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Performance Enhancement of Gas Turbine using CFD after Thermal Barrier Coating

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ABSTRACT

Axial flow compressors have the same axial direction of flow entering the compressor and exiting the gas turbine (parallel to the axis of rotation). An axial-flow compressor's working fluid is first accelerated, and then it is diffused to increase pressure. As air passes through the stages of an axial flow compressor, the pressure slightly rises. The torque generated by the rotor blades when an electric motor, steam turbine, or gas turbine is used amplifies the kinetic energy of the air or gas moving through the rotor.The designs and simulations of an axial flow compressor in this thesis were made using the 3D modelling programmes CATIA and Ansys 15.0. Aluminum is now in use. The scientists used Computational Fluid Dynamics (CFD) Simulation to plan the subsequent research steps, which comprised replacing the material with Titanium alloy and Nickel alloy, after conducting a few initial experiments. a fuel-air mixture's motion during combustion.The swirl effect and the fuel-air mixture ratio are also factors in determining the overall efficiency. To enable whirling recirculation flow, holes have been drilled all around the body of the combustion chamber's liner wall. This variable also has an impact on the combustion process' efficiency. Simulation was used to find the flow pattern. The results of the simulation can be used to improve the design of the combustion chamber and to guide future efforts to increase the effectiveness of the combustion process.

1. INTRODUCTION

One of the most expensive pieces of equipment used in aviation and stationary mechanical applications in the 20th century is the gas turbine (GT). It is also frequently utilised in the petrochemical, oil, gas, and power generation sectors, where dependability of quality and accessibility are essential. Yet, before the Second World War, the development of gas turbines was focused on electric power applications, and its first deployment was for military purposes. GT-based power plants have gained popularity because of their effectiveness and low CO2 emissions. The GT infrastructure is rising quickly to meet the soaring power demands brought on by expanding economies and populations. Gas turbines come in two varieties: those used in aviation and those utilised in fixed power plants.

Introduction to Gas turbine:

An internal combustion engine that uses a rotational configuration is called a gas turbine. No longer do internal combustion engines with cylinders and pistons require external fuel sources. The design of a gas turbine power plant is simple. The gas turbine is a unique device because it generates heat by burning fuel in a combustor, a specialised chamber.In the combustion chamber of a gas turbine, liquid fuel and compressed air are created. The gas must be produced at extreme pressure and heat. The injured gas expands and is used by the turbine to generate power. Gas is forced down a tunnel of blades, where its kinetic energy is transformed at the shaft into mechanical rotation. Similar principles to those used in steam turbines are applicable here.

The chemical energy of fuel is converted into mechanical energy by gas turbines, either in the form of shaft power or kinetic energy. Shaft gas turbines are another name for gas turbines that produce electricity. The thrust produced by a gas turbine is then utilised to propel the aircraft. many components of the energy stored in the gasoline is converted into the shaft power or propulsive force that drives the vehicle by a series of interconnected engines.

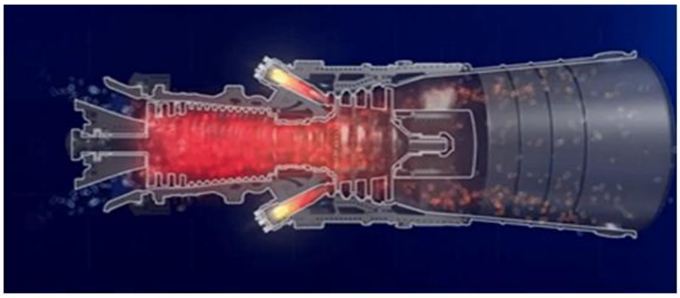

Figure: gas turbine

A working gas (air) is compressed and heated using the combustion energy of a fuel in a gas turbine. The working gas undergoes changes when its pressure and temperature increase. The engine converts the energy of the working gas into the rotational energy of the blades by contact between the gas and the blades. The basic components of both kinds are the air compressor, the combustor, and the turbine.The gas turbine can handle a higher gas flow than reciprocating internal combustion engines because it uses a continuous combustion process. If so, the high-power engine should be replaced by a gas turbine. The jet engine, a gas turbine used in aeroplanes, benefits from this. A gas turbine may be able to recycle part of the heat from the exhaust gas to warm the air entering the combustor by using a regenerator (heat exchanger). This cycle is widely used on low-pressure ratio turbines to produce hot gas, which is then allowed to expand through a turbine to produce work.

