

Optimizing Pressure Rise in Transonic Axial Compressor Stage Using Tandem Rotors

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Abstract—

Axial flow compressors play a crucial role in various engineering applications, particularly in aerospace and industrial power generation. Their efficiency and performance directly impact system reliability, making continuous advancements in compressor blade design essential. This study focuses on the comparative aerodynamic analysis of single and tandem rotor blade configurations in a transonic axial flow compressor using Computational Fluid Dynamics (CFD) simulations.

The primary objective is to assess how tandem rotor configurations influence pressure rise, flow uniformity, and overall compressor efficiency compared to traditional single rotor designs. The tandem rotor arrangement, which incorporates two sequential blades within a single stage, is hypothesized to reduce flow separation, minimize aerodynamic losses, and improve pressure recovery. Through high-fidelity 2D CFD simulations, comparison of total pressure ratios of single and tandem rotor configurations were done.

The results indicate that tandem rotor configurations exhibit a notable improvement in total pressure rise and efficiency, demonstrating their potential in enhancing compressor performance. Additionally, the study explores optimal inter-blade spacing and stagger angles

to further refine tandem blade effectiveness. While challenges in design complexity and manufacturing exist, ongoing advancements in CFD modelling and materials science are paving the way for practical implementation of tandem rotor technology.

This research contributes to the development of more energy-efficient and high-performance axial compressors, addressing the growing need for improved aerodynamic efficiency and operational stability in modern turbo machinery applications.

Keywords—*Axial flow compressors, transonic, Tandem rotors,*

CFD (Computational Fluid Dynamics)

I. INTRODUCTION

Axial flow compressors are crucial in engineering applications, particularly in gas turbines, aircraft engines, and industrial sectors. Their operational effectiveness directly influences system efficiency, making design improvements essential. The performance of an axial flow compressor depends on the efficiency of the rotor blades in transferring kinetic energy to the air. Conventional axial compressors use single rotor blade configurations due to their simplicity and energy conversion

mechanisms. However, these can limit efficiency under specific operating conditions. Tandem rotor blade designs, which involve placing two rotor blades sequentially within a single stage, improve aerodynamic performance. This enhances flow continuity, minimizes turbulence-induced losses, and allows for better pressure restoration. The advancement of computational technologies, such as Computational Fluid Dynamics (CFD), has revolutionized compressor aerodynamics study. This study aims to conduct a comprehensive aerodynamic analysis of single and tandem rotor blade configurations in Transonic axial flow compressors, evaluating the performance characteristics of both designs and determining potential advantages offered by tandem blade arrangements over conventional single rotors.

II. OBJECTIVE

This study aims to analyse single and tandem rotor blade stages in Transonic axial flow compressors using computational fluid dynamics (CFD). The research focuses on restoring pressure levels, flow uniformity, and overall compressor efficiency. The study includes developing computational models, performance analysis, flow characteristics investigation, optimization strategies, comparison with experimental data, and visualization and interpretation of results. The findings can be applied to Transonic axial compressors in aerospace, HVAC systems, and turbo-machinery industries, identifying potential efficiency gains. The study's findings can be applied to various industries, including aerospace, HVAC systems, and turbo-machinery.

III. LITERATURE REVIEW

Our literature survey explored various studies on tandem rotor configurations, pressure rise improvements, and aerodynamic efficiency in axial compressors. Key references that shaped our design and analysis are categorized below.

A. Design

[1] Mohamed Mohsen Ahmed et al. analyzed tandem rotor blades in transonic axial compressors, reporting a **17% increase in total pressure ratio** and improved efficiency, guiding our rotor geometry and flow turning optimization.

[2] Baojie Liu et al. confirmed that tandem blades **increase stall margins from 16.9% to 22.3%**, validating our blade stagger and spacing approach for transonic stages.

[3] Bhaskar Roy and Srivatsava V. Puranam introduced a **part-span tandem design**, balancing pressure rise and

aerodynamic losses, influencing our rotor arrangement strategy.

[4] Lakshya Kumar and Dilipkumar B Alone emphasized **structured meshing (ANSYS Turbogrid) and k- ω SST turbulence modeling**, refining our meshing and numerical accuracy.

