iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** III **Month of publication:** March 2018

DOI: http://doi.org/10.22214/ijraset.2018.3371

Understanding the Basic Concepts of Exergy and Real-Time Exergy Analysis of Economiser, Superheater and Reheater of 210MW Coal Fired Boiler in Thermal Power Plant

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Abstract: Improving efficiency of the thermal systems by the optimum utilization and conversion of energy into exergy is always a concept of research. This paper takes an effort to understand the basic concepts of exergy by extensive literature reviews and attempts to highlight the conversion factors of energy into available exergy through different but essential components of boiler in thermal power plant. As per the scope of our study, Feed water system through Economiser and Superheat steam systems through Superheater & Reheater are analysed for energy added and exergy available in the process of thermal heat addition using the real-time data. With the help of exergy analysis, it is concluded that maximum losses occur in Superheater system and least in the Economiser.
Keywords: Energy, Exergy, Efficiency, Thermal Power plant, Boiler

I. INTRODUCTION

Power is one of the basic needs for any country and directly linked with its economic and infrastructure growth. In global scenario, India is the third largest electricity producer with total installed capacity of 334.40 GW (as on January 2018). Out of total production, about 85% (284.24 GW) of electricity is generated by thermal power plants and majority of the plants are coal based. (Wikipedia)

Due to emerging concerns of the climate change and its impact on environment globally, it is the need of the time to reduce waste emissions, disposals and address the key issues like energy efficiencies, current energy conversion technologies, improvement of design and operating systems of power producing plants. The core concern is to save the globe from impacts of climate change and preserve our resources to the best possible.

The efficiencies of the thermal power plants have always been the major issue for power sector in India. In the other way, energy saved is energy produced. According to a report by Centre for Science and Environment (CSE), only few coal based power plants meet the global standards in terms of efficiency. The operating performance and design of the majority of plants lies away below the global standards. Therefore, the analysis of power generation system in view of increasing utilization factors or improved useful energy is of scientific interest and also essential for efficient utilization of energy resources.

The energy analysis based on first law of thermodynamics cannot provide the true measure of efficiency and losses. To study the true understanding of energy analysis, both first law and second law of thermodynamics comes into picture. Exergy analysis based on second law of thermodynamics provides the clear understanding between energy loss to environment and internal irreversibility in the process. It is a methodology for the performance evaluation of various components and processes analysing the exergy at different points in series of energy conversion steps. (Rakesh Dang et al., 2016)

A. Concept of Exergy

"The useful work potential of a given amount of energy at a specified state is called exergy (Dincer, 2002)". Exergy of any thermodynamic process shows efficiency or inefficiency of that process. Exergy is the phenomenon provides us with a better understanding of processes for qualifying energy. Therefore, it would better to use exergy to identify, qualify and quantify energy destruction. It gives the indication of maximum useful work which can be drawn out from a thermodynamic system at given state in a given surrounding without violating any thermodynamic laws. Although the unit of exergy is same as that of energy, the energy focuses on "quantity" whereas exergy emphasize on "quality" of the energy where energy is conserved but exergy can be degraded. [Dincer, 2002]

B. Exergy Analysis

The conventional thermodynamic analysis is backed by the first law of thermodynamics which is based on conservation of energy. Energy analysis essentially accounts for the quantity of energy entering and exiting the system, while efficiencies of the processes are the measure of the ratios of the energy entering and exiting. But, energy efficiencies do not always assess how nearly performance approaches ideality and are consequently often misleading (Marc A. Rosen, 2011).

Exergy analysis is a tool for the analysis of thermodynamic systems which is based on the second law of the thermodynamics and entropy irreversibility concept. It overcomes all the drawbacks of energy analysis. Exergy analysis allows one to visually determine the degree of perfection and power losses in systems and to determine ways to improve them (O.V. Afanasyeva, Energy Efficiency 2015).

Generally, the overall plant efficiency in thermal power is of the order of 25-35%, as large fraction of energy (65-75%) is wasted or lost. Inspite of the fact that complete conversion of heat energy into work is not possible, the major portion of this wasted heat is the prime concern to be addressed.

