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AN EXPERIMENTAL ANALYSIS OF FLOW THROUGH ANNULAR DIFFUSER WITH AND WITHOUT STRUTS

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ABSTRACT

This paper presents the static pressure development and the effect of struts on the performance of an annular diffuser. A typical exhaust diffuser of an industrial gas turbine is annular with structural members, called struts, which extend radially from the inner to the outer annulus wall. An annular diffuser model, primarily intended for fundamental research, has been tested on a wind tunnel. Similar conditions that prevail in an industrial gas turbine have been generated in the diffuser. Measurements were made using a five holed Pitot probe. The research had been carried out to make a detailed investigation on the effect of struts and to advance computational and design tools for gas turbine exhaust diffusers.

1. INTRODUCTION

The exhaust diffuser of an industrial gas turbine recovers the static pressure by decelerating the turbine discharge flow. This permits an exhaust pressure lower than the atmospheric pressure, thus increasing the turbine work. Hence the exhaust diffuser is a critical component as it increases the pressure ratio across the turbine.

A number of experimental and numerical studies has been carried out on simple diffusers [1-3]. These studies are confined only to geometrical and flow parameters such as inlet length, size of duct, Reynolds number, area ratio and diffuser angle.

In diffusers situated downstream of a gas turbine, the inlet flow presents a swirl component and high level of turbulence. The exhaust diffusers have inlet flow distortion due to the presence of turbo machinery in the upstream. More over, these diffusers employ structural members such as struts which act as supporting loads and passages for engine cooling and lubrication systems. These structural members induce wake type distortion in the down stream of the diffuser Lohmann et al [4] reported that the increase in swirl, increase the distortions in the meridional velocity profile at the diffuser exit. It was reported that the static pressure recovery increases with increase in inlet turbulence level [5] while it decreases with increase in inlet swirl [6].

Stefano Ubertini and Desideri [7] have conducted experiments and observed the detrimental effect of the strut on the diffuser performance. They reported that one of the main effects of the strut is the conversion of fluctuations from the axial direction to the tangential direction. Fric et al [8] conducted experiments in an annular exhaust diffuser and found that the tapered strut was effective in reducing wake amplitude and noise. Although a great deal of investigation on flows in annular diffuser has been done very little of it has been found for flow with inlet wake type distortion.

The aim of this paper is to study the effect of two different struts on the overall performance of the diffuser by measurement of static and total pressure. The analysis has also been made in the diffuser without struts.

2. EXPERIMENTAL SETUP AND INSTRUMENTATION

An experimental rig, schematic of which is shown in Fig.1 was designed and built. The diffuser with axial length 300mm and aperture angle 7^o was fabricated. The inlet and outlet diameters are 100mm and 174 mm respectively. The hub diameter was 58mm being constant along the diffuser model and rotatable over 360^o. The model was designed to operate in geometric and Reynolds number similarity with the PGT 10 Industrial gas turbine exhaust diffuser.

The inlet section features 15 axial guide vanes which provide both as means of introducing swirl into the test section as well as producing wakes representative of those produced by the last turbine rotor of the industrial gas turbine. A typical gas turbine operates with a Reynolds number exceeding 10^6 and the models Reynolds number is 2.3×10^6, which is sufficient to assume that similar flow conditions exist.

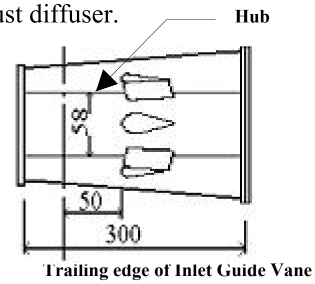


Figure 1. Diffuser Model

Two strut designs namely a baseline strut and a tapered strut are used in the present investigation to study their effect on the pressure recovery of the diffuser.