A.Gas Turbine Applications

Gas turbines are among the most frequently utilised technologies for power generation. Refineries for chemicals and oil could gain from their electricity production as well. They have had a significant influence on the transition to more environmentally friendly electricity generation in recent years. Electricity generation, transportation, and aviation are just a few of the energy-intensive industries where gas turbines play a significant role. Modern aeroplanes are propelled by these turbo motors, which also generate electricity for power plants and chemical companies. Gas turbines power a wide range of aircraft, from little passenger jets like the magnificent Hawker 400 (formerly known as the MU-300) to the enormous A380. They are also used by the Airbus Beluga and other freight aircraft of various sizes.

Advantages of Axial flow gas turbine:

- **Effective:**decreases drag and allows for use at high temperatures.
- **Efficient:**Reduces jet detachment and cooling inefficiency
- **Clean:**results in cleaner burning and more efficient combustion in turbine engines.
- **Better and easier to produce:** uses an uncomplicated layout that can be easily built**Introduction to Gas turbine blade:**

Introduction to Coatings:

Due to the necessity for them to function under constantly rising firing temperatures and high levels of environmental contamination, it is getting harder to build super alloys with the necessary creep strength on one side and the essential resistance to corrosion/oxidation on the other. Thus, coatings must be applied to the blades' surfaces in order to provide the required protection.This article explores the creation of coatings for gas turbine airfoils that serve as a reservoir for elements that will form highly protective and adherent oxide layers, protecting the underlying base material from oxidation, corrosion attack, and deterioration. Given the huge disparities between hot corrosion and pure oxidation in an aircraft environment, coatings for heavy-duty gas turbines have different capabilities than coatings for aviation engines.There are three basic types of coatings

- Aluminize (diffusion) coatings

- Overlay coatings
- Thermal barrier coatings (TBCs)

Introduction to thermal barrier coatings:

A typical TBC system is made up of four layers: a substrate, a thermally generated oxide (TGO) layer between the topcoat and bond coat, a metallic bond coat layer, and a ceramic thermal barrier layer. TBC's essential functions are satisfied by each layer's distinct physical and chemical properties.In a TBC configuration, the substrate materials are frequently superalloys based on Ni or Co, such as SC superalloys and conventional polycrystalline, directional solidified, and superalloys. High working temperatures cause interdiffusion between the bond coat and the substrate. High concentrations of refractory elements can be added to new generation SC alloys to ensure superior high temperature performance, but they also make the super alloys more susceptible to microstructure instability due to inter diffusion's significant impact on the mechanical properties of the substrate and the thermal cycling lifetime of TBCs. A topologically close-packed (TCP) phase and a so-called secondary reaction zone (SRZ) are produced as a result of inter diffusion, and both are known to weaken the mechanical properties of super alloys.

Materials in a TBC system:

A) Top coat:

TBC's top layer serves as insulation against the gas turbine exhaust's high temperatures. It is simple to understand why the gas turbine as a whole depends so much on the effectiveness and quality of the top coat; damage to the coat would expose the underlying turbine components to the hot gases. The substrate is kept cool enough to maintain its ability to support weight thanks to the top coat and internal cooling (which involves channelling some air from the compressor's exhaust through the internal channels of the turbine component). The top coat's temperature drop can range from 100 to 300 oC for coating thicknesses between 0.1 and 0.5 mm; as a result, the top coat's substance should have a low thermal conductivity.

B) Bond coat:

Top coat materials like YSZ are transparent to oxygen at high temperatures while still offering the essential thermal insulation. Moreover, the top coat's pores and microfractures allow deposits of corrosive salts to melt, penetrate, and eventually reach the substrate. Greater Al and Cr concentrations will affect the material's creep strength, hence they are frequently absent in sufficient amounts in the substrate to give corrosion and oxidation resistance at high temperatures. To provide the necessary oxidation and corrosion resistance and to help the top ceramic coat adhere to the metallic foundation, a protective metallic coating known as a bond coat is applied on top of the substrate.

Research background

For applications involving thermal spray, the APS is a proven technique. Traditional plasma spray-deposited coatings have an unfavourable microstructure characterised by large splat boundaries or fissures parallel to the substrate interface. Liquid precursors are pumped into the plasma jet to produce coatings with a finely structured surface, enhancing the coating's quality and performance.

Aim of the study

- Improve gas turbine efficiency in axial flow by optimizing blade geometry and improving blade materials.
- A method for designing the thickness distribution of TBCs for gas turbine blades was devised in this work. Here, a weighted-sum strategy was used to solve a multi-objective optimization issue based on results from three-dimensional finite element models.
- Production precision, output, and fabrication costs were all taken into account while designing a suitable multi-region top-coat thickness distribution strategy.

The outer surface of the turbine blade needs to be thermally insulated by the TBC. The performance of the coating on a certain Super-alloy substrate depends on the type of bond coat used. On the other hand, performance depends on the Super-alloy composition used for a certain bond coat.

