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CFD Analysis of Steam Boiler Used in Power Plants with Diverse Materials

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Abstract: Boilers are widely used in power plants and industrial applications to generate steam for heat and power production. In a steam boiler, water is converted into steam by the application of thermal energy, and the generated steam is supplied to various power-generating and heating systems. After performing useful work, the steam is condensed and returned to the boiler, completing the thermodynamic cycle. In this project work, a steam boiler tube is modelled using SolidWorks parametric design software and analysed using ANSYS Workbench. Structural, thermal, and computational fluid dynamics (CFD) analyses are performed to evaluate the mechanical strength, heat transfer characteristics, and flow behaviour of steam inside the boiler. CFD analysis is carried out for steam inlet velocities of 25 m/s, 30 m/s, 35 m/s, and 40 m/s to determine pressure distribution, heat transfer coefficient, and heat transfer rate. Thermal analysis is conducted using Steel 440C, Stainless Steel 316L, and Brass by applying heat transfer coefficients obtained from CFD results. Static structural analysis is performed by applying internal steam pressure to evaluate deformation, stress, strain, and factor of safety for the selected materials.

I. INTRODUCTION

A. Boiler

A closed vessel is used in a boiler to warm a fluid, which is usually water, without necessarily boiling the fluid. The main job that the system does is to add heat to the fluid and maintain the liquid state when needed. The North American usage of the term furnace is typically used when it is the aim to warm the fluid but it is not intended to reach a boil. The fluid leaves the boiler after heating or vaporization into a variety of uses in numerous processes and heating applications such as heating household water, heating plant, power generation through boilers, cooking, and sanitation.

B. Steam Generator (Boiler)

A steam generator is a boiler that uses a small amount of water such as a flash-boiler. It is typically constructed by a spiraling around coil. It is a forced-circulation boiler and pump-pushes steam through the unit only once. The design is safe even at high pressure because it lacks large drums or tanks. The velocity of the pump is varied rapidly to suit the quantity of steam required. The burner is regulated to maintain the temperature constant. Hence burner is powered by how much water is converted to steam. This could be regulated through a simple mechanism that monitors the pump flow or through a mechanism that monitors the temperature They are used as auxiliary boilers on ships

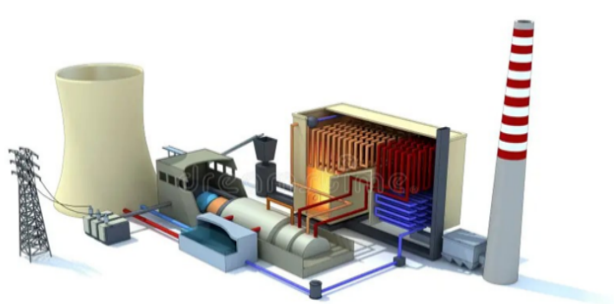

Fig 1. Schematic Layout of thermal power plant

II. LITERATURE REVIEW

A thorough review of the boiler performance has been done by Jaswinder Singh and others, where different coating materials were used as well as the prevention of high temperature erosion and corrosion on the boiler surfaces. The analysis they perform shows that the substrate can be coated with relative ease using the implemented process, and a desired set of material properties can be obtained, without taking a toll on the integrity of the substrate. Specifically, they investigated high-velocity oxy-fuel spray (HVOF) coating on T91 steel in operational boiler structures and discovered a significant reduction in oxidation and erosion (85.8 per cent) when compared with conventional cold-spray Ni-20Cr coating on SA516 alloys, which only led to 55.2 per cent. improvement.

Kotha Kranthi Kumar et al. [2] numerically studied on low-capacity power plant boiler by considering various materials i.e., convectional material and functionally graded material. They concluded that because of high strength, toughness, and low-cost functional graded material is suitable.

Senthil Kumaran.S et al. [3] experimentally studied by joining two different boiler grade materials and Taguchi and ANOVA methods to upgrade mechanical and metallurgical properties. They conclude in both clearance and interference fit welding area as 2355.30 and 2371.41 MPa respectively.

