CFX ANALYSIS OF AN IMPELLER BLADE DESIGN OF CENTRIFUGAL COMPRESSOR

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ABSTRACT– *Turbochargers are devices that increase the output power of an internal combustion engine by forcing extra compressed air into the combustion chamber. An accurate and sustainable design of the turbocharger will improve the efficiency of our combustion engine. The most important part of the centrifugal compressor used to compress air is the impeller. Radial impellers have wide range of applications in turbochargers. The aim of this project is to design an impeller blade with the optimum back swept angle so that it can work efficiently. The study is to design and optimize an impeller blade using CFX analysis in Ansys software. The back swept angle will be changed and iterations will be taken until an optimum angle is found. The output data obtained from the analysis will be analyzed and parameters such as pressure ratio, Mach number and flow rate will be considered. Thus, an efficient blade design will help in improving the air flow distribution in the impeller and will in turn increase the overall efficiency of the turbocharger.*

KEYWORDS – Impeller Blade, Turbocharger, CFX Analysis, Back-Swept Angle, Centrifugal Compressor, Mach Number

1. INTRODUCTION

In this project our main aim is to design an impeller blade in such a way that it has an appropriate back swept angle. At various back swept angles input parameters will be entered and CFX analysis using Ansys will be performed. Output parameters such as Mach number, pressure ratio and volume flow rate will be compared after the simulation. This process will be done for different back swept angles and all of the data obtained will be compared. After comparing this data, we will find out at which back swept angle is our impeller design failing and at which angle is our design the most efficient. The design where the airflow over the impeller blade is the best will be considered the optimum back swept angle. Thus, by determining the optimum back swept angle an accurate impeller blade design will be obtained.

1.1 Turbocharger

Turbocharger is a device which helps in forcing extra compressed air into the combustion chamber. This increases the power output of the engines. Thus, an efficient and accurate design of a turbocharger is crucial to increase the output power of an engine. Turbochargers have become an essential component in modern automobiles as the need for faster and more efficient vehicles has increased. In the modern age more and more gasoline engines have started installing turbochargers.

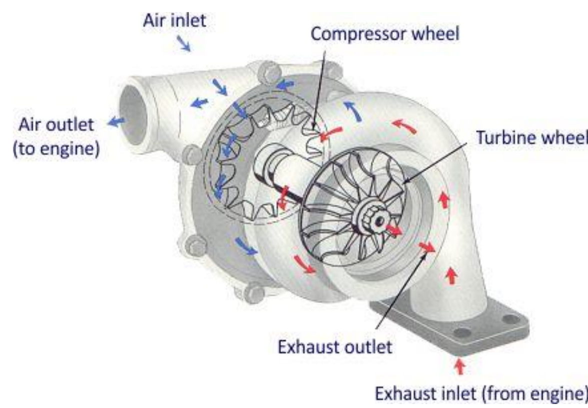


Fig 1. Turbocharger with its fundamental components.

1.1.1 Components

The primary components of a turbocharger are divided into two main parts –

The Turbine – The turbine consists of a turbine wheel and turbine housing. It is the job of the turbine housing to guide the exhaust gas into the turbine wheel. The energy from the exhaust gas turns the turbine wheel, and the gas then exits the turbine housing through an exhaust outlet area.

The Compressor – The compressor wheel and the compressor housing. The compressor's mode of action is opposite that of the turbine. The compressor wheel is attached to the turbine by a forged steel shaft, and as the turbine turns the compressor wheel, the high-velocity spinning draws in air and compresses it. The compressor housing then converts the high-velocity, low-pressure air stream into a high-pressure, low-velocity air stream through a process called diffusion. The compressed air is pushed into the engine, allowing the engine to burn more fuel to produce more power.

