CHAPTER 6
COMPUTATIONAL RESULTS AND DISCUSSION

6.1. INTRODUCTION

In the present computational analysis the performance characteristics of a centrifugal compressor focus to evaluate the effect of tip clearance on the performance of a centrifugal compressor designed with 2 mm extension of partial shroud attached on the rotor blade tip pressure surface side is evaluated in this fifth stage. The results are presented in the form of efficiency, energy coefficient, total pressure coefficient, static pressure coefficient and velocities for configurations with and without partial shroud, for three values of tip clearances viz. $\tau = 2.2\%, 5.1\%$ and $7.9\%$ and four values of flow coefficients, viz. $\phi = 0.34, 0.28, 0.18$ and $0.12$.

The numerical results for the three values of tip clearances considerers were compared with the experimental data. The overall flow structure predicted by the computational simulations was compared with the experimental results. The CFD results obtained in this work were satisfactory when compared with the experimental results over the full range of operating conditions.

6.2 FIFTH STAGE OF INVESTIGATION

In the fifth stage of investigation computational analyses are carried out to validate the experimental data with numerical data by using commercial software ANSYS-CFX 15.0. The tip geometry without and with partial shrouds with three different values of tip clearances considerers at four flow coefficients, namely as stated above are investigated. In this computational work partial shroud on the tip of the blade with a very small extension of 2 mm on the pressure surface side is provided for simulation also. The computational method will be a major design analysis tool for the design of centrifugal compressor without and with partial shroud on tip of the blade. Effect of configurations with and without partial shroud of a centrifugal compressor with experimental results and simulation results can be observed that partial shroud is very beneficial to the performance of the compressor. The performance characteristics of a centrifugal
compressor in terms of energy coefficient ($\psi$) vs. flow coefficient ($\phi$) and efficiency ($\eta$) vs. flow coefficient ($\phi$) for three values of tip clearance for both with and without configurations are shown in figs. 6.1 and 6.2. The energy coefficient is reduced where flow coefficient is maximum thereby increasing stable operating range. The partial shroud is to improve the compressor performance in terms of increased energy coefficient ($\psi$) and efficiency ($\eta$) at the three values of tip clearance and at four flow coefficients when compared to without partial shroud. The performance curves are drawn between energy coefficient vs. flow coefficient the maximum value is limited up to $\phi = 0.40$. However for efficiency vs. flow coefficient curves complete range of performance is presented, i.e. up to the maximum value of $\phi$ of 0.50. A configuration with partial shroud clearly shows that the higher efficiencies as much as 6% as compared with basic configuration. Because of the extension of the partial shroud 2 mm pressure surface side of the blade, the tip leakage flow has to travel a longer distance before interacting with the main flow. Hence both energy coefficient and efficiency of the rotor with partial shroud compressor performance is improved compared to those for the rotor without partial shroud. The tip leakage flow is stronger near the exit of the impeller, due to higher loading. Hence partial shroud on the rotor in this region has substantial effects. It can be also observed that computationally partial shroud has beneficial effects on the performance of the compressor, except at higher value of tip clearance.

From the results it is observed that with partial shroud had a relatively higher efficiency and wider operating range, as compared to experimental results as shown in figs. 6.1 and 6.2. This is because of the extension of the partial shroud and the shroud section has a more general distribution of the blade loading. At higher flow coefficients, the effect of tip clearance is predominant.

The partial shroud gives higher value of energy coefficient at all values of tip clearances as the partial shroud obstructs the tip leakage flow. It may be observed that the performance of the compressor with partial shroud at $\tau=2.2\%$ is showing better performance than without partial shroud. Similar trend is observed for the impeller with
partial shroud at $\tau=5.1\%$ and $7.9\%$ tip clearances. Figure 6.2 shows the compressor with partial shroud has higher value of efficiency compared to that without partial shroud for all values of tip clearance, due to reduced tip leakage flows. In fact the efficiency of the impeller with partial shroud even at the highest value of tip clearance is observed higher than the efficiency of the rotor without partial shroud at the lowest value of tip clearance.

