

Flame macrostructures and thermoacoustic instabilities in stratified swirling flames

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Abstract

The present article investigates the correlation between flame macrostructures and thermoacoustic combustion instabilities in stratified swirling flames. Experiments are carried out in a laboratory scale longitudinal test rig equipped with the Beihang Axial Swirler Independently-Stratified (BASIS) burner, a novel double-swirled combustion system developed by adapting an industrial lean premixed prevaporized (LPP) combustor. At first, the flame macrostructures are investigated and discussed for various total equivalence ratios (ϕ_{total}) and stratification ratios (SRs). Depending on operating conditions, three different flame types are stabilized in the combustor: two attached flames comprising a stratified flame and a V-shaped flame (V-flame), as well as a lifted flame. Thermoacoustic instabilities are then investigated. The amplitude of the oscillations is found to be more sensitive to SR than the ϕ_{total} .

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Large amplitude limit cycles are found for low and high values of SR, for which the V-flame and the lifted flame are observed in the combustor, respectively. The flame dynamics are also investigated using a local Rayleigh index map. It is found that for both the lifted flame and V-flame, the major driving force comes from the flame-to-wall impingement region. Coherent structures associated with flame wrinkling are found along the flame brushes of the V-flame. On the contrary, the stratified flame is found to be more thermo-acoustically stable. Finally, incompressible Large Eddy Simulations is used to obtain the flame responses to forcing at 300 Hz, which is very close to the frequencies at which limit cycle oscillations occur. The results show that the global heat release rate response of the stratified flame exhibits a significant phase shift compared to the responses of the other two flame types, and this is the most likely cause of thermoacoustic stabilisation.

Keywords:

Stratified swirling flame, Flame macrostructure, Thermoacoustic instabilities

1. Introduction

Lean premixed prevaporized (LPP) combustors are often affected by combustion instabilities arising from mutual interactions between pressure fluctuations (p') and heat release rate oscillations ($\dot{q}'$) produced by the flame. To ensure a wide stable operating range, LPP combustors often feature staged combustion with a central pilot flame surrounded by an annular main flame. The interaction of the pilot and main flames is complex and often show stratification [1]. Figure 1 shows a typical structure for a concentrically staged

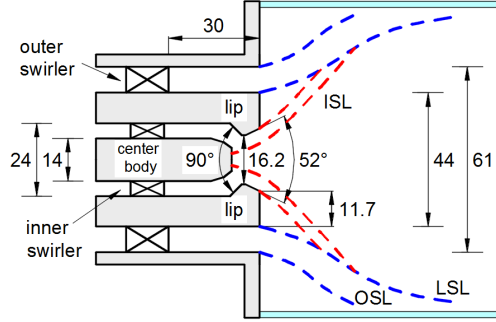


Figure 1: Detailed geometry of the BASIS combustor, all to scale except for the flame tube. Dimensions are in millimeter. ISL stands for the inner shear layer originating from the inner stage, while LSL and OSL stand for the lip shear layer and the outer shear layer of the outer stage, respectively.

combustor, which consists of inner and outer swirlers separated by a lip structure. The resulting flow field features three major shear layers, the inner shear layer (ISL), lip shear layer (LSL), and outer shear layer (OSL). Swirling flames are usually stabilised inside the shear layers with relatively low local flow velocity. The flame macrostructure provides information on stabilization point and spatial heat release distribution. It is an important flame characteristic [2] that affects combustor emissions [3], blowoff [4], and tendency to thermoacoustic instabilities [5, 6].

For these reasons, over the years many works have studied flame macrostructures and their links to thermoacoustic instabilities. Most of them focus on configurations featuring a single swirling flame in a longitudinal flame tube. Lee et al. [7] calculated the Rayleigh index based on the measured OH-PLIF and found that under unstable conditions, the index in the corner recirculation zone (CRZ) is positive, which implies a driving effect. Taamallah et al. [6] observed “flame flickering” in the CRZ under certain equivalence ratios,

