EFFECT OF DIFFUSER GEOMETRY ON THE PERFORMANCE OF AN ANNULAR AERO GAS TURBINE COMBUSTOR

R.K. Mishra*, R.D. Navindgi* and M.N. Bhat*

Abstract

Combustor is an important component of a gas turbine engine and its performance governs the overall performance of the engine. This paper describes the effect of diffuser geometry on the performance parameters of short annular combustors. Full-scale combustors having similar liner configurations but different diffuser geometry were tested in the combustor test facility for this investigation. The combustor aerothermal characteristics such as light-up behavior, exit temperature pattern factors and combustion efficiency are found to be independent of diffuser geometry. But the major aerodynamic parameters such as diffuser pressure loss, static pressure recoveries etc are significantly affected by the diffuser geometry.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_{\text{ref}}$</td>
<td>reference area of the combustor, m$^2$</td>
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<tr>
<td>$C_p$</td>
<td>pressure recovery coefficient</td>
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<tr>
<td>$D_{\text{ref}}$</td>
<td>combustor reference diameter, m</td>
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<tr>
<td>$P_3$</td>
<td>total pressure at combustor inlet, Pa</td>
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<tr>
<td>$P_4$</td>
<td>total pressure at combustor outlet, Pa</td>
</tr>
<tr>
<td>$P_{ii}$</td>
<td>total pressure at any plane/location in combustor flow passage, Pa</td>
</tr>
<tr>
<td>$P_{si}$</td>
<td>static pressure at any plane/location in combustor flow passage, Pa</td>
</tr>
<tr>
<td>$P_{\text{inlet}}$</td>
<td>static pressure at combustor inlet, Pa</td>
</tr>
<tr>
<td>$P_{\text{si}}$</td>
<td>static pressure at any section under consideration, Pa</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>combustor overall pressure loss</td>
</tr>
<tr>
<td>$\Delta P_{\text{diff}}$</td>
<td>diffuser pressure loss</td>
</tr>
<tr>
<td>$T_{\text{3avg}}$</td>
<td>inlet average temperature, K</td>
</tr>
<tr>
<td>$T_{\text{4cir-avg}}$</td>
<td>circumferential averaged exit temperature, K</td>
</tr>
<tr>
<td>$T_{\text{4avg}}$</td>
<td>exit average temperature, K</td>
</tr>
<tr>
<td>$V_{\text{inlet}}$</td>
<td>velocity of air at combustor inlet, m/s</td>
</tr>
<tr>
<td>$W_a$</td>
<td>combustor inlet air flows, kg/s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density at combustor inlet, kg/m$^3$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>combustion loading parameter</td>
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</table>

Introduction

The combustor is one of the main components of a gas turbine engine whose operational performance governs the reliability and efficiency of the engine itself. The life of turbine vanes and blades are directly affected by the combustor exit temperature non-uniformity. Diffuser pressure losses and air mass flows in different combustor zones are responsible in controlling the exit temperature non-uniformity and the cooling air passing through the passages of nozzle guide vanes. The engine thrust and specific fuel consumption are adversely affected by combustor overall pressure loss and combustion inefficiency respectively. In developing an engine, each component of the engine must be extensively tested in the component test facility to validate its design objectives prior to its integration in the engine.

In the weight reduction program of a practical aero gas turbine engine under development, weight of the combustor is reduced by reducing its overall length. In this program, the diffuser length alone is reduced without modifying the flame-tube and to achieve the required level of diffusion, the diffuser angle is increased. Experimental investigation has been carried out on two combustor configurations having similar flame-tubes, i.e., the flame-tube (also known as liner) length and configuration of different zones are same in both the combustors. The full-scale combustors of both the configurations were tested in the test facility to study the effect of the diffuser geometry change on the overall performance of the combustor. No attempt has been made in this exercise to study the inde-

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pendent effect of pre-diffuser and dump diffuser geometry on the overall performance of the combustor and also more than two configurations could not be tested due to the long manufacturing cycle. However, tests can be continued with more configurations as well as focusing on individual components. Due to the limitations of instrumentation on a practical full-scale annular combustor, scaled models are generally studied to evaluate the effect of diffuser geometry but modeling the flame-tube is carried out with certain assumption and approximation. This always causes a different flow field in the diffuser of the model than that of the actual combustor. Notwithstanding the limitations, the present experimental investigation provides very useful input to the engine development program and reveals that the aerodynamic parameters such as overall pressure loss, diffuser pressure losses and diffuser pressure recoveries are affected due to the change in the diffuser geometry. Also it confirms that the flame-tube geometry largely controls the lightup characteristics, exit temperature non-uniformity and combustion efficiency of a combustor.

