TECHNICAL NOTE

EFFECT OF GEOMETRICAL PARAMETERS ON THE EXIT PATTERN FACTORS OF AN ANNULAR COMBUSTOR: AN EXPERIMENTAL STUDY

R. K. Mishra*, R. D. Navindgi** and Kuldeep Singh+

Abstract

Combustor is an important component of a gas turbine engine and its performance governs the overall performance of the engine. Combustor exit pattern factors are very critical from the consideration of turbine blade and vane life. To achieve the desired goal of pattern factors, the air-management through different zones of combustor is to be carried out very carefully with proper fuel-air mixing followed by complete combustion in the primary zone. During the development stage, extensive studies have been carried out to establish the effect of different geometrical parameters of the combustor on the exit pattern factors. This paper describes the details of the experimental investigations carried out on a full- scale combustor with different geometrical parameters such as diffuser geometry, swiller configuration, atomizer flow passage and dilution zone configurations to study their effect on the exit pattern factors. Dilution zone geometrical parameters and swirler configuration are found to have strong influence in controlling the combustor exit pattern factors and there is an optimum size and spacing of the dilution holes to achieve desired pattern factors at combustor exit.

Nomenclature

d_j = jet diameter

d_p = port diameter

C_d = coefficient of discharge

FN = flow number

H = liner height

S = spacing of ports in a row

T_{3avg} = average temperature at inlet, K

$T_{4cir\text{-}avg}$ = circumferentially averaged exit temperature at any radii, K

T_{41} = local temperature at any circumferential location at combustor exit plane, K

T_{4avg} = exit average temperature, K

W_f = fuel flow rate, gallons/hour

DP_B = pressure drop across the atomizer

Introduction

In order to achieve high specific thrust and low specific fuel consumption, the present day gas turbine engines are operating under high turbine entry temperatures. Elevated turbine inlet temperature imposes stringent limitations on the temperature profiles at exit of the combustor. Therefore these temperature profiles have become very critical from the consideration of life and stressing of turbine blades and vanes and the performance of the aero gas turbine engine.

The development of the temperature profiles at combustor exit depends primarily on the complete combustion of fuel-air mixture in the primary zone and mixing process between the cooling air and the hot combustion gases in the dilution zone of the combustor. During the development stage, extensive studies have been carried out on this combustor to establish the effect of different geometrical parameters on the exit pattern factors and the combustor is in the process of optimization to meet the design goal.

Though considerable work has been done by researchers in the field of combustor design and computation of aerodynamic and chemical processes in a combustor, most of them are carried out on scaled models or sector combustors. However, the complex effects of aerodynamic and thermal load on the combustor can only

*Scientist, Regional Centre for Military Airworthiness (Engines), CEMILAC, HAL Engine Division, CV Raman Nagar, Bangalore-560 093, India, Email : rkmishra_gtre@yahoo.com
** Scientist, Gas Turbine Research Establishment, CV Raman Nagar, Bangalore-560 093, India
+ Scientist, Directorate of Aeronautics, DRDO Bhawan, Rajaji Marg, New Delhi-110 011
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be shown in full-scale, full-annular tests under high pressure and high temperature simulating the actual engine conditions as in the present investigation. This paper describes the details of the experimental studies carried out on some of the geometrical parameters such as dilution zone configuration, diffuser, swirler and atomizers. Further studies can be carried out to analyze the effect of many other geometrical parameters of the combustor. As optimization is a continuous process in aero gas turbine engines either to meet the performance or to improve it depending on the application or mission, the present study provides very useful input for combustor design. Dilution zone geometric parameters, i.e., air injection hole size and spacing are found to control the combustor exit temperature profiles. The optimum configuration of the dilution zone is to be adopted in the combustor before it is integrated in the engine for achieving the desired goal of pattern factors.

Combustor Configuration

Figure 1 shows the combustor configuration with its major components. The combustor consists of a short pre-diffuser followed by a dump diffuser. The dump diffuser is extended as outer and inner flow passages also known as outer and inner diffusers. 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 combustor is provided with axial flow straight vane swirlers holding equal numbers of air blast type atomizers concentrically.

