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Stabilization of Lean Premixed Flames Anchored to Hollow Cylinders with Modified Top-Surface Geometries

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Abstract - *Stable combustion of lean premixed flames with high velocity approaching reactants has been investigated by researchers over decades. There are several techniques for stabilizing a flame during combustion, and this research work focuses on flames anchored to bluff bodies. A novel design of a combustion chamber with co-benefits of preheating the approaching fuel-air mixture as well as trapping the recirculation zone within a modulating-height gap was investigated. Three bluff bodies with different blockage ratios and modified top surfaces were experimentally tested, and flammability limits of an LPG/air gaseous mixture were obtained. Operating conditions associated with bluff bodies were found to range from the lowest equivalence ratio of 0.44 at a blowoff velocity of 124 m/s to 0.53 at 145 m/s blowoff velocity. A maximum operating temperature of 1965 K was achieved during stoichiometric operation.*

Keywords - *Bluff bodies, flame anchoring, lean premixed flames, preheating, flammability limits, hollow cylinders, trapped vortex cavity.*

I. INTRODUCTION

Practical combustion systems ranging from stationary applications for power generation to jet propulsion and aero engines require a wide range of operating conditions under a high-velocity flow of reactants [1, 2, and 3]. Aligned with the global concerns to harmful emissions as a trigerrs precedent to climate change, this research area has become of great importance nowadays [4, 5-7].

On the other hand, stabilizing a flame with high-velocity reactants under very lean conditions is a complicated process that requires a deep understanding of the physical phenomena associated with blowoff [10, 11, 12, 13, and 14]. Bluff bodies are commonly used to stabilize flames over a wide range of operations, with continuous research related to the improvement of flammability limits of flames anchored to bluff bodies. Stabilization of flames with bluff bodies is attributed to the recirculation zone formed immediately downstream bluff objects as a result of high-velocity gradients and shear layer at the recirculation zone's envelope. Hot combustion products trapped in the high turbulent zone serve as an ignition source to the fresh adjacent reactants [8 and 9].

The idea of a trapped vortex between bluff bodies was historically developed for aero-engines. A trapped vortex helps in eliminating the vortex shedding instabilities (BVK) near blowoff; however, there is an optimum length of the cavity height below or over this length flames couldn't sustain over a wide length of flammability limits [15, 16, and 22].

The effects of bluff surface temperature on flame stabilization were investigated by several researchers [17-21 and 23-28] with a fous on meso and microscale combustors.

In this research, an experimental investigation of a hollow bluff body assisted with internal preheat of the approaching fuel-air mixture took place with the existence of a trapped recirculation zone between the downstream surface of the bluff body and the vertical combustor floor.

II. EXPERIMENTAL SETUP

A cylindrical combustor with 100mm diameter and 200mm length was used for experiments. The fuel-air mixture enters the combustor from its bottom via an 8mm supply pipe. The combustor and the supply pipe material is Steel ANSI Schedule 80. A 3D perspective of the combustor is shown in Fig. 1.

The supply pipe outer surface is threaded to allow for varying its length portion immersed within the combustion zone. At the supply pipe upper end, a hollow bluff body is mounted to allow the preheated mixture to enter the body's hollow cavity and reverse its impingement direction, and exiting from the face openings located at the bluff body's downstream surface. A schematic section of the combustor test rig is shown in Fig. 2.

