Effect of inlet swirl and dump-gap on the wall pressure distribution of a model can-combustor

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Wall static pressure distributions along the casing and liner wall have been measured using a Scanivalve digital manometer, for a model can-combustor under isothermal flow conditions for non-swirling and swirling flow at inlet with different positions of the liner (dump-gap). It is observed that swirl reduces the size of wall recirculation zone and permits earlier flow development whereas, dump-gap alters the reattachment length for weak swirling flows only. It is also observed that liner wall pressure (specific dome region) has a strong dependence on dump-gap for strong swirling flows due to formation of a central recirculation zone.

Single can-combustors are used for low power output in small gas turbine engines. These are widely utilized in the industry and in vehicles because of their compact size. A can-combustor with dump diffuser system is preferred over faired diffuser system due to its wide range of applicability. Swirlers are provided at the inlet for better fuel/air mixing and flame stabilization. The overall performance of the combustor depends on the mixing process and the air flow split occurring at various zones of the combustor liner. Further, for aircraft engines, the requirements of low size and weight are of paramount importance. Flow through can-combustor is both turbulent and swirling at inlet with dump diffusion. Wall static pressure variation along casing and liner walls is established to give a reasonable approximation for the size of recirculation zone and flow uniformity in the annular region of combustor. Many researchers have carried out investigations of flow through combustors with emphasis on the liner flow characteristics\textsuperscript{1-14}. Bicen and Jones\textsuperscript{1} have experimentally investigated the velocity characteristics under isothermal and combusting flow conditions in a model can-combustor. They have observed that more flow enters the combustor through the primary holes at low Reynolds number. Koutmos and McGuirk\textsuperscript{2} have investigated in detail the variation of the flow split between the primary and the dilution holes on the flow pattern in the primary zone of a model can-combustor using water as the fluid. McGuirk and Palma\textsuperscript{3} have predicted the mean velocity and turbulence kinetic energy inside a model can-combustor and compared them with measurements. They observed large discrepancies between measurements and the predictions in the primary region which may be due to higher level of momentum diffusion. Annular dump diffuser system has been investigated by Fishenden and Steven\textsuperscript{4} for monitoring the overall system performance while varying the pre-diffuser area ratio, dump gap and mass flow split to the inner and outer annuli. They have concluded that the principal determinants of total pressure loss in such systems are the amount of diffusion being attempted and the radius of curvature undertaken by the flow as it passes around the flame tube/liner. Carrotte \textit{et al.}\textsuperscript{5} experimentally investigated the flow characteristics and aerodynamics performance of a modern gas turbine dump diffuser and found that stagnation pressure loss is a strong function of dump-gap. Bharani\textsuperscript{6} experimentally investigated the flow characteristics in the annuli of a reverse flow gas turbine combustor and concluded that changes in the dump-gap do not significantly influence the nature of velocity profile. However, velocity magnitudes reduce with the increase in the dump-gap. Ahmed and Nejad\textsuperscript{7} have investigated the effect of inlet swirl on the characteristics of a co-axial dump combustor model in an isothermal environment using LDV. Two sets of experiments were carried out to examine the effect of swirl strength on the flow...
field characteristics and the effect of inlet swirl profile and its evolution throughout the combustor. The results indicate that inlet swirling motion alters the flowfield and reduces the corner recirculation region significantly. Agrawal and Singh have experimentally investigated the influence of swirl on the flow development of co-axial jets in a dump confinement. They observed that imposition of swirl on the flow improves mixing and flow development. They also observed that the imposition of swirl in co-swirl mode could lead to flame stabilization. Based on the literature review, it is observed that the emphasis of research on combustors has been to establish the flow characteristics in the liner of the combustors and there are some studies in a combustor model without the liner. Flow through the annulus is crucial as it feeds air to the liner through various holes on the liner wall. Flow split through the annulus to the liner is affected by the wall pressure of air casing and liner. Pressure variation along the air casing and liner and its dependency on inlet condition and dump-gap have not been investigated thoroughly to now. The present study is a systematic attempt to fill this void.

Experimental Procedure
The experimental set-up used in the present investigation is shown in Fig. 1a. The apparatus is composed of a blower, rectangular diffuser, the settling chamber with a set of screens for reducing the turbulence level and making flow uniform, a bell mouth entry, inlet pipe, and the model can-combustor. Air from the blower passes through the rectangular diffuser, settling chamber and enters the model can-combustor through the inlet pipe. Provisions have been made in the inlet pipe to measure the inlet velocity profile. A U-tube manometer is connected between the settling chamber and inlet pipe for continuous monitoring of the mass flow rate. Wall static pressure taps are fixed on the air casing wall as well as on the dome/liner surface to measure the static pressure distribution on these units.

Vane swirlers were provided between the inlet pipe and model can-combustor with the help of coupling to provide swirling flow at inlet. These swirlers were installed 250 mm upstream of the dump expansion so as to ensure that the wake of the swirler did not interfere with the flow characteristics in the model can-combustor. Vane swirlers were designed as per the procedure given by Mathur. Each vane swirler had eight vanes made of 0.5 mm thick brass sheet.

