

Aerodynamic Design, Analysis and Optimization of Transonic Axial Compressor Blade with the Combination of NACA 65, Double Circular Arc (DCA) and Multiple Circular Arc Airfoil (MCA)

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Abstract: This paper deals with the Design, Analysis and optimizing a single stage axial transonic compressor. The recent trend to increase the capacity of modern heavy duty gas turbine compressors requires high performance transonic rotors with increasing tip Mach numbers. When developing a transonic compressor, an important subject is to design an airfoil shape which gives good performance in transonic flow region. NACA-65 aerofoil is best suitable for subsonic regime. While Multi Circular Arc (MCA) airfoil design and DCA aerofoil design are suitable in transonic regimes. Therefore an attempt is made to design and study the aerodynamic characteristics of a transonic compressor stage with NACA-65, MCA and DCA aerofoil combinations. CF-turbo is used to design the aerofoil and computational analysis is carried out in Ansys CFX. The air mass flow rate is considered of 5kg/sec at 10,000 RPM, blade tip speed 454 m/sec rotor hub to tip speed ratio=0.7. Overall performance of all the combinations were inlet total pr =1 atm. Comparatively good having the isentropic efficiency ranging from 77.9 % to 84.8% having MCA-DCA combinations the lowest & NACA-MCA being the highest but overall pr.ratio is observed to be 1.244 in MCA-MCA and MCA-DCA combinations while NACA-MCA is only 1.23. Flow coefficient and head coefficient being the highest in MCA-MCA & MCA-DCA combinations of 24.87 and 13.62 respectively. Blade loading coefficient is observed as -8.7 and it is nearly flat over the upper surface of rotor as well as stator in MCA-DCA combinations, while NACA-MCA having uneven behavior of -7.86. Thereby through my study i conclude that NACA-65 aerofoil with MCA for the rotor and NACA-65 with DCA for stator as the best combination among all the different cases studied in this attempt.

Keywords: Turbomachinery, Compressor, Blade Optimization, Blade Sweep, NACA ,CFTurbo,
DCA, MCA

1. Introduction To Axial Flow Compressors

1.1 Introduction

Compressors are the machines that are deployed in discharging the fluid at higher pressure than their intake. These are classified into two subcategories: Positive Displacement compressors that increases the fluid pressure by reducing its volume and Rotor-Dynamic compressors that achieves its objectives through a series of rotors and stators tandem arrangement. Rotor-Dynamics Compressors can be further classified into axial flow compressors and centrifugal compressors. In Centrifugal flow compressors air inlet flow is parallel to the shaft axis and exit flow is radial. Rotating impellers/vanes induce kinetic energy to the fluid and stationary involute passage converts the kinetic energy to pressure. While in axial flow compressors air flows parallel to the axis of the shaft throughout from inlet to exit. Rotating blades known as rotor blades impart the kinetic energy and stationary blades known as stator blades converts the available energy into pressure energy.^[1]



Figure 1.1: General Electric J85 Cutaway with Axial Flow Compressor^[2]

1.2 Construction and Working of Axial Flow Compressor

A typical axial flow compressor sucks the air axially and increases its pressure energy level by passing air through the two main elements rotor and stator. Each consecutive pair of rotor and stator is referred as a stage. Rotor is the rotating element having blades fixed on the spindle or drum. These blades, turning at high speed, takes the air at the inlet and impel torque to the air along the axial path similar to propeller because of its airfoil shape and pitch angle. Now the stator is the stationary blades mounted on the stator casing slows down the air velocity and convert the circumferential component of air into pressure. Stator blades are arranged to form the diverging passage to act as the diffusers at every stage, partially converting kinetic energy to pressure. Pressure ratio increases with the number of stages. Each stage has the ability of achieving the compression ratio of approximately 1.25:1. Most aircraft engines consists of up to 16 stages in order to fulfill higher pressure ratio requirements.

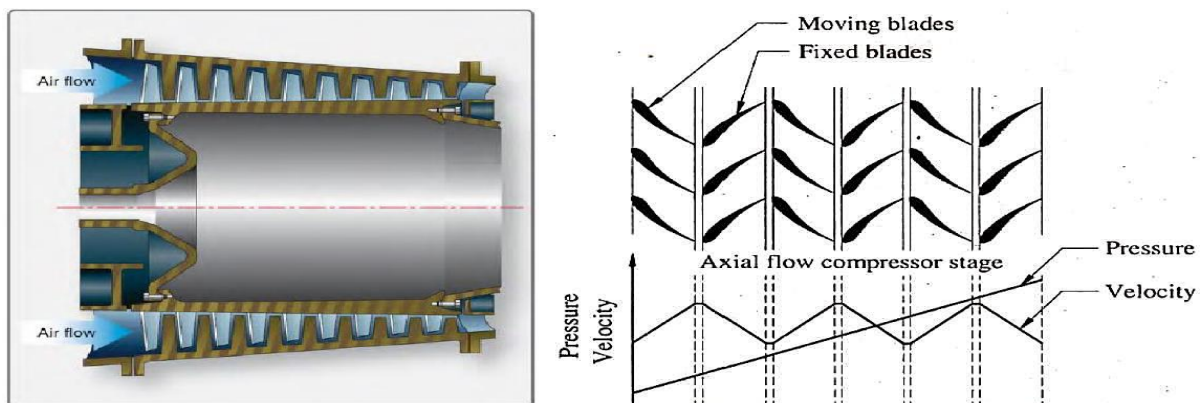


Figure 1.2: Velocity and Pressure variation over rotor and stator in axial flow compressor^[2]