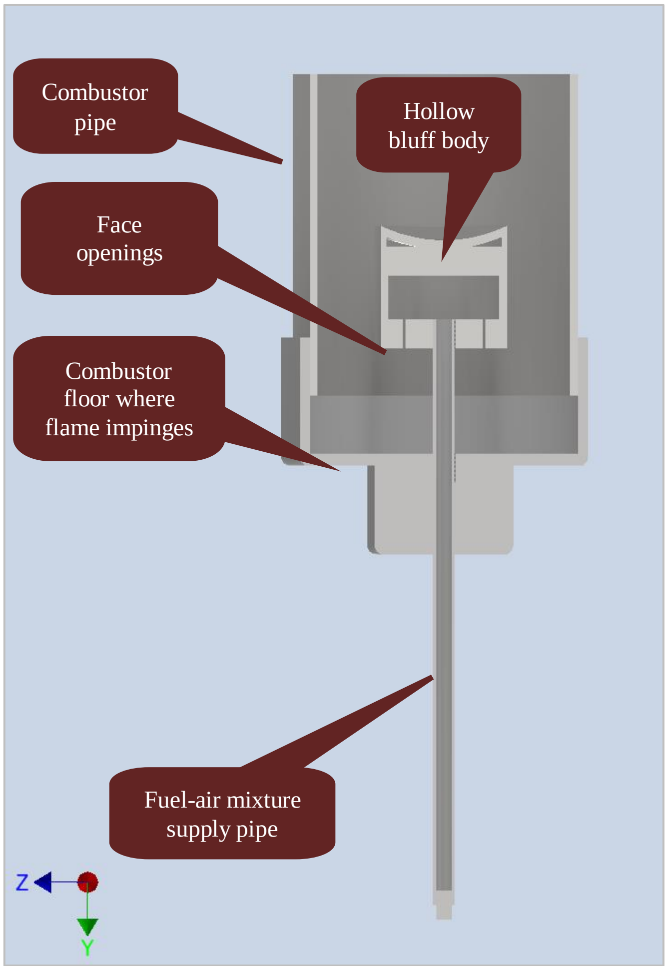

Fig. 1: 3D view of the combustion chamber

Flow rate measurements were conducted using U-tube manometers with orrifices, while ball valves were controlling the flow rates. Temperature measurements were conducted using thermocouples attached along the combustor's length for temperature screening at different locations. Temperatures inside the combustion zone are measured using S-type thermocouples, while the preheated mixture temperature inside the bluff bofy was measured using a K-type thermocouple; all thermocouples are connected to a multichannel data logger (make: Omni instruments - UK, model: MCR-4V/4TC) with a minimum recording interval of 2 ms, and ±0.3% accuracy over its full range. Four locations where the temperatures are measured: (i) the preheated mixture temperature (Tp) inside the hollow bluff body, (ii) flame impingement temperature at the combustor's bottom wall (Ti), (iii) exhaust gases temperatures (Te) measured 1cm downstream the bluff body top surface and at half the distance between the bluff body and combustor sidewall, and (iv) bluff body surface temperature (Tb).

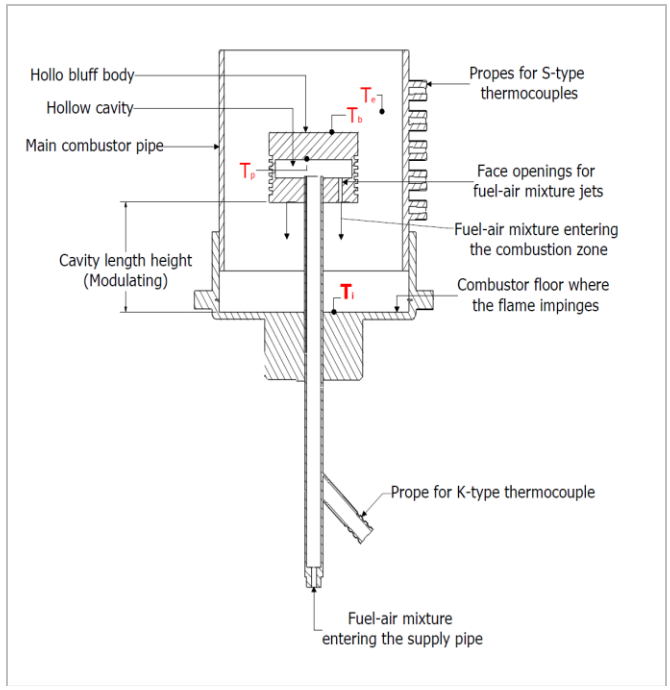

Fig. 2: Schematic section of the combustion chamber

Three bluff body geometries were used in this research work; geometries and dimensions are shown in Fig. 3.

