VIGV Angle Optimization for Subsonic Axial Flow Compressor

Prabhat SINGH*,[1], Dharmahinder Singh CHAND[1]

*Corresponding author
[1]Faculty of Aerospace Engineering, Chandigarh University,
Mohali, Punjab, India,
prabhatsinghrbl@gmail.com*, sdsinghchand25@gmail.com

DOI: 10.13111/2066-8201.2020.12.2.18

Received: 15 February 2020/ Accepted: 23 March 2020/ Published: June 2020
Copyright © 2020. Published by INCAS. This is an "open access" article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

Abstract: *Long-term performance of an axial-flow compressor by the scheduling of inlet guide vanes at off-design conditions has been studied in this paper. The compressors are used in various industries and in aviation sectors for different operations at different climatic conditions; due to diverse climatic conditions the compressor is unable to give good performances as expected. At the design conditions, the results show that the variations in total pressure loss coefficient, volume flow rate, pressure ratio, and others like thermodynamics, aerodynamic properties are different at different stagger angles of 15°, 30° and 45°. BladeGen tools were used to design the inlet guide vanes for the investigations. The performance parameters of the axial flow compressor were analyzed by using ANSYS CFX and were validated using the analytical method. The objective of this study is to minimize the total pressure loss coefficient and improve the aerodynamic characteristics of an inlet guide vanes at different stagger angles and hence reduce the overall fuel consumption. The outcomes of this work give an improved insight into the efficient use of a VIGV in axial flow compressor.*

Key Words: *Stagger angle, VIGV, BladeGen, climatic condition, Axial-flow compressor, Aerodynamics behaviour*

1. INTRODUCTION

In the axial-flow compressor, the shape optimization has been the subject of several numerical studies and analyzes in the past decades.

In axial-flow compressor [1] the incoming air enters in parallel from the first stage to another stage and all stages of compressor increasing the pressure very slowly.

A practical and effective optimization method is used to improve the pressure ratio and efficiency of an axial-flow compressor.

Particular modifications are accomplished with a limited number of optimization parameters, by IGVs blades re-staggering [2].

A CFD model has been prepared and verified through experimental data, which are obtained from the result of CFD simulation; the effects of stator stagger angle distributions on the axial-flow compressor performance are investigated.

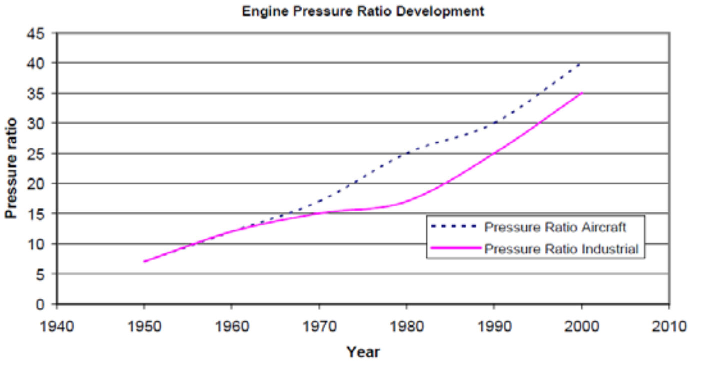


Fig. 1 Growth of pressure ratio over the earlier period of 50 years [1]

The optimization is carrying out at the axial flow compressor design operating condition. In this paper, performance analysis of the axial flow compressor by transforming the stagger angle of IGVs with special emphasis on diverse climate circumstances has been carried out to improve the pressure ratio and efficiency.

Figure 1 represents the overall development of the pressure ratio in an aircraft engine and in an industrial gas turbine engine over the last 50 years.

The graph indicates the firing temperature and pressure ration are almost parallel for both, as mutually improvements are important to achieve the best thermal efficiency in the gas turbines engine.

Studying the effect of guide vane stagger angle

Most compressors have inlet guide vanes with variable stagger angles. Variations in stagger angle of guide vane including geometrical variations of the stage would have resulted in variation of the stage characteristic curves in compressors. Theoretically, changing the stagger angle of inlet guide vane will result in variations made in the characteristics curves of the stage under study.

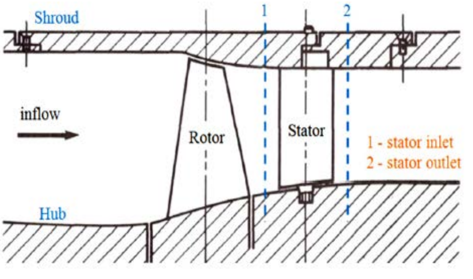


Fig. 2 Schematic picture of meridional plane for compressor stage [13]

The stagger angles of IGV or stator rows can be scheduled so that the throat area is increasing at low rotational speeds [3].

Figure 2 depicts the inlet guide vane scheduling for a compressor in the gas turbine engine [5], where IGVs are pivotally associated with sync rings consisting of an annular groove within the hub casing.

