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Numerical Simulation of the Effect of Post Injection on SOOT Formation in a DI Diesel Engine Using CFD

Moses Aravind[1], Hemachandra Reddy[2]
[1]Research scholar, Mechanical Engineering, JNT University Anantapur, Andhra Pradesh, India.
[2]Professor, Mechanical Engineering, JNT University Anantapur, Andhra Pradesh, India.

***Abstract:** An advanced numerical study is carried out to understand the effect of post injection on SOOT and NOx formation. A post injection is a small injection given after the main injection, to reduce SOOT to meet exacting emissions standards. Flow characteristics in internal combustion engine is the most demanding and challenging fluid mechanics problems because of the large density and temperature variations, turbulence, unsteady, and dynamic, both spatial and temporal. Significant progress has been made in CFD model development for engines in recent years.*

Computational Fluid dynamics (CFD) has emerged as an inevitable tool in the design of IC engines. Unlike the conventional experimental techniques, CFD predicts the detail insight into the spatial temporal variations of all the variables, without modifying or installing the components. Advent of powerful hardware, parallel processing techniques, cloud computing further enhanced CFD to significantly reduce the cost and turnaround time in the design process.

In this study three dimensional reactive flow analyses is carried out using two injection strategies. Small amount of fuel injected after the main injection and the effect is analysed in reducing particulate matter.

Keywords: Internal Combustion Engine, Computational Fluid Dynamics, Injection strategies, Performance of a compression ignition engine, NOx, SOOT, Particulate Matter, Emission standards. Post injection.

Acronyms: IVC = Intake Valve Close; IVO = Intake Valve Opening; ATDC = After Top Dead Centre; ABDC = After Bottom Dead Center; CO = Carbon Monoxide; CO2 = Carbon Dioxide; NO2 = Nitrogen Dioxide EVC = exhaust valve close; EVO = exhaust valve opening;

I. INTRODUCTION

Diesel engine continues to popular and widely used in submarines, ships, power plants, automobiles, trucks and many more. Diesel engine has the highest thermal efficiency of any practical internal combustion, however when compared diesel engines have higher emissions of SOOT. In diesel engine the fuel in injected near the end of compression stroke over the compressed air, which results in a heterogeneous mixture leading to incomplete combustion. Also in diesel engine, the ignition delay is less and low self ignition temperature results insufficient time to form a uniform mixture.

This attributes to the formation of particulate matter and soot. It is well known that fuel injection strategies play a significant role in reducing emissions and particulate matter.

From the available literature it is clearly understood that any in-cylinder techniques adopted to reduce NOx results in an increase in soot. Recently many research studies have been conducted to understand the effect of multiple injections on the simultaneous reduction of NOx and SOOT because normally there is trade-off between those two emission quantities.

D. Kouremenos et al [1] discussed the effect of retardation of fuel injection timings and the resulted trade-off between NOx and SOOT quantities. Tow et al. [3] (1994) concluded from an experimental study a double injection with a significantly long delay between injections reduced particulate by as much as a factor of three over a single injection at 75% load with no increase in NOx. Zhang [2] (1999) showed that by increasing the dwell between pilot and main injection and reducing the fuel in pilot injection resulted lower soot.

In the current study, two studies were conducted to assess the effect of post injection and the effect on SOOT. In first simulation two pulses are given i.e. Pilot Injection and Main injection. In second simulation, 10% of extra fuel is added at high pressure as post injection.

Many studies have concluded that post-injection enhances the mixing process, increases the oxidation of the SOOT.

