iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** XII **Month of publication:** December 2016

DOI:

Volume 4 Issue XII, December 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Performance Prediction of a Gas Turbine Operating on Air Using 3D CFD

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Abstract - In this paper the work is to demonstrate the performance of single stage gas turbine which is able to operate with hot air as a working fluid at specific boundary conditions. These boundary conditions were chosen to be compatible with a Brayton cycle. The evaluation is dependent on the turbine efficiency and output power. Firstly, preliminary design work was completed in order to figure out the turbines shapes and find initial information about the impact of various factors on their efficiency values and output powers. Factors considered were: inlet pressure, inlet temperature, rotational speed and the mass flow rate. The performance was predicted at two different operating pressures (2 bar and 3 bar) at constant temperature (600K) by varying rotational speeds. Subsequently, three-dimensional computational fluid dynamics (CFD) modeling was completed for gas turbine to study the effect of other factors and have accurate results. The simulation results showed that an improvement in total turbine efficiency from 80-90% for a fixed cycle boundary conditions.
Key words: - CFD, Gas Turbine, Rotational Speed, Turbine Efficiency, Output Power

I. INTRODUCTION

Medium-scale gas turbines (MSGT) are considered as a promising technology because of their low initial costs, low maintenance, durability and simple construction. The need for an efficient medium-scale gas turbine, which can operate at low mass flow rates, relatively low pressure ratios and moderately high temperatures, was the driving force for investigating the Medium-scale gas Turbine (MSGT). A gas turbine function is to produce mechanical power to drive a pump, compressor or an electric generator etc. within the gas turbine, fuel chemical energy is converted into heat energy and is used to producing mechanical energy. Air is served as a working fluid for the engine which is compressed in the compressor, used in combustion in combustor and resulting combustion gases are fed into the expander for production of mechanical energy. Gas turbines produce high quality heat that can be used for industrial or district heating steam requirements. Gas turbine systems operate on the Brayton cycle. In a Brayton cycle, atmospheric air is compressed, heated, and then expanded, with the excess of power produced by the turbine over that consumed by the compressor used for power generation. The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the device. Consequently, it is advantageous to operate the expansion turbine at the highest practical temperature consistent with economic materials and internal blade cooling technology and to operate the compressor with inlet air flow at as low a temperature as possible. As technology advances permit higher turbine inlet temperature, the optimum pressure ratio also increases.

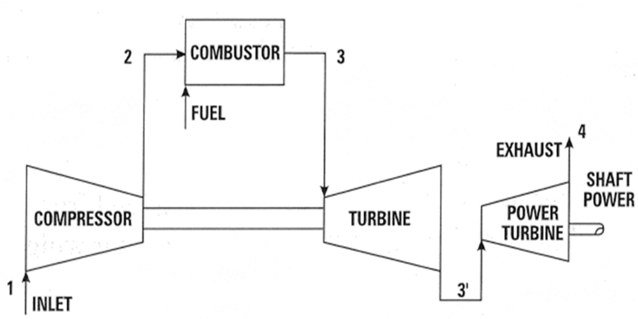

Fig. 1 General Brayton Cycle

There are varying opinions about what characterises a medium-scale gas turbine, however the significance of the power output is commonly agreed upon. Several studies investigated separately different components of the cycle: such as the thermal cavity receiver of a medium-scale solar Brayton cycle [1]; the effect of some boundary conditions on the overall cycle efficiency [2]; and the optimum performance of the cycle [3]. However, they neglected the turbines' performance. The off-design performance of a medium-scale humid air turbine cycle was studied by Wei et al. [4].

It is stated that the axial flow type has been used specifically in aircraft gas turbine engines and they are also usually engaged in industrial and shipboard purposes [5]. The Siemens Gas Turbine (SGT)-100 is an industrial gas turbine in the power output range from 4 to 5 megawatts (MW) which combines compact and rugged construction with advanced technology. For industrial power generation a single-shaft version of the SGT-100 is used which has a power output of 4.05 MW. Low power gas turbine generating sets with capacities up to 5 MW are used in transportation containers to provide mobile emergency electricity supplies delivered by the truck to the point of need. This Expression of Interest seeks response from Original Equipment Manufacturers, who are willing to be associated with BHEL through a license & technology collaboration agreement on long term basis, to enable BHEL to Engineer, Manufacture, Assemble, Test, Supply, Field Install, Commission, Repair, Service and Retrofit 1.5 MW (ISO) rating Gas Turbine and its auxiliaries. The Gas Turbine should be suitable for marine (defence) application.