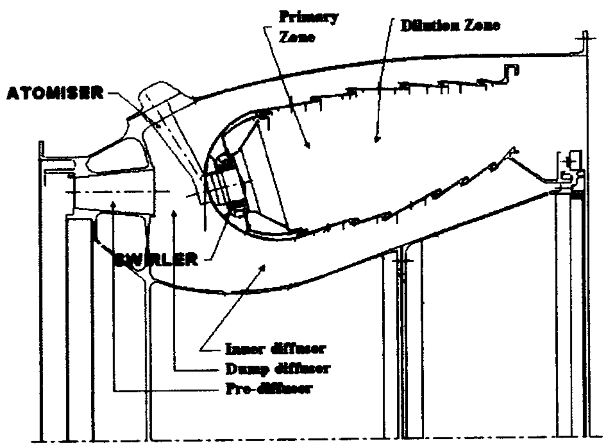

Fig.1 Combustor configuration

Test Facility

Figure 2 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 exchange is used as pre-heater, which 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

The full-scale combustor was tested in the test facility with extensive instrumentation at inlet and exit sections. 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. Fig. 3 shows the location of temperature probes at combustor exit plane and their relative position with respect to upstream fuel atomizers when looking from the rear. 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. The combustors with different geometrical configurations were tested under near identical conditions and sufficient sets of steady state data have been acquired to establish repeatability of the test results.

Test and Test Procedure

During this experimental investigation, tests are carried out at combustor inlet pressure of about 400 kPa and temperature of 550 to 600 K with an inlet Mach number

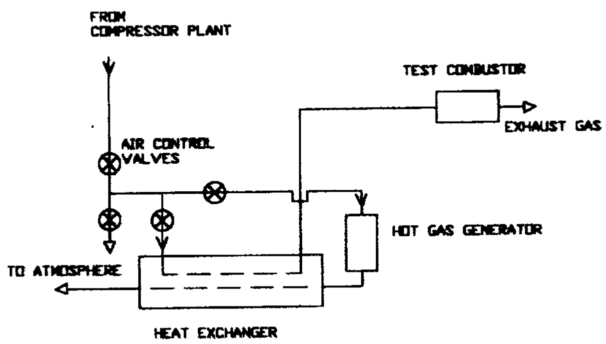

Fig.2 Combustor test facility

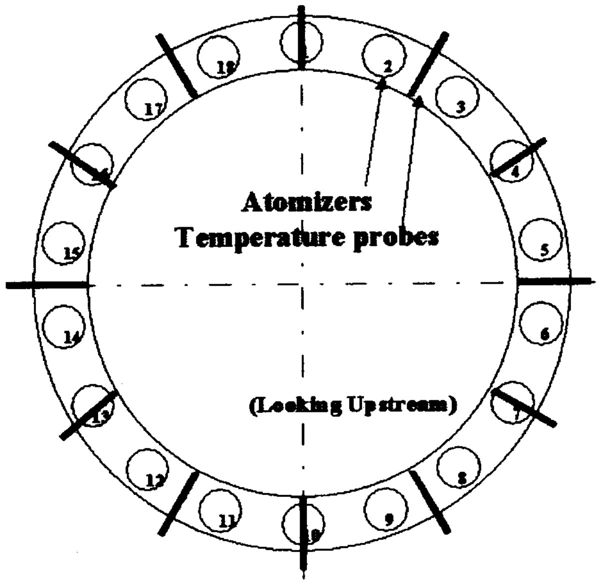

Fig.3 Instrumentation at exit plane

of 0.32 ± 0.01. The combustor exit average gas temperature was maintained in the range of 1100 to 1200 K simulating a fuel-air ratio of 0.025 ± 0.0005. Jet-A1 fuel was used throughout these experiments.

Attention is focused only on the exit pattern factors. 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 generally defined by the following equations [1];

$$RPF = \left[T_{4cir-avg} - T_{4avg}\right] / \left[T_{4avg} - T_{3avg}\right] \quad (1)$$

$$CPF = \left[T_{4\,local} - T_{4avg}\right] / \left[T_{4avg} - T_{3avg}\right] \quad (2)$$

At exit plane the temperature values at each radius are first averaged to give $T_{4cir\text{-}avg}$. All such $T_{4cir\text{-}avg}$ are then averaged to give rise the average exit temperature T_{4avg}. The non- dimensionalized temperature profiles normalize the operating conditions and are usually used for comparing the performance of different combustors and combustors operating at different conditions.

