iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 **Issue:** IV **Month of publication:** April 2019

DOI: https://doi.org/10.22214/ijraset.2019.4460

Theoretical Study of Desalination System along with Thermal Comfort

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Abstract: Increasing population combined with pollution of water bodies makes human being on this earth fully dependent on purified water. There have been many distillation systems proposed by industrial establishments and research groups, among the known water purification system HDH has become popular due to its simple operation. This type of system effective for small scale to midscale desalination systems in many arid and semi-arid countries, in desalination process the main objective is to obtain the fresh water from brackish water or seawater. In this work theoretical study of humidification and dehumidification system has been carried out from which it is found that fresh water production along with space comfort would be obtained at specific operating conditions such as 120 liters per day of freshwater and exit air from the dehumidifier is reduced to 25ºC, 50% relative humidity respectively by varying the operating condition.
Keywords: Desalination, Thermal Comfort.

I. INTRODUCTION

Water is available in abundant quantities around the earth in the form of ice glaciers, saltwater etc. In fact, the major portion of the earth covered by oceans in which 97% of water is seawater while another 2% is locked in icecaps and glaciers. The available amount of fresh water accounts for less than 0.5% of the earth's total water. But the fresh water is not equally distributed across the globe. Further, the availability of fresh water varies by place to place as well with the climatic conditions.

A limited amount of freshwater is usually found in form of rivers ponds, lakes and rivers. Hence there is shortage of potable water in many places around the world. A huge proportion of the world's population does not have access to good quality of drinking water.

By the year 2050**,** relative freshwater sufficiency will be 58%, while water scarcity, defined as the population living under the freshwater consumption limit above, will be 24%, as estimated by *Population Action International*. Lack of fresh water forces people to drink water from untreated or contaminated sources. 90%of diarrheal illnesses in developing countries are attributed to the consumption of contaminated drinking water. With cholera, typhoid fever, dysentery, and other diarrheal illnesses accounting for half the hospitalized people in the world, this is a very serious global health problem. In addition to contaminants of microorganism water sources are often polluted bychemical contaminants like pesticides, fluoride, iron, arsenic, nitrates, and sodium. In India, 66million people consume water with dangerous fluoride levels.

In the demand of serious freshwater supply around the world, there are various types of desalination systems were proposed to separate potable water from the seawater or brackish water.

The large scale of desalination plants based on the method of multi-effect evaporator, multi-stage flash, thermal vapor compression, mechanical vapor compression and reverse osmosis were put into applications. A water heated solar desalination and theoretical simulation model with energy equation of each component was established to evaluate the relevant performance and the productivity . Sea water desalination can be realized by thermal distillation using evaporation and condensation, electro-dialysis or reverse osmosis etc according to their drive force such as temperature, electro potential and pressure difference.

Thermal desalination technologies such as multi stage flash and multi effect desalination are not suitable for small scale applications. Numerous investigations have been studied about integrated generation system for power, cooling and heating, but quite less studies involved with seawater desalination.

It is well known that the essential thing to survive in earth is water. But the availability of hygienic freshwater tends to the point of important concern about national issue in most countries. In areas such as Middle East countries, the shortage of water become the principal point restricting the development of arid and hyper arid regions. As a result of that there is a great dependence on desalination processes of seawater and brackish water to substitute the lack of freshwater for safe drinking purpose. Around the globe numerous desalination plants are located.

II. METHODLOGY

A. Mathematical Modeling

Humidification-dehumidification (HDH) desalination is a fairly simple technology that mimics nature's water cycle and has the potential to operate with solar heating.

In HDH cycle, seawater enters the system at the dehumidifier and is used to cool and dehumidify a warmer, moist air stream. In the associated condensation process, the enthalpy of vaporization is transferred from the moist air to the seawater, thus warming the feed stream.

The condensate is collected as product of fresh water and the seawater is then further heated in a heater (potentially a solar heater). The hot seawater is then used to humidify a cooler air stream and the remaining seawater is extracted as brine. In the evaporation process, heat and mass is transferred from the hot seawater stream to the moist air stream. In this configuration, the air stream continuously circulates between the humidifier and the dehumidifier.

In HDH process, air is humidified using saline water source (e.g. seawater or brackish water) in a humidifier where it carries as much water vapour as possible from the saline water.

The main reason for selecting the open water, open air with water heated type is because of its simple in construction as well as the able to get the fresh water and comfort air from the exit point of the fluids involved in cycle that are seawater and wet air respectively.