which was related to the onset of thermoacoustic instabilities. Shanbhogue et al. [2] used a normalized strain rate to collapse the oscillation amplitudes for different fuel blends and found the onset of instabilities is linked to the transition of flame shape. Huang and Yang [8] used Large Eddy Simulations (LES) to reproduce the flame dynamics found in experiments of [9]. When the inlet temperature increased over a critical value, the flame penetrates the CRZ and was stabilised at both the inner and outer shear layers eventually. The flap of this compact flame results in unsteady heat release and leads to the thermoacoustic instabilities. These links can also be found in spray flames. Based on a dual-swirler fuel-staged injector, Providakis et al. [10] found that two different averaged flame shapes can occur at the same fuel split ratio by varying the operating routines, implying a hysteresis phenomenon. These two flames also have different thermoacoustic properties [11], and transition between the two flames can be triggered by acoustic excitation [12].

Much work has focussed on non-swirling stratified flames [13–16], which has been reviewed recently in [17, 18]. However, very few works specifically address stratified swirling flames, especially the correlation between flame macrostructures and thermoacoustic instability. For this typology, in addition to the parameters listed above (equivalence ratio, fuel blending, operating condition and routine, etc.), two more coefficients have a direct effect on flame macrostructures: the stratification ratio (SR), defined as the ratio of the inner equivalence ratio to the outer equivalence ratio [19]; and the air split ratio (ASR), defined as the ratio of mass flow rate of inner stream to outer stream [3]. Kim and Hochgreb [19] observed that in an undivided stratified swirl burner, SR directly controls the flame shape. The flame lifts

off when SR equals 2 and is attached to the burner when SR equals 0.5 and 1. SR was also found to influence also the flame angle, an expanded flame was obtained with a leaner inner stream. Chong et al. [3] examined the effect of ASR on the flame shape and found that larger inner flow increases the flame intensity, which results in a longer flame and a larger reaction zone. Sweeney et al. [20] conducted delicate measurements of flame structures in a stratified swirl burner, but did not study thermoacoustic properties. However, the above three configurations do not feature a separation lip between the inner and outer streams, which is essential to reduce NO_x emissions [21]. Li et al. [22] tested a single swirl burner with a non-swirled pilot, and found that the presence of heat release in the inner shear layer leads to a destabilization of the global flame. The flow and reaction fields of a full-scale industrial LPP burner fuelled with kerosene have been measured by Dhanuka et al. [23]. The stratified flame structure was shown by flame surface density distribution, with separate pilot and main flames ahead of merging downstream of the lip structure. Combustion instabilities exhibiting a Helmholtz mode were observed [1], but the few operating conditions limited the variety of observed flame macrostructures.

In the present study, we aim to fill the gap by examining the link between flame macrostructures and thermoacoustics for stratified flames across a wide range of operating conditions. This is achieved by presenting an experimental analysis of the flame macrostructures and thermoacoustic instabilities featured by premixed stratified swirl flames for varying total equivalence ratios and stratification ratios. Thermoacoustic instabilities are characterised with the amplitudes of pressure fluctuations as a function of the flame macrostruc-

ture. The flame dynamics are also analysed via local Rayleigh index maps, to provide insights into the mechanism driving thermoacoustic instability. Finally, for each flame type the response of the unsteadiness in the global heat release rate to incoming velocity perturbations is computed using LES and these responses are compared across different flame types.

2. Experimental setup

The burner employed in this work is the Beihang Axial Swirler Independently-Stratified (BASIS) burner, sketched in Fig. 1 with detailed geometrical dimensions. This burner was developed at Beihang University by adapting an industrial LPP combustor and maintaining its main aero-thermodynamic characteristics. The burner features a central staged structure with an inner and an outer stage. The inner stage comprises an axial swirler containing 8 straight blades of 45° , a center body and a converging-diverging throat to enhance the stability of inner flame. The outer stage comprises an axial swirler with 20 straight blades of 30° . The inner and outer swirl numbers are estimated using the geometry method [24] to be 0.88 and 0.56, respectively. The height of the lip between the inner and outer stages is 11.7 mm. The shape of the lip structure is designed to control the divergence of the inner stream and the merging of the two streams. A lip recirculation zone (LRZ) exists near the lip, which separates the two flame brushes and facilitates NOx reduction [21]. These features aim to better represent the complex aerodynamics of real combustors, while remaining configurational simplicity for research. The burner opens to a quartz tube of 800 mm in length and 140 mm in diameter. This length is chosen to achieve a balance of the onset

of combustion instabilities and the feasibility of experiments.

