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Review on Energy and Exergy Analysis of Boiler in Cogeneration Coal Power Plant

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Abstract**: *Based on several research activity and local power plant experience some key observation has made and the aim of this work is to be find out amount and source of irreversibility generated in boiler of 6 MW captive power plant and also calculate the losses of boiler by using first law and second law of Thermodynamic i.e. Energy and Exergy analysis, compare the efficiency of both Energy and the Exergy efficiency of boiler so that any process in the system that having largest energy destruction can be identified that help designer to re-design the system components. The aim of exergy analysis is to identify the losses in boiler in order to improve the existing system like boiler, economizer super-heater, furnace, boiler tube, air pre-heater, boiler feed pump.***
Keywords: Irreversibility, Exergy Analysis, Energy analysis, Coal based Thermal Power Station, Fossil fuels, Irreversibility, Second Law of Thermodynamics.

I. INTRODUCTION

India's energy basket is a mixture of all available resources i.e., both renewable and non renewable energy resources. Coal is the major source for the power production when compared with other sources. A thermal power plant is a plant in which steam is used to drive the prime mover. Around 58.75% of the power generation is from coal based power plants of the total installed capacity. Natural gas contribute around 8.91%, Nuclear and oil contribute around 2.11% and 0.52%. The share of coal and petroleum is expected to be around 66.8% in the total commercial energy produced. The share of crude oil in production and consumption is expected to be around 6.7% and 23% by 2021-22. Fig 1 shows sources of electricity in INDIA by installed capacity as of 2013.

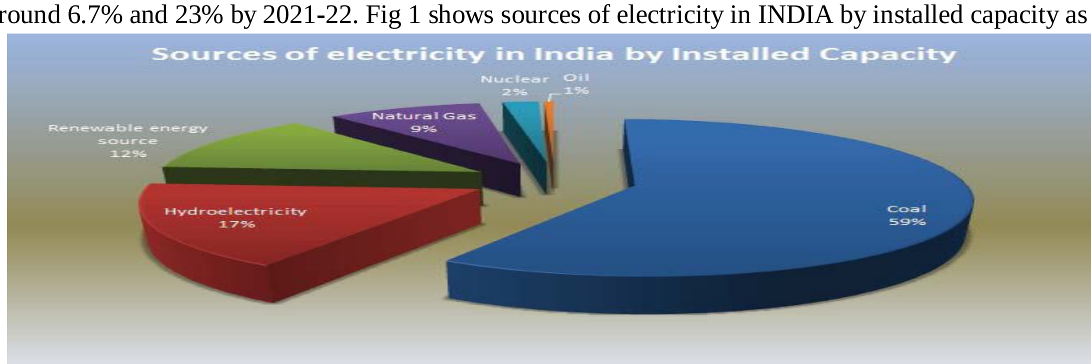

Figure 1 Sources of electricity in INDIA by installed capacity as of 2013

World net electricity generation up to year 2007 and projected generation up to year 2035 by different fuels is shown in the Fig. 2

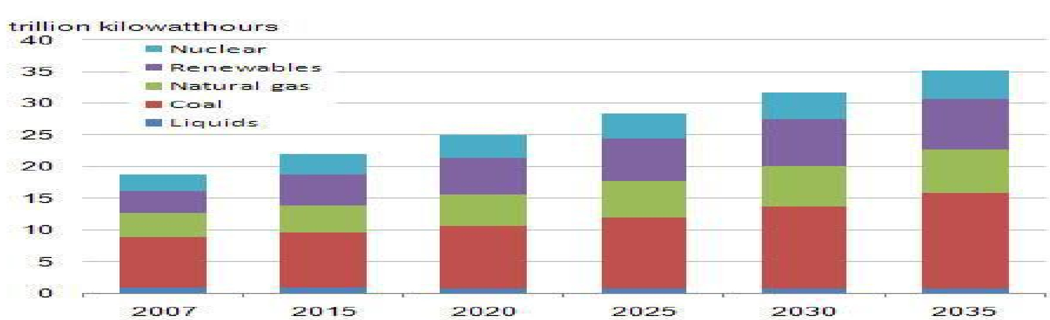

Fig. 2 World net electricity generation by fuel (trillion kilowatt hours)