The water in the tank was heated by the latent heat of refrigerant vapour condensation. The hot water leaving the tank was sprayed on the humidifier, in which the mass and heat transfer between the air flow and the hot water were completed. Part of the sea water evaporated and the air flow was humidified. The concentrated sea water would back to the sea water tank.

B. System Configuration and Principle Description

The Bi-generative system is diagrammatically shown in figure3.2. The Bi-generative system consists of compressor and heat recovery zone in addition to the traditional components of humidification dehumidification such as humidifier, dehumidifier and heater. The dehumidifier plays a role of humid air per-cooling to get some fresh water and feed water preheating to recover the part of latent heat.

The humidifier, a honeycomb construction having enormous surface to increase the effect of the heat and mass transfer, was a key component to make the separation between water and salt. Seawater is pumped through the pipes of the dehumidifier to recover some energy from the condensing humid air. Upon leaving the dehumidifier, the preheated water is further heated in a water heater (e.g. solar collector or waste heat exchanger).

Hot water is sprayed in the humidifier over a structured-type packing-material to increase the surface area for effective heat and mass transfer. A portion of water evaporates in the air stream whereas the rest is rejected as brine at the bottom f the humidifier. Air (dotted line) flows in the humidifier in a counter-flow direction through the packing material. Air is heated and humidified through its direct contact with the sprayed hot water.

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On leaving the humidifier, it almost approaches saturation condition. The hot and humid air then flows to the dehumidifier where water vapour condenses out to produce fresh water and the cold air is ducted to the thermal comfort zone. The major components involved in the selected process layout above are:

1) Dehumidifier
2) Heater
3) Humidifier
4) Compressor
5) Heat Exchange
6) Comfort space

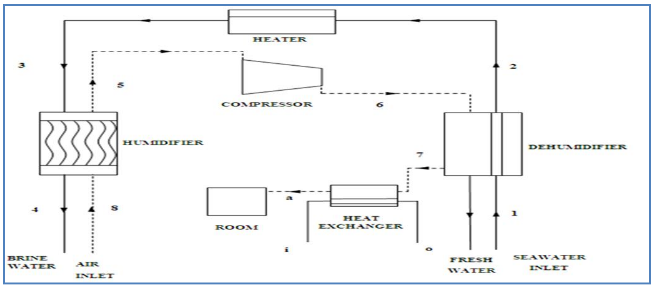

Figure 1: schematic of a water-heated bi-generative HDH cycle.

In Dehumidifier the humid air entering from exit of compressor at the top point (6) at specific condition begins to condense at below boiling point temperature due to contact with cooled surface the seawater entering from bottom which at lower temperature compared to the moist air. From the dehumidifier fresh water which is obtained by condensation of moist air exit at bottom point (Pw), in addition to that less moist air also exit from the dehumidifier at point (7) .Latent heat of condensation is used for preheating the seawater enters at point (1). In this section the exit of seawater from the dehumidifier at point (2) is sensibly heated to higher temperature. The heating is to be done by external electrical or solar heat source. In humidifier hot water which is heated by an external heat source such as heater, is in contact with air on a packed bed and a certain quantity of vapour is extracted by air. Finally the hot and humid air leaves the humidifier at point (5) and enters to inlet compressor. At the exit of the humidifier at point (4) remaining seawater is drained out. The atmospheric air enters at the point (8) of the Humidifier respectively. In this process centrifugal compressor is employed to compress the humid air from the humidifier to increase the pressure slightly before entering the dehumidifier point (6).At the exit of compressor temperature also slightly increased due to adiabatic compression. In this section the slightly humid air from the exit of dehumidifier enters whose temperature and moisture content is reduced further for the purpose of thermal comfort. The temperature is reduced by contact with the cool surface. The exit air from the heat exchanger enters the comfort zone in order to bring the ambient condition of the space to the thermal comfort that is 25ºC, 50% RH. To model the water-heated bi-generative HDH system the following assumptions are considered:

a) Cycles operate at steady-state conditions
b) Heat loss from any of the cycle components is neglected
c) Pumping and fan powers are negligible compared to thermal energy Input
d) Condensed water in the dehumidifier is assumed to leave at a temperature which is the average of the dew-point temperature of the inlet air and dry-bulb temperature of the exit air in the dehumidifier
e) The relative humidity of moist air entering the dehumidifier is 85%.