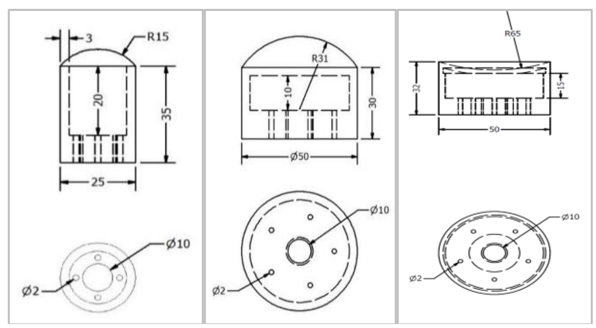

Fig. 3: Hollow flameholders geometries, Type 1 (left), Type 2 (middle), Type 3 (right)

Bluff bodies type 2 and 3 have the same blockage ratio (BR=d/D) of 0.5, while type 1 has a 0.25 BR. Types 2 and 3 have corrugated sides, while type 1 and type 2 have a convex top, type 3 has a concave top.

II. RESULTS AND DISCUSSIONS

A. The effect of cavity length on lean limits

Experiments were conducted at different lengths of the cavity between the combustor floor and the bluff body, and it was found that there is an optimum cavity length at which the equivalence ratio is minimum. The lean operation (low and high limits) range of the three bluff body geometries at different cavity lengths are shown in Fig. 4 and Fig. 5.

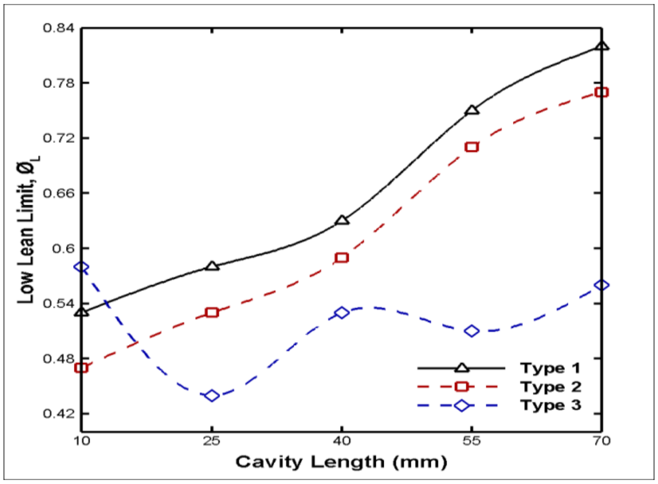

Fig. 4: Low lean limits at different cavity lengths

Low lean limits are corresponding to operating points that coincide with the maximum airflow rates at which minimum fuel flow rates near blowoff were considered, while the maximum lean limits are corresponding to maximum airflow rates near blowoff that are coinciding with the stoichiometric fuel flow rates.

The combined effects of an increased blockage ratio as well modified top surfaces were investigated with the three bluff body geometries; it was concluded that the lowest equivalence ratio is achieved with type 3, while the highest equivalence ratio was obtained with type 1 (the lowest blockage ratio). Type 2 (same blockage ratio as type 3 but with a convex top) has a moderate performance between type 1 and type 3; hence the effect of a concave surface is better than the convex one. Similar findings were reported in previous researches [29-31].

B. blowoff velocities

To have a good understanding of the blockage ratio effects, we should analyze the operating velocities achieved by each geometry during low lean and high lean operation, as shown in Fig. 6 and Fig. 7, respectively.