1.2 Compressor

The high output power of the engine is the results of the expanding exhaust gas in the turbine to drive the compressor and the high intake charge density compared to the natural aspirated engine. A Turbocharger uses a radial flow type compressor because of its compact and light weight structure and high efficiency. The design of the compressor wheel has to follow the aerodynamic requirements, mechanical strength considerations and the foundry capabilities. To achieve high mass flow and compressor efficiency, impeller blades need to be very thin, but a blade with robust root is needed to keep steady state levels and vibrating process under control. Smaller compressor tip diameter and high backswept impellers account for high pressure ratio, large flow range and low inertia turbocharger compressor impeller which in turn, increases the impeller rotational speed. Such high rotational speed induce very high in the impeller hub and the blades which govern the maximum speed of the compressor and vibration problems. Thus splitter design is implemented in the turbocharger impeller to increase the efficiency and aluminum casting is used in most of the production.

Fig. 2 Turbocharger compressor impeller

1.2.1 Impeller Blade

An impeller is a rotating component which consists of blades and vanes used in turbo-machinery. The Air Flow deflection after striking at the impeller vanes converts the mechanical power into pump power output.

Depending upon the flow line patterns of the gases in the impeller (especially in the outer diameter area of impeller), impellers can be subdivided into these following types :

1. Radial Impeller
2. Mixed Flow Impeller
3. Axial Flow Impeller
4. Peripheral Impeller

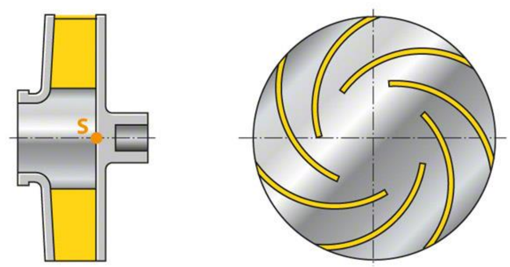


Fig 3. Impeller: Radial impeller with purely radial vanes, stagnation point S (shown with front shroud removed)

The design of impeller blades is a difficult task due to the fact that, ideally, three separate and equally important requirements must be satisfied. The first requirement is that the impeller provide acceptable distributions of relative velocity on both driving and trailing surfaces of the blades in order to minimize the possibility of flow separation and the accompanying loss in performance. In addition, the selected blade shape must be such that it can be manufactured accurately and economically by means of automated fabrication procedures. Finally, the blades should be designed so as to keep the stresses at a safe level, eliminating the possibility of excessive distortion or fracture occurring during operation. For many applications, these three requirements are somewhat incompatible. For example, it is possible to define a blade shape which theoretically would give ideal velocity distributions throughout. However, it is often the case that such a shape is virtually impossible to fabricate in any reasonable manner. Therefore, any practical design method must involve some reasonable compromises with regard to the conflicting requirements.

With the improvement in impeller designs engine speeds have been reaching up to 5000 rpm. Due to this wide range of engine speeds the design of turbochargers has been getting tougher. In order to adjust for this wide range of engine speeds the selection of back swept angle has become most important factor for impeller design.

2. METHODOLOGY

2.1 Design Study

During the design stage of the project, the impeller blade design was generated with the given dimensions. The blade geometry dimensions were specified along with the fluid properties using the Vista CCD function in Ansys software and the specific design geometry was generated using the BladeGen function.

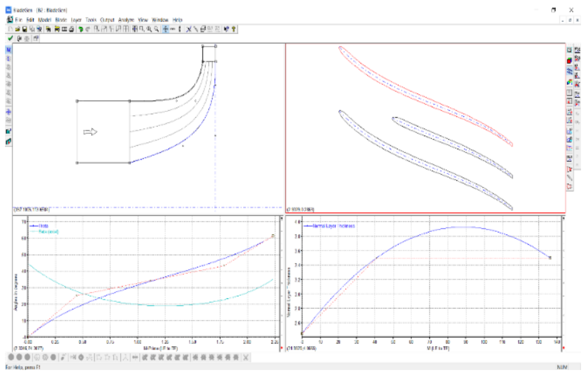


Fig 4. 3D Design of Impeller using BladeGen

2.2 Pre-Processing

In this stage the data was imported from BladeGen. The design was meshed and the topologies of the design were defined using the TurboMesh function. As a result, the flow path for the fluid was guided from inlet of blade to the outlet of blade. This process made the design ready for analysis.