Researchers are continuously carrying out various studies on energy and exergy analysis for the overall plant as well as individual equipment and systems. The efforts are being made to raise the useful energies and reducing the losses. For e.g. with the help of waste recovery of flue gases by reducing the stack temperature by 22 deg C, boiler efficiency can be increased by 1%. Not only increases in efficiency, the benefits are manifold in terms of cost and saving in new generation. Exergy analysis is a powerful tool to study the thermodynamic systems and losses associated with it and efforts can be made to optimize the design and existing systems.

II. OBJECTIVE

The objective of this study is to understand the concept of exergy by reviewing the existing literature on the exergy analysis, conducting a real-time exergy analysis on different essential components of a boiler of thermal power plant of large capacity, comparing between energy added and exergy available and to highlight the importance of exergy analysis and its important aspects with future scope of research.

III. LITERATURE REVIEW

Mehmet Kanoglu. Ibrahim Dincer and Yunus A. Cengel (2008) have done the exergy analysis on various systems to study its impact on environment. It was illustrated that the exergetic analysis plays a vital role in the performance of the thermodynamic system which directly impact the environment. The performance voids in the system can be revealed by exergy analysis and efforts can be made to redesign the system to enhance the efficiency.

Mali Sanjay and Dr. Mehta N. S. (2012) has shown the exergy analysis carried out on 125 MW coal fired power plant. It was seen that the first law of thermodynamics only depicts the quantity whereas the second law of thermodynamics depicts the quality. It was concluded that exergy efficiency was lower as compared to the energy efficiency. The main components responsible for exergy losses were air pre-heaters, super heater and economizer (heat exchanger). It was also found that 47.43% exergy loss occurred in the furnace chamber alone. Hence, the heat exchanger components must be inspected very carefully.

M. K. Pal, Anil Kumar and H. Chandra (2013) has determined the thermodynamic analysis of different components of a thermal power plant i.e. boiler and turbine. In this paper energy and exergy analysis of 210MW capacity of Rihand Super thermal power station was carried out. In this, the first and second laws of thermodynamics have been used to calculate energy and exergy analysis. It was concluded that the exergy losses in the boiler was approximately 61% of the total input.

Sarang J. Gulhane and Prof. Amit Kumar Thakur (2013) did the analysis of a boiler in cogeneration coal fired thermal power plant. The objective of this research paper was to find out the highest energy destruction component or system in a boiler of 35TPH in 6MW captive power plant. It was concluded that the plant should be run at the peak load to minimize the losses and irreversibility.

Krishan Kumar, Dharmendra Patel, Vinod Sehravat and Tarun Gupta (2013) using mass and exergy balance as a basis did the exergy analysis of a boiler in order to find out the exergy losses or irreversibility and second law efficiency. It was found the maximum exergy destruction occurs in the boiler during the combustion process in combustion chamber and also significant amount of losses have been noted in some pressure parts of the boiler. Exergetic efficiency of the boiler was found 35.781% and also observed that the best exergetic efficiency of the boiler can be obtained when bituminous coal is used for combustion.

Vatsal P. Patel and I. J. Patel (2014) suggested various modification or changes that can be made in the thermal power plant components which would be eventually helpful for the designers to redesign the components. The analysis was done using various literatures and concluded that the main component responsible for exergy destruction is boiler and order to improve the efficiency the irreversibility has to be reduced.

Aljundi I H (2009) did both energy and exergy analysis of all the components of a power plant. In this paper, each component has taken into the study in order to find out the energy and exergy losses in each component. It was found that the maximum energy loss of about 135MW occurred in condenser and 13MW in boiler subsystems. On the other side the maximum exergy destruction of about 77% occurred in the boiler. It was concluded that the major source of exergy destruction is boiler due to chemical reactions in the combustion chamber and in order to reduce the destruction in combustion chamber pre-heating of air should be done.