In this research, thermodynamic and aerodynamic performance parameters are obtained for a different angle of blade rotation relative to the starting IGVs positions 15^0, 30^0 and 45^0 stagger angles with the diverse climatic conditions for summer, average, and winter. The existing compressor consists of IGVs (20 blades).

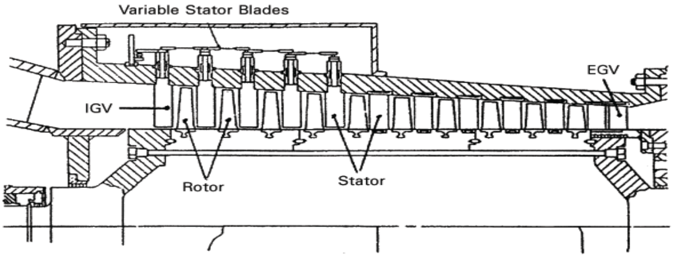


Fig. 3 Axial flow compressor with Variable stator Vane [5]

The different geometric angles depicted in cascade geometry show the blade setting and their relationship with the flow angles for a compressor cascade.

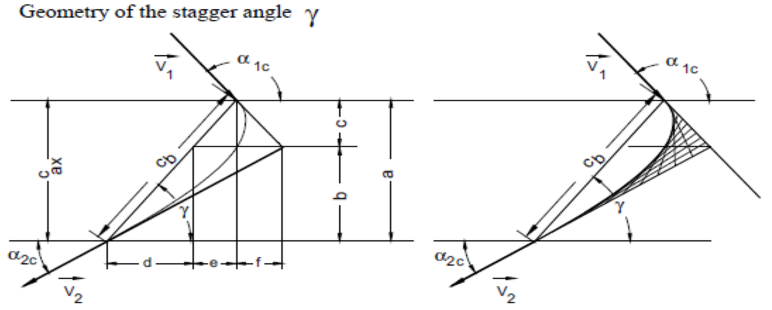


Fig. 4 Compressor cascade nomenclature

The geometry for determining the calculation of the stagger angle is illustrated in fig. 4. In low subsonic blade design [6] as illustrated in the figure, the stagger or setting angle can be calculated graphically, by means of the flow angles tangent as depicted in fig. 3 to the camber leading and tailing edge, for both stator and rotor row beside [7] with the axial-chord a. Also, the maximum camber distance from the leading edge c to trailing edge b with, the stagger angle is evaluated as follows:

$$\tan\gamma = \frac{a}{\frac{a-c}{\tan\alpha_2} - \frac{c}{\tan(\pi-\alpha_1)}}$$

From the above equation, the stagger angle can be easily calculated. IGVs intended to normalize the stagger angle in order to enhance the efficiency of the axial-flow compressor at different operating conditions. The purpose of variable inlet guide vanes (VIGV) is to direct the air on to the runner blades at the appropriate angle [8].

2. METHODOLOGY

The methodology proposed for this work is to attain the optimum performance of the axial flow compressor working at three different climate conditions summer, average, and winter. From the various works of literature, the base settings can improve the performances in all climatic conditions to achieving high efficiency and a large mass flow rate. In this paper, the ANSYS software is used to simulate the VIGV in diverse operating circumstances and to obtain the overall aerodynamics behavior of the axial flow compressor through changing the IGVs stagger angles. Taking advantage of the velocity triangle, Euler equation, and mathematical relationships; the derivative relationship between the guide vanes stagger angle variations and the coefficients of pressure and flow have been obtained.

Problem Identification

The compressor will not be performing well in different climatic conditions or not get optimum performance results at different atmospheric circumstances when the density of the air and temperature increase or decrease [2]. These affect the pressure ratio, mass flow rate and other performance parameters of an axial-flow compressor. The compressors are used in the different atmospheric circumstance in industries and aviation sectors, due to diverse climatic conditions which are unable to give better performance. The inlet guide vane is the main part of the gas turbine engine compressor which directs the incoming air into the compressor with different velocity or mass flow rates.

Atmospheric Performance Parameters Calculations

Atmosphere performance parameters were calculated just before IGVs. Seasonal and annual temperature series from India (minimum & maximum) has been taken from the "India Meteorological Department" web page [9].

Table 1. Average Temperatures Series (All Season)

Average Temperatures (Degree Celsius)	Summer	Winter	Average
	29.13	19.34	24.67

The table shows the 114-year data from 1901-2014 seasonal and annual temperature series used to investigate the performance of the axial flow compressor by adjusting the inlet guide vanes at different stagger angles.

Problem Formulation and types of Analysis

The optimum results can be found by the variation of stator stagger angle of IGV at diverse climate conditions as given by simulation. BladeGen, Turbogrid and CFX tools are used for the CFD analyses for this investigation.

The mean line prediction technique is used to determine the blade geometry and BladeGen software for profile generation of the stator blade [10].