In this study a comparison, with a range of around 1-5MW was considered. From the perspective of the application, it is necessary to have a suitable gas turbine which is able to work efficiently at some fixed boundary conditions. Then CFD techniques were used to evaluate the mean-line approach and improve the blade loading by some adjustment of the angles of the blades. Their results showed that achieving a high power output required a higher inlet temperature, mass flow rate and pressure ratio. The results also showed that the minimum number of rotor blades, which was suggested by meanline modelling, was overestimated.

II. 3D GEOMETRY MODELING AND MESH GENERATION

The three dimensional blade generations ability which ANSYS 17 has enables the users to generate three dimensional Turbo Grid models for the stator and the rotor of the medium scale gas turbines (MSGT). When the Preliminary Design was performed, the blade geometry and dimensions for both stator and rotor were exported to the detailed blade design module in ANSYS 17 called Blade-Gen to construct the blade geometry of turbine stage. CFX Turbo-Grid was used to mesh the fluid domain. As it is well known, the discretization of the domain has a direct effect on the quality of the solution in terms of accuracy and computational costs. The structured 3D mesh generation for blade-blade passage used in the simulations is shown in Fig.2&3. Also the Fig. 2 shows a section of turbine stage consists of stator and rotor in which stator has single blade and rotor has two blades in a flow passage for a particular section.

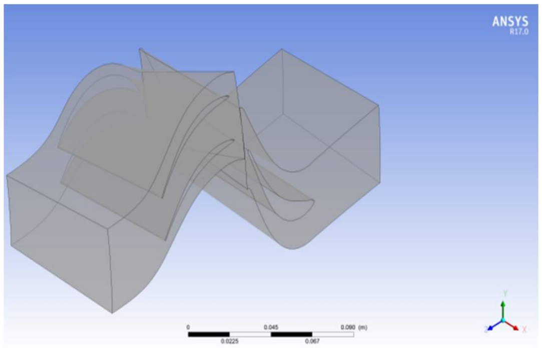

Fig. 2 Design of Turbine Stage

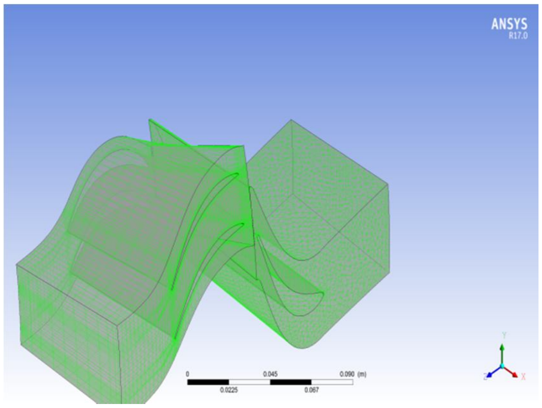

Fig.3 Turbo grid Mesh

Volume 4 Issue XII, December 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Table: 1.Mesh Report For Gas Turbine

Domain	Nodes	Elements
Rotor	38360	33202
Stator	36768	136297
All Domains	75128	169499

In a mesh, grid size for the gas turbine section of 75128 nodes was used; 36768 for stator and 38360 for rotor with a refined mesh near the blade wall. It is worth noting that in the zone near to the blade surface and walls, the grid was refined to maintain a good compromise between computational costs and solution accuracy. The k-ω based on SST turbulence model was implemented to produce a highly accurate prediction by the inclusion of transport effects in terms of flow separation prediction into the formulation of the turbulent viscosity (eddy-viscosity). To account the wall effects in the simulation, an automatic wall treatment was applied, which allows smooth shift between wall functions formulation and low-Reynolds number through computational grids without losing accuracy [6]. y+ is the dimensionless distance from the wall which is used to check the distance from the wall to the first node. The k - ω transport equations are:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u i)}{\partial x} = \frac{\partial(\Gamma \frac{\partial k}{\partial x})}{\partial x} + Gk - yk + Sk$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u j)}{\partial x} = \frac{\partial(\Gamma \frac{\partial \omega}{\partial x})}{\partial x} + G\omega - y\omega + S\omega$$

The k-ω based SST model accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients.