An extra row of fixed vanes called inlet guide vanes are placed at the inlet of the compressor to guide the air to the first row of rotating blades as shown in figure 1.2. These compressors are highly efficient and are capable of handling large flow rates with respect to their size. They offer the most compact and light weight design for large flow rate applications. In every stage the gap between the rotor and stator must be as close as possible for efficient flow. Designing length of the blade with minimal tip clearance is a challenging task. The height of the blades is reduced over successive stages so as to compensate the reduction in fluid volume and contribute to rise in pressure. Thus the axial flow velocity is maintained constant throughout the compressor.^[1]

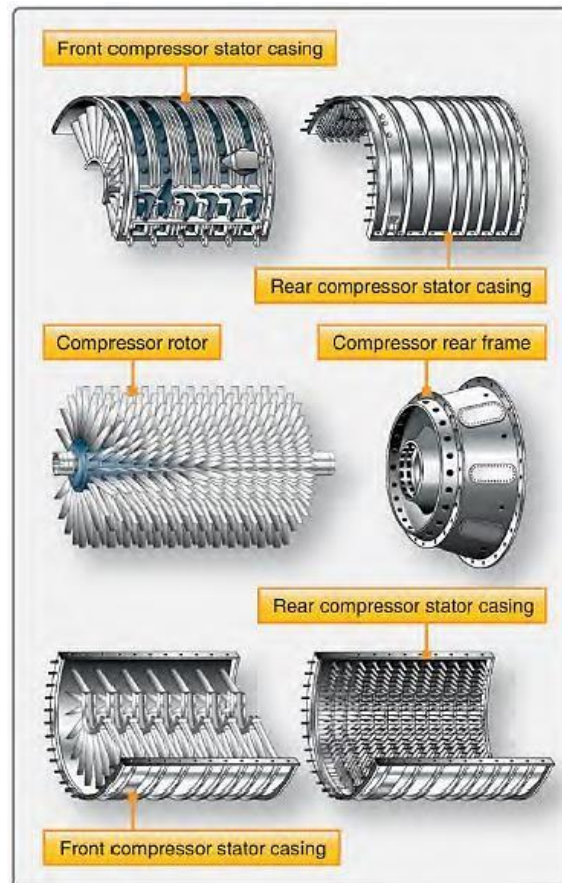


Figure 1.3: Various components in axial flow compressor^[2]

1.3 Advantages of Axial Flow Compressor

1. Small frontal area of the anterior lobe for a given airflow rate reduces the drag.
2. High ram efficiency can be achieved with a straight flow.
3. Highly efficient compared to centrifugal flow compressors.
4. Operable at large mass flow rates compared to positive displacement compressors.
5. Higher pressure ratios can be achieved by increasing the no. of stages with negligible losses.^[3]

1.4 Disadvantages of Axial Flow Compressor

1. Highly efficient only within the narrow rotational speed range.
2. Their complex design lead to manufacturing difficulties.
3. Expensive.
4. Higher power demands to initiate the compression process.
5. Pressure rise in single stage is low, so as to achieve higher pressure ratios multiple stages are required.
6. Relatively heavy, making its installation difficult.^[3]

1.5 Applications of Axial Flow Compressor

1. Most commonly used in aircraft turbojet engine.
2. Used in ship engines for higher speeds.
3. Used in high flow rate applications.
4. Used in industrial applications such as blast furnaces and nitric acid plants.
5. Fossil fuel power stations when the gas turbines are used to increase the station outputs above its normal peak loads.^[3]

1.6 Losses in Axial Flow Compressor

Losses experienced in axial flow compressors are grouped under the following types: ^[1]

1. **Profile loss:** arises due to the peculiarity of their blade aerofoil design. In other words, arises due to the boundary layer growth and its subsequent separation over the blade.
2. **Skin Friction loss:** also known as Annulus loss or viscous loss. This accounts up to 50% of the total losses. This arises due to axial growth of boundary layer.
3. **Secondary Flow loss:** arises due to the secondary flow occurrence in the passages formed between curved blades.
4. **Tip Leakage loss:** arises due to the gap between the rotor blades and the casing.