IV. GAP ANALYSIS AND SCOPE OF STUDY

Different authors have tried to do the exergy analysis for various power plants and different energy intensive systems. A wide variety of literature is available across the research zones of the world. Some researchers also highlight the economic analysis for the exergy losses and exergy efficiencies. However, from extensive literature reviews, it is felt that macro analysis is generally done in thermal power sectors and researchers tried to encompass the complete power plant as a whole with several impractical assumptions. Generally, plant efficiencies and exergies in vast varieties of components is covered based on designed data causing cumulative errors and arriving on incorrect conclusions.

This paper attempts for micro analysis of some of the essential components of thermal power plant and focusses on energy added in particular system and processes through identified components and calculating the exergy analysis for the same components for having a clear picture of energy losses and correct conversion factors. Real time data is taken from a large capacity thermal power plant, feedwater system through Economiser and superheat heat additions in Superheater and Reheater are taken under scope of present study.

V. METHODOLOGY, MATHEMATICAL FORMULATION, CALCULATIONS

A. System Description

A thermal power station works on the basic principle that heat liberated by burning fuel is converted into mechanical work by means of a suitable working fluid. A coal based thermal power plant converts the chemical energy of the coal into electrical energy. This is achieved by raising the steam in the boilers, expanding it through the turbine and coupling the turbines to the generators which converts mechanical energy into electrical energy.

B. NTPC Limited: An Introduction

NTPC Ltd is one of Maharatna Public Sector Undertaking of Government of India. Since, its inception in 1975, NTPC has created several benchmarks with its current installed capacity of 51,383 MW; which is almost one fourth of country's total generation at any point of time. Located across India, NTPC has 48 generating stations with a mix of thermal, gas, hydro and renewable energy portfolio. [NTPC website]

Out of its various thermal power plant, Badarpur Thermal power plant is chosen for our study due to ease of accessibility and permissions accorded. A very old thermal station of NTPC, Badarpur thermal power plant in New Delhi is a coal-based plant which has a total installed capacity of 705 MW consisting of 3x95 MW and 2x210 MW capacity units. 210 MW boiler of Unit#04 has been selected for our pilot study to carry out exergy analysis.

Water is heated in economizer using the waste heat of flue gases. The feed water then enters in boiler water walls, where it heated and converted into steam which is collected in drum. Steam is separated in drum and goes to super-heater for being superheated. This superheated steam goes in HP turbine for giving useful work. Steam is reheated after HP turbine exhaust before going to inlet of IP turbine.

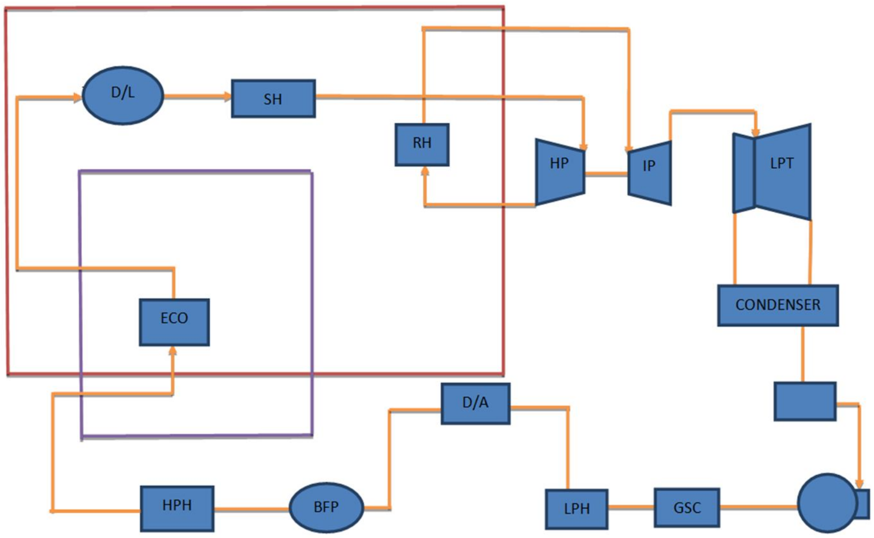

Fig. 1: Schematic diagram of Thermal Power Plant

C. *Data Collected*

Data collected is tabulated below in Table-01

TABLE I DATA COLLECTED

System	Points as per Schematic	T(deg C)	P (Ksc)	Mass flow rate(TPH)
Feed water	Economiser Inlet	247	170	678
Feed water	Economiser Outlet	278	165	678
Steam	SuperHeater inlet	380	150	640
Sup Steam	SuperHeater outlet	537	133	640
Steam	Reheater inlet	340	27	570
Sup Steam	Reheater outlet	537	25	570
Mass flow of main steam (at Superheater outlet)				640
Mass flow of fuel (Coal intake in boiler)				145
GCV of Coal is given as 3410 Kj/Kg				
Sp. Heat of water is given as 4.18 Kj/Kg degC				

