Experimental Prediction of Lean Blowout Limits for 3kW Micro Gas Turbine Combustor fuelled with LPG

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Abstract: *The Lean Blowout Limit of the combustor is one of the important performance parameters for a gas turbine combustor design. This study aims to predict the total pressure loss and Lean Blowout (LBO) limits of an in-house designed swirl stabilized 3kW can-type micro gas turbine combustor. The experimental prediction of total pressure loss and LBO limits was performed on a designed combustor fuelled with Liquefied Petroleum Gas (LPG) for the combustor inlet velocity ranging from 1.70 m/s to 11 m/s. The results show that the predicted total pressure drop increases with increasing combustor inlet velocity, whereas the LBO equivalence ratio decreases gradually with an increase in combustor inlet velocity. The combustor total pressure drop was found to be negligible; being in the range of 0.002 % to 0.065 % for the measured inlet velocity conditions. These LBO limits predictions will be used to fix the operating boundary conditions of the gas turbine combustor.*

Key Words: *Lean Blowout Limit, Total pressure loss, Micro Gas Turbine Combustor*

1. INTRODUCTION

The development of a micro gas turbine combustor is challenging when compared to a small and large gas turbine combustor. The combustion chamber of a gas turbine engine decides the overall performance of the engine. The flow field inside the combustor is very complex because of the turbulent flow field. The combustor consists of several subcomponents like pre-diffuser, snout, swirler, flame tube, and annulus. The pre-diffuser converts the high kinetic energy of incoming air from the compressor to pressure rise with minimal loss, which gives sufficient time to mix the air/ fuel for complete combustion. Along with the downstream, the component called snout is placed in line with the pre-diffuser. It is a sub-component of the combustor which distributes the designed mass flow to the flame tube and annulus. Followed by a component called a swirler, it is used to create a recirculation zone inside the flame tube. This is responsible for better air/ fuel mixing and igniting fresh incoming air/ fuel mixture from burnt gas to ensure continuous combustion. The flame tube has primary, secondary, and dilution zones. The primary zone maintains a stoichiometric air/fuel ratio, in which combustion is initiated. It is followed by a secondary zone in which the complete combustion will take place. The secondary zone exhibits the highest flame temperature in the entire engine.

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This high-temperature gas directly enters the turbine and may lead to damage to the turbine blades, since turbine blades are experiencing high stress due to centrifugal force because of its rotation. It is necessary to step down the temperature of gas before entering the turbine. Dilution zones take this responsibility to dilute the high-temperature gas coming from the secondary zone and maintain a suitable profile at the exit of the combustor. The exploded view of the in-house designed 3kW can-type combustion chamber is shown in fig. 1. The prediction of LBO limits for a gas turbine combustor is an important characteristic to fix an operating boundary for any gas turbine engine.