Results and Discussion

The following geometrical parameters are varied during this investigation to study their effect on the exit pattern factors:

- Diffuser
- Dilution zone
- Swirler
- Atomizer flow passage

In this section, the radial pattern factors are presented as RPF in abscissa versus annulus height in coordinate. The annulus height is the combustor flame-tube exit passage height, which is similar to that of nozz1e guide vanes of high-pressure turbine. The 0% height represents root or hub of the nozzle guide vanes and 100% represents the tip Similarly the CPF is presented with respect to angular location where 0° and 360° represent the top dead center and 180° represent the bottom dead center of the combustor exit annulus passage while looking upstream.

Diffuser Geometry

Two combustors having similar flame-tubes and swirler and atomizers but different diffuser geometrical configuration were tested in the airflow facility [2]. The radial pattern factors for these two combustors (say A and B) under similar test conditions are presented in Fig.4. No significant effect on RPF is noticed. Liner geometries with similar air injection passages and atomizer characteristics have resulted in similar radial pattern factors [3].

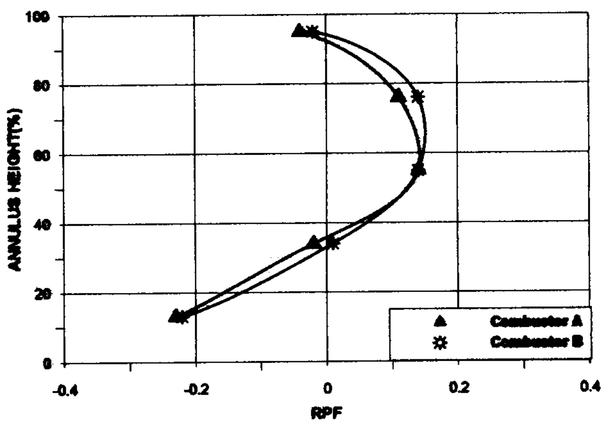

Fig.4 Radial pattern factor

Similarly, the circumferential pattern factors estimated based on temperature measurements are shown in Fig.5. The CPF is also a function of dilution zone geometry and size and disposition of air injection ports in this zone [3][4]. 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.

Dilution Zone

The attainment of a satisfactory or desired pattern factor at combustor exit is dependent on the mixing of air and combustion products to the required levels at different radial locations in the dilution zone. The key factors governing the mixing rates are the diluent jet-to-mainstream density ratio and the diluent-to-mainstream velocity ratio [3][5].

For a given dilution air in percentage of the total combustor air, the geometric variations are obtained by varying the dilution port diameter, d_p, and the spacing of the ports in the row, S. These in turn describe the geometry in terms of the liner height (or equivalent height) -to-port diameter ratio H/d_p and the port spacing-to-port diameter ratio S/d_p. These geometrical parameters, i.e., H/d_p and S/d_p regulate the maximum jet penetration of the diluent jet and control the rate of mixing with the mainstream flow in the dilution zone [6]. The actual geometric diameter of ports is given by [7]

$$d_p = d_{Pj} / C_d^{0.5} \qquad (3)$$

The discharge coefficient of the dilution holes play an important role in the accurate estimation of air mass flows through the holes or alternatively to decide the geometrical size of the air injection holes. The outer and inner dilution jets may be arranged in-line or staggered to each other and further they can be in-line and in-between the atomizers. Out of a number of configurations worked out for the present study, only three configurations are presented here. The dilution zone configuration matrix in terms of the non- dimensional parameters S/dp and H/dp is presented in Table-1. The outer liner is provided with only one row of dilution air injection holes in all the configurations. The inner liner has two rows of dilution holes in configuration 3.

Tests were carried with all these configurations keeping other geometrical parameters, such as primary air injection holes, secondary air injection holes, cooling passages, air swirlers and atomiser dimensions etc. of the combustor constant.

