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Research Article

Investigation on the Flow Structure and the Performance of an Annular Diffuser with Two Different Types of Struts

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Abstract. In this present work, the flow structure and the performance of an annular diffuser are discussed. Two types of struts were used namely baseline struts and tapered struts. A Five-hole pitot pressure probe with a digital manometer was used to measure pressure. A DANTEC Dynamics make constant temperature anemometer with X-probe was used to measure mean velocity, turbulence level in axial and tangential directions. The numerical investigation was carried out by using STAR-CCM+, a commercial Computational Fluid Dynamics code. The experimental results are compared with CFD results. The results suggested that tapered design performed well compare with the baseline design.

Keywords. Annular diffuser; Hotwire anemometer; Pressure recovery; Strut; CFD

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1. Introduction

Exhaust diffusers are critical components of a gas turbine in both the propulsion and power system applications. The flow through these diffusers is receiving a considerable attention in the present because of its significant impact on overall efficiency and range of applications. Adenubi [1] investigated the effects of transient inlet flow parameters on flow regime, the performance and the mechanism of the annular diffusers in the downstream of the turbomachinery. Lohmann *et al*. [9] experimentally investigated the performance of a series of diffusers of various lengths, area ratios and cant angles with swirl. Kumar and Kumar [8] have investigated the effect of swirl on flow through annular diffusers having diverging hub and casing boundaries. Djebedjian and Renaudeaux [4] have done numerical and experimental investigations in an axial steam turbine engine exhaust diffuser with and without swirl at inlet. Ubertini and Desideri [15] have analysed the effect of struts on the performance of an annular diffuser. Sheeba and Ganesan [13] studied the pressure recovery in annular diffuser with and without struts. Cherry *et al*. [3] have made detailed three component velocity measurements for two different annular diffusers with and without upstream wake disturbances.

Ganesan [6] predicted the flow and boundary layer development in straight core annular diffusers. Singh *et al*. [14] investigated the effect of inlet swirl on the performance of annular diffusers having the same equivalent cone angles. They concluded that the parallel diverging hub end casing annular diffuser produces the best performance at high swirl intensities. Mahalakshmi *et al*. [10], and Prakash *et al*. [12] studied the conical diffusers of half cone angles 5° and 7° with velocity and wake type distortion at inlet. Pfeil and Going [11] studied the boundary layer measurements at the outer wall of an annular diffuser behind a one stage axial compressor. Fric *et al*. [5] have studied various strut designs in an annular exhaust diffuser. Baskharone [2] developed a finite element model of turbulent flow field in the annular exhaust diffuser of a gas turbine. Yu *et al*. [16] numerically analysed the internal flow in an annular diffuser with swirling flow by using three-dimensional momentum integral equation. Kanemoto and Toyokura [7] theoretically analysed the flow in annular diffusers. They concluded that the diffuser performance and the boundary layer thickness decreases with increase in whirl at inlet of the diffuser.

The present study focuses on the analysis of annular diffuser flow with and without struts and with inlet guide vane wakes. Experimental have been carried out to study the effect of strut shapes on the performance of an annular diffuser. For this purpose two strut designs a baseline and tapered were considered.

2. Experimental Setup

The experiments were conducted in a subsonic blower type wind tunnel, which delivers a steady, uniform stream of air. A motor of 11 kW capacity and constant speed of 2900 rpm drives the blower. The turbulent intensity of the air at the exit is measured to be 0.6 % at 55 m/s. A schematic of the wind tunnel is shown in Figure 1.

The diffuser assembly used for the present experimental investigations is shown in Figure 2. The diffuser employed was made of mild steel. The length of the diffuser is 300 mm. The outer diameters of the inlet and the outlet stations are 100 mm and 174 mm, respectively. The hub diameter is 58 mm and it is constant along the diffuser model. The inner hub in the present study, is rotatable over 360° and the area ratio is 1.73.

