Energy Proceedings
Vol 28, 2022
ISSN 2004-2965

Static Stability and Flame Macrostructure of Stratified Jet Flames#

Mohammad Raghib Shakeel[1], Esmail M. A. Mokheimer [1,2*]

1 Department of Mechanical Engineering, College of Engineering, King Fahd University of Minerals & Petroleum (KFUPM), 31261 Dharhan, Saudi Arabia

2 Researcher at K.A. CARE Energy Research & Innovation Center at Dhahran, Saudi Arabia

ABSTRACT

Stratified Flames have gained prominence in the combustion research applications due to its improved stability and lower emission characteristics. In the present study, stratified jet flames are studied in a dual annular combustor. The static stability and the flame macrostructure have been presented and discussed. Stratification by making the inner annulus mixture rich was found to significantly improve the static stability limits. Furthermore, stratification by making the inner annulus rich was found to lead to attached flame at lower equivalence ratios of 0.22-0.38. Thus, stratification is more helpful at lower equivalence ratios.

Keywords: Stratified flames, static stability, lean blowoff limit, dual annular burner

NONMENCLATURE

Abbreviations	
LBO	*Lean Blowoff limit*
SR	*Stratification Ratio*
Symbols	
A	*Volume of Air*
F	*Volume of fuel*
Re	*Reynolds number*
ϕ	Equivalence Ratio

1. INTRODUCTION

The introduction of compositional inhomogeneity in the reaction zones through inlets with different compositions leads to "Stratified Flames". Stratified flames are considered to be special cases of partially premixed flames wherein the fluid streams are within flammable limits such that the reaction front propagates over a range of equivalence ratios. Studies involving laminar stratified flames [1–5] have shown improvement of flammability limits and a higher rate of reaction in comparison to premixed flames. The improvement is attributed to the back-supported burning, wherein the radicals and heat from the reaction zone propagate towards the mixture ahead of the flame front similar to the case of burning happening from stoichiometric to lean mixtures. Kang and Kyritsis [6] reported significant improvement in flame speed prediction by taking into account the history of stratified flame propagation apart from local equivalence ratio values and its spatial gradient. A similar observation was made by Pasquier et al. [7] when experimentally examining flame propagation through a lean, turbulent, and stratified mixture of propane and air. The flame propagation in the turbulent flame was found to improve with stratification. Furthermore, in the turbulent flame, the local burning velocity can vary depending upon the local composition of the mixture and the distribution of mixture composition along the flame front.

Several laboratory scale burners have been designed and experimentally examined to study the flame propagation and behaviour of stratified turbulent flames. Some of the prominent burners that have been extensively studied experimentally and numerically are the Oracle burner [8], Cambridge slot burner [9], Darmstadt burner [10], Cambridge Swirl burner [11], Sydney inhomogeneous piloted burner [12], and the BASIS burner [13].

Sweeney et al. [9,14] experimentally studied the structure of stratified flames with low turbulence. In comparison to premixed flames, the stratified flames were found to have higher surface density and scalar dissipation. However, in another burner at a higher turbulence level the surface density, curvature and scalar dissipation were found to show negligible dependence on stratification [15]. Stratification was found to elevate the H_2 and CO levels in the flame in comparison to premixed cases [11]. Swirl was found to affect the extent of preferential transport and enhance the mean stratification gradient.

Han et al.[16] studied the flame macrostructures and thermoacoustic instabilities of stratified swirling flames. Depending upon the operating conditions they observed different flame shapes. They found that the amplitude of flame oscillation was more sensitive to stratification ratio than the change in global equivalence ratio. Thermoacoustic instabilities arise due to fluctuations in flow velocity or mixture compositions and can lead to damaged burners.

