* bandpass filter was used to measure heat release fluctuations. The sound pressure variation was recorded using microphones.

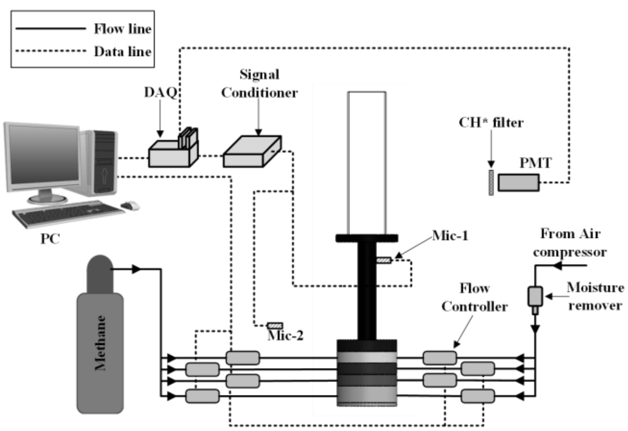

Fig. 1. Schematic Diagram of the experimental setup

The detailed geometry of the stratified swirl dual annular burner is shown in Fig. 2 below. The burner consists of three coaxial tubes, with the innermost tube of dimension 12.7 mm being used only to support the ceramic bluff body for anchoring the flame and there is no flow of gases or air supplied in the inner tube.

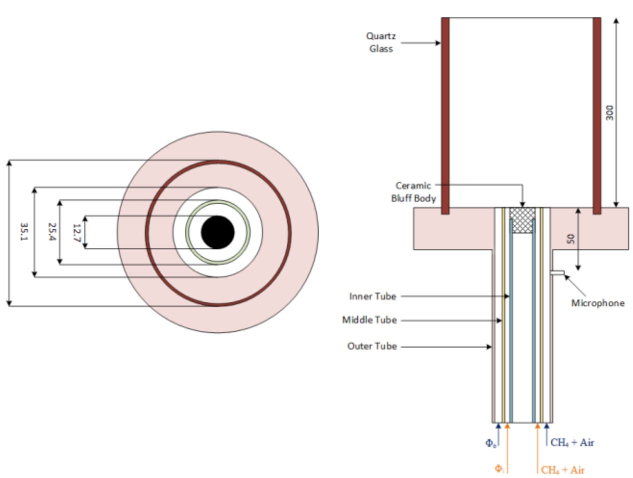

Fig. 2. Detailed geometry of the stratified swirl dual annular combustor (all dimensions in mm)

The middle and the outer tube form the dual annular geometry i.e., the inner and outer annulus, respectively, through which premixed mixture of air and methane flows into the combustion chamber. Further details regarding the geometry and dimensions of the burner and the different plenums through which straight and swirl flows are supplied into the inner and outer annulus can be found in the study carried out by Shakeel and Mokheimer [18] investigating the static stability and flame macrostructure for this stratified burner.

2.2 Instrumentation and operating conditions

The acoustic pressure fluctuations are measured by high intensity microphones (MIC-093) manufactured by Kulite semiconductor products Inc. One of the microphones is installed 50 mm upstream of the combustor dump plane in the outer annulus by flush mounting as indicated in Fig. 2. A second microphone was installed away from the combustor to capture the background noise such that it can be eliminated from the sound pressure fluctuations captured by the first microphone. For controlling factors such as gain and overload a signal conditioner manufactured by Kulite Semiconductors has been used in combination with the microphones to obtain the acoustic pressure fluctuations.

The heat release fluctuations in the flame can be captured and represented by chemiluminescence intensities produced by intermediate radicals such as CH* and OH*. These radicals have narrow spectral band at which they emit radiation with CH* radicals emitting at around 431 nm and OH* radicals emitting at around 308 nm. In this study CH* chemiluminescence is measured by a photomultiplier tube module (PMT), model H10722-110, manufactured by Hamamatsu Photonics UK LTD. The PMT is used along with a CH* bandpass filter manufactured by Thorlabs, that has peak transmission at 430±5 nm wavelength . The PMT is placed at a fixed distance from the flame aligned in such a way that the flame profile is accurately captured by the PMT.

The data obtained for the sound pressure and heat release measurements are fed into a data acquisition system from National Instruments (NI) and is recorded using LABVIEW software. The data was collected at a sampling frequency of 5 kHz for 10 seconds and a total of 50,000 data points were taken for each condition. All experiments are carried out at atmospheric pressure and ambient temperature conditions. Spectral analysis of the data obtained was done by using Fast Fourier Transform (FFT) to convert the data from time domain to frequency domain in order to identify the peak amplitudes and frequencies.

The equivalence ratio(Φ) is defined as the ratio of actual to stoichiometric fuel-air ratio and is given by:

$$\phi = \frac{\left(\frac{F}{A}\right)_{\text{actual}}}{\left(\frac{F}{A}\right)_{\text{stoichiometric}}} \quad (1)$$

The global equivalence ratio (ϕ_g) is determined from the inner annulus equivalence ratio (ϕ_{inner}) and the outer annulus equivalence ratio (ϕ_{outer}) of the stratified burner. The inner and outer equivalence ratio is varied by varying the air fuel mixture entering the inner and outer annulus.