Figure 2 shows the schematic of the test rig. The burner is operated at atmospheric pressure with perfectly premixed mixtures of methane-air. The fuel and oxidizer mixing is achieved in premixing units located upstream of the two swirlers. In order to achieve the target stratification ratio (SR) and air split ratio (ASR), fuel and oxidizer mass flow rates are continuously monitored before entering the premixing units. Air mass flow rates are regulated by means of standard orifice flowmeters with an accuracy of 2 %. Mass Flow Controllers (Sevenstar, CS200) with an accuracy of 1 % are used for the fuel lines. In both channels, the mixture is maintained at a constant temperature equal to 310 K, continuously monitored by a thermocouple. An intensified high-speed camera (Photron, Fastcam SA4) is used to capture the flame dynamics. The image dimension is 160 mm $\times$ 160 mm, corresponding to 768 $\times$ 768 pixels. A total of 3882 snapshots are obtained at an exposure time of 200 μ s and a sampling rate of 5000 fps. The time-averaged flame shapes are also measured by a digital single-lens reflex (DSLR) camera with an exposure time of 1 s and ISO of 640. A photomultiplier (PMT) of Hamamatsu, H9306, is used to measure the global CH* chemiluminescence emission as representative of heat release rate [25]. The above three optical instruments are equipped with CH* filters (430 $\pm$ 5 nm). To monitor the pressure fluctuation, 5 dynamic pressure sensors (PCB, 112A22) are installed along the test rig as shown in Fig. 2. Note that S1 and S2 are flush mounted to the outer channel while S3-S5 are installed with semi-infinite tubes due to the overheated flame tube. All data are collected by a DAQ system (National Instruments, NI9215) at a sampling frequency of 5 kHz. A total of 30,000

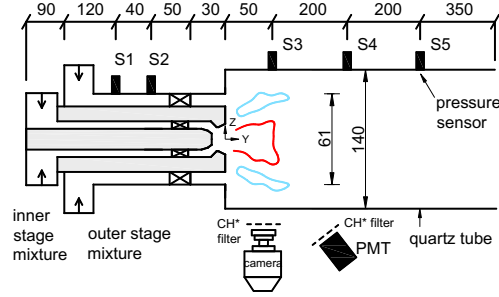


Figure 2: Schematic of the test rig (not to scale). All dimensions are in millimetre.

data points are taken for each condition.

The test conditions in the present study are chosen as follows: the total mass flow rate of air is kept constant at 20 g/s with an ASR of 1:8 between the inner and outer channels, consistent with the typical split in LPP combustors. The bulk velocities of the inner and outer stream are around 6.5 m/s and 11 m/s, resulting in Reynolds numbers of around 4000 and 12000, respectively. The total equivalence ratio (ϕ_{total}) varies from 0.5 to 0.8 across a wide range of stratification ratios from 0.25 to 2.5, increasing in steps of 0.25.

3. Results and discussion

3.1. Flame macrostructures

The time-averaged flame shapes observed for varying SR and ϕ_{total} are shown in Fig. 3. The flame shapes at $\phi_{total}=0.5$, 0.6, and 0.7 (first three rows in Fig. 3) are recorded using a DSLR camera with a long exposure time of 1 s, whereas results at $\phi_{total}=0.8$ (last row in Fig. 3) are obtained averaging 3882 snapshots from a high-speed camera. It is seen that the differences between these two acquisition methods are small. Since all images are symmetric,

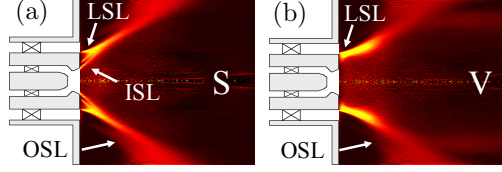


Figure 4: Flame macrostructures of (a) the stratified flame for $\phi_{total}=0.6$ with $SR=1.25$ condition and (b) the V-flame for $\phi_{total}=0.6$ with $SR=2.5$ condition.