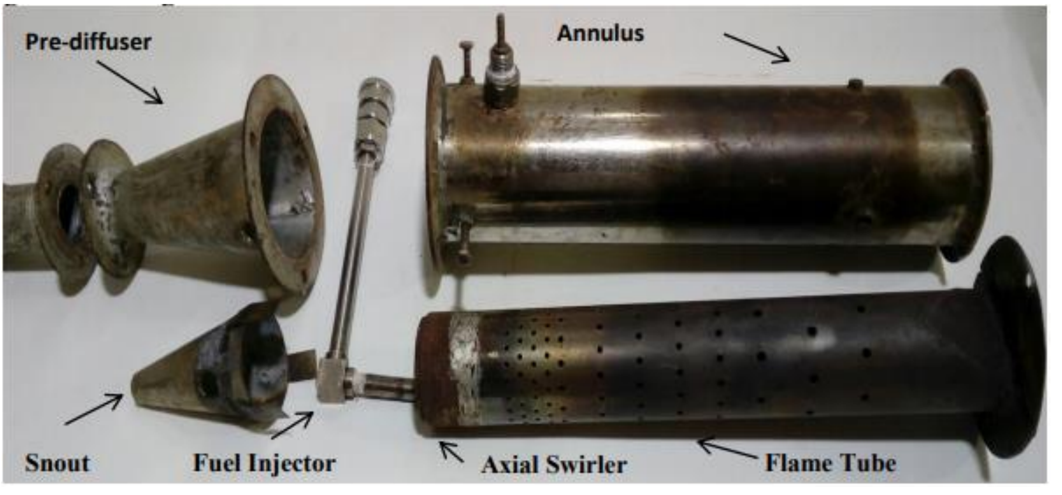

Figure 1. Exploded view of 3kW can-type combustion chamber

A considerable number of researchers predicted the LBO limits on actual and model gas turbine combustor through experimental predictions. Notably, the experimental visualization of the LBO process in a combustor model was carried out [1]. The flame images from their experiments indicate that the flame exists only in a small space of the primary zone rather than the whole region of the combustor near LBO. They confirmed that the flow area near the primary swirler region has a greater effect on the LBO fuel-air ratio. Cavaliere et al. conducted an experimental study on the flame blowout behaviour of swirl stabilized premixed, non-premixed, and spray flames. The methane is used as a fuel for premixed and non-premixed cases, and spray flames are fuelled by heptane. They found that the mean lift-of height increased with increasing fuel jet velocity and decrease with an increase in air velocity approaches zero just before blow off condition [2]. The researcher Xiao carried out an experimental study on LBO limits of a single dome combustor with swirl cups. Three different types of swirl cups dual-axial, axial-radial, and dual-radial cups were taken for their studies. They concluded that the LBO limits increase with primary swirler airflow for dual-radial swirler cup, whereas for dual-axial swirl cup LBO limits decrease with primary swirler airflow. Moreover, the LBO limit increases with the swirl intensity for all three swirl cups [3]. Zubrilin conducted experimental and numerical studies on the prediction of lean blowout limit in a combustor with the pilot flame. They observed that the LBO limit of the combustor will reduce up to four times besides of pilot flame in the main combustor [4]. Grohmann et al. experimentally studied the influence of single-component fuels on LBO performance in model gas turbine combustors. Three single component hydrocarbon fuels of n-hexane and n-dodecane and iso-octane were compared with kerosene jet A-1 fuel. Results show a noticeable difference in LBO limits of various fuels at comparable flow conditions [5].

In this present study, the total pressure loss and LBO limits of in-house design swirl stabilized 3kW can-type micro gas turbine combustor fuelled with LPG is experimentally predicted for combustor inlet velocity ranges from 1.7 m/s to 11 m/s.

2. COMBUSTOR GEOMETRY

A 3kW can-type swirl stabilized combustion chamber was designed by considering the design principles mentioned in standard textbooks [6], [7], [8]. The combustor dimension detail is shown in fig. 2. The gas turbine combustion chamber consists of several sub-components like diffuser, snout, air swirler, pressure swirl fuel injector, flame tube, and annulus. The diffuser expands the combustor incoming flow and it reaches the flow splitter called snout, where, the snout splits the incoming flow as primary and secondary flows.

The primary flow expands while passing through the snout, further downstream of the snout the flow enters through a swirler, where a strong swirling motion imparted to the flow, which helps to create a recirculation zone inside the combustor.

This recirculation zone is responsible for better mixing of air/fuel and it insists on continuous combustion. The secondary flow passes through the annulus of the combustor, where the flow enters perpendicular to the flame tube with the help of primary, secondary, and dilution ports. In general, the primary flow is responsible for combustion whereas the secondary flow will be used to dilute the hot combustion gases.

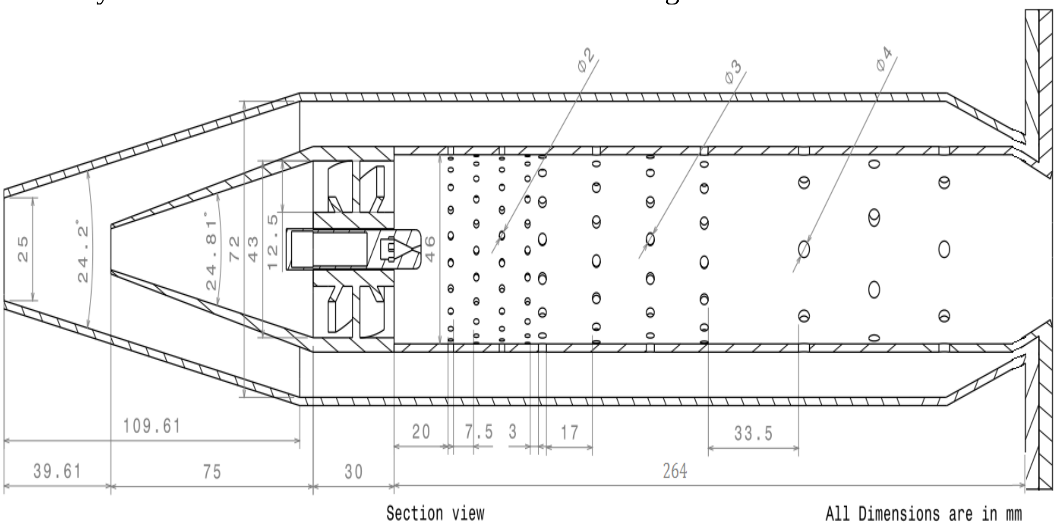

Figure 2. Combustion chamber dimension details.