A. Source: International Energy Outlook 2010

The first law deals with the amounts of energy of various forms transferred between the system and its surroundings and with the changes in the energy stored in the system. It treats work and heat interactions as equivalent forms of energy in transit and offers no indication about the possibility of a spontaneous process proceeding in a certain direction. The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur. This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the second law of thermodynamics. The exergy method of analysis is based on the second law of thermodynamics and the concept of irreversible production of entropy. The fundamentals of the exergy method were laid down by Carnot in 1824 and Clausius in 1865. The energy-related engineering systems are designed and their performance is evaluated primarily by using the energy balance deduced from the first law of thermodynamics. Engineers and scientists have been traditionally applying the first law of thermodynamics to calculate the enthalpy balances for more than a century to quantify the loss of efficiency in a process due to the loss of energy. The exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes and plant systems since it has been seen that the first law analysis has been insufficient from an energy performance stand point. Keeping in view the facts stated above, it can be expected that performing an analysis based on the same definition of performance criteria will be meaningful for performance comparisons, assessments and improvement for thermal power plants. Additionally, considering both the energetic and exergetic performance criteria together can guide the ways of efficient and effective usage of fuel resources by taking into account the quality and quantity of the energy used in the generation of electric power in thermal power plants. The purpose of this study presented here is to carry out energetic and exergetic performance analyses, at the design conditions, for the existing coal and gas-fired thermal power plants in order to identify the needed improvement. For performing this aim, we summarized thermodynamic models for the considered power plants on the basis of mass, energy and exergy balance equations. The thermodynamic model simulation results are compared. In the direction of the comprehensive analysis results, the requirements for performance improvement are evaluated

II. OBJECTIVE

A. To compare the energy and exergy efficiencies.
B. To reduce the loss of energy.
C. To increase the overall performance of thermal power plant.
D. Reduced the coal consumption
E. Reduced the auxiliary power consumption
F. Increase the plant load factor

III. ENERGY - ENERGY ANALYSIS

Basically Boiler efficiency can be tested by the following methods

A. Direct Method or Input Output Method

Direct method compares the energy gain of the working fluid (water and steam) to the energy content of the fuel. This is also known as „input-output method" due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency

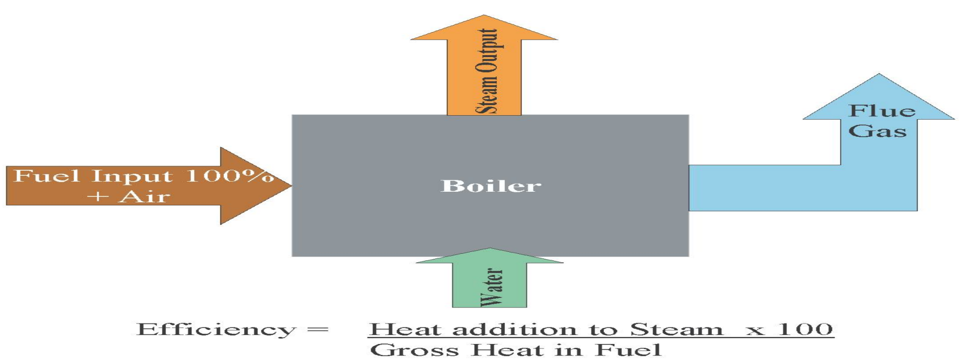

Fig.3 Direct Method or Input Output Method

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$$\text{Boiler Efficiency } (\eta) = \frac{\text{Heat Output}}{\text{Heat Input}} \times 100$$

$$\text{Boiler Efficiency } (\eta) = \frac{\text{Steam Flow Rate} \times (\text{steam enthalpy} - \text{feed water enthalpy})}{\text{Fuel firing rate} \times \text{Gross calorific value}} \times 100$$

Where,
η = boiler efficiency in %.
SFR= steam flow rate in kg/hr.
SE= steam enthalpy in kCal/kg.
FEW= feed water enthalpy in kCal/kg.
FFR= fuel firing rate in kg/hr.
GVC= gross calorific value of coal in kCal/kg.