For $\tau = 2.2\%$, the effect of the partial shroud is to improve the compressor performance, in terms of increased energy coefficient and efficiency at the three values of tip clearance and four flow coefficient is observed. The result of the computational investigations revealed that, energy coefficient across the centrifugal compressor is reduced as the tip clearance is increased. Effect of tip clearance of a centrifugal compressor with experimental and simulation results can be observed that partial shroud is very beneficial to the performance of the compressor.

![Figure 6.1. Performance of the centrifugal compressor energy coefficient, ($\psi$) vs. flow coefficient, ($\phi$) curves](image-url)
Fig. 6.2. Performance of the centrifugal compressor efficiency, ($\eta$) vs. flow coefficient, ($\phi$)

The figure 6.3 shows that the performance characteristic in terms of efficiency vs. flow coefficient for four flow coefficients $\phi=0.12$, 0.18, 0.28 and 0.34 and at the tip clearance $\tau=2.2\%$, for both configurations. At the value $\tau=2.2\%$, of tip clearance, partial shroud gives higher efficiency as compared to that of the compressor without partial shroud due to reduced tip leakage flows. Experimental and Simulation results can be concluded that partial shroud is very beneficial to the performance of the compressor.
Fig. 6.3. Performance of the centrifugal compressor at 2.2% tip clearance efficiency, ($\eta$) vs. flow coefficient, ($\phi$)

6.3 IMPELLER EXIT FLOW MEASUREMENTS

The following parameters are considered for impeller exit flow measurements.

6.3.1 Total pressure coefficient, ($\psi_0$)

Distribution of total pressure coefficient at the rotor exit for both configurations and for four flow coefficients $\phi=0.12, 0.18, 0.28$ and $0.34$ and for the three values of tip clearances $\tau=2.2\%, 5.1\%$ and $7.9\%$ is shown in fig. 6.4. From the figure, it can be clearly observed that the rotor with partial shroud shows increased total pressure coefficient, compared to basic configuration for all the flow coefficients and at the three values of tip clearances. From the figure, it is also observed that at the tip region total pressure coefficient increases with reduction in flow coefficient. That means the higher the loading more is the benefit due to the partial shroud. For all the flow coefficients it is also observed that the total pressure coefficient decreases with increase in tip clearance.
At larger flow coefficients the reduction in total pressure coefficient with tip clearance is high. It can also be observed that, the total pressure coefficient increases as the flow coefficient decreases for all the tip clearances. This may be attributed due to the partial shrouds attached on the tip of the blades restricting the tip leakage flow. Trend of the total pressure coefficient is almost same for both configurations at three values of tip clearances. The total pressure coefficient is decreases at flow coefficient 0.34 for with partial shroud and without partial shroud. At flow coefficient 0.28, for all the tip clearances total pressure coefficient rise is observed and there after decreases as the flow coefficient increases due to separation of flow.

![Fig. 6.4 Total pressure coefficient variation at the rotor exit](image)

### 6.3.2 Static pressure coefficient, ($\psi_s$)

The static pressure coefficient distribution at the rotor exit for two configurations with and without partial shroud and four flow coefficients, at three values of tip clearances is shown in Fig. 6.5. From the figure, it is observed that the rotor with partial
shroud shows increased static pressure coefficient ($\psi_s$) compared to without partial shroud configuration for all the flow coefficients at the three values of tip clearances $\tau = 2.2\%$, 5.1\% and 7.9\%. The similar trend like the total pressure distribution, the partial shroud improves static pressure for a larger extent from the shroud, as the flow coefficient decreases. It is also be observed that, the static pressure coefficient is increasing as the flow coefficient decreases for all the tip clearances. This may be attributed due to the partial shrouds attached to the tip of the blades restricting the tip leakage flow. Trend of the static pressure coefficient is almost same for both configurations with and without partial shroud at three values of tip clearances. However for higher flow coefficients the static pressure coefficient is decreasing near the casing. The static pressure coefficient is reducing with increase in tip clearance for all flow coefficients. The static pressure coefficient is reducing with increase in tip clearance. The static pressure coefficient drop with increment in tip clearance is more for higher flow coefficient. The maximum static pressure coefficient is found at flow coefficient of 0.28 is observed. At flow coefficient 0.34, for 2.2\% tip clearance the static pressure coefficient rise is gradually decreasing order as separation of flow is observed.