3. DESIGN AND ANALYSIS OF IGVS

Stationary gas turbines aim to improve the off-design performances and expand the operational range Inlet guide vanes blade designing using ANSYS tool BladeGen for the geometry of turbomachinery blades [11]. It is mainly used to create a 3D shape of a blade and construct an entire row of stages including inlet guide vanes (IGVs). The following BladeGen parameters mentioned in table 2 are taken as mean line analysis for inlet guide vanes (IGVs).

Table 2. BladeGen Input Parameters

Parameters in MM	**Parameters Values**
Inlet radius (hub)	218.66
Exit radius (hub)	224.74
Inlet Radius (tip)	282.18
Exit Radius (tip)	275.27
Number of Blades	20
Inlet Beta (degree)	43.18
Outlet beta (degree)	4.83

Inlet Beta (degree)	36.06
Outlet Beta (degree)	3.95
Machine Type	Axial-Flow Compressor
Stagger Angle	$15^0, 30^0, 45^0$

Configuration of IGVs

In the baseline case, three new IGV designs have been created, each design including baseline and being analyzed for the following three cases IGV_15_NC, IGV_30_NC, and IGV_45_NC stagger angle. The IGVs are created from uncambered airfoil with a 60mm of the chord length, Meridional Length (M) = 58, Pitch Cord Ratio (S/C) = 0.800. For this study volume flow rate changed and analysis performed at revolutions of 1500 1/min. IGV_0_NC: IGV – indicates that the IGV the part was investigated, 0 – indicates the angle of the blades (stagger angle), NC – indicates that the computation is without the compressor part (No Compressor).

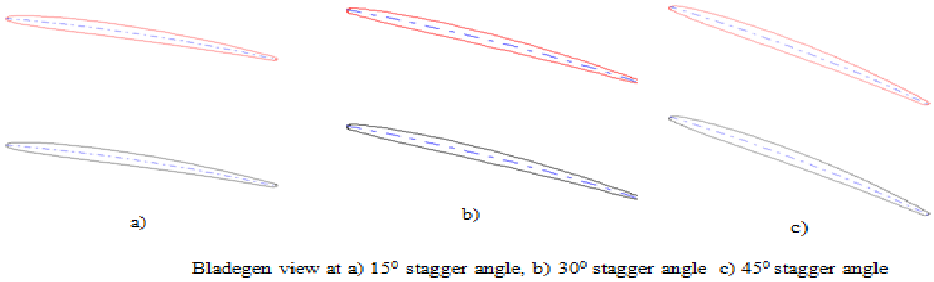


Fig. 5 BladeGen view at different Stagger's angle

The most important part is the design of the inlet guide vane of CFD analysis which is obtained from the BladeGen tool. Three cases of IGV are considered for the investigation of the performance of the compressor.

Case-1 IGV_15_NC
Case-2 IGV_30_NC
Case-3 IGV_45-NC

Turbo-Grid comes after generating different inlet guide vane (IGVs) used for 3D Hexa meshing of H/C/O-type mesh.

Table 3. Mesh Nodes and Elements

Component Axial-flow compressor	Nodes	Elements
IGV_15_NC	78562	71694
IGV_30_NC	76824	70077
IGV_45_NC	116451	107640

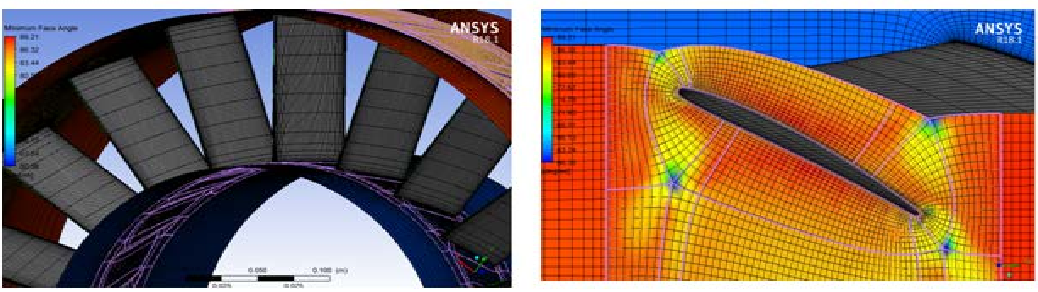


Fig. 6 3D Turbogrid Isometric mesh views

It‘s a powerful-quality tool hexahedral that meshes using an automatically high created mesh topology for the blade geometry: (ATM) technology.

Inlet Boundary Conditions for Simulation

Investigations of performance parameter, adiabatic non-slipping conditions are carried out to the solid boundaries.

After the mesh import, the CFX generates the topology of the calculation domain and SST k- turbulence modeling was used with the CFD solver, ANSYS CFX.

The imported mesh is divided into primitive regions (volumes, surfaces). In the beginning, these regions are defined as a part of “Default Domain”. In the next steps, it is necessary to define what kind of boundaries are these regions. The fluid type is a real gas.

The operating inlet conditions for simulation are illustrated in the table below.