B. Indirect Method or Heat Loss Method

In the heat loss method the efficiency is the difference between the losses and the energy input. In indirect method the efficiency can be measured easily by measuring all the losses occurring in the boilers using the principles to be described. The weaknesses of the direct method can be overwhelmed by this method, which calculates the various heat losses associated with boiler. The efficiency can be arrived at, by subtracting the heat loss percentages from 100. An important advantage of this method is that the errors in measurement do not make significant change in efficiency. The indirect method does not account for Standby losses; Blow down loss, energy loss in Soot blowing, and energy loss running the auxiliary equipment such as burners, fans, and pumps.

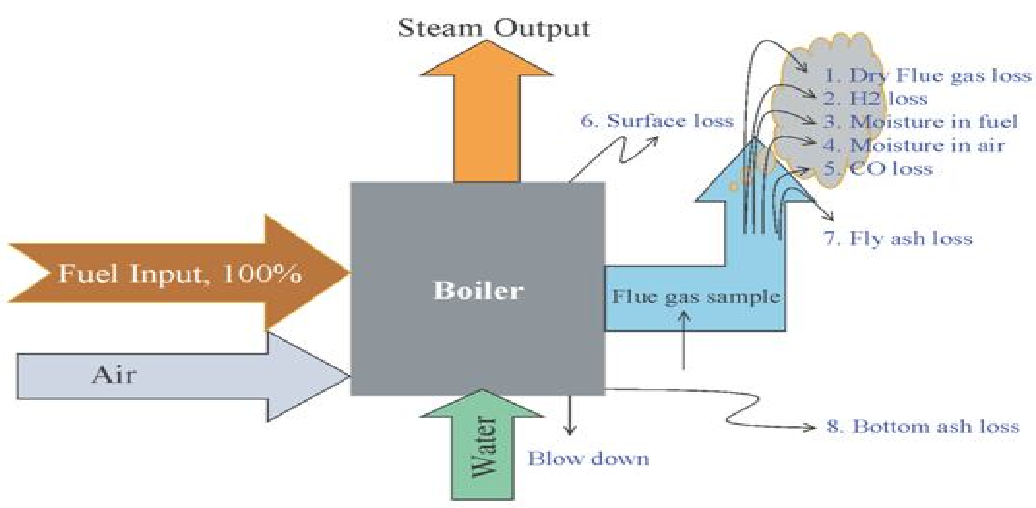

Fig.4 Indirect Method or Heat Loss Method

Valid losses incorporate with to coal fired boiler:

1) Heat loss due to dry flue gas as sensible heat (L1)
2) Heat loss due to moisture in the coal (L2)
3) Unburnt losses in bottom ash as carbon (L3)
4) Loss due to surface radiation and convection (L4)
5) Heat loss due to moisture from burning of hydrogen in coal (L5)
6) Heat loss due to moisture in air (L6)

Total Losses= L1+L2+L3+L4+L5+L6
Boiler efficiency by indirect method:
Boiler Efficiency= 100- Total Losses

Energy analysis is done by calculating losses of the boiler by using indirect method Coal energy is the main source of thermal power plant for that we require the ultimate analysis of coal as well as proximate analysis of coal (Report from western coal field limited Nagpur)

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TABLE 1 ULTIMATE ANALYSIS OF COAL

Coal Constituent	Unit	Coal Sample
carbon (c)	%	45
hydrogen (h)	%	13
nitrogen (n)	%	1.69
oxygen (o)	%	4.5
sulfur (s)	%	0.5
ash	%	29.31
moisture	%	9.82
volatile matter	%	20.16
fixed carbon	%	34.71
calorific value	kcal/kg	4187

IV. ENERGY ANALYSIS

The following are the losses to be taken into account for the boiler

A. Heat loss due to dry flue gas as sensible heat (L1)
B. Heat loss due to moisture in the coal (L2)
C. Unburnt losses in bottom ash as carbon (L3)
D. Loss due to surface radiation and convection (L4)
E. Heat loss due to moisture from burning of hydrogen in coal (L5)
F. Heat loss due to moisture in air (L6)

