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Thermodynamic Analysis of Vapor Absorption Refrigeration System and Calculation of COP

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***Abstract*— This paper provides an analytical study of absorption refrigeration technology. Through the application of the first and second laws of thermodynamics upper and lower limits for the coefficient of performance (COP) of absorption cooling cycles are derived. These upper and lower limits, besides being dependent on the environmental temperatures of components of the cycle, are also dependent on the thermodynamic properties of refrigerants, absorbents, and their mixtures. The objective of this work is to design a lithium bromide–water (LiBr-H2O) absorption refrigerator with a nominal capacity of 5.25 kW. The various stages of refrigeration system are presented including the design of the evaporator, absorber, solution heat exchanger, generator and condenser and finally COP is calculated.**

***Keywords*—Refrigeration, Refrigerant, Absorption, Coefficient of performance(COP), Heat pump.**

I. INTRODUCTION

In recent developments of thermal engineering the Refrigeration technologies play an important role in today's industrial applications [1]

But as far as COP of these refrigeration system is concerned, it is always a challenge to the researchers to significantly increase the COP for these systems.

The most popular refrigeration and air conditioning systems at present are those based on the vapour absorption systems. These systems are popular because they are reliable, relatively inexpensive and their technology is well established. However, these systems require high grade energy (mechanical or electrical) for their operation. Apart from this, the recent discovery that the conventional working fluids of vapour absorption systems are causing the ozone layer depletion and greenhouse effects has forced the scientific researchers to look for alternative systems for cooling applications. The natural alternative is of course the absorption system, which mainly uses heat energy for its operation. Moreover, the working fluids of these systems are environment friendly [2].

A suitable working fluid is probably the single most important factor in any refrigeration system. The cycle efficiency and operation characteristics of an absorption refrigeration system depend on the properties of refrigerant, absorbent and their mixtures. The most important thermo-physical properties are: heat of vaporization of refrigerant, heat of solution, vapour pressure of refrigerant and absorbent, solubility of refrigerant in solvent, heat capacity of solution, viscosity of solution and surface tension and thermal conductivity of the solution. Apart from this, the other selection criteria for the working fluids are their toxicity, chemical stability and corrosivity. Vapour Absorption Refrigeration Systems belong to the class of vapour cycles similar

to vapour absorption refrigeration systems. However, unlike vapour absorption refrigeration systems, the required input to absorption systems is in the form of heat. Hence these systems are also called as heat operated or thermal energy driven systems. Both vapour absorption and absorption refrigeration cycles accomplish the removal of heat through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure. The basic difference is that a vapour absorption system employs a mechanical compressor to create the pressure differences necessary to circulate the refrigerant whereas an absorption system uses heat source and the differences cause an absorption system to use little to no work input, but energy must be supplied in the form of heat. This makes the system very attractive when there is a cheap source of heat, such as solar heat or waste heat from electricity or heat generation [3].

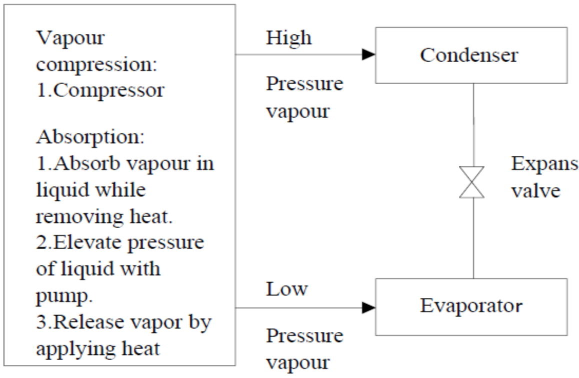

Fig.1

Method of transforming low pressure vapor into high pressure vapour in a refrigeration system.

Vapour Absorption Systems offer many advantages like it offers flexibility to utilize any sort of low grade, low cost heat energy available to produce cooling and thus giving a high savings in operating costs. It can operate on steam or any other waste heat source as the energy source instead of costly and unreliable electric power. No moving parts ensure noiseless, vibration-less and trouble free operation. Moreover maintenance costs are negligible as compared to power driven mechanical systems. Refrigerating effect is produced using a clean refrigerant in place of ozone-depleting chlorine based compounds[2].