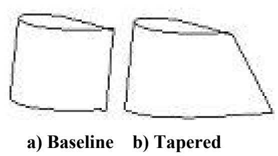


Figure 2. Strut Designs

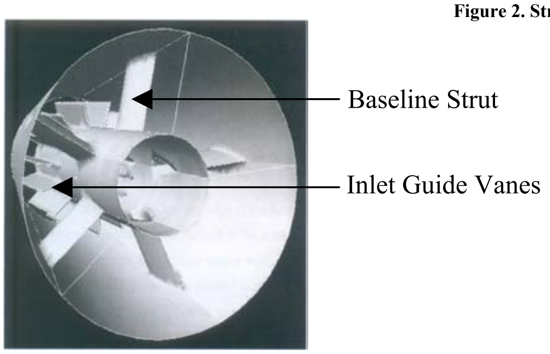


Figure. 3. View of diffuser with baseline strut

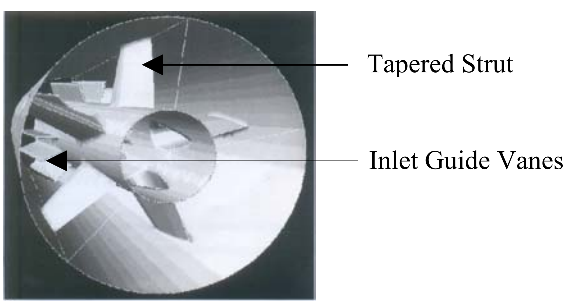


Figure 4. View of diffuser with tapered strut

The baseline strut (Fig.2a) is a model of an industrial gas turbine exhaust diffuser strut. The strut profile is NACA 0021 with a maximum thickness of 12.6mm and chord of 60mm.

To test the effect of the varying characteristic length scale, a tapered strut (Fig.2b) with a variable chord along its span is tested. Tapered 1.5 strut with NACA 0021 profile is used. Taperedness indicates that the strut chord (and thickness) varies linearly along its span. The strut profile remains the same at all cross sections. '1.5' indicates the amount of chord taper i.e., the chord at one end is fixed 1X (60 mm) and the chord at other end of the strut is 1.5X (90 mm). Fig. 3 and 4 show the diffuser with baseline and tapered struts.

A Pitot tube was used to measure static pressure along the diffuser. The static and the total holes have a nominal diameter of 1.5 mm. The probe could be traversed into the diffuser wall at various axial locations. The effect of viscosity is negligible since the Reynolds number is over 10^5 in the duct. The static holes are placed at some distance from the total pressure hole, so the streamlines next to the tubes must be longer than those in the undisturbed flow and there is an increase in velocity and a reduction in static pressure, causing errors in static pressure measurement. For the Pitot tube used, the ratio between the total and static taps distance and the tube diameter is six, thus producing an error of around 0.5%.

3. EXPERIMENTAL PROCEDURE

Measurements were taken in the model with and without struts in order to understand and quantify the effect of the struts. The measurements were made for varies radial positions from the hub to the outer diffuser wall. The line has 9 probe positions (Table1) disposed at required intervals in the flow direction. The probe was moved in the radial direction in steps of 6 mm starting at 4 mm from the hub to a safe distance from the outer casing. The hub was rotated in steps of 4^o covering the required sector. For the diffuser model with struts, the measurements were taken for a 36^o sector from the mid section of one strut and for the diffuser model without struts, measurements covering a sector of 12^o were taken. The positions of measuring sections are referred in terms of axial positions and radial positions. Fig.5 shows the various measurement stations along the length of the diffuser. The axial position of 0 mm is the leading edge of the inlet guide vanes and radial position is measured from the hub to the shell.

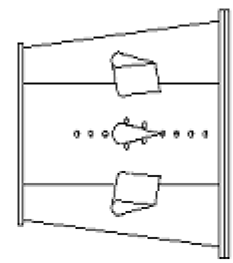


Figure 5 Measurement Stations

Table 1. Measurement Stations

Station	X /L	Station	X /L
1	0.1444	6	0.7778
2	0.2278	7	0.8778
3	0.3111	8	0.95
4	0.4444	9	1
5	0.6111		

4. DATA REDUCTION

Static pressure along the diffuser is given interms of pressure recovery coefficient (C_P).

$$C_P = \frac{P_{S,x} - \overline{P}_{S,1}}{\overline{P}_{t,1} - \overline{P}_{S,1}} \tag{1}$$

where subscript '1' denotes the first axial location ,
'S' denotes the static pressure and 't' denotes the total pressure.