1) Heat Loss Due to Dry Flue Gas as Sensible Heat **(L1)**

Theoretical air required = $\frac{1}{23}(2.67C + 8(H_2 - \frac{O_2}{8} + s)$

Excess air required = $\frac{O_2\%}{21 - O_2\%}$

Actual mass of air supplied

= (1+ Excess air/100) × Theoretical air required in kg/kg of coal

Total mass of flue gas (m)/kg of fuel

= mass of actual air supplied/kg of fuel + 1 kg of fuel

This is the greatest boiler loss and can be calculated with the following formula:

Heat loss due to dry flue gas L1 = $\frac{mass \times Cp \times (Tf - Ta)}{G.C.V. of\ fuel}$

Where,

L1 = % Heat loss due to dry flue gas
m = Mass of dry flue gas in kg/kg of fuel
= Combustion products from fuel: CO2 + SO2 + Nitrogen in fuel + Nitrogen in the actual mass of air supplied + O2 in flue gas. (H2O/Water vapour in the flue gas should not be considered)
Cp = Specific heat of flue gas in kCal/kg°C
Tf = Flue gas temperature in °C
Ta = Ambient temperature in °C

2) Heat Loss Due to Moisture in the Coal **(L2)**

Moisture entering the boiler with fuel leaves as a superheated vapour, this moisture loss made up of sensible heat during the to bring the moisture to the boiling point ,the latent heat of evaporation of the moisture ,the loss can be calculated by Following formula , taken from paper energy performance assessment of boiler.

% Heat loss due to moisture in fuel (L2) = $\frac{M \times \{584 + Cp(Tf - Ta)\} \times 100}{G.C.V.\ of\ fuel}$

By putting the above value from table we get

Where,

L2 = % Heat loss due to dry moisture in fuel
m = kg moisture in fuel on 1 kg basis
Cp = Specific heat of superheated steam in kCal/kg°C
Tf = Flue gas temperature in °C
Ta = Ambient temperature in °C
584 = Latent heat corresponding to partial pressure of water vapour

3) Unburnt Losses in Bottom Ash as Carbon **(L3)**

Carbon particle are found in the boiler bank bottom, when flue gas is flowing from boiler to stack heavy particle of ash containing coal particles fallen in the boiler bank and remaining small size of ash practical are gone to stack and then atmosphere

(Below formula taken from literature and boiler efficiency)

%Heat loss due to unburnt in bottom ash (L3)

$$= \frac{Total\ ash\ collected\ per\ kg\ of\ coal\ burnt * GCV\ of\ bottomash * 100}{GCV\ of\ fuel}$$

4) Heat Loss Due to Surface Radiation and Convection **(L4)**

As per the boiler company manual, radiation loss would be considered as a 1 % after proper insulation done. **(**Above value taken from literature also**)**

5) Heat Loss Due to Moisture from Burning of Hydrogen in Coal **(L5)**

The combustion of hydrogen causes heat losses because the product of combustion is water. This water is converted to the steam and this carries away heat in the form of its latent heat

% Heat loss due to evaporation of water formed due to H2 in fuel (L5)

$$= \frac{9 \times H2 \times \{584 + Cp(Tf - Ta)\} \times 100}{GCV\ of\ coal}$$

Where,
L5 = % Heat loss due to dry moisture in fuel
H2 = kg of hydrogen present in fuel on 1 kg basis
Cp = Specific heat of superheated steam in kCal/kg°C
Tf = Flue gas temperature in °C
Ta = Ambient temperature in °C
584 = Latent heat corresponding to partial pressure of water vapour

6) Heat Loss Due to Moisture in Air **(L6)**

Vapors in the form of humidity in the incoming air, is superheated as it passes through the boiler, since heat passes through the stack, it must be included as a boiler loss to related the losses to the loss of coal burned, the moisture content of the combustion air and the amount of air supplied per unit mass of coal must be known

