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Thermodynamic Analysis of Combined ORC-VCR System Using Low Grade Thermal Energy

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Abstract— The world is facing energy and environmental challenges due to population growth and economy development. The utilization of renewable energy can significantly contribute to reduction in consumption of conventional energy and environmental pollution. Low grade thermal energy can be utilized in organic Rankine cycle driven vapour compression refrigeration system (combined ORC-VCR) to produce refrigeration effect. Low grade renewable energy can be obtain from the source such as solar, geothermal and waste heat of industries. This work deals with thermodynamic analysis of combined ORC-VCR system with low GWP working fluids. In this paper four hydrocarbons; butane (R600), iso-butane (R600a), propane (R290) and propylene (R1270) are used as a working fluid to analyze the effect of various operating parameters of combined organic Rankine cycle drive vapour compression refrigeration system and evaluated to find the best candidate for the system. It is found that the butane (R600) gives the highest overall COP of combined system as the boiler exit temperature is between 60 to 90 ^{0}C, the condenser temperature 30 to 55 ^{0}C and evaporator temperature range -15 to 15 ^{0}C. At boiler exit temperature 90 ^{0}C, the butane (R600) gives maximum overall system COP is 0.4696.

Keywords— Organic Rankine Cycle; Vapour Compression Refrigeration Cycle; Low Grade Energy; Hydrocarbons; Low GWP

I. INTRODUCTION

World is facing energy crisis and environmental challenges due to the rapid growth of population and industrial development. The utilization of low-grade thermal energy can significantly contribute to reduce the conventional energy consumption and meanwhile to relieve the environmental pollution. In this respect, thermally activated cooling technologies as methods to recover the low-grade thermal energy have gained considerable interest **[1]**. The thermally activated refrigeration can be fulfilled by sorption (adsorption and absorption), thermoelectric and Rankine cycle powered vapour compression refrigeration (VCR) systems. Comparing with the others, the last one has flexibility associated with the mechanical power delivered by an expander, which makes the system to continuously utilize the thermal energy throughout the year **[2]**. The temperature of heat sources below 100 °C is called low grade heat because a Rankine cycle using water cannot work efficiently at such low temperatures. Statistical data indicates that 50 % or more of total heat generated by industry is low-grade waste heat **[3]**. Generally, low grade thermal energy produced during industrial processes as well as natural ones like such as geothermal heating, ocean heating, solar heating and biomass combustion etc. is discarded in the atmosphere as waste heat. This thermal pollution has become major environmental concern **[4]**. Fig. 1 shown **[5]** that contribution of biomass organic Rankine cycle (ORC) is a highest and geothermal energy which used is the most significant one is in second position currently. Waste heat recovery in different industries which is in third place and solar ORC still has only 1% of ORC market due to lack of awareness. But this technology has also a huge potential.

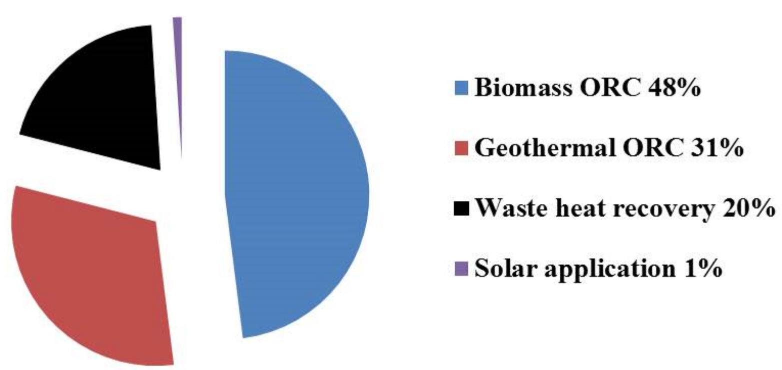

Fig. 1. ORC market share for different heat sources

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A. Organic Rankine Cycle

Organic Rankine cycle is a simple Rankine power cycle in which working fluid are mainly an organic fluid instead of water. Organic fluids are the high molecular mass fluids with lower degree of boiling temperature in comparison with water.