Another type of stability called the static stability limit of combustors is characterized by their blowout tendencies. This stability comes into play at high equivalence ratio where flame flashback occurs or at extremely low equivalence ratio, where, as the flame gets leaner, they can get lifted from their anchoring position followed by extinction or direct extinction of flames. It helps determine how lean the combustor can be operated. Operating combustors under lean conditions help lower the emissions while also helping in controlling the power output from the combustor. Previous experimental studies have focused only on the flame structure and the thermoacoustic instabilities. Thus, there is a significant gap in understanding the effect of stratification on the static stability limits. In this regards a dual annular burner was designed and manufactured to study stratified flames. In the present study non-swirling or jet flames are studied experimentally on a dual annular burner. The effect of stratification on the flame macro structure and static stability is presented and discussed.

2. EXPERIMENTRAL METHADOLOGY

2.1 Experimental Setup

A mixture of air and methane is burned in a dual annular stratified burner. Air is supplied from a compressor; a moisture remover is used to remove the water vapor in the compressed air. In addition, Ultra-high purity methane of grade *N4.5* (99.995%) is supplied from a compressed gas cylinder, to be used as fuel. The gases are transported to the burner via 12.7 mm diameter stainless steel pipes. The pipes are directly connected to the plenum of the burner where mixing of air and fuel takes place before it travels downstream towards the combustion chamber. Figure 1 shows the schematic diagram of the experimental setup. The flow of gases is regulated using flow controllers manufactured by Alicat Inc. The flow controllers were factory calibrated with flow accuracies that fall within ±0.8% of the reading and ±0.2% of the full-scale reading.

The equivalence ratio (ϕ) is calculated as,

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

The Stratification ratio (*SR*) is defined as,

$$SR = \frac{\phi_{in}}{\phi_{out}} \tag{2}$$

Where ϕ_{in} is the equivalence ratio in the inner annulus and ϕ_{out} is the equivalence ratio in the outer annulus. In addition to ϕ_{in} and ϕ_{out} we can also have ϕ_g, called as global equivalence ratio which is calculated based on the total air fuel mixture entering the combustion chamber.

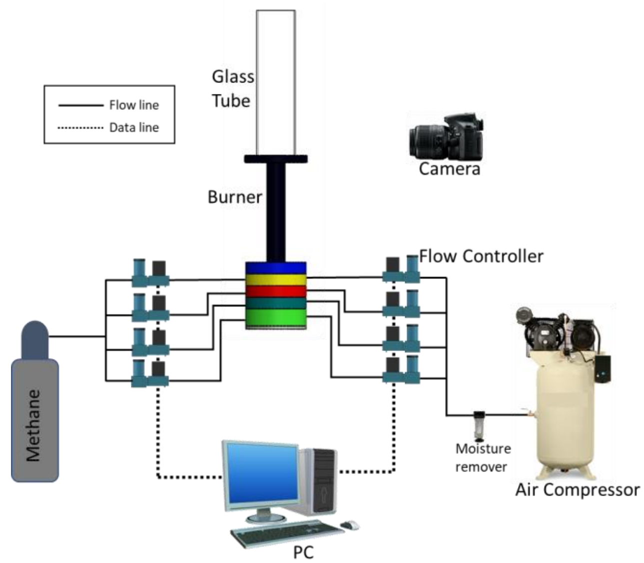

Figure 1: Schematic diagram of the experimental setup

2.2 Burner Details

Figure 2 shows the schematic diagram of the modified dual swirl burner used in the present study. The burner consists of three concentric tubes (*A*-*C*) forming a double annular geometry. The outer tube has a diameter of 38.1 mm and a thickness of 1.5 mm, the middle tube has a diameter of 25.7 mm and a thickness of 1.2 mm, while the inner most tube has a diameter of 12.7 mm. No flow is supplied through the inner most tube and is only meant to support the bluff body (*D*). A ceramic cap is used as bluff body (*D*) to cover the inner most tube and provide flame anchoring. The length of the tubes varies, but from the top of the no flow plenum (*E*) the tubes extend by an additional 30 cm, towards the combustion chamber, which is sufficient length to allow for a fully developed flow.