III. 3D NUMERICAL SIMULATION

The simulation of 3D turbulent viscous flow in the gas turbine of SST geometry was performed using ANSYS 17-CFX solver. Steady state 3D viscous, single phase, compressible flow was used. Topology with a first order upwind advection scheme was chosen because it is numerically stable. These assumptions were suggested by [7]. A stage interface was applied for the interface between the stator and rotor. The Generalized Grid Interface feature of CFX was chosen for stage analysis and the steady state flow. The periodic boundary conditions were applied for blade passages for both the stator and the rotor. The shear stress turbulence model (SST) was chosen and combined with Navier-Stokes equations. Simulations are carried out on the gas turbine with different operating pressures 2 bar and 3 bar at a constant inlet temperature 600K.The applied Boundary conditions are the total temperature, total pressure, flow direction, and the rotational speed as inlet conditions. A rotational, adiabatic wall was chosen for the blade and hub surface. The static pressure was chosen to be an output Boundary Condition. The convergence criteria for the residuals of both velocity and the continuity equations were of the order of 10^{-5} while for the energy equation 10^{-6}.

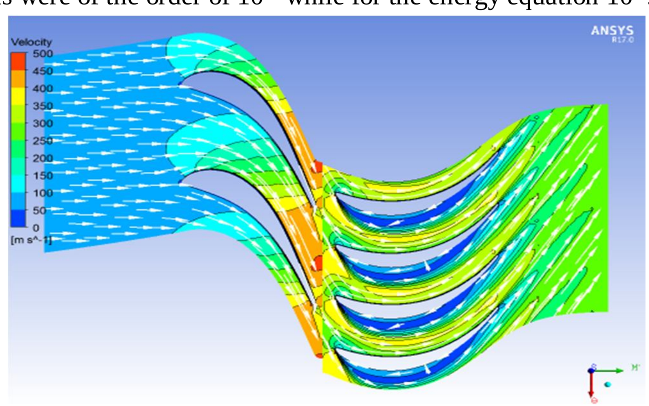

Fig.4 Velocity contour at 2 bar, 2000 rpm

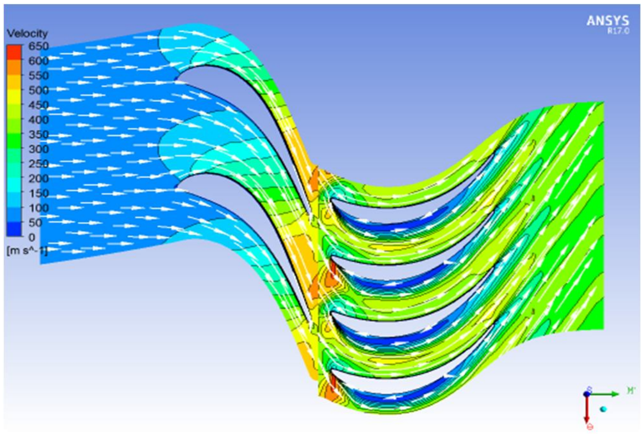

Fig. 5 Velocity contour at 3 bar, 2000 rpm

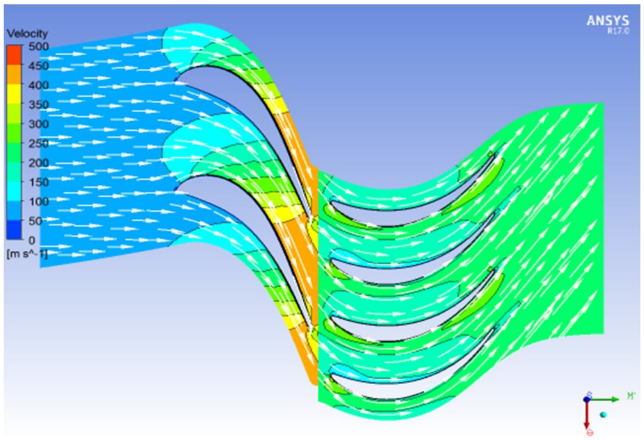

Fig.6 Velocity contour at 2 bar, 5000rpm

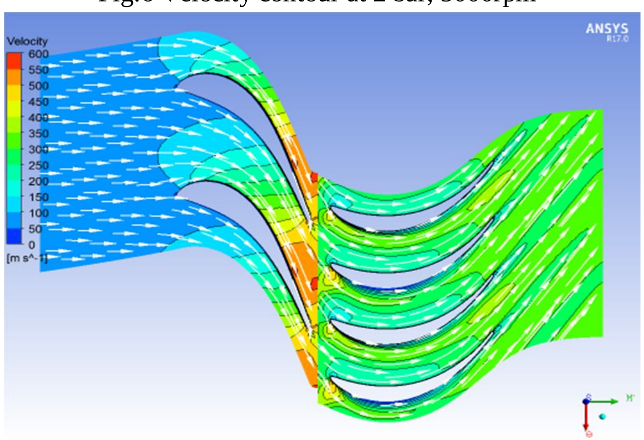

Fig.7 velocity contour at 3 bar, 5000 rpm

The solutions were achieved once the convergence criteria were satisfied. Typical shapes of velocity distributions, for the gas turbine are shown in Fig. 4,5,6,7 respectively at two different operating pressures. Since, Simulations are carried out at two different operating pressures 2 bar and 3 bar. For each operating pressures, the analysis is performed at five different speeds