1.7 Comparison between Centrifugal Compressor and Axial Flow Compressor

Table 1.1: Comparison between centrifugal compressor and axial flow compressor ^[3]

Sl. No.	Parameters	Centrifugal Compressor	Axial Flow Compressor
1	Direction of flow	Radial flow	Axial flow (parallel to the axis of rotation)
2	Pressure ratio per stage	4.5:1	1.25:1
3	Isentropic efficiency	80-82%	86-88%
4	Frontal area	Large	Small
	Mass flow rates	Low	High
5	Operation	Wide range of operational speeds between choking and surging limits. Part load performance is better.	Narrow range of operational speeds between choking and surging limits. Part load performance is poor.
6	Starting power	Needs low starting torque	Needs higher starting torque.
7	Deposits	Almost insensitive to deposit accumulation on the blade surfaces.	Sensitive to deposit accumulation on the blade surfaces.
8	Construction complexity and cost	Simple and relatively cheap.	Complex and costly
9	Suitability for multistage	Slightly difficult	Suitable for multi staging
10	Applications	Supercharger in IC engine, air conditioner, low pressure refrigerators.	Jet engines, large marine gas turbine engines.

2. Objectives Of The Project Work

2.1 Objectives

1. To design and analyze computationally a single stage axial transonic axial compressor with NACA 65 airfoil.
2. To optimize the performance of the rotor and stator blades of the designed transonic axial flow compressor with the combinations of NACA 65, Double Circular Arc (DCA) and Multiple Circular Arc Airfoil (MCA) airfoils.

2.2 Scope of the project work

1. The recent trend is to increase the capacity of modern heavy duty gas turbine compressors, it requires high performance transonic rotors with increasing tip Mach numbers.
2. NACA 65 airfoil is suitable for subsonic flow regime, while Double Circular Arc Airfoil is compatible to High Subsonic and Transonic Regime and Multiple Circular Arc Airfoil is compatible to Transonic and Low Supersonic Regime.
3. Combinations of these three different profiles will give rise to a new optimal profile suitable for transonic regime.
4. It is well known that the highly three-dimensional flow in those rotors, is associated with a radially swept shock wave. New sophisticated design approaches based on 3-D CFD therefore needed to maximize their performance.

3. Methodology

3.1 Work Flow

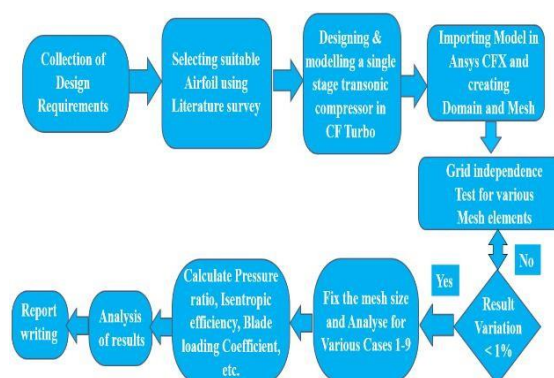


Figure 3.1: Workflow adopted in the present research work

3.2 Methodology Adopted

Methodology followed in the present research work in three stages are explained below:

Stage-1:

Preliminary transonic axial compressor is designed in CF Turbo using NACA 65 airfoil for both rotor and stator. CFD analysis is carried out in Ansys CFX. Grid independence test is carried out for various mesh element size.

Stage-2:

Morphed NACA 65 airfoil with Double Circular Arc (DCA) and Multiple Circular Arc (MCA) to obtain new airfoil profiles.

Stage 3:

CFD analysis is carried out in Ansys CFX for all the nine different combinations for rotor and stator as stated below.

Table 3.1: Different combinations studied in the present research work

CASE No.	Rotor	Stator
1	NACA	NACA
2	NACA	MCA
3	NACA	DCA
4	MCA	MCA
5	MCA	NACA
6	MCA	DCA
7	DCA	DCA
8	DCA	NACA
9	DCA	MCA

3.3 Blade Geometry Details

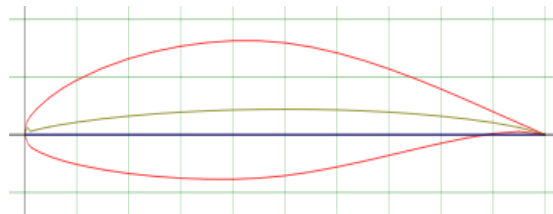


Figure 3.2:NACA 65 Airfoil

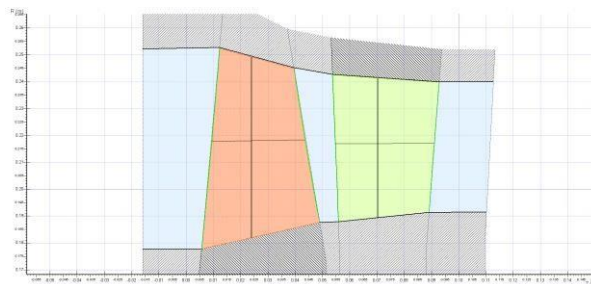


Figure 3.3:Meridional view (R v/s Z) of single stage transonic axial compressor, Case-1