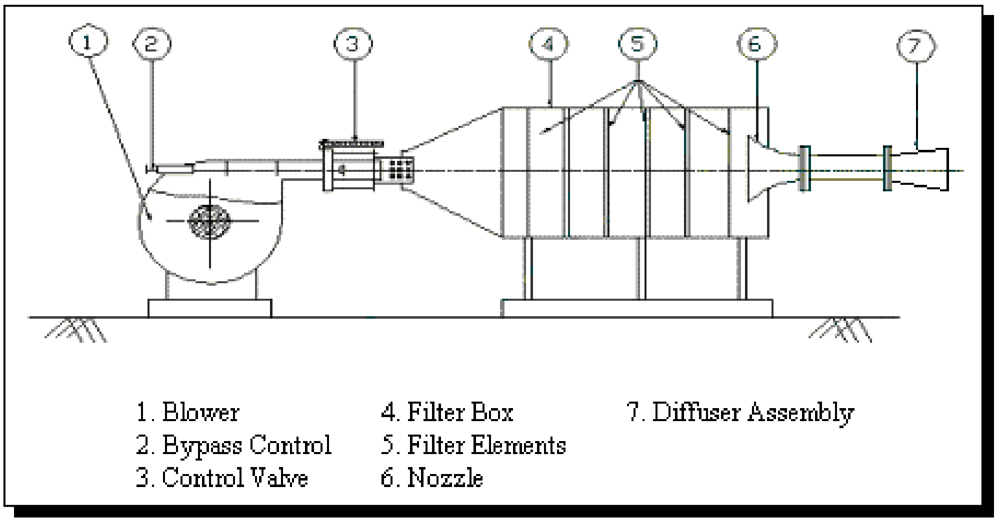

Figure 1. Schematic of the wind tunnel

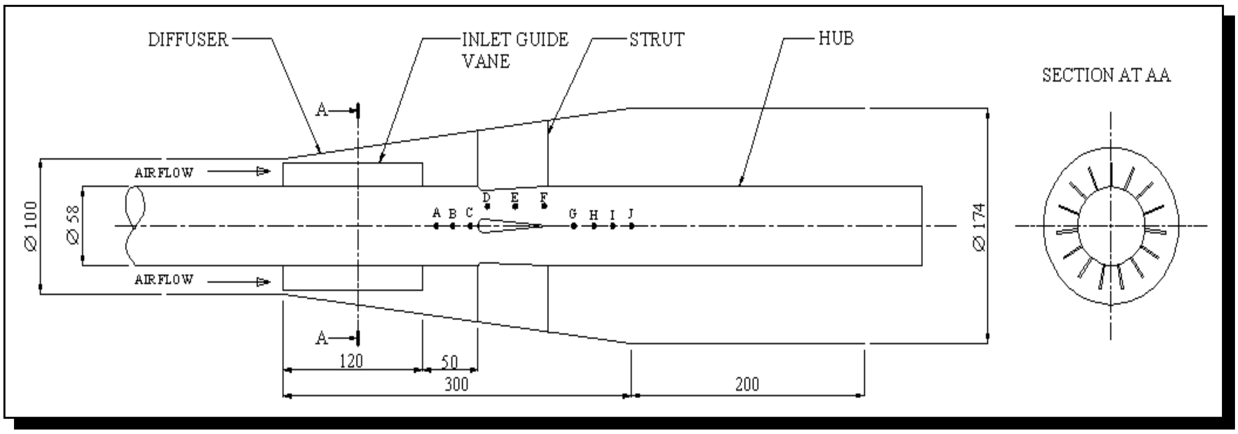

Figure 2. Diffuser with measuring stations

Experiments were conducted in a scaled down model of an industrial gas turbine diffuser with and without struts. The inlet station features 15 axial guide vanes and five equally spaced radial struts are located approximately one chord length from the leading edge of the inlet guide vanes. Two strut concepts were studied, namely baseline strut and tapered strut. Baseline strut profile is a NACA 0021 with a maximum thickness of 12.6 mm and a chord of 60 mm. The tapered struts design as the chord at one end is fixed at 1 X (60 mm) and the chord at other end is fixed at 1.5 X (90 mm).

A Dantec Dynamics make constant temperature hot-wire anemometer (CTA) with an X-probe and a five-hole pitot tube with digital differential manometer were used for the flow measurements.

2.1 Uncertainty Analysis

The total uncertainty (G_{tot}) as a combination of standard uncertainty of every individual output variable (c_i) at a given confidence level. The output variable is defined as $c_i = f(i)$, where 'i' is the input variable.