Table 4. Operating Inlet boundary conditions

Inlet parameters		**Summer**	**Winter**	**Average**
Inlet total temperature	ºC	29.13	19.34	24.67
Inlet total Pressure	KPa	106.22	102.77	104.65
Rotational speed	r/min	1500		
Reference pressure	0 ATM			

The 3D isometric view of inlet guide vane for different stagger angles is designed using the BladeGen tool, which is considered for CFD analysis. Isometric 3D views of the stator blade, hub, and shroud are depicted in fig. 7.

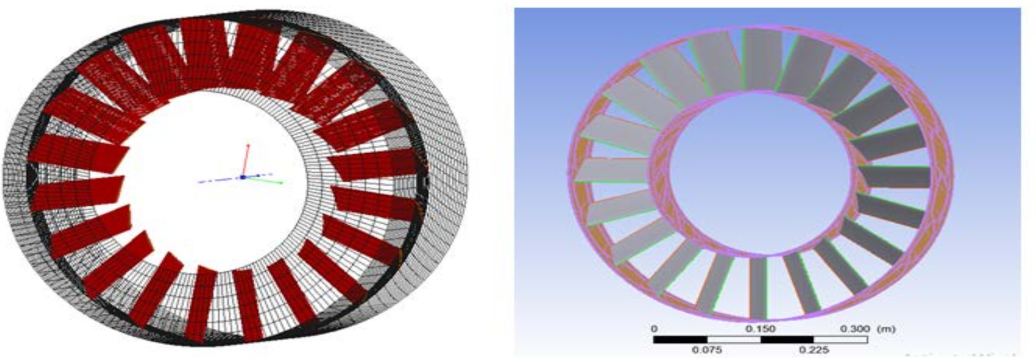


Fig. 7 Design model Isometric view of IGVs

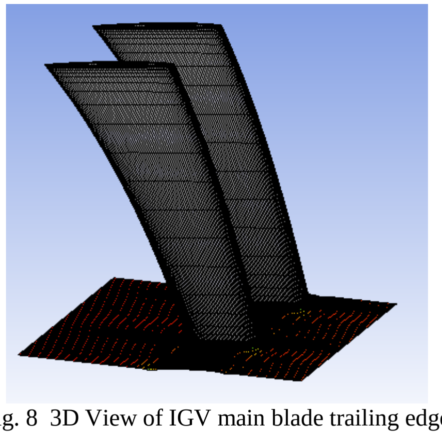


Fig. 8 3D View of IGV main blade trailing edge

The IGVs comprise a system on one of the split ends that allows both an axial and a turning movement of the inlet guide vane pin, its pivot with reference to a fixed pin on an opposite end of the guide vanes.

Physical Setup in CFX Pre (Turbo-Mode)

Nowadays, the CFD is one of the basic design tools helping to reduce the design time and to increase the effectiveness of the engineering work. CFD is widely used in fields of power and energy, the engine industry, aerodynamics, thermodynamics, aeronautics, etc. CFX is started in Turbo mode after the mesh generation is completed using a turbo grid; CFX-Pre has been used to setup the design in the axial-flow compressor for simulation. Table 5 represents the Pre-setup of CFX used in simulation process. Mass and Momentum results represent one of the important features of ANSYS CFX, in which all the hydrodynamic equations are solved as a single process. The coupled solver is faster than the traditional solver and less iterations are required to obtain a converged flow simulation results.

Table 5. ANSYS Pre-Setup (Physical definitions)

Machine type	Axial flow compressor
Rotation axis	Z
Analysis Type	Steady State
Component	IGV_15_NC, IGV_30_NC, IGV_45_NC
Fluid	Air Ideal gas
Wall function	Automatic
Advection scheme(solver	High Resolution
Turbulence model	Shear stress transport
Time scale control	Auto Timescale
Mass and momentum Wall roughness Heat transfer	No slip wall Smooth Adiabatic

These conditions are directly taken from the mean line analysis of the blade designing. The operating inlet boundary conditions used are total pressure and temperature with a mass flow rate. The shear stress transport (SST) is used for turbulence modeling with total energy as the energy model. For the turbulence modeling, the SST model is used because it is well suited to handle flow separation over a curved surface.