D. *Mathematical Formulation and Calculations*

1) *Boiler Evaporative Ratio:* $M_a = \frac{Mass\ flow\ of\ main\ steam}{Mass\ flow\ of\ fuel(coal)} = \frac{Ms}{Mf}$

As per actual data, Boiler Evaporation Ratio $M_a = \frac{640\ TPH}{145\ TPH} = 4.44$

2) *Boiler Efficiency (by Direct method):* $\eta_{boiler} = m_a\ x\ \frac{H-h}{G.C.V}$

Putting the Values, $\eta_{boiler} = 4.41\ X\ \frac{3456.8-2825.83}{3410} = 81.6\ \%$

Where, H = Enthalpy of main steam at 537˚C and 133 kg/cm^2 = 3456.8 KJ/Kg
And, h = Enthalpy of feed water at Eco inlet at 240˚C and 170 kg/cm^2 = 2825.83 Kj/Kg

3) *Energy added on Feed Water through Economizer:*

ENERGY ADDED IN FEEDWATER $= H_{out} - H_{in}$
$= (1164 - 1034)$
$= 130$ Kj/Kg

4) *Energy added on steam through Superheater:*

ENERGY ADDED IN SUPERHEATER $= H_{out} - H_{in}$
$= (3456.8 - 2891.49)$
$= 565.31$ Kj/Kg

5) *Energy added on steam through Reheater:*

ENERGY ADDED IN REHEATER $= H_{out} - H_{in}$
$= (3542.9 - 3106.2)$
$= 436.7$ Kj/Kg

6) *Exergy of Feed Water at Economizer Inlet and Outlet:*

Exergy for the fluid is defined as $\Psi_{i/l} = C_{pwi}(T_w - T_o) - T_o \ln(T_w/T_o)$, where C_{pwi} is specific heat of water, T_{fwi} is Temperature of feed water at Eco. Inlet, T_o is ambient Temperature.

Therefore, Exergy of Feed Water at Economizer Inlet is

$\Psi_{fw\ i/l} = C_{pfwi}(T_{fwi} - T_o) - T_o \ln(T_{fwi}/T_o)$; at $T_{fwi} = 247^oC = 520K$ and $T_o = 25^oC = 298K$
$= 4.18(520-298) - 298 \ln(520/298)$
$= 927.96 - 165$
$= 762.04$ Kj/Kg

Exergy of Feed Water at Economizer Outlet is

$\Psi_{fw\ o/l} = C_{pfwo}(T_{fwo} - T_o) - T_o \ln(T_{fwo}/T_o)$; at $T_{fwo} = 278^oC = 551K$ and $T_o = 25^oC = 298K$
$= 4.18(551-298) - 298 \ln(551/298)$
$= 1057.54 - 183$
$= 874.54$ Kj/Kg

7) *Exergy of Steam at Superheater Inlet and Outlet:* Exergy for the gaseous fluid/steam is defined as $\Psi_{i/l} = (H - H_o) - T_o(S - S_o)$, where H_i and Si is enthalpy and entropy of steam at Superheater Inlet respectively, To and So is temperature and entropy of steam at Superheater Inlet respectively. Therefore, at given and calculated parameters ($T_o = 298K$, $H_o = 2547.3$, So = 8.559 and at $T_i = 380C$ & $P_i = 150Ksc = 147bar$, $H_i = 2891.49$, Si = 5.326)

Exergy of Steam at Superheater Inlet

$\Psi_{sh\ i/l} = (H_i - H_o) - T_o(S_i - S_o)$
$= (2891.49 - 2547.3) - 298(5.326 - 8.559)$
$= 344.19 + 963.43$
$= 1307.624$ Kj/Kg