Statement of problem:

- In axial flow turbines, the temperature impacts the blade geometry through thermal cracking, which can negatively impact the performance of the rotor system. Cracking has a negative impact on performance that must be mitigated.
- After applying barrier coatings to the blades, it is necessary to conduct computational and experimental analysis to determine how to

counteract the negative impacts of thermal degradation on turbine performance.

2. LITERATURE REVIEW

Adel Ghenaiet. (2016). simulated the stator/rotor interactions and their characterisation in a two-stage axial turbine under steady and unsteady flow conditions. Operating conditions included an average inlet total pressure of 2841460 Pa, a temperature of 1510 K, and a rotational speed of about 9823 rpm. ANSYS CFX code was used in these conditions. A two stage high pressure axial turbine drove a high pressure compressor to record the interactions. The Fast Fourier Transform (FFT), which is characterised by a space-time periodicity, was used to examine the flow's unsteadiness.

Anna Minasyan (2018). Data gathering across a wide range of flow conditions was necessary to model the engine's performance following axial turbine integration, which produced a high isentropic efficiency of 86.2% at 102,000 rpm. The focus of the study also included creating and optimising a volute for an axial inflow turbine. Once a basic design was chosen after being tested using CFD models, additional optimization increased the stage's overall efficiency to 81.2%.

Avwunuketa, A. A et al (2019) . The performance, characterisation, and evaluation of the aircraft axial flow gas turbine engine are the main subjects of this study. Earlier research tried to increase the power of the turbine to improve performance. In order to boost the turbine blades' effectiveness, a higher temperature was applied to them. Using knowledge from material science and engineering, blades that can operate dependably at greater temperatures were created.

C. De Maesschalck, et al. (2014).The research of the associated aerothermodynamics effect and tight rotor tip clearance in enshrouded turbines was conducted numerically. The HP turbine stage was analysed using the FINE/Turbo code and the k-SST turbulence model under engine-like circumstances. Five clearing values, ranging from 0.1% to 1.9%, were simulated. Findings showed that when the clearance was less than 0.5% of the blade span, streamlines displayed reversed flow and a large heat transfer gradient towards the tip. When the clearance was greater than 0.5%, the influence of leaky vortices was also substantial. That came to an end; the tight tip clearance led to a slightly better efficiency because of lesser leakage flow but has severe heat impact on the blades.

Fanzhou Zhao (2018) introduced 3D blade features for a multi-stage axial compressor rotor, such as sweep and dihedral, and showed how they affected the flow physics through comprehensive CFD and experimental research. A second thorough CFD examination of steady and unsteady systems was performed.

J. Cui, (2017) performed a numerical simulation of secondary flows in a high lift-based LP turbine. It was solved using Rolls Royce's HYDRA solver, which was second order accurate in both time and space. The velocity was reduced to match the Turbulent Boundary Layer (TBL) and Laminar Boundary Layer (LBL) case Reynolds number using an unstructured, edge-based finite volume algorithm. Also taken into consideration was a wake with secondary flow (W&S) situation.Further disturbances within the blade passage in TBL and W&S improved mixing of the flow, which significantly increased total pressure loss when compared to LBL. W&S caused the loss generation rate to rise upstream of the transition point while falling downstream of it. Their work was determined to be essential for further research since it utilised three significant intake circumstances and contrasted the results of secondary flows. It also illustrates the various effects secondary losses have on modern high-lift low pressure turbines.

Mauro Righi et al (2018).However, recent developments in CFD have significantly reduced the time and costs associated with designing any component of turbo machinery by providing a holistic prediction of the flow due to small or significant design changes. This has been demonstrated by many researchers, including the development of a streamline curvature through-flow code that incorporates 3D flow phenomenon and was validated with experimental data from a multistage axial compressor that showed a very close match.

Milan (2016).carried out a comparison of through flow analysis and conventional CFD for multistage compressor They came to the conclusion that both methods had advantages and disadvantages. Through flow methods, in contrast to standard CFD methods, are suitable for quick and reliable analysis, especially for multistage machinery.

Nader A et al (2017) This study offers an analytical method for enhancing the initial 3D aero thermodynamic design of a single-stage axial flow turbine that drives the compressor in the tiny Jet Cat p200 turbojet engine. The small gas turbine's geometrical characteristics, which were obtained by reverse engineering, are the foundation of the new design. Stage dimensions at baseline are 0.5 by 1.14 inches, with the NGV (stator) row showing the highest expansion. Stage loading factor and flow coefficient are likewise close to 1.14.