Components of a Vapour Absorption Cooling System:

The components of Vapour Absorption Refrigeration Cooling System are as[4].

Generator: The purpose of the generator is to deliver the refrigerant vapour to the rest of the system. It accomplishes this by separating refrigerant from the solution. In then generator, the solution vertically falls over horizontal tubes with high-temperature energy source typically steam or hot water flowing through the tubes. The solution absorbs heat from the warmer steam or water, causing the refrigerant to boil (vaporize) and separate from the absorbent solution. As the refrigerant is boiled away, the absorbent solution becomes more concentrated. The concentrated absorbent solution returns to the absorber and the refrigerant vapour migrates to the condenser.

Condenser: The purpose of condenser is to condense the refrigerant vapours. Inside the condenser, cooling water flows through tubes and the hot refrigerant vapour fills the surrounding space. As heat transfers from the refrigerant vapor to the water, refrigerant condenses on the tube surfaces. The condensed liquid refrigerant collects in the bottom of the condenser before travelling to the expansion device. The cooling water system is connected to a cooling tower.

Expansion Valve: From the condenser, the liquid refrigerant flows through an expansion device into the evaporator. The expansion device is used to maintain the pressure difference between the high-pressure (condenser) and low-pressure (evaporator) sides of the refrigeration system. As the high-pressure liquid refrigerant flows through the expansion device, it causes a pressure drop that reduces the refrigerant pressure to that of the evaporator. This pressure reduction causes a small portion of the liquid refrigerant to boil off, cooling the remaining refrigerant to the desired evaporator temperature. The cooled mixture of liquid and vapour refrigerant then flows into the evaporator.

Evaporator: The purpose of evaporator is to cool the circulating water. The evaporator contains a bundle of tubes that carry the system water to be cooled/chilled. At low pressure existing in the evaporator, the refrigerant absorbs heat from the circulating water and evaporates. The refrigerant vapours thus formed tend to increase the pressure in the vessel. This will in turn increase the boiling temperature and the desired cooling effect will not be obtained. So, it is necessary to remove the refrigerant vapours from the vessel into the lower pressure absorber. Physically, the evaporator and absorber are contained inside the same shell, allowing refrigerant vapours generated in the evaporator to migrate continuously to the absorber.

Absorber: Inside the absorber, the refrigerant vapour is absorbed by the solution. As the refrigerant vapour is absorbed, it condenses from a vapour to a liquid, releasing the heat it acquired in the evaporator. The heat released from the condensation of refrigerant vapours by their absorption in the solution is removed by the cooling water circulating through the absorber tube bundle. The weak absorbent solution is then pumped to the generator where heat is used to drive off the refrigerant. The hot refrigerant vapours created in the generator migrate to the condenser. The cooling tower water circulating through the condenser turns the refrigerant vapours to a liquid state and picks up the heat of condensation, which it rejects to the cooling tower. The liquid refrigerant returns to the evaporator and completes the cycle.

Refrigerent-Absorbent combinations for Vapour Absorption Cooling Systems:

Absorption machines are commercially available today in two basic configurations. For applications above 50C (primarily air-conditioning) the cycle uses lithium bromide/water. For applications below 50C, ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent.

Desirable Properties of Refrigerant-Absorbent mixtures:
Refrigerant-absorbent mixtures for Vapour Absorption Cooling System should possess some desirable properties like the refrigerant should be more volatile than the absorbent in other words the boiling point of refrigerant should be much lower than the absorbent. There must be large difference in the boiling points of refrigerant and absorbent (greater than 2000 ^{0}C), so that the solution in the Generator need only to be heated to the temperature required to boil off only the refrigerant. This ensures that only pure refrigerant circulates through refrigerant circuit (condenser-expansion valve-evaporator). The refrigerant should exhibit high solubility with solution in the absorber. The absorbent should have strong affinity for the refrigerant. This will minimize the amount of refrigerant to be circulated. Operating pressures should be preferably low, so that the walls of the shells and connecting pipes need not to be thick. It should not undergo crystallization or solidification inside the system. Because crystallization will block the free flow of solution in the line. The mixture should be safe, chemically stable, non-corrosive, inexpensive and should be available easily. The refrigerant should have high heat of vaporization[5], [6].