to estimate how the performance characteristics of a gas turbine are affected. From the above figures it can be seen how the velocity was homogeneously distributed along the blades' height, which is essential in order to decrease secondary flow effects. At lower speed, the velocity distribution in rotor blades is low as compared to higher speed which shows that by increasing the rotational speeds. It can be seen that the differences between the velocities are increased with changing the pressure ratio to higher values. From these figures it can be seen that even though very good agreement was achieved, there was some deviation in the results; however, it was within the acceptance limit.

IV. RESULTS AND DISCUSSIONS

In this paper, the simulation of 3D turbulent viscous flow of SST geometry has been performed by using ANSYS 17-CFX solver. As a result, the effect of each: pressure ratio, rotational speed and temperature on the total to static turbines efficiency and output power have been figured out. Some of these results are shown in Figs. 8, 9, 10, 11, 12. Since, the simulations are performed on a gas turbine with two different operating pressures at a constant inlet temperature. Analysis is progressed at various rotational speeds to estimate the behavior of performance parameters. From the fig. 9, 10 as the rotational speed is increased, the efficiencies (total isentropic efficiency and total polytropic efficiency) are simultaneously increased. Comparison is made between the 2 bar and 3 bar operating conditions. It was seen that the former gives slightly better efficiency as compared to the latter. At 2 bar pressure condition due to low enthalpy drop the flow velocity is decreased because the fluid having low Mach number. As the rotational speed increased, the difference between the two efficiency trend lines of 2 bar and 3 bar conditions shows that 3 bar pressure condition the total isentropic efficiency and total polytropic efficiency is slightly lower than 2 bar pressure condition.