show the magnified flame structure at the flame root for S- and V-flames, respectively. It is seen in Fig. 4(a) that the flame is stratified with the flame stabilised at the inner shear layer (ISL) and the lip shear layer (LSL) separated by the lip recirculation zone. The inner flame enters the diverging part of the inner stage (see the arrow of ISL), while the outer flame anchors at the edge of the lip structure (see the arrow of LSL). The two flame brushes then merge at the lip recirculation zone leading to a stratified flame. This flame macrostructure differs from the typical flame shapes observed for swirling flames previously enlisted in [3, 19, 27] and is specific to staged combustors, similar to the flames in [23]. For the V-flame cases, shown in Fig. 4(b), the inner stream flame quenches and the flame is only anchored in the LSL of the outer stage. The recirculation zone near the lip structure provides a low-velocity zone for the flame to stabilize, which is also the region with higher chemiluminescence intensity. This is consistent with the typical structure of a single swirling flame.

Lifted flames are often observed for low and high SR values at high ϕ_{total} . Interestingly, for lower SR , the lifted flame is stabilized in both the inner and outer shear layers of the outer stage. On the contrary, for higher SR the flame is toroidal detached and similar to those found in [28]. However,

in this paper, we do not differentiate these two types of flame and consider them simply as lifted flames.

3.2. Thermoacoustic instabilities

The frequency and amplitude of the pressure oscillations measured by the S3 sensor (Fig. 2) are used as a marker of thermoacoustic oscillations across all operating conditions. The amplitude (top) and frequency (bottom) are shown in Fig. 5, based on 6 seconds of signal sampled at 5,000 Hz (FFTs for 6 signal segments each spanning roughly 17 thermoacoustic oscillation cycles are performed). Figure 5 connects the mean frequencies and amplitudes at each operating condition with lines. The amplitude for $\phi_{total}=0.5$ is so low that it is not included. The scatter in the amplitude, also observed in other configurations [29–31], is within 25%, other than for a few cases ($\phi_{total}=0.8$ and SR of 0.25, 2 and 2.25). The scatter in the frequency is very low, remaining below 2%.

The influence of the stratification ratio on the thermoacoustic stability for a given total equivalence ratio will be first discussed. The amplitude plot for $\phi_{total}=0.6$ (yellow line with circular marks in Fig. 5), starts from an unstable condition at SR=0.25 where a limit cycle of $\simeq 100$ Pa amplitude is recorded. A decrease in oscillation amplitude with increasing stratification ratio is then observed, with the shift from unstable to stable occurring at SR=1.0, as observed from the almost flat spectrum and collapsed phase space reconstruction [32] for the pressure signal shown in Fig. 6(a). Beyond this further increasing the SR leads to the combustor becoming unstable again. Analysing the pressure signals, this new unstable region can be further divided into two zones. For stratification ratios higher than SR=1.75,

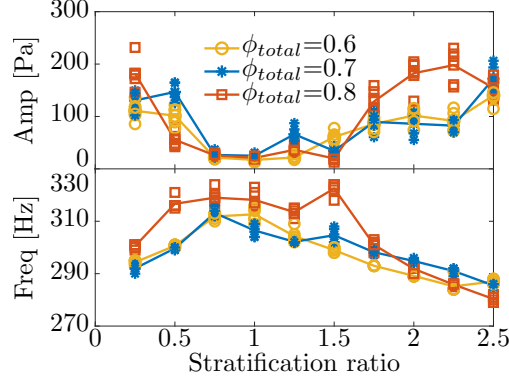


Figure 5: Pressure fluctuation amplitude (top) and frequency of peak oscillation (bottom) for various total equivalence ratios and stratification ratios. Yellow hollow circles for $\phi_{total}=0.6$, blue solid circles for $\phi_{total}=0.7$, red hollow squares for $\phi_{total}=0.8$.

the signals spectra feature a sharp peak with high signal-to-noise ratio and a clear limit cycle is observed in the phase plot, as shown in Fig. 6(c) for SR=2.5. On the contrary, for SR between 1.25 and 1.75, although an amplitude peak of $\simeq 50$ Pa is clearly observed in the pressure signal spectra, the phase space plots reveal a transition status between stable and unstable conditions, as shown in Fig. 6(b) for SR=1.5. Focusing now on the frequency plot (the bottom of Fig. 5), limit cycles are concentrated around 300 Hz, a frequency value compatible with the quarter-wave acoustic mode of the 800 mm flame tube. The frequency range across various SR varies from 325 Hz to 280 Hz and will be caused by changes in the flame response or in the combustor temperature distribution for different cases. Similar trends for both amplitude and frequency are obtained for the higher total equivalence ratios. A general increase in oscillation amplitude with ϕ_{total} is observable with the maximum peak for $\phi_{total}=0.8$ at SR=0.25 and SR=2.25.

