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Bluff Body Assisted Combustion with Internal Preheat of Fuel-Air Mixture

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Abstract: A critical requirement for practical combustion systems is to sustain a stable flame over a wide range of operating conditions in terms of equivalence ratios and velocity of reactants. Historically, bluff bodies were considered prime candidates for flame anchoring that is attributed to the generated recirculation downstream the bluff body which acts as a continuous ignition source for the fresh reactants. In present work, a novel hollow bluff body design with a trapped recirculation zone is employed to allow for preheating the fuel-air mixture before entering the combustion chamber. Flammability limits of an LPG/air gaseous mixture were experimentally obtained considering the effects of a modified geometries as well as the variable length of the preheated fuel-air mixture path. These new geometries were found to be performing under very low lean limits and high operating velocities, an equivalence ratio of 0.46 that is corresponding to 119 m/s blowoff velocity was achieved when using a hollow bluff body with 0.5 blockage ratio, while the maximum operating temperature of 1608 K was obtained by similar geometry but with a blockage ratio of 0.25.

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1. Introduction

In real life propulsion and energy systems, high-velocity reactants are forced to enter the combustion chamber, hence, sustaining a stable combustion under high velocity operating conditions is of a great importance (Lieuwen, 2012, Shanbhogue et al., 2009, Geikie et al., 2017). Nowadays, stricter, and more strengthen regulations have been put in place aiming at the reduction of harmful emissions generated by combustion applications, this has emphasized the adoption of lean combustion systems to maintain a low level of GHG emissions. For that reasons, flame stabilization of high-velocity reactants under very lean conditions is a challenging research topic that grasps a lot of interest (Miguel et al., 2016, Chowdhury et al., 2018, Zukoski and Marble, 1983).

Flame stabilization over a wide range of equivalence ratios and blowoff velocities using bluff bodies as a flame anchoring mechanism has been investigated by several researchers over decades (Foster, 1956).

The advantages of bluff body stabilized flames are attributed to the generated recirculation zone that envelopes high-temperature combustion products and active species with low velocity, that serve as a continuous ignitions source for the upcoming fresh reactants, the recirculation zone is a direct result of the velocity gradient generated by the blockage effect of a bluff body, this gradient forces a portion of the upcoming high velocity reactants to enter the recirculation zone and ignite (Vance et al., 2019, Michaels et al., 2016). Deep understanding of the physical phenomena associated with flame blowoff and how this could affect stabilization characteristics is the core research area of bluff body assisted combustion systems (Kim et al., 2010 and 2011, Lin et al., 2010, Kang et al., 2012, Kiel et al., 2007).

Several researchers have investigated the effect of fuel-air mixture preheating before entering the combustion zone, and flammability limits were improved with preheating (Wan et al., 2016, Ma et al., 16, Wan et al., 2015) additionally. However, special attention should be taken to avoid excessive heat loads as well as the earlier initiation of chemical reaction upstream, and flame flash back (Hong et al., 2013).

Most researchers that studied the effect of a preheated fuel-air mixture on flammability limits were focusing on miniaturized combustors (Wan et al., 2016), while research related to trapped recirculation zone were focusing on aeroengines (Xavier, 2014).

This research work aims at investigating the fuel-mixture preheating effects assisted by a trapped recirculation zone on lean flammability limits of a high-velocity premixed reactants. A novel bluff body geometries are employed in this research.

2. Methodology

A 100mm internal diameter vertical combustor with 8mm fuel-air mixture supply pipe were used for the experimental work. The combustor body as well as the supply pipe material is Steel ANSI Schedule 80. A 3D perspective of the combustor is shown in Figure 1.

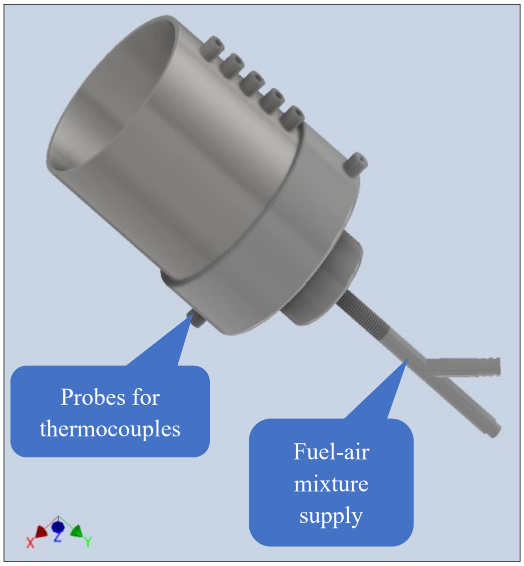


Figure 1. 3D Perspective view of the combustor

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 Figure 2.