Refrigerant-Absorbent pairs: The two most commonly used refrigerant-absorbent pairs in commercial systems are[6]:

Water-Lithium Bromide (H2O-LiBr) system for moderate temperatures (above 50C) applications specifically air conditioning. Here water is the refrigerant and lithium bromide is the absorbent.

Ammonia-Water (NH3-H2O) system for low temperature(less than 50 C) refrigeration applications with ammonia as refrigerant and water as absorbent.
The Lithium Bromide-Water pair satisfies majority of the above listed properties. For these reasons Li-Br and Water systems are becoming more popular. Comparison of Lithium Bromide-Water systems and Ammonia-Water Systems

Ammonia-Water Systems:
Since the invention of absorption refrigeration system, NH3-Water has been widely used. Both *NH*3 (refrigerant) and *water* (absorbent) are highly stable for a wide range of operating temperature and pressure. *NH*3 has a high latent heat of vaporization, which is necessary for efficient performance of the system. It can be used for low temperature applications, as the freezing point of *NH*3 is -77°C. But since both *NH*3 and *water* are volatile, the cycle requires a rectifier to strip away water that normally evaporates with *NH*3 .Without a rectifier, the water would accumulate in the evaporator and offset the system performance. There are other disadvantages such as its high pressure, toxicity, and corrosive action to copper and copper alloy. Ammonia/Air mixtures are barely inflammable but may be explosive in the case of high percentages of ammonia between 15.5 and 27 % by volume[7].

LiBr-Water Systems
The use of LiBr-Water for absorption refrigeration systems began around 1930. Two outstanding features of LiBr-Water are non-volatility absorbent of LiBr (the need of a rectifier is eliminated) and extremely high heat of vaporization of water (refrigerant). However, using water as a refrigerant limits the low temperature application to that above
0°C. As water is the refrigerant, the system must be operated under vacuum conditions. At high concentrations, the solution is prone to crystallization. One way to prevent this to happen is to add one or more extra salts e.g., ZnBr2, ZnCl2 .The addition of

the third component into the basic water-lithium bromide solution pushes the crystallization limit away from the normal operating zone. Hence the strong solution can be cooled in the heat exchanger to near absorber temperature without salt crystallization, thus improving the performance of the system. COP is high (0.7 to 0.9) as compared to (0.5 to 0.6) for Ammonia-Water systems[8], [9].

II. THERMODYNAMIC ANALYSIS OF THE SYSTEM

Thermodynamic analysis of the system involves finding important parameters like enthalpy, mass flow rates, flow ratio, Heat and Mass Transfers for the whole system to finally calculate the system Coefficient of Performance (COP). These values are to be then used for design of the system. First some set of thermodynamic equations have been derived in terms of mass flow rates and enthalpy by applying mass and energy balance for each component. Then the actual system conditions like temperature, pressures, enthalpies are substituted in the equations to finally obtain the COP value for the system [10], [11].Thermodynamic analysis of the system is carried out with the following assumptions:

A. Steady state and steady flow
B. No pressure drops due to friction
C. Only pure refrigerant boils in the generator.

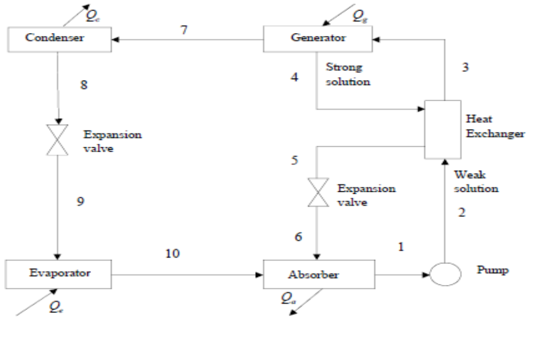

Fig.2 Block diagram of Vapor Absorption Refrigeration System**.**

Let m = mass flow rate of refrigerant, kg/s
m_{ss} = mass flow rate of strong solution, kg/s
m_{ws} = mass flow rate of weak solution, kg/s

Heat (Q) **and Mass** (m) **balance for each component[]**:

Condenser
$m_7 = m_8 = m$
$Q_c = m(h_7 - h_8)$, kJ/s

Expansion Valve
$m_8 = m_9 = m$
$h_8 = h_9$(isoenthalpic), *kJ / kg*

Evaporator
$m_9 = m_8 = m$
$Q_e = m(h_9 - h_8)$, kJ/s

Absorber
From total Mass balance
$m + m_{ss} = m_{ws}$

Now **Circulation Ratio**,
$\lambda = m_{ss}/m$

Therefore, $m_{ws} = (1+\lambda)m$
From Mass balance of pure water
$m + (1+\xi_{ss})m_{ss} = (1+\xi_{ws})m_{ws}$
Solving for λ we get,
$\lambda = \xi_{ws} / (\xi_{ss} - \xi_{ws})$

and
$Q_a = mh_{10} + \lambda mh_6 - (1+\lambda)mh_1$, KJ/s

Solution Pump
$m_1 = m_2 = m_{ws}$
$w_p = (1+\lambda)mV_{sol}(p_c - p_E)$ kJ/s
where V_{sol} . is specific volume of solution which can be taken as approx. 0.00055 m^3/kg.

Solution Heat Exchanger
$m_2 = m_3 = m_{ws}$
$m_4 = m_5 = m_{ss}$
$Q_{HX} = (1+\lambda)m(h_3 - h_2) = \lambda m(h_4 - h_5)$,kJ/s

Generator
$m_3 = m_4 + m_7$
Heat input to the Generator,

$Q_g=mh_7+\lambda mh_4-(1+\lambda)m_3$, kJ/s

now Coefficient of Performance (COP):
In this system the net refrigerating effect is the heat absorbed by the refrigerant in the evaporator. The total energy supplied to the system is the sum of work done by the pump and the heat supplied in the generator. Therefore, the Coefficient of performance (COP) of the system is given by COP= Heat Absorbed in the Evaporator /(Work done by pump +Heat Supplied in the Generator)
or $COP=Q_e/(Q_g+W_p)$

Neglecting the Pump work

$COP=Q_e/Q_g$
is the expression for Coefficient of Performance(COP) of the System.

III. MATHEMATICAL CALCULATIONS FOR EACH COMPONENT

Operating temperatures and pressures

The most favourable working temperatures for a Single effect lithium-bromide and water refrigeration system (for a COP value between 0.7 and 0.9) are
Generator Temperature, T_g= 55- 90 ℃
Condenser Temperature, T_c= 24 46 ℃
Absorber Temperature, T_a = 16 32 ℃
Evaporator Temperature, Te= 2.5 10 ℃
The operating temperatures chosen are

Generator Temperature, , T_g =64℃
Condenser Temperature, T_c= 30℃
Absorber Temperature, T_a =20℃
Evaporator Temperature, Te =4℃

Operating Pressures

The operating Pressures can be known corresponding to the temperatures. Say for example the saturation pressure for condensation in the Condenser at 300C can be obtained from steam tables and is equal to 0.0425bar. Also 1bar = 750.06mm of Hg. Therefore 0.0425bar= 32mm of Hg which is also equal to Generator pressure because Condenser and Generator operate at same pressure. Now the saturation pressure for saturated vapors formed in Evaporator at a temperature of 40C can again be obtained from steam table which comes to be 0.0081bar or 6.1mm of Hg which will also be equal to the Absorber pressure as both operate under same pressure.

Capacity of the system or Refrigerating Effect (Q_e)= 1.5*ton* = 5.25*kW*

Calculation of Enthalpy (*h*) at every designated point of the system:

Enthalpy of pure water and of superheated water vapors at any temperature can
be determined from steam tables. Enthalpies of solutions are calculated from LiBr-Water Pressure-Temperature-Concentration-Enthalpy(P-T-ξ-h) Chart.