%Heat loss due to moisture present in air (L6)

$$= \frac{AAS\ x\ humidity\ factor\ x\ Cp\ x\ (Tf.Ta)\ x\ 100}{GCV\ Of\ coal}$$

Where,
L6 = % Heat loss due to dry moisture in air
Cp = Specific heat of superheated steam in kCal/kg°C
Tf = Flue gas temperature in °C
Ta = Ambient temperature in °C
AAS = Actual mass of air supplied per kg of fuel
Humidity factor = kg of water/kg of dry air

Boiler Efficiency

Boiler efficiency can be calculated as

=100- (L1+L2+L3+L4+L6)

V. EXERGY ANALYSIS

The exergy analysis can be evaluated for the following

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A. Exergy Analysis of Fuel

Exergy of fuel can be calculated by the equation proposes by shieh and fang for calculating the Exergy of fuel.

€f = 34183.16(C) + 21.95(N) + 11659.9(H) + 18242.90(S) + 13265.90(O) ----------(1)

According to the T.J kotas say that the ratio of Exergy of fuel to caloric value of the fuel lies between 1.15 to 1.30. According to the ultimate analysis we get Exergy of the fuel is = 17683.84 kj/kg and calorific value is 17585.4 kj/kg thus ratio we get is 1.01 that is nearer to T.J kotas ratio.

B. The Exergy of Feed Water

Before entering the water into the economizer, the water is allowed to get heated in the deaerator thus the temperature of feed water is increased to higher temperature, the temperature of water at economizer inlet from above table.

Exergy of feed water can be calculated by

$$€\hat{w} = (C_{pw})\,(T_4 - T_a) - T_a \ln\left(\frac{T_4}{T_a}\right)$$

Where,

1) C_{pw} = Specific heat of water kJ/kgK
2) T_4 = Temperature of feed water °C
3) T_a = Temperature of ambient temperature °C

C. The Exergy of Air

The Exergy of air can be calculated by following

$$€a = (C_{pa})\,(T_2 - T_a) - T_a \ln\left(\frac{T_2}{T_a}\right)$$

Where,

1) C_{pa} = Specific heat of air kJ/kgK
2) T_2 = Temperature of air of combustion at APH O/L °C

T_a = Temperature of ambient temperature °C

D. The Exergy of Economizer

The water entering the economizer from deaerator is already at higher temperature is then heated almost saturated temperature at that pressure but leaving the economizer remain in liquid without change in phase

$$€a = (C_{pw})\,(T_5 - T_4) - T_4 \ln\left(\frac{T_5}{T_4}\right)$$

Where,

1) C_{pw} = Specific heat of water kJ/kgK
2) T_5= Temperature of Eco O/L °C
3) T_4= Temperature of Eco I/L °C

E. The Exergy of Steam Drum can be calculated

$€_{drum} = (h_6 - h_5) - T_6\,(s_{6-s_5})$

Where,

1) T_6= Temperature of Drum °C
2) h_6 =Enthapy at temperature of Drum at pressure 68.6 kg/cm2, kJ/Kg
3) h_5 = Enthapy at drum Inlet or Eco O/L , kJ/Kg

F. The Exergy of Super Heater

Super heater is place at the end of boiler mounting and water circuit after super heater. Super heated steam is produced. The super heater for a given boiler is made up of three different component of super heater, primary super heater is rise the temperature by extracting the heat from flue gas is called as convective super heater, and secondary super heater is exposed to the flame to which heat is done by radiation thus caused radiating super heater, temperature range for the turbine inlet is fix if the steam temperature is rises above the rang it is found that attemptator or spray control valve is open, after that steam goes to the bed super heater.

Exergy rise in the drum = $(h_8 - h_6)$-$T_8(S_8 - S_6)$

Where,

1) T_8= Temperature at super heater O/L °C
2) h_6 =Enthapy at temperature of Drum at pressure 68.6 kg/cm2, kJ/Kg
3) h_8 = Enthalpy Temperature at super heater O/L, kJ/Kg

G. The Exergy of Flue Gas

$$€a = (C_{pg})\,(T_g - T_a) - T_a \ln\left(\frac{T_g}{T_a}\right)$$

Where,

1) C_{pg} = *specific heat of Flue gas* kJ/kgK
2) T_g = Temperature of flue gas °C
3) T_a = Temperature of Ambient °C