The conical diffuser and snout have a divergence angle of 24.2 degrees and 24.8 degrees. An axial swirler with eight numbers of flat vanes has 30mm length, 45 degrees of axial, and 25 degrees of radial inclination. The swirl number (S_N) is estimated for the present geometry configuration is 0.75. The combustor flame tube has 265 mm length and 46 mm of diameter, and its primary zone has 88 numbers of 2 mm diameter arranged in 4 rows, secondary zone having 60 numbers of 3 mm diameter arranged in 4 rows, and dilution zone having 24 numbers of 2 mm diameter arranged in 3 rows.

The flame tube ports entry holes distribution is given in Table 1. The combustor annulus has 300mm length, 72 mm and 44 mm of inner and outer diameter. The overall wall thickness of the can combustor is maintained as 2 mm.

Table 1. Flame tube ports entry holes distribution detail

S. No	Description	Primary port	Secondary port	Dilution port
1	Diameter of holes (mm)	2	3	4
2	Number of rows	4	4	3
3	Spacing between the rows (mm)	8	20	26
4	Angle between the holes (degree)	18	24	45
5	Number of holes in each row	22	15	8
6	Total number of holes	88	60	24
7	Area of flow passage (mm^2)	276.32	423.9	301.44

3. COMBUSTOR EXPERIMENTAL SETUP

The detailed combustor experimental setup layout is given in fig. 3. The experimental setup is specially designed to predict the LBO limit of the micro gas turbine combustor. The experimental setup has a separate line for oxidizer (air) and fuel line (LPG). In the oxidizer line, it has a dual-stage reciprocating compressor driven by a 5 hp motor with 200 litres tank capacity; the maximum operating pressure of the compressor is limited to 12 bar.