The standard uncertainty of the output variable is defined as

$$g(c_i) = \left(\frac{1}{c_i}\right)\left(\frac{\partial c_i}{\partial i}\right)\left(\frac{\Delta i}{f_i}\right) \tag{1}$$

where $\left(\frac{\partial c_i}{\partial i}\right)$ is the sensitivity factor and f_i is the coverage factor.

Coverage factor of either 2 or $\sqrt{3}$ is multiplied with the standard uncertainty $g(c_i)$ when the error distribution takes a Gaussian distribution to achieve 95% confidence level. Therefore, the total uncertainty (G_{tot}) is expressed as

$$G_{tot} = 2\sqrt{\sum g(c_i)^2} \tag{2}$$

Total uncertainty $G_{tot} = 0.0431 = 4.31\%$.

The relative uncertainty in pitot tube is

$$e_V = \sqrt{\frac{u_C^2}{C^2} + \frac{1}{4}\frac{u_{\Delta P}^2}{\Delta P^2} + \frac{1}{4}\frac{u_T^2}{T^2} + \frac{1}{4}\frac{u_P^2}{P_{atm}^2}} = \pm 1.45\%. \tag{3}$$

3. CFD Studies

The model of the diffuser representing the fluid domain was modeled using the pre-processor tool Pro-E for diffuser with and without struts. The mesh for all the three cases was generated using STAR-CCM+. Polyhedral volume cells were used for meshing all the three diffuser models. The k-ϵ model is used to study the flow in diffuser with and without struts. The boundary conditions used in the simulation are listed in Table 1.

Table 1. Description of boundary conditions

Inlet:	
(i) Velocity boundary	55 m/s
(ii) Turbulence intensity	0.6%
Outlet:	
(i) Pressure boundary	Static pressure is specified
Wall:	
(i) Wall influence on flow	No slip wall
(ii) Wall roughness	Smooth wall

4. Result and Discussion

The flow parameters such as the boundary layer parameters namely the displacement thickness and the momentum thickness are discussed in Section 4.1. The performance parameter namely pressure recovery coefficient, ideal pressure recovery, diffuser efficiency and Pressure loss coefficient are discussed in Section 4.2.

4.1 Boundary Layer Parameters

Inner wall

The boundary-layer displacement thickness

$$\delta_{iw} = \int_0^{R_\delta} \left(1 - \frac{U}{U_m}\right) \frac{r}{R_N} dr. \tag{4}$$

The momentum thickness

$$\theta_{iw} = \int_0^{R_\delta} \left(1 - \frac{U}{U_m}\right)\left(\frac{U}{U_m}\right)\left(\frac{r}{R_N}\right) dr. \tag{5}$$

Outer wall

The boundary-layer displacement thickness

$$\delta_{ow} = \int_{R_\delta}^{R_N} \left(1 - \frac{U}{U_m}\right) \frac{r}{R_N} drdr. \tag{6}$$

The momentum thickness

$$\theta_{ow} = \int_{R_\delta}^{R_N} \left(1 - \frac{U}{U_m}\right)\left(\frac{U}{U_m}\right)\left(\frac{r}{R_N}\right) dr, \tag{7}$$

where U is the local velocity as a point distant r from the diffuser inner wall; U_m is the maximum velocity in the cross-station; R_N is the outer wall radius; R_δ is the distance from the inner wall where $U = U_m$; suffix iw and ow represent inner wall and outer wall, respectively.

The variation of the displacement thickness and momentum thickness for both inner wall and outer wall are shown in Figure 3 and Figure 4, respectively.