For low-grade heat recovery systems, the working fluid used is mainly an organic fluid. The main reason for this is that these always have a lower heat of vaporization than water and hence can be vaporized more easily with low-grade heat. Such characteristics make ORC favourable for applications of low temperature heat recovery. ORC is preferable for the low-grade thermal energy utilization due to which it has a good efficiency over a wide temperature range **[6]**. ORC has several advantages over steam cycle. It is known that working fluids in ORC has higher molecular weight than water. This will increase mass flow rate of fluid for the same sizes of turbine. More mass flow rates will give better turbine efficiencies and less turbine losses **[7]**. Many studies had been carried out on Combined ORC-VCR systems with various working fluids: chlorofluorocarbons (CFCs), hydro chloro fluoro carbons (HCFCs) and hydro fluoro carbons (HFCs) **[8-10]**. However, these working fluids have negative impact on environment **[11]**, so various hydrocarbons (natural fluids) are recognized as possible alternatives to the CFCs, HCFCs and HFCs **[12]**. Hydrocarbon refrigerants (R290, R600, R600a & R1270) are natural, nontoxic refrigerants that have excellent thermo-physical properties, no ozone depleting properties (zero ODP) and absolutely low global warming potential (GWP).

TABLE I: PROPERTIES OF THE FOUR HYDROCARBONS

Refrigerant	Chemical Formula	M (kg/mol)	NBP (^{0}C)	T_{crit} (^{0}C)	p_{crit} (kpa)	Safety group
R290	C_3H_8	44.10	-42.09	96.68	4247	A3
R600	C_4H_{10}	58.12	-0.55	151.98	3796	A3
R600a	C_4H_{10}	58.12	-11.67	134.67	3640	A3
R1270	C_3H_6	42.08	-47.69	92.42	4665	A3

Hydrocarbons are highly flammable as they are in A3 safety group but Venkatarathnam *et al.* (2012) and Palm (2008) indicated that with adequate safety precautions and regulations, the flammability will not be a major problem in the usage of hydrocarbons **[13-14]**.

II. COMBINED ORC-VRC SYSTEM DESCRIPTION

The schematic diagram of the ORC–VCR system is shown in Fig. 2. This system consists of two cycles, first is ORC identified as 1-2-3-4-1 and the other is VCR cycle as 5-6-3-7-5. This system uses the same working fluid for both the power and refrigeration cycles. In this system, expander of the organic Rankine cycle and the compressor of the vapour compression refrigeration cycle are directly coupled through shaft. The mechanical power delivered from the organic Rankine cycle through the expander is just enough to drive the compressor and boiler feed pump and the organic Rankine cycle and vapour compression refrigeration cycle share a common condenser.

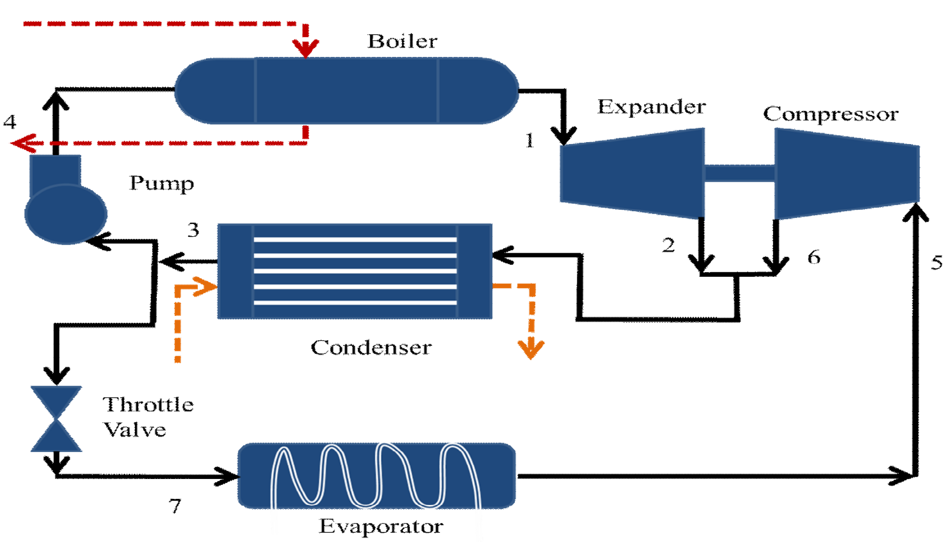

Fig. 2. Schematic diagram of the Combined ORC-VCR system

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The T-s diagram of the organic Rankine cycle drive vapour compression refrigeration cycle is shown in Fig. 3. Accordingly, the various processes of the system are presented as follows:

$1 \rightarrow 2$	: actual expansion in the expander;
$1 \rightarrow 2s$	: isentropic expansion in the expander;
$2 \rightarrow 3$	: heat rejection (condensation) in the ORC;
$3 \rightarrow 4$	: actual pumping work;
$3 \rightarrow 4s$	: isentropic pumping work;
$4 \rightarrow 1$	: heat addition in the boiler;
$3 \rightarrow 7$	: isenthalpic expansion in the throttle valve;
$7 \rightarrow 5$	: heat absorption (evaporation) in the VCR cycle;
$5 \rightarrow 6$	: actual compression in the compressor;
$5 \rightarrow 6s$	: isentropic compression in the compressor;
$6 \rightarrow 3$	: heat rejection (condensation) in the VCR cycle.

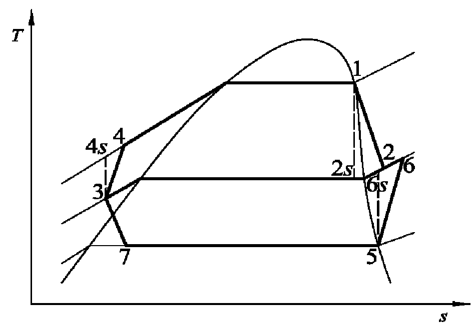

Fig. 3.T-s diagram of the combined ORC-VCR system

III.THERMODYNAMIC ANALYSIS

Thermodynamic analysis of ORC-VCR system has been carried out in this work. In order to simplify the analysis, some assumptions are made as follows: steady-state conditions are considered in all components; heat and friction losses in the system is neglected; the condenser has a given subcooling of 3 ^{0}C to prevent boiler feed pump cavitations; the working fluid leaving the boiler and evaporator is saturated. The thermo-physical properties of the hydrocarbon refrigerants were calculated using a software package called an Engineering Equation Solver (EES).A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability **[15]**.

A. Governing Equations

Based on these assumptions and referring to the ORC–VCR system presented in Fig. 2 and Fig. 3, the mathematical model for the system is given below.

For the organic Rankine cycle

$$W_{exp} = \dot{m}_{ORC}(h_1 - h_{2s})\eta_{exp} \quad (1)$$

$$W_{pump} = \dot{m}_{ORC}(h_{4s} - h_3)/\eta_{exp} \quad (2)$$

$$W_{net} = (W_{exp} - W_{pump}) \quad (3)$$

$$Q_{boiler} = \dot{m}_{ORC}(h_1 - h_4) \quad (4)$$

The thermal efficiency of the ORC is defined as

$$\eta_{ORC} = \frac{W_{net}}{Q_{boiler}} \quad (5)$$

For vapour compression refrigeration cycle

$$Q_{evap} = \dot{m}_{VCR}(h_5 - h_7) \quad (6)$$

$$W_{comp} = \dot{m}_{VCR}(h_5 - h_{6s})/\eta_{comp} \quad (7)$$

$$W_{comp} = W_{net} \quad (8)$$

The COP of the VCR cycle is expressed as

$$COP_{VCR} = \frac{Q_{evap}}{W_{comp}} \quad (9)$$

$$COP_{overall} = \eta_{ORC} COP_{VCR} \quad (10)$$

The working fluid mass flow rate of per KW cooling capacity in ORC-VCR system:

$$MkW - \frac{\dot{m}_{ORC} + \dot{m}_{VCR}}{Q_{evap}} \quad (11)$$

The expansion ratio across the expander and the compression ratio across the compressor, which are proportional to the expander and compressor sizes, respectively:

$$EPR = \frac{V_2}{V_1} \quad (12)$$

$$CMR = \frac{p_6}{p_5} \quad (13)$$

IV. RESULTS AND DISCUSSION

The input parameters and boundary conditions are presented in Table II. The maximum boiler exit temperature is set to 90 ^{0}C.