The flow to the concentric tubes is provided through 4 plenums, with each annulus being supplied by two of the four plenums. Plenum *E* is used to hold all the plenums together to prevent gas leakages. Plenum *F* supplies swirling flow to the outer annulus while Plenum *G* supplies straight flow to the outer annulus. Similarly, plenums *H* and *I* are used to supply swirl and straight flows, respectively, to the inner annulus. In the present study only jet flames have been investigated and discussed while the investigation into swirling flows have been left for future study. Therefore, all the flow passes through straight flow plenums *G* and *I*. Flow straighteners (*M* and *O*) has also been used to straighten the flow coming from the straight flow plenums. The combustion chamber comprises of a Quartz glass tube to enable optical access to the flame. The outer diameter of the glass tube was 80 mm while the thickness was 3 mm. A circular disc of 20 mm thickness was welded to the outer tube of the burner to seat the quartz glass tube and confine the flame.

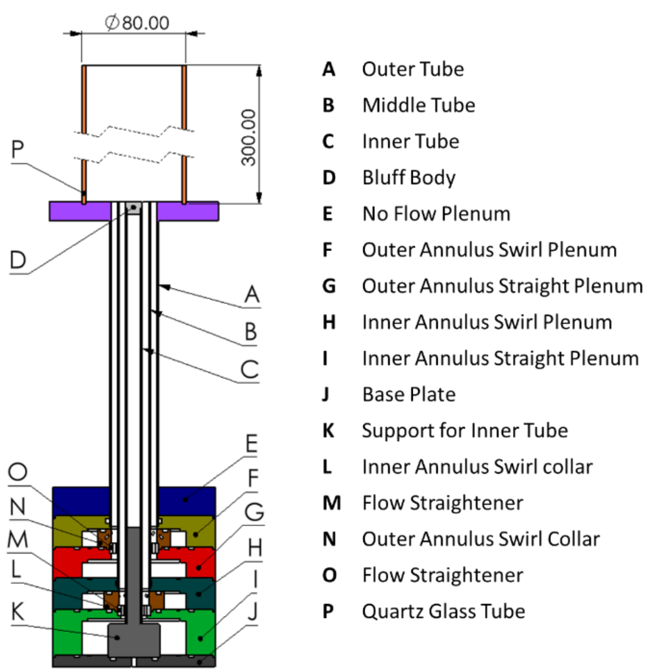

Figure 2: Schematic diagram of the modified dual swirl burner

3. RESULTS AND DISCUSSION

3.1 Static Stability

In a combustor stable flame can only be sustained over a certain range of equivalence ratios [17]. The event when the flame extinguishes completely in a combustor is called as blowoff. The limit at which flame blowoff occurs is also called as the Lean Blowoff limit (*LBO*). A higher LBO generally means a lower equivalence ratio at which the flame extinguishes.

Figure 3 shows the flame stability map for stratified jet flames. The power levels are presented as contour maps in the background. The study was carried out for different Reynolds umber of flow in the inner and outer annulus. The Reynolds number in the outer annulus (Re_{out}) was varied between 2000 and 10000. The ratio of Re_{in}/Re_{out} in all cases was fixed to 2. In our preliminary studies we observed that this ratio did not affect the static stability limits by much. At a fixed Re_{out} and *SR*, the equivalence ratio was decreased until flame blowoff occurs.