And, at given and calculated parameters ($T_{o/l} = 537C$ & $P_{o/l} = 333kg/cm^2 = 326.7bar$, $H_{o/l} = 3456.8$, $S_{o/l} = 6.541$)

Exergy of Steam at Superheater Outlet

$\Psi_{sh\ o/l} = (H_{o/l} - H_o) - T_o(S_{o/l} - S_o)$
$= (3456.8-2547.3) - 298(6.541 - 8.559)$
$= 909.5+601.354$
$= 1510.864$ Kj/Kg

8) *Exergy of Steam at Reheater Inlet and Outlet:*

Using the same equation for gaseous fluid/steam at Reheater, at given and calculated parameters (at $T_i = 340C$ & $P_i = 27Ksc = 26.5bar$, $H_{i/l} = 3106.2$, Si = 6.784)

Exergy of Steam at Reheater Inlet

$\Psi_{rh} = (H_{I/L} - H_O) - T_O(S_I - S_O)$
$= (3106.2 - 2547.3) - 298(6.784 - 8.554)$
$= 558+528.95$
$= 1086.95$ Kj/Kg

And, at given and calculated parameters ($T_{o/l} = 537C$ & $P_{o/l} = 25kg/cm^2 = 24.5$ bar, $H_{o/l} = 3542.9$, $S_{o/l} = 7.444$)

Exergy of Steam at Superheater Outlet

$\Psi_{rh\ o/l} = (3542.9 - 2547.3) - 298(7.444 - 8.559)$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue III, March 2018- Available at www.ijraset.com

= 995.6+332

= 1327.87 Kj/Kg

9) *Exergy added in feedwater through Economizer:* $= \Psi_{out} - \Psi_{in}$

= 874.54 – 762.04 = 112.5 KJ/KG.

10) *Exergy added in steam through Superheater:* $= \Psi_{out} - \Psi_{in}$

= 1570.86 – 1307.62 = 203.24 KJ/KG.

11) *Exergy added in steam through Superheater:* $= \Psi_{out} - \Psi_{in}$

= 1327.87 – 1086.95= 240.92 KJ/KG.

VI. RESULTS AND DISCUSSIONS

Exergy analysis and energy added in different processes are tabulated below as Table-02 and Table-3. The results are plotted and represented in Figure-02 and Figure-03 underneath.

Table Ii Exergy Analysis

System/ Process	Components	T(deg C)	P(Bar)	Exergy equation	Mass flow rate(TPH)	Mass flow (Kg/Sec)	Exergy Ψ (kj/kg)	Exergy Ψ (kj)
Feed water	ECO Inlet	247	166.6	Ψw(fwi) = Cpw (Tfwi - To) - To ln (Tfwi / To)	678	191	762.04	145820.42
Feed water	ECO Outlet	278	161.7	Ψw(fwo) = Cpw (Tfwo - To) - To ln (Tfwo / To)	678	191	874.54	167347.89
Steam	SH inlet	380	147	Ψ(SHi) = (h – ho) – To (S - So)	640	181	1307.62	236195.92
Sup. Steam	SH outlet	537	130.34	Ψ(Sho) = (h – ho) – To (S - So)	640	181	1510.86	272907.25
Steam	RH inlet	340	26.46	Ψ(Rhi) = (h – ho) – To (S - So)	570	161	1086.95	174861.94
Sup. Steam	RH outlet	537	24.5	Ψ(Rho) = (h – ho) – To (S - So)	570	161	1327.87	213619.69

Table Iii Energy Added, Conversion Factors, Losses

System	Energy added (Ho-Hi) KJ/Kg	Mass Flow (TPH)	Mass Flow (Kg/sec)	Energy added (Ho-Hi) KJ	Exergy available Ψ (kj)	% Conversion of Energy into Exergy	% Loss in system
Feed Water System	130	678	191	24876.1929	21527.47	86.54%	13.46%
Superheater System	565.31	640	181	102112.171	36711.32	35.95%	64.05%
Reheater System	436.7	570	161	70253.654	38757.75	55.17%	44.83%

It is clearly understood from the above tables that energy added in each process is not fully receivables in the form of exergy and only a fraction of energy is converted into useful energy. The same is also reflected with the help of following bar-charts.