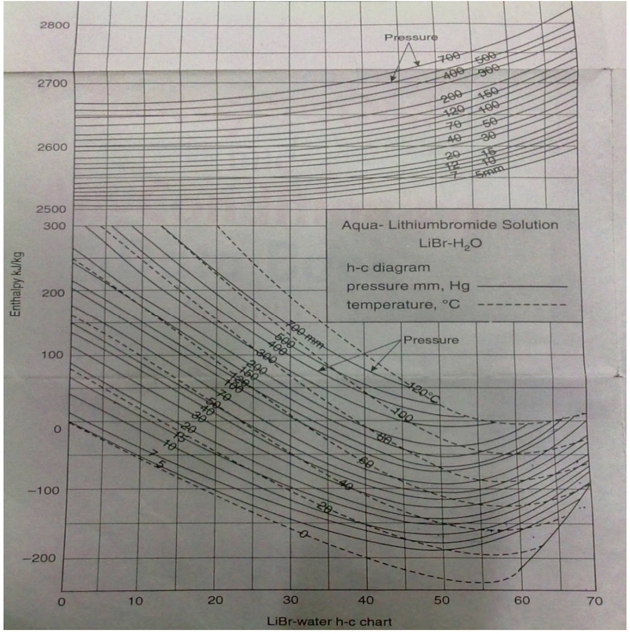

Fig.2
LiBr-Water Pressure-Temperature-Concentration-Enthalpy Chart.

The results obtained are tabulated below:

Table I

Li-Br-Water Enthalpy-Pressure-Temperature-Concentration Table.

State Points	**Temp. in °C**	**Pressure in mm of Hg**	**Enthalpy *h* ,Kj/kg**	**Concentration ξ**
7	64	32	2616.50	-
8	30	32	125.70	-
9	30	6.1	125.70	-
10	4.0	6.1	2508.70	-
1	20	6.1	-180.0	0.48
2	20	32	-180.0	0.48
3	53.85	32	-115.70	0.48
4	64	32	-120.0	0.56
5	20	32	-195.0	0.56
6	20	6.1	-195.0	0.56

Obtaining Heat transfers for each component:

Evaporator: Applying the Energy balance
Qe = *Refrigerating effect* =5.25$kW = m(h_{10} - h_9)$

$= m\times(2508.70 - 125.70)$
m=5.25/ (2508.70- 125.70)
or $m = 2.203\times10^{-3}$ kg/s = mass flow rate of refrigerant.
Now, Circulation Ratio , $\lambda=\xi_{WS}/(\xi_{SS}-\xi_{WS})$
λ=0.48/(0.56-0.48) = 6

therefore, $m_{SS}=\lambda\times m=13.22\times10^{-3}kg/s$

and $m_{ws}=(1+\lambda)m=(1+6)\times2.203\times10^{-3}=15.42\times10^{-3}$ kg/s

Absorber: Applying the Energy balance

$Qa=mh_{10}+m_{ss}h_6-m_{ws}h_1$

$=(2.203\times10^{-3}\times2508.70)+(13.22\times10^{-3}\times-195)(15.42\times10^{-3}\times-180)$

$=5724W=5.724kW$

Solution Heat Exchanger (H_X): Writing the Energy balance for Heat Exchanger,

$m_{ws}\times(h_3\times-h_2)=m_{ss}\times(h_4-h_5)$

$=15.42\times(h_3+180)=13.22\times(-120+195)$

$h_3=-115.70$ kJ / kg

Generator

$Q_G=mh_7+m_{ss}h_4-m_{ws}h_3$

$=(2.203\times10^{-3}\times2621.32)+(13.22\times10^{-3}\times-120)-(15.42\times10^{-3}\times-115.70)$

$=5906W=5.96kW$

Condenser

$Q_c=m(h_7-h_8)$

$=2.203\times10^{-3}\times(2616.50-125.70)$
$=5487W=5.487kW$

COP = Q_E/Q_G
$=5250/5960$
$=0.881$

IV. RESULT

In this paper, we have developed a method of calculation that is based on simple analytical data which relate the thermodynamic variable of the H2O-LiBr fluid couple. Detailed analytical procedure for the calculation of the COP for the design is given and the COP of the system for the different parameters is calculated to be .881.For the better understanding of the results we have given a design parameters table.

Table :II
Final parametric table.

S.NO	COMPONENS	HEAT TRANSFER RATE	VALUE(kw)
1	Evaporator	Q_E	5.25
2	Absorber	Q_A	5.724

3	Generator	Q_G	5.96
4	Condenser	Q_C	5.487

V. CONCLUSION

COP of the system is greatly influenced upon the system temperatures. The effect of parameters like Condenser, Generator, Absorber and Evaporator temperature on system COP have been studied. The results have shown that all these four parameters greatly influence the system COP.