For the completely premixed case, i.e., at *SR=1* the flame blowoff occurs at global equivalence ratios (ϕ_g) between 0.49-0.58 for outer Reynolds number between 2000-10000. The equivalence ratio at which flame blowoff occurs ($\phi_{g,bf}$) increases with increase in outer Reynolds number, i.e., the lean blowoff limit (*LBO*) decreases with increase in Reynolds number (flow velocity). This is due to the presence of larger vortices at higher flow velocity which lower the vortical temperature [18] and the extinction strain rate leading to blowoff occurring at higher equivalence ratio [19]. Increasing the stratification ratio (*SR*) beyond 1 (mixture in inner annulus is rich) significantly improves the static stability of the flame enabling it to continue burning even at lower equivalence ratios. In comparison to flames at *SR=1*, at *SR=2* the global equivalence ratio at which blowoff occurs is reduced by 42.85% for $Re_{out}=2000$ and by 19-23% at higher outer Reynolds number. At *SR=3* further improvement in the *LBO* can be observed with 55% reduction in equivalence ratio at which flame blowoff occurs for $Re_{out}=2000$, and between 34-40% for Re_{out} between 4000-10000. This significant improvement in the LBO can be attributed to the back support provided by stratification wherein the heat and radicals from the richer burned mixture behind the flame move towards the leaner mixtures in the flame. The richer burned mixture is located at the center of the flame from which the radicals and heat diffuse to the outer regions of the flame. It is worth mentioning that the input power, i.e., the mass of methane entering the combustor also decreases with decrease in equivalence ratio. Thus, higher *SR* can also improve the operating range of the combustor, enabling lower fuel consumption when the power demand required by the use scenario is reduced.

The improvement in *LBO* is observed only for *SR>1*. At *SR<1* (mixture in outer annulus is rich) the *LBO* limit decreases. Flames with *SR<1* blowoff at equivalence ratios higher than that at *SR=1*. In comparison to flames at SR=1, the global equivalence ratio at which blowoff occurs increases by 2-8% for *SR=1/2* and by 3-10% at *SR=1/3*. At *SR<1* the stream from the outer annulus is richer than the stream from the inner annulus. Therefore, the flame propagates from the stoichiometric regions in the flame to the rich region which result in decrease in burning velocity. Furthermore, this also leads to lifted jet flames as the mixture near the burner is not sufficiently mixed for burning.

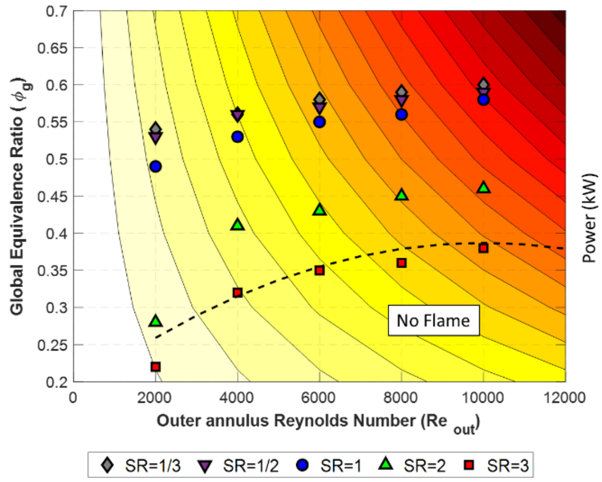

Figure 3: Flame stability map for stratified jet flames along with contours of input power (Re_{in}/Re_{out}=2)

The improvement in *LBO* is observed only for *SR>1*. At *SR<1* (mixture in outer annulus is rich) the *LBO* limit decreases. Flames with *SR<1* blowoff at equivalence ratios higher than that at *SR=1*. In comparison to flames at SR=1, the global equivalence ratio at which blowoff occurs increases by 2-8% for *SR=1/2* and by 3-10% at *SR=1/3*. At *SR<1* the stream from the outer annulus is richer than the stream from the inner annulus. Therefore, the flame propagates from the stoichiometric regions in the flame to the rich region which result in decrease in burning velocity. Furthermore, this also leads to lifted jet flames as the mixture near the burner is not sufficiently mixed for burning.

Based on the experimental data for the blowoff at different Reynolds number and *SR,* an empirical equation was developed to predict the global equivalence ratio at which blowoff occurs. The equation is given below,

$$\phi_{(g,LBO)} = a_0 - a_1 SR + a_2\, ln(Re_{out}) + a_3 SR \times ln(Re_{out}) \quad (3)$$

Where,

Table 1: Coefficients for the prediction of LBO for stratified air combustion using Equ. 3

a_0	a_1	a_2	a_3
0.366	0.3325	0.0293	0.02738

Using Equ. 3, an average error of 3.4% has been observed with a maximum error of 6.3%. If we were to fix the power and let the Reynolds number to vary with change in global equivalence ratio, similar results observations can be made. This is evident from Figure 3, wherein if we move along any of the plotted power contour levels, we can see that higher *SR* ratio leads to lower equivalence ratio at which blowoff occurs. Furthermore, one can also observe that at the same power level, the Re_{out} at which blowoff occurs is also increased with increase in *SR*.