III. OBJECTIVE OF THE PROJECT

The main objective of this project is to design a steam boiler by using solid works with the help of real time dimensions and then analyzing it with different boundary conditions like static and thermal and fluent by varying materials in each case. From analysis results it is possible to know how much pressure can generate inside the pressure when it performs in real time, whether this pressure is allowable pressure or not, these factors can discuss with the help of static and fluent analysis results, from thermal analysis results it is possible to know the heat transfer rate of the object for each materials, by knowing all these results it is easy to say which material is more optimum when object performing in real time and their advantages with disadvantages with limitations,

IV. SOLIDWORKS MODELING PROCESS

To create stream boiler first open the solid works and then select "part" and then click on sketcher now click on circle option, create a circle with 150mm, and make sure it is in closed form to avoid errors, after creating circle then exit 2-d sketcher window and then select extrusion option 5mm and then click ok

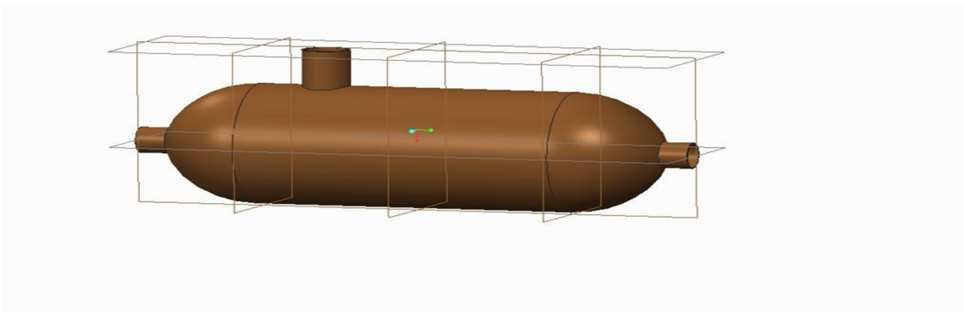

Fig 2. Final Assembly of Steam Boiler

After completing all designs, the above model is showing final assembly model of the steam boiler and to import this object into Ansys, it should be in either step/iges format so that save object once then after save as it in step/iges format.

A. Material properties

1) Stainless Steel 410

Young's modulus: - 2.0*10^11 Pa
Poisson's ratio: 0.28
Density: 7850 kg/m³
Yield strength: 275MPa
Thermal conductivity: 24 W/m·K

2) Brass

Young's modulus: - 1.17*10^11 Pa
Poisson's ratio: 0.31
Density: 8490kg/m³

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Yield strength: 310 MPa
Thermal conductivity: 115 W/m·K

3) Steel AISI 316

Young's modulus: - 1.9*10^11 Pa
Poisson's ratio: 0.29
Density: 7700 kg/m³
Yield strength: 300 MPa
Thermal conductivity: 16 W/m·K

B. Fluid properties

1) Steam

Density: 0.6 kg/m³
Specific heat: 2010 J/kg-K
Thermal conductivity: 0.025 W/m-k
Dynamic viscosity: 1.33*10^-5 kg/m-s

2) Water

Density:0998.2 kg/m³
Specific heat: 4182 J/kg-K
Thermal conductivity: 0.6 W/m-k
Dynamic viscosity: 1.013*10^-3 kg/m-s"

After defining the material properties, The three-dimensional model of the steam boiler tube is created using SolidWorks parametric modeling software based on real-time dimensions. The model is saved in STEP/IGES format and imported into ANSYS Workbench for further analysis.