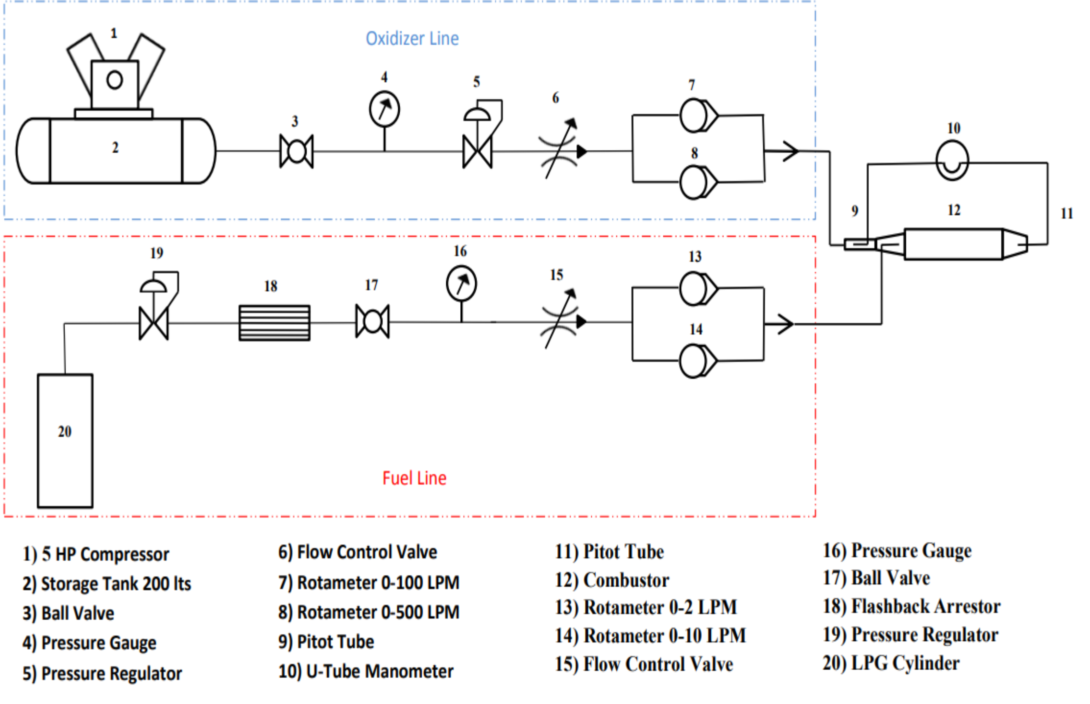

Figure 3. Combustor experimental set-up layout

The outlet of the compressor is connected to a ball valve for on/off airflow control, followed by a pressure gauge and pressure regulator which can handle up to 10 bar pressure. The air mass flow is controlled by a flow control valve, the outlet of the control valve is connected as an inlet for two rotameters (7&8) connected parallel. The rotameter-7 is used for coarse control of air mass flow rate from 0 to 500 LPM with 10 LPM as a least count (measurement error within 0.2 - 20 LPM, is ± 4%) and the rotameter-8 is used for fine control of air mass flow rate from 0 to 100 LPM with 1 LPM as a least count (measurement error within 0.04 - 4 LPM, is ± 4%). The net mass flow of air passes through the combustor is the sum of two rotameters flows. Whereas the fuel line starts with an LPG cylinder followed by a pressure regulator and flashback arrestor. The fuel mass flow is controlled by a flow control valve, the outlet of the control valve is connected as an inlet for two rotameters (10&11) connected parallel. The rotameter-10 is used for coarse control of fuel mass flow rate from 0 to 10 LPM with 1 LPM as a least count (measurement error within 0.004 – 0.4 LPM, is ± 4%) and the rotameter-11 is used for fine control of fuel mass flow rate from 0 to 2 LPM with 0.1 LPM as a least count (measurement error within 0.0008 – 0.08 LPM, is ± 4%). The net mass flow of fuel passes through the combustor is the sum of two rotameters flows. The two pitot tubes, one in the inlet and the other at the outlet of the combustor, are used to measure the total pressure. A U-tube water manometer is connected to these two pitot tubes to read the difference of total pressure, directly. The existence of flame inside the combustor is visualized axially from the combustor exit plane.

4. RESULT AND DISCUSSIONS

4.1 Combustor total pressure loss

The total pressure loss is a good measure of energy dissipated in the combustor, which also influences the performance, efficiency, and emission of gas turbine engines [9]. The total pressure loss coefficient (PDC) can be calculated by,

$$PDC = \frac{P_{in} - P_{out}}{P_{in}} \times 100$$

Where P_{in} and P_{out} is combustor inlet and outlet total pressure. The experiment was conducted for different combustor inlet velocities ranges from 1.7 m/s to 11 m/s.

The total pressure loss across the combustor for various combustor inlet velocities is shown in fig. 4. As seen in fig. 4, the pressure loss increases almost linearly concerning combustor inlet velocities.

