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Preliminary Design of a Reverse Flow Annular Combustor and Experimental Investigations at Design and of Design Operating Conditions

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Abstract: ***This paper presents design optimization of a Reverse flow annular combustor based on the calculation of geometric parameters, gas temperature profile, liner wall temperatures and position of air admission holes using the preliminary design procedure proposed by Melconian and Modak[1] with Jet A as fuel. It includes fabrication process of the combustion chamber and study of experimental results obtained from the testing of the combustor for temperature distribution at centerline, inlet and outlet of the combustor carried out at design and off design operating conditions for a small gas turbine engine***

Index Terms**:** ***Reverse flow annular combustor, Preliminary design, Combustor test rig, Experimental investigations***

I. INTRODUCTION

As compared to the conventional combustion chamber, a Reverse Flow Combustion Chamber in one in which the flow leaves in the opposite direction. It is mainly used in engines whose last compressor stage is centrifugal flow type and it also reduces the length of the engine. Vibration and maintenance problems are low as its reduced length allows single shaft sitting on two bearings instead of three. Warmer dilution air serves to control the formation of NOx formation during the reverse flow process. The operating parameters for a combustor are based on the basic geometric parameters of combustor, gas temperature profile, liner wall temperatures and position of air admission holes in the three zones of combustor.

The aim of this work is to design a Reverse flow annular combustor based on calculation of the geometric parameters, gas temperature profile, liner wall temperatures and number of air admission holes for a small gas turbine engine using the preliminary design procedure proposed by Melconian and Modak[1]. It also includes the modelling, fabrication of the combustor and experimental investigations which is carried out at different operating conditions of the small gas turbine at carried out at different operating conditions of the small gas turbine engine.

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II. BASIC DESIGN OF REVERSE FLOW COMBUSTOR

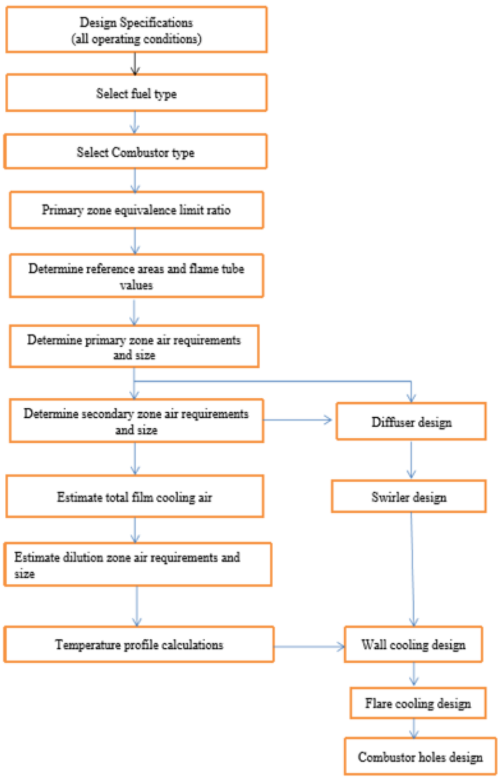

Fig 1: Proposed Preliminary design procedure (Melconian and Modak)

Initial conditions as obtained from the compressor outlet is used to carry out the design of the Reverse Flow Annular Combustor. Table below summarizes the main characteristics of a small gas turbine engine. The dimensions of a combustor can be determined either by aerodynamics or by chemical rate control. It is sufficient to accommodate the chemical process, when the combustor is sized for a specific pressure loss. Attention is given to both aerodynamic and chemical considerations to verify all the possibilities before the final choice. The configurations thus determined is as shown above.

The basic configurations of the reverse flow combustor were obtained based on the preliminary design procedure and the gas turbine characteristics as mentioned in table

Table I: Characteristics of a small gas turbine engine at maximum operating conditions

Parameter	Value
Speed	50500 rpm
Compressor isentropic efficiency	77%
Compressor outlet temperature, T3	445 K
Compressor outlet pressure, P3	367 kPa
Turbine inlet temperature, T4	1142 K
Fuel	Jet A

Table II: Basic configurations of Reverse Flow Combustor

Parameter	Results
Reference diameter, D_{ref}	0.263 m
Flame tube diameter, D_{ft}	0.250 m
Internal diameter, d_i	0.152 m
Length of the dome	0.0213 m
Swirler diameter	11.5 mm

Table III shows the total length of the flame tube, primary, secondary and dilution zones of the designed reverse flow combustor. The primary zone length (Lpz) is within 2/3 to ¾ of Dft and a value of a half of Dft is taken for secondary zone length (Lsz). Total length of the flame tube is considered based on the traverse quality (TQ) of temperature distribution on the combustor exit. The values obtained is based on the method of calculation of total length given in Lefebvre (1983) and a TQ of about 15% is considered. the difference between total length and the sum of the primary and secondary zone length is taken as the length of the dilution zone.