Premixed fuel-air mixture enters the combustor through the supply pipe and then fills the hollow cavity inside the bluff body before exiting from the openings on the body's downstream face. Fuel-air jets then enters the combustion zone trapped along the cavity length height between the combustor's floor and the bluff body downstream surface. Preheating of the fuel-air mixture takes place because of the supply pipe length portion immersed in the combustion region.

Fuel and air flow rates are measured by orifice flow meters using U-tube manometer for air flow and inclined manometer for fuel flow, both manometers are using colored water with approximate density of 1000 kg/m3, and attached to two orifices to create pressure drop, both flow rates are controlled by ball valves.

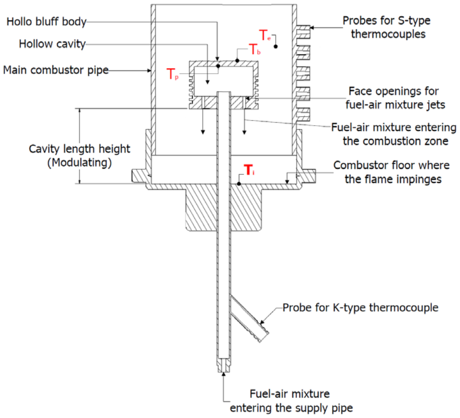


Figure 2. Schematic illustrative section of the combustor test rig

Probes for temperature screening are attached along the combustor length to allow for temperature recordings at different cavity lengths. Temperature measurements within the combustor are measured using S-type thermocouples, while the preheated fuel-air mixture temperature inside the hollow cavity was measured using a K-type thermocouple, all thermocouples were connected to multichannel data logger (make: omni-instruments - UK, model: MCR-4V/4TC) with a minimum recording interval of 2 ms, and ±0.3% accuracy over the full range. Thermocouples are used to measure: (i) the preheated mixture temperature (T_p) inside the hollow bluff body, (ii) flame impingement temperature at the combustor's bottom wall (T_i), (iii) exhaust gases temperatures (T_e) measured 1cm downstream the bluff body top surface and at half the distance between the bluff body and combustor side wall, and (iv) bluff body surface temperature (T_b). Three bluff body geometries were used in this research work, geometries and dimensions are shown in Figure 3.

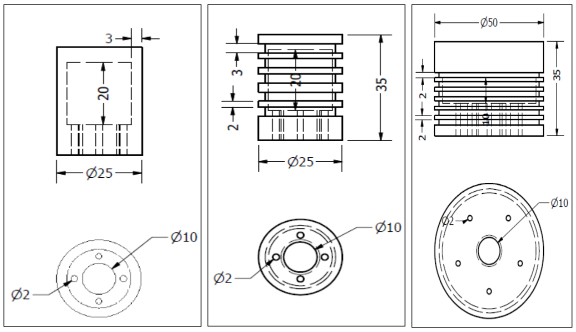


Figure 3. Hollow bluff body geometries, Type 1 (left), Type 2 (middle), Type 3 (right)

Bluff bodies type 1 and 2 have the same blockage ratio ($BR = \frac{d_b}{D_c}$) of 0.25, while type 3 has a 0.5 BR.

Types 2 and 3 have corrugated sides, while type 1 is a plain hollow cylinder.

3. Results

Examining the relation between the varying steps of cavity length/height and the lean equivalence ratio limits near blowoff, it is found that there is an optimum cavity height at which the equivalence ratios were found to be minimum. To specify the lean operation range associated with each bluff body in terms of low and high lean limits (i.e., the lowest and highest lean equivalence ratios), the low lean limits were corresponding to the maximum air flow rate with the coincident fuel flow rate after which any further increase in air flow or decrease in fuel flow will result in an immediate blowoff.