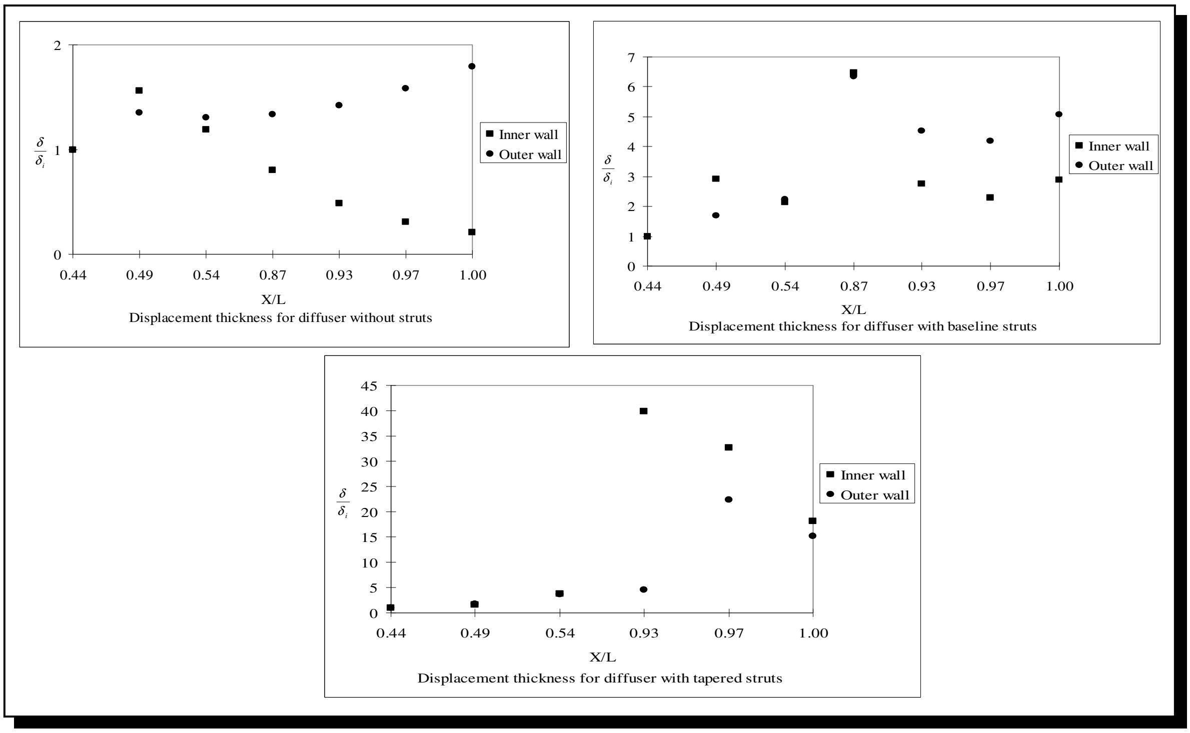

Figure 3. Variations of displacement thickness

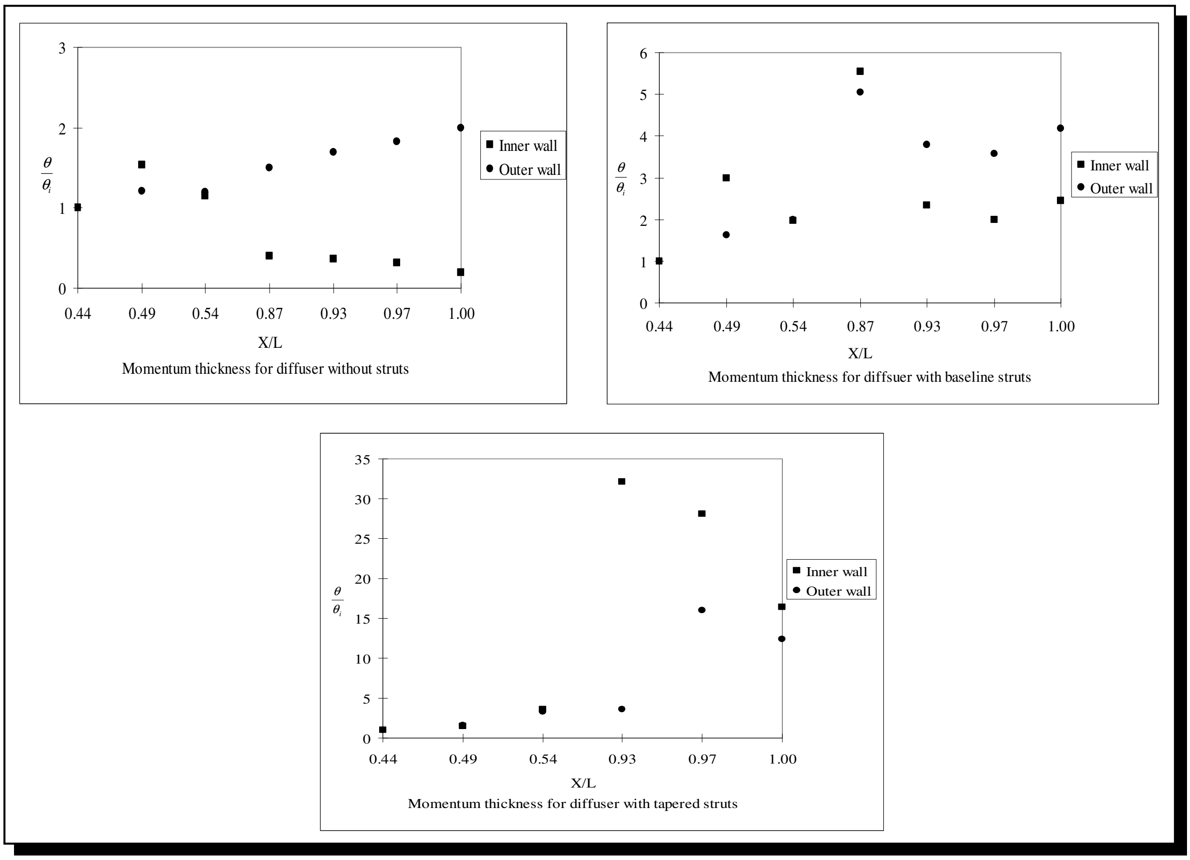

Figure 4. Variations of momentum thickness

It can be seen that the displacement thickness for diffuser without struts gradually increases along the axial direction at the outer wall. This is due to the divergence of the outer wall. At the inner wall initially the displacement increases but decreases gradually after the station B. The same trend is observed in momentum thickness. In the diffuser with baseline struts, the rate of increase of the displacement thickness of the outer wall is more that of the inner wall. Similar trend is seen in the momentum thickness. In the diffuser with tapered struts the rate of increase of the displacement thickness in the inner wall is more that of the outer wall. Similarly, the rate of increase of momentum thickness in the inner wall is more that of the outer wall. This is due to the tapered shape of the struts.

4.2 Performance Parameters

The diffuser performance determined by the following parameters

(i) Pressure recovery coefficient

$$C_P = \frac{(P_x - P_i)}{q_i} \tag{8}$$

(ii) Ideal pressure recovery

$$C_{Pi} = 1 - \left(\frac{A_1}{A_2}\right)^2 \tag{9}$$

(iii) Diffuser efficiency

$$\eta = \frac{C_P}{C_{Pi}} \tag{10}$$

(iv) Pressure loss coefficient

$$K = C_{Pi} - C_P \tag{11}$$

where P_x is the average static pressure at a station; P_i is the average static pressure at the inlet to the diffuser; q_i is the dynamic head; A_1 and A_2 are the inlet and outlet cross-sectional area respectively.

From Table 2, the diffuser efficiency with tapered struts is 7% greater than the diffuser with baseline struts. It is evident that the stream line design of tapered designs. It will help to a significant gain to the whole turbo machinery system. The pressure loss coefficient is increased from a mean value of 0.06 to 0.19.

Table 2. Efficiency for diffuser with and without struts

Parameters	Without struts	With struts	
		Baseline	Tapered
η (%)	92.0	67.8	75.3
K	0.06	0.24	0.19

Figure 5 shows the comparison of pressure recovery coefficient of the predicted results with the experimental results of the diffuser with and without struts. Pressure recovery in the diffuser without struts increases more rapidly in the first part of the diffuser, which is due to the absence of the struts effect. In the case of diffuser with struts, due to the presence of struts, the reduction of flow passage in the region between the struts reduces the diffusion and so the dynamic to static pressure conversion is reduced. In the diffuser with tapered struts, since the longer chord is fixed at the hub, the pressure recovery coefficient increases along the radial direction.

