Numerical Analysis of axial flow compressor

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Abstract: **Axial compressor is prime device in concern with gas turbine engines. This type of axial compressors used in aircraft, helicopters, hovercraft, ships, hydrofoils, cruise missiles, small gas turbine turbofan and turboprop engines. In this paper single stage compressor is designed at rotational speed of 36000 rpm, mass flow rate of 6.8 kg/s, inlet total pressure and total temperature of 1.01325 bar and 288.3K, pressure ratio and isentropic efficiency of 2.5 and 87% respectively as design specification. Design result and analysis result are compared. To verifying the preliminary design results analysis is done in AxSTREAM software. In this work, total pressure at rotor inlet and total pressure at outlet is used to carry out analysis. In the numerical simulation results the mass flow rate and total pressure ratio are found as 6.82 kg/s and 2.52 bar. The efficiency obtained from simulation is 90.145%.**

***Index Terms* – Axial flow compressor, Meanline Design of compressor, AxMap, analysis**

I. PROBLEM STATEMENT

This study aims at analysis of aerodynamic design of an axial flow compressor for gas turbine engine for process industries. Design specification and assumptions for Stage Design are

Mass Flow rate at Atmospheric condition 6.8 kg/sec

Rotor speed	36000 RPM
Inlet total Temperature	288.3 K
Inlet total Pressure	101325 N/m2
No. of Stages	2

II. PRELIMINARY DESIGN

The preliminary design is preliminary solution generator which helps to select flow path parameter, such as no of stages, geometrical dimensions and angles also it depends on power and heat drop distribution. Preliminary design procedure is based on boundary conditions i.e. it performs inverse task calculation and calculates flow path geometry. In the preliminary design solution generator, design starts from technical specification, setting up design task and ends with axial fan layout which includes following steps:

i. Inlet and outlet boundary conditions such as inlet temperature, pressure, speed, pressure ratio etc.
ii. Design and sizing layout i.e. no of modules inside axial fan, no of stages meridional and axial sizes limitations, work coefficient, flow coefficient.
iii. Then designer has to decide geometrical parameter as design constrains such as specific diameter (mean diameter or hub diameter), blade height and its range or exact value. Also angles based on calculations or assumptions

In the preliminary design we have to decide following machine parameters:

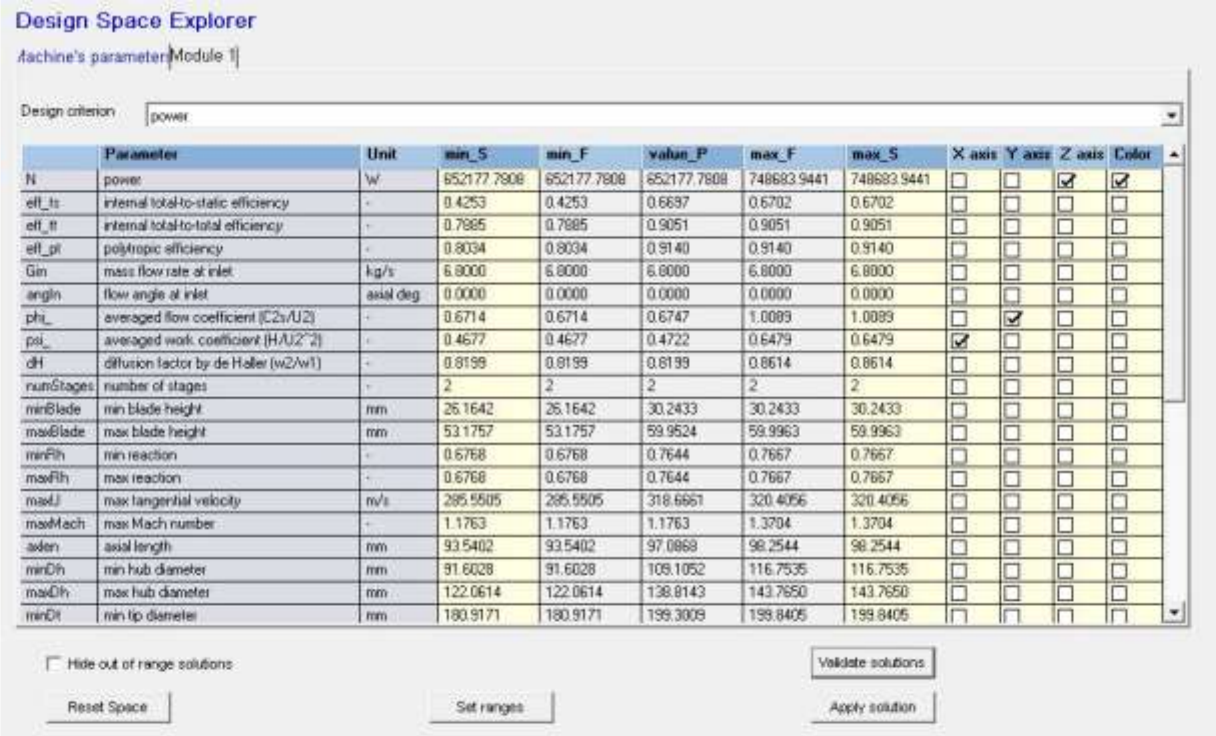
a. Inlet and outlet condition.
b. Design criterion i.e. power and choice of efficiencies.
c. Number of modules.