**Combustor Configuration**

Figure 1 shows the combustor configuration ‘A’ with its major components. Fig. 2 shows the configuration of combustor ‘B’ where the geometrical differences from combustor A, are illustrated by indicating the combustor A parameters in parentheses. Both the combustors, i.e., combustor A and combustor B, consist of short pre-diffuser followed by a dump diffuser.

The flame tube (liner) is held at the upstream end with the atomizer and swirler assembly and suitable outlet interface assembly at downstream end. This enables to mount the combustor exit instrumentation. This plane simulates the leading edge of the high-pressure turbine nozzle guide vanes of the actual engine. Flame tube front end consists of smoothly shaped cowl structure that guides the necessary core airflow inside the flame tube.

The combustors are provided with axial flow straight vane swirlers holding equal numbers of air blast type atomizers concentrically. The distance from the pre-diffuser exit plane to the liner front end is known as dump gap and the ratio of this dump gap to pre-diffuser exit height known as dump gap ratio is an important parameter controlling the diffuser performance. In the configuration ‘B’ the pre-diffuser length is reduced, diffuser angle is increased and the dump gap ratio is reduced. The major differences between the two combustors are presented in Table-1. Compared to combustor A, there is also a change in the diffuser contour. The air injection holes on both the flame tubes are same.

**Test Facility**

Figure 3 shows the combustor test facility schematically. Air required for combustion is received from the compressor plant at the required inlet conditions through a pre-heater system in unvitiated mode. A gas generator with a heat exchanger is used as pre-heater, which in-

![Fig.1 Configuration of Combustor A](image1)

![Fig.2 Configuration of Combustor B](image2)

<table>
<thead>
<tr>
<th>Table-1: Combustor configuration details</th>
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<tbody>
<tr>
<td>Parameters</td>
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<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Overall length</td>
</tr>
<tr>
<td>Pre-diffuser length/height</td>
</tr>
<tr>
<td>Pre-diffuser angle</td>
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<tr>
<td>Dump gap ratio</td>
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increases the supply air (from plant compressor) temperature to the combustor inlet. This unvitiated air enters the combustor through a plenum chamber as a uniform stream.

Instrumentation and Data Acquisition

Full-scale combustors of two different configurations were tested in the test facility with extensive instrumentation at inlet, exit and different zones. But instrumentation could not be provided at some of the places and particularly in the dump diffuser region due to practical difficulties. The pre-diffuser exit is provided with only static pressure measurements to evaluate the static pressure recoveries. All probes (total pressure and total temperature) are designed in such a way that their sensing points lie on centers of equal areas. At the combustor exit, multipoint temperature probes are installed at fixed locations to measure the gas temperature for computation of pattern factors and combustion efficiency. The data acquisition system in the control room incorporates 300 channels of pressures, temperatures and fuel flow etc. On-line monitoring of important parameters is also provided in the control room for setting up of test points. Both the combustors were tested under similar test condition, each for about 20 hours and sufficient sets of steady state data have been acquired to establish repeatability of the test results.

Tests and Test Procedure

During this experimental investigation, tests were carried out at combustor inlet pressure of about 400 kPa and temperature of 550 to 600 K. The combustor exit average gas temperature was maintained in the range of 1100 to 1200 K. The following tests are carried out to study various performance parameters.

Cold Flow Tests

These tests are intended to study the aerodynamic behavior of the combustor and to estimate parameters like pressure losses (ΔP), diffuser pressure losses (ΔP_{	ext{diff}}), pressure recoveries (Cp), mass flow splits etc. inside the combustor. ΔP, ΔP_{	ext{diff}} and Cp are defined in equations 1, 2 and 3 respectively. During these tests, the combustor inlet Mach number is varied by controlling the exit area. Diffuser loss is calculated from pre-diffuser inlet plane to dump diffuser outlet passages before flow enters through primary holes. The combustor air mass flow splits between the annuli are measured at the diffuser outlet passages.

\begin{align*}
ΔP &= \frac{[P_3 - P_4]}{[P_3]} \quad (1) \\
ΔP_{\text{diff}} &= \frac{[P_3 - P_{ti}]}{[P_3]} \quad (2) \\
Cp &= \frac{[P_{si} - P_{sinlet}]}{[0.5 \ast \rho \ast V_{inlet}^2]} \quad (3)
\end{align*}

Light-Up Trials

These trials are carried out on the combustor at different inlet pressures and temperatures representing the light-up points of the engine, to observe the light-up fuel-air ratio and light-up duration. Temperature probes are mounted at combustor exit plane to register the light-up moment. Transient data is acquired during these trials to register test parameters and light up moments.