TABLE II: INPUT PARAMETER AND BOUNDARY CONDITIONS

Parameters	Value	Range
Working fluid mass flow rate in ORC	1 kg/s	-
Evaporator temperature	5 ^{0}C	-15 to15 ^{0}C
Boiler exits temperature	80 ^{0}C	60 to 90 ^{0}C
Condensation temperature	40 ^{0}C	30 to 55 ^{0}C
Expander isentropic efficiency	0.80	0.60 to 0.90
Compressor isentropic efficiency	0.75	0.60 to 0.90
Boiler feed pump isentropic efficiency	0.75	-

A. Effect of Boiler Exit Temperature

Fig. 4 shows the Variation of $COP_{overall}$ and MkW with boiler exit temperature. It has been observed from the figure that $COP_{overall}$ of the combined ORC-VCR system increases with increase in boiler exit temperature. Performance of the system is

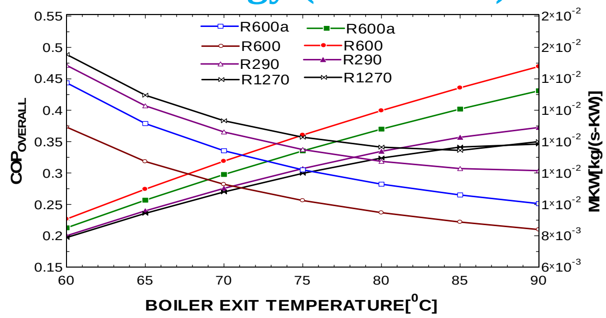

Fig. 4. Variation of $COP_{overall}$ and MkW with boiler exit temperature.

best with butane (R600) than follow by R600a, R290 and R1270 over the entire range (60 to 90 ^oC) of the boiler exit temperature. The maximum overall thermal efficiency in the case of R600 is due to the higher critical temperature. So it can be concluded that higher critical temperature organic fluids may leads to better performance. Fig. 4 also shows that the MkW decreases with the boiler exit temperature for the four hydrocarbons, and the minimum is seen in the case of R600 within the temperature range, followed by R600a, R290 and R1270.

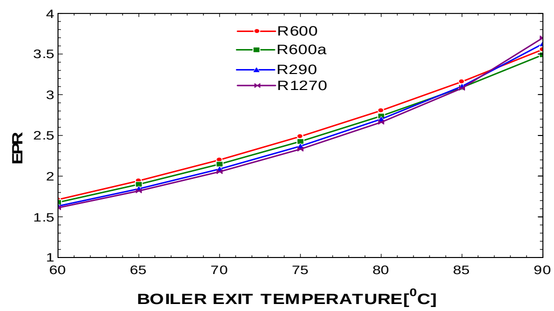

Fig. 5. Variation of EPR with boiler exit temperature.

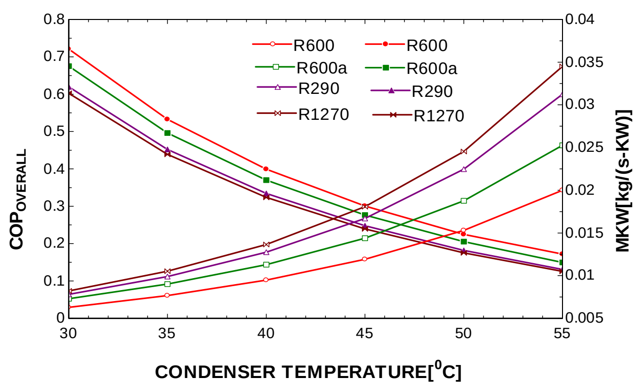

Fig. 6. Variation of $COP_{overall}$ and MKW with condensation temperature

Fig. 5 shows the variation in the EPR with boiler exit temperature. It can be seen in the figure that EPR increases with increase in boiler exit temperature and at 90 ^oC its value approximately doubles that at 60 ^oC for four hydrocarbons. It is found that higher value of EPR is in the case of R600, followed by R600a, R290 and R1270, except for those with the boiler exit temperature between 85 and 90 ^oC. However, the differences among the EPR values for these hydrocarbons are very small.

B. Effect Of Condenser Temperature

Fig. 6 shows the Variation of $COP_{overall}$ and MkW with condenser temperature. It has been observed from the figure that $COP_{overall}$ of the combined ORC-VCR system decreases with increase in condenser temperature. Performance of the system is best with butane (R600) than follow by R600a, R290 and R1270 over the entire range (30 to 55 ^oC) of the condenser temperature. Fig. 6 also shows that the MkW increases with increase in condenser temperature for the four hydrocarbons, and the minimum is seen in the case of R600 within the temperature range, followed by R600a, R290 and R1270.