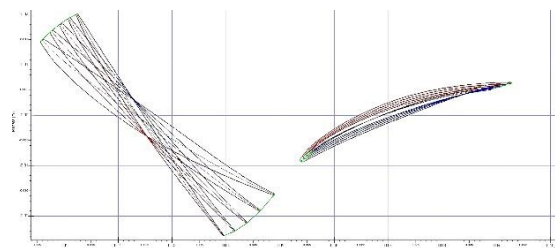


Figure 3.4:Meridional view (R_0 v/s Z) of single stage transonic axial compressor, Case-1

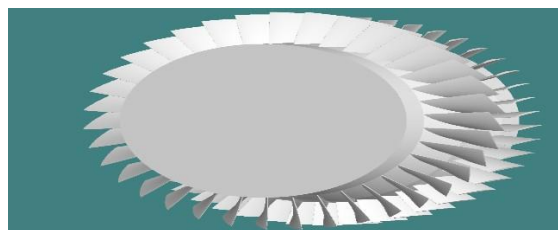


Figure 3.5:3D CAD model of single stage transonic axial compressor in CF Turbo

Particular	Rotor (36 Blades)			Stator (46 Blades)		
	Hub	Mean	Tip	Hub	Mean	Tip
Solidity	1.634	1.413	1.188	1.452	1.375	1.330
Pitch/Chord	0.612	0.708	0.842	0.689	0.727	0.752
Throat/Pitch	0.644	0.551	0.467	0.783	0.761	0.738
Inlet Angle (deg)	- 49.645	- 57.636	- 64.947	42.520	44.669	46.818
Exit Angle (deg)	- 23.284	- 43.319	- 53.820	4.863	3.209	1.554
Stagger Angle (deg)	- 36.495	- 50.486	- 59.384	23.706	23.917	24.142
Radius at LE (m)	0.178	0.218	0.252	0.188	0.217	0.243
Radius at TE (m)	0.188	0.218	0.245	0.191	0.217	0.240

Table 3.2: Blade geometry details of rotor and stator for Case-1 in CF Turbo

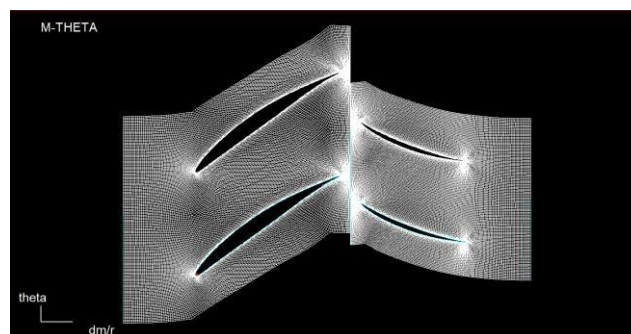


Figure 3.6: Meshed Model 2D view of the compressor stage in Ansys CFX

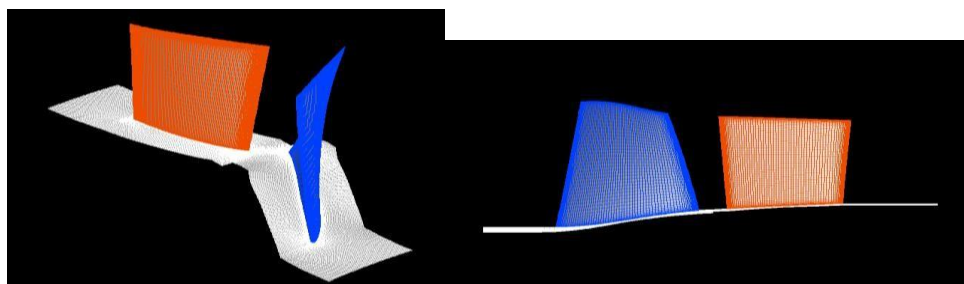


Figure 3.7: Meshed Model 3D view of the compressor stage in Ansys CFX

Grid topology adopted in the present study is HOH grid as shown in figure 4.6 and figure 4.7, total number of elements in the study is 1.6 million.