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II. GEOMETRY & MESHING

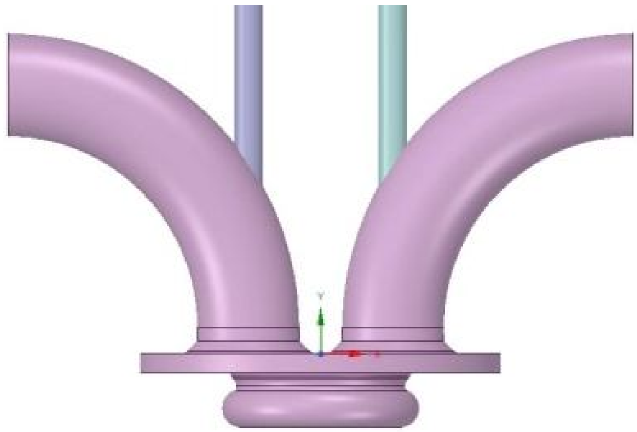

Figure 1: re-entrant bowl

Connecting rod length of 165mm and crank radius of 55mm with 0.0 piston offset is used to create the geometry. Compression ratio was set to 15.75:1. Engine speed is set to 1500 RPM. Deep Re-Entrant bowl is considered for piston bowl as shown in figure 1.
In both the simulations approximately 0.5 Million elements were used to discretize the geometry. Injector is located at the centre of the combustion chamber, and because of this symmetrical location, Sector was used for the simulation. The valves are not considered because this simulation is carried out between closures of inlet valve (IVC) and opening of outlet valve (EVO). For the purpose of simulation beginning of crank angle is considered as 360^0. In this case, the piston reaches the bottom dead centre at a crank angle 540°. The Inlet valve closes at 570° i.e. 30° ABDC (after BDC). Piston reaches the TDC at 720° and BDC at 900°. The Outlet valve opens at 60° (approx) before BDC i.e. 833^0 of crank angle. Spray starting crank angle is 712 ° (8^0 before TDC). Spray angle is 70^0.

III.INJECTION PROFILES

The main aim of this work is to understand the effect of split injection on SOOT reduction capability. In first simulation two pulses are given as approximately 25% of the total fuel is injected from crank angle 712^0 to 716^0 as pilot injection. Main injection