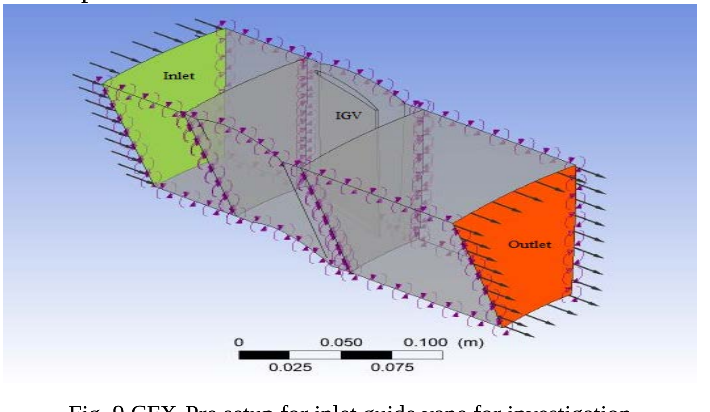
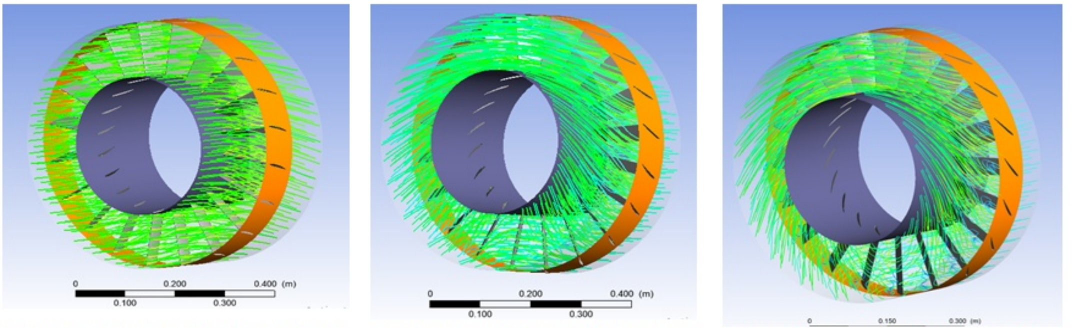


Fig. 9 CFX-Pre setup for inlet guide vane for investigation

The above figure depicts the CFX-Pre setup for IGV with inlet and outlet conditions for simulations. It is necessary to solve several equations, which describe processes of momentum, heat end mass transfer, etc., to describe and predict a flow behavior. These equations are known as Navier-Stokes equations.

These equations are defined from the mathematical point of view as partial differential equations. They were derived in the early nineteenth century. These equations can be discretized and solved numerically.



Case_1 Isometric 3D View of the Blade, Hub and Shroud with velocity streamline flow

Case_2 Isometric 3D View of the Blade, Hub and Shroud with velocity streamline flow

Case_3 Isometric 3D View of the Blade, Hub and Shroud with velocity streamline flow

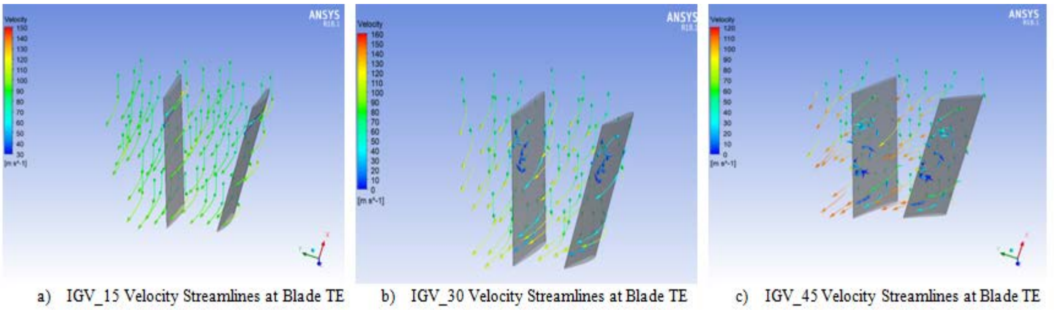
Fig. 10 Streamline in 3D Views

The 3D isometric views of the inlet guide vane for different stagger angles show the velocity streamlines flow as depicted in figure 10.

Case_1 at IGV_15 3D view with velocity streamline flow is more uniform as compared to the other two cases.

4. RESULTS AND DISCUSSIONS

The following information is available from the CFX baseline cases that were examined at different stagger angles with climate change like summer, average and winter condition cases. Recall the pressure ratio, mass flow rate, and total pressure loss coefficient.



a) IGV_15 Velocity Streamlines at Blade TE b) IGV_30 Velocity Streamlines at Blade TE c) IGV_45 Velocity Streamlines at Blade TE

Fig. 11 Velocity Streamline at blade trailing edge for different stagger angles

The primary variable that was first examined is the total pressure loss coefficient because it is directly linked to changes in efficiency [12], which shows as a close up of loss against the lower IGV stagger for clarity.

Investigation of the flow behavior inside the channel (velocity streamline stream blade TE View) as depicted in figure 11 illustrates the velocity streamline stream blade TE view. Vortex inflow increases as increasing the stagger angle of inlet guide vane.