3.4 Computational Setup and Boundary Conditions

Analysis Type	Steady State
Solver	3D Reynolds-Averaged Navier-Stokes - (3D RANS)
Turbulence Model	Shear Stress Transport Turbulence Model - (SST)
Turbulence Intensity	1%
Turbulent length scale	1.5mm
Outlet Condition	Static Pressure: 110 kPa
Interface	Rotor exit – Stator inlet : Mixing zone
Solver Control	High resolution advection scheme

Table 3.3: Numerical Setup details for CFD analysis in Ansys CFX

Table 3.4: Boundary conditions applied in CFD analysis in Ansys CFX

Boundary Conditions	
Rotating Domain Speed	10000 RPM
Blade Tip Speed (m/s)	454
Inlet Total pressure	101.325 KPa
Inlet Total Temperature	288.15 K
Rotor Hub to Tip Ratio	0.700
Design Tip Clearance	0.2% of Span
Stator Hub to Tip Ratio	0.700

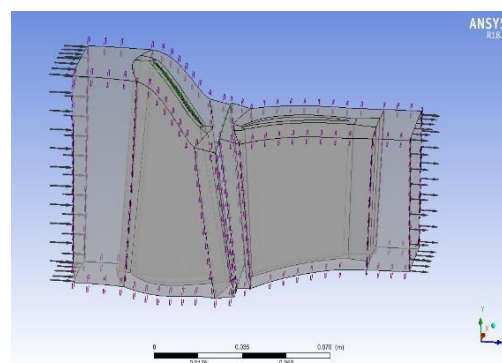


Figure 3.8: Boundary Conditions applied over the compressor stage in Ansys CFX

4. Results And Discussion

Computational results obtained, variation of Mach number contour and variation of static pressure contours over the blade profile and velocity streamlines in the passage between the blades are reported case wise here in this chapter. Discussions over the results obtained is made at the end of this chapter using comparison graphs of blade loading, total pressure ratio, total temperature ratio, flow coefficient, head coefficient, blade loading coefficient and isentropic efficiency of the stage.

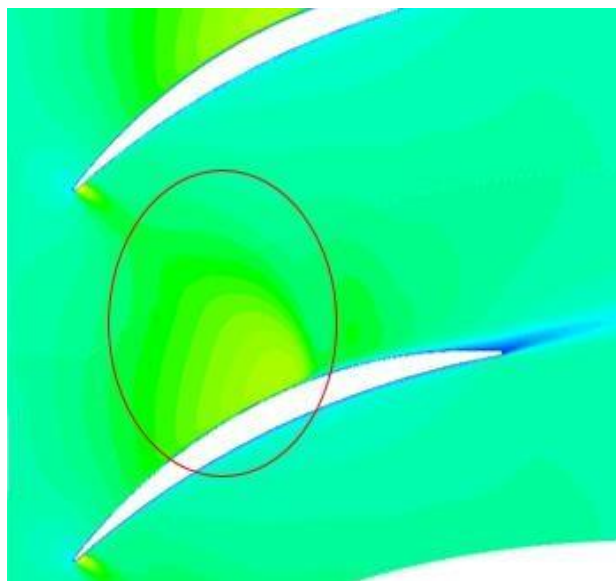


Figure 4.1 :Obliqueshock formation over DCA stator blade in Case 6 – (MCA-DCA)

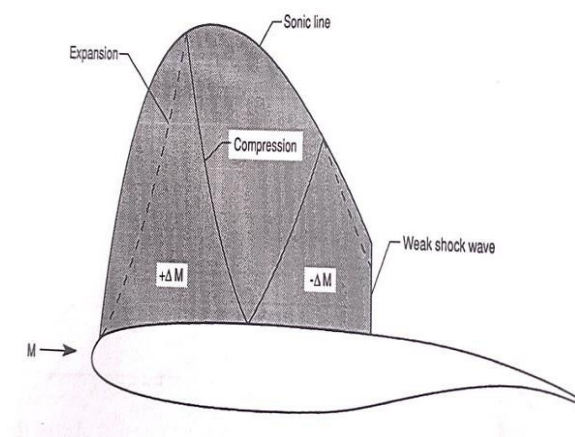


Figure 4.2 :Pressure Profile over Super Critical Airfoils^[3]

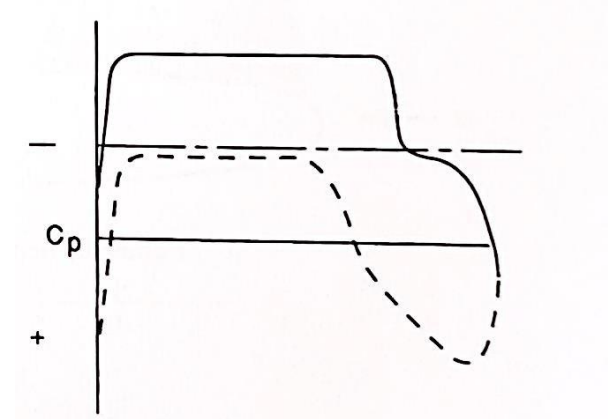


Figure 4.3 :Coefficient of pressure variation over super critical airfoils across the chord length.^[3]