The diffuser performance have been determined by the following parameters

Ideal pressure recovery

$$C_{Pi} = 1 - \left[\frac{A_1}{A_2} \right]^2 \tag{2}$$

Diffuser efficiency

$$\eta = \frac{C_{Pi}}{C_P} \tag{3}$$

Pressure loss coefficient

$$k = C_{Pi} - C_P \tag{4}$$

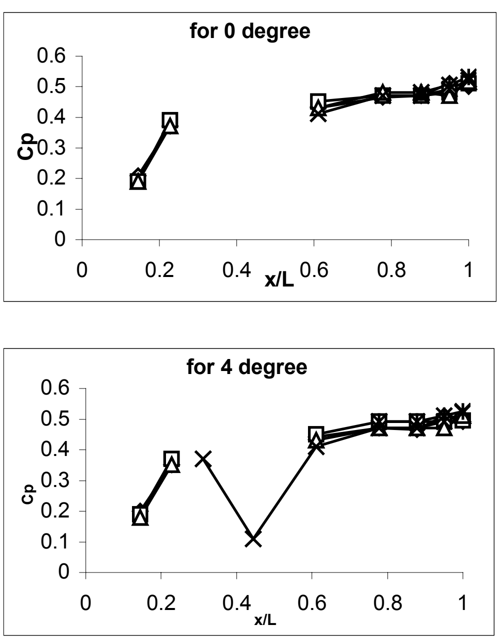
5. RESULTS AND DISCUSSION

5.1 Diffuser with Baseline struts

Figure 6 shows the variation of the pressure recovery coefficient along the axial direction at different radial positions for the diffuser with baseline struts.

From the figures, it is seen that in the first part of the diffuser, at the first two axial locations, the pressure rise is much higher than that at 36°. This is due to the stagnation zone produced by the downstream strut, where dynamic pressure is converted into static pressure. Because of the presence of the struts, around the strut (third and fourth axial positions), the static pressure has much less value due to the decrease in the cross passage section resulting in increase in velocity. The sudden collapse of static pressure at the third axial location, the first around the strut, is due to the flow separation from the strut. Immediately behind the strut that is at the fifth axial location, the static pressure recovery is more and this is due to the reduction of blockage of the strut.

Closer to the strut surface, for circumferential positions 4°, 8° and 12° at the first axial location around the strut, the pressure recovery is high near the hub and it decreases



