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Heat transfer through porous medium: A Review

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***Abstract*— this review article represents the effect of Porosity of material, mass flow rate and velocity of flow on heat transfer rate in porous medium. In this article, different cases are studied to summarize that heat transfer rate is considerably increased by using porous medium.**

***Keywords*— Porosity, porous medium, heat transfer, modes of heat transfer.**

I. INTRODUCTION

Heat transfer through porous material has a great scope in chemical, mechanical, aerospace, medical, biological engineering, materials sciences & many more fields. Due to increase in contact surface with fluid and efficient heat transfer property, Porous material being a part of interest of many researches. Number of Experiments, analytical work, researches has been done to investigate heat transfer phenomena through porous materials such as sintered metals, foams (metal or polymeric), ceramics, etc.

Recent advances in electronic system, heat exchangers, chemical reactors, etc; have lead to dramatic increases in heat flux. Heat transfer through porous media is being explored to thermal management of such systems. Many studies & experimental work have reported that Heat transfer through porous media is more efficient techniques than traditional one.

Enhancement in heat transfer depends upon porosity of material as well as other thermodynamic parameters. The porosity is characterized by volumetric amount, size and shape of pores, cellular structure, and is typically homogeneous and uniformly distributed [1].

II. HEAT TRANSFER

Heat transfer continues to be a field of major interest to engineers, scientific researchers, manufacturers. It is transfer of heat from one body to another body due to temperature difference. Heat transfer takes place whenever there is a temperature gradient within a system or whenever two systems at different temperatures are brought into contact.

Generally heat transfer takes place in three different modes: conduction, convection and radiation.

A. Conduction

It is a transfer of heat energy from one part of the body to another part of the same body due to molecular interaction or transfer of heat energy between two bodies brought in physical contact when there is temperature gradient exist between them. Conduction occurs in solid, liquid and gases.

This process is govern by Fourier's law and mathematically expressed as

$$Q_x = -k.A.\frac{dT}{dx}$$

Where, Qx is the rate of heat transfer by conduction in x-direction, (dT/dx) is the temperature gradient in x-direction, A is the cross-sectional area normal to the x-direction and k is a proportionality constant, called thermal conductivity.

B. Convection

Convection heat transfer takes place between a surface and a moving fluid, when there is temperature gradient exists. Convection is effect of fluid motion and conduction. The rate of heat transfer is depend upon temperature difference as well as fluid motion.

Convection heat transfer process is express by Newton's law of cooling as;

$$Q= h\ A\ (Ts - Tf)$$

Where Q is rate of heat transfer, h - convective heat transfer coefficient, A - area through which heat is transfer, Ts - surface temperature and Tf - temperature of fluid.

C. Radiation

Unlike conduction and convection, radiation heat transfer does not require a medium for transmission as energy transfer occurs due to the propagation of electromagnetic waves. Every body emits electromagnetic radiation at a certain temperature.

It is propagated with the speed of light (3 x 108 m/s) in a straight line in vacuum.

For a real surface the radiation energy given by Stefan-Boltzmann's law is,

$$Q_r = \varepsilon.\sigma.A.T_s^4$$

Where,

Q_r = Rate of thermal energy emission, W
ε = Emissivity of the surface
σ = Stefan-Boltzmann's constant, 5.669 X 10^{-8} W/m^2.K^4
A = Surface area, m^2
T_s = Surface Temperature, K

The emissivity is a property of the radiating surface.

III.POROSITY

A porous medium is a material which contains pores or voids. The skeletal portion of the material is often called the "matrix" or "frame". The pores are typically filled with a liquid or gas [2]. Because of uniform pore size, large surface area and flexible frameworks porous material enhances heat transfer.

The skeletal material is usually a solid, but foams are also analyzed using concept of porous media. Porous mediums reduce the thermal resistance at the gas/solid interface and enhance heat transfer rates.

Porosity (ϕ) is defined as a ratio of total pore volume (VP) to the apparent volume of the particle or powder.

Φ= VP/ V

Porous materials can be grouped into three classes based on their pore diameter (Ø), pore sizes in the range of 2 nm and below are called micropores, those in the range of 2 nm to 50 nm are denoted mesopores, and those above 50 nm are macropores. The distribution of sizes, shapes and volumes of the void spaces in porous materials directly relates to their ability to perform the desired function in a particular application [3].

IV.CASE STUDIES

A. Case study-I

Pei-Xue Jiang et.al [4] studied the effect of forced convection heat transfer of water and air in sintered porous plate channels. In this research the effects of fluid velocity, particle diameter, type of porous media (sintered or non-sintered), and fluid properties had studied on the convection heat transfer and heat transfer enhancement were investigated.

The water system included a water tank, a pump, a constant water head tank, a test section, a heat exchanger, a data acquisition system (Keithley 2000), pressure gauges