Model can-combustor
The model can-combustor used in the present study is shown in Fig. 1b. It consists of a cylindrical air casing having diameter of 152.4 mm and length of 457.2 mm attached to the inlet pipe having diameter of 54 mm. Wall static pressure taps at eight locations along the axial length of the air casing at equal distances are fixed for measurement of wall pressure. The wall static pressure at any given axial location is measured as an average of three pressure taps placed at equal angles along the circumference. To model the flame tube, a circular pipe of diameter 76.2 mm with hemispherical dome at one end is placed co-axially with the air casing. Seven pressure taps are provided on the dome surface and sixteen on the liner surface. Pressure taps are closer on the dome surface as compared to the liner surface. The other end of liner is attached to the support system, as shown in Fig. 1a, resting on a platform by which dump-gap can be varied.

Determination of parameters
Wall pressure tappings of casing and liner were connected to the Scanivalve Digital Interface Unit. The Scanivalve Digital system was calibrated against a Betz micromanometer to obtain pressure in mm of water column. To ensure the geometrical symmetry of the liner in the air casing, a circular disk having external diameter equal to casing and internal diameter equal to liner diameter was fabricated to check the placement of liner regularly. To keep the
liner in its position, three screws were provided at 120° apart through the air casing. Inlet conditions were changed by providing different vane swirlers at inlet. Vane swirlers with angles of 0°, 15°, 30°, and 45° were selected for the present study. The corresponding swirl numbers for the swirlers are 0, 0.18, 0.38 and 0.67. For each inlet condition, measurements were taken at three dump-gaps, viz. DG = 0.5, 1.0 and 1.5 at a Reynolds number of $1.2 \times 10^5$. The dump-gap denotes the distance of liner dome from the dump inlet plane. Velocity and turbulence intensity were measured by three-hole probe and hot-wire probe respectively at different axial locations. Measurements by three-hole probe were taken using the null technique.

**Results and Discussion**

The co-ordinate system is as shown in Fig. 1b where the distances are normalized with the diameter of casing and liner, and the origin is located at the dump inlet plane. The inlet conditions have been measured in the pipe at a distance of 200 mm downstream of the swirler (50 mm upstream of the dump expansion).

**Inlet conditions**

The velocity profile at inlet has been measured from wall-to-wall. However, only the data for the upper half are shown here with its mirror image in the lower half. In actual measurements, the discrepancy between the upper half velocity profile and lower half is in the range of 3-4%. This deviation is as a result of the blockage effect of the probe. Figs 2-5 present the variation of inlet axial velocity, inlet tangential velocity, static pressure and turbulence intensity for non-swirling and swirling inlet conditions. Fig. 2 shows inlet profiles for non-swirling flow. It is seen that axial velocity is flat in the middle and falls gradually towards the wall showing the growth of boundary layer. The tangential velocity is nearly zero. Static pressure is constant across the pipe cross section. Turbulence intensity variation shows the existence of strong shear layer close to the wall, which is expected due to the growth of boundary layer. In the central portion, the value is constant and is around 1%. In the figure, it appears that the peak value is approximately 7%. However, if measurements much closer to the wall are made, it is expected that the intensity could rise to values close to 15%, which is typical of standard boundary layers.

Fig. 3 shows the inlet conditions for 15° swirler. It is seen that the axial velocity on the central line drops and the flow is forced outwards, the peak velocity lying somewhere midway between the centre and the wall on both sides. The tangential velocity distribution shows a forced vortex nature close to the centre over a very small region. For the remaining cross section, the tangential velocity is constant. Static pressure variation across the pipe cross section is still nearly constant and the value is also same as that of
non-swirling flow. The turbulence intensity variation is also similar to the non-swirling case with slight increase in magnitude.

Fig. 4 depicts the inlet conditions for the 30° swirler. It is seen that the axial velocity on the centre line drops significantly and the peak velocity is forced outwards. The tangential velocity distribution shows a forced vortex nature from the center axis up to the midway between centre line and wall and then drops down towards the wall showing a free vortex nature. The static pressure variation is similar to the axial velocity variation, i.e., minimum pressure on the centerline that increases towards the wall. This is due to the setting of radial pressure gradients because of centrifugal force. The turbulence intensity variation shows a presence of strong shear at the centre and existence of shear layer close to the walls as in other cases.
Air casing wall pressure variation

Fig. 6a shows the casing wall pressure variation without the liner for all the inlet conditions and Figs 6b, 6c, and 6d show the wall pressure variation with liner at three dump-gaps for the same inlet conditions. The wall static pressure at any given axial location was measured as an average of three pressure taps placed at equal angles along the circumference.