C. Geometry Import

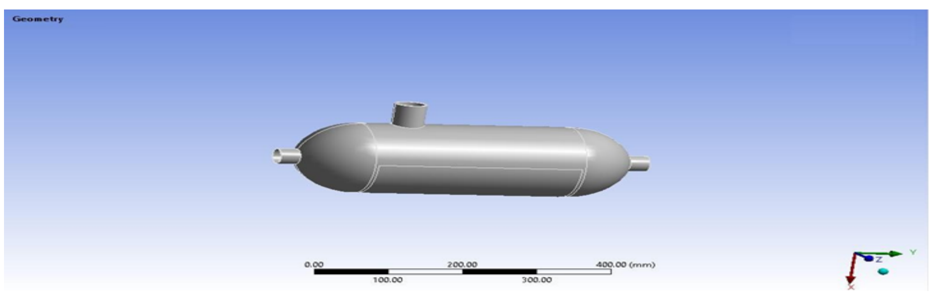


Fig 3. Geometry Import

The above image is imported model of steam boiler, after importing this object now need to generate meshing to carry forward Ansys process into further, this meshing is useful to transfer the applied loads on it, and the process is simple, this mesh will create object into small particles and those particles are known as elements and these elements were generated with the help of nodes and the final meshing object shown in below.

D. Meshing

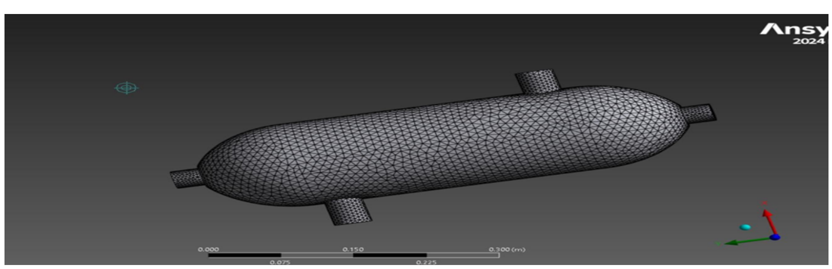


Fig 4. Meshing

V. SIMULATION AND RESULTS

Static structural analysis is performed to evaluate the mechanical behaviour and structural integrity of the steam boiler tube under steady-state loading conditions. Boiler tubes are subjected to significant internal pressure and thermal loads during operation, which can induce stresses and deformation. Therefore, it is essential to ensure that the induced stresses remain within the allowable limits of the material to guarantee safe and reliable operation.

In the present work, static structural analysis is carried out using ANSYS Workbench to determine the stress distribution, total deformation, maximum principal stress, and factor of safety for the boiler tube under operating conditions.

VI. STRUCTURAL ANALYSIS

Stainless Steel 410

- Deformation

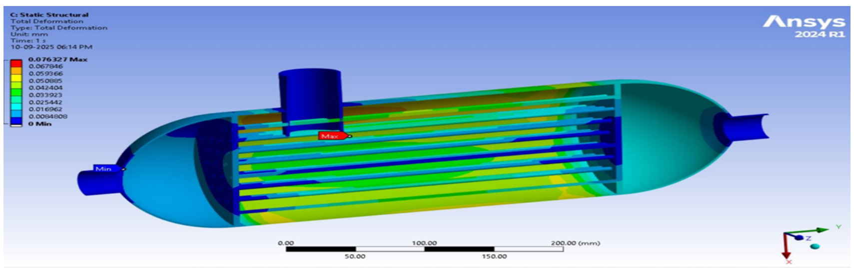


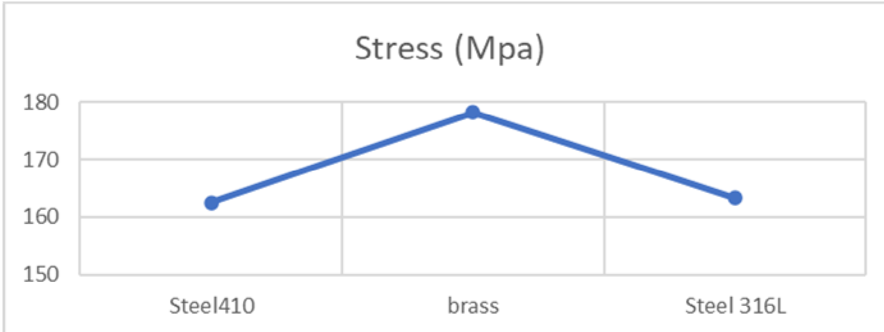
Fig 5. Total deformation distribution in stainless steel 410