Figure 7 shows the distribution map of the oscillation amplitudes and

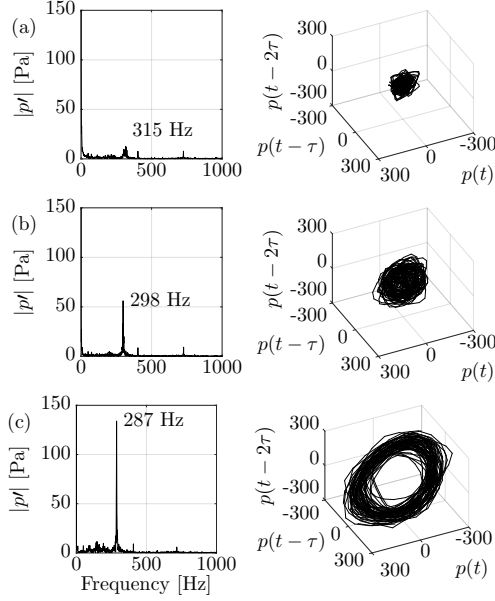


Figure 6: Spectrum (left) and phase space reconstruction (right) of the pressure signals at $\phi_{total}=0.6$ and (a) SR=1.0 (stable), (b) SR=1.5 (transition) and (c) SR=2.5 (unstable).

flame types plotted as a function of the inner and outer equivalence ratios (ϕ_i and ϕ_o , respectively). First of all, the relationship of flame macrostructures to ϕ_i and ϕ_o is considered. Generally, one can notice that flame types seem to be distributed vertically rather than horizontally, implying ϕ_i is of more importance on flame macrostructures. Specifically, it is found that the stratified flame exists only with $\phi_i=0.5-1.0$ with only one exception (SR=2.5 for $\phi_{total}=0.5$). In this range, almost all cases observe a stratified flame no matter how the ϕ_o changes. It is believed that the ϕ_i is the main factor affecting the formation of stratified flames. This is reasonable because the inner stream is relatively independent of the outer stream, due to the separation of the lip structure.

The link between flame macrostructure and thermoacoustic instabili-

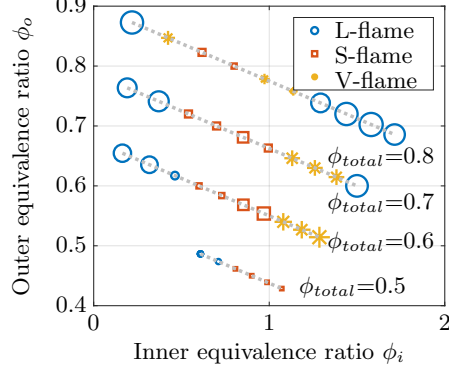


Figure 7: Distribution map of flame macrostructures and amplitude of thermoacoustic instabilities. The size of symbols denotes for the fluctuation amplitude.

ties is then discussed. The L-flame and V-flame generally correspond to the combustor being unstable, with few exceptions for the $\phi_{total}=0.8$ case for low values of the inner equivalence ratio ϕ_i . To better illustrate the flame dynamics of these flame types, the normalised local Rayleigh index maps of two unstable cases are shown in Fig. 8 for one corresponding to L-flame and one V-flame, respectively. The index maps are calculated using $R_{local} = \tau^{-1} \int_{\tau} p' \cdot I'_{CH^*} dt$ [1], where p' is the pressure fluctuation, measured by the S3 sensor and I'_{CH^*} is the fluctuation of heat release rate, obtained by the intensity of CH^* chemiluminescence from a high-speed camera with the averaged value subtracted. τ is the calculation period, set to 60 cycles for each case based on its oscillation frequency. In the local Rayleigh index maps, a positive region denotes a contribution driving thermoacoustic instabilities while a negative region denotes damping. For both flames, a large driving region can be observed in the flame-to-wall impingement zone. This is in line with previous studies [2, 33, 34], where the presence of flame in the