B. Analysis

[5] Jiajia Ji et al. introduced a **3D transient model for stall and surge prediction**, aiding our flow stability assessment.

[6] Srinivas G et al. studied **shockwave interactions and turbulence effects**, guiding our shock mitigation and optimization strategies.

[7] Rajadurai M et al. compared **single and tandem rotors**, showing improved pressure distribution and reduced total pressure loss, supporting our aerodynamic loading analysis.

IV. METHODOLOGY

• Literature Review and Background Study:

This study reviewed literature on axial flow compressors, tandem rotor configurations, and computational methods, focusing on fluid flow governing equations, performance differences, pressure rise, efficiency, and loss mechanisms.

• Blade Profile Selection and CAD Model Development:

Blade profiles for single and tandem rotor stages designed using NACA airfoil series.

- Tandem rotors configured with optimized stagger angles and axial spacing to enhance flow diffusion and reduce pressure gradients.

- Blade geometries modeled in a parametric design environment for easy parameter modification.

- Geometries exported in STEP/IGES formats for CFD simulation software.

- Tandem rotor configuration tested at multiple pitch angles to determine impact on velocity distribution and pressure levels.

• Structured Grid Development:

- A detailed meshing approach was used to improve grid resolution in high flow gradient areas, while a boundary layer mesh was created to resolve near-wall turbulence effects.

• Simulation Setup for Compressor Operation

- Inlet and Outlet Boundary Condition: Supersonic inflow condition applied at inlet with Mach number of 1.4 for transonic flow simulation.
- Wall Conditions: No-slip boundary condition applied on all solid surfaces for accurate modeling of wall shear stress and boundary layer effects.
- Turbulence Modeling: k- ω SST turbulence model selected for effective prediction of flow separation and shockwave interactions in transonic flow regimes.

Blade Airfoil Series: NACA 65a006

Single Blade – Chord Length: 100mm

Tandem Blade – Chord Length (each): 50mm

Axial Pitch: 0%

Percent Pitch: 5%

Pitch Angle of Rotor Blades: 50 , 45 and 55 degrees

Domain: 400mm x 800mm

• CFD Simulation and Solver Settings:

The simulation used a steady-state pressure-based solver, RANS equations, second-order upwind schemes, and ANSYS Fluent to ensure stability and accuracy in turbomachinery applications.

• Flow Analysis and Performance Evaluation in Transonic Axial Compressor Stage Using Tandem Rotors

- Analysis of CFD simulations using velocity contours, pressure distributions, and aerodynamic performance parameters.
- Tandem rotor configuration showed more uniform velocity distribution than single rotor stage.
- Single rotor experienced greater velocity losses at higher pitch angles (55°).
- Tandem rotor at 50° pitch angle showed optimized flow diffusion, improving aerodynamic efficiency.
- Tandem rotor stage showed higher pressure rise than single rotor stage, indicating superior performance in controlling adverse pressure gradients.
- Pressure Rise and Loss Estimations computed using the formula: $\text{Pressure Rise} = P_{out} - P_{in} / P_{in}$.
- Tandem rotor at 50° pitch showed highest pressure level restoration efficiency.

• Turbomachinery Results Validation and Optimization Recommendations

- Simulation findings compared with experimental and numerical data.
- Trends in pressure rise, velocity distribution, and loss mechanisms aligned with established principles.

- Analysis of velocity triangles revealed tandem rotors improve realignment of flow direction, reducing incidence losses and increasing work efficiency.
- Lower relative velocity at rotor exit in tandem configurations enhances performance.
- Recommended design optimizations: fine-tuning pitch angle, increasing blade aspect ratio, and using unsteady simulations for better compressor behavior prediction.

V. NUMERICAL ANALYSIS

The Numerical Analysis section of our project focuses on Computational Fluid Dynamics (CFD) simulations to evaluate the performance of single and tandem rotor stages in a transonic axial compressor. The study examines velocity and pressure contours for different blade pitch angles (45°, 50°, and 55°), assessing their impact on pressure rise, flow uniformity, and aerodynamic efficiency.