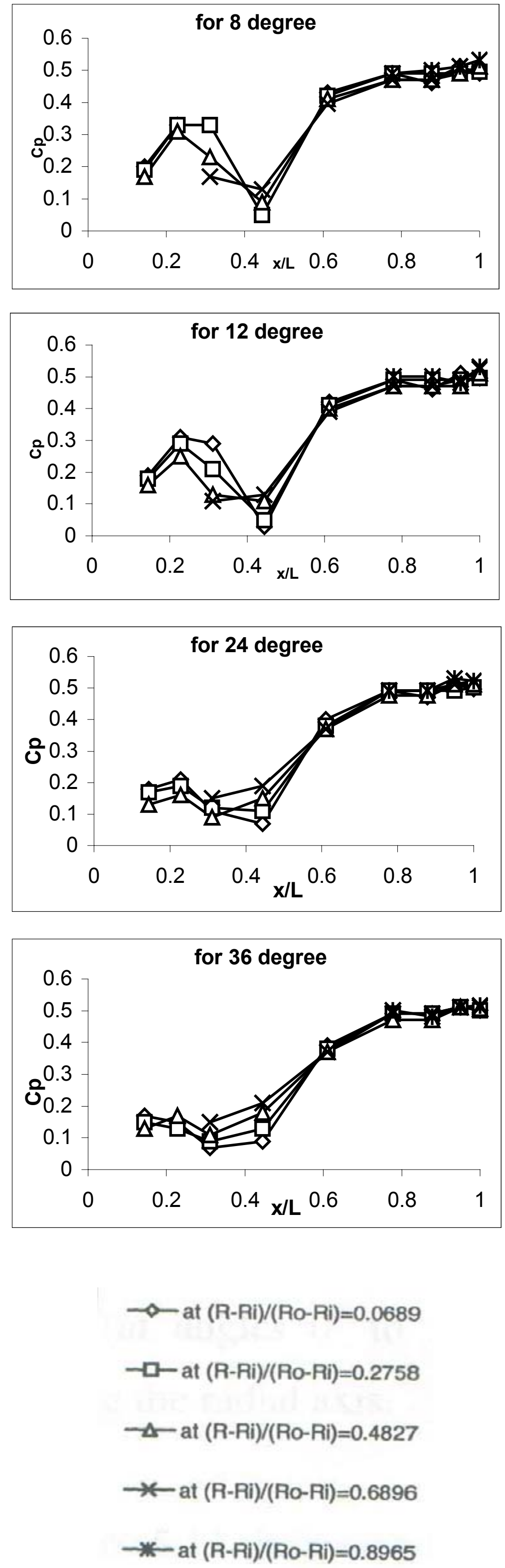


Figure 6. Static pressure profiles along the axial positions – Diffuser with Baseline Struts

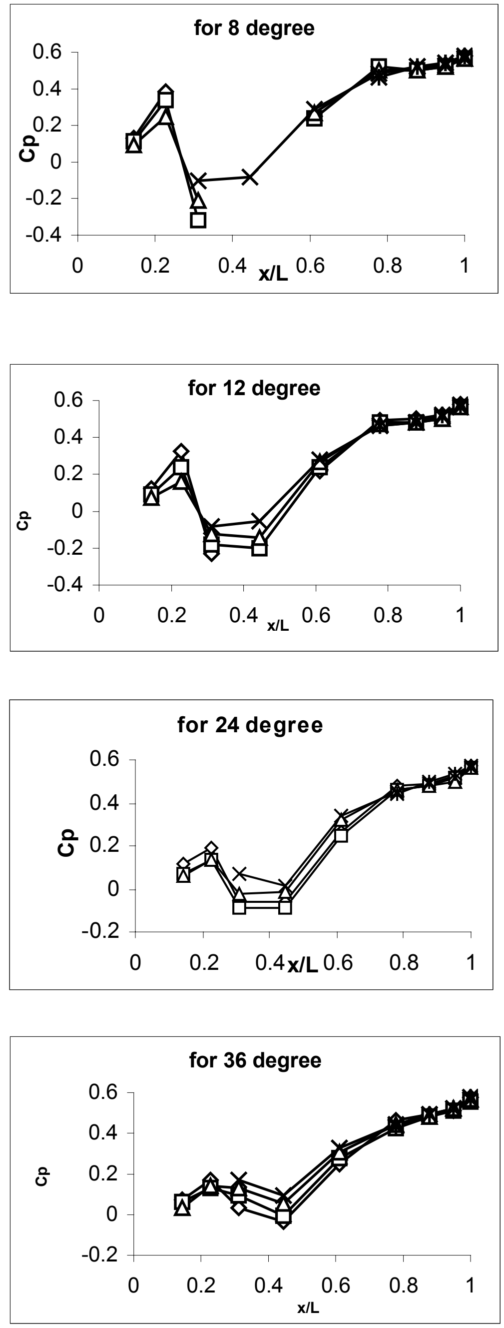
towards the casing. In the next axial location, the trend is reversed that is the pressure recovery decreases from the hub to the casing. This may be due to the formation of the boundary layer from the casing due to the adverse pressure gradient. In the last part of the diffuser, the static pressure near the hub is slightly lower than that near the casing. Behind the strut, to some extent, the rise in pressure gradient is less, which may be due to the strut wakes. The turbulence intensity, reaching high values behind the strut, and also the consequences of the non-axial component of velocity causing errors in pressure measurements behind the strut are to be taken into account.