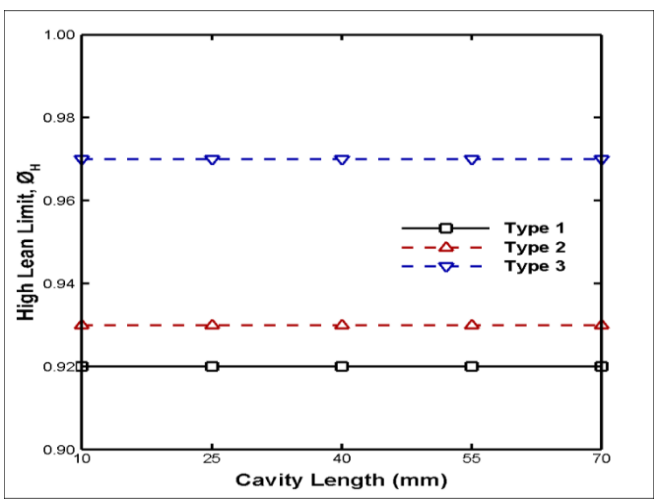

Fig. 5: High lean limits at different cavity lengths

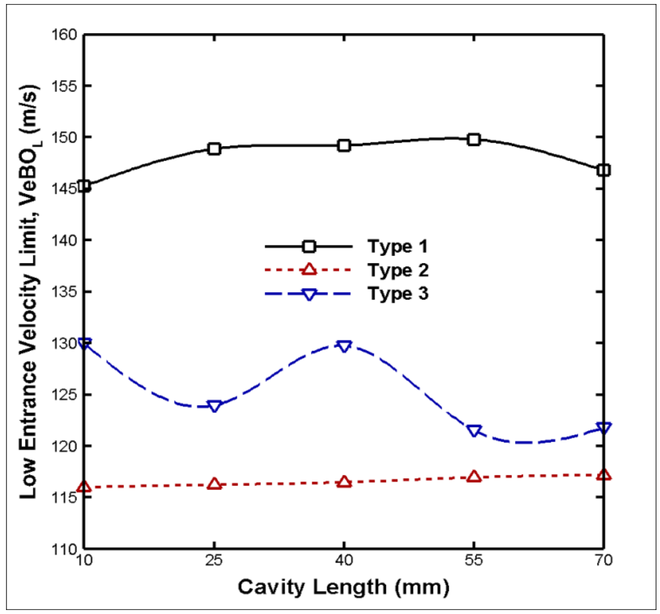

Fig. 6: Velocity limits at low lean operation

It is clearly shown that during low lean operation, the highest velocities were obtained with type 1 with the lowest blockage ratio amongst all types, while the lowest speeds were found to be constant over the full range of operating cavity lengths, type 3 was found to operate at moderate speeds that are closer to type 2. Thus, the reduction in blockage ratio is associated with high blowoff limits; hence the fuel-air mixture residence time within the recirculation zone will be lower than the case with a high blockage ratio, where the residence time is higher, and lower lean limits could be achieved.

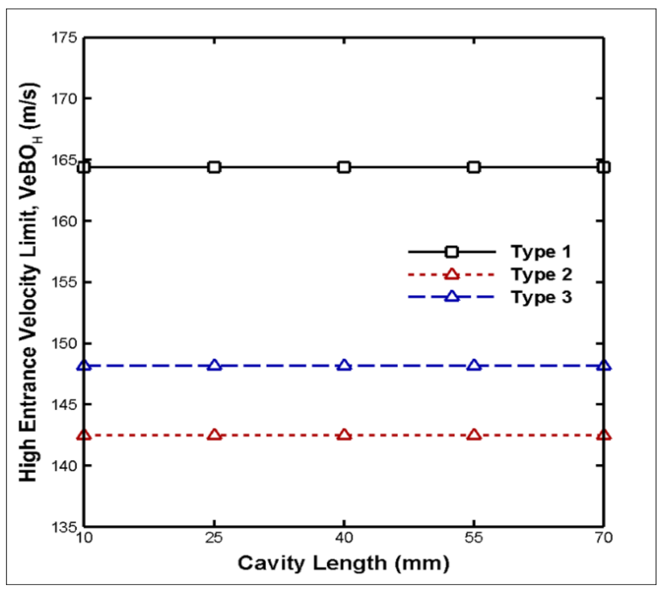

Fig. 7: Velocity limits at high lean operation

The same analogy could be depicted at high lean limit operations with the effect of a modulating cavit length seems with no significance. The summary of operating conditions in low and high lean points is shown in Table 1.

Table 1: Operating points within low and high lean conditions

Bluff body	$\emptyset_L$	$\emptyset_H$	$VeBO_L$ (m/s)	$VeBO_H$ (m/s)
Type 1	0.53	0.92	145	164
Type 2	0.47	0.93	116	142
Type 3	0.44	0.97	124	148

C. The effect of cavity length on operating temperatures

The variations of operating temperatures at different cavity lengths are shown in Fig. 8 and Fig. 9, respectively. The maximum bluff body preheating temperature was obtained by type 3 at the point corresponding to the lowest lean limits, henec this geometry has better preheating effects compared to the others. The concave top surface of type 3 has the advantage of increased wake turbulence generated by the exhaust gas stream flowing adjacent to the body's surface. Even with its low impingement temperature, however, type 3 achieved the best stability limits due to the preheating effects and the recirculation zone strengths associated with this geometry, as well as the low operating velocities where the high residence time is attributed to it. The effect of operating velocity on the impingement temperature and bluff body preheating is shown in Fig. 10. It is clearly shaown that type 3 preheating temperatures are narrow over a wider range of relatively moderate blowoff speeds.