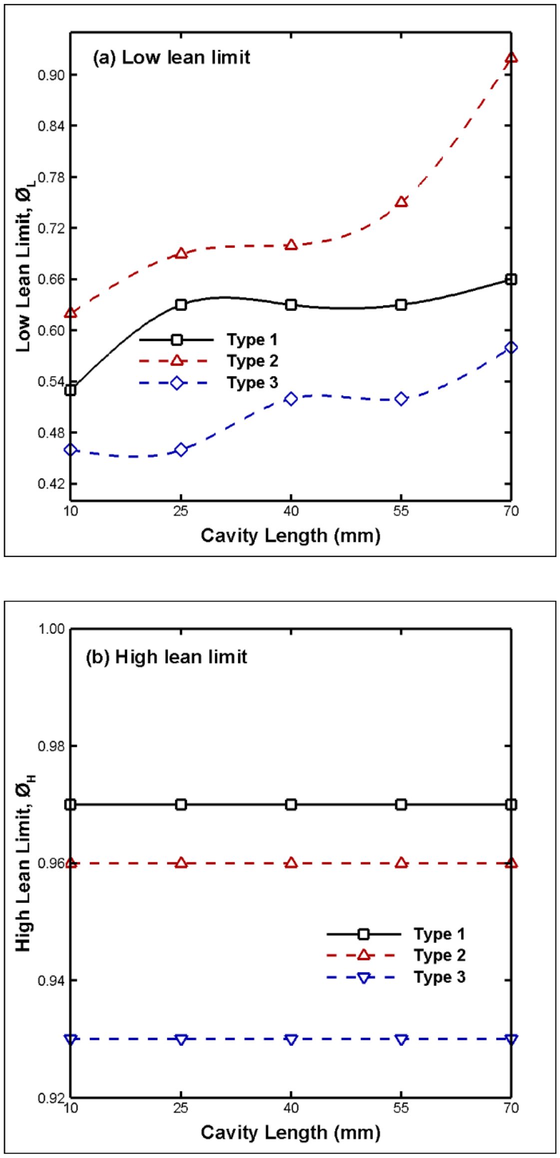
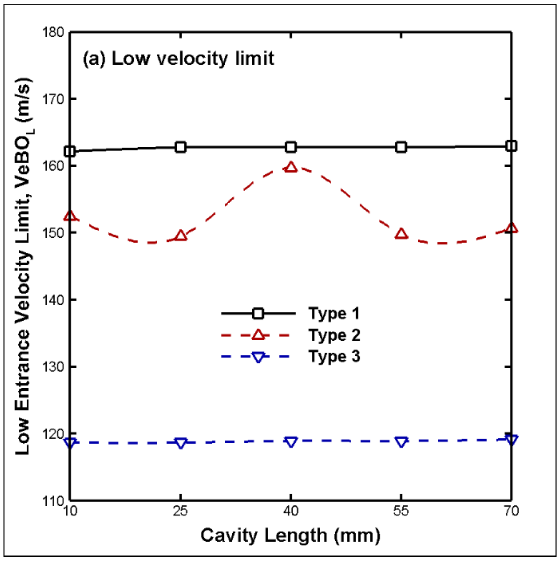


Figure 4. Equivalence ratio limits at different cavity heights, (a) low lean limits, (b) high lean limits

The maximum fuel flow rate that could be achieved during stoichiometric operation is used for high lean limit operation; the high lean limit is determined by further increasing the coincident air flow rate till blowoff. The low ($\emptyset_L$) and high ($\emptyset_H$) lean equivalence ratios are plotted in Figure 4.

The lowest lean limit $\emptyset_L$ is obtained by bluff body type 3 at 25mm cavity height, while at the same cavity height, the highest equivalence ratio was obtained by bluff body type 2, bluff body type 1 is found to have a nearly average performance between the other two types. Side corrugated surfaces in type 2 were found to be negatively affecting lean limits, while in case of type 3 with a doubled blockage ratio, the effect of side corrugated surfaces is almost neglected compared to the improved effect of having a larger recirculation zone downstream the bluff body. The negative effects of side corrugations in case of low blockage ratios could be attributed to the high bluff body surface temperature that makes the flame tends to move upwards towards the bluff body and consequently lowering the recirculation zone strength due to the reduced mixing, similar findings were reported by Kedia and Ghoniem, 2014, and Wan et al., 2018. The high lean limits $\emptyset_H$ achieved by the three geometries are constant over the whole experimental range, while it is lowest with type 3, a highest with type 1.

Low limit (VeBO_L) and high limit (VeBO_H) blowoff velocities of the preheated mixture exiting the hollow bluff bodies and entering the combustion region were plotted in Figure 5. The lowest blowoff velocities were reported with the case of bluff body type 3.