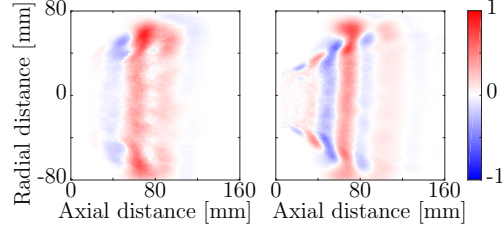


Figure 8: Local Rayleigh index maps at $\phi_{total}=0.6$ for (a) L-flame at SR=0.5 and (b) V-flame at SR=2.0.

OSL was found to enhance the flame-wall interaction, contributing to the driving mechanisms. Coherent structures are also clearly observable along the flame brushes in Fig. 8(b), implying a wrinkling of the V-flame.

A different scenario is observed in Fig. 7 for the stratified flame. The pressure oscillation amplitudes are always smaller than for the lifted or V-flames, meaning that the stratified flame is thermoacoustically more stable. This is regardless of the presence of heat release in the OSL (shown in Fig. 4(a)). A possible explanation of this can be deduced from Fig. 7. A shift from S-flame to L-flame or V-flame normally accompanied by destabilization of thermoacoustics. Exception is $\phi_{total} = 0.8$ for which both S and V-flames correspond to stability. From this, it appears that the presence of flame in the inner shear layer facilitated by the presence of the lip is a stabilizing condition for the analysed burner. This result is different with what observed in [22], where the heat release in the pilot was found to destabilize the global flame. However, in [22] a non-swirled pilot was used, providing a stream with positive axial velocity downstream of the pilot, rather than the central recirculation zone with negative axial velocity. This will alter the global response of the flame to oscillations, hence leading to very different thermoacoustic stability

characteristics.

3.3. Flame responses via LES

To better investigate the thermoacoustic properties of the analysed combustor, the impact of the flame types on the flame response to longitudinal acoustic forcing is further investigated. In the frequency domain, in the limit of small perturbations, this function is usually given in terms of the so-called Flame Transfer Function (FTF) [35], i.e., a function that relates the heat release rate perturbation ($\dot{Q}'/\bar{Q}$) at the flame location with longitudinal velocity fluctuations ($|u'/\bar{u}|$) taken at an upstream reference point. Mathematically, this results in a complex function defined as $F(\omega) = \frac{\dot{Q}'/\bar{Q}}{u'/\bar{u}} = G(\omega)e^{i\varphi(\omega)}$, where G and φ are the gain and phase of the FTF, respectively, and ω is the angular frequency. The measurement of this function was not possible in BASIS at the time of the experiments. For this reason, LES using OpenFOAM is performed with an incompressible approximation for the flow-field with the density considered a function only of the temperature – this has been used in previous LES studies of perturbed and unperturbed turbulent combustion [36]. To close the Favre-filtered reactive flow conservation equations, the WALE sub-grid model [37] is applied to define the filtered Reynolds stresses. The partially-stirred reactor (PaSR) combustion model [38] is used to model the filtered chemical reaction rates based on a global four-step methane-air reaction mechanism with 6 intermediate species [39]. The adiabatic flame temperature and laminar flame speed of this scheme have been validated using the GRI-Mech 3.0 full scheme. The computational domain used for the LES starts from 55 mm upstream of the dome (11 mm upstream of the outer swirler) and ends at 200 mm downstream, and is discretised us-