3.2 Flame Macrostructure

To examine the effect of *SR* on the flame macrostructure images of the flame were captured using a *DSLR* camera. The Re_{out}, global equivalence ratio was fixed resulting in a fixed input power, while the SR was varied between 1/3 and 3. The Re_{out} was fixed at 6000 while Re_{in} was fixed at 3000 for all the cases that has been discussed in the present section. Figure 4 depicts the captured flame structures at different *SR* for two different global equivalence ratios.

For flames with *SR=1*, ϕ_g =0.7, a typical jet flame structure can be observed with the addition of two flame branches on either side of the bluff body, as highlighted by region "*A*" in Figure 4. These branches occur due to the existence of flame in the shear layer between the corner recirculation zone and the flow coming from the outer annulus. The flame in the branch region goes through a cycle of ignition and extinction at a very fast rate. That is the flame appears for a fraction of a second and then extinguishes. The intensity of the branch flame is quite low and is not easily captured with the DSLR camera. At lower equivalence ratio of, ϕ_g =0.6 the overall flame intensity is reduced due to the lower fuel content in the mixture. The intensity of the branched flame is also significantly reduced.

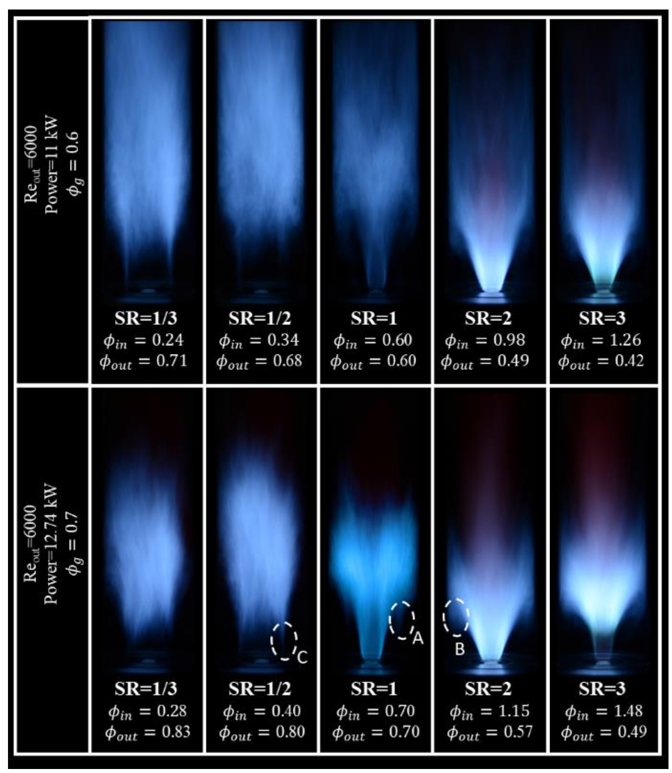

Figure 4: Effect of Stratification Ratio on turbulent air jet flames (Re_{out} =6000, Re_{out}//Re_{in} = 2)

When the *SR* is increased from 1 to 2 the length of the flame branches and its intensity is significantly reduced as highlighted by region "*B*" in Figure 4. Furthermore, the length of the combustion region is also reduced, and the flame burns much more intensely near the bluff body. Similar flame structure is observed for ϕ_g=0.6, however, the length of the combustion zone is greater than that for ϕ_g=0.7. Furthermore, a reddish plume of gases can be observed in Figure 4 for ϕ_g=0.6 and 0.7. This is due to the higher equivalence ratio in the inner annulus which could lead to unburnt hydrocarbons in the central region of the combustor.