![Static pressure coefficient variation at the impeller exit](image)

*Fig. 6.5 Static pressure coefficient variation at the impeller exit*
6.3.3 Mass Averaged Flow Performance of Impeller

In the present computational investigation the partial shroud with a very small extension of 2 mm on the pressure surface side of the impeller blade is provided at the tip of the blade region along the axial direction away from the shroud is analyzed by CFD due to a higher intensity tip clearance flow. Total pressure ratio and static pressure ratio vs. normalised mass flow rate for three tip clearances are shown in figures 6.6 & 6.7. From the figure, it is observed that the numerical results of the total pressure ratio and static pressure ratio at the rotor exit for both configurations clearly shows that the partial shrouds are beneficial in improving the pressure rise of the compressor as compared to the basic configuration.

The exit of the impeller total pressure ratio is increased for the compressor with reduced tip clearances. The compressor with partial shroud the higher static and total pressures ratio are observed as compared with the basic configuration, because of the tip gap is reduced at the tip of the blade. At 2.2% tip clearance improvement is observed in the static pressure and total pressure ratio as compared to 5.1% and 7.9% tip clearance respectively. The static and total pressure ratio curves also indicated that a smaller tip clearance at the trailing edge was more effective than a smaller tip clearance at the leading edge. Large total pressure losses generally result from leakage flow through the tip gap. Because of the mass flow rate through the impeller was reduced much more than the mass flow rate through the tip of the blade. Therefore the decreased tip clearance was still effective even at the lower mass flow rate. The performance of a centrifugal compressor is significantly affected by tip clearance in two ways. First, tip leakage flow causes large pressure losses due to mixing with the main passage flow, as mentioned above. Second, the impeller cannot transfer its momentum to the fluid across the tip clearance, which decreases the total work input. That partial shroud is beneficial in improving the pressure rise of the compressor, compared to the basic configuration. Also mass averaged values decrease with increase in tip clearance is observed.

The mass averaged values decrease with increase in tip clearance. From the figure 6.8, the partial shrouds are found to have more beneficial effects at 2.2% of tip clearance. It is also
observed that, the mass averaged pressure ratio at the rotor exit for both configurations is decreasing as the flow coefficient increases.

Figure 6.6 Total pressure ratio vs. Normalised mass flow rate ($\phi/\phi_d$)

Figure 6.7 Static pressure ratio vs. Normalised mass flow rate ($\phi/\phi_d$)
6.4 STATIC PRESSURE CONTOURS ON CASING

Pressure contours on casing for two cases, with and without partial shroud on tip of the blade at 2.2% tip clearance is shown in figure 6.9. The contours show gradual pressure rise from inlet to outlet of the compressor due to dynamic action of the rotating impeller. Pressure gradient above the blade is observed due to the high pressure on pressure side and low pressure on suction side of the blade. With partial shroud on tip of the blade, significant change in pressure is observed. The low pressure on both pressure and suction side of the blade is observed for the compressor without partial shroud on tip of the blade due to more leakage of flow.

The static pressure is found on the casing similar trend is observed for all the flow coefficients. Gradual increase of static pressure is observed from meridional distance,
after this meridional distance there is increase in curvature of the casing. Because of this the flow accelerates, due to which velocity increases and the pressure decreases. This decrease in static pressure can be clearly observed.

![Pressure contours on casing without and with partial shroud at 2.2% tip clearance](image)

**Fig. 6.9** Pressure contours on casing without and with partial shroud at 2.2% tip clearance

### 6.5 VELOCITY CONTOURS ON CASING

Velocity contours on casing for two different cases with and without partial shroud on tip of the blade at 2.2% tip clearance is shown in figure 6.10. The contours show gradual increase of velocity from inlet to outlet of the impeller. The tip clearance for 2.2%, rotational vertical flow is observed due to the boundary layer on stationary casing. Fluid flow with partial shroud on tip of the blade, significant change in pressure is
observed, the velocities are high on suction surface side than pressure surface side because of blade curvature. For other tip clearances, near the suction side shroud corner leakage flow is observed. With the increase in the tip clearance, the wake region is increasing as leakage fluid mass flow increases.