3. METHODOLOGY

Basic steps involved in the project

1. Design of axial flow compressor is done by using NX 12.0
2. The analysis gets carried out by using a ANSYS version 2020R1
3. The Ansys is carried out by using materials

The efficiency at the design point of an axial flow compressor is maximized by modifying the geometry supplied by the software. The program's organizational framework Using dimensional analysis for just one step, and presuming the following:

1. Constant axial velocity C_x
2. Constant mean radius $r_m = 1/2(r_h + r_t)$.
3. Identical velocity vectors C1 and C3 at entry to and exit from the stage at the mean radius r_m. The efficiency η_t of this stage is dependent upon the following variables,

Independent Design Variables:

About the duty coefficients (,), the design was done at will. The efficiency of the stage and the completion of the task are significantly influenced by the shape of the velocity triangles and the flow environment of the operating blades in addition to the degree of reactivity (R) control the reins Due to its triangular design and heightened effectiveness.

DEPENDENT DESIGN VARIABLES:

The experimental cascade testing also affects the loss coefficients Rs, which depend on the inlet Mach number and the blade row Reynolds numbers. We would also assume that the three axes of the velocity triangle in which the blades must work,,, and R, will affect the loss levels.

Flow solution

ANSYS CFX v12.1 was used as solver. The numerical settings for the solver are described below.

Boundary conditions:

a single row of blades in alignment The study considered the 3D journey for each of the three steps, as seen in the image. The assumption that all of the solid borders were walls eliminated any chance of slippage or heat transfer. Regular borders were built along the perimeter of the territory. As long as the flow was normal to the boundary, the total pressure and temperature were imposed at the compressor stage's inlet. The exit boundary was defined by static pressure at the centre of the stage, with pressure average over the entire face.

Flow solver:

The computational study for each of the three stages was carried out simultaneously using an adaptation of ANSYS CFX's steady state density-based RANS (Reynolds Averaged Navier Stoke) solver that takes viscous work into account. For turbulence closure, the SST (Shear Stress Transport) k-model with 5% inlet turbulence intensity was taken into consideration. Rotor stator interaction plane was described as a mixing plane that averages the flow parameter circumferentially to communicate information at the interface.

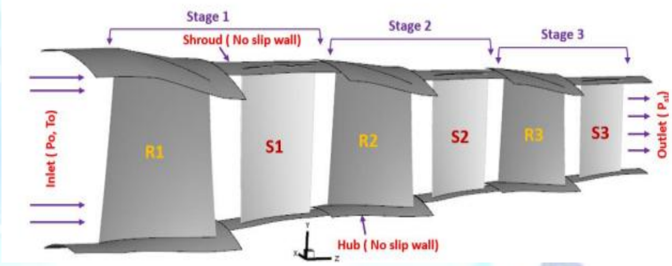

Fig: Computational domain with boundary conditions.

Design of Axial flow compressor:

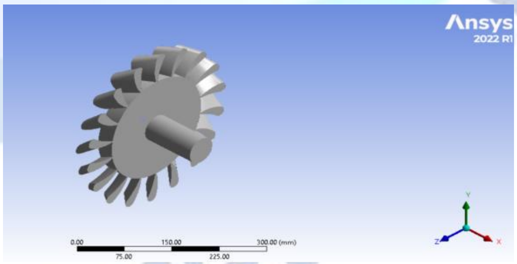

Figure: Imported model

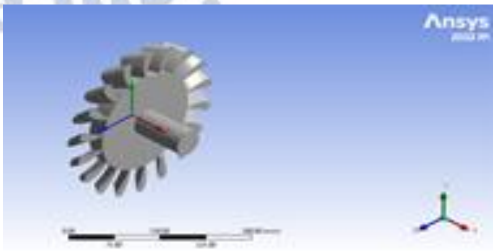

Figure: Displacement

Figure: Meshed model

Area: 66454.74 mm2

Solution Solution – Solve – Current LS – ok Post Processor General Post Processor – Plot Results – Contour Plot - Nodal Solution – DOF Solution – Displacement Vector Sum

4. RESULTS AND DISCUSSIONS

The direction of flow exiting the gas turbine from an axial flow compressor is parallel to the axis of rotation. An axial-flow compressor accelerates its working fluid before dispersing it to increase pressure. In an axial flow compressor, the pressure progressively rises as air passes through each stage. The rotor blades apply torque to the fluid travelling through the turbine, which is powered by an electric motor, steam turbine, or gas turbine.

