3D Numerical Investigation of the Tandem Compressor Cascade with varying Sidewall Gap Distance

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ABSTRACT

Literature available till date shows superiority of tandem blades cascade over single blade cascade in terms of high loading and turning of the flow. However, most of these investigations are done excluding the effect of tip on the performance of tandem cascade. The present work is carried out to investigate the effect of tip and sidewall on the flow losses. To analyze the 3D flow characteristic in the sidewall gap region for high loading and turning cascade, NACA 65 blades with low aspect ratio of $b/l = 1.9167$ and overall spacing ratio of $t/l = 0.6$ is chosen. The cascade is designed using Lieblien’s diffusion factor and Lie’s diffusion number. The study reveals that the losses are increased due to generation of sidewall vortex and flow leakage at the tip of the tandem blades. It is observed that sidewall gap distance has significant effect on the flow losses. The off design performance of the optimum sidewall gap distance exhibit wide incidence range.

Keywords: Tip leakage loss, sidewall gap distance, tandem blade, axial compressor, CFD

1. INTRODUCTION

The axial flow compressors for gas turbines are designed to deliver high pressure ratio, but increase of pressure in flow direction increases adverse pressure gradient and eventually flow separation limits the compression per stage. Hence, to increase the pressure ratio, tandem blade arrangement is proposed which can deplete the boundary layer growth and control flow separation. The study of geometric parameters like percent pitch, chord ratio, camber ratio, shape of gap nozzle region, etc on tandem blade performance are well documented in literature. However, much less information of flow behavior near tip region is available. The present study is conducted to study the effect of geometric parameters of tandem blade near tip region. The aim is to reduce flow losses by controlling tip leakage flow and sidewall vortexes.

The literature describing the effects of 3-D flow losses includes, the effect of end wall turbulence on tandem blade cascade studied by Schuler et al. [1]. The study concluded that the load split has a major effect on overall loss, deviation and end-wall loss. McGlumphy [2] examined the effect of 3-D flow between the forward blade and aft blade. NACA 65 series

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blade was considered for the study and noticed that aft blade performance was strongly dependent on the flow it received from the forward blade. The flow became more three-dimensional and non-uniform than forward blade.

Schlaps et al. [3] investigated effect of geometric parameters for 3-D flow domains. Blade shape, gap nozzle and end wall regions were optimized in this study. The effect of hub and tip region on the flow stream of tandem airfoils was investigated by Tesch and Ortmanns [4]. The secondary losses in a tandem stator flow were analyzed in span wise direction for low speed axial compressor. The study concluded that hub effect is higher in the tip region for tandem configuration. The gap affected the size of secondary flow since the high momentum air pushes the secondary flow. The study on effect of sidewall region for subsonic tandem compressor cascade was done by Bohle and Frey [5]. Various flow turning was analyzed by changing the incidence angle at constant Re for two cascades. Hertel et al. [6] examined the secondary flow of subsonic tandem cascades for three different incidences, and results showed that front airfoil secondary flows were significantly affected by the aerodynamic loading, whereas that of the rear airfoil was almost unchanged. Investigations by Tesch et al. [7] on 3-D flow field of a tandem stator revealed that the gap nozzle flow created higher losses at the hub. Separation of the wake flow at the mid section of both airfoils was noticed and was affecting the shape of the loss zones in the hub, tip corner and end-wall locations. He also noticed that tandem configurations were working well at various flow conditions.
It can be observed from literature that much less information is available at present regarding the effect of tip region on the performance of tandem blade cascade. Therefore, the objective of the current study are:

(i) To investigate the effect of variation of sidewall gap distance on tandem cascade performance,

(ii) To analyze the effect of off-design incidence on tandem cascade performance.

2. TANDEM CASCADE SETUP

Cascade geometry is generated using the design rule proposed by McGlumphy et al. [2], Lieblein’s diffusion factor [8], Lie’s Diffusion number [9] and blade Mellor diagram for NACA 65 airfoils. A schematic of 3-D tandem blade arrangement is shown in Figure 1. The method involves obtaining blade stagger angles from the Lieblin’s diffusion factor equation and Mellor diagram by assuming the individual diffusion factors of the front and rear airfoils.

![Figure 1. Schematic of tandem blade arrangement](image1)

The overall diffusion factor is described as,

\[
DF_{ov} = \left[ 1 - \frac{\cos \beta_{11}}{\cos \beta_{22}} \right] + \frac{\cos \beta_{12} (\tan \beta_{11} - \tan \beta_{22})}{2\sigma} \quad \ldots (1)
\]

The overall Lie’s diffusion number for tandem cascade is given as,

\[
D_{ov} = \frac{t}{l} \left[ 1 - \left( \frac{\cos \beta_{11}}{\cos \left( \frac{\beta_{11} - \beta_{22}}{2} \right)} \right)^2 \right] (i_1 - \varphi_1) \quad \ldots (2)
\]

The Load split is described as,
\[ LS = \frac{DF_1}{DF_1 + DF_2} \ldots (3) \]

Where, \( DF_1 \) is a diffusion factor of forward blade and \( DF_2 \) is a diffusion factor of aft blade. \( LS = 0.5 \) is used in the present simulations.