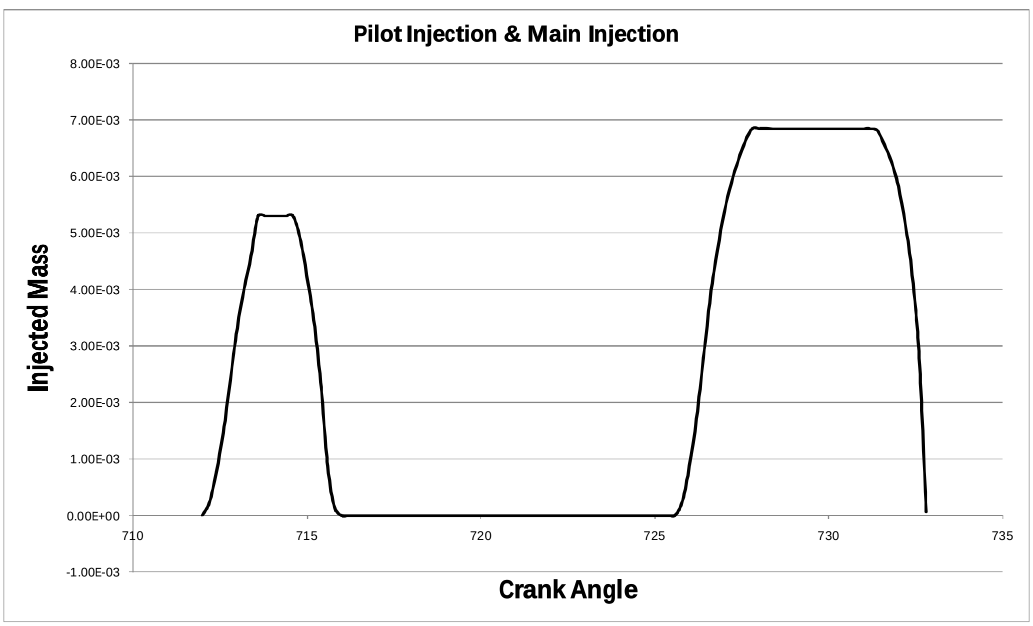

Figure 2: Pilot Injection & Main Injection

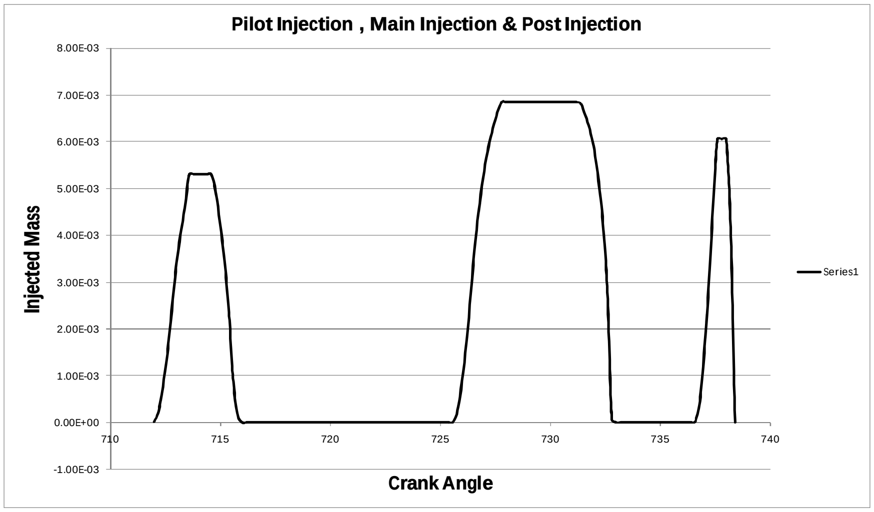

Figure 3: Pilot Injection, Main Injection & Post Injection

IV. BOUNDARY CONDITIONS & SOLVER SETTINGS

Wall temperature of 440 K is imposed on cylinder wall, 480 K on cylinder head and 560 K is specified on piston top. Two equation k-e model is used to account the turbulence effects with standard wall functions based on the work of Launder and Spalding. Turbulent kinetic energy and dissipation rate are calculated using the equations [1 &2] given below.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k$$

Equation 1: Transport equation for Turbulent Kinetic Energy (k)

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_i}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

Equation 2: Transport equation for Dissipation rate (ϵ)

Where: G_k is the turbulent kinetic energy generated because of the mean velocity gradients, G_b is the turbulent kinetic energy generated due to buoyancy, Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, σ_k is turbulent prandtl number for k, σ_ε is turbulent prandtl number for ε, $C_{1\varepsilon}$ $C_{2\varepsilon}$ $C_{3\varepsilon}$ are constants.

For species model, the standard Diesel Unsteady Flamelet model based on the work of Pitsch et al. and Barths et al. is used with 2 unsteady flamelets. Single transport equation is solved for the mass fraction of SOOT based on Khan and Greeves model as shown in equation 3.

$$\frac{\partial}{\partial t}(\rho Y_{soot}) + \nabla.(\rho\vec{v}Y_{soot}) = \nabla.\left(\frac{\mu_t}{\sigma_{soot}}\nabla Y_{soot}\right) + \mathcal{R}_{soot}$$

Equation 3: Transport equation for SOOT mass fraction

Where: Y_{SOOT} is SOOT Mass fraction, σ_{SOOT} is turbulent prandtl number for SOOT transport R_{SOOT} is the balance of SOOT formation and combustion.

V. RESULTS AND DISCUSSIONS

SOOT formation is more in diesel engine because of the way fuel is injected and ignited in the cylinder. Unlike in the SI engine where the fuel air mixture ignited by spark, in diesel engine fuel is injected directly into the compressed air resulting a heterogeneous mixture. Fuel rich regions will produce CO, SOOT and unburnt hydrocarbons. Oxygen rich locations may produce NOx at high temperature conditions. Many studies have proved that the post-injection pulse results an additional heat release can enhance the oxidation of SOOT. However at high temperatures molecular nitrogen may dissociate to its atomic state and form different oxides like NO N_2O resulting high NOx formation.