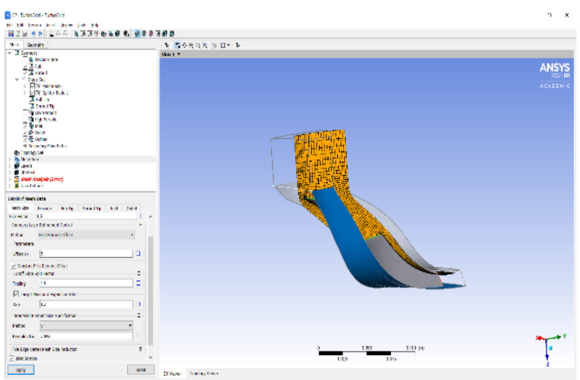


Fig 5.1. Pre-Processing: Meshing

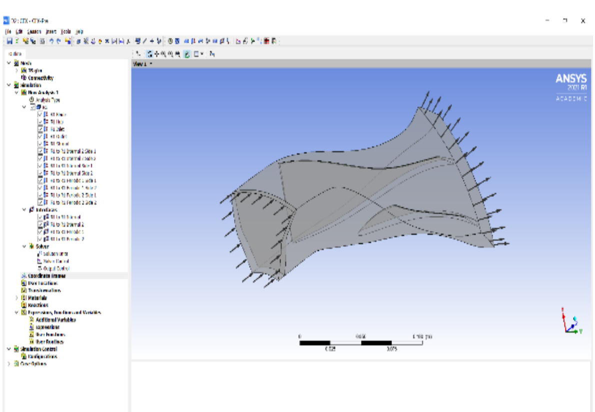


Fig 5.2 Pre-Processing: Flow Path Generation

2.3 Solution and Results

The pre-processed data was imported in the Ansys CFX solver. Using the design data and pre-processed data, a number of iterations were performed on the design geometry in CFX solver to obtain results. The solution was post processed to obtain and plot the results for the impeller performance showcasing many fundamental parameters.

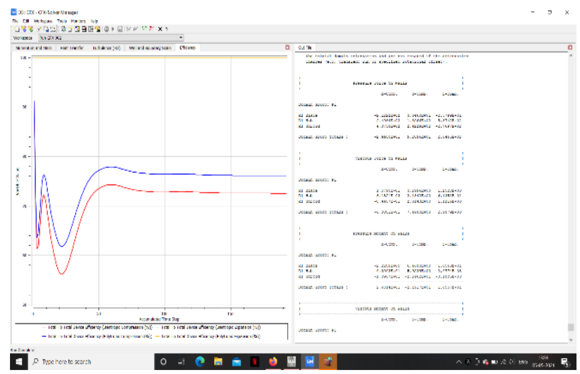


Fig 6. CFX Solver shows convergence of results

2.4 Optimization

After plotting of results for one set of design the same process is repeated for the new design sets. The variable parameter for design change is the back swept angle of the impeller blade. After performing the same methodology for all different design sets, the most optimized back swept angle design will be considered as the most efficient design of all.

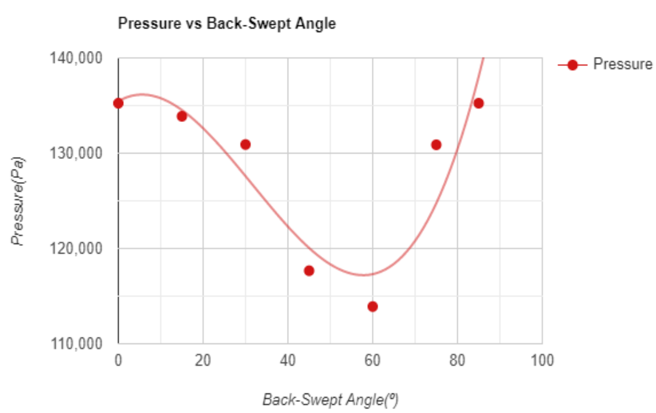
2.5 Result Table:

	Backswept Angle		
	0°	15°	30°
Pressure (Pa)	135242	133873	130911
% Increase in Pressure	33.33	32.04	30.48
Temperature (K)	323.346	322.405	320.681
Mach Number	1.048	1.057	1.0725
Isentropic Efficiency (%)	89.922	89.927	89.387
Velocity (m/s)	377.913	380.42	384.98

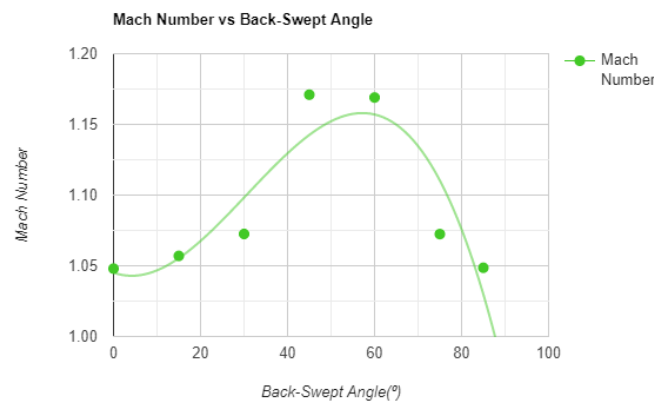
Result Table for angles **0º, 15º, 30º.**

	Backswept angle		
	45º	**60º**	**75º**
Pressure (Pa)	117665	113906	130883
% Increase in Pressure	16.05	12.38	29.11
Temperature (K)	310.172	309.723	320.691
Mach Number	1.171	1.169	1.0724
Isentropic Efficiency	90.182	87.172	89.354
Velocity (m/s)	411.301	412.374	384.931

Result Table for angles **45º, 60º, 75º.**



This graph represents the relation between Pressure plotted against different Backswept angles.



This graph represents the relation between Mach Number plotted against different Backswept angles.

2.6 Conclusions :

1) The pressure graph and temperature graph shows a strong correaltion. This is a proof that our results are consistent with our design. The selection of the appropriate angle was based on two considerations
   A) Aerodynamic Considerations
   B) Geometric Considerations
2) The backswept angles 45º and 60º were found not suitable due to the aerodynamic conditions. The gain in pressure as well as the gain in temperature were also low. According to geometric considerations the blade shape must be restricted to moderate inclinations against normals to the hub surface. Thus a blade shape consisting of straight elements on both surfaces is prefered. As a result,angles above 60º are eliminated as they are not optimal.
3) As we can see from the table above, for 0º backswept angle, albeit the percentage gain in pressure and temperature is very high manufacturing of impeller with 0º backswept angle is not feasible.
4) We find angles 15º to 30º, to provide the optimum ratio of pressure increase while keeping the Mach Number sufficiently low at the outlet of the impeller

- **At 15º** : we observe higher percentage increase in pressure and a higher isentropic efficiency as compared to 30º backswept angle.
- **At 30º** : we observe lower outlet temperature and higher outlet velocity as compared to 15º backswept angle.

5) Depending upon the material used for the design of the blade, different tolerances of pressure

maybe desired. In certain cases lower temperatures after compression are desired. Therefore, depending upon the application the user may choose a backswept angle between **15° to 30°.**

3. LITERATURE REVIEW

This review paper deals with the study of topics covered in the following research papers

3.1 Back swept angle performance analysis of centrifugal compressor

By Tie Wang et al. This paper takes into account the growing popularity of turbo-chargers in the automobile industry and how more and more cars of different models are adopting its benefits. In the paper, the authors point out a need to maintain and improve the performance of the compressor for a wide range of engine RPM, that can affect the isentropic efficiency and the pressure generated by the compressor. This paper takes inspiration from the past work, highlighting how difference in back-sweep angle of the impeller blade of the compressor can be used to vary the afore-mentioned parameters. The paper adopts TurboSystem (a software application and feature tool for turbo-machinery designs in the ANSYS Workbench) to create simulations for impeller flow field which is impellers with backswept angles of 0°, 2.5°, 5°, 7.5°, 10°, 12.5°, 15° and 17.5° It also uses CFX (Computational Fluid Dynamics software) to simulate every backswept angle impeller design. The authors further compare and analyze the results of flow field on different back swept angles through considerations on pressure ratio, isentropic efficiency, volume flow rate and Mach number.