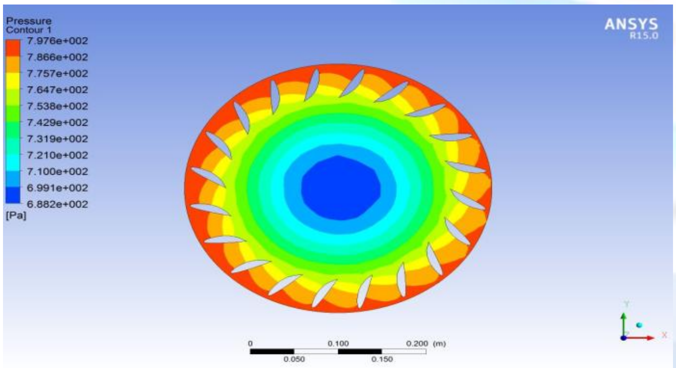

Figure: Pressure contour along x-direction

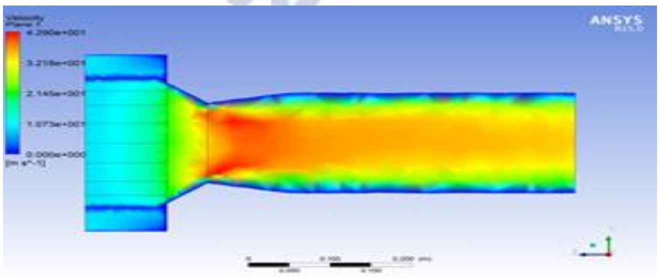

Figure: Velocity plane

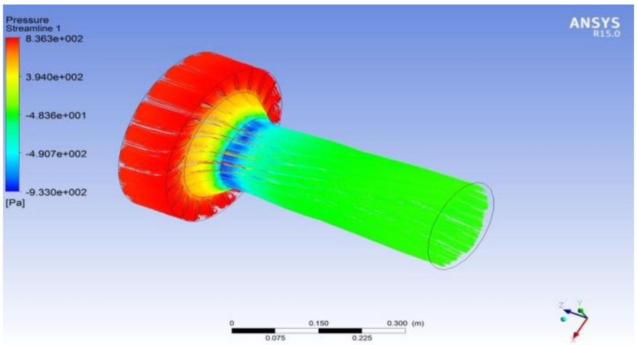

Figure: Pressure streamline

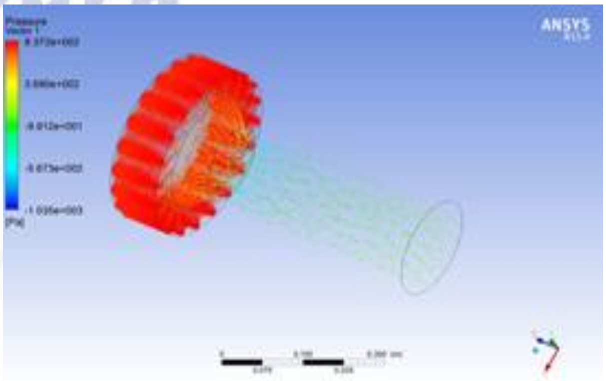

Figure: Pressure vector

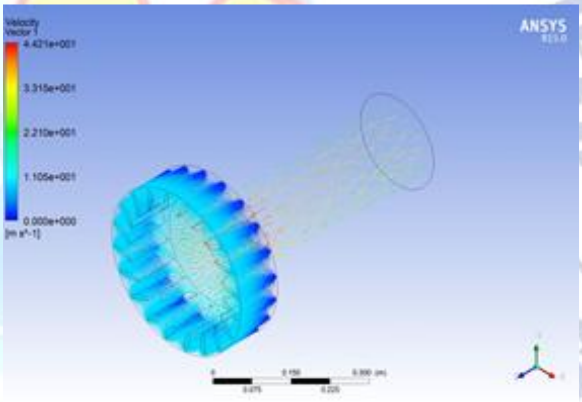

Figure: Velocity vector

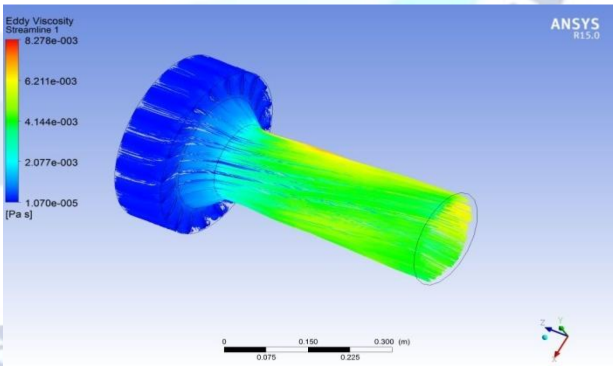

Figure: Eddy viscosity

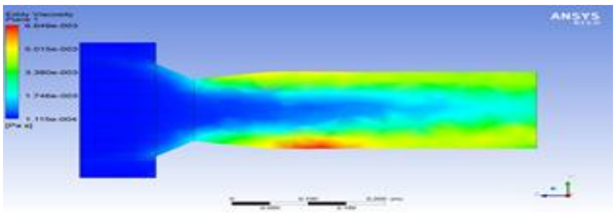

Fig: Eddy viscosity along x-direction

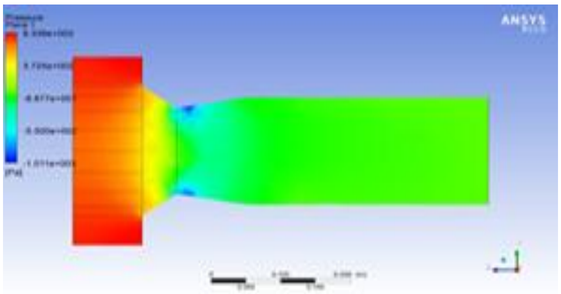

Figure: Pressure plane

Profile study

Here we will look at regional averages for YZ, YZ, YZ, and YZ real estate. Keep in mind that the span has a value of 0 at the center line and a value of 1 at the walls, and that it varies linearly.