Wall pressure variation depicted in Fig. 6a for no liner shows the existence of wall recirculation zone extending beyond the points of measurement of pressure for 0° and 15° swirl. For 0° swirl, the pressures variation is seen to be nearly constant up to half-length of the casing and then increases gradually. For 15° swirl, variation is almost similar to the 0° swirl with slight increase in velocity and pressure due to the centrifugal force. For 30° swirl, the flow attaches to the wall around \( X/D_c = 1.25 \). For 45° swirl, the flow is forced outwards due to large centrifugal force resulting in sudden increase of pressure at the wall. The point of attachment of flow is seen to be close to \( X/D_c = 0.5 \) but the flow reattaches and only attaches to the casing wall around \( X/D_c = 1.0 \) same as 30° swirl. The variation of pressure is seen to be identical to the flow observed in sudden expansions. From the pressure variation, it can be concluded that the wall recirculation zone is the smallest for 45° swirl.

Figs 6b, 6c, and 6d show the wall pressure variation along the air casing length with liner at three dump-gaps (0.5, 1.0, and 1.5). From the pressure variation, it is clearly seen that the point of reattachment moves closer compared to the case of no liner. This is due to deflection of flow towards the wall as a result of the liner placement. The width of the wall recirculation zone is also affected. For dump gap of 0.5, the reattachment points for the flow on the wall are \( X/D_c = 1.75 \) for 0°, 1.5 for 15°, 0.75 for 30° and 1.25 for 45°. The pressure variation for 45° shows that the flow attaches faster but reattaches to reattach only by \( X/D_c = 1.25 \). The flow reattaches from the wall due to sudden pressure created due to acceleration of flow at the dome of the liner, which does not happen for other swirl conditions. The wall pressure variation for other dump gaps has similar variation (Figs 6c and 6d) except in the shift of attachment point for the flow. For dump gap of 1.0, the attachment points are 1.75 for 0° swirl, 1.5 for 15° swirl, 0.75 for 30° swirl and 1.0 for 45° swirl. In this case, the pressure variation for 45° swirl still shows the reseparation of flow at the

Fig. 5 highlights the inlet conditions for 45° swirling flow. It is seen that the variation of axial velocity, tangential velocity, static pressure and turbulence intensity are similar to the 30° swirl conditions (Fig. 4) with slight increase in magnitude which is expected with the exceptions that turbulence intensity reduces slightly. The reduction in the turbulence intensity is due to the increase in the size of the central shear region with a corresponding decrease in the gradient.
Fig. 6a — Wall pressure variation along the casing without liner

Fig. 6b — Wall pressure along the casing with dump-gap = 0.5

Fig. 6c — Wall pressure along the casing with dump-gap = 1.0

Fig. 6d — Wall pressure along the casing with dump-gap = 1.5
Fig. 7a — Wall pressure variation along the liner with dump-gap = 0.5

Fig. 7b — Wall pressure variation along the liner with dump-gap = 1.0

Fig. 7c — Wall pressure variation along the liner with dump-gap = 1.5
From the wall pressure variation, it can be concluded that 30° swirl is the optimum swirl for dump gap 0.5 in terms of flow attachment and size of recirculation zone whereas it is 30° and 45° swirl for other two dump gaps.

**Liner wall pressure variation**

Figs 7a, 7b and 7c show the wall static pressure variation on dome and liner for three dump-gaps 0.5, 1.0 and 1.5, respectively, for the same inlet conditions.

Fig. 7a shows that the wall pressure at the dome is the highest at the centre for 0° swirl, which reduces drastically over the dome resulting in negative pressure over the liner due to acceleration of flow on the dome. The pressure starts to recover in the liner wall through different liner holes provided on the liner wall. For 1.5 dump gap, the corresponding lengths are 2.5, 1.75, 1.0 and 1.0, respectively.

From pressure measurements on the casing and liner, following conclusions have been drawn: (i) Swirling flow reduces the size of wall recirculation zone both in terms of length and width, resulting in possibility to improve the flow mixing in the annulus; (ii) Attachment length increases with increasing dump-gap for weak swirling flows only; (iii) Dump-gap has no marked effect on the variation of liner wall pressure for a weak swirling flow, whereas for strong swirling flow, the liner wall pressure is nearly constant for the entire annulus length for dump-gaps of 1.0 and 1.5, a desirable feature for flow split into the liner through different liner holes provided on the liner wall; and (iv) The optimum combination for achieving better mixing and flow development appears to be 30° swirl at inlet for dump gap=1.0.

**Nomenclature**

- \( D_c \): combustor air casing diameter, m
- \( D_L \): liner diameter, m
- \( DG \): dump-gap, \( L/D_1 \)
- \( L \): distance of dome head from the dump inlet plane, m
- \( P \): static pressure, N/m²
- \( P_{in} \): inlet dynamic pressure, N/m²
- \( P_w \): wall pressure, N/m²
- \( R \): radial distance of measurement location from the axis of symmetry, m
- \( R_i \): inlet pipe radius, m
- \( T_I \): turbulence intensity, (%) 
- \( U_a \): axial velocity, m/s
- \( U_{ax} \): mass averaged inlet velocity, m/s 
- \( U_t \): tangential velocity, m/s 
- \( X_c \): distance of axial location on casing from dump inlet plane, m
- \( X_i \): distance of axial location on dome/liner from dome head, m

**References**