Hot Flow Tests

In these tests, attention is focused mainly on the exit pattern factors and combustion efficiency. Combustor inlet Mach number, and fuel-air ratio is kept nearly constant during these tests. Pattern factors are very critical from the point of turbine blade and vane life and overall performance of the gas turbine engine. These are the temperature profiles in radial (RPF) and circumferential (CPF) directions at the combustor exit and non-dimensionalized by the temperature rise across the combustor and represent the temperature non-uniformity of the combustion gases entering the turbine. The loci of the non-dimensional temperature profiles are estimated using the following relations:

\begin{align*}
\text{RPF} &= \frac{T_{4 \text{cir-avg}} - T_{4\text{avg}}}{T_{4\text{avg}} - T_{3\text{avg}}} \\
\text{CPF} &= \frac{\frac{T_{41} - T_{4\text{avg}}}{T_{4\text{avg}} - T_{3\text{avg}}}}
\end{align*}

![Combustor test facility](image)
Combustion efficiency is another important performance parameter of a combustor as well as of an aero gas turbine engine. It is defined as the ratio of the energy liberated to the chemical energy stored in the fuel. The combustion efficiency is presented as a function of a combustion loading parameter known as theta (θ) parameter. The θ parameter correlates the combustion efficiency to the operating conditions and the geometrical parameters of the combustor and is expressed by the following relation:

$$\theta = \left[ \frac{P_{3}^{1.75} D_{ref}^{0.75} A_{ref} \ln (T_{3\text{avg}}/300)}{W_{a}} \right]^{(1/6)}$$

(6)

**Results and Discussion**

The following performance parameters are analyzed to study the effect of diffuser geometry:

- Diffuser pressure loss
- Pressure recovery
- Combustor air mass flow splits
- Overall pressure loss
- Lightup characteristics
- Radial pattern factor
- Circumferential pattern factor
- Combustion efficiency

**Diffuser Pressure Loss**

The diffuser pressure losses are the driving forces for air jets entering into the flame tube through primary, secondary and dilution air injection ports. This controls the jet penetration and mixing in various zones inside the flame tube [1]. Also the air bleed from combustor annulus for turbine nozzle cooling is affected by the diffuser pressure loss. This is measured at the location where air from dump diffuser enters to the annulus passages and before the air enters through any row of holes in the flame tube. These losses are shown in Fig.4. Diffuser pressure loss is the sum of pre-diffuser loss and dump diffuser loss. The dump gap ratio is reduced from 1.724 in combustor A to 1.0 in combustor B. Generally the diffuser pressure loss does not change for dump gap ratio in the range of 1.0 to 2.0 for a constant pre-diffuser divergence angle [2][3]. In the present case the dump gap ratio is reduced but pre-diffuser divergence angle is increased simultaneously, which has changed the flow distribution in the conical as well as in the dump region causing a higher pressure loss in the diffuser. The contribution of pre-diffuser to the diffuser loss could not be ascertained due to measurement difficulties in this practical combustor.

**Pressure Recovery**

This is an important aerodynamic parameter of the combustor, which indicates the efficiency of diffusion, and higher the diffusion better is the diffuser performance. The measurement of this parameter (pressure recovery coefficient Cp) was done with extensive static pressure measurement both at outer and inner surfaces of pre-diffuser exit plane. The entry of outer and inner annulus passages was also provided with maximum number of wall tapings for static pressure measurement. As shown in Figs. 5 and 6, there is a remarkable decrease in pressure recoveries in pre-diffuser and dump diffuser compared to that in combustor configuration ‘A’. Though the dump gap ratio in the range under consideration does not affect the dump diffuser pressure recovery, the change in divergence
angle coupled with dump gap ratio has resulted in a low pressure recovery [2][3]. Low static pressure recovery in the pre-diffuser is an indication of possible flow separation at the lip of the conical portion if not at aft location, and it has been reflected on the pressure recovery of the diffuser, as inlet static pressure has been taken for calculation of pressure recovery for both pre-diffuser and diffuser.