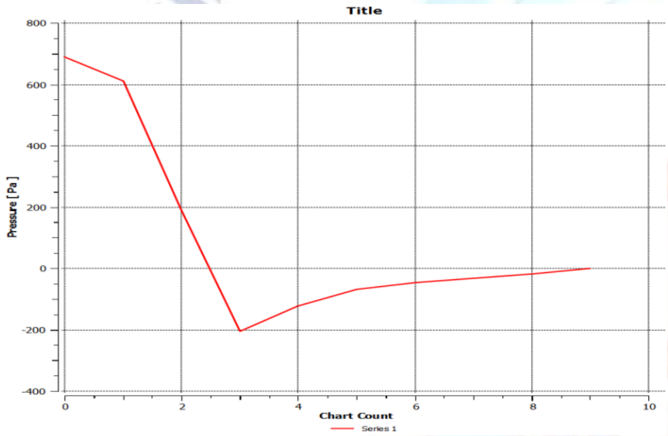

Figure: Pressure profile case1 model

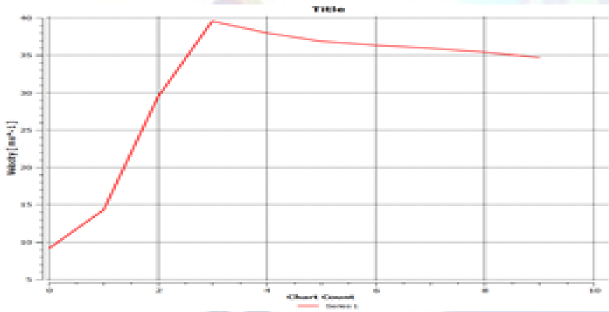

Figure: velocity

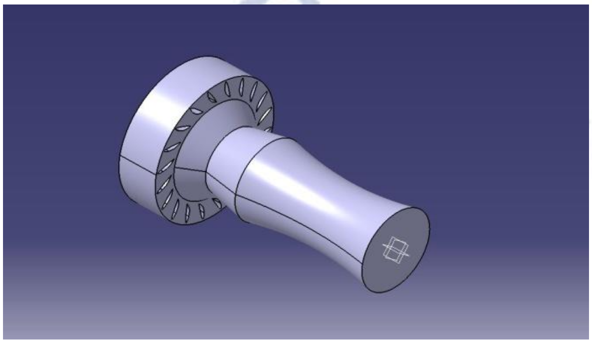

Figure 4.20 model

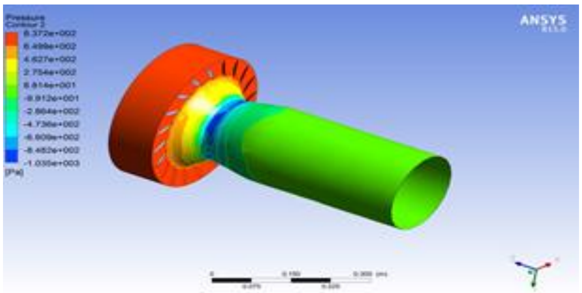

Figure: Pressure contour

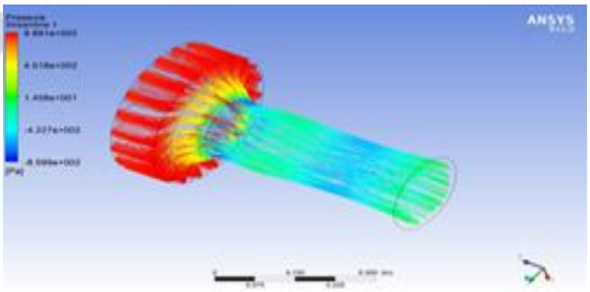

Figure: Pressure streamline

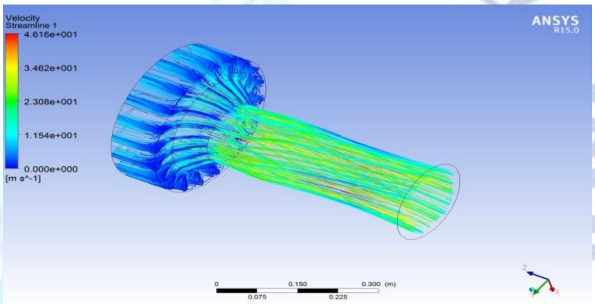

Figure: Velocity streamline

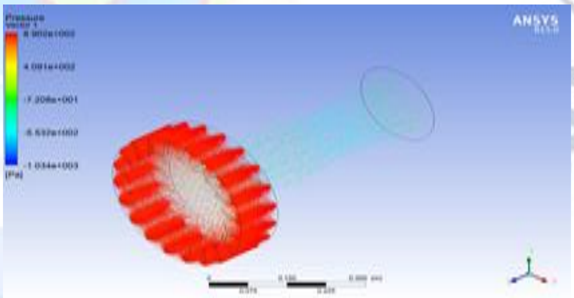

Figure: Pressure vector

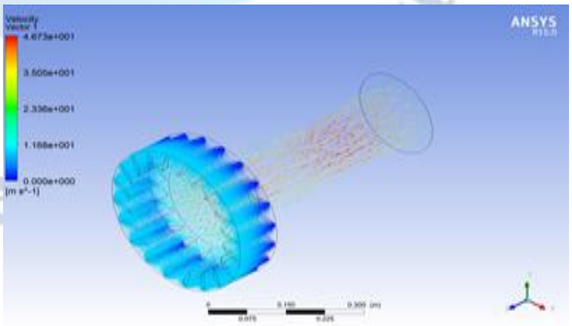

Figure: Pressure vector along x-direction