Three pulse injection (additional post injection) leads to lower SOOT but resulting high temperature may lead to increase in NOx as discussed earlier. Similar trend is observed in the comparative simulations where the NOx is increased in three pulse injection simulations and SOOT is reduced. Figure 4 shows the mass fraction of NO in three pulse injection and Figure 5 shows the same for two pulse simulations.

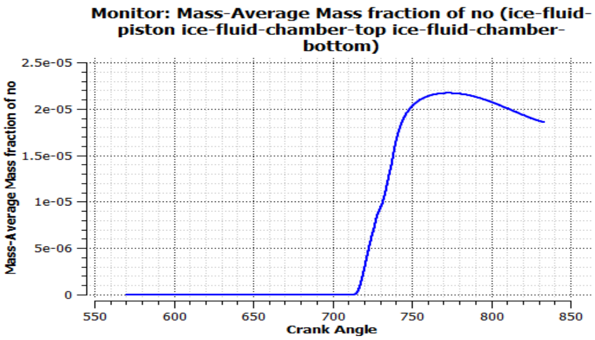

Figure 4: Mass Fraction – NO- Three pulses.

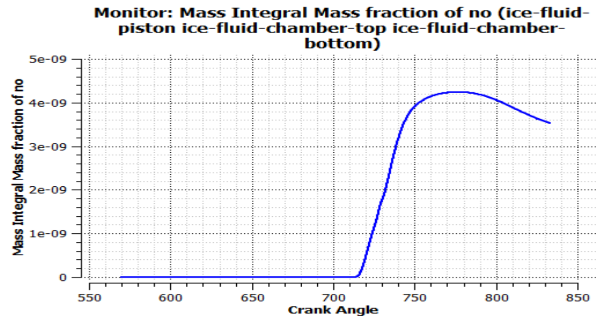

Figure 5: Mass Fraction – NO- Two pulses.

Figure 6 shows the mass fraction of NO_2 in three pulse injection and Figure 7 shows the same for two pulse simulations. Mass fraction of NO and NO2 are found to be more in the system of three pulse injection in comparison to two pulse injection system.

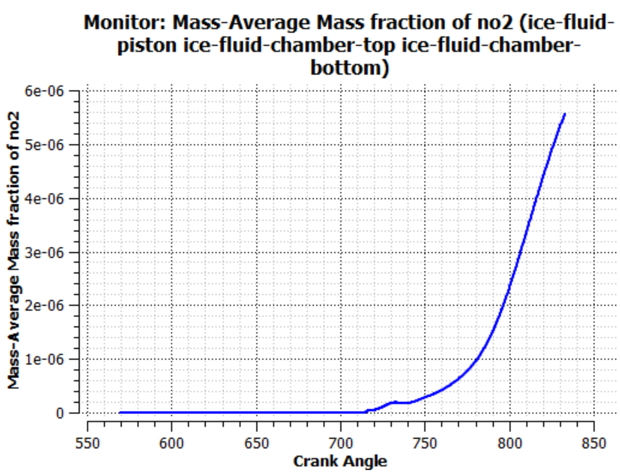

Figure 6: Mass Fraction – NO_2- Three pulses.

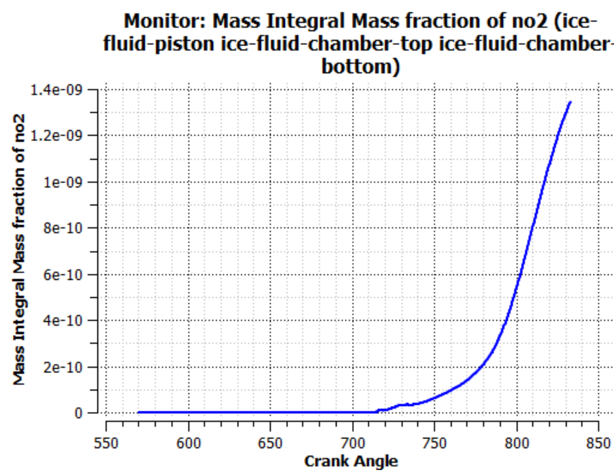

Figure 7: Mass Fraction – NO_2- Two pulses.