VI. SCOPE FOR FUTURE WORK

Any change can be done that can bring an overall improvement in the system COP or material saving or more simple design procedure. Any other parameters effect can be studied. Of course the future scope also lies in the system fabrication and practical application[12].

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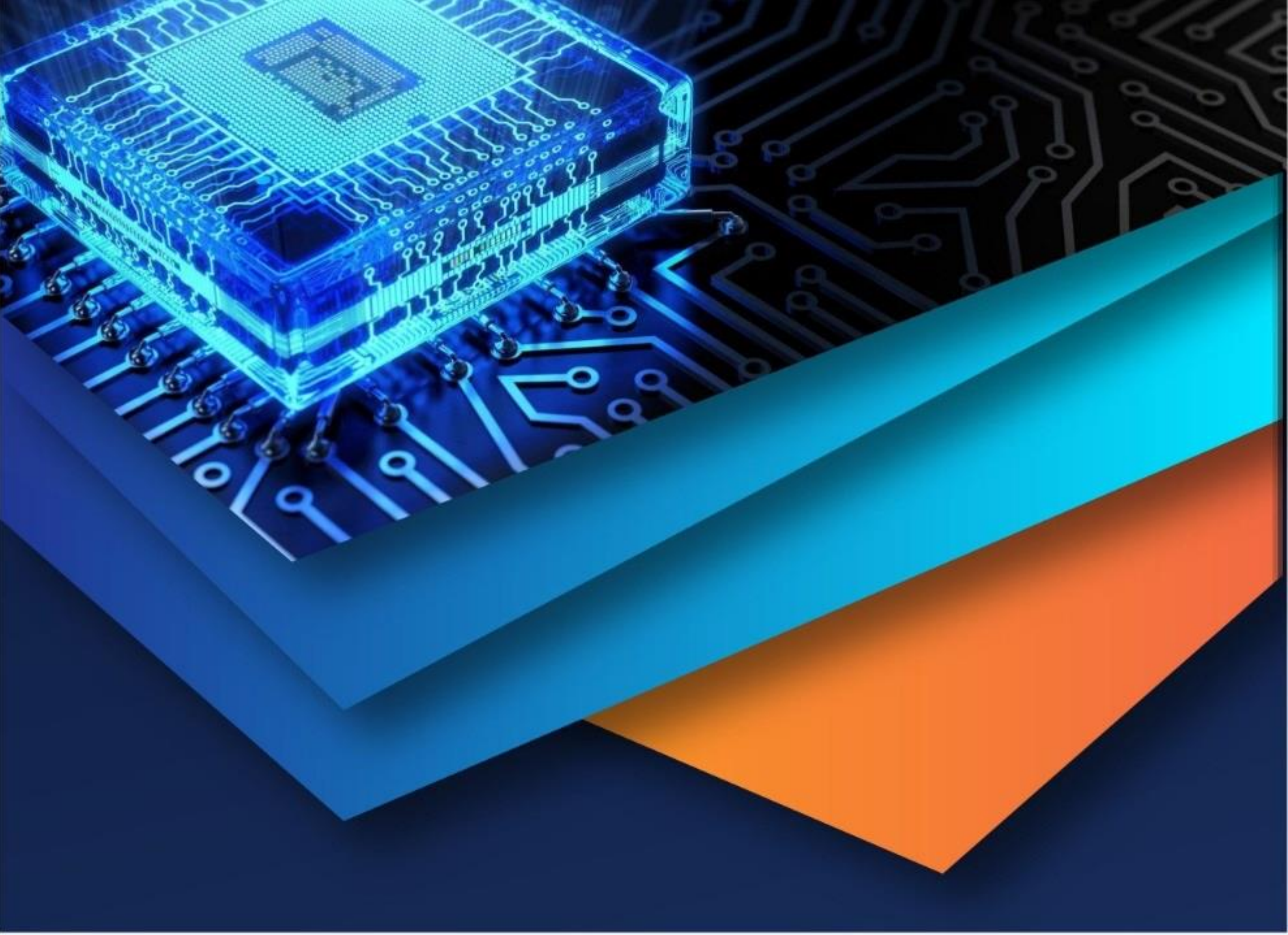

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