Next step needs design data. The available options are specific diameter, range of search points i.e. number of possible design solutions that will be considered, outlet pressure, use of IGV or OGV, design parameters ranges or exact values. Module constraints are number of stages and axial length limitations. Obtaining possible designs within the given data and constraints:

a. Generated designs
b. Solution review table

• Best in space • Best in show • Applied solution • Picked solution

This design is approximate estimation and overview of possible designs. For correct design, we have to adjust solution according to requirements using the Design Space Explorer as shown in fig 1.



Design Space Explorer

Machine's parameters | Module 1

Design criterion: power

	Parameter	Unit	min_S	min_F	value_P	max_F	max_S	X axis	Y axis	Z axis	Color
N	power	W	652177.7808	652177.7808	652177.7808	748683.9441	748683.9441	☐	☐	☑	☑
eff_ts	internal total-to-static efficiency	-	0.4253	0.4253	0.6697	0.6702	0.6702	☐	☐	☐	☐
eff_tt	internal total-to-total efficiency	-	0.7885	0.7885	0.9051	0.9051	0.9051	☐	☐	☐	☐
eff_pl	polytropic efficiency	-	0.8034	0.8034	0.9140	0.9140	0.9140	☐	☐	☐	☐
Gin	mass flow rate at inlet	kg/s	6.8000	6.8000	6.8000	6.8000	6.8000	☐	☐	☐	☐
angIn	flow angle at inlet	axial deg	0.0000	0.0000	0.0000	0.0000	0.0000	☐	☐	☐	☐
phi_	averaged flow coefficient (C2s/U2)	-	0.6714	0.6714	0.6747	1.0089	1.0089	☐	☑	☐	☐
psi_	averaged work coefficient (H/U2^2)	-	0.4677	0.4677	0.4722	0.6479	0.6479	☑	☐	☐	☐
dH	diffusion factor by de Haller (w2/w1)	-	0.8199	0.8199	0.8199	0.8614	0.8614	☐	☐	☐	☐
numStages	number of stages	-	2	2	2	2	2	☐	☐	☐	☐
minBlade	min blade height	mm	26.1642	26.1642	30.2433	30.2433	30.2433	☐	☐	☐	☐
maxBlade	max blade height	mm	53.1757	53.1757	59.9524	59.9963	59.9963	☐	☐	☐	☐
minRh	min reaction	-	0.6768	0.6768	0.7644	0.7667	0.7667	☐	☐	☐	☐
maxRh	max reaction	-	0.6768	0.6768	0.7644	0.7667	0.7667	☐	☐	☐	☐
maxU	max tangential velocity	m/s	285.5505	285.5505	318.6661	320.4056	320.4056	☐	☐	☐	☐
maxMach	max Mach number	-	1.1763	1.1763	1.1763	1.3704	1.3704	☐	☐	☐	☐
axlen	axial length	mm	93.5402	93.5402	97.0868	98.2544	98.2544	☐	☐	☐	☐
minDh	min hub diameter	mm	91.6028	91.6028	109.1052	116.7535	116.7535	☐	☐	☐	☐
maxDh	max hub diameter	mm	122.0614	122.0614	138.8143	143.7650	143.7650	☐	☐	☐	☐
minDt	min tip diameter	mm	180.9171	180.9171	199.3009	199.8405	199.8405	☐	☐	☐	☐