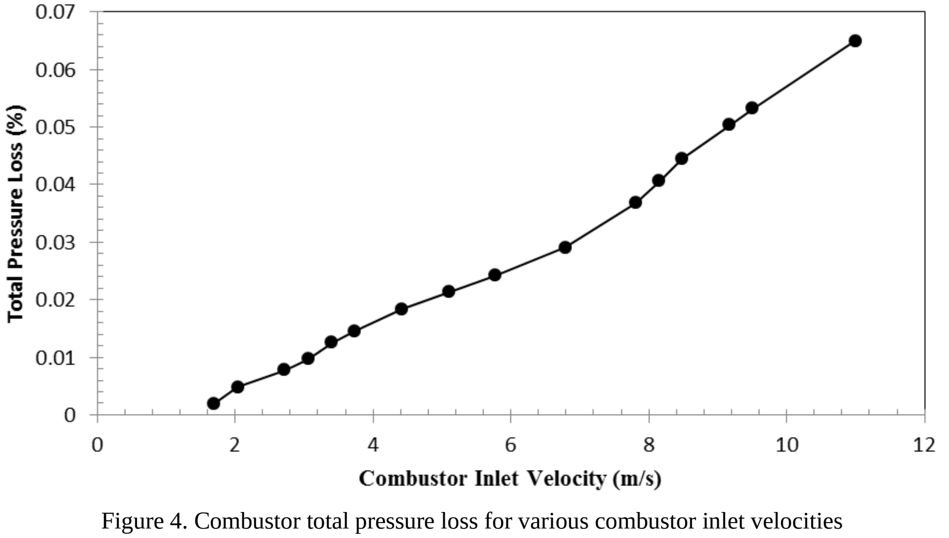

Figure 4. Combustor total pressure loss for various combustor inlet velocities

4.2 Prediction of a lean blowout

The experiments were conducted on an in-house developed swirl stabilized 3kW can-type micro gas turbine combustor to predict the lean blowout limit for different combustor inlet velocity ranges from 1.7 m/s to 11 m/s. The lean blowout limit for the combustor is predicted by keeping the combustor air mass flow rate a constant and by varying the fuel flow rate to vary the fuel-air ratio of combustion. After combustor light up for each test case, the fuel flow rate was initially kept at the higher flow rate, and leave the combustor flow parameters undisturbed for 60 seconds to get stabilized flow conditions, and then decreasing the fuel flow rate gradually to predict the lean blowout fuel flow rate. At some point in fuel flow rate for fixed mass flow, the combustor will experience the blowout, that fuel flow rate is taken as lean blowout fuel flow. The blowout condition of the combustor is predicted through flame visualization from the combustor exit plane. Figure 5 represents the process of a flame blowout from the stable flame to blowout for different equivalence ratios for 11 m/s inlet velocity case.

$\Phi = 1.2$	$\Phi = 1.0$	$\Phi = 0.8$	$\Phi = 0.6$	$\Phi = 0.4$	$\Phi_{LBO}=0.26$

Figure. 5 Flame visualization from combustor exit plane from the stable flame to flame blowout for 11 m/s .

To ensure the repeatability of results, each flow condition was repeated three times and the average is taken as a lean blowout fuel flow rate by which the lean blowout equivalence ratio will be calculated.

The predicted lean blowout equivalence ratio for different inlet velocities is shown in fig. 6. From fig. 6, its clear that the combustor lean blowout equivalence ratio decreases with an increase in combustor inlet velocities.

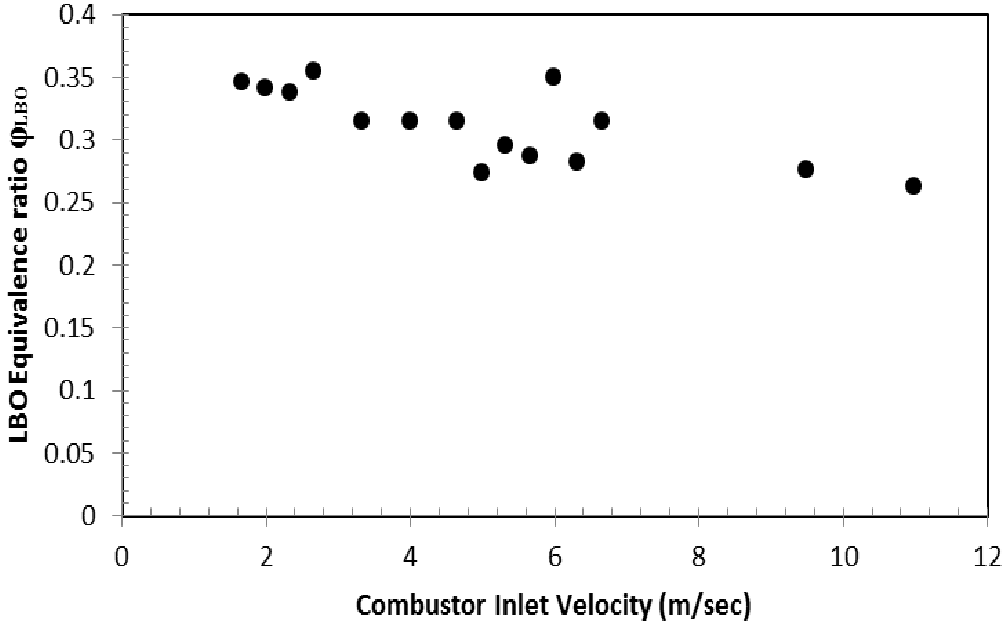

Figure 6. LBO equivalence ratio for different combustor inlet velocities

5. CONCLUSIONS

The combustor pressure drop and lean blowout limits of the 3kW can-type gas turbine combustion chamber were studied experimentally for inlet velocity ranges from 1.7 m/s to 11 m/s. The major outcome of the study is,

1) The combustor total pressure loss was found to be negligible being in the range of 0.002% to 0.06 % for the combustor; inlet velocity ranges from 1.7 m/s to 11 m/s. As the inlet velocity increases the total pressure loss across the combustor also increases.
2) The combustor lean blowout equivalence ratio decreases with an increase in combustor inlet velocity. In a swirl stabilized combustor, the key explanation behind this is that the flame stability characteristics largely depend on the inlet velocities. As the velocity of the combustor inlet increases with increased swirl strength, better features of air-fuel mixing are catalysed, resulting in complete combustion even in a low equivalence ratio.

This work can be extended to predict combustor lean blowout performance on different fuels combination. A numerical study is also planned to establish a detailed understanding of combustor flame blowout characteristics.

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