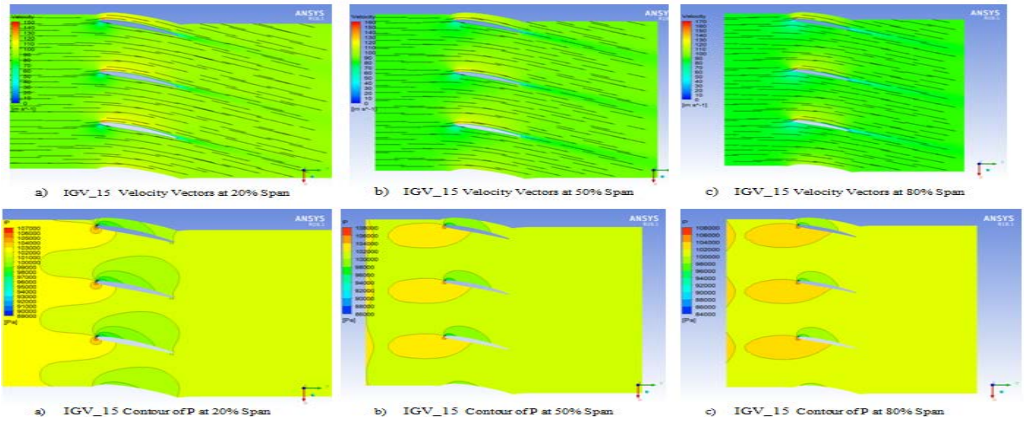


Fig. 12 Velocity vector and Pressure contour of the IGV at 15 degrees of stagger angle

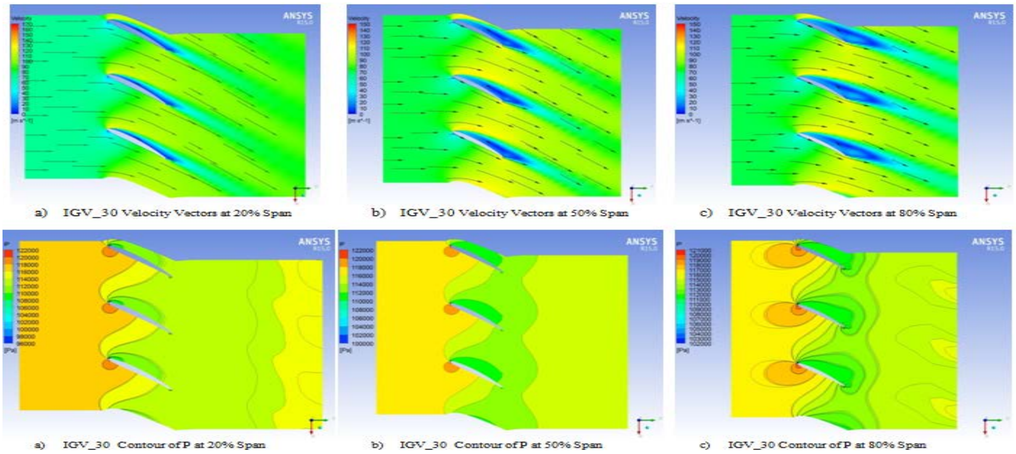


Fig. 13 Velocity vector and Pressure contour of the IGV at 30 degrees of stagger angle

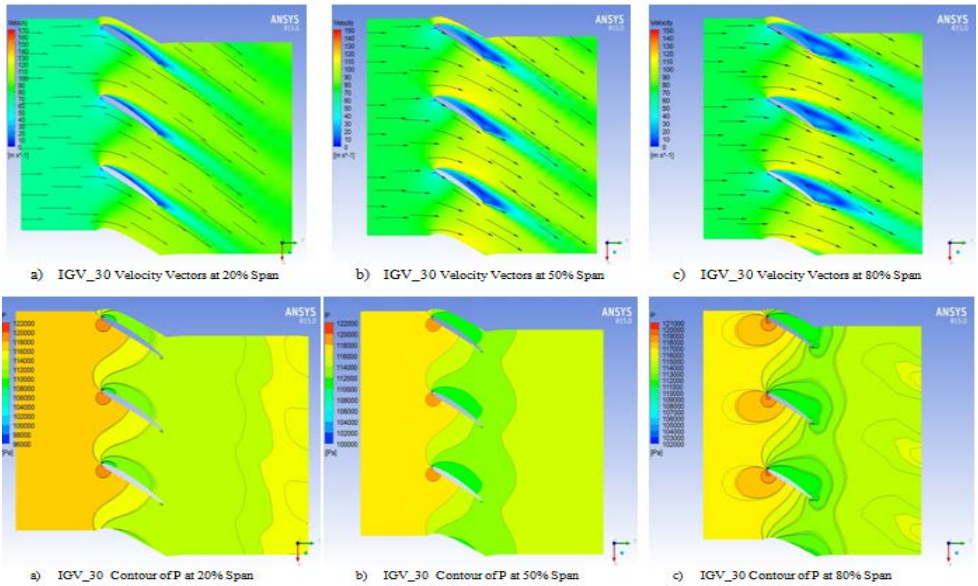


Fig. 14 Velocity vector and Pressure contour of the IGV at 45 degrees of stagger angle

Pressure waves can be seen at the entrance of the passage at IGVs at different stagger angles.