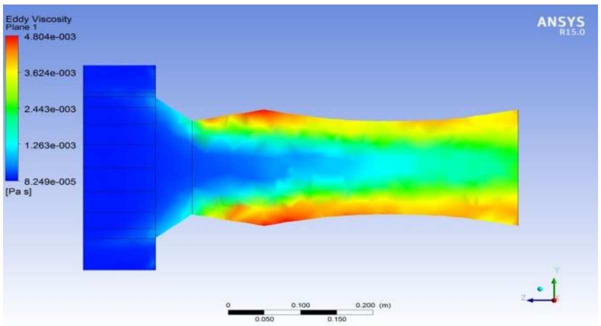

Figure: Eddy viscosity

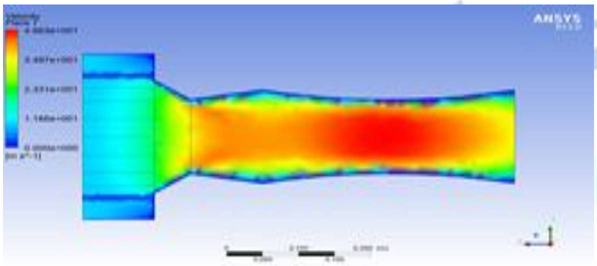

Figure: Velocity plane

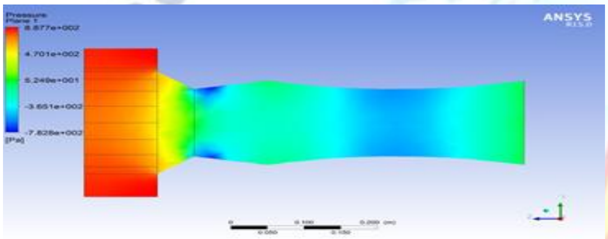

Figure: Pressure

Profile study

In this section we will study area average values of properties on YZ, YZ, YZ and YZ.

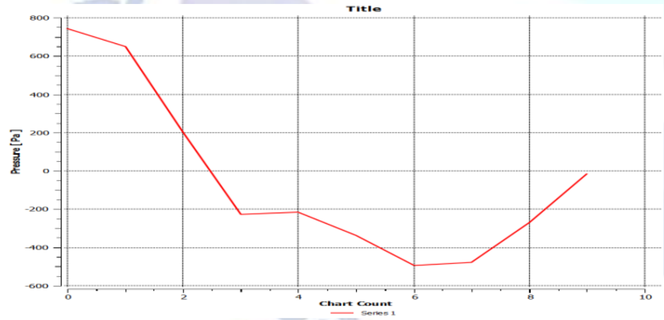

Figure: Pressure profile at different YZ planes

All of these profiles exhibit the same pressure distribution, with the exception of the YZ profile, which exhibits a jump that represents a numerical error in solution rather than a significant physical reality.