As the *SR* is increased to *SR=3*, there is a significant change in flame structure for ϕ_g=0.7. In Figure 4 a very weak attached flame can be seen for SR=3 and ϕ_g=0.7. The combustion intensity significantly decreases with the intense combustion region having a larger area, suggesting that the combustion process takes longer time due to oxygen deficiency in the central region of the combustor.

The deficiency of oxygen in the central region of the combustor arises because of the higher inner equivalence ratio of 1.48, which approaches the rich flammability limit of stratified methane-air flames. At this high equivalence ratio, the flame speed is significantly reduced as a result of which the intense burning region is moved slightly downstream [1]. For ϕ_g=0.6 the flame structure at *SR=3* is similar to that of *SR=2*, at the same equivalence ratio. The inner equivalence ratio in this case was 1.26, as a result, the flame at *SR=3* and ϕ_g=0.6, was found to be attached to the periphery of the bluff body. Thus, stratification is much more helpful in improving the flame stability at lower equivalence ratio than at higher equivalence ratio.

At *SR=1/2* and *1/3* the flame structure is significantly different than those at *SR>=1*. Figure 4 shows the flames at *SR<1* to be detached from the bluff body and instead very weakly attaches to the periphery of the outer annulus. The flame branches observed at *SR=1* is now dominant in stabilizing the flame and preventing it from blowoff, as observed from the highlighted region "*C*" in Figure 4. The flame in the inner annulus is very lean, with equivalence ratio lower than the lean flammability limit. Thus, the incoming charge needs a premixing zone where the flow from inner and outer annulus mix to increase the equivalence ratio above the lean flammability limit.

Although the flame between the corner recirculation zone and the flow from the outer annulus stabilizes the flame, it can be considered to be a lifted flame since the flame is not attached to the bluff body. The flames for ϕ_g=0.7, 0.6 and *SR<1* are similar in structure, with the flame at ϕ_g=0.6 and *SR<1* having a higher combustion length with combustion continuing past the quartz tube.

4. CONCLUSION

The static stability decreases with increase in Reynolds number. Even a small degree of stratification, by increasing the inner equivalence ratio resulting in *SR>1* can significantly improve the static stability of the combustor. On the other hand, *SR<1* can result in worse static stability limits. A branched flame structure was observed when studying the flame macrostructure, due to burning region also existing between the corner recirculation zone and mixture coming form the outer annulus. Stratification was found to be much more effective in enabling attached flame at lower equivalence ratio. Thus, stratified flames can improve the lean operation limit of combustors.

ACKNOWLEDGEMENT

The support provided by the DROC of King Fahd University of Petroleum and Minerals (KFUPM) via the internally funded Project No. DF181008 is acknowledged and highly appreciated by the authors of this article. The support provided by the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) is also highly acknowledged.

REFERENCE

[1] Pires Da Cruz A, Dean AM, Grenda JM. A numerical study of the laminar flame speed of stratified methane/air flames. Proceedings of the Combustion Institute 2000;28:1925–32. https://doi.org/10.1016/S0082-0784(00)80597-4.

[2] Richardson ES, Granet VE, Eyssartier A, Chen JH. Effects of equivalence ratio variation on lean, stratified methane-air laminar counterflow flames. Combustion Theory and Modelling 2010;14:775–92. https://doi.org/10.1080/13647830.2010.490881.

[3] Zhou R, Hochgreb S. The behaviour of laminar stratified methane/air flames in counterflow. Combustion and Flame 2013;160:1070–82. https://doi.org/10.1016/j.combustflame.2013.01.023.

[4] Balusamy S, Cessou A, Lecordier B. Laminar propagation of lean premixed flames ignited in stratified mixture. Combustion and Flame 2014;161:427–37. https://doi.org/10.1016/j.combustflame.2013.08.023.