The primary variable is the total pressure loss coefficient because it is directly linked to the inefficiency of change.

For each IGV loss is plotted against the IGV stagger angle with climatic condition illustrated in figures in this section. Evaluated results are displayed in the following graphs.

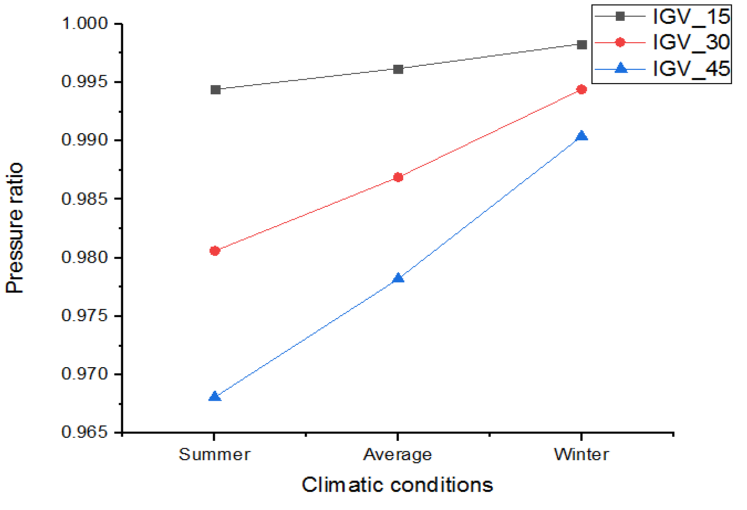


Fig. 15 Pressure ratio versus different IGVs with diverse climatic conditions

The pressure ratio is increasing in winter conditions in all three stagger angles. Figure 15 depicts that at IGV_15 the pressure ratio is 0.9983 in winter condition and minimum in summer condition. At 15^0 stagger angle performance of axial-flow compressor enhanced.

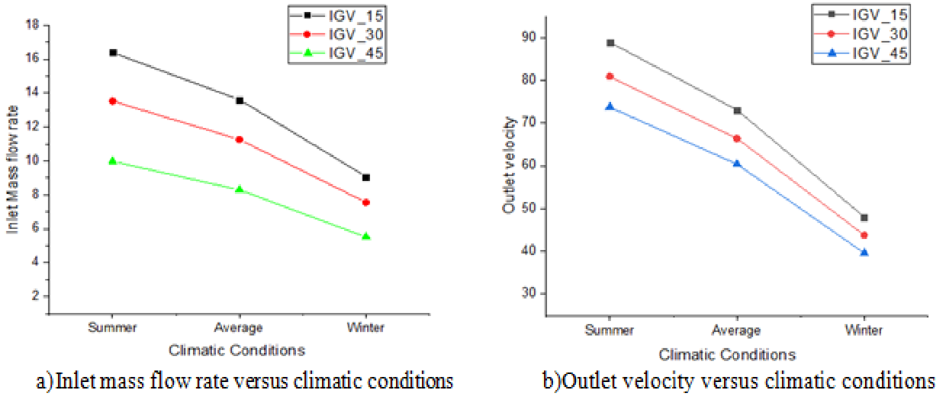


Fig. 16 Performance parameter of compressor with different stagger angle

From the observation or investigation of this study it is found that under summer operating circumstances [2], a huge amount of mass flow rate is requisite, as under winter circumstance, the compressor is operational in a comparatively low mass flow rate and an adequate stall margin is required.

Figure 16 depicts the variation of the inlet mass flow rate versus climatic conditions; in all cases more mass flow rate is required and winter required less mass flow rate.

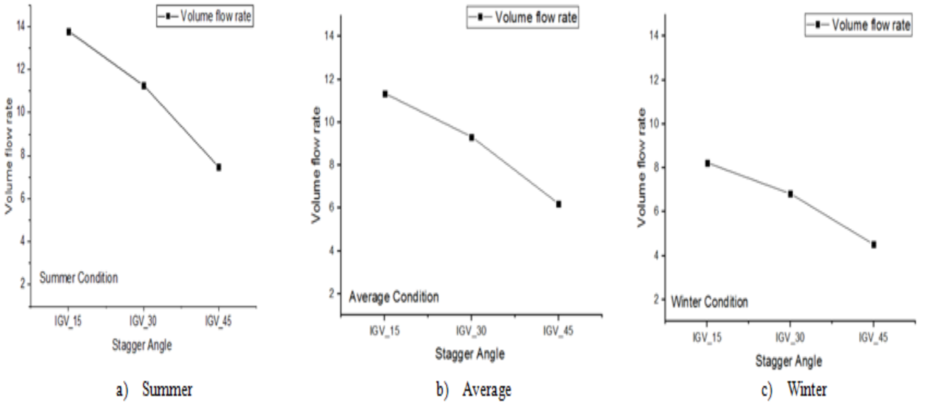


Fig. 17 Flow rate with diverse climatic conditions at different climatic conditions