(i) Dimensions (Geometric Specifications)

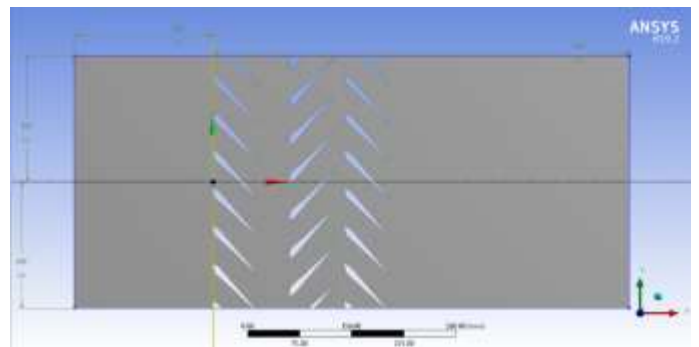


Fig. 1. Model of Single blade rotor-stator stage at 50 degree pitch angle

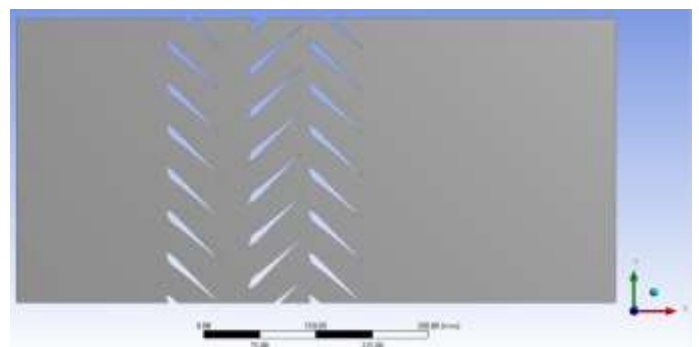


Fig. 2. Model of Single blade rotor-stator stage at 45 degree pitch angle

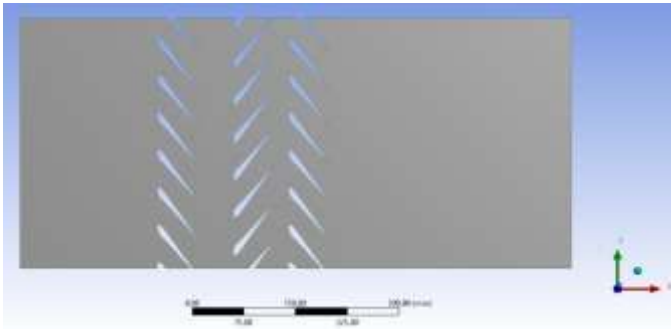


Fig. 3. Model of Single blade rotor-stator stage at 55 degree pitch angle

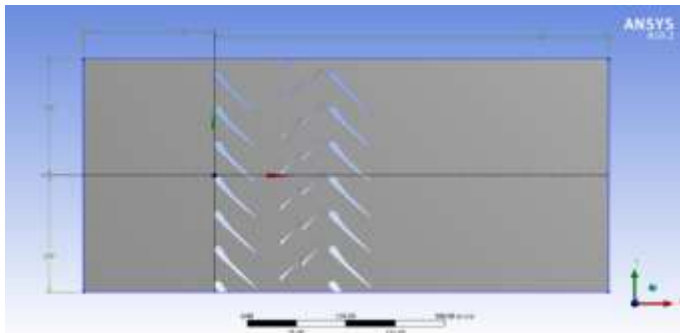


Fig. 4. Model of Tandem blade rotor-stator stage at 50 degree pitch angle

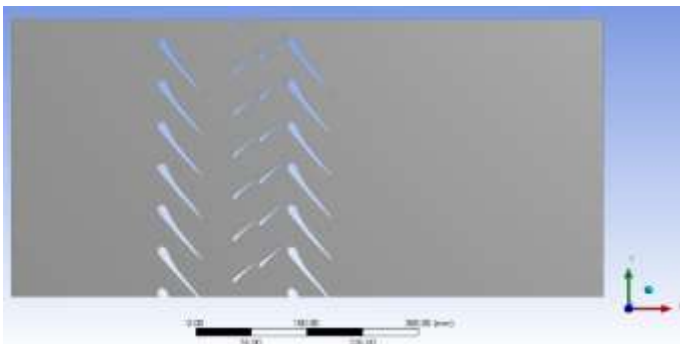


Fig. 5. Model of Tandem blade rotor-stator stage at 45 degree pitch angle

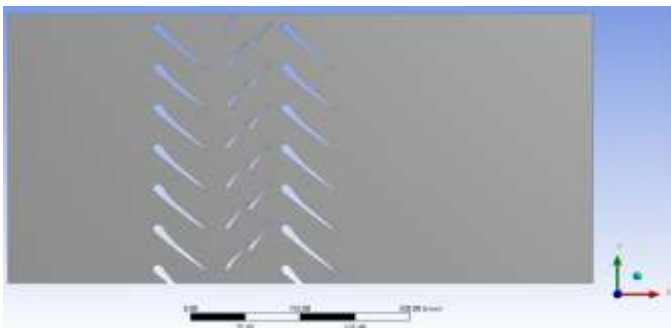


Fig. 6. Model of Tandem blade rotor-stator stage at 55 degree pitch angle

(ii) Boundary Conditions

To replicate realistic operating conditions of a transonic axial compressor, the following boundary conditions were applied:

Inlet:

- Velocity Inlet Condition
- Velocity Magnitude: 100 m/s (for Mach 0.8 at standard atmospheric conditions)
- Total Temperature: 288 K
- Turbulence Intensity: 5%

Outlet:

- Static Pressure Outlet Condition
- Pressure: 101325 Pa (1 atm, ambient pressure)
- Backflow Turbulence Intensity: 5%