☐ Hide out of range solutions

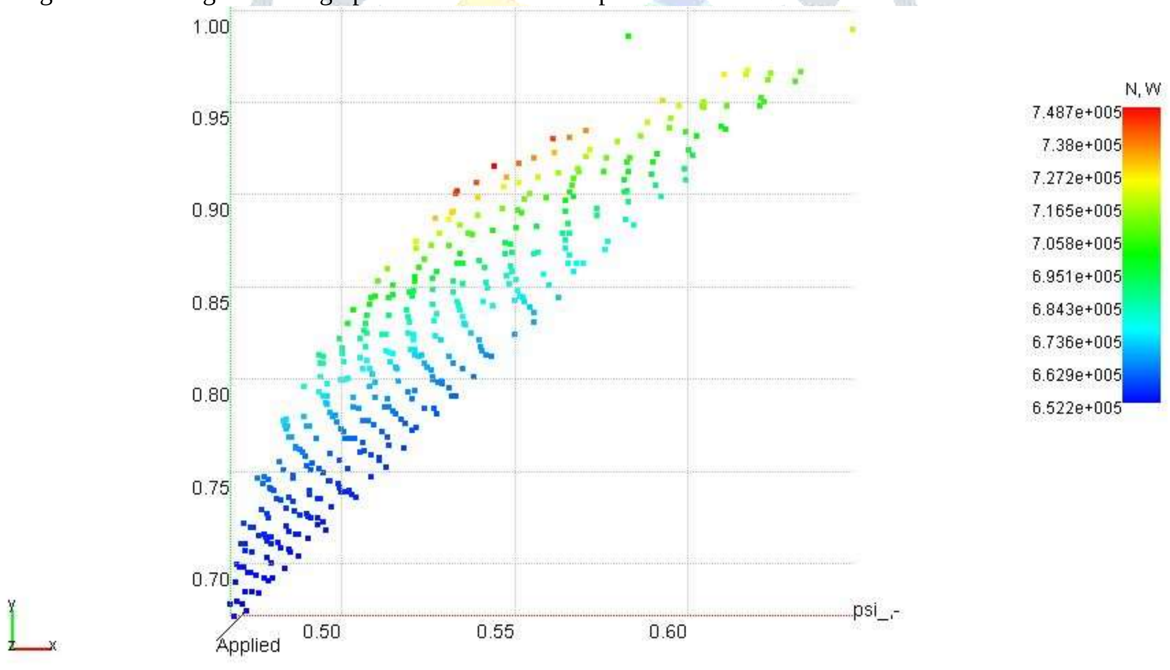
Validate solutions

Reset Space | Set ranges | Apply solution

"Fig.1" Design Space Explorer

III.COMPRESSOR PERFORMANCE CHARACTERISTIC CURVES

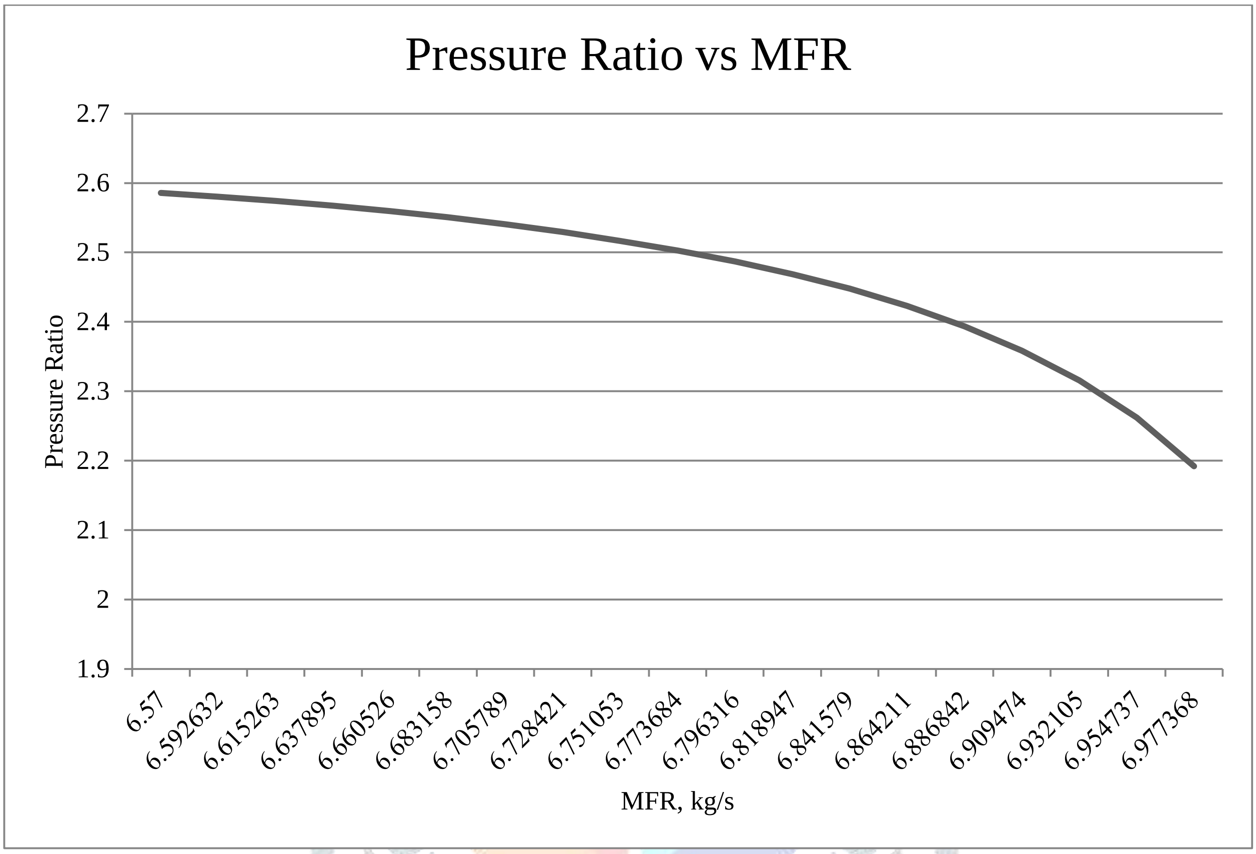
Preliminary Design phase is completed and having couple of points on PD space which correspond to design requirements. We have to choose optimal solution from the PD space as shown in fig 2. In the PD space we choose solution on the basis of best efficiency i.e. point #259. Hence we choose this point as current design point. Now it is necessary to check applied solution with different settings like matching with design point or some certain operation criteria.



"Fig.2" PD space

- PERFORMANCE MAP GENERATION IN PD MAP

PD map is tool to evaluate selected design performances on speed graph. This stage of design process needs to check the coincidence of the speed line with design point and evaluate gas dynamic stability ranges to ensure, that one can move ahead with created design. Check and edit inlet and outlet pressure range. Run calculation and see its results on visualized Map. This calculated performances map shows the difference between designed compressor performances and target design point. Designer can make a decision to redesign compressor on different performances and match design point, therefore it's necessary to increase or decrease mass flow rate in preliminary design. To shift gas dynamic stability ranges relatively to design point it's necessary to change pressure ratio in preliminary design. Filter solutions basing on the same criteria (flow coefficient, work coefficient ranges, maximal Mach number), and save best solution as new design replacing existing one.



"fig.3" Graph of Pressure Ratio vs. MFR (Performance curve)