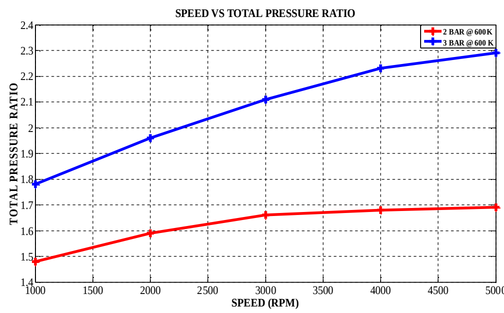

Fig. 8 Speed Vs Total Pressure Ratio

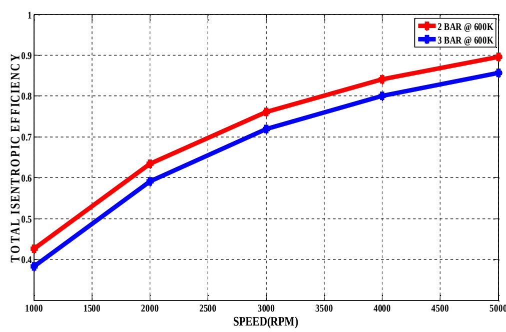

Fig.9 Speed Vs Total Isentropic Efficiency

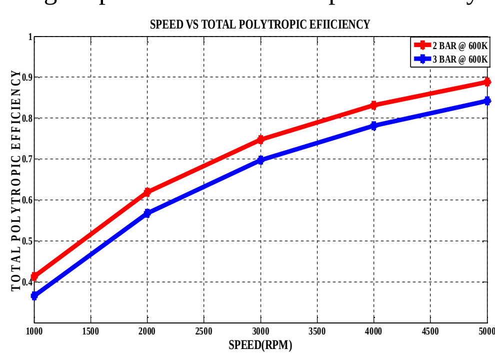

Fig.10 Speed Vs Total Polytropic Efficiency

This is because increasing the Rotational speed allows a reduction in both Secondary and leakage losses. And also from the results obtained from the simulation, the entropy variation is more in 3 bar condition and hence more irreversibility is the major cause of slight variation of efficiency compared to 2 bar condition. Turbine outlet temperature is also major reason for efficiency difference

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between 2 bar and 3 bar pressure conditions. Since, the turbine inlet temperature is constant (600K) more outlet temperature results higher efficiency of a turbine stage.

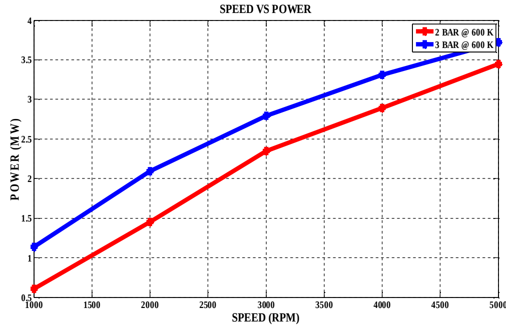

Fig.12 speed vs power

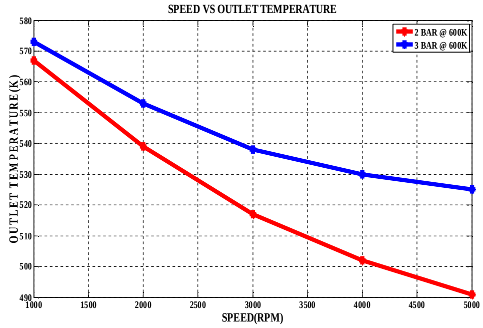

Fig.13 Speed Vs Outlet Temperature

Generally speaking, the output powers are strongly depended on the pressure ratio, which increased from 2 to 3. Interestingly, both of the cases had almost the same trend with increasing both the pressure ratio and the rotational speed. Furthermore, an increase in the output power was continuous with increasing SST rotational speeds. Again the reason for that is relating to the values of both secondary and leakage losses. A qualitative assessment of the output power for the same Boundary Conditions (BCs), can be done comparing their trends. It can be seen that the higher rotational speed the higher difference in the extracted power values. The maximum achieved output power values were 3.45MW and 3.72MW for the 2 bar and 3 bar pressure conditions respectively. At this point it is importance to emphasize that same Boundary conditions were applied for the two investigated SST.

V. CONCLUSION

In this paper, a series of computational simulations have been conducted to provide pretest performance for the single stage gas turbine. The performance of single stage gas turbine with compressed air as a working fluid has been investigated at different boundary conditions. The performance was predicted at constant temperature at two different operating pressures by varying rotational speeds. At 2 bar constant temperature boundary condition the total isentropic and total polytropic efficiencies are 89.8 %, 86.9% respectively which are maximum as compare to 3 bar pressure. The simulation results showed that an improvement in total turbine efficiency from 80-90% for a fixed cycle boundary conditions. The maximum power output for a gas turbine is 3.72 MW which is obtained at 3 bar constant temperature boundary condition.