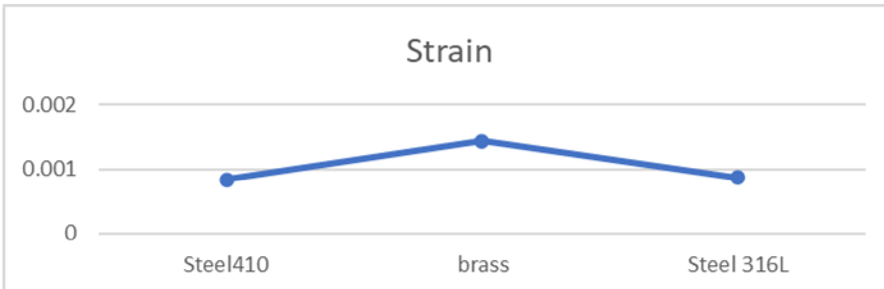
Figure shows the results of steam boiler, and the image shows that it is a deformation value for Stainless Steel 410 material, and it has maximum deformation value 0.076mm.

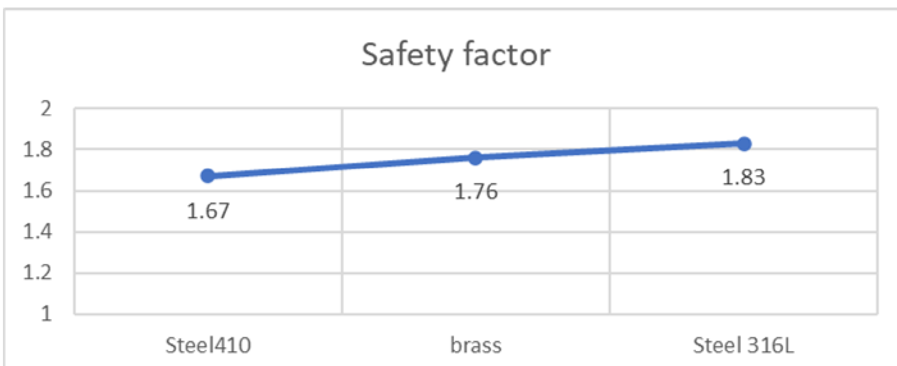
Table no: 1 Structural analysis Results Table

	Steel410	brass	Steel 316L
Deformation (mm)	0.076327	0.12959	0.079202
Stress (Mpa)	162.5	178.2	163.3
Strain	0.0008387	0.001437	0.000869
Safety factor	1.67	1.76	1.8286

- Graphs







The structural analysis results indicate that Stainless Steel 316L exhibits consistent and reliable mechanical behaviour under the applied operating conditions. The maximum deformation of 0.079202 mm, along with an equivalent stress of 163.3 MPa and a strain of 0.000869, suggests that the material is capable of effectively resisting elastic deformation while maintaining structural integrity. The observed deformation is well within acceptable limits for pressure-bearing components, demonstrating that Stainless Steel 316L provides adequate stiffness combined with stable stress distribution, which is essential for steam boiler applications.

In comparison, Brass shows a higher deformation of 0.12959 mm and strain of 0.001437, indicating a greater tendency toward elastic deformation under the same loading conditions. Although Brass remains structurally safe, as indicated by a factor of safety of 1.76, the increased deformation limits its suitability for applications where dimensional stability is critical. Stainless Steel 316L achieves the highest factor of safety of 1.8286, reflecting a superior safety margin and enhanced reliability. This balanced performance, characterized by controlled deformation and improved safety, confirms that Stainless Steel 316L is the most appropriate material for the steam boiler configuration considered in the present study.