Figure 8 shows the contours of SOOT on cylinder walls for three injections and Figure 9 show the same for two pulses.

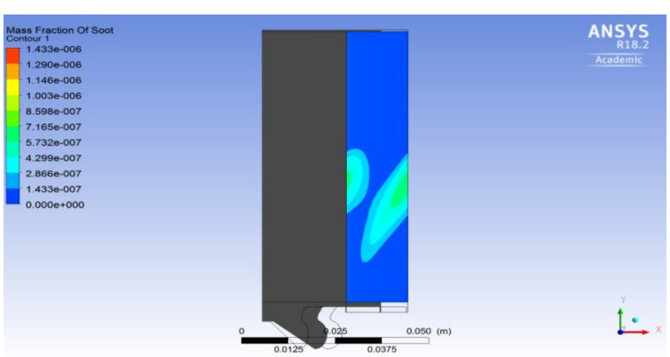

Figure 8: Mass Fraction – NO2- Cylinder wall-Three pulses.

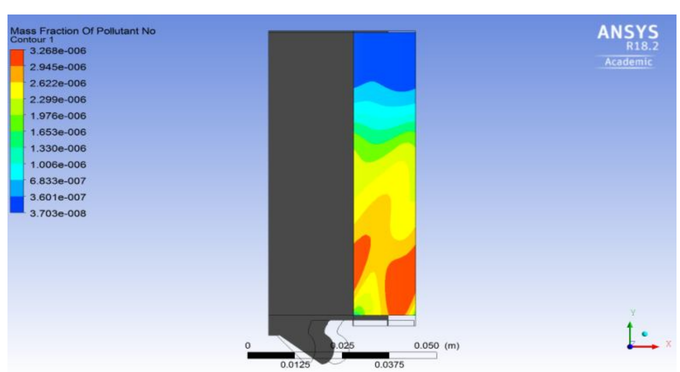

Figure 9: Mass Fraction – NO2- Cylinder wall-Two pulses.

Figure 10 shows the contours of SOOT on mid plane for three injections and Figure 11 shows the same for two pulses.

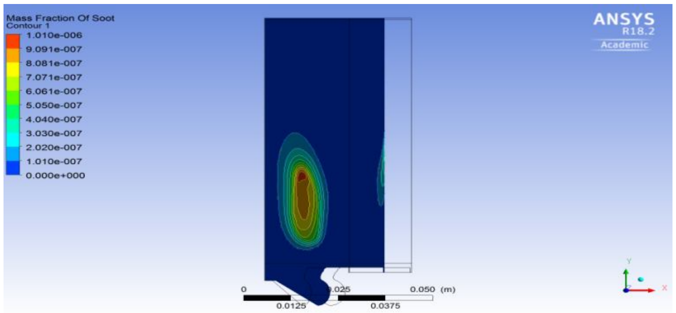

Figure 10: Mass Fraction – NO2- Cylinder Midplane-Three pulses.

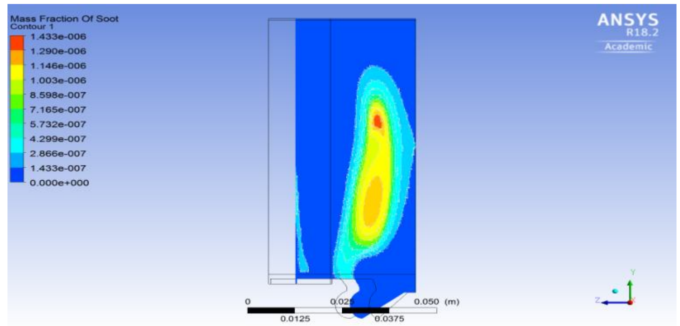

Figure 11: Mass Fraction – NO2- Midplane-Two pulses

VI. CONCLUSIONS

It is observed that post injection strategy is reducing the SOOT but NOx is increased because of the additional heat release. Further investigation of variable injection pressure, retarding fuel injection timings and other injection strategies may result in simultaneous reduction of both SOOT and NOx.