Fig. 6.10 Velocity contours on casing without partial shroud and with partial shroud at 2.2% tip clearance

6.6 VELOCITY STREAM LINES:

Velocity streamlines inside impeller with and without partial shroud for three tip clearances and flow coefficient at 0.34 is shown in figures 6.11 (a), (b) and (c). The streamlines show the movement of low energy fluid from the hub to shroud on both sides of the compressor blade. From the pressure surface side this low momentum fluid pass
through the tip clearance region as a jet flow. The tip leakage flow interacts with the low momentum fluid on the suction surface side causing the roll down and move towards the exit. At the rotor exit fluid flow pushes the low momentum fluid back in to the impeller passage from the pressure surface side to suction surface side. This causes further deceleration of the flow from suction side. The strength and location of the wake region at the exit of impeller blade is heavily depended upon the tip leakage flow. When the vanes of diffuser are closer to the impeller the reverse flow enhances the tip leakage flow near the impeller exit. This is clearly observed from the streamlines pattern. The separated flow from the diffuser vane does not influence the impeller exit flow when there is sufficient radial gap. At $\varphi=0.12$, 0.18 and 0.28 velocity stream lines shows the same trend as $\varphi=0.34$. But the velocity lines increases with increase in tip clearance is more as flow coefficient increases.

Fig.6.11 (a) Velocity streamlines inside impeller at 2.2% tip clearance for without and with partial shroud at 0.34 flow coefficients
Fig. 6.11 (b) Velocity streamlines inside impeller at 5.1% tip clearance for without and with partial shroud at 0.34 flow coefficient.

Fig. 6.11 (c) Velocity streamlines inside impeller at 7.9% tip clearance for without and with partial shroud at 0.34 flow coefficient.
6.7 STATIC PRESSURE CONTOURS AT MERIDIONAL PLANE

Static pressure contours at meridional plane for two cases with and without partial shroud at three tip clearances $\tau = 2.2\%$, $5.1\%$ and $7.9\%$ is shown in figure 6.12 (a), (b), (c), (d), (e), (f), (g), (h), (i), (j), (k) and (l). The contours show high pressure on pressure surface side of the blade and low pressure on suction surface side of the blade. Fluid flow with partial shroud on tip of the blade a slight pressure drop is observed on suction side. Fluid flow without partial shroud on tip of the blade, significant reduction in pressure on suction side is observed. The static pressure reduction with increase in tip clearance at the tip of the blade is significant due to high pressure fluid leakage at the tip of the blade for all cases. Similar trend is observed for all the tip clearances.

Fig. 6.12(a) Static pressure contours at meridional plane with and without partial shroud at $2.2\%$ tip clearance for $\varphi = 0.12$
Fig. 6.12(b) Static pressure contours at meridional plane with and without partial shroud at 2.2% tip clearance for $\phi=0.18$.

Fig. 6.12(c) Static pressure contours at meridional plane with and without partial shroud at 2.2% tip clearance for $\phi=0.28$. 
Fig. 6.12(d) Static pressure contours at meridional plane with and without partial shroud at 2.2% tip clearance for $\phi=0.34$.

Fig. 6.12(e) Static pressure contours at meridional plane with and without partial shroud at 5.1% tip clearance for $\phi=0.12$. 
Fig. 6.12(f) Static pressure contours at meridional plane with and without partial shroud at 5.1% tip clearance for $\varphi=0.18$.

Fig. 6.12(g) Static pressure contours at meridional plane with and without partial shroud at 5.1% tip clearance for $\varphi=0.28$. 
Fig. 6.12(h) Static pressure contours at meridional plane with and without partial shroud at 5.1% tip clearance for $\varphi=0.34$.

Fig. 6.12(i) Static pressure contours at meridional plane with and without partial shroud at 7.9% tip clearance for $\varphi=0.12$. 
Fig. 6.12(j) Static pressure contours at meridional plane with and without partial shroud at 7.9% tip clearance for $\varphi=0.18$.

Fig. 6.12(k) Static pressure contours at meridional plane with and without partial shroud at 7.9% tip clearance for $\varphi=0.28$.