The model presented in this section is basically a thermodynamic model where mass and energy balances are applied on each of the cycle components following the first law of thermodynamics and mass balance as given in many thermodynamic textbooks. In addition to that some of the parameters involved in the process should be known in order to mathematically analyze the cycle and calculate its performance. Those important parameters are minimum or bottom temperature of the seawater at the inlet to the dehumidifier part, hot water temperature at the inlet to the humidifier that is also called as the maximum are or top temperature, and the effectiveness of both the humidifier dehumidifier. Normally the minimum temperature in the system especially at the entrance to dehumidifier may range between 10-40°C due to the seasonal temperature changes. The Top temperature that is the hot water temperature to the humidifier is assumed to be in the range of 40-55°C to reduce the formation impurities such as scales. The effectiveness of both the humidifier and dehumidifier are assumed to be within the range of 60–95%. This effectiveness is defined as the actual enthalpy variation to the maximum possible enthalpy variation for a simultaneous heat and mass exchanger. The important model equations in the bi-generative humidification dehumidification system can be summarized as follows

i) Energy and mass balances of the dehumidifier part results in, respectively,

Mass Balance $\dot{m}_p = \dot{m}_a(\omega_6 - \omega_7)$ (1)

Energy Balance

$$\dot{m}_p h_p = \dot{m}_w(h_1 - h_2) + \dot{m}_a(h_6 - h_7) \quad (2)$$

ii) Energy and mass balances of the humidifier part results in, respectively,

Mass Balance $\dot{m}_b = \dot{m}_a(\omega_8 - \omega_5) + \dot{m}_w$ (3)

Energy Balance $\dot{m}_b h_b = \dot{m}_a(h_8 - h_5) + \dot{m}_w h_3$ (4)

iii) Energy balance of the water heater $Q_{in} = \dot{m}_w(h_3 - h_2)$ (5)

iv) Energy balance of the Compressor

$w_{in} = \dot{m}_a(h_5 - h_6)$ (6)

(e) Energy balance of the Comfort space

Assumed: Volume of the space = 3*3*2 = 18 m^3

Heat gain = sensible heat + latent heat

$Q_{GAIN} = Q_{SEN} + Q_L$

$\dot{m}_a C_{pa}(t_b - t_a) = \dot{m}_a C_{pa}(T_i - T_f) + \dot{m}_a h_{fg}$ (7)

Cooling Load $= \dot{m}_a(h_b - h_a)$ (8)

v) Energy balance of the Heat Recovery zone

$\dot{m}_a C_{pa}(t_7 - t_a) = \dot{m}_a C_{pa}(T_i - T_o)$ (9)

C. Theoretical Analysis of Humidifier

1) Assumption

a) Effectiveness of humidifier, Eh = 0.6
b) Relative Humidity of air at inlet of humidifier, R
c) Temperature of hot seawater at inlet of humidifier, T1
d) Temperature of air at inlet of humidifier, t1

i) *Step7:* To find air outlet temperature at humidifier

$$t_5 = \frac{\xi_h \times Q_{\max}}{\dot{m}_a \times c_{pa}} + t_8$$

ii) *Step8:* To find brine flow rate

Saturated Partial pressure of air at inlet,

$$pv_{sa8} = (0.6108) \times \exp\left(\frac{17.27 \times t_8}{t_8 + 237.3}\right)$$

Humidity Ratio of air at inlet,

$$\omega_8 = \frac{0.62198 \times RH_8 \times pv_{sa8}}{\left(P_{2atm} - (RH_8) \times pv_{sa8}\right)}$$

Saturated Partial pressure of air at exit,

$$pv_{sa5} = (0.6108) \times \exp\left(\frac{17.27 \times t_5}{t_5 + 237.3}\right)$$

Relative humidity of air at outlet,

$$RH_5 = \frac{pv_{sa5}}{pv_{sa8}}$$

Humidity Ratio of air at exit of humidifier,

$$\omega_5 = \frac{0.62198 \times RH_5 \times pv_{sa5}}{(P_{2atm} - (RH_5) \times pv_{sa5})}$$

Mass flow rate of brine,

$$\dot{m}_b = m_w - m_a \times (\omega_5 - \omega_8)$$

iii) *Step9:* To find reject brine brine Temperature at humidifier

$$T_b = \frac{m_a \times c_{pa} \times (t_5 - t_8)}{m_b \times c_{pb}}$$

iv) *Step10:* To find work required for compressor

$$w_c = R \times T_o \times \ln\left(\frac{p_6}{p_5}\right)$$

v) *Step11:* To find the cooling load

$$\text{Cooling Load} = \dot{m}_a (h_b - h_a)$$

By solving the above equations we would able to get the amount of potable water as well the cooling load. To solve the above equations involved in this system we adopted a simple FORTRAN program which is discussed in the following section.