The radial and circumferential pattern factors at combustor exit are strongly influenced by the dilution zone geometrical parameters as shown in Figs. 6 and 7. Since, the tip and root regions are comparatively cooler than that

Table-1 : Dilution zone configuration matrix

Configuration	Dilution Holes			
	Outer		Inner	
	S/d_p	H/d_p	S/d_p	H/d_p
1	2.71	5.0	1.83	5.0
2	2.55	4.7	1.73	4.7
3	5.09	4.7	1.83	5.0
	-	-	2.88	11.8

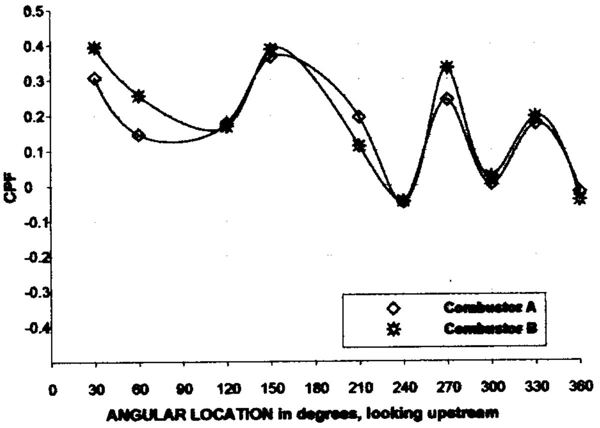

Fig.5 CPFs for different tests

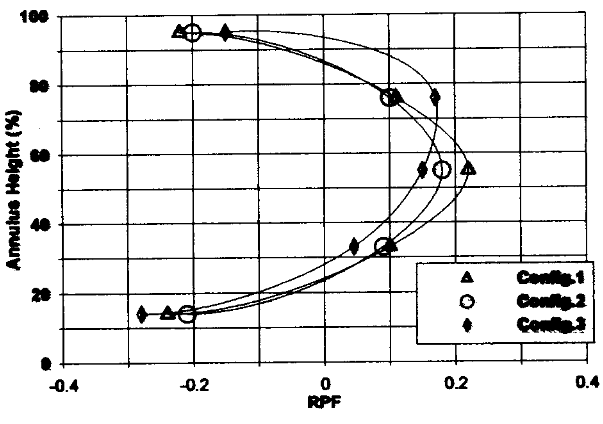

Fig.6 Effect of dilution zone geometrical paramters on RFP

at the core region, the CPFs at 75% heights from the root are only discussed in this paper.

Swirler Configuration

Axial swirlers are widely used in present day combustors for creating a recirculation zone necessary for flame stabilization. The extent of recirculation obtained is expressed in terms of a swirl number. Swirl number is a function of swirler geometrical parameters such as outer and inner diameters and vane angle and is a measure of the recirculation zone created in the combustion or primary zone of the combustion chamber. Combustor is tested with two different swirler configurations; one with 6-vanes and the other with 12-vanes, both having similar swirl numbers. Under similar test conditions the 6-vane swirler shows better performance with a low peak temperature in the radial pattern factor as presented in Fig.8. However, 12-vane swirler exhibits a better circumferential temperature pattern at combustor exit as shown in Fig.9. Similar swirl numbers have generated similar recirculation zones in axial direction in both cases but the swirl potential at radial and circumferential locations due to different number of vanes would be different causing different temperature profiles coming out of primary zone. Having similar dilution zone configuration these have influenced the exit pattern factors [3].

Typical ranges of vane angle for these axial swirlers are between 30° to 60° with the optimum vane angle hovering around 50°. In the 12-vane configuration further studies have been carried out with two vane angles, i.e., 50° and 55°. The radial and circumferential profiles are shown in Figs. 10 and 11.

Though the effect of vane angle is not felt on RPF, swirler with the 50° vane angle has shown a marginally better circumferential temperature distribution.