Wall Boundary Conditions:

- No-slip condition for blade and casing surfaces
- Standard roughness assumption for metallic compressor walls

Turbulence Model:

- $k-\omega$ SST (Shear Stress Transport) model was chosen for its ability to capture boundary layer effects, predict shockwave interactions and flow separation in transonic regimes.

VI SIMULATION RESULTS

Velocity and Pressure Contours

- Tandem rotors showed a more uniform velocity distribution compared to single rotors.
- Higher pitch angles (55°) led to increased flow separation in single rotors, while tandem rotors at 50° pitch exhibited optimal flow diffusion and aerodynamic efficiency.

Tandem rotor stage demonstrated a higher pressure rise than the single rotor, confirming its effectiveness in controlling adverse pressure gradients.

- The 50° pitch angle configuration in tandem rotors showed the most balanced pressure recovery and minimal losses.

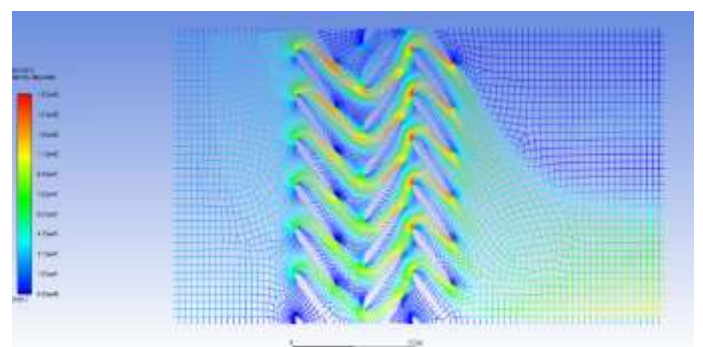


Fig. 7. Velocity Contour for Single Blade Rotor-Stator Stage at Pitch angle 50 degrees

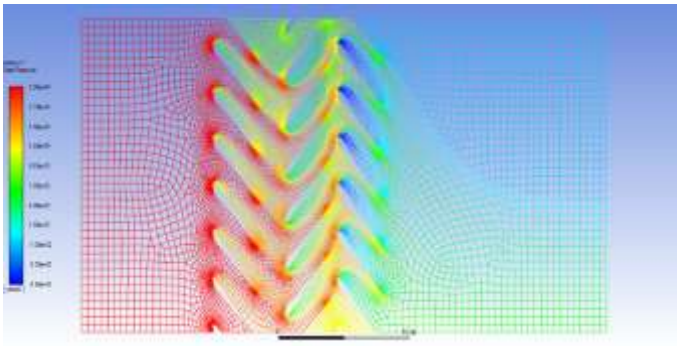


Fig. 8. Pressure Contour for Single Blade Rotor-Stator Stage at Pitch angle 50 degrees