Overall chord length is chosen as \( l = 0.1917 \) m, to match the criteria of experimental test section of Bohle and Frey[5]. Chord ratio of 0.428 was assumed and was found suitable for low losses. Axial overlapping is not considered for the present study. Percent pitch is assumed as 90\% of chord length. Table 1 summarizes the geometric parameters considered for the present study. Stagnation pressure loss coefficient is used to compare the performance of tandem cascades and is described as,

\[ \omega_c = \frac{\dot{p}_{o,11} - \dot{p}_{o,22}}{\dot{p}_{o,11} - \dot{p}_{11}} \ldots (4) \]

Where, \( \dot{p}_{o,11} \) and \( \dot{p}_{o,22} \) are the mass averaged stagnation pressures at inlet and outlet plane. In order to get the idea of wake behavior term dimensionless wake loss coefficient [5], \( \zeta \) is used. It is defined as,

\[ \zeta = \frac{\dot{p}_{o,11} - \dot{p}_{o,r}}{\frac{1}{2} \rho V_i^2} \ldots (5) \]

\( \dot{p}_{o,r} \) is mass averaged stagnation pressures at the plane of result where wake loss has to be evaluated and \( V_i \) the mass averaged velocity at inlet plane.

### 2.1 DETAILS OF NUMERICAL SETUP

A 3D, steady, incompressible turbulent flow model using CFD code ANSYS FLUENT 16 is used in the present study. Flow domain was discretized using ANSYS ICEM 16.2 grid generation tool. The domain was split into different blocks using hybrid meshing strategy. Figure 4 shows the details of the mesh generated for a particular case. The mesh at the boundary layer was developed such that it maintains a \( y^+ \) value close to 1 so that the first layer can capture the viscous sublayer and the numerical simulation can be run without using any wall function approximation.

<table>
<thead>
<tr>
<th>Geometric Parameters</th>
<th>Forward Blade</th>
<th>After Blade</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>0.4547</td>
<td>0.4547</td>
<td>0.5775</td>
</tr>
<tr>
<td>D</td>
<td>0.4235</td>
<td>0.2330</td>
<td>0.3577</td>
</tr>
<tr>
<td>LS</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>
The simulation domain is bounded by the air inlet, outlet, airfoil surface, and periodic and wall boundary condition on sides. Velocity at inlet surface is chosen as 62 m/s at 50° incidence. The outlet surface is provided with pressure outlet boundary condition. Pressure-velocity coupling is achieved through a semi-implicit method for pressure-linked equations [SIMPLE] algorithm. Second order upwind scheme is used for spatial discretization. Solution convergence was established by confirming the residual to drop below $10^{-5}$. It is also ensured that the mass imbalance within the domain was less than 0.001% and the drag due to the front
blade and rear blade reached a constant value. Grid independence study is conducted by varying the resolution of the grid by a factor of about 2 and the result is shown in Figure 5.

![Comparison of loss coefficient for different number of grids](image1)

**Figure 5.** Comparison of loss coefficient for different number of grids

![Validation of numerical flow model plotted as dimensionless wake-loss coefficient in pitch-wise direction](image2)

**Figure 6.** Validation of numerical flow model plotted as dimensionless wake-loss coefficient in pitch-wise direction

The computational model used is validated based on experimental works of Bohle and Frey [7] and is shown in Figure 6. In order to measure the loss distribution due to flow separation from walls, two turbulent models were used (Spalart Allmaras turbulent model and SST $k$-$\omega$ Transition turbulent model). It is observed that Spalart Allmaras model predicts better loss distribution of wake of the aft blade and is not predicting the loss-distribution due to wake from forward blade. SST $k$-$\omega$ Transition turbulent model showed good agreement at aft blade wake as well as it is capable to predict the loss generation due to forward blade wake. Hence, SST $k$-$\omega$ Transition turbulent model can be considered for the future investigations of the present tandem cascade. The maximum deviation of 15 % is observed at 0.45 $y/t$ distance.

### 3. RESULTS AND DISCUSSION

The study is conducted to obtain the 3-D flow field near tip of the blade and to select optimum sidewall gap which can help to reduce the losses and to avoid flow separation at tip of the tandem blades. The range of sidewall gap distances evaluated for present investigation is summarized in Table 2. The concept of variable sidewall gap distance is shown in Figure 7.
The loss coefficient $\omega_c$ is plotted as a function of sidewall gap distance $g/h$ in Figure 8. It is observed that the loss is minimum at sidewall gap distance of 0.05$h$ and is 0.12.