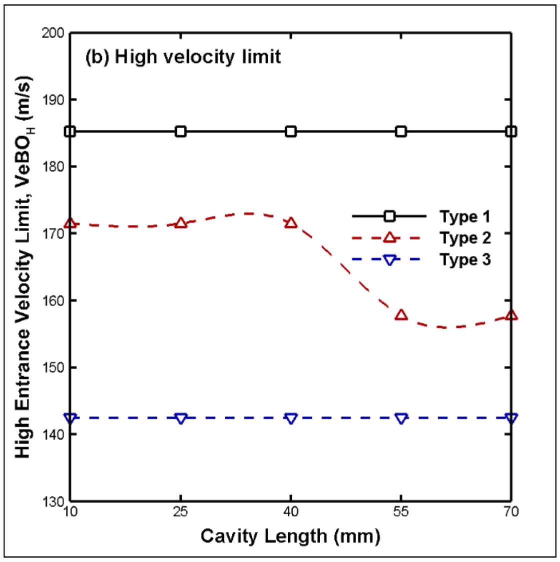


Figure 5. Blowoff velocity limits at different cavity heights, (a) low velocity limits, (b) high velocity limits

During high lean operation, maximum blowoff velocities ($VeBO_H$) were found to be independent to the varying steps of cavity length, except for type 2. Summary of the experimental results of flammability limits during the low and high lean operating conditions are presented in Table 1.

Table 1. Summary of flammability limits during the low and the high lean operating conditions

Bluff body	$\emptyset_L$	$\emptyset_H$	$VeBO_L$ (m/s)	$VeBO_H$ (m/s)
Type 1	0.53	0.97	162	185
Type 2	0.62	0.96	152	171
Type 3	0.46	0.93	119	142

The operating range of experimental results (blowoff velocity coincident to the lowest lean limit and the highest blowoff velocity achieved during stoichiometric operation) versus the data presented in literatures are plotted in Figure 6.

Several researchers studied the effect of a preheated mixture on lean stabilization, and they observed that in most cases, preheating has advantageous lean stabilization characteristics (Wan et al., 2020, Wan and Zhao, 2020, Radhakrishnan et al., 1981) The concept of fuel-air mixture internal preheat relies on the heat exchange between combustion gases and approaching stream in two locations: (i) the supply pipe that are completely immersed within the center of the recirculation zone, and (ii) the hollow cavity within the bluff body where heat flows from the flowing exhaust gases passing through the bluff body. Hence, analysis of these four temperature profiles is necessary to understand flame stabilization.

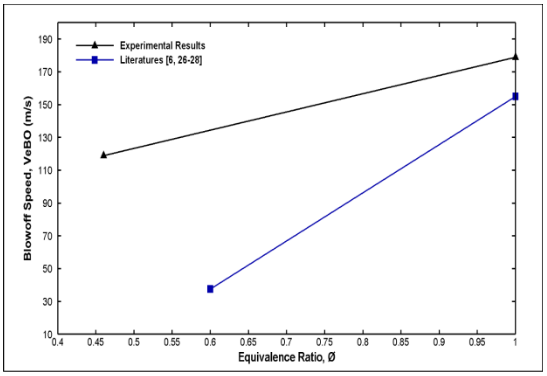


Figure 6. Range of experimental operating conditions versus data in literatures

Operating temperature profiles are plotted in Figure 7. Highest impingement temperatures were noticed in the case of bluff body type 2, while the lowest values were obtained with type 3. For each geometry the lowest lean operation point is coincident to the lowest flame impingement temperature and vice versa. Bluff body temperature (Tb) profiles were found to be following the same pattern as the exhaust gases temperature (Te).

Summary of the operating temperature range during low lean operation (lowest temperatures) and stoichiometric conditions (highest temperatures) are presented in Table 2 and Table 3.

Table 2. Summary of low lean operating temperatures

Bluff body	T_i (K)	T_e (K)	T_p (K)	T_b (K)
Type 1	1550	1210	455	618
Type 2	1335	1271	373	625
Type 3	1528	1134	408	654

Table 3. Summary of stoichiometric operating temperatures

Bluff body	T_i (K)	T_e (K)	T_p (K)	T_b (K)
Type 1	1970	1429	558	722
Type 2	1886	1392	494	754
Type 3	2031	1262	535	808

Fuel-air mixture as well as the bluff body preheating effects in terms of impingement and exhaust gases temperatures are plotted in Figure 8.