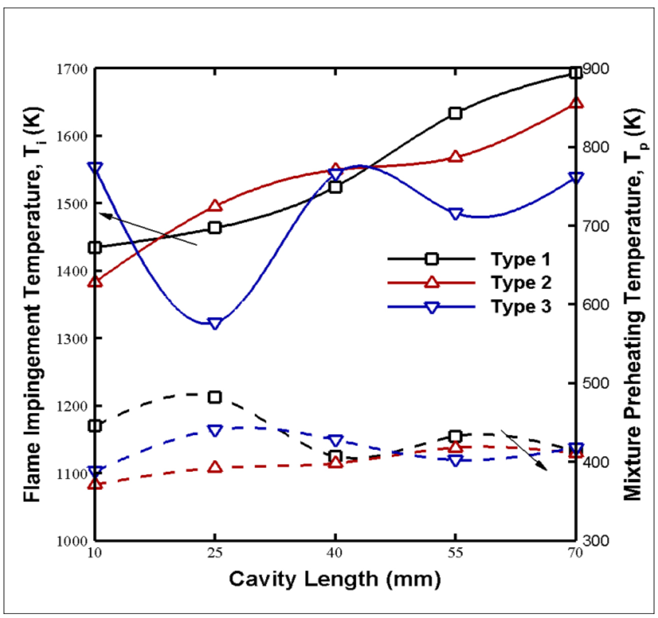

Fig. 8: Flme impingement and mixture preheating temperatures during low lean operation

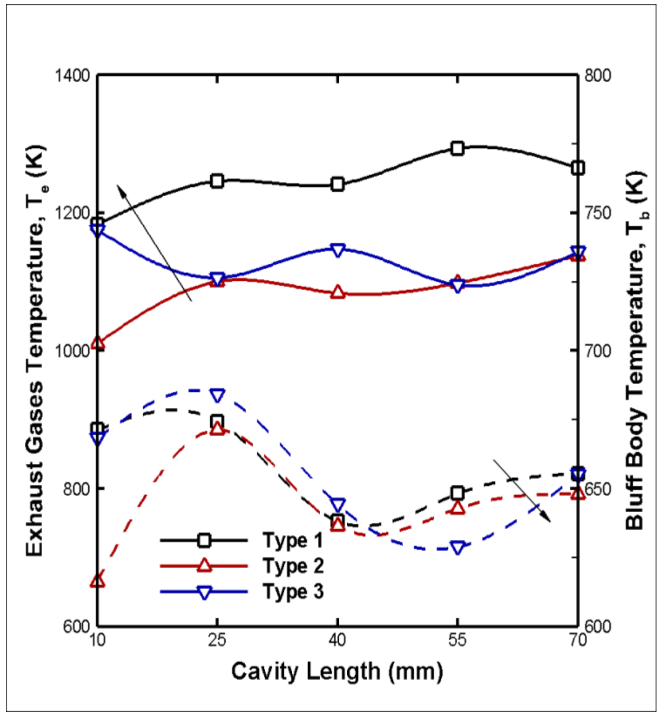

Fig. 9: Exhaust gases and bluff body temperatures during low lean operation

The summary of operating temperatures during low and stoichiometric operating conditions are summarized in Table 2 and Table 3, respectively.

Table 2: Summary of low lean operating temperatures

Bluff body	T_i (K)	T_e (K)	T_p (K)	T_b (K)
Type 1	1434	1183	446	671
Type 2	1383	1010	371	616
Type 3	1323	1106	441	684

Table 3: Summary of stoichiometric operating temperatures

Bluff body	T_i (K)	T_e (K)	T_p (K)	T_b (K)
Type 1	1875	1398	566	761
Type 2	1714	1253	511	745
Type 3	1918	1514	532	825