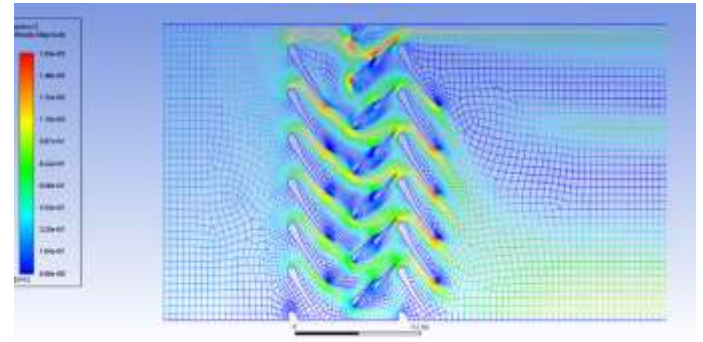


Fig. 12. Velocity Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 45 degrees

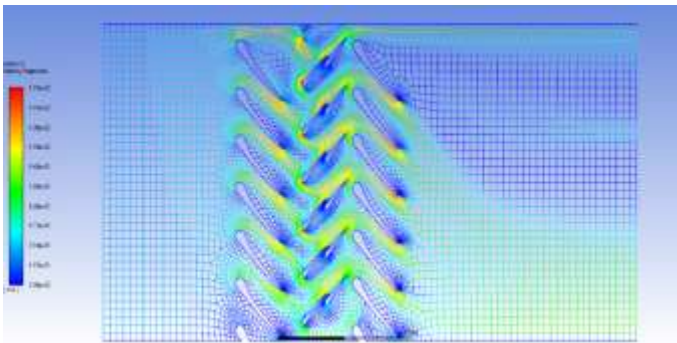


Fig. 9. Velocity Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 50 degrees

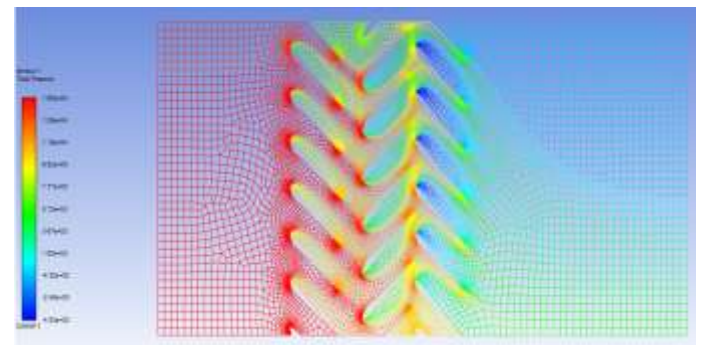


Fig. 13. Pressure Contour for Single Blade Rotor-Stator Stage at Pitch angle 45 degrees

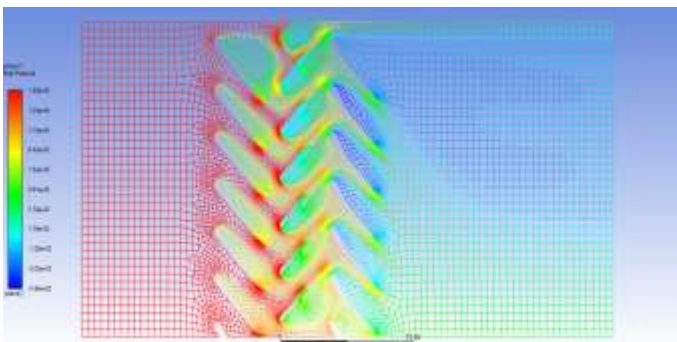


Fig. 10. Pressure Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 50 degrees