Table III. Flame Tube zone length

Total Length (m)	Primary zone length (L_{PZ}, m)	Secondary zone length (L_{SZ}, m)	Dilution Zone length (L_{DZ}, m)
0.173	0.0583	0.050	0.065

Table IV: Admission Holes

Parameter	Primary zone	Secondary zone	Dilution zone	Cooling
No. of holes	60	80	12	12
Diameter (mm)	8	6	24	12

An iterative process is used to determine the size and number of admission holes after determining the air mass flow rate that enters into each combustion zone. This iterative process occurs as the discharge coefficient is unknown. Using the sequence of calculations described in Lefebvre and Mellor the number and diameters of the admission holes are determined as shown in Table IV.

III. FABRICATION AND EXPERIMENTAL SET UP

Based on the above obtained dimensions a reverse flow annular combustor is designed and the fabricated model is as shown in figure 2 which is further investigated experimentally in a test rig.

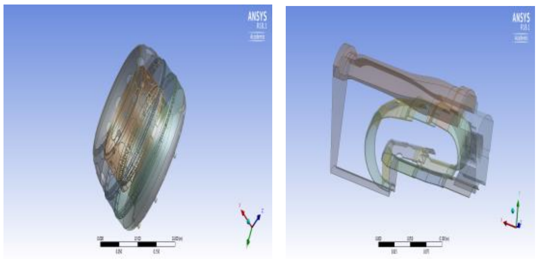

Fig 2: Catia Model of the Reverse Flow Annular Combustor

The above model is subjected to various off-design operating conditions as stated in Table V in a test rig and the details of combustor test rig is as follows:

The basic facilities available in the test rig are
- Air and fuel supply system
- Instrumentation system
- Supply of high pressure and high temperature air to perform design and off-design estimation
- To tap compressed air from an existing engine running on the test-bed

Objectives of Testing: To evaluate the performance parameters for given test conditions at design and off-design conditions

- Total pressure loss
- Combustion efficiency by thermocouple and gas sampling methods
- Exit Temperature profile and Pattern Factor analysis
- Study the light up characteristics
- Conduct endurance test for the study of liner integrity and life

Instrumentation: For the instrumentation of the combustor, the required probes and pressure transducers/transmitters at all the location of combustor was arranged.

- Suitable rotameters were used for measuring the flow rate
- Dynamic pressure transducers are mounted on the outer casing.
- For the measurement of temperature traverse and total pressure at combustor exit plane, cooled total pressure and temperature combine probes are used.
- Three to four numbers of gas-sampling probes to suit

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the entire operating ranges are provided.

The following constituent to be measured in % volume basis and are recorded for the test conditions specified. The constituent are as follows:

- Carbon dioxide
- Carbone monoxide
- Total hydro carbon
- Oxygen oxides of Nitrogen
- Hydrogen

Data Acquisition: The Data Acquisition System (DAS) required for acquiring data and on-line monitoring of test conditions and other important parameters during the test is provided. The facility has the capacity to monitor important channels and parameters during the test runs. The details of data acquisition system including the scanning rate is obtained before the commencement of the tests.

Online Monitoring: During the test, the parameters are monitored on-line. The data acquisition system has the provision to display on-line, the calculated performance parameters like combustor inlet Mach number, combustor inlet mass flow and fuel-air ratio, the selection of channels for on-line monitoring and for calculated parameters are specified. The equation to be used for calculated parameters are specified and a print out of all channels and their locations with respect to combustor is available before the commencement of each test.

Test Data Analysis: The test data is analyzed to study the performance parameters of the combustor. The analysis of the test run data is made during the run at intervals.
The boundary conditions considered as shown in Table below.