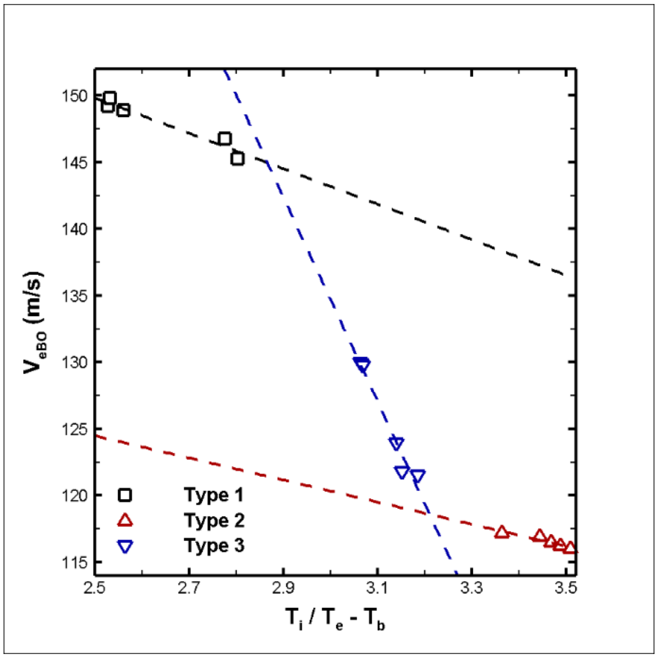

Fig. 10: Blowoff velocity effects on bluff body preheating temperatures

III. CONCLUSIONS

Hollow bluff bodies with a preheated fuel-air mixture are a novel approach developed for enhancing lean stability limits of high-velocity premixed flames. It was observed that the effect of blockage ratios, modified bluff body surface geometries, as well as the trapped recirculation zone between the bluff body downstream surface and combustor's floor, have significant effects on enhancing lean stability limits, that improves with blockage ratio, and preheating of the bluff body surface, while stability limits decline with the increase in operating velocities.

REFERENCES

[1] Lieuwen, T. C., Unsteady combustor physics. Cambridge University Press.,(2012).

[2] Shanbhogue, S. J., Husain, S., & Lieuwen, T., Lean blowoff of bluff body stabilized flames: Scaling and dynamics. Progress in Energy and Combustion Science, 35(1) (2009) 98-120.

[3] Geikie, M. K., Carr, Z. R., Ahmed, K. A., & Forliti, D. J., On the flame-generated vorticity dynamics of bluff-body-stabilized premixed flames. Flow, Turbulence and Combustion, 99(2) (2017) 487-509.

[4] Miguel-Brebion, M., Mejia, D., Xavier, P., Duchaine, F., Bédat, B., Selle, L., & Poinsot, T., Joint experimental and numerical study of the influence of flame holder temperature on the stabilization of a laminar methane flame on a cylinder. Combustion and Flame, 172 (2016) 153-161.

[5] Chowdhury, B. R., & Cetegen, B. M., Effects of fuel properties and free-stream turbulence on characteristics of bluff-body stabilized flames. Combustion and Flame, 194 (2018) 206-222.

[6] Zukoski, E. E., & Marble, F. E., Experiments concerning the mechanism of flame blowoff from bluff bodies., (1983).

[7] Foster, J. R., Effects of combustion chamber blockage on bluff body flame stabilization (Doctoral dissertation, California Institute of Technology)., (1956).

[8] Vance, F. H., Shoshin, Y., van Oijen, J. A., & de Goey, L. P. H.. Effect of Lewis number on premixed laminar lean-limit flames stabilized on a bluff body. Proceedings of the Combustion Institute, 37(2) (2019) 1663-1672.

[9] Michaels, D., & Ghoniem, A. F., Impact of the bluff-body material on the flame leading edge structure and flame–flow interaction of premixed CH4/air flames. Combustion and Flame, 172 (2016) 62-78.

[10] Kim, W., Im, S. K., Do, H., & Mungal, M. G., Flame liftoff height dependence on geometrically modified bluff bodies in a vitiated flow. Experiments in Fluids, 49(1) (2010) 27-41.

[11] Lin, C. X., & Holder, R. J., Reacting turbulent flow and thermal field in a channel with inclined bluff body flame holders. Journal of heat transfer, 132(9) (2010).