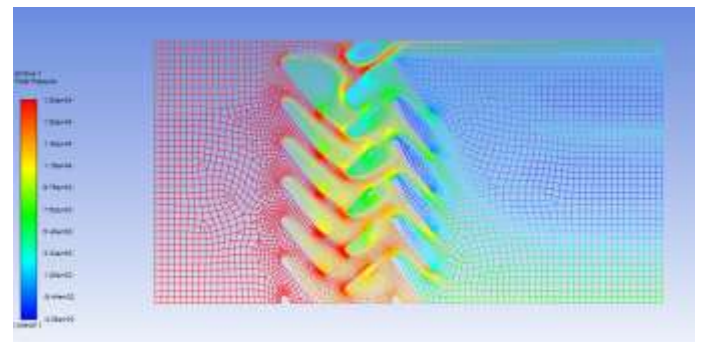


Fig. 14. Pressure Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 45 degrees

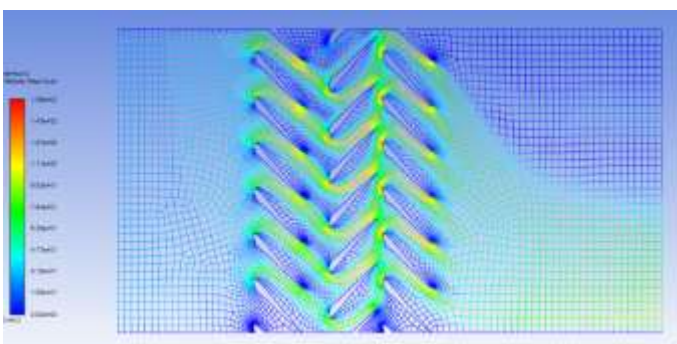


Fig. 11. Velocity Contour for Single Blade Rotor-Stator Stage at Pitch angle 45 degrees

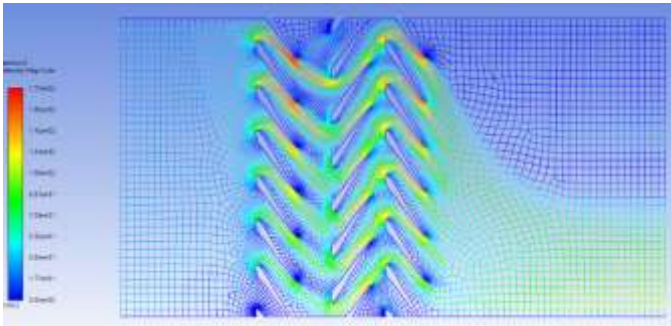


Fig. 15. Velocity Contour for Single Blade Rotor-Stator Stage at Pitch angle 55 degrees

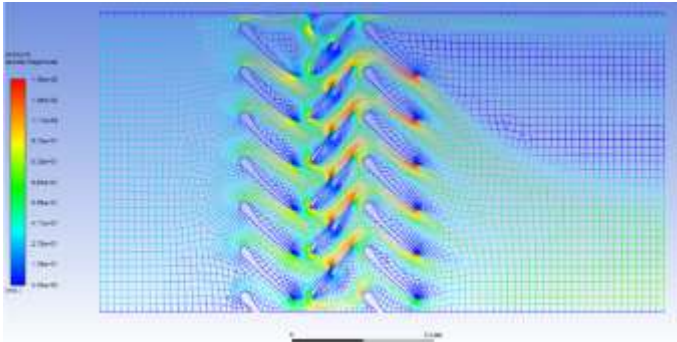


Fig. 16. Velocity Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 55 degrees

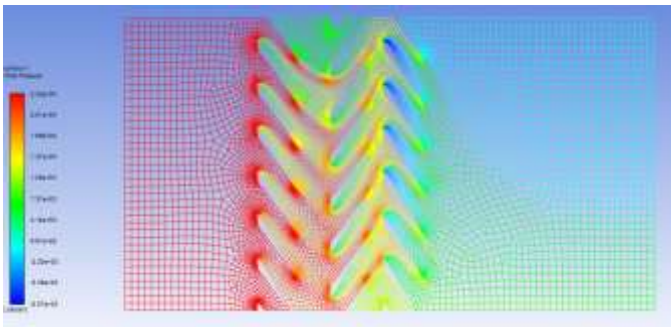


Fig. 17. Pressure Contour for Single Blade Rotor-Stator Stage at Pitch angle 55 degrees