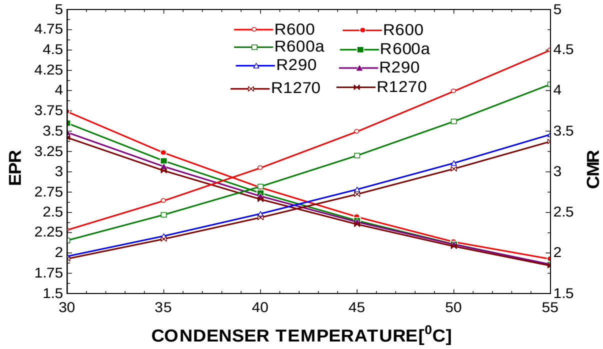

Fig.7. Variation of EPR and CMR with condensation temperature

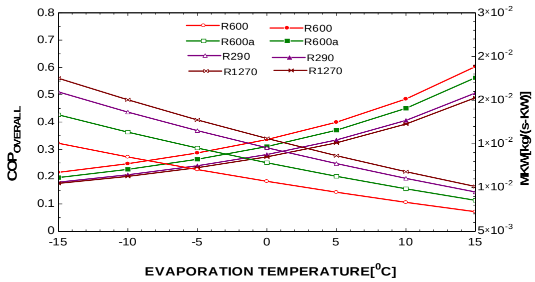

Fig. 8. Variation of $COP_{overall}$ and MKW with evaporation temperature

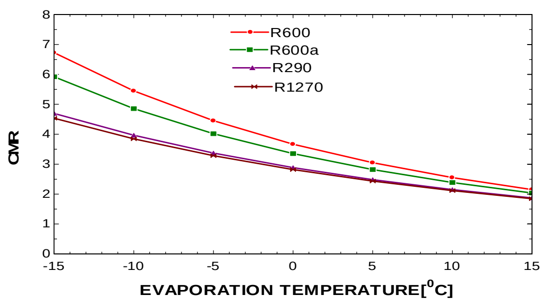

Fig. 9. Variation of CMR with evaporation temperature

It is observed from Fig.7 that as the condenser temperature increase, EPR across the expander in the ORC decreases. The differences between EPR values for the four hydrocarbons are small and these differences are further reduced at a higher condenser temperature. However CMR increases with increase in condenser temperature and the differences between CMR values for the four hydrocarbons are significant and these differences are further increased at a higher condenser temperature.

C. Effect Of Evaporator Temperature

Fig. 8 shows the effect of evaporation temperature on $COP_{overall}$ and MkW of the combined ORC-VRC system. It has been observed from the fig. 8 that increase in evaporator temperature increases the $COP_{overall}$ of the ORC–VCR system and decreases the MkW of the ORC–VCR system. Performance with R600 is best and MkW for R600 is lowest. Fig. 9 shows the effect of evaporation temperature on CMR. It can be shown in the fig. 9 increase in evaporator temperature, decreases compression ratio across the compressor in the VCR cycle.

Nomenclature			
COP_{VCR}	:	refrigeration cycle coefficient of performance	-
$COP_{overall}$	:	overall system coefficient of performance	-
CMR	:	compression ratio in compressor	-
EPR	:	expansion ratio in expander	-
MkW	:	working fluid mass flow rate of per kW cooling capacity	(kg/(s-kW))
ORC	:	organic Rankine cycle	-
VCR	:	vapour compression refrigeration	-
W_{comp}	:	compressor work input	(kW)
m_{ORC}	:	power cycle mass flow rate	(kg/s)
m_{VCR}	:	refrigeration cycle mass flow rate	(kg/s)
W_{pump}	:	pump power consumption	(kW)
W_{net}	:	network output	(kW)
W_{exp}	:	expander work output	(kW)
$P_{critical}$	:	critical pressure	(kPa)
Q_{evap}	:	evaporator cooling capacity	(kW)
Q_{boiler}	:	boiler heat input	(kW)
h	:	enthalpy	(kJ/kg)
$t_{critcal}$	:	critical temperature	(^{0}C)
v_1	:	specific volume of working fluid at expander inlet	(m^3/kg)
v_2	:	specific volume of working fluid at expander outlet	(m^3/kg)

V. CONCLUSIONS

Thermodynamic analysis is the key tool to study the performance of ORC-VCR system. Thermodynamic analysis is used to find out the vital parameters affecting the system performance. In this work thermodynamic analysis of combined ORC-VCR system using hydrocarbon refrigerants (R600, R600a, R290 and R1270) has been carried out which leads to following conclusions:

Overall COP of the combined ORC-VRC system increases with increase in, boiler exit temperature and evaporator temperature. However, performance decreases with increase in condenser temperature.