- CFD analysis at Different Inlet Velocities

Inlet Vel velocity (m/s)	Pressure (pa)	Velocity o/L (m/s)	Heat transfer co-efficient (w/m2- k)	Mass flow rate (kg/s)	Heat transfer rate (w)
25	306.54	34.2	159.45	0.001198	952.52
30	401.31	39.65	169.56	0.001129	1126.87

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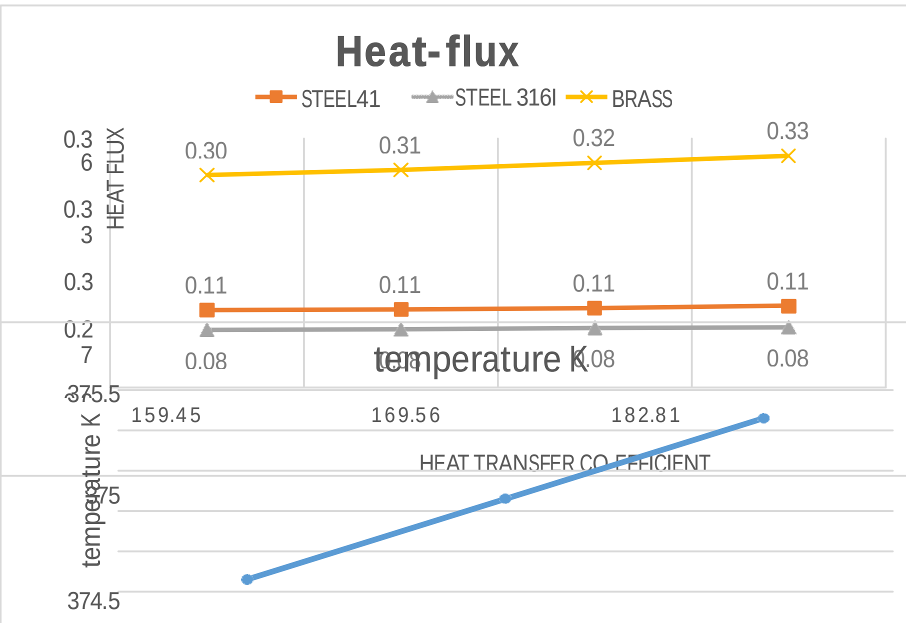
35	514.59	44.42	182.81	0.002634	1508.26
40	664.77	50.57	197.77	0.006241	1692.12

- Thermal Results Table

Heat transfer co-efficient (w/m2-k)	RESULT	MATERIALS		
		STEEL410	STEEL 316I	BRASS
159.45	Temperature (K)	373.15	374.15	375.15
	Heat flux (W/mm²)	0.112	0.083	0.307
169.56	Temperature (K)	373.15	373.15	373.15
	Heat flux (W/mm²)	0.113	0.084	0.315
182.81	Temperature (K)	373.15	373.15	373.15
	Heat flux (W/mm²)	0.115	0.086	0.325
197.77	Temperature (K)	373.15	373.15	373.15
	Heat flux (W/mm²)	0.118	0.087	0.335

- Graphical Analysis



From above graphs Brass shows higher heat flux values, this results in greater heat loss from the boiler to the surroundings. In contrast, Steel 316L exhibits lower heat flux, indicating better heat retention inside the boiler, which is desirable for efficient steam generation.

- Combined CFD and thermal analysis Results discussion

At a steam inlet velocity of 25 m/s, the flow inside the boiler is relatively calm and stable. Consequently, the pressure (306.54 Pa) and outlet velocity (34.2 m/s) are comparatively low.

The heat transfer coefficient of 159.45 W/m²·K indicates that heat transfer has initiated but is not yet very strong. Since the mass flow rate is low (0.001298 kg/s), the total heat transfer rate is moderate, with a value of 952.52 W.When comparing materials, brass exhibits the highest heat flux (0.307 W/mm²), followed by Steel 410 and Steel 316L. This behavior is attributed to the higher thermal conductivity of brass, which allows it to absorb and transfer heat more efficiently than steel materials. Overall, at 25 m/s, heat transfer occurs steadily but with limited intensity.