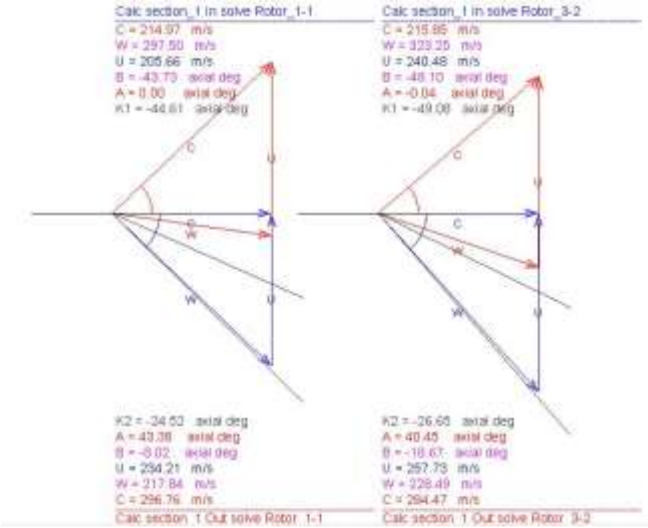
PD map helps to calculate compressor curves for compressor characteristics assessment. In this stage of design process, we have to match design criteria with performance speed line and evaluate gas dynamic stability range. This ensures that one can move with selected design. Next step is to check and edit inlet and outlet pressure range. Run calculation and see its result on visual map. But we just calculate points on PD map and plot graph as shown above. Designer should take decision to redesign compressor from above performance curve. Hence for this, it is necessary to increase or decrease mass flow rate in preliminary design and for the gas dynamic stability ranges relatively to design criteria, it is necessary to change pressure ratio in preliminary design. The differences in acceptable range proceed with current results. Filter solution based on flow coefficient, work coefficient, maximum Mach number and save best solution as a new design with replacing existing one.
The performance characteristics curve obtained is shown in graph. Above performance curve shows compressor design is matching with performance. It delivers required mass flow rate of air at designed outlet pressure with wide range of stall and chock margin. The chock range at designed rpm is 2.59 bar and stalling range is 2.18 bar.

IV.POST DESIGN

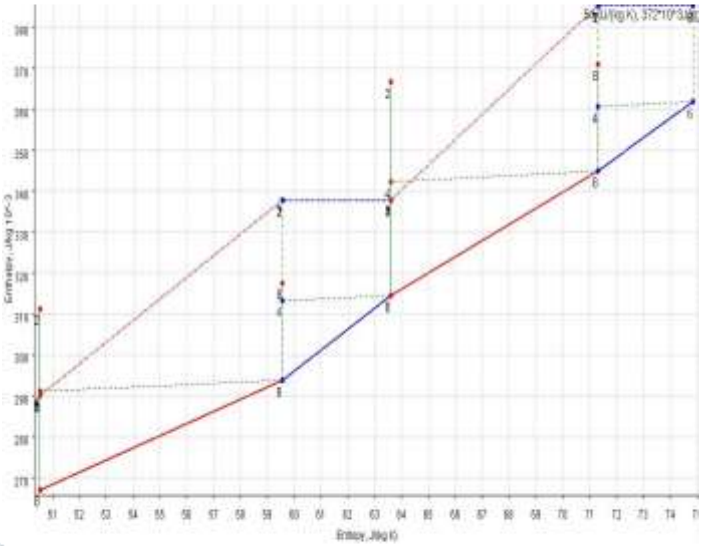
In the post design, flow path editing is done. Flow path editing is completed by using inverse design task as solver specified boundary condition and mass flow rate are preserved while changing flow path geometry and options are

a. Specific diameter
b. Aspect ratio and chords

We can change flow path by editing blade height and specific diameter at outlet. The meridional shapes adjustments can be performed by adjusting the distribution of flow path specific diameters using spline. When specific diameter changes inverse design task solver recalculates blade heights and metal angels. Post design shows velocity triangles and H-S diameter as shown in fig 4 and fig 5 respectively. For respective section fig and fig shows velocity triangle and H-S diagram which shows smooth flow turning i.e. no excessive turning of blades.



"Fig.4" Velocity triangle


"Fig.5" H-S diagram

V.STREAMLINE CALCULATIONS

In streamline calculations we need to provide our input data of inlet condition and add flow coefficient setting those given below: P_{01} = 1.01325 bar, T_{01} = 288.2 K, P_{02} = 2.533 bar, MFR= 6.8 kg/s, N=36000 rpm

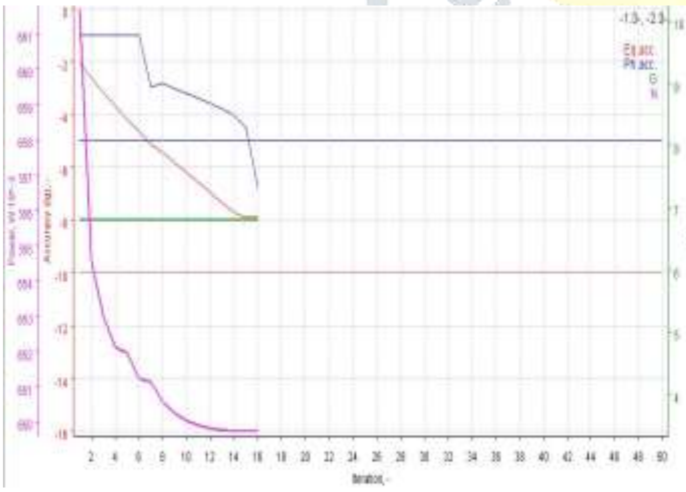
The streamline calculation task solver has two modes