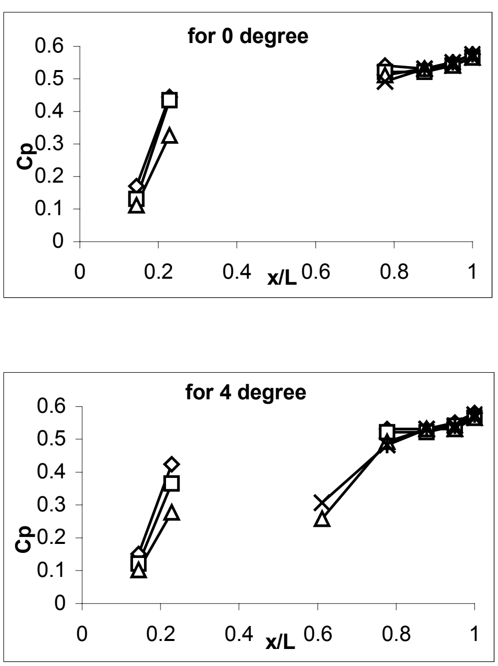
5.2 Diffuser with Tapered struts

Figure 7 shows the variation of the pressure recovery coefficient along the axial direction at different radial positions for diffuser with tapered struts. In the first part of the duct, the pressure rise around 0^o is higher than that at 36^o. This is due to the stagnation zone produced by the downstream strut, where the dynamic pressure is converted into static pressure.

The presence of the struts reduces the flow passage section and hence the pressure gradient decreases. The taper in the strut, causes a steady increase in the static pressure recovery along the radial axis.

It is also observed that for circumferential positions 12° - 36°, at axial locations x/L=0.3111, 0.4444 and 0.6111, the pressure recovery is high for radial positions away the hub which is due to the tapered design of the strut having longer chord fixed at the hub.





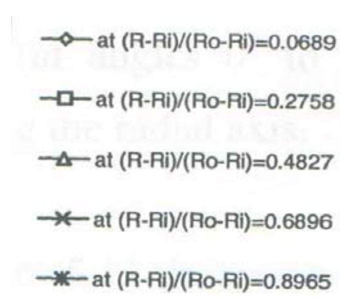


Figure 7. Static pressure profiles along the axial positions– Diffuser with Tapered Struts

5.3 Diffuser without struts

The static pressure profiles along the axial positions (Fig. 8) show the regularity of the pressure recovery through the diffuser. No significant differences can be detected between one and any other radial positions.