4.1 Blade Pressure Loading Chart over Rotor and Stator Blades of all 9 Cases

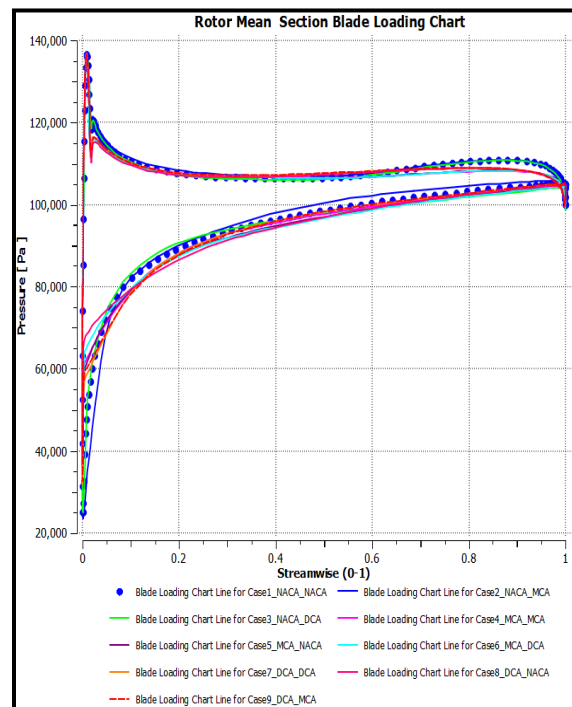


Figure 4.4: Blade pressure loading chart over rotor blades of all 9 cases.

Blade pressure loading distribution over the rotor blades in all the cases examined is shown above in figure 4.4. As we have discussed earlier the blade pressure loading should be uniform throughout the maximum extent of the blade chord length/surface. MCA and DCA rotor blades are showing comparatively flat results over the blade's upper surface, while the pressure loading is slightly increased in NACA 65 rotor blades near to the trailing edge.

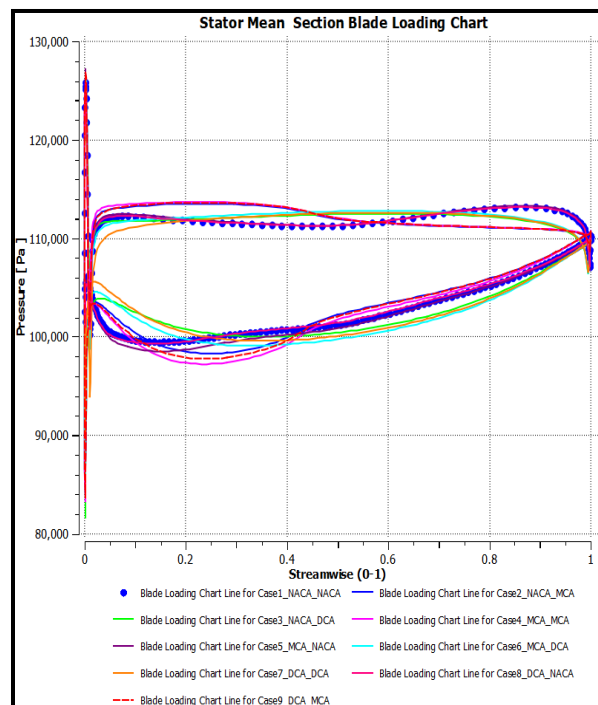


Figure 4.5 : Blade pressure loading chart over stator blades of all 9 cases.

Blade pressure loading distribution over the stator blades in all the cases examined is shown above in figure 4.5. As we have discussed in figure 4.4 over the rotor blades, MCA and DCA stator blades are also showing comparatively flat results over the blade's upper surface, while the pressure loading is slightly increased in NACA 65 stator blades show a dip in the pressure loading at its mid chord and again it raises near the trailing edge.

In comparison between MCA stator blade and DCA stator blade. DCA is showing good results as the pressure loading is completely flat, while in MCA blades there is a slight rise in the pressure loads in the mid chord of the blade.

4.2 Comparison of Total Pressure Ratio obtained in all 9 Cases

CASE	Airfoil Combination	Total Pressure Ratio
1	NACA_NACA	1.24058
2	NACA_MCA	1.23924
3	NACA_DCA	1.23923
4	MCA_MCA	1.24461
5	MCA_NACA	1.24432
6	MCA_DCA	1.24322
7	DCA_DCA	1.23566
8	DCA_NACA	1.23601
9	DCA_MCA	1.23639

Table 4.1: Tabulated values of Total Pressure Ratio obtained in all 9 Cases.