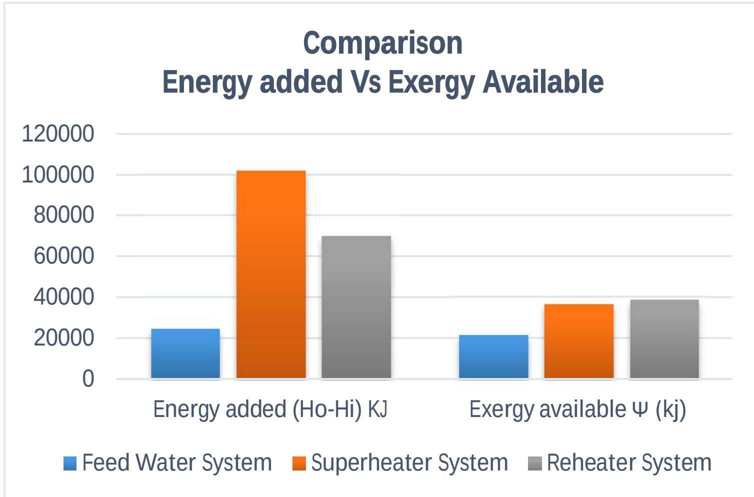

Fig. 2 (Comparison: Energy added Vs Exergy available)

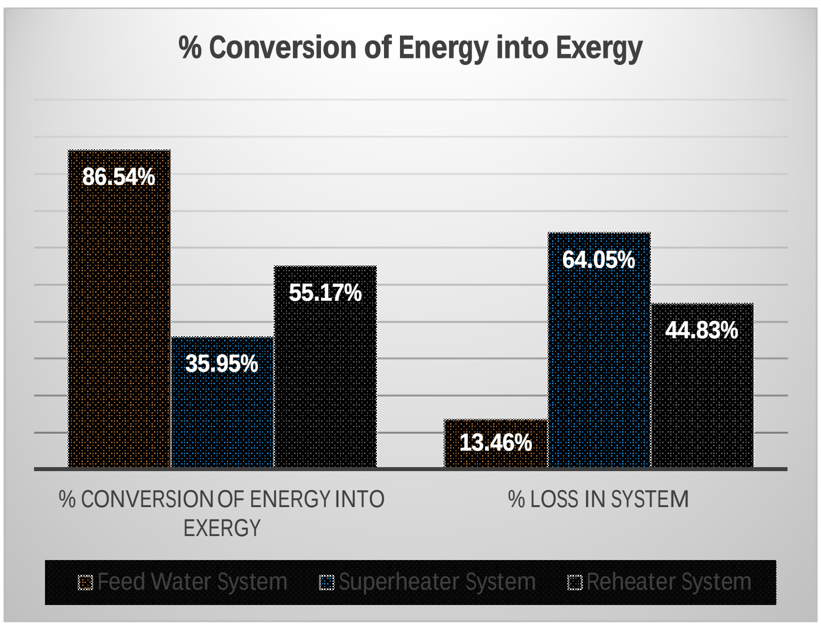

Fig. 3 (Conversion and Loss percentages)

Energies added to feed water system and steam through superheater, reheater were compared to exergies available. It is concluded that maximum loss of energy takes place in Superheater i.e. 64.05% and minimum loss takes place in Economiser. However, 44.83% loss occurs in Reheater system. If individual system is studied and losses are calculated, we get a focused target for improving energy efficiencies and exergy availability.

VII. FUTURE SCOPE OF RESEARCH

A thermal power plant consists of several energy intensive components. Inspite of performing exergy analysis for comlete plant as a whole with several unrealistic assumptions, it is more beneficial to conduct equipment-wise analysis on the real-time data.