III. RESULT AND DISCUSSION

A. General

The Governing equations obtained are solved using FORTRAN which uses a numerical iterative procedure to solve the set of equations. The procedure is repeated until the required exit condition of air as well condensed product is obtained. The properties of air, water and seawater are assumed appropriately. The above theoretical analysis has yielded the following results that are subsequently used to compare the HDH cycles. It is important to note that the following presentation focuses on the effect of the main system parameters (i.e. effectiveness of the humidifier, water minimum temperature, and relative humidity (RH) and water maximum temperature) on the GOR, the optimum mass-flow rate ratio (MR), and the recovery ratio (RR) and exit temperature of air from the dehumidifier part for the purpose of cooling as well.

B. Performance Analysis

1) Variation Of Maximum Temperature With Minimum Temperature

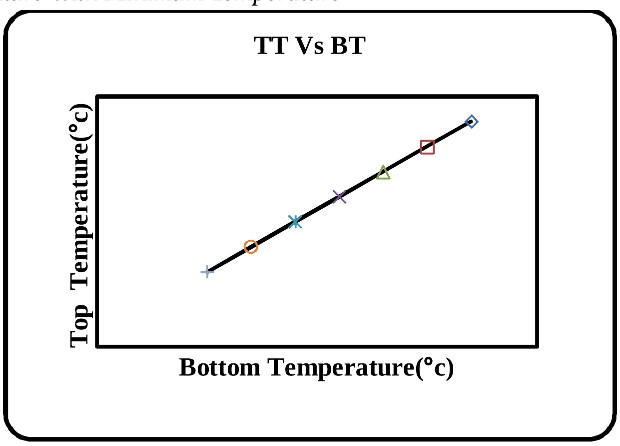

Figure 2: Top Temperature Vs Bottom Temperature

Figure 2 shows the effect of bottom temperature T_1 (ºC) of the process on the top temperature T_3 (ºC) of the process. It is found that the variation is linear with respect to each other. From this it is understood that all temperatures involved in the other components must be within this maximum and minimum limit. In this case for the purpose of desalination with thermal comfort the bottom temperature T_1 is found to be 20 ºC and the maximum temperature or the top temperature of process T_3 is found to be 41ºC. Normally for conventional desalination process the temperature of top point is in range of 40 to 60ºC, whereas the bottom temperature is in the range of 20 to 25ºC respectively.

2) Effect Of Bottom Temperature On Recovery Ratio

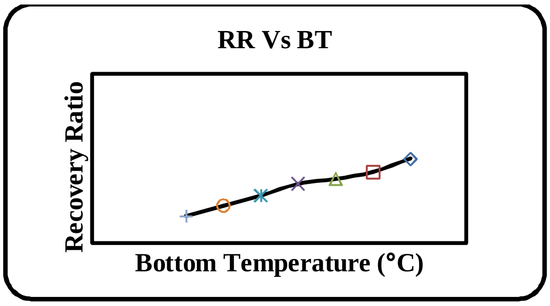

Figure 3: Recovery Ratio Vs Bottom Temperature

Figure 3 shows the influence of bottom temperature on recovery ratio. It is understood that the recovery ratio increases with respect to bottom temperature. Recovery ratio indicates the ratio of fresh water to the feed amount of seawater. In this case for the purpose of desalination with thermal comfort the bottom temperature T_1 is found to be 20 ºC and the recovery ratio is found to be 0.17. Normally for conventional desalination process the temperature of top point is in range of 40 to 60ºC, whereas the bottom temperature is in the range of 20 to 25ºC respectively. If the multistage method adopted we may get higher recovery ratio. Recovery ratio is somewhat depends on the lower temperature. If we want achieve more amount freshwater the obviously the feed water temperature must be high.