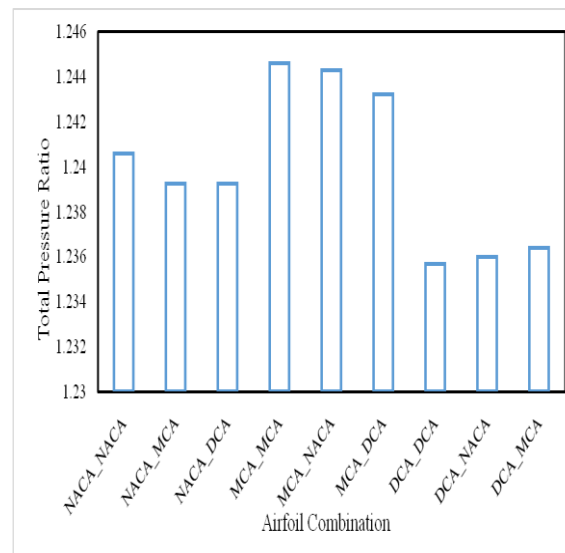


Figure 4.6 : Bar Chart in comparison of Total Pressure Ratio obtained in all 9 Cases

Total pressure ratio obtained in all 9 cases are tabulated in table 4.1 and comparison is made in figure 4.6. Case 4, 5 and 6 are showing higher pressure ratios of about 1.24322 to 1.24461. Case 4 shows the highest total pressure ratio of 1.24461 and the least is observed in case 7 of 1.23566.

4.3 Comparison of Flow Coefficient in all 9 Cases

CASE	Airfoil Combination	Flow Coefficient
1	NACA_NACA	24.507
2	NACA_MCA	24.6495
3	NACA_DCA	24.5149
4	MCA_MCA	24.8714
5	MCA_NACA	24.6084
6	MCA_DCA	24.4005
7	DCA_DCA	24.0948
8	DCA_NACA	23.9279
9	DCA_MCA	24.1893

Table 4.2: Tabulated values of Flow Coefficient in all 9 Cases.

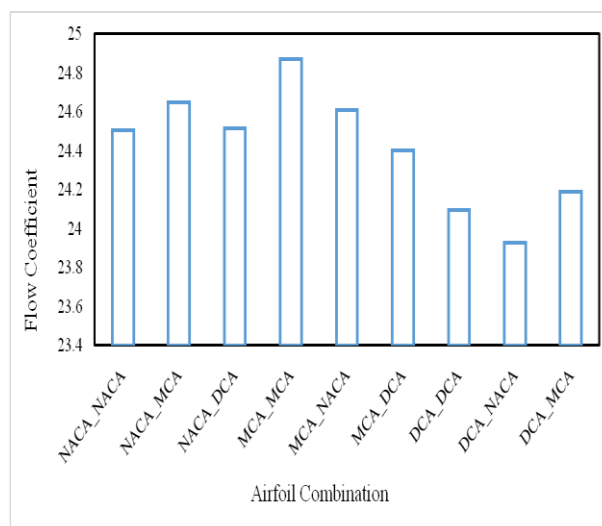


Figure 4.7 :Bar Chart in comparison of Flow Coefficient in all 9 Cases

Flow Coefficient in all 9 cases are tabulated in table 4.2 and comparison is made in figure 4.7 .Case 4, 5 and 6 are showing higher flow coefficient of about 24.8714 to 24.4005. Case 1, 2 and 3 are also resulting in flow coefficient of 24.507 to 24.649. Case 4 shows the highest flow coefficient of 24.8714 and the least is observed in case 8 of 23.9279.

4.4 Comparison of Blade Loading Coefficient in all 9 Cases

CASE	Airfoil Combination	Blade Loading Coefficient
1	NACA_NACA	-7.96385
2	NACA_MCA	-7.86814
3	NACA_DCA	-7.9467
4	MCA_MCA	-8.39066

5	MCA_NACA	-8.39502
6	MCA_DCA	-8.70122
7	DCA_DCA	-8.07832
8	DCA_NACA	-8.07604
9	DCA_MCA	-8.39215

Table 4.3 :Tabulated values of Blade Loading Coefficient in all 9 Cases.

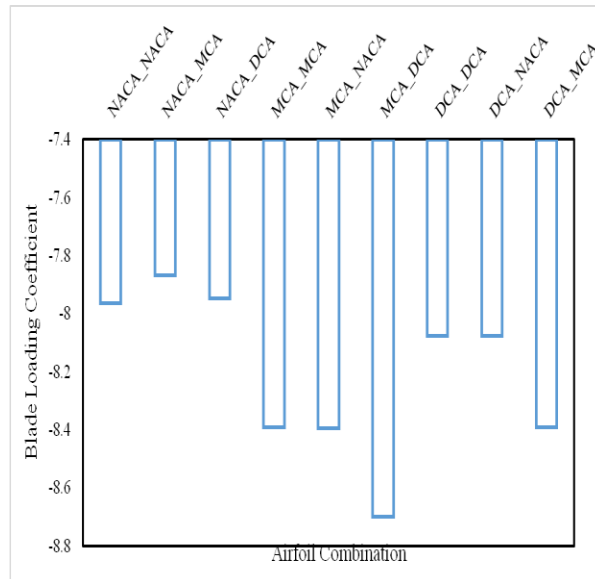


Figure 4.8 :Bar Chart in comparison of Blade Loading Coefficient in all 9 Cases

Blade Loading Coefficient in all 9 cases are tabulated in table 4.3 and comparison is made in figure 4.8. Case 4, 5 and 6 are showing lower blade loading coefficient of about -8.39066 to -8.70122. Case 6 shows the lowest blade loading coefficient of -8.39066 and the highest is observed in case 2 of -7.86814.