Total Exergy Gain by the Steam

4) As load increase, Exergy of flue gas increases, but it is again depend upon the temperature of flue gas and boiler load if at particular load temperature is less and boiler load is less then also Exergy of flue gas is less.
5) Total Exergy Entering in the boiler =(Exergy of fuel + Exergy of Eco + Exergy of water + Exergy of air)
6) Total Exergy Leaving from the boiler=(Exergy of super heater + Exergy of drum + Exergy of flue gas)
7) Irreversibility = (Exergy Leaving from the boiler) **-** (Exergy Entering in the boiler)

a) Boiler Efficiency

Boiler efficiency

= (Total Exergy Leaving from the boiler/ Total Exergy Entering in the boiler)

i) Total Exergy Entering in the boiler = (Exergy of fuel + Exergy of Eco + Exergy of water + Exergy of air)

ii) Total Exergy Leaving from the boiler **= (**Exergy of super heater + Exergy of drum + Exergy of flue gas)

VI. DISCUSSION ON RESULTS OF DIFFERENT EXERGY - ENERGY STUDY OF CO-GENERATION POWER PLANT

A. Energy Analysis

1) Moisture present in the coal means temperature of furnace or maintained the pressure of boiler required more coal, for minimizing this losses combustion air temperature is increases as well as coal should be selected in such mine whose moisture percentage should be less, another way if coal is dried before feeding the coal in the boiler
2) As load increases heat loss due to bottom ash decreases, carbon content form in the bottom ash due to incomplete combustion so proper air fuel ration is maintain is the only way to reduced the heat loss due to bottom ash, for AFBC boiler coal should be crushed up to 6 mm otherwise heavy particle of coal content in carbon found in the bottom ash
3) As load increases the loss due to moisture decreases because the temperature of flue gas increases.
4) As the load increases heat loss due to evaporation of water formed due to Hydrogen in the fuel increases.
5) As per our above discussion it is now found that load increases boiler losses reduces, so that plant should be run on the pick load ,this also shows that minimum load has maximum energy loss ,and pick load has minimum energy loss.

B. Exergy Analysis

1) As load increases the exergy of fuel also increases, so the plant should always be run at pick load.
2) As load increases the exergy of water also increases, so the plant should always be run at pick load.
3) The exergy of air is dependent upon the combustion of air temperature as well as flue gas temperature. Due to that it is found that exergy at full load is less as compared home load, so maintaining proper combustion air temperature as well as flue gas temperature is necessary.
4) As it also shows that as load increases, exergy of drum also increases, but in some cases exergy is reduced due to steam flow reduction, as it depends upon the extraction steam or process steam
5) It also shows that as load increase exergy rise of super heater also increase and it depends upon the temperature of the drum as well as temperature of super heater.

6) As load increases exergy of flue gas increases, but it is again dependent upon the temperature of flue gas and boiler load. If at particular load temperature is less and boiler load is less then also exergy of flue gas is less.
7) Irreversibility increases according to the load increase. To reduce the irreversibility heat transfer rate is required to increase. So as per boiler efficiency, from exergy analysis is that when load increases the efficiency also increases

VII. CONCLUSIONS

Energy and Exergy analysis of cogeneration power plant is useful tool for analyzing various losses occurring in different parts of power plant. Exergy analysis in different power plant concluded that maximum losses are occurring in boiler. Which we already tried to minimize by adopting different accessories. Further plant efficiency can be improved by adopting methodology used in big thermal power plants. Irreversibility generally due to heat loss to atmosphere and heat lost to exhaust gas which is impossible to remove but can be minimized to optimum value. The minimum exergy loss occur in turbine generally due to insulation, which works with minimum losses. Condensers are important part of power plant which is necessary to create the back pressure and increase the efficiency of power plant. This heat rejected by steam or hot water is the reused by circulating cold feed water to hot water which could otherwise be rejected to atmosphere. The demand of power per hour varies with situation and tise leads to fluctuation of load on to power plant. According to different loading condition the exergy and energy analysis can be the scope of study for optimizing the different values to improve the performance of power plant. This also can be studied with change in operating parameter and then its effect on load which difficult to carry out practical but with aid of new computational it may be possible to work with some ready data calculation. This paper helps designer about the working parameter where we can improve the efficiency, lower the irreversibility higher performance of boiler.