[5] Inanc E, Chakraborty N, Kempf AM. Analysis of mixture stratification effects on unstrained laminar flames. Combustion and Flame 2020;219:339–48. https://doi.org/10.1016/j.combustflame.2020.06.009.

[6] Kang T, Kyritsis DC. Theoretical investigation of flame propagation through compositionally stratified methane-air mixtures. Combustion Theory and Modelling 2009;13:705–19. https://doi.org/10.1080/13647830903093765.

[7] Pasquier N, Lecordier B, Trinité M, Cessou A. An experimental investigation of flame propagation through a turbulent stratified mixture. Proceedings of the Combustion Institute 2007;31 I:1567–74. https://doi.org/10.1016/j.proci.2006.07.118.

[8] Ribert G, Champion M, Gicquel O, Darabiha N, Veynante D. Modeling nonadiabatic turbulent premixed reactive flows including tabulated chemistry. Combustion and Flame 2005;141:271–80. https://doi.org/10.1016/j.combustflame.2004.12.019.

[9] Barlow RS, Wang GH, Anselmo-Filho P, Sweeney MS, Hochgreb S. Application of Raman/Rayleigh/LIF diagnostics in turbulent stratified flames. Proceedings of the Combustion Institute 2009;32 I:945–53. https://doi.org/10.1016/j.proci.2008.06.070.

[10] Arndt CM, Severin M, Dem C, Stöhr M, Steinberg AM, Meier W. Experimental analysis of thermo-acoustic instabilities in a generic gas turbine combustor by phase-correlated PIV, chemiluminescence, and laser Raman scattering measurements. Experiments in Fluids 2015;56:1–23. https://doi.org/10.1007/s00348-015-1929-3.

[11] Sweeney MS, Hochgreb S, Dunn MJ, Barlow RS. The structure of turbulent stratified and premixed methane/air flames II: Swirling flows. Combustion and Flame 2012;159:2912–29. https://doi.org/10.1016/j.combustflame.2012.05.014.

[12] Meares S, Masri AR. A modified piloted burner for stabilizing turbulent flames of inhomogeneous mixtures. Combustion and Flame 2014;161:484–95. https://doi.org/10.1016/j.combustflame.2013.09.016.

[13] Han X, Laera D, Morgans AS, Sung CJ, Hui X, Lin YZ. Flame macrostructures and thermoacoustic instabilities in stratified swirling flames. Proceedings of the Combustion Institute 2019;37:5377–84. https://doi.org/10.1016/j.proci.2018.06.147.

[14] Sweeney MS, Hochgreb S, Barlow RS. The structure of premixed and stratified low turbulence flames. Combustion and Flame 2011;158:935–48. https://doi.org/10.1016/j.combustflame.2011.02.007.

[15] Sweeney MS, Hochgreb S, Dunn MJ, Barlow RS. The structure of turbulent stratified and premixed methane/air flames I: Non-swirling flows. Combustion and Flame 2012;159:2896–911. https://doi.org/10.1016/j.combustflame.2012.06.001.

[16] Han X, Laera D, Morgans AS, Sung CJ, Hui X, Lin YZ. Flame macrostructures and thermoacoustic instabilities in stratified swirling flames. Proceedings of the Combustion Institute 2019;37:5377–84. https://doi.org/10.1016/j.proci.2018.06.147.

[17] Sturgess GJ, Sloan DG, Lesmerises AL, Heneghan SP, Ballal DR. Design and development of a research combustor for lean blowout studies. Proceedings of the ASME Turbo Expo 1990;3:13–9. https://doi.org/10.1115/90-GT-143.

[18] Zukoski EE, Marble FE. Experiments Concerning the Mechanism of Flame Blowoff From Bluff Bodies. Proceedings of the Gas Dynamics Symposium on Aerothermochemistry 1956:205–2010.

[19] Nair S, Lieuwen T. Near-blowoff dynamics of a bluff-body stabilized flame. Journal of Propulsion and Power 2007;23:421–7. https://doi.org/10.2514/1.24650.