Fig. 6.12(l) Static pressure contours at meridional plane with and without partial shroud at 7.9% tip clearance for $\varphi=0.34$. 
6.8 TOTAL PRESSURE CONTOURS ON MERIDIONAL PLANE AT TURBOSURFACE 1.8:

Total pressure contours on meridional plane for two configurations with and without partial shroud for three tip clearances 2.2%, 5.1% and 7.9% are shown in figures 6.13 (a), (b), (c), (d), (e), (f), (g), (h) and (i). Fluid flow for basic configuration at tip of the blade on suction side near tip region high total pressure area of passage wake is observed. With partial shroud on tip of the blade, low total pressure area of passage wake is reduced. The leakage flow from the pressure side is interacting with passage wake. With partial shroud on tip of the blade for 2.2% clearance, total pressure is higher at pressure surface side due to the rotation and meridional curvature and low total pressure is observed near the suction surface side because of the boundary layer on stationary casing. For other tip clearances the wake region is observed. As compared to low tip clearance at other tip clearances, due to leakage flows, total pressure on suction side is further reduced and the total pressure on pressure side is also reduced.

The wake passage area is increasing with increase in tip clearance. At 7.9% tip clearance the low total pressure region is significant and also the position is away from the suction side shroud corner. With the tip clearance increase, the total pressure on pressure side is reduced as mass flow rate of leakage fluid from tip gap increases. The increase in wake region and movement of wake along shroud towards pressure surface is observed. The total pressure coefficient at suction side of hub corner is increased, because of secondary flow, which causes the fluid to move vertically up. Total pressure gradient near the blade end which cause jet and wake flow at trailing edge is also observed. Similar trends are observed for all flow coefficients.
Fig. 6.13(a) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 2.2% tip clearance for flow coefficient 0.18.

Fig. 6.13(b) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 2.2% tip clearance for flow coefficient 0.28.
Fig. 6.13(c) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 2.2% tip clearance for flow coefficient 0.34.

Fig. 6.13(d) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 5.1% tip clearance for flow coefficient 0.18.
Fig. 6.13(e) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 5.1% tip clearance for flow coefficient 0.28.

Fig. 6.13(f) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 5.1% tip clearance for flow coefficient 0.34.
Fig. 6.13(g) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 7.9% tip clearance for flow coefficient 0.18.

Fig. 6.13(h) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 7.9% tip clearance for flow coefficient 0.28.
Fig. 6.13(i) Total pressure contours at meridional plane surface at 1.8 with and without partial shroud at 7.9% tip clearance for flow coefficient 0.34.

6.9 VELOCITY CONTOURS AT MERIDIONAL PLANE

Velocity contours on meridional plane for two configurations with and without partial shroud at 2.2% tip clearance is shown in figures 6.14. The contours show improved velocities on suction side with partial shroud. The low velocity passage wake area on suction side of the blade is reducing with without partial shroud on tip of the blade. However, the velocity in passage wake region is much lower with without partial shroud on tip of the blade as more leakage flow is interacting with the main flow.

Fig. 6.14 Velocity contours at meridional plane of the blade for 2.2% tip clearance for with and without partial shroud
6.10 STATIC PRESSURE CONTOURS AT SPAN 0.7

Static pressure contours in blade to blade view, at span 0.7 for $\tau = 2.2\%$, 5.1% and 7.9% tip clearance for with and without partial shroud is shown in figure 6.15 (a), (b), (c), (d), (e), (f), (g), (h), (i), (j), (k) and (l). The contours show gradual pressure rise from inlet to outlet of the compressor due to dynamic action of the rotating impeller. Gradual increase of static pressure from inlet to outlet is clearly observed at all tip clearances. With partial shroud on tip of the blade, significant pressure change is observed at exit of the impeller. But without partial shroud on tip of the blade, the pressure at outlet is reduced. High pressure on pressure side of the blade and low pressure on suction side of the blade are clearly observed at all tip clearances. With increase in tip clearance, reduction in pressure on both pressure side and suction side is found. Similar trend is observed for all the tip clearances.

Fig. 6.15(a) Static pressure contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.
Fig. 6.15(b) Static pressure contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.

Fig. 6.15(c) Static pressure contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.
Fig. 6.15(d) Static pressure contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.

Fig. 6.15(e) Static pressure contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.
Fig. 6.15(f) Static pressure contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.

Fig. 6.15(g) Static pressure contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.
Fig. 6.15(h) Static pressure contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.