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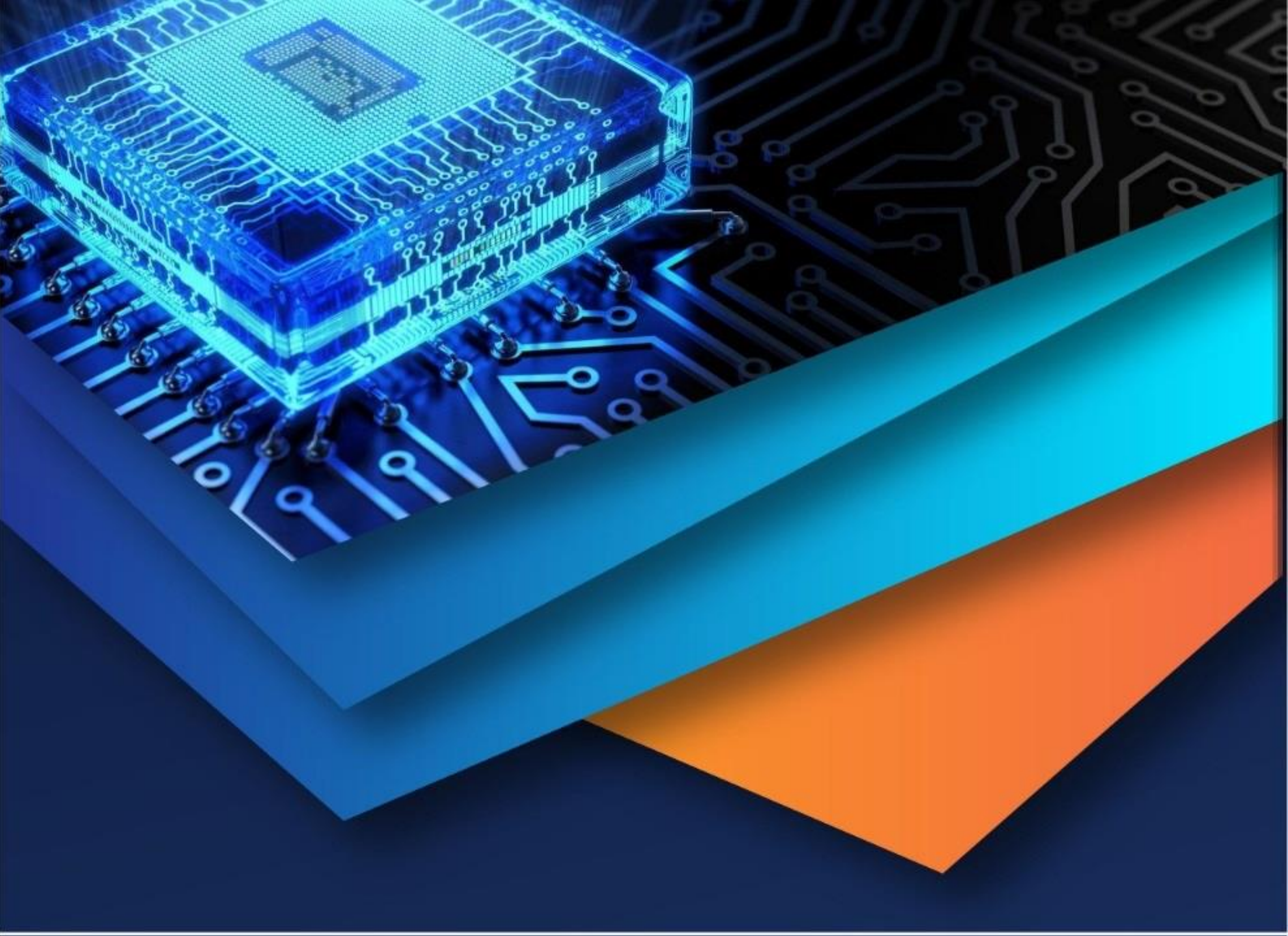

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