VII. ACKNOWLEDGEMENT

ANSYS Workbench 18.2 Academic version is used to conduct the simulations.

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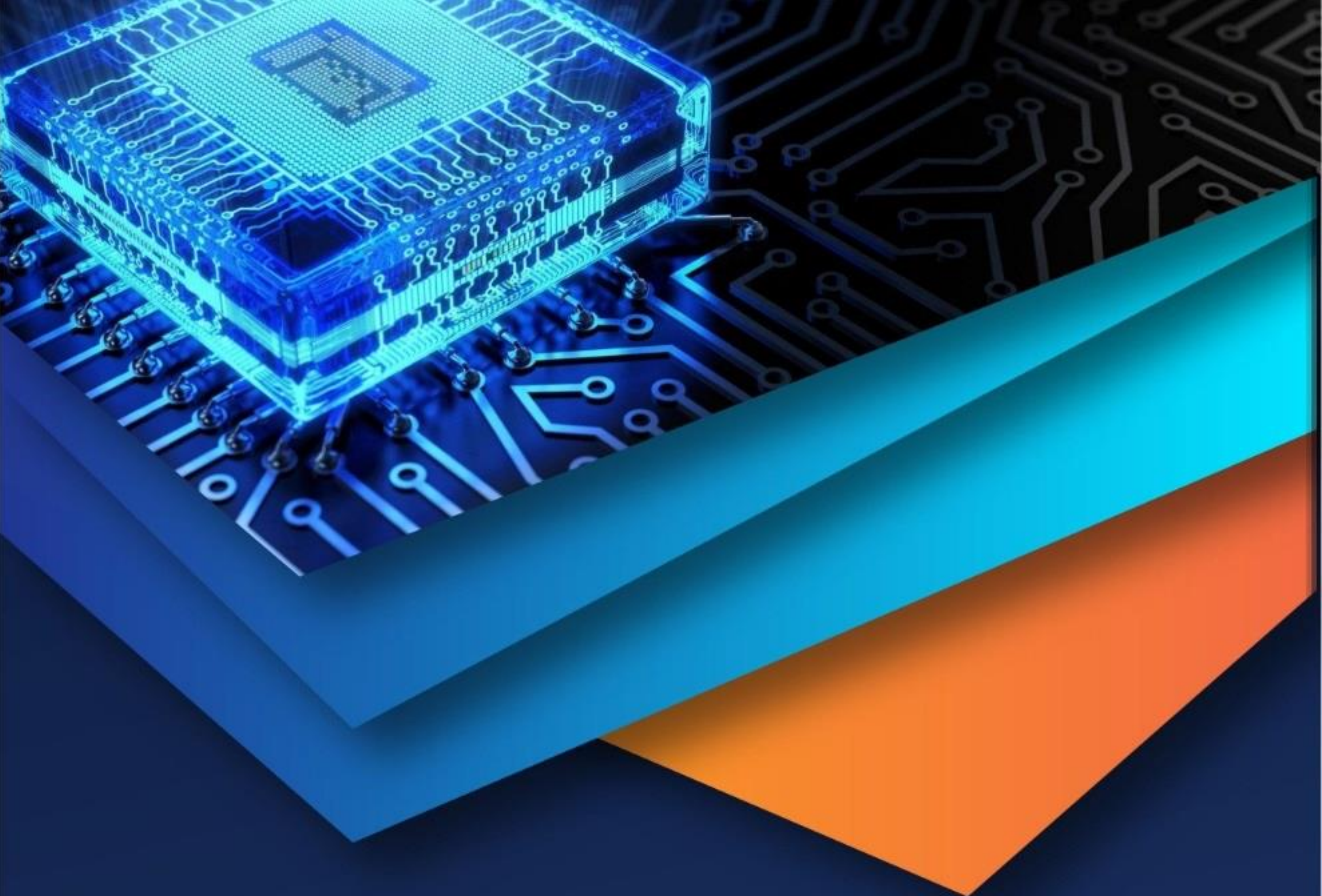

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