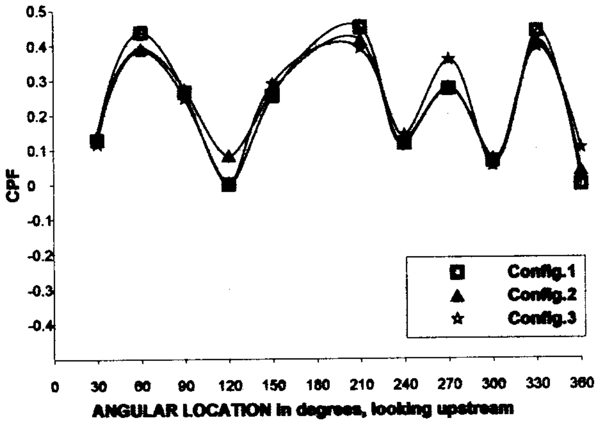

Fig.7 Effect of dilution zone geometrical paramters on CPF

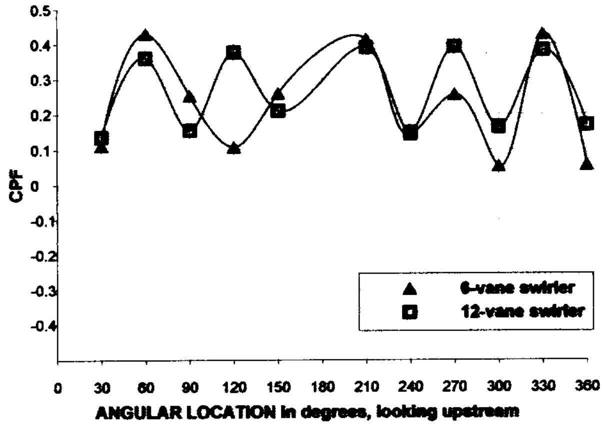

Fig.9 Effect of swirler vane on CPF

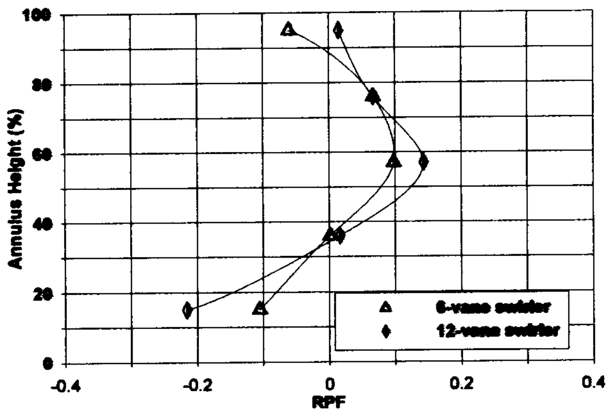

Fig.8 Effect of swirler vane on RFP

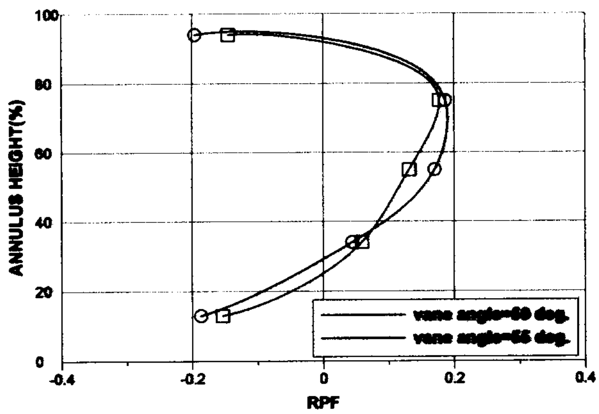

Fig.10 Influence of swirler vane angle of RPF

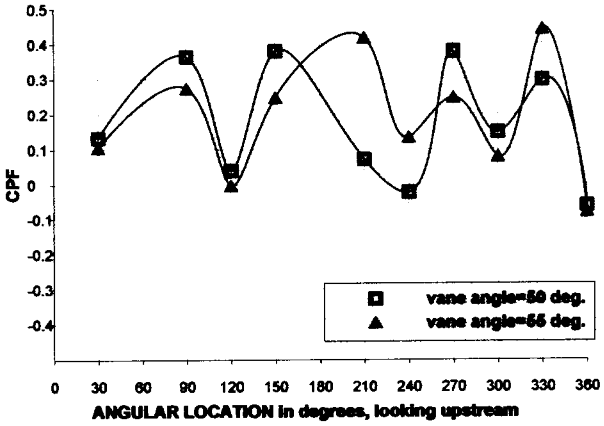

Fig.11 Influence of swirler vane angle of CPF

Since both the swirler configurations have similar swirl number, their contribution towards exit temperature are very similar.