MkW of the combined ORC-VRC system decreases with increase in, boiler exit temperature and evaporator temperature. However value of MkW increases with increase in condenser temperature.

EPR across the expander in the Organic Rankine Cycle increases with increase in boiler exit temperature and decreases with condenser temperature.

CMR across the compressor in the vapour compression refrigeration cycle increases with increase in condenser temperature and decreases with evaporator temperature.

The results show that each parameter has similar effects on the performance of the ORC–VCR system using different hydrocarbon refrigerants. From the analysis it is concluded that R600 (butane) is most promising working fluid in combined ORC-VCR system.

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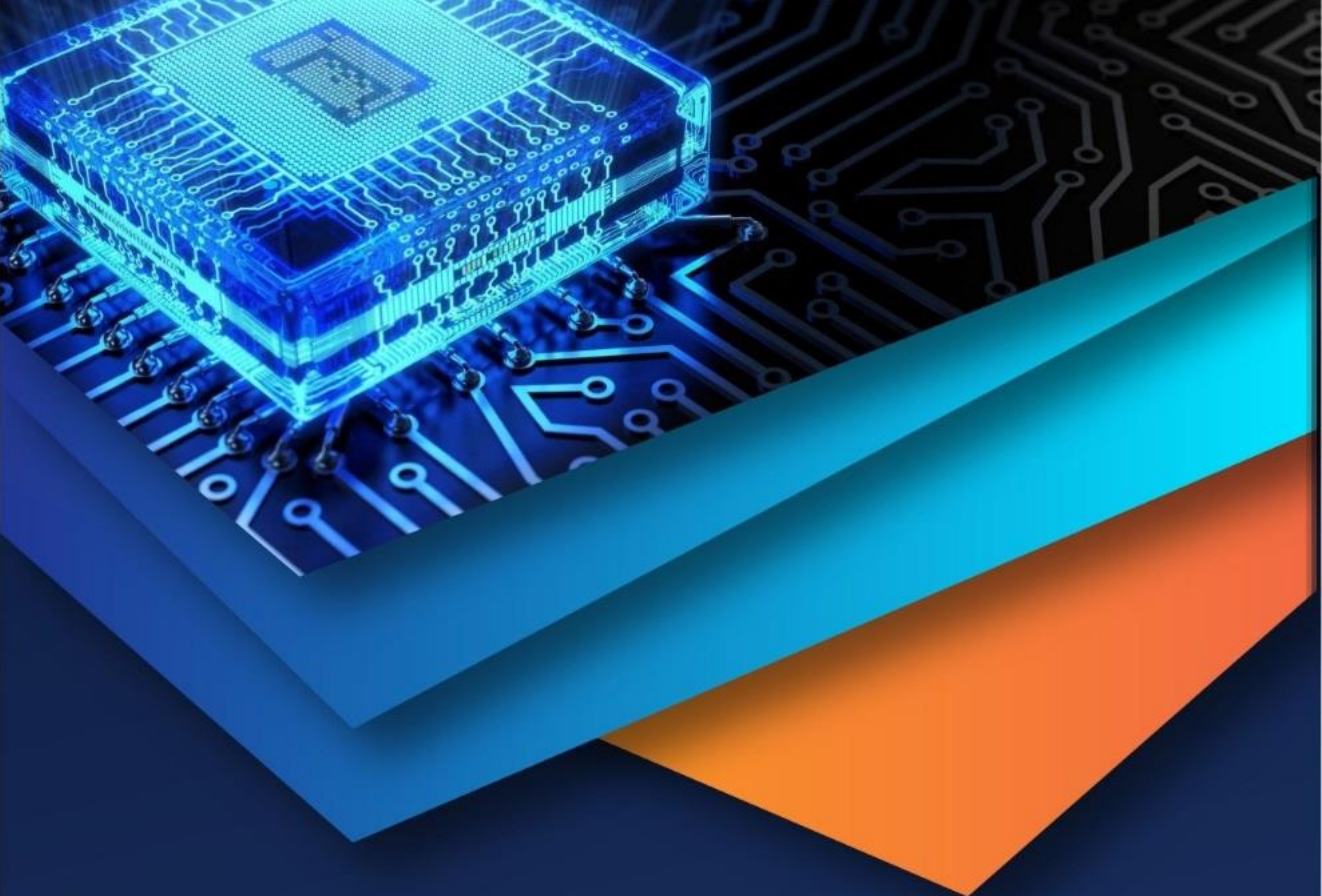

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