4.5 Comparison of Isentropic Efficiency in all 9 Cases

CASE	Airfoil Combination	Isentropic Efficiency
1	NACA_NACA	84.2
2	NACA_MCA	84.8
3	NACA_DCA	83.4
4	MCA_MCA	81.2
5	MCA_NACA	81.0
6	MCA_DCA	77.9
7	DCA_DCA	81.4
8	DCA_NACA	81.6
9	DCA_MCA	78.6

Table 4.4: Tabulated values of Isentropic Efficiency in all 9 Cases.

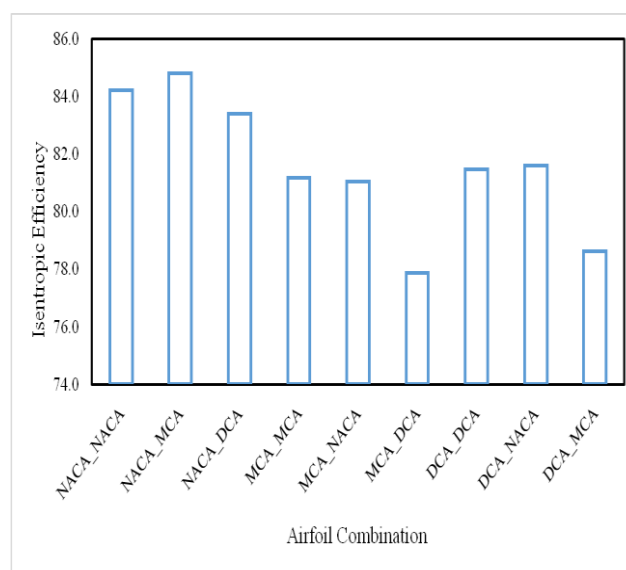


Figure 4.9 :Bar Chart in comparison of Isentropic Efficiency in all 9 Cases

Blade Loading Coefficient in all 9 cases are tabulated in table 4.4 and comparison is made in figure 4.9. Case 1, 2 and 3 are showing highest isentropic efficiency of about 84.2% to 83.4%. Case 6 shows the least isentropic efficiency of 77.9% and the highest among case 4, 5 and 6 is observed in case 4 of 81.2%.

5. Conclusion

Design and computational study of a transonic axial flow compressor stage consisting of combination in NACA 65, Double Circular Arc (DCA) and Multiple Circular Arc Airfoil (MCA) airfoil blades is has been carried out. The geometrical model of the compressor design was carried out using CFTurbo. Computational study is carried out in Ansys CFX. NACA 65 blades were used for both rotor and stator in the initial design of a single stage axial flow compressor. Steady state flow analysis was carried out at rotor speed of 10000 RPM with 5 kg/sec mass flow rate at 1 atm inlet pressure conditions. 3D RANS solver equations were solved using Shear Stress Transport (SST) model. High resolution advection scheme was considered for solver control. Grid dependence study was carried out to confirm that the results obtained are independent of the grid size variations. Nine different cases are considered for the study with the combinations of NACA 65, DCA and MCA profiles for rotor and stator. The behavior of the shock waves on the cascade blades is observed. Shock wave is observed when the free stream velocity reaches critical Mach number on the stator blades. The shock is stronger in the mid chord of the NACA 65 blade, shock wave is followed immediately by a decelerating flow to the trailing edge. MCA and DCA blade profiles give rise to weaker shocks. Elimination of flow acceleration over the upper surface of the blade was due to the reduced curvature over the mid chord region of the blade resulting in weaker shocks. Properties such as pressure, temperature, density experienced drastic changes downstream the shock wave. There is a small vortex flow observed at the tip of the stator blade. Overall pressure ratio per stage is observed to be achieved to 1.24. Among all cases, case 6 with MCA for rotor and DCA for stator gives relatively similar results of case 4 with MCA for rotor and stator. Isentropic efficiency of the MCA-DCA combinations is 77.9%, it is the lowest of all combinations, while the MCA-MCA combination is 81.2%. But the pressure loading graph shows that loading is uniformly distributed over DCA blades in stator than in MCA blades. Blade loading coefficient for MCA-DCA blade configuration is the lowest -8.70122. Though the NACA_NACA, NACA_MCA and NACA_DCA combinations results in higher isentropic efficiency, stands inferior in comparison with other cases in other evaluating parameters such as flow coefficient, blade pressure loading coefficient and total pressure ratio and total temperature ratios. Hence through my computational analysis over the results obtained here I come to conclusion that the morphed NACA 65 series airfoil with MCA-DCA combination for rotor-stator gives an improved performance characteristics for the parameters considered for the study.

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