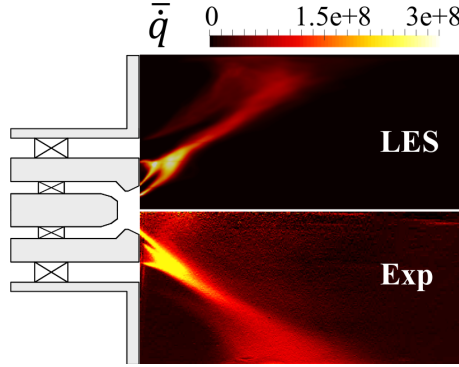


Figure 9: Time-averaged heat release field from unforced LES (top) and experimental flame shape (bottom) of stratified flame with $SR=1.5$ and $\phi_{total}=0.6$. The LES result is plotted by averaged volumetric heat release rate in the range of $0-3 \times 10^8 \text{ W} \cdot \text{m}^{-3}$.

ing a 12-million-elements fully-structured mesh. A prescribed velocity inlet and convective outflow boundary conditions are applied. All the solid boundaries are defined as non-slip walls. To account for the heat exchange effect, a constant temperature of 700 K is imposed at the backplane of the combustion chamber and a linear distribution from 700 K to 1500 K is fixed on the combustion chamber wall, values being derived from experimental observations. All the other walls are adiabatic. The employed numerical setup has proven able to predict experimentally observed flame shapes under different test conditions [40]. The comparison of the time-averaged S-flame between LES and experiment is shown in Fig. 9, with the LES agreeing well with experimental observation. Similar agreement is also found for the L-flame and V-flame, and detailed comparison can be found in [40].

The unsteady responses of the flame to forcing are simulated by superimposing a harmonic velocity perturbation onto the mean mixture inflow velocity at both annular passages of the inner and outer streams. An imposed

Table 1: Simulated flame responses of different SRs with $\phi_{total}=0.6$, with the forcing frequency of 300 Hz.

Cases	Flame type	Amplitude (Pa)	Gain	Phase ($/\pi$)
SR=0.5	L-flame	101	0.16	-1.11
SR=1.0	S-flame	-	0.51	-1.47
SR=2.5	V-flame	140	0.67	-1.06

velocity of the form $u_i=\bar{u}_i [1 + A \sin(2\pi ft)]$, with $A=|u'/\bar{u}|$ the normalised forcing amplitude and f the forcing frequency, is used. In the present analysis, only one amplitude level of $A=0.1$ is considered for a single forcing frequency of 300 Hz, the value around which all limit cycles are concentrated. Following [36], the gain and phase of the numerical FTF are computed using 15–20 simulation cycles after the simulation transient has died away; this ensures scatter of less than 1%. Three stratification ratios covering all the flame types were then chosen at $\phi_{total}=0.6$. Results of the predicted gain and phase, together with the measured oscillation amplitude are enlisted in Tab. 1. It is noted that the flame responses at the two unstable conditions, i.e., the L-flame at SR=0.5 and the V-flame at SR=2.5, are characterized by the same value for phase but different gains, with higher value for the V-flame. This can be considered consistent with the results reported in Fig. 7, where the V-flames features the stronger limit cycle¹. The SR=1.0 flame

¹Please note that this is strictly true if a monotonic decrease of the gain with increasing velocity forcing level together with an almost constant acoustic damping is assumed. Both hypotheses are often verified in practice [41, 42]

response features a gain value in line with the other configurations but with a significant increment of the phase shift of $\sim 0.4\pi$. This increase of the time delay between the velocity and the heat release rate oscillations can be assumed as the factor leading to the thermoacoustic stabilization of the system.

4. Conclusions

This paper describes the correlation between flame macrostructures and thermoacoustic instabilities in the stratified BASIS burner developed at the Beihang University. Three different flames types, i.e., stratified flame, V-shaped flame, and lifted flame, are observed as a function of total equivalence ratio (ϕ_{total}) and stratification ratio (SR). Further analysis shows that the inner equivalence ratio is the main factor affecting the flame macrostructure. Among the three types of flame macrostructures, the lifted and V-shaped flames are more susceptible to instability with the major driving force coming from the flame-to-wall impingement zone, which is in line with previous studies. On the contrary, no limit cycles are observed for the stratified flames. This is linked to the flame anchoring in the inner shear layer which is eased by the lip separating the two independent swirls. The forced LES results at 300 Hz have revealed a phase shift between the stratified flame response and the other two configurations, which is expected to account for the stabilization of the combustor. More investigations are required to further correlate the stability of the stratified flame with the heat release rate in the inner shear layer.

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