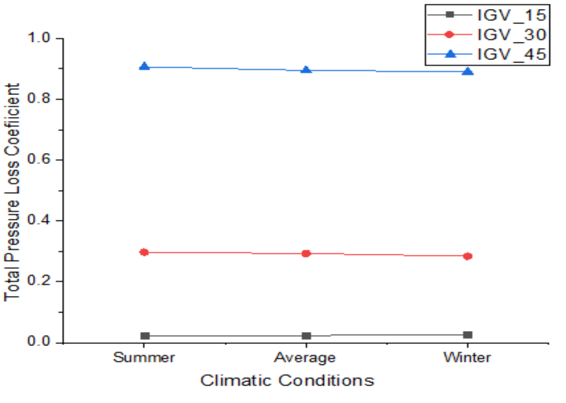


Fig. 18 Total pressure loss coefficient rate with diverse climatic conditions at different climatic conditions

The total pressure loss coefficient behavior is according to the expectation. The pressure drop is changing according to the angle of the rotation of the IGVs blades at different stagger angles throughout the simulation. As figure 18 illustrated, at stagger angle 15-degrees stagnation pressure loss coefficient is minimum as 0.0223 in summer condition. Losses increase as climatic conditions change with different stagger angles.

5. CONCLUSIONS

Variable inlet guide vanes are generally adapted in compressor design for stationary gas turbines as well as jet engines, to enhance the off-design performances and enlarge operational range. IGVs and bleed valves are fitted to decrease opportunities for the surge in axial flow compressor and also to increase the power output of the gas turbine engine. Experimental results obtained by cascade testing can be used to predict the performance of an IGVs system. The IGVs loss can be significantly improved at higher stagger angles but not without worsening the loss at low stagger angles.

With the best IGV design IGV_15_NC, the axial flow compressor overall mission-weighted improves the working performance of an axial-flow compressor. It is found that at IGV_15_NC the pressure loss coefficient is minimum for all climatic conditions as a comparison to the other two cases. There is another possible benefit for an inlet guide vane that has lower losses at a small stagger angle. Some aircraft engines struggle with noise and vibration issues at high stagger angles. The change in compressor efficiency will also affect the specific fuel consumption. Hence the specific fuel consumption is low at a 15-degrees stagger angle because of the minimum loss of coefficient.

REFERENCES

[1] M. P. Boyce, *Axial-flow compressors, Gas Turbine Engineering Handbook*, pp.274-335, 2006.

[2] H. Chang, et al., Numerical investigation of base-setting of stator's stagger angles for a 15-stage axial-flow compressor, *Journal of Thermal Science*, **23**.1, pp.36-44, 2014.

[3] J. Kurzke and I. Halliwell, *Compressors, InPropulsion and Power*, pp. 313-356, Springer, Cham, 2018.

[4] Z. Xue-lei, W. Song-ling, C. Hai-ping & Z. Lan-xin, *The influence of IGV and relative humidity of air on performance map of axial flow compressor*, In TENCON 2005-2005 IEEE Region 10 Conference, pp. 1-3,2005.

[5] M. T. Gresh, *Compressor Performance: Selection, Operation, and Testing of Axial and Centrifugal Compressors*, Butterworth-Heinemann, Oxford, 1991.

[6] M. T. Schobeiri, *Blade Design, InGas Turbine Design, Components and System Design Integration*, pp. 249-276. Springer, Cham, 2018.

[7] H. Karrabi, S. Meysam and B. Mostafa, Effect of aging and manufacturing tolerances on multi-stage transonic axial compressor performance, *Energy Equipment and Systems*, **7**.2, pp. 133-147, 2019.

[8] H. Lu, Z. Yang, T. Panand Q. Li, Non-uniform stator loss reduction design strategy in a transonic axial-flow compressor stage under inflow distortion, *Aerospace Science and Technology*, Vol. **92**, Pages 347-362, September 2019.

[9] * * * Seasonal and Annual Min/Max Temp Series-India from 1901 to 2014 https://data.gov.in/resources/seasonal-and-annual-minmax-temp-series-india-1901-2014.

[10] Uday Chandra Gollapalliand Chhavi Chhavi, *Design and optimization of a stator turbine blade profile using control parameters*, In2018 IEEE Aerospace Conference, pp. 1-12, IEEE, 2018.

[11] D. F. Ronald, *Fundamentals of jet propulsion with applications*, Cambridge University Press, Cambridge, UK, 2005.

[12] B. Ghazanfari, M. Nili-Ahmadabadi, A. Torabi-Farsani and M. Hossein Noorsalehi, Numerical study of camber and stagger angle effects on the aerodynamic performance of tandem-blade cascades, *Propulsion and Power Research* **7**, no. 1, pp. 30-42, 2018.

[13] M. D. Hathaway, *Unsteady Flows in a Single-Stage Transonic Axial-Flow Fan Stator Row*, NASA Technical Report NASA-TM-88929, 1986.