The temperature ratio $(T_i - T_e)/(T_i - T_p)$ describes the bluff body preheating, the higher this ratio is, the higher the preheating effects are. It is worth to point out that the increase in this temperature ratio is inversely proportion to blowoff speed of the mixture entering the combustion zone, hence this ratio is also describing the maximum allowable blowoff velocity.

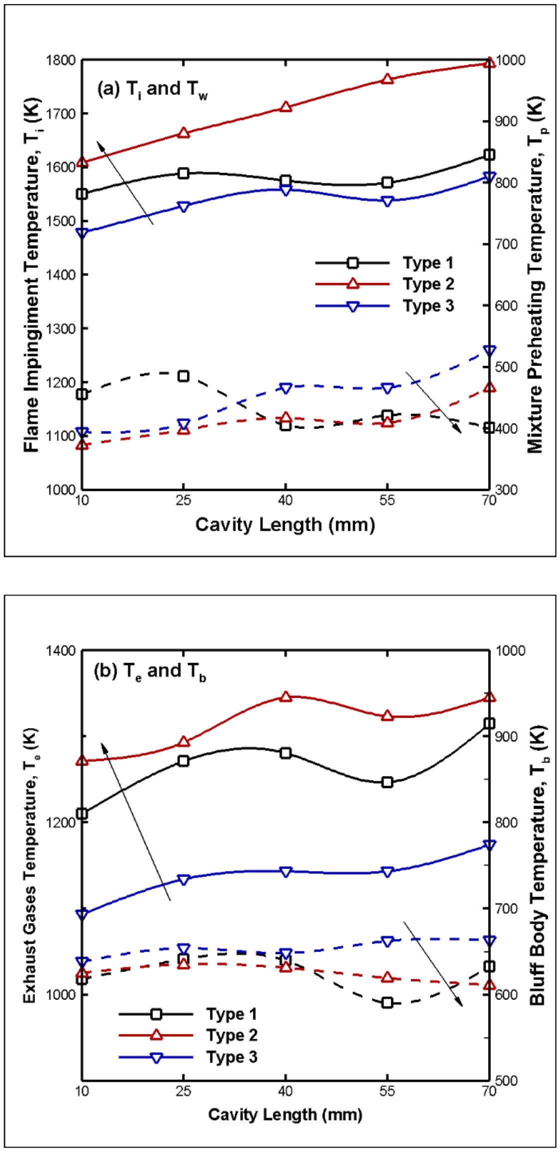


Figure 7. Operating temperatures at different cavity heights, (a) flame impingement and preheating, (b) exhaust gases and bluff body

Bluff body type 3 was found to have the largest temperature at all cavity lengths compared to other geometries, while the lowest temperature gains are associated with type1 except at low cavity heights.

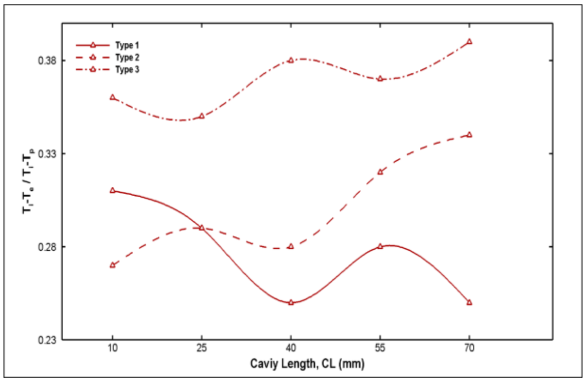


Figure 8. Preheating temperature ratio at different cavity heights

4. Conclusions

Internal preheating of fuel-air mixture improved the flammability limits of lean premixed flames anchored to bluff bodies. The recirculation zone trapped between the bluff body downstream surface and the combustor's floor was found to be bigger with improved mixing between fresh reactants and combustion products especially with high blockage ratio with the case of bluff body type 3, additionally, the low operating velocity of the 0.5 BR geometry has enabled the reactants to stay longer within the recirculation zone, hence the residence time was increased and lowest lean limits amongst all types was achieved.

Side surface corrugations attached to type 2 with a 0.25 BR enhanced the heat exchange between the exhaust gases and the bluff body surface, this positively affected the entrained fuel-mixture preheating inside the cavity and the resulted impingement temperature was also the highest amongst all geometries, however, the increased surface temperature, low recirculation zone size, and high blowoff velocity are the reasons behind the high low lean limit achieved with this body.

Generally, hollow bluff bodies with internal preheating effects and trapped recirculation zone have a significantly improved low lean flammability limits even with high blowoff velocities.

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