Table V. Inlet Boundary Conditions

Sl No	Parameter	Unit	Case1	Case2	Case3	Case4
1.	Spool Speed	rpm	43000	45000	48000	50500
2.	Air mass flow rate	Kg/s	0.938	1.005	1.175	1.266
3.	Fuel mass flow rate	Kg/s	0.009	0.012	0.013	0.014
4.	Fuel Air Ratio	---	0.009	0.010	0.011	0.012
5	Total pressure at inlet	kPa	287	301	337	367
6.	Total Temperature at inlet	K	411	416	432	445

IV. RESULTS AND DISCUSSIONS

Table VI shows the results obtained from the experimental investigations of the designed combustor at design and off-design operating conditions. This phenomenon can be explained on the basis of the fact that the fuel mixing and evaporation of fuel takes place thereby indicating reduction in temperature levels. While an evaporation gets completed and more and more air is available from air admission holes, and thus the performance of the combustor is improved and maximum expected levels are reached.

The following parameters are used in this work to evaluate the performance of the Reverse Flow Annular Combustor

Equivalence Ratio, is defined as the ratio of actual fuel air ratio to stoichiometric fuel-air ratio which is 0.0667 for the fuel used and is given by

$$\varphi = \frac{Fuel\ air\ ratio_{actual}}{Fuel\ air\ ratio_{stoichiometric}}$$

Pattern Factor, is obtained by adding together the temperature measurement around each radius of the liner and then dividing by the number of locations at each radius i.e., by calculating arithmetic mean at each radius and is given by

$$Pattern\ Factor = \frac{T_{Max} - T_{Avg\ Exit}}{T_{Avg\ Theoritical} - T_{inlet}}$$

Percentage Pressure Loss, is obtained by dividing the difference between inlet and outlet pressure by inlet pressure and is given by,

$$Percentage\ Pressure\ Loss = \frac{P_{inlet} - P_{outlet}}{P_{inlet}}\ x\ 100$$

Table shows the output parameters obtained through experimental testing of the combustor at various operating conditions.

Table VI: Various output parameters obtained at the outlet

Sl. No	Parameter	Unit	Case1	Case2	Case3	Case4
1.	Spool Speed	rpm	43000	45000	48000	50500
2.	Total pressure at outlet	kPa	279	293	328	358
3.	Total Temperature at outlet	K	741	902	916	928
4.	Equivalence Ratio	--	0.34	0.47	0.54	0.57
5	Pattern Factor	--	0.641	0.643	0.765	0.894
6	Percentage Pressure Loss	%	2.82	2.71	2.56	2.50

The plots below show the variation of fuel-air ratio, equivalence ratio, pattern factor, exit temperature percentage pressure losses at various operating speeds of the gas turbine engine.

Figure 3 shows the variation of fuel-air ratio at different mass flow rate of rate which defines the stability loop of the combustor. The term "stability" is often used in combustion, as a measure of the maximum air velocity the system can tolerate before flame extinction occurs. If the combustor is capable of burning over a wide range of mixture or its blowout velocity is high, then it is described as good stability performance. It has been observed that the region of stable burning is wider than the existing reverse flow annular combustors.

Improvement in the exit temperature of the combustor (acceptable by the turbine blades) is obtained by better fuel atomization and flame stabilization. Figure 4 and 5 shows the effect of exit temperature and maximum

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temperature at different fuel air ratios through the combustor.

This shows that the combustion is lower at lower air flow rates or low speeds of the gas turbine engine due to improper mixing of air and fuel and poor flame stabilization at lower pressures