3) Variation Of Recovery Ratio With Top Temperature

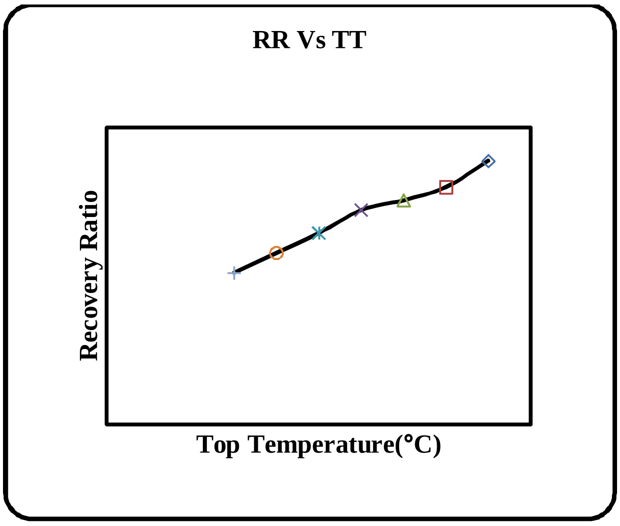

Figure 4 Recovery Ratio Vs Top Temperature

Figure 4 shows the variation of recovery ratio of the dehumidification process with the top temperature of hot seawater T_3 (ºC) or inlet seawater temperature of the humidifier. It is found that the recovery ratio is also increasing with respect to the maximum temperature. Recovery ratio indicates the ratio of fresh water to the feed amount of seawater. In this case for the purpose of desalination with thermal comfort the top temperature T_3 is found to be 41 ºC and the recovery ratio is found to be 0.17. Normally fresh water production from the humid air is based on the about of moisture content which is depends on the top temperature at which the hot water stream get vaporized. If the multistage method adopted we may get higher recovery ratio. Recovery ratio is somewhat depends on the moisture content. More amount freshwater can be achieved when the feed water temperature is high.

4) Relationship Between Relative Humidity And Mass Flow Rate Of Water

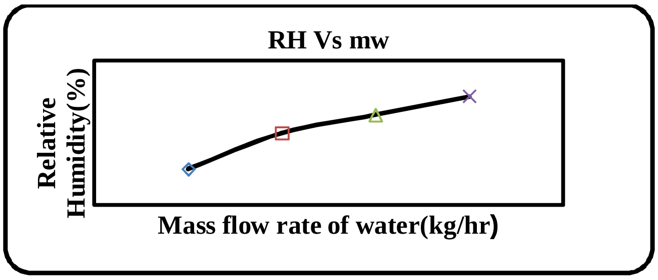

Figure 6: mass flow rate of water Vs relative humidity

Figure 6 shows the relationship between the relative humidity and mass flow rate of water. It is found that the relative humidity varies with respect to the magnitude of mass flow rate of water used in the dehumidifier. The moisture content in the humid air depends on the mass flow rate of water. In this case for the relative humidity of 85% is attained at 25 kg/hr of water supplied this condition in advisable to achieve the thermal comfort in addition to the potable water production.

5) Relationship Between Mass Flow Rate Of Air And Mass Flow Rate Of Water

Figure 7 Mass flow rate of air Vs mass flow rate of water

Figure 7 shows the relationship between the mass flow rate of air and mass flow rate of water. It is found that the mass flow rate of air increases with the mass flow rate of water .It indicates that the for change in magnitude of mass flow rate seawater the mass flow rate of air has to altered . In this case the for the mass flow rate 25 kg/hr of seawater the amount of air supplied is 1273 kg/hr, this condition is to be attained in order achieve the thermal comfort in addition to the potable water production.

IV. CONCLUSION

The single stage HDH process for desalination has been carried out. In addition to desalination process, thermal comfort has also been taken into consideration for the purpose of theoretical analysis. It is concluded that bi-generation effect with desalination solely depends on the parameters such as inlet seawater temperature, hot water temperature at humidifier, heat supplied, temperature of humid air at inlet of dehumidifier, relative humidity at the inlet of dehumidifier and exit air temperature and productivity of potable water. It is further concluded that, in order to get better bi-generation effect with desalination, an optimum value of parameters should be maintained as the inlet seawater temperature to be 20ºC, 1 atmospheric pressure, humid air to be 30 ºC, 2 atmospheric pressure, hot water temperature of 41ºC, relative humidity to be 85%. Table 5.1 shows the representative values of parameters associated with bi-generation effect.