Fig. 6.15(i) Static pressure contours at 7.9% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.
Fig. 6.15(j) Static pressure contours at 7.9% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.

Fig. 6.15(k) Static pressure contours at 7.9% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.
Fig. 6.15(l) Static pressure contours at 7.9% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.

6.11 VELOCITY CONTOURS AT SPAN 0.7

Velocity contours at span 0.7 for both configurations is shown in figure 6.16(a), (b), (c), (d), (e), (f), (g), (h), (i), (j), (k) and (l). The velocity contours show improved velocities on suction side with partial shroud. The low velocity passage wake area on suction side of the blade is reducing with partial shroud on tip of the blade. At 2.2% tip clearance, velocities are more on the suction surface side and velocities are low on pressure surface side of the blade. Due to the centrifugal forces and curvature, velocity on suction side is higher than pressure side. For other clearances, more leakage of flow from pressure side to suction side of the blade through the tip gap is observed. Near the shroud a low velocity wake region is observed for all flow coefficients. Vertical flow near the suction side of the blade meets the tip leakage flow near suction side. At impeller exit pressure at different flow coefficients is an increase with partial shroud on tip of the blade is observed at all flow coefficients. But without partial shroud on tip of the blade, reduction in pressure is observed at all flow coefficients because of more fluid leakage through the basic configuration. Similar trend is observed for all the tip clearances.
6.16(a) Velocity contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.

6.16(b) Velocity contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.
6.16(c) Velocity contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.

6.16(d) Velocity contours at 2.2% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.
6.16(e) Velocity contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.

6.16(f) Velocity contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.
6.16(g) Velocity contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.

6.16(h) Velocity contours at 5.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.
6.16(i) Velocity contours at 7.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.12.

6.16(j) Velocity contours at 7.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.18.
6.16(k) Velocity contours at 7.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.28.

6.16(l) Velocity contours at 7.1% tip clearance without and with partial shroud at span 0.7 for flow coefficient 0.34.
6.12 VELOCITY VECTORS AT TURBO SURFACE 1.8

A velocity vector at turbo surface 1.8 at the exit of the impeller for four flow coefficients $\phi=0.12, 0.18, 0.28$ and $0.34$ and for the different tip clearances $\tau=2.2\%, 5.1\%$ and $7.9\%$ for both configurations is shown in figures 6.17(a), (b), (c), (d), (e), (f), (g), (h), (i) and (j). The fluid flows with partial shroud on tip of the blade velocities are high on suction surface than pressure surface because of centrifugal forces and blade curvature. For other tip clearances, leakage of flow from pressure side to suction side of the blade is higher through the tip gap of the blade is observed. For other tip clearances $5.1\%$ and $7.9\%$, near the suction side leakage flow is rolling up forming a wake. With the increase in the tip clearance $2.2\%$ to $7.9\%$, the wake region is increasing as leakage fluid mass flow rate increases. Circulating flow near the suction surface is observed due the strong centrifugal forces. At $7.9\%$ clearance, the wake region is near the middle of the pitch and is significant. Downstream of the blade, absence of centrifugal force causes the flow nearly uniform. However, the passage wake is still observable at this meridional plane. At the trailing edge of the blade, velocity difference on pressure and suction sides of the impeller is observed with jet and wake flow. For $2.2\%$ to $7.9\%$ tip clearances, high velocity of the fluid from pressure side to suction side through tip clearance is observed. But the velocity vectors increases with increase in tip clearance is more as flow coefficient increases. The velocity distribution is minimum near hub and shroud is observed. Near the casing higher energy transfer is also observed. Similar trend is observed for all the flow coefficients.
6.17(a) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 2.2% tip clearance for flow coefficient 0.12
6.17(b) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 2.2% tip clearance for flow coefficient 0.18.
6.17(c) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 2.2% tip clearance for flow coefficient 0.28.
6.17(d) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 2.2% tip clearance for flow coefficient 0.34.
6.17(e) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 5.1% tip clearance for flow coefficient 0.18.
6.17(f) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 5.1% tip clearance for flow coefficient 0.28.
6.17(g) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 5.1% tip clearance for flow coefficient 0.34.
6.17(h) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 7.9% tip clearance for flow coefficient 0.18.
6.17(i) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 7.9% tip clearance for flow coefficient 0.28.
6.17(j) Velocity vectors at turbo surface 1.8 of the blade with and without partial shroud at 7.9% tip clearance for flow coefficient 0.34.
6.13 STATIC PRESSURE DISTRIBUTION