**Combustor Air Mass Flow Splits**

The air mass flows at the entry to annulus passages and through the core are shown in Fig.7. The test results are within a wide band due to the measurement difficulties and inaccuracies at these locations. However, in combustor B, the outer mass flows are found more and inner mass flows are less than that of combustor A. The annulus mass flows have been redistributed, but the core mass flows are nearly same in both the combustors since the controlling flow areas for air entering the core are same in both combustors. The mass flow splits are responsible for providing the required temperature distribution at combustor exit for best life of turbine vanes and blades. As will be discussed later, this changes is mass flow spits are not clearly visible to be reflected on the exit radial and circumferential temperature profiles.

**Overall Pressure Loss**

The overall pressure loss of a combustor is the sum of pre-diffuser loss, dump diffuser loss, liner loss and fundamental loss due to heat addition. The overall pressure losses for both the combustors are presented in Fig.8. The pre-diffuser loss and dump diffuser loss are combined to form the diffuser loss and higher diffuser loss has resulted in a higher overall pressure loss. The fundamental loss due to heat addition is a small fraction of the total loss and since similar test conditions are considered, it would be same for both the combustors. The possible change in the liner loss due to jet mixing seems to be marginal as it depends on liner geometry and air injection port size and location which were maintained same in both the combustors.

Higher pressure losses are beneficial to mixing and for a better temperature distribution as well as turbine vane cooling but are not acceptable from engine overall performance point and hence action has to be taken to modify the combustor geometry to reduce it. Generally the annulus flow passages, liner open hole areas and diffuser geometry are modified to optimize the overall pressure ratio without sacrificing the other aerothermal performances of the combustor [4].

Without altering the liner open hole areas, the diffuser geometry such as diffuser divergence angle and dump gap ratio and dump diffuser contour and annulus passage geometry may be optimized for a better overall pressure loss.
Light-up Characteristics

The light-up trials are carried out on the both the combustors in the test facility simulating engine ground lightup conditions, i.e., inlet pressure of 110-125 kPa and temperature of 300-330 K. Both the combustors have exhibited smooth light-up within 6 to 8 seconds and at a fuel-air ratio in the range of 0.020 to 0.025 as shown in Fig.9.

As the flame tube configuration, atomizer characteristics, type and location of ignitors are same in both the cases, the change in diffuser geometry alone has no significant effect on the light-up characteristics of the combustors [5].

Radial Pattern Factor

The radial pattern factors for both the combustors under similar test conditions are presented in Fig.10. No significant effect on RPF is noticed except that at 75% height of the exit annulus, which falls within the measurement accuracy. Liner geometries with similar air injection passages and atomizer characteristics have resulted in similar radial pattern factors [6]. Small change in the mass flows in annulus passages has not contributed to the radial pattern factor.

Circumferential Pattern Factor

The circumferential pattern factors estimated based on temperature measurements for a number of tests are shown in Fig.11. CPFs of both the combustors lie in the range of 0.35 to 0.42. The CPF is also a function of dilution zone geometry and size and disposition of air injection ports in this zone [6][7]. Thus, change in diffuser geometry alone has not affected the CPF and RPF as well. Therefore, to improve the pattern factors, attention should be focused on the modification of liner geometry rather than that of the diffuser.

Combustion Efficiency

The combustion efficiencies for both the combustors were found to lie in the range of 95% to 98% as shown in Fig.12. This parameter (θ) is a function of evaporation, mixing and chemical reaction, which in turn depend on the combustion volume and spray characteristics of fuel nozzles and the operating pressure and temperature [8][9]. The wide variation of combustion efficiency for any loading factor is mainly due to the methodology of estimation. In this exercise the efficiency is estimated based on limited number of temperature measurements using thermocouples whereas the exhaust gas sampling technique gives more accurate values. However, it is clearly evident from Fig.12 that diffuser geometry with similar reference areas has no influence on the combustion efficiency.
Conclusion

In this experimental investigation, the effect of diffuser geometry on the overall performance of an annular combustor is studied and the following conclusions can be drawn:

- Aerodynamic performance of a combustor is mainly a function of diffuser geometry. Increasing the diffuser angle, decreasing the dump gap ratio and changing the diffuser contour have caused higher diffuser pressure loss, and a fall in the pressure recoveries.

- Light-up characteristics is independent of diffuser geometry for a given atomizer characteristics, similar igniters and primary zone configuration.

- The pattern factors and combustion efficiencies are mainly independent of diffuser geometry. Modification of flame-tube configuration should be attempted for any improvement in these parameters.

- Rise in diffuser pressure loss and marginal change in mass flow splits with similar flame-tube configuration has not affected the pattern factors.

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References