When compared with radial impellers, the variations in the back-swept angle shows no improvement in the pressure-ratio. However, when operated between the range of 1000 rpm to 2000 rpm, these impeller blades can provide an improved isentropic efficiency. For less than 1500 rpm, the volume flow rate increases, however above the engine speed of 3500 rpm shock waves develop at the base of splitter blades that can cause reduction in the overall pressure generated.

3.2 Impeller Blade Analysis of a Centrifugal Gas Compressor.

By Vivek V. Kulkarni et al. This paper is focused on understanding the flow characteristics of the fluid in a centrifugal compressor. The study is focused on the flow around the impeller blade and studies various parameters like isentropic efficiency, pressure ration, mass flow rate and Mach number to derive a conclusion. The authors stress on avoiding 'Surge', or generation of high pressure at the outlet which creates a reverse flow of the fluid. This is especially detrimental to the compressor as it can lead to the compressor completely stalling. In this paper, the authors have kept all the design parameters constant while studying the effect of mass flow rate of different magnitude. The grid generation is done using TurboGrid tool in ANSYS workbench which consists of hexahedral cells of HJCL type with O-grid around the blades. At inlet, total pressure and total temperature are the boundary conditions applied and mass flow for outlet The impeller rotation speeds were also specified. The standard Shear Stress Transport (SST) k-ω turbulence model is used for this study.

In order to avoid super-sonic condition (Mach number > 1), an optimum mass flow rate of 0.2kg/s was found. Beyond this limit, shock waves are generated on the trailing edge of the impeller blade. With increasing mass flow rate, Isentropic efficiency increases, reaches a maximum value, and then drops significantly as the mass flow rate continues to increase. To understand that the design is working, we look at the interrelation of two parameters: pressure ration and temperature. As the pressure ratio increases, the density of the fluid increases which leads to the increase in the temperature. A graph of total pressure ratio and mass flow rate is plotted which is used for identifying the choke line.

3.3 Impeller Blade Design Methods

By Willem Jansen et al. In this research paper the authors discuss the conventional way of designing the impeller blade taking into consideration 3 parameters that are critical. The authors have explained, first, Aerodynamic considerations that come into play while designing the impeller blade. Losses in a centrifugal compressor are generally caused by boundary layer and separated flow-developments in the impeller and their subsequent effects in the diffuser. The development of the boundary layers and separated flows is directly a result of the velocity distributions along the blade, hub, and shroud surfaces. From an aerodynamic point of view, it is thus desirable to specify a velocity distribution along the pressure and suction surfaces of the blade such that the generation of separated flows is kept to a minimum. Secondly, geometrical considerations are taken into account. The ideal blade which would be composed of an arbitrary number of individually loaded streamlines represents a very general three-dimensional blade surface. The authors question whether such a blade could be economically produced with the required accuracy. Impeller casting patterns are very difficult to manufacture, particularly when the surface of the blade has an arbitrary shape, when close tolerances have to be maintained, or when the impeller size is small. A more desirable blade shape is one defined by straight-line elements; such a shape facilitates setting up the pattern and allows close tolerances to be maintained.

3.4 Material Analysis for manufacturing of Impeller Blade

By Azmil Jamri et al. Here the authors discuss the assembly of the turbocharger and the importance of designing the compressor blades well. The authors analyze the performance of the compressor based on three parameters: pressure, velocity and temperature inside the turbocharger compressor. For the aluminum alloy, a pressure of 130kPa was reached with 30m/s for velocity and 340K temperature. The material used for the new fan is Polyester/Epoxy IPN. This is cheaper than aluminum. This material can be used to design the impeller blade by casting which is significantly easier than the costly machining method used for the aluminum alloy. The results were different for the value obtained at this fan which were 140 kPa for pressure, 190 m/s for velocity and 340 K for temperature. This shows that the air pressure of the fan that made by the Polyester/Epoxy IPN increased, but decreasing the air temperature inside the turbocharger compressor.

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