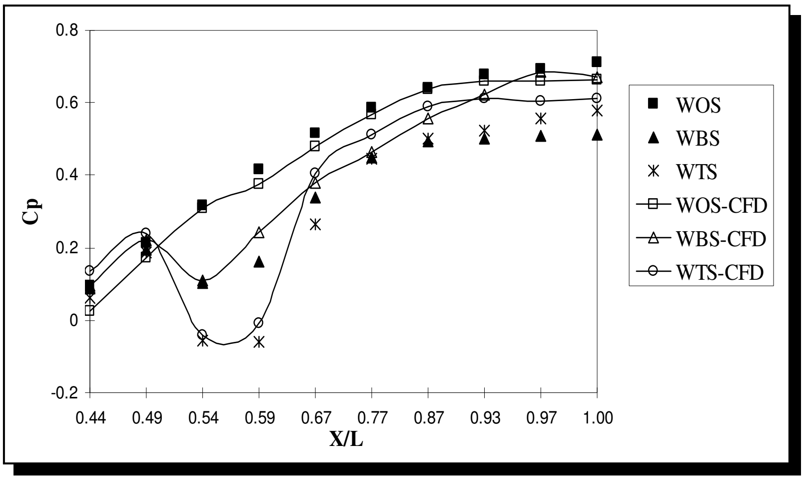

Figure 5. Comparison of pressure recovery coefficient along the diffuser

The kinetic energy is gained because of the strut blockage is converted into potential energy in the last part of the diffuser. This explains the pressure recovery gradient rise behind the struts. Thus, the highest diffusion occurs in the last part of the diffuser. For all cases, diffuser with and without struts, the pressure recovery gradient rise in the last part of the diffuser is less. This may be due to the boundary layer growth and flow separation.

Even though there is an increase in the annular passage station, behind the baseline struts, there is a decrease in pressure recovery gradient. This may be due to the strut wakes reducing the flow station. Near the exit, an increase in pressure recovery is seen, which may be due to the disappearance of the strut wakes or increased annular passage station.

For the diffuser with tapered struts, there is a steady increase in the pressure recovery until the exit, and this may be due to the varying characteristic length (chord & thickness) along the strut span that would have disrupted the formation of the wakes. It is seen that for all the cases, the agreement between the prediction and the experiments are good.

5. Conclusions

Studies were carried out with three different configurations viz., diffuser without struts, with baseline struts and with tapered struts. The result shows that the strut design had the potential to change the diffuser dynamics. The major conclusions drawn from the present investigations are summarised below:

1. From the experimental results it is observed that wakes are present behind the inlet guide vanes and struts, which affects the performance and flow pattern of the diffuser.
2. In the downstream side of the struts, the boundary layer parameters for baseline struts are higher than that of the tapered struts, which favours the tapered strut design.
3. Large regions behind the strut are occupied by their wakes.
4. In the diffuser without struts, a low pressure recovery gradient was observed in the later part of the diffuser, due to the separation of the flow from the walls. Pressure recovery in the diffuser without struts is higher than in the diffuser with struts.
5. The pressure loss increases with the presence of struts. The pressure loss mainly occurs in the axial region of the struts and in the end wall regions where the flow separates from the hub and the casing. The diffuser with struts of tapered design had a minimum pressure loss compared to the diffuser with baseline struts.
6. Efficiency of the diffuser with tapered design of struts is 7% more than that of the diffuser with baseline struts. This increase will lead to a significant gain in the whole turbo-machinery system.

Thus it can be concluded that that for all the cases, the agreement between the prediction and the experiments are good.

Nomenclature

P	:	Absolute pressure	C_{Pi}	:	Ideal pressure recovery
A	:	Area	η	:	Diffuser efficiency
ρ	:	Density	K	:	Pressure loss coefficient
δ	:	Displacement thickness	1	:	Inlet
θ	:	Momentum thickness	2	:	Outlet
G_{tot}	:	Total uncertainty	U	:	Local velocity
e_v	:	Relative uncertainty	U_m	:	Maximum velocity
iw	:	Inner wall	R_N	:	Outer wall radius
ow	:	Outer wall	R_δ	:	Distance from the inner wall where $U = U_m$
C_P	:	Pressure recovery coefficient			

Competing Interests

The author declares that he has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

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