Static pressure distribution along stream-wise direction from inlet to outlet is shown in figures 6.18 (a) & (b). These figures show that the pressure from inlet to the outlet of the compressor is increasing gradually along the stream wise direction due to the dynamic head developed by the rotating impeller. A drop in static pressure near streamwise direction is observed for two cases due to the acceleration of the flow in to the eye of the impeller. Static pressure reduction is observed with partial shroud on tip of the blade. With partial shroud on tip of the blade, static pressure at outlet is more than the static pressure of without partial shroud. The compressor with partial shroud static pressure is constant before the impeller passage. Static pressure drop at impeller leading edge is observed which causes the fluid to accelerate in to the compressor. Pressure is increasing steadily in the impeller passage for all tip clearances due to the energy transfer taking place in the impeller. The drop in static pressure with increase in tip clearance is found to be high at the tip of the blade due to high pressure fluid leakage at the tip of the blade. For all the tip clearances it is observed that the total pressure decreases with increase in tip clearance.

Fig.6.18 (a) Static pressure distribution from inlet to outlet
6.14 TOTAL PRESSURE DISTRIBUTION

Total pressure distribution along stream-wise location with and without partial shroud is shown in figure 6.19. Gradual increase of pressure along stream-wise direction is observed because of dynamic action of the impeller and total pressure improvement with partial shroud is also observed. With partial shroud on tip of the blade, the fluid flow from pressure surface side to suction surface side of the blade is interacting with passage wake. The pressure change is not significant but substantial velocity improvement is the cause for total pressure rise. For all the flow coefficients it is observed that the total pressure decreases with increase in tip clearance. At larger flow coefficients the reduction in total pressure with tip clearance is high. For 2.2% tip clearance the total pressure is higher than the other tip clearances as the mass flow rate increasing above operating range. The total pressure difference for 2.2% and 5.1% clearance is increasing with flow coefficient increase. At φ=0.34 the difference in total pressure coefficient for 2.2% and 5.1% clearance is significant.
6.15 RADIAL VELOCITY DISTRIBUTION

Radial velocity distributions from the hub to the shroud at the impeller exit for three tip clearances and for four flow coefficients at two configurations is shown in figure 6.20 (a), (b) and (c). It is observed that radial velocity slightly increases at flow coefficients $\phi = 0.34$ and 0.28 in the impeller shroud region for the configuration with partial shroud as compared to the basic configuration. It is also observed that at the shroud region for three values of flow coefficients show decrease in radial velocity. At shroud region boundary layer thickness increases due to partial shroud. Therefore higher loading on the blade causes decrease in radial velocity.

At the impeller exit with partial shroud the flow near the shroud is secondary flow that block the flow passage. The tip clearance flow influences the secondary flow structure and further blocks the flow passage, thereby generating a large total pressure loss near the shroud. The blockage shows in a rapid decrease in the radial velocity near the shroud in all three tip clearances. However at 2.2% tip clearance no reverse flow was
observed near the shroud, the blockage is smaller in this case than in the without partial shroud. For the tip clearance 2.2% included the low loss region near the shroud. The increased radial velocities near the shroud in 2.2% tip clearance were the reduced tip leakage flow in the tip region. The radial velocity distribution is for 5.1% and 7.9% tip clearances are almost identical. This result suggested that the radial velocity distribution in the spanwise direction at the impeller exit depended strongly on the tip clearance at the trailing edge.

6.20 (a) Radial velocity distribution from hub to shroud at impeller exit for flow coefficient 0.18.
6.20 (b) Radial velocity distributions from hub to shroud at impeller exit for flow coefficient 0.28.