- Result at Velocity = 30 m/s: When the steam velocity increases to 30 m/s, the steam flow becomes faster and more energetic. As a result, the pressure rises to 401.31 Pa, and the outlet velocity increases to 39.65 m/s. The heat transfer coefficient increases to 169.56 W/m²·K, indicating enhanced convective heat transfer due to improved mixing of steam near the tube walls. Although the mass flow rate slightly decreases, the overall heat transfer rate increases to 1126.87W. This confirms that increasing steam velocity improves heat transfer efficiency. Brass again shows the highest heat flux (0.315 W/mm²), while Steel 410 and Steel 316L show moderate improvements. These results demonstrate that higher velocity significantly enhances heat transfer, especially for materials with higher thermal conductivity.
- Result at Velocity = 35 m/s: At a steam velocity of 35 m/s, the flow becomes stronger and more energetic. This leads to a higher pressure of 514.59 Pa and an outlet velocity of 44.42 m/s. The heat transfer coefficient further increases to 182.81 W/m²·K, indicating that convective heat transfer becomes more dominant. The mass flow rate increases to 0.002634 kg/s, which contributes to enhanced heat transfer. Consequently, the heat transfer rate rises significantly to 1508.26 W. Brass continues to exhibit the highest heat flux (0.325 W/mm²), while Steel 410 and Steel 316L show moderate values. At this stage, the temperature distribution inside the boiler becomes more uniform, indicating stable and efficient heat transfer.
- Result at Velocity = 40 m/s: At 40 m/s, the steam velocity reaches its maximum, and the flow becomes highly turbulent. This results in the highest pressure (664.77 Pa) and outlet velocity (50.57 m/s). Due to increased turbulence, the heat transfer coefficient attains its maximum value of 197.77 W/m²·K. The mass flow rate increases sharply to 0.006241 kg/s, leading to the highest heat transfer rate of 1692.12 W. Brass again shows the highest heat flux (0.335 W/mm²), followed by Steel 410 and Steel 316L. This clearly indicates that at higher velocities, materials with superior thermal conductivity perform more effectively.

VII. CONCLUSION

In the present study, a steam boiler model was developed using SolidWorks and analyzed in ANSYS Workbench to evaluate its structural, thermal, and fluid flow (CFD) performance under realistic operating conditions. Three materials—Stainless Steel 410, Brass and Stainless Steel 316L—were considered to assess their suitability for boiler applications. The analyses were conducted under identical boundary conditions to ensure a consistent and meaningful comparison of material behavior.

The results of the static structural analysis indicate that the steam boiler can safely withstand a maximum internal pressure of 2.5 MPa for all the materials considered. Among them, Stainless Steel 316L exhibits the highest factor of safety, demonstrating superior resistance to yielding and enhanced structural reliability under high-pressure conditions. This confirms that Stainless Steel 316L provides a greater safety margin compared to Steel and Brass, making it more suitable for pressure vessel applications.

The thermal analysis results show that Brass exhibits the highest heat flux, while Steel and Stainless Steel 316L display comparatively lower and closely similar heat flux values. Although the higher thermal conductivity of Brass enhances heat transfer, it also leads to increased heat loss to the surroundings, which adversely affects boiler efficiency. Consequently, despite its favorable heat conduction characteristics, Brass is less suitable for steam boiler applications where thermal energy retention is critical.

The CFD analysis further reveals that Stainless Steel 316L produces higher outlet temperature values with relatively lower heat transfer coefficients, indicating its ability to retain thermal energy within the boiler while allowing controlled heat transfer. This behavior is desirable for efficient steam generation, as excessive heat transfer to the surroundings reduces system performance. Materials exhibiting higher heat transfer coefficients tend to experience greater thermal losses, thereby lowering overall efficiency.

Based on the combined assessment of structural integrity, thermal behavior, and fluid flow performance, Stainless Steel 316L is identified as the most suitable and optimum material for steam boiler applications among the materials investigated. Its superior factor of safety, controlled deformation, balanced thermal performance, and stable fluid flow characteristics make it a reliable choice for real-time boiler operation. Hence, Stainless Steel 316L can be recommended as an effective alternative to conventional steel for high-pressure and high-temperature steam boiler systems.