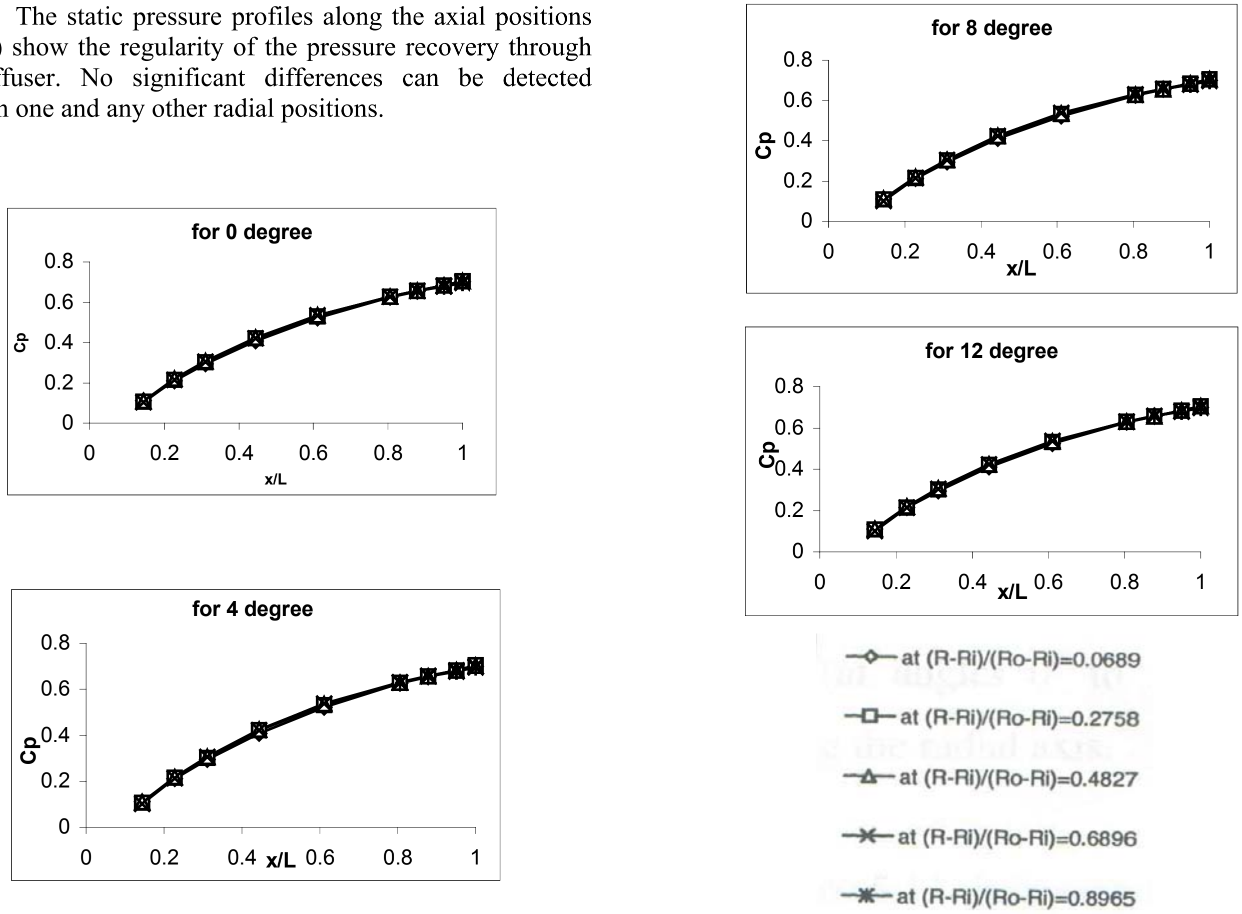


Figure 8. Static pressure profiles along the axial positions– Diffuser without Struts

5.4 Comparison

The diffuser flow situations in the annular diffuser can be compared through the performance coefficients summarized in the Table 2.

Table 2. Global Parameters for Diffuser with and without Struts

Parameters	Without Struts	With Struts	
		Baseline	Tapered
$C_{p\ ideal}$	0.756	0.756	0.756
C_p	0.701	0.513	0.569
η (%)	92	67.8	75.3
k	0.0547	0.242	0.186

The overall performance of the diffuser is highly influenced by the presence of struts. Due to the presence of the struts, the efficiency of the diffuser is reduced by 17% – 25% and the pressure losses increases from a mean value of 0.05 to 0.24.

From Table 2, it is evident that the diffuser with tapered struts performs better than the diffuser with baseline struts as the efficiency is about 8% higher. This increase in the efficiency could lead to a significant gain to the whole turbo machinery system. Also the pressure loss for the diffuser with tapered design of struts is less than that of the diffuser with baseline design of struts.

Figure 9 shows the static pressure recovery along the diffuser for different cases. Pressure recovery in the diffuser without struts increases more rapidly in the first part of the diffuser, and this is due to the absence of the struts effect causing losses and reduction of flow passage. 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 C_P increases along the radial direction.