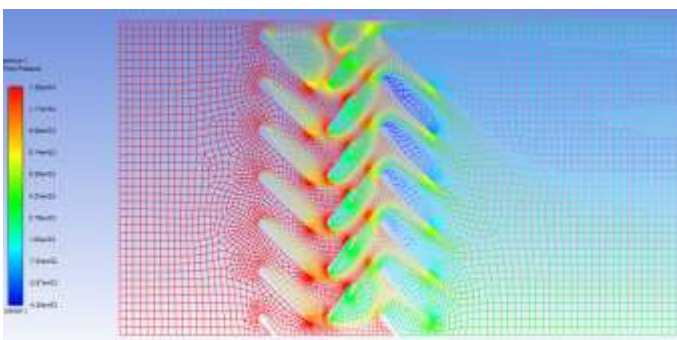


Fig. 18. Pressure Contour for Tandem Blade Rotor-Stator Stage at Pitch angle 55 degrees

VII RESULTS AND DISCUSSIONS

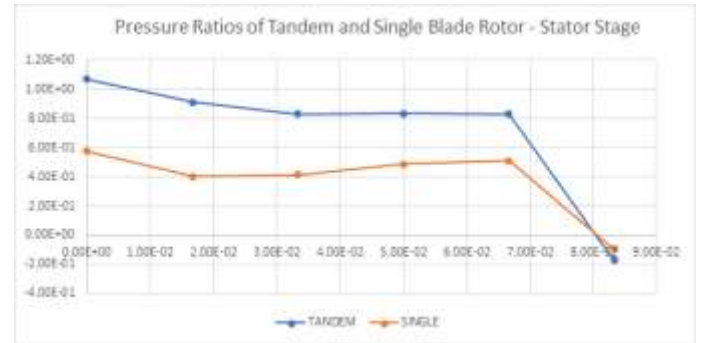


Fig. 19. Plot of Total Pressure Ratios for Tandem and Single Blade Rotor- Stator stage

Table. 1. Total Pressure Ratios

Case	Total Pressure Ratio
Single Rotor (EXP) (Rotor 37)	2.016
Single Rotor (CFD)	2.127
Tandem Rotor (CFD)	2.495
Percentage Increase	17.3%

The tandem rotor exhibits a **17.3%** improvement in total pressure ratio over the conventional single rotor. This substantial enhancement supports the hypothesis that tandem blade configurations enable better compression efficiency while mitigating aerodynamic losses. CFD simulations highlight that tandem rotors outperform single rotors in pressure rise, efficiency, and stall margin within a transonic axial compressor.

- Velocity Contours: Single rotors exhibit higher velocity gradients and flow separation, while tandem rotors ensure smoother velocity reduction and less turbulence, with 50° pitch offering the best balance.
- Pressure Contours: Tandem rotors achieve higher pressure recovery, with 50° pitch showing optimal diffusion. At 55° pitch, increased aerodynamic losses were observed.
- Stall Margin & Efficiency: Tandem rotors minimize flow detachment, improving stall resistance and efficiency, with 50° pitch providing the best compromise.
- Velocity Triangle: Tandem rotors reduce relative exit velocity, ensuring better energy conversion and lower incidence losses.

VIII CONCLUSION

This study demonstrates that tandem rotor configurations significantly enhance pressure recovery, efficiency, and stall margin compared to single rotor designs in a transonic axial compressor. The CFD analysis confirms that 50° pitch tandem rotors provide the optimal balance between flow diffusion, pressure rise, and aerodynamic stability.

Key findings include:

- Smoother velocity reduction and reduced turbulence in tandem rotors.
- Higher pressure recovery and controlled shockwave interactions at 50° pitch.
- Improved stall resistance due to better aerodynamic loading distribution.
- Lower aerodynamic losses compared to high pitch angles like 55°

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