A. Values Of Parameter Associated With

Bi-generation

Parameters	Condition
Inlet seawater	20ºC,1atm
Inlet humid air	30ºC,2atm
Partial pressure of humid air	4243.07Pa
Humidity ratio or specific humidity	0.0113
Relative humidity	85%
Inlet air	25ºC,1atm
Inlet hot water	41ºC,2atm
Partial pressure of air at exit of humidifier	3306.64Pa
Exit air at dehumidifier	25ºC,70%
Inlet to thermal comfort zone	22ºC,50%
Comfort space	25ºC,50%
Fresh water production	120liters/day

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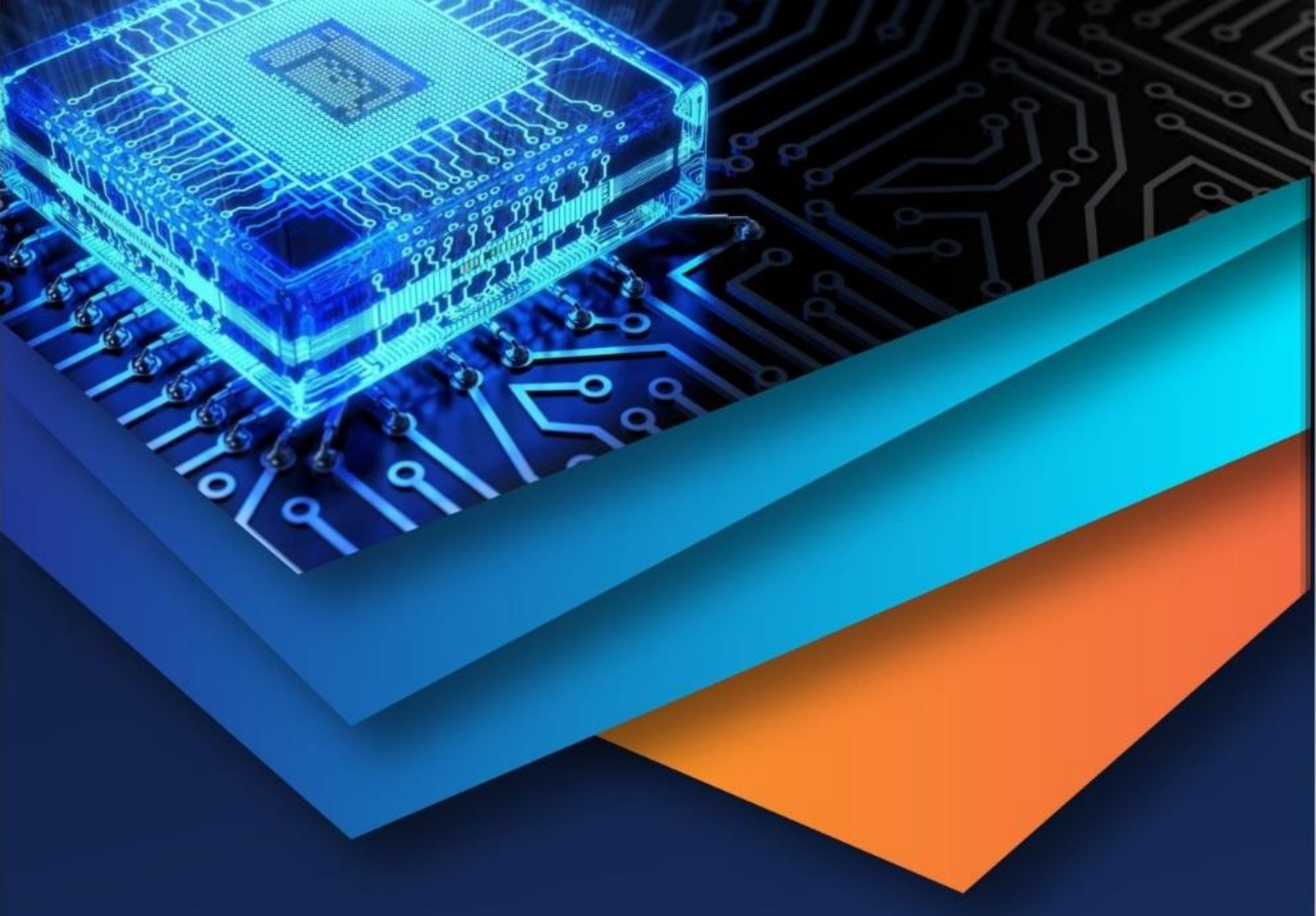

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