The kinetic energy 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.

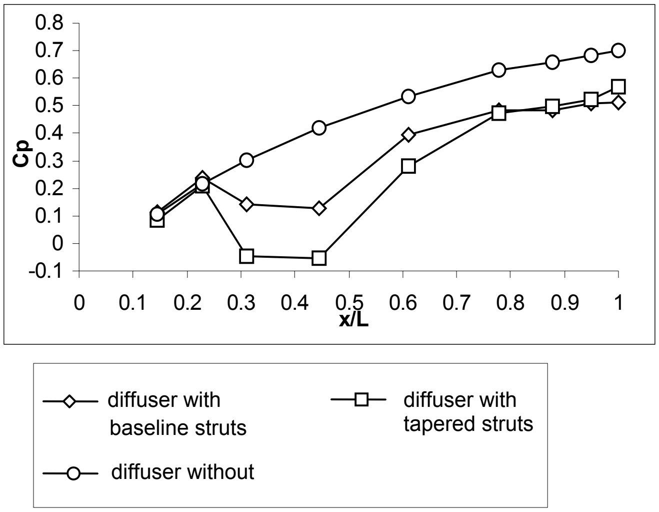


Figure 9. Static pressure recovery along the diffuser for different cases

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

For the diffuser with tapered struts, there is a steady increase in the pressure recovery until the exhaust 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.

Figure 10 shows the variation of total pressure loss along the length of the diffuser with and without struts. The pressure losses for the diffuser without struts are less compared to that of the diffuser with struts. At the midspan, where the struts are present, the pressure loss is seen to be high when compared to the diffuser without struts. This shows the effect of struts on the pressure losses. For the diffuser with tapered struts, the pressure loss is almost constant in the downstream region.

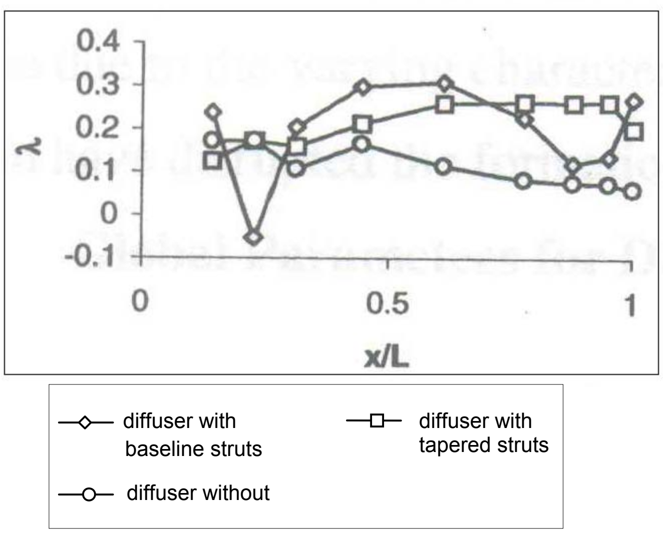


Figure 10. Total pressure loss along the diffuser for different cases

6. CONCLUSIONS

The major conclusions drawn from the present investigations are summarized below:

The diffusion in the diffuser with struts is interrupted by the reduction of the cross passage section due to the struts and their wakes. This means that the flow potentially has more diffusion to achieve.

A higher pressure recovery gradient is observed behind the struts.

Even in the diffuser without struts, a low pressure recovery gradient is observed in the very last part of the diffuser, due to the separation of flow from the walls.

The efficiency of the diffuser with struts is 17% – 25% lower than that of the diffuser without struts.

The pressure loss is significantly increased by the presence of struts.

Tapered design of struts performs better than the baseline design of struts by the fact that the static pressure recovery is more and the pressure loses are less in the diffuser with tapered struts.

The efficiency of the diffuser with tapered design of struts is 8% more than that of the diffuser with baseline design of struts. This increase in efficiency could lead to a significant gain to the whole Turbo machinery system.

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