a. Meanline mode

b. Streamline mode

We can use streamline or the meanline calculation, as streamline calculation mainly used for axial flow compressors. Now post design part is completed. The streamline solver is estimating design results by performing some benchmark calculation in streamline solver. The streamline has to options

- Find MFR for given inlet temperature, pressure and outlet static or total pressure.
- Find total or static outlet pressure for given mass flow rate.


"Fig.6" Streamline convergence

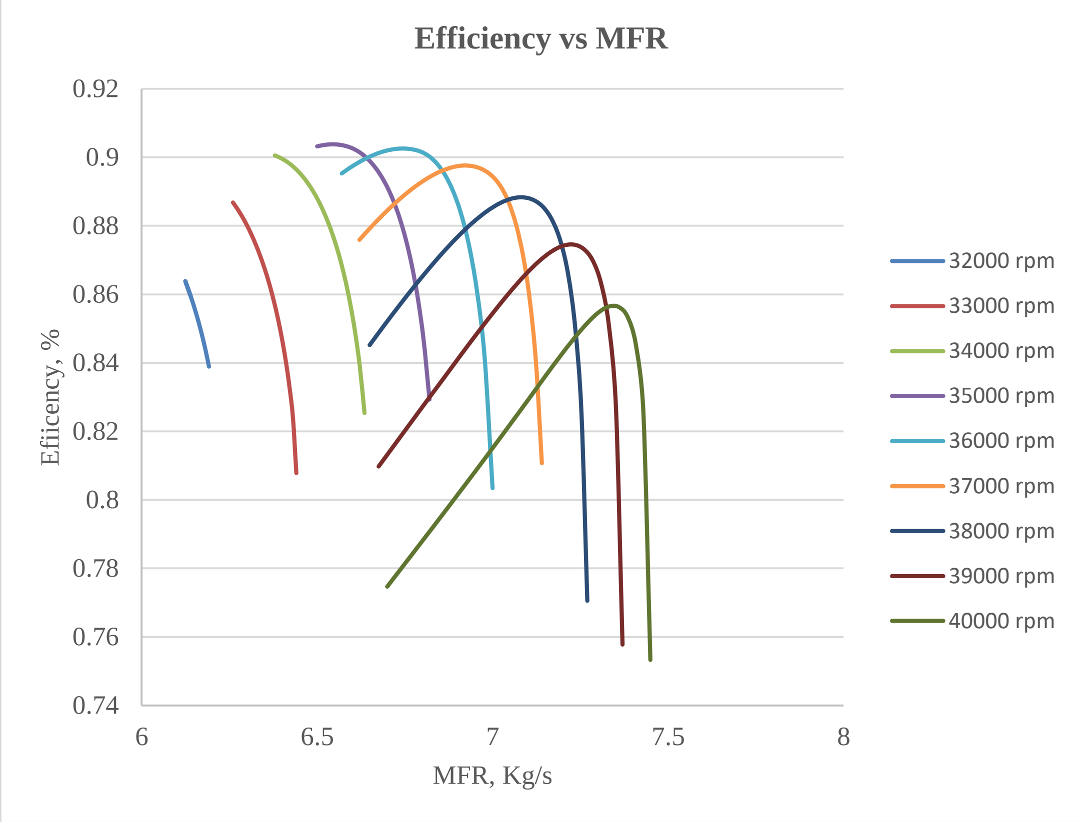

"Fig.7" Streamline convergence report

It is assumed that design task is now finished. Now solver runs mean line analysis task. This analysis provides accurate performance estimation i.e. power, MFR, efficiency. Next step is to assume some design details that we cannot take into account during design i.e. clearance data, type and location of extractions, injections.