The stratification ratio (SR) is an important parameter and is defined as:

$$SR = \frac{\phi_{inner}}{\phi_{outer}} \quad (2)$$

The operating conditions that are employed for the present study only illustrated the results for swirling flames for stratification ratio 1, 2, and 3. Thermoacoustic instability is investigated at these three stratification ratios, for various global equivalence ratios from lean conditions (flame blowout) to rich conditions (1.2). Reynolds number in the inner and outer annulus is fixed at 3000 and 6000 for the experiments, respectively. Further experiments for swirling flames for a more wider range of stratification ratios will be carried out later along with the investigation of jet flames as well.

3. RESULTS AND DISCUSSION

Swirling flames are investigated to study the effect of stratification on the peak amplitudes and frequencies and identify the impact of stratification for controlling and suppressing the thermoacoustic instabilities. The swirling flames occurred due to the supply of air-fuel mixture flowing only through the plenums containing the swirler, connected to the inner and outer annulus.

Fig. 3 illustrates the acoustic and heat release spectra at different global equivalence ratios varying from 0.8 to 1 for premixed swirling flames (SR=1). Under lean conditions from 0.46 (flame blowout) up to 0.75 no peaks appear in the acoustic pressure spectra, the heat release spectra show some peaks but with no coupling or onset of thermoacoustic instability occurs in this range of equivalence ratio. These peaks in the heat release spectra occur below 200 Hz and above 960 Hz. These low frequency (below 200 Hz) and high frequency (around 960Hz) peaks in the heat release sectra do not produce any subsequent amplification in pressure fluctuations and hence also do not excite any thermoacoustic modes. Hence the sound pressure and heat release spectra under these conditions are not illustrated in the figure. The absence of thermoacoustic instability under lean conditions near blowoff allows for the operation of the stratified burner without any instability risks thus reducing CO emissions.

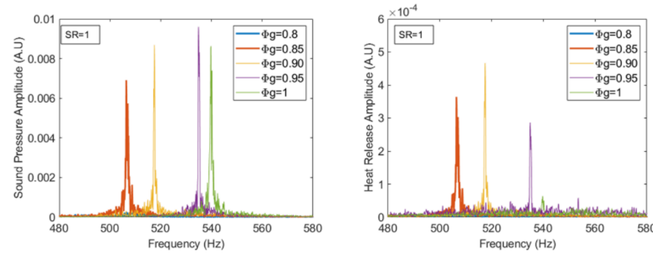

Fig. 3. Acoustic and heat release spectra for varying equivalence ratio at SR=1 for premixed swirling flames

At 0.8 equivalence ratio similar peaks appear in both pressure and heat release spectra indicating the onset of thermoacoustic instabilities, however, at slightly different frequencies with 506.8 Hz in pressure spectra and 508.8 Hz in heat release spectra indicating that coupling had not occurred yet. At 0.85 equivalence ratio the coupling of pressure and heat release spectra can be observed at same frequency of 506.4 Hz indicating the amplification of thermoacoustic instabilities with the peaks having significant amplitude in both the spectra. The maximum amplitude in both the spectra occurs at 0.9 while the frequency of both the dominant peaks shifts to a slightly higher value of 517.5 Hz. At this point the physical noise during the experiment is extremely high and very unpleasant compared to when there was no coupling of the spectra. Following this, a decrease in the amplitude for heat release is observed for Φ_g=0.95 at frequency of 534.9 Hz, however, the sound pressure spectra indicate the highest amplitude for this condition. The coupling shifts towards very low amplitude coupling under stoichiometric conditions (Φ_g=1) and is eventually decoupled under rich conditions at equivalence ratio of 1.1. The maximum frequency reaches 539.7 Hz under stoichiometric conditions.

Fig. 4 represents the acoustic pressure and heat release spectra for stratification ratio of 2. Under this condition the equivalence ratio in the inner annulus is double of the outer annulus signifying a rich flame in the inner annulus. At SR=2, flame blowout occurred at Φ_g=0.45 with no peaks appearing in the sound pressure spectra from this condition up to Φ_g=0.75. The heat release spectra had some low and high frequency peaks, however no coupling or thermoacoustic instability was observed across this range. Similar to the flame at SR=1 the onset of thermoacoustic instability occurs at global equivalence ratio (Φ_g) 0.8 with the coupling taking place at Φ_g=0.85.