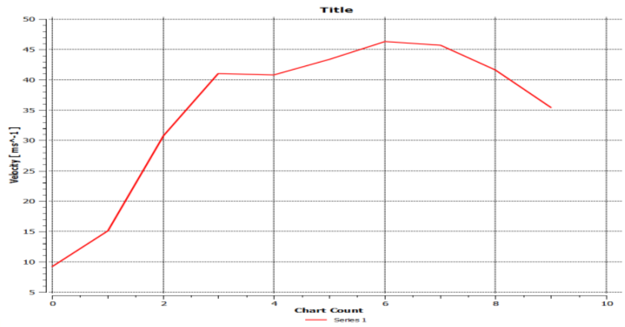

Figure: Velocity

The accompanying chart illustrates how the mole fraction of CO changes throughout time. Since the fuel is consumed as the water flows downstream, as the name suggests, there is nothing to burn and produce carbon monoxide. It is crucial to remember that CO profiles, which are determined by the section of a flame, are extremely iteration-sensitive due to the unavoidable change in a flame's actual shape.

Table: Data table Case a, Case b,

	CH4	O2	CO	CO2	T(ave)	T(max)
Mid plane	9.680e-03	1.071e-01	7.260e-04	8.068e-02	1.715e+03 [K]	2.088e+03 [K]
YZ	3.679e-02	2.165e-01	2.791e-03	3.020e-03	6.793e+02 [K]	1.590e+03 [K]
YZ 1	2.494e-02	1.725e-01	8.706e-03	2.627e-02	1.089e+03 [K]	2.085e+03 [K]
YZ 2	2.134e-03	8.162e-02	8.755e-03	8.875e-02	1.944e+03 [K]	2.087e+03 [K]
YZ 3	9.042e-05	6.893e-02	8.231e-04	1.068e-01	2.073e+03 [K]	2.086e+03 [K]
YZ 4	6.608e-06	6.816e-02	8.663e-05	1.082e-01	2.082e+03 [K]	2.087e+03 [K]
YZ 5	2.974e-07	6.807e-02	2.721e-06	1.084e-01	2.085e+03 [K]	2.088e+03 [K]

	CH4	O2	CO	CO2	T(ave)	T(max)
Mid plane	8.932e-03	1.041e-01	6.732e-04	8.281e-02	1.744e+03 [K]	2.087e+03 [K]
YZ	3.671e-02	2.162e-01	2.888e-03	3.089e-03	6.817e+02 [K]	1.556e+03 [K]
YZ 1	2.168e-02	1.604e-01	1.010e-02	3.300e-02	1.202e+03 [K]	2.087e+03 [K]
YZ 2	9.322e-04	7.473e-02	5.074e-03	9.783e-02	2.012e+03 [K]	2.087e+03 [K]
YZ 3	2.029e-05	6.832e-02	2.320e-04	1.079e-01	2.079e+03 [K]	2.087e+03 [K]
YZ 4	8.395e-07	6.812e-02	1.235e-05	1.083e-01	2.082e+03 [K]	2.086e+03 [K]
YZ 5	1.341e-07	6.810e-02	5.728e-07	1.084e-01	2.085e+03 [K]	2.087e+03 [K]

It is calculated what each variable's averages are. The highest average CH4 concentration of the three scenarios is seen in Case C, where heat transfer takes place. The maximum temperatures at mid-plane, YZ 3, YZ 4, and YZ 5 are all fairly comparable. Due to the two scenarios' different flame shape patterns, Tmax differs between YZ 1 and YZ 2.

Heat transfer coefficient calculation

The test case shown in Figure A3 with a 2-mm-thick steel plate in the middle and two air inlets on either side can be used to calculate the heat transfer coefficient. Incoming hot air is 1800K whereas incoming cold air is 600K in temperature. Post the heat transfer coefficient's calculated result. Both hot and cold air are permitted at 20 metres per second.

5. CONCLUSION

CFD study and axial flow compressor design have both been completed, and they are mostly focused on small gas turbine (SGT) applications. To examine how all the stages interact, in-depth flow physics is looked into. During the simulation, it was found that convergence of the solution was highly challenging for low pressure ratios with large flux variation at all three operating speeds. CFD analysis is used to test the airflow. Blades are experiencing an increase in both pressure and outlet speed. This being the case, we reasoned that titanium alloy compressor blades would be advantageous.The Mass Flow Rate, Pressure Ratio, and Pressure at a Given Altitude are used. Both rotors and stators have analytically derived blade profiles. To rule out the alternative possibility of flow separation, Mach number and pressure coefficient are also applied. The stresses are less than the yield stresses for alloys of nickel and titanium. It is better to utilise titanium alloy because it has a lower stress value than nickel alloy. The computation spreadsheet is created so that the user can input their own values to receive the parameters needed to compute the blade coordinates.Results from the CFD study are found to agree with the theoretical results within an acceptable range, as determined by comparison with the analytical results of the design.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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