VIII. ACKNOWLEDGEMENTS

The authors acknowledge Mr. Ajit Kumar Bhatnagar (Executive Director, NTPC Power Management Institute) for his extended kind hearted support. Authors are also thankful for the help extended by Mr. Vijay Shankar, Sr. Manager (Energy Efficiency Management Group, NTPC Badarpur Thermal Power Plant) in collection of real-time data.

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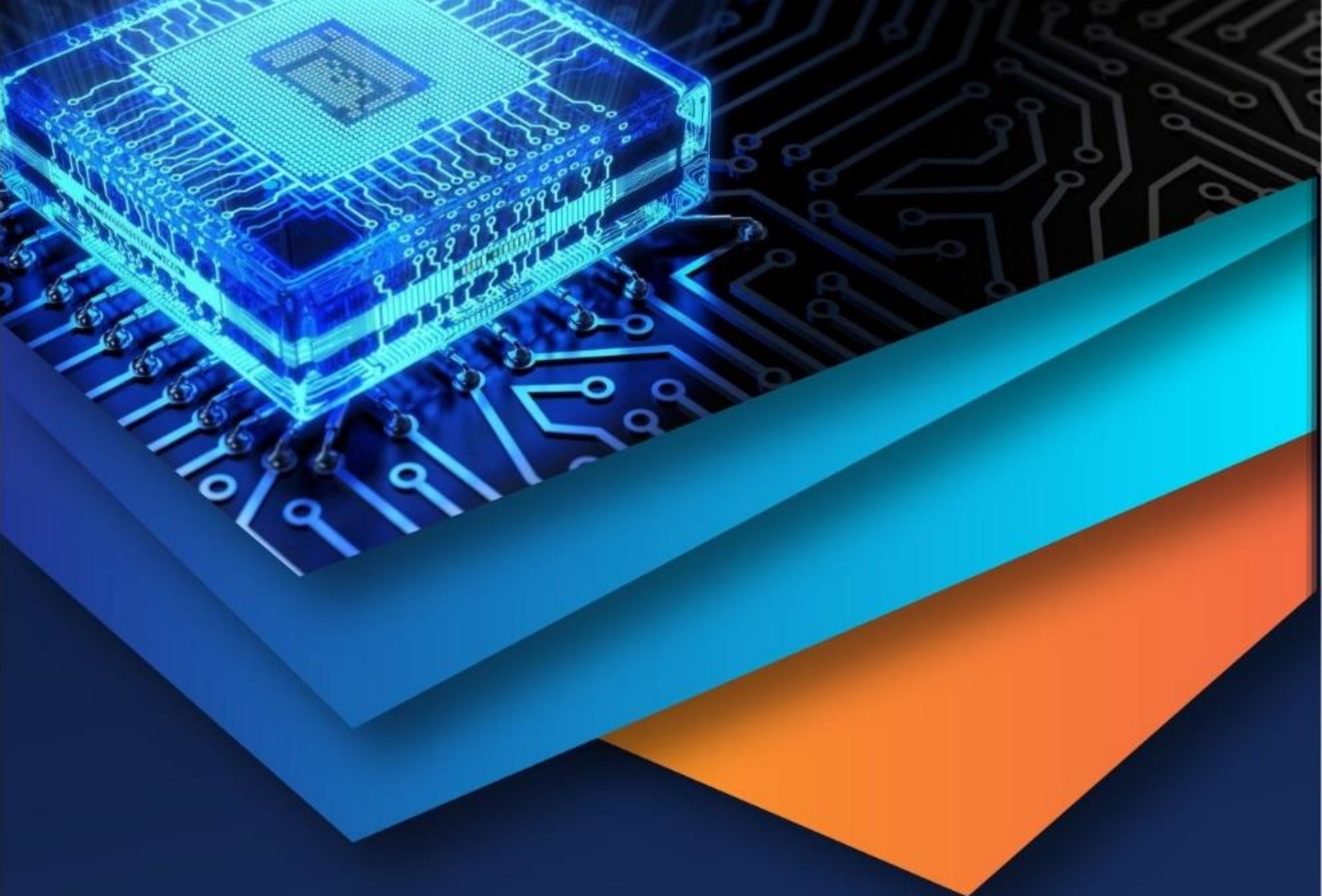

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