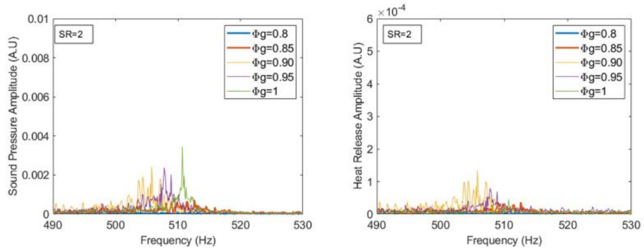

Fig. 4. Acoustic and heat release spectra for varying equivalence ratio at SR=2 for swirling flames

The maximum amplitude coupling for both sound and heat release spectra occurs at Φ_g=0.9 at the frequency of 505.8 Hz followed by a decrease in both pressure and heat release amplitudes at Φ_g=0.95 at frequency of 507.8 Hz. The sound pressure amplitude reaches its highest value at stoichiometric conditions (at Φ_g= 1.0) at a frequency of 510.7 Hz, however, the heat release fluctuation is substantially diminished. Following this, decoupling of sound pressure and heat release occurs at Φ_g = 1.1. The maximum frequency of 512.7 Hz occurred at Φ_g = 0.85 for this condition differing from SR=1. The frequencies at which the coupling occurred shifted to slightly lower values under stratified condition.

The amplitude of the peak frequencies is significantly lower compared to the SR=1.0 for all equivalence ratio conditions. Under peak coupling conditions at at Φ_g = 0.9, comparing both the cases the sound pressure amplitude was damped by 72% and the heat release amplitude was damped by 70.4% at SR=2. The amplitudes are significantly suppressed under this condition.

Fig. 5 represents the acoustic pressure and heat release spectra for stratification ratio 3. Under this condition the equivalence ratio in the inner annulus is triple that of the outer annulus signifying a very rich flame in the inner annulus. At SR=3, flame blowout occurred at Φ_g=0.38 with no peaks appearing in the sound pressure spectra from this condition up to Φ_g=0.75. The heat release spectra had some low and high frequency peaks, however no coupling or thermoacoustic instability was observed across this range. Similar to the flames at SR=1 and SR=2 the onset of thermoacoustic instability occurs at global equivalence ratio (Φ_g) 0.8 with the coupling taking place at Φ_g=0.85.

The maximum amplitude coupling for both sound and heat release spectra occurs at Φ_g=0.9 at the frequency of 503.9 Hz. This is followed by a decrease in both sound pressure and heat release amplitudes at Φ_g=0.95 at frequency of 506.6 Hz. The sound pressure amplitude and heat release amplitude further decreases under stoichiometric conditions (Φ_g=1) at a frequency of 511.3 Hz which is the highest frequency observed at this condition. Following this, decoupling of sound pressure and heat release occurs at Φ_g =1.1. Under highly stratified conditions the frequency of coupling had shifted to lower values similar to SR=2, compared to SR=1.

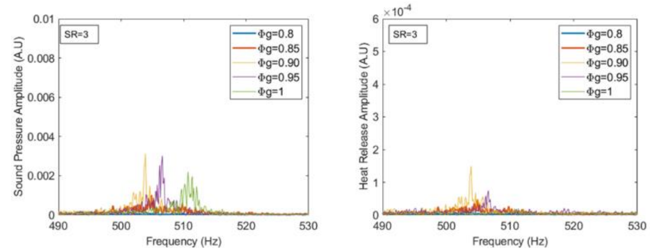

Fig. 5. Acoustic and heat release spectra for varying equivalence ratio at SR=3 for swirling flames

At SR=3, the amplitude of the peak frequencies is significantly lower as well compared to the SR=1.0 for all equivalence ratio conditions. Under peak coupling conditions at at Φ_g = 0.9, comparing both the cases the sound pressure amplitude was damped by 64% and the heat release amplitude was damped by 68% at SR=3. The damping of amplitudes were slightly lower compared to SR=2 which showed the highest damping approximately 72% however the damping was still very significant.

Hence, this represents significant suppression of thermoacoustic instability under stratified conditions and thus stratification is hugely beneficial for control of thermoacoustic instability. Further studies will be carried out for a wider range of stratification ratios as well as for jet flames to better understand the thermoacoustic instability phenomena in the dual annular stratified burner.

4. CONCLUSION

This research examined the thermoacoustic instability for swirling flames with varied equivalence ratios at constant Reynolds numbers in a stratified swirl dual annular burner. To investigate how stratification affects the suppression of thermoacoustic instabilities, the stratification ratio was changed from the premixed condition (SR=1) to the rich inner stream (SR=3). In the range of equivalence ratios from 0.8 to stoichiometry (1.0), the premixed swirling flames (SR=1) demonstrated the initiation, coupling, and amplification of thermoacoustic instability. At rich equivalence ratio condition (Φ_g=1.1), the oscillations subsequently decoupled from one another. Thermoacoustic instability also manifested itself within the same range of equivalence ratio under stratified conditions (SR=2 and SR=3). However, stratification assisted in lowering the peak sound pressure amplitudes by 72% at SR=2 and 64% at SR=3. In both stratified conditions, the heat release amplitude was also reduced by almost 70%. This demonstrates that stratification can be used to reduce and control thermoacoustic instabilities in practical combustion applications. The stratified burner allows for lean operation and reduce CO emissions since there is no thermoacoustic instability in very lean situations close to blowoff.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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