Atomizer Flow Passage

Atomizer flow passage is generally defined by a so-called flow number FN. It is an important parameter which specifies the fuel discharge through the atomizer and is expressed as [1]

$$FN = W_f \Big/ \sqrt{(\Delta P_B)} \qquad (4)$$

It is a function of the nozzle geometry and the discharge coefficient and therefore characterizes the size of the nozzle for a given application. In the present study, atomizer flow number is changed by changing the fuel flow passage dimensions and three different flow numbers are investigated, i.e., FN = 2.5, 3.3 and 5.0. Flow numbers are found to have a little effect on the exit pattern factors as shown in Figs. 12 and 13.

The concept of flow number was originated with pressure jet atomizers where the pressure plays an important role in controlling the atomizer characteristics. In the present case of air blast atomizers, relative velocity between air and fuel and fuel properties are rather more important than the pressure alone [8].

Three major components which contribute to form the combustor exit radial temperature profile are; the primary zone exit temperature profile, dilution zone mixing temperature profile and cooling jet mixing temperature profile

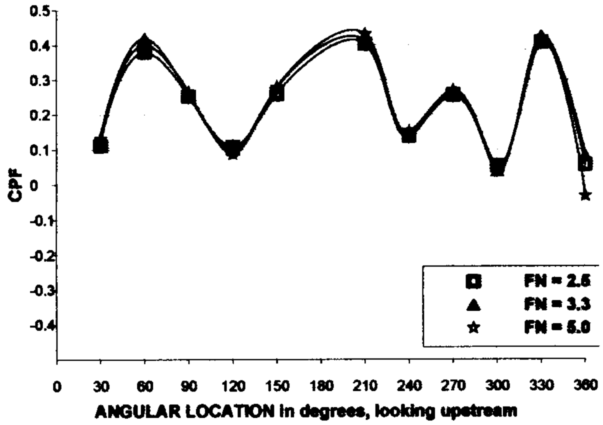

Fig.12 Influence of atomizer flow number on circumferential pattern factor

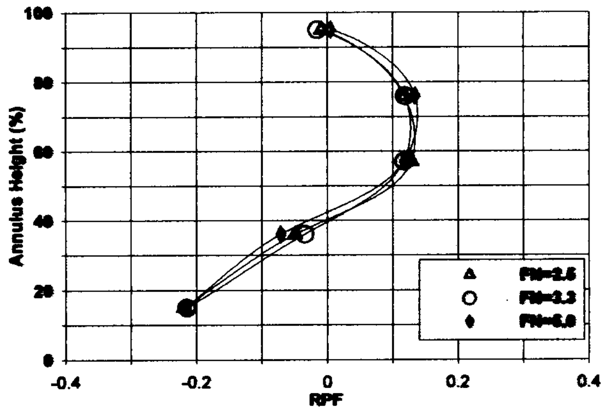

Fig.13 Influence of atomizer flow number on RFP

[4] [5]. Any pre- combustion zone geometrical parameter and characteristics of swirler and atomizer which directly control the combustion phenomena may influence the primary zone exit temperature profile, which in turn affects the combustor exit pattern factors. Therefore it is the general practice to attempt optimization of dilution zone geometrical parameters at the final stage.

Atomizer characteristics in terms of spray angle, droplet size and droplet distribution may be further studied to find their influence on temperature distribution at combustor exit.

Conclusion

In this experimental investigation, the effect of different geometrical parameters on combustor exit temperature distributions are studied and the following conclusions can be drawn.

- The pattern factors are mainly independent of diffuser geometry as long as liner configuration and atomizer characteristics remain unchanged.
- Number of vanes in swirler affects the pattern factor but vane angle has marginal effect on pattern factors as long as it is operating in the strong swirl region.
- The flow number concept for air blast atomizer is not relevant and spray cone angle, droplet size etc are to be further studied for their possible influence on exit pattern factors.
- Dilution zone configuration strongly influences both radial and circumferential pattern factors. Optimizing the air injection port size and spacing after freezing all other geometrical parameters of the combustor can achieve a desired pattern factor.

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