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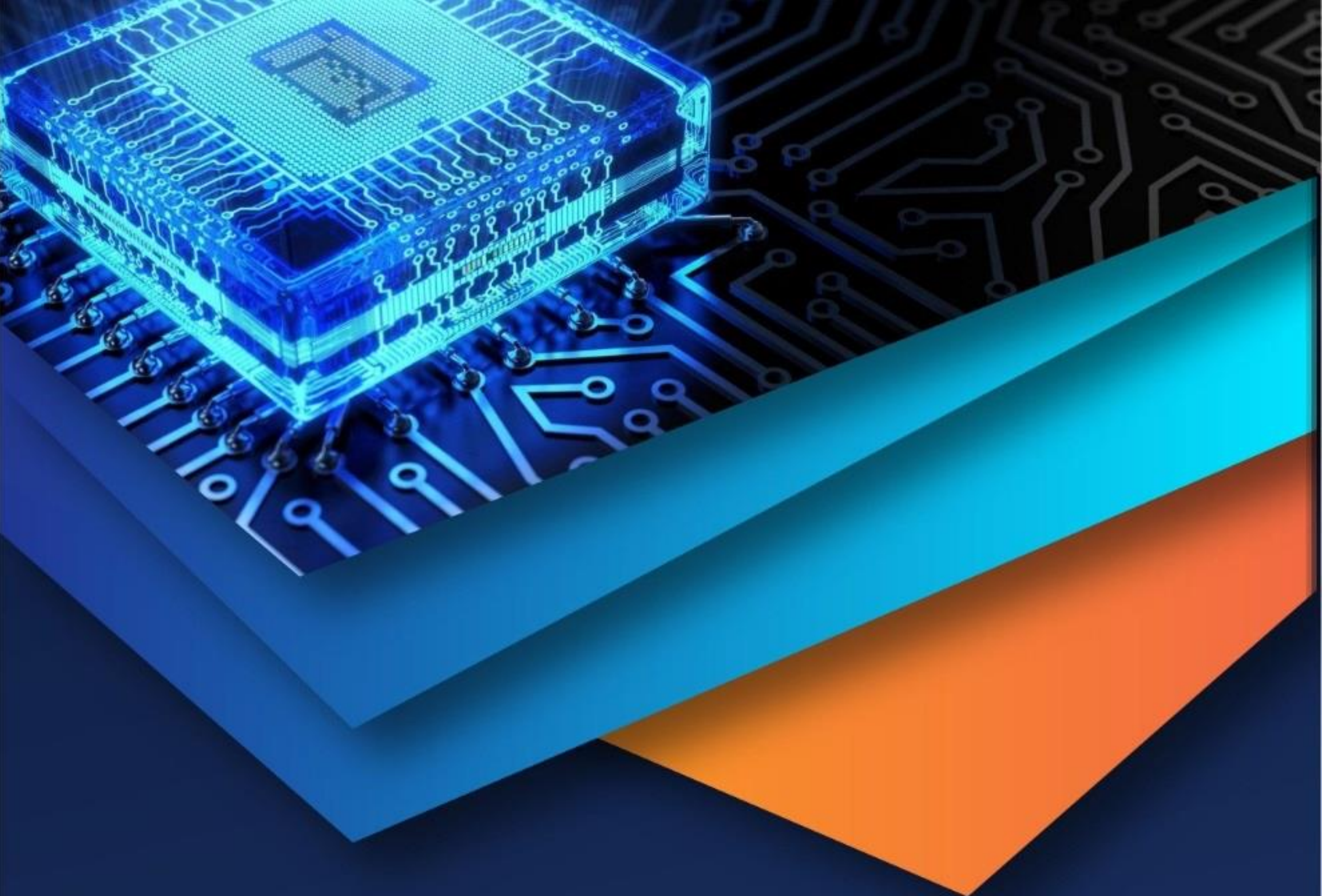

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