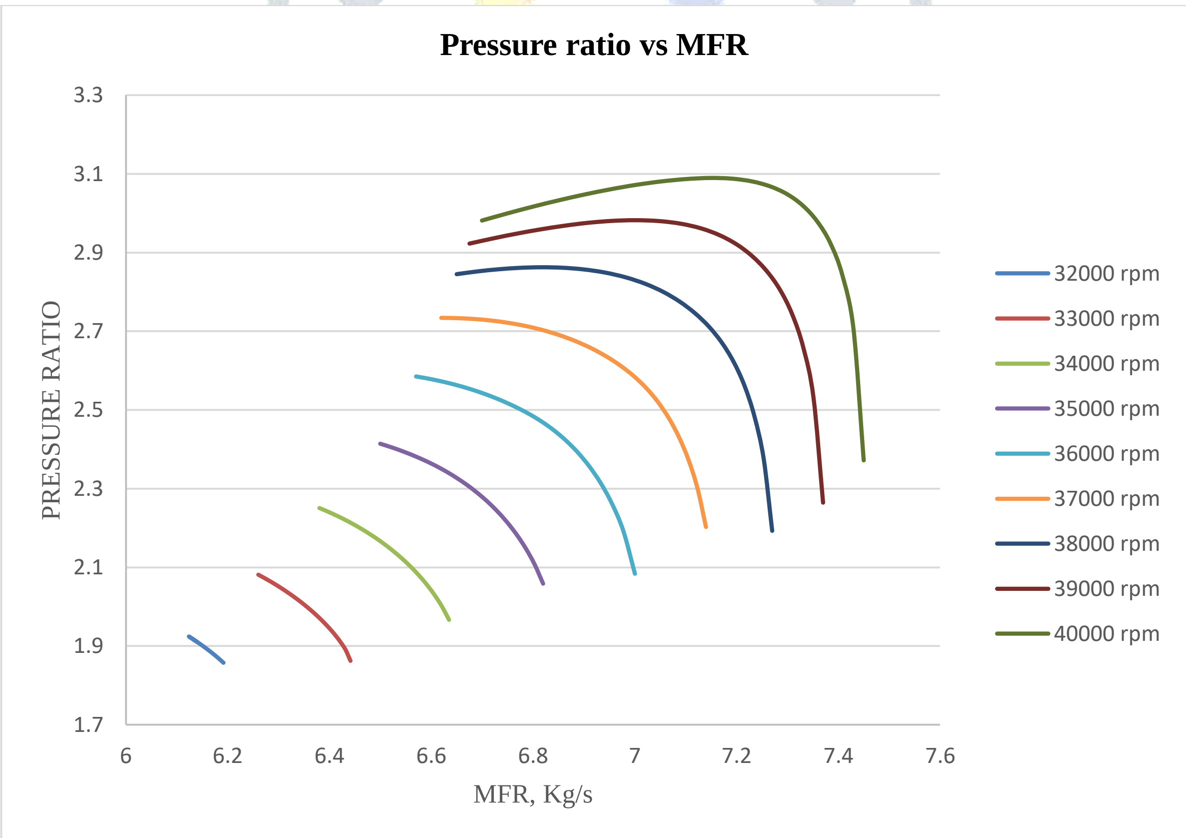
VI.OFF-DESIGN PERFORMANCES CALCULATIONS WITH AxMAP

AxMap is a multi-task tool to run multiple calculations for two variables (we can use additional variables as parameters). AxMap is used to study the effect of operational parameters on compressor off-design performance. AxMap can also be used to calculate compressor curves that are necessary for turbine-compressor matching. In AxMap, for map calculations we can select rotational speed, total outlet pressure as a variables and power, total-to-total efficiency, MFR at outlet and total pressure ratio etc. as objectives.

We select rotational speed as a primary variable and set nine speed lines ranging from 32000 to 40000 rpm. Total outlet pressure and efficiency it as a row with 20 numbers of points. After finishing the calculations, the results are shown in fig. 8 and fig 9