![Figure 7. Concept of varying sidewall gap distance of tandem compressor cascade](image)

**Table 2.** Geometric and Flow parameters to investigate for 3D tandem cascade configuration.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Range of values studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidewall gap distance, $g$</td>
<td>0.03$h$ to 0.1$h$ in steps of 0.02 &amp; 0.1$h$ to 0.3$h$ in steps of 0.1</td>
</tr>
<tr>
<td>Off design incidence, $\beta_{11}$</td>
<td>$40^\circ$ to $70^\circ$</td>
</tr>
</tbody>
</table>
No significant increase is observed when sidewall gap distance increased from 0.1 h to 0.3 h. At 0.03h sidewall gap distance, the sidewall vortex near TE at tip of the FB is evident as shown in Figure 9. The generation of this vortex is due to pressure gradient developed between SS of the FB and surface of the sidewall. The tip flow separation is not evident on forward or aft blade of the tandem cascade. It is due to blockage of flow through sidewall gap. At 0.05h sidewall gap distance, the strong sidewall vortex is seen. Due to increase in
sidewall gap, the mass flow crossing the gap increases. At 0.07h sidewall gap distance, the sidewall vortex strikes on the pressure surface of the aft blade at the tip region. At 0.1h sidewall gap distance, the tip flow separation at TE of aft blade is observed. It is due to increase in sidewall gap distance which reduces the static pressure at gap region and results in increase of flow crossing the gap. Variation of dimensionless wake-loss coefficient, for various sidewall gap distance is plotted in Figure 10.

![Figure 10. Wake loss coefficients at various gap distance](image)

The loss coefficient for sidewall gap distance of 0.05h at various inlet flow angles is shown in Figure 11. It is observed that minimum loss of 0.125 is generated at flow incidence of 50°, and twice the value of loss is found near 60° of incidence. Beyond this, the loss tends to
increase abruptly. The sudden increase of loss is due to large flow separations and increase in 3-dimensionality of flow. However from the loss study, it can be concluded that the tandem cascade can perform well in the range of 40° to 65° for the present configuration. The pressure difference between SS and PS of the tandem blades is the main cause of tip vortexes and increase in tip flow causes early flow separation. In Fig 12 the stream lines are traced in the sidewall gap region, in gap nozzle region, on the suction surfaces, on the pressure surfaces and near vortices. At 0.03h sidewall gap distance, the sidewall vortex was evident near tip of the forward blade, and its intensity increased with the gap distance. Due to increase in gap, the interaction of turbulent boundary layer of sidewall and tip of the blade decreased. The flow started crossing the sidewall gap clearance and the flow phenomena associated with tip clearance changed. It is observed that intensity of sidewall vortex reduces in this case. As a consequence, the stream lines coming from SS of the FB deflects less towards mid-span due to reduction in sidewall vortex strength. The streamlines coming from gap nozzle region starts deflecting towards mid-span due to increase in mass flow from pressure side. These two phenomena contributes for larger turbulence generation and consequently higher loss and higher flow mixing at outlet surface.

![Fig 12. Loss distribution at various incidence for tandem blade configuration with sidewall gap distance of 0.05h](image)

4. CONCLUSION

In present work, a 3-D, steady, incompressible numerical model of tandem blades cascade was developed to investigate the effect of tip on the performance of tandem cascade compressor. The sidewall gap distance was varied from 0.03h to 0.07h in steps of 0.02 and 0.1h to 0.3h in steps of 0.1. The numerical model was largely confirmed by the experimental results, but differences between the two may be due to shortcomings of the turbulence
modeling. It was noticed that flow losses generated by tip leakage flow can be reduced by imparting proper sidewall gap clearance. The off-design performance for best case of sidewall gap was investigated.

NOMENCLATURE

- \(a\) Axial spacing, \(mm\)
- \(t\) Pitch-wise spacing between blade rows, \(mm\)
- \(p\) Tangential spacing, \(mm\)
- \(l\) Chord length, \(mm\)
- \(b\) Blade span, \(mm\)
- \(g\) Sidewall gap distance, \(mm\)
- \(h\) distance between sidewall wall and midspan, \(mm\)
- \(\beta\) Flow angle, \degr\)
- \(V\) Flow velocity, \(m/s\)
- \(\lambda\) Blade Stagger angle, \degr\)
- \(\varphi\) Camber angle, \degr\)
- \(P_o\) Stagnation pressure, \(Pa\)
- \(\rho\) Density, \(kg/m^3\)
- \(i\) Incidence, \degr\)
- \(\omega_c\) Stag. Pressure Loss coefficient, \(\zeta\) Dimensionless wake loss coefficient

ABBREVIATIONS

- AO Axial overlap
- DF Diffusion Factor
- D Lie’s Diffusion Number
- LE Leading edge
- PP Percent Pitch
- PS Pressure surface
- SS Suction surface
- TE Trailing edge

REFERENCES