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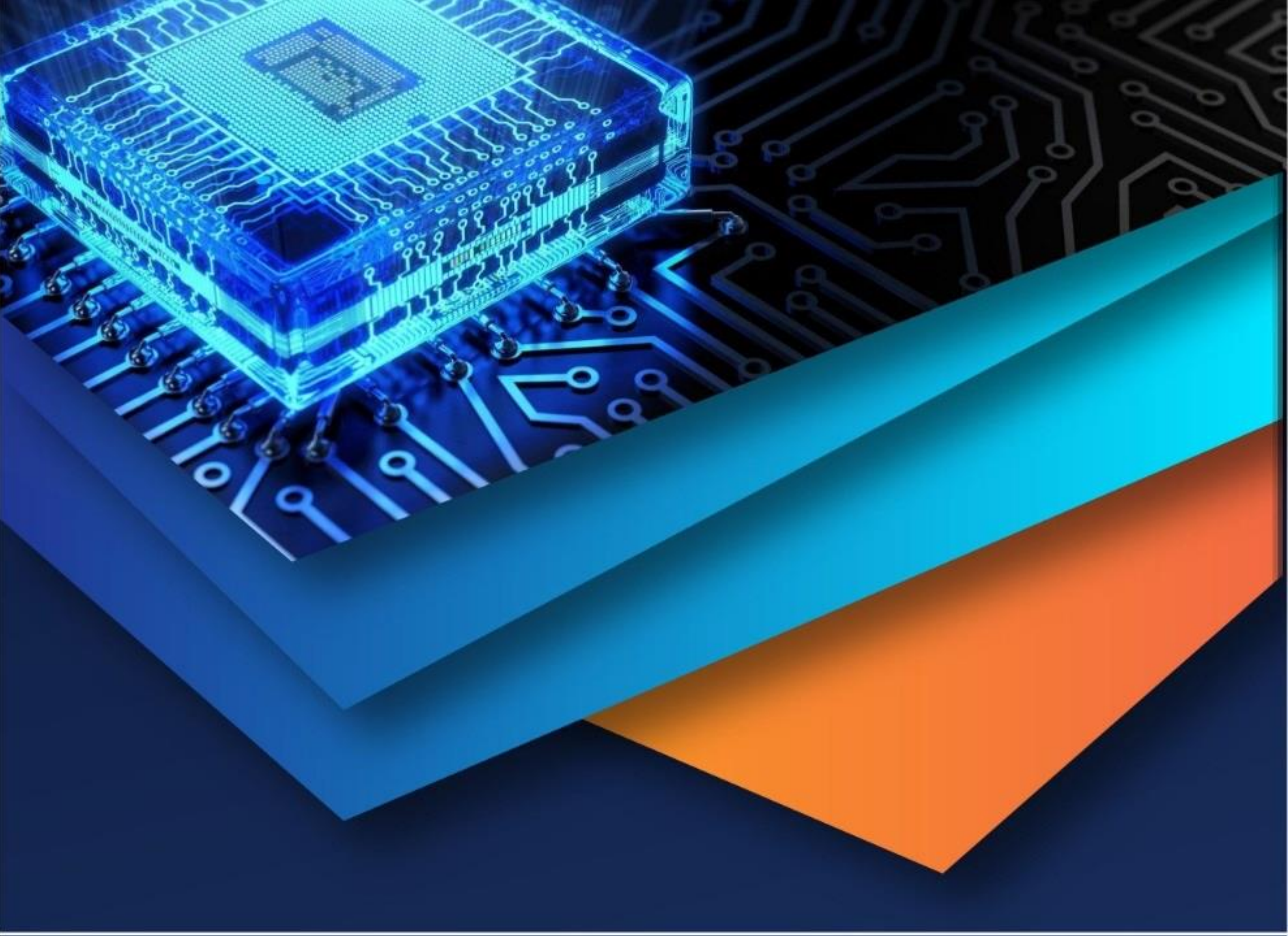

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