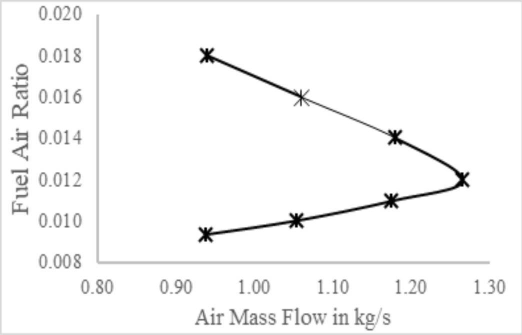

Figure 3: Fuel Air Ratio vs Air Mass Flow in kg/s

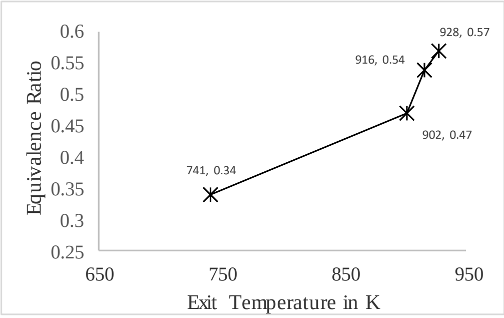

Figure 4: Equivalence Ratio vs Exit Temperature in K

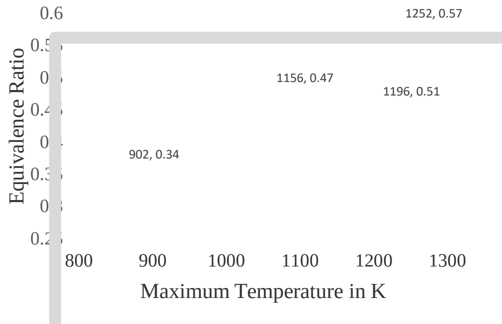

Figure 5: Equivalence Ratio vs Maximum Temperature

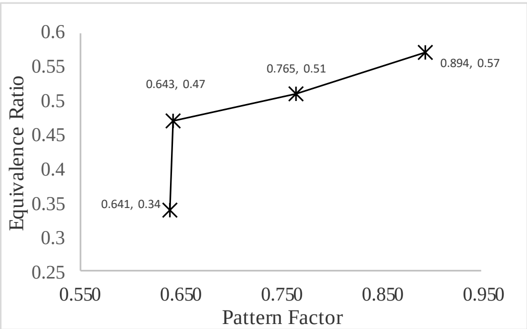

Figure 6: Equivalence Ratio vs Pattern Factor

Figure 6 show the effect of pattern factor at different fuel air ratios or equivalence ratio of the combustor. At lower air flow rates pattern factor is obtained in the range of 0.60 to 0.87 and at higher mass flow rates it is in the range of 0.73 to 0.87 because of higher operating pressures. Figure 7 shows the percentage pressure losses at different fuel air ratios and it is noted that lower total pressure loss is observed at higher air flow rates. Figure 8 illustrates the correlation between the inlet and outlet pressure at different speeds of the engines.

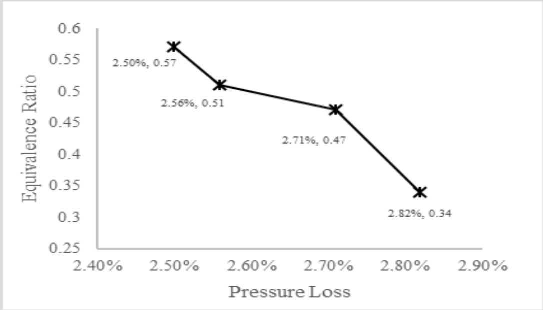

Figure 7: Equivalence Ratio vs Percentage Pressure losses

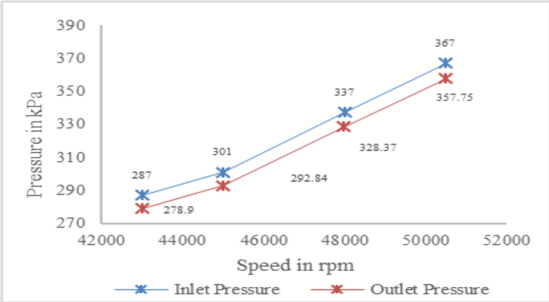

Figure 8: Inlet and Outlet Pressure vs Speed in rpm

VI. CONCLUSIONS

The design of the Reverse Flow Combustor and experimental investigations is carried out at basic design point operating conditions which shows a well-behaved flow with flame stabilization and equivalence ratio with in the stability limits. The Temperature distribution profile at the outlet is uniform which suggests that the number and diameter of the air admission holes is optimized. Experimental Investigations is conducted at design and off-design operating conditions of the gas turbine engine and the results tabulated. Values of exit temperature, maximum temperature, pattern factor, percentage pressure losses are plotted at different equivalence ratios of the combustor which shows that the variation of these parameters at various operating conditions is better than the existing combustor and results in better performance and cooling of the combustor walls.

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