[12] Kang, S. H., Lee, Y. J., Yang, S. S., & Choi, B., Effects of flame holder configurations on combustion in scramjet engines. Journal of Propulsion and Power, 28(4) (2012) 739-746.

[13] Kim, W., Do, H., & Mungal, M. G., The improvement of blowout limit is partially/fully premixed flames with geometrically modified bluff-body bases. Experiments in Fluids, 51(5) (2011) 1315-1328.

[14] Kiel, B., Garwick, K., Gord, J., Miller, J., Lynch, A., Hill, R., & Phillips, S., A detailed investigation of bluff body stabilized flames in 45th AIAA Aerospace Sciences Meeting and Exhibit (168) (2007).

[15] Hsu, K. Y., Goss, L. P., & Roquemore, W. M., Characteristics of a trapped-vortex combustor. Journal of Propulsion and Power, 14(1) (1998) 57-65.

[16] Xavier, P., Investigation of flame stabilization mechanisms in a premixed combustor using a hot gas cavity-based flame holder (Doctoral dissertation, INSA de Rouen).(2014).

[17] Wan, J., Fan, A., & Yao, H, . Effect of the length of a plate flame holder on flame blowout limit in a micro-combustor with preheating channels. Combustion and Flame, 170 (2016) 53-62.

[18] Ma, L., Xu, H., Wang, X., Fang, Q., Zhang, C., & Chen, G., A novel flame-anchorage micro-combustor: Effects of flame holder shape and height on premixed CH4/air flame blow-off limit. Applied Thermal Engineering, 158 (2019) 113836.

[19] Wan, J., & Fan, A., Effect of solid material on the blow-off limit of CH4/air flames in a micro combustor with a plate flame holder and preheating channels. Energy Conversion and Management, 101 (2015) 552-560.

[20] Hong, S., Shanbhogue, S. J., Kedia, K. S., & Ghoniem, A. F., Impact of the flame-holder heat-transfer characteristics on the onset of combustion instability. Combustion science and technology, 185(10) (2013) 1541-1567.

[21] Wan, J., Fan, A., Yao, H., & Liu, W., Experimental investigation and numerical analysis on the blow-off limits of premixed CH4/air flames in a mesoscale bluff-body combustor. Energy, 113(2016) 193-203.

[22] Xavier, P., Investigation of flame stabilization mechanisms in a premixed combustor using a hot gas cavity-based flame holder (Doctoral dissertation, INSA de Rouen).,(2014).

[23] Kedia, K. S., & Ghoniem, A. F., The anchoring mechanism of a bluff-body stabilized laminar premixed flame. Combustion and Flame, 161(9) (2014) 2327-2339.

[24] Wan, J., Shang, C., & Zhao, H., Anchoring mechanisms of methane/air premixed flame in a diverging mesoscale combustor with cylindrical flame holder. Fuel, 232 (2018) 591-599.

[25] Wan, J., & Zhao, H., Experimental study on blow-off limit of a preheated and flame holder-stabilized laminar premixed flame. Chemical Engineering Science, 223 (2020) 115754.

[26] Wan, J., & Zhao, H., Effect of the thermal condition of a solid wall on the stabilization of a preheated and holder-stabilized laminar premixed flame. Energy., 200 (2020) 117548.

[27] Radhakrishnan, K., Heywood, J. B., & Tabaczynski, R. J., Premixed turbulent flame blowoff velocity correlation based on coherent structures in turbulent flows. Combustion and Flame, 42 (1981) 19-33.

[28] Wan, J., & Zhao, H., Dynamics of premixed CH4/air flames in a micro combustor with a plate flame holder and preheating channels. Energy, 139 (2017) 366-379.

[29] Williams, G. C., Hottel, H. C., & Scurlock, A. C., Flame stabilization

and propagation in high-velocity gas streams. In Symposium on Combustion and Flame, and Explosion Phenomena 3(1) (1948) (21-40). Elsevier.

[30] Wright, F. H. (1959). Bluff-body flame stabilization: blockage effects. Combustion and Flame, 3 (1959) 319-337.

[31] Bagheri, G., Hosseini, S. E., & Wahid, M. A. (2014). Effects of bluff body shape on the flame stability in premixed micro-combustion of the hydrogen-air mixture. Applied Thermal Engineering, 67 (2014) (1-2) 266-272.