6.20 (c) Radial velocity distributions from hub to shroud at impeller exit for flow coefficient 0.34.
6.16 TANGENTIAL VELOCITY DISTRIBUTION

Tangential velocity distribution from normalised hub to shroud is shown in figs. 6.21 (a), (b), (c), (d) and (e). The tangential velocity is minimum near hub and shroud indicating the boundary layer. The maximum tangential velocity is observed near the shroud, indicating higher energy transfer near shroud. However the tangential velocity moves away from the shroud as the tip clearance increases. Also the tangential velocity moves away from the casing as the flow coefficient decreases.

From this figure it is clearly shows that at mass flow rate 0.018 and 0.14 kg/sec, the tangential velocity is moving away from shroud as tip clearance is increasing. The 2.2% clearance at mass flow rate 0.285 kg/sec is showing a low tangential velocity as the mass flow rate falling beyond operating range. At flow coefficient $\phi=0.12$ the tangential velocity minimum is observed near hub and shroud. The tangential velocity is increase with decreases tip clearance up to mid span and then it is decreasing with decrease in tip clearance. The minimum tangential velocity at hub is increasing with flow coefficient increase, whereas tangential velocity at shroud is decreasing with flow coefficient increases. Also tangential velocity is decreasing with flow coefficient increase.

6.21 (a) Tangential velocity distributions at impeller exit
6.21 (b) Tangential velocity distributions at impeller exit for flow coefficient 0.12.

6.21 (c) Tangential velocity distributions at impeller exit for flow coefficient 0.18.
6.21 (d) Tangential velocity distributions at impeller exit for flow coefficient 0.28.

6.21 (e) Tangential velocity distributions at impeller exit for flow coefficient 0.34.
6.17. BLADE LOADING CURVES

Blade loading curves for four flow coefficients and three tip clearances with partial shroud and without partial shroud is shown in fig. 6.22(a), (b), (c), (d), (e), (f), (g), (h), (i) and (j). Static pressure on suction surface side and pressure surface side to the partial shroud of the blade was estimated for different tip clearances at four flow coefficients for two configurations namely below design (choke), at design and above design (surge). The area inside the curve represents that the blade loading, which indirectly represents the work done by the impeller. It is observed that the static pressure change at the tip of the blade is greatly affected by tip clearance. The pressure drop increases at the exit of the blade as the tip gap increases due to the strong interaction between leakage flow and main flow. The static pressure at impeller outlet drops with increase in tip gap although the inlet static pressures are same. The static pressure on the suction surface side initially drops and then increases gradually till the trailing edge. Though the similar behavior is observed on the pressure surface side, the static pressure slightly increases then drops at the leading edge, and then increases continuously till the trailing edge. This behavior at the leading edge is due to the blade and boundary layer blockage effects. Similar behavior was observed with lesser effect at mid plane where tip clearance had no effect on the pressure distribution.

Fluid flow without partial shroud and with partial shroud on tip of the blade, significant change in pressure on suction side is observed. Low static pressure on suction surface side and high pressure on pressure surface side of the blade is observed. With increase in tip clearance, static pressure on both pressure side and suction side are reducing. Deterioration of tip static pressure with the increase in tip clearance is clearly evident from the figures. Similar trend is observed for all the tip clearances.
6.22(a) Blade loading for 2.2% clearance at with and without partial shroud at flow coefficient 0.12.

6.22(b) Blade loading for 2.2% clearance at with and without partial shroud at flow coefficient 0.18.
6.22(c) Blade loading for 2.2% clearance at with and without partial shroud at flow coefficient 0.28.

6.22(d) Blade loading for 2.2% clearance at with and without partial shroud at flow coefficient 0.34.
6.22(e) Blade loading for 5.1% clearance at with and without partial shroud at flow coefficient 0.12.

6.22(f) Blade loading for 5.1% clearance at with and without partial shroud at flow coefficient 0.18
6.22(g) Blade loading for 5.1% clearance at with and without partial shroud at flow coefficient 0.28.

6.22(h) Blade loading for 5.1% clearance at with and without partial shroud at flow coefficient 0.34
6.22(i) Blade loading for 7.9% clearance at with and without partial shroud at flow coefficient 0.12.

6.22(j) Blade loading for 7.9% clearance at with and without partial shroud at flow coefficient 0.18
6.22(k) Blade loading for 7.9% clearance at with and without partial shroud at flow coefficient 0.28

6.22(l) Blade loading for 7.9% clearance at with and without partial shroud at flow coefficient 0.34