“Fig.8” Graph of efficiency vs. MFR

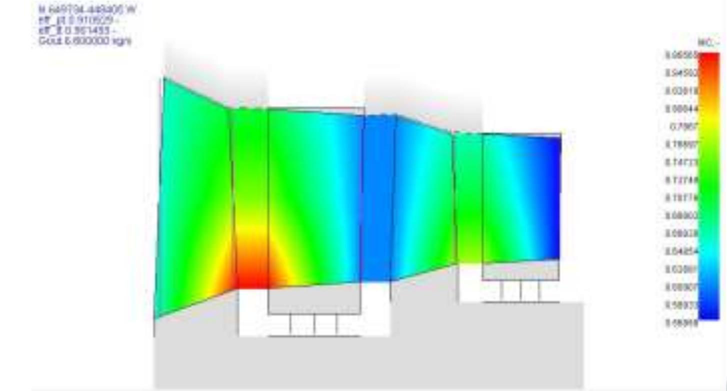


“Fig.9” Graph of Pressure ratio vs. MFR

The crucial question for all compressor designer is how to predict, where (at which rows) stall possibility is highest for current operating mode. AxMAP can be used for this kind of prediction, using indirect, but very accurate criterion of diffusion factor. The off design performance of an axial flow compressor is evaluated using AXMAP by selecting variables as Total outlet pressure and RPM whereas Power, Mass flow inlet, Total Pressure ratio and efficiency as objectives, which indicated a wide operation range as shown in Fig. . With the diffusion factor ranges from 0.445to 0.38 and Dehaller No. from 0.67 to 0.79.

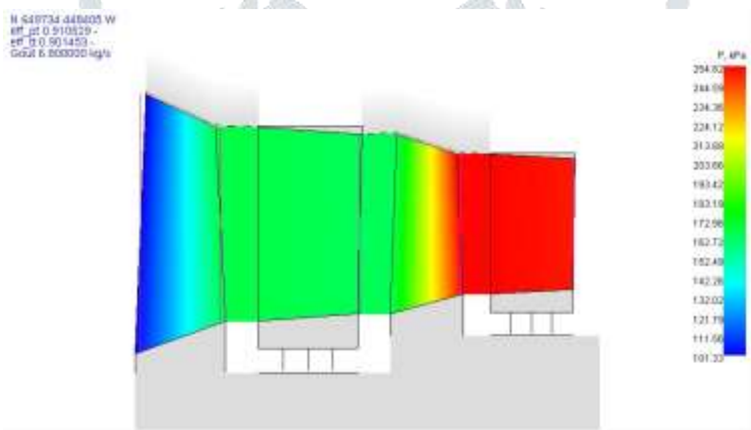
VII.RESULTS

- **Absolute Mach number distribution**



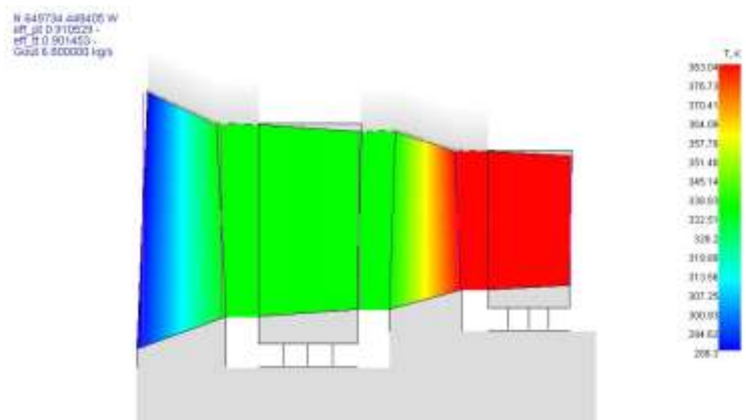
“Fig.10” Absolute Mach no distribution

- **Total Pressure distribution**



“Fig.11” Total Pressure distribution

- **Total Temperature distribution**



“Fig.12” Total Temperature distribution

Results of absolute Mach no, pressure distribution and temperature distribution are shown in above figures. After completing the calculations when the target mass flow reached i.e. inlet mass flow rate is equal to outlet mass flow rate. Fig. 10, 11, 12 shows variation of flow parameters through machine Such as Pressure, Temperature and Mach No. very close to the design value with wide choke and stall margin.

VIII. CONCLUSION

The analysis of aerodynamic design for an axial flow compressor of a gas turbine engine is achieved using AxSTREAM. Stage exit average pressure ratio and Mach. No. are matching with the design intent. The diffusion factor and Dehaller no. are in the allowable range for both rotor and stator throughout the machine. The total loss coefficient is in the range of 0.025 to 0.078 for both rotor and stator. The analysis results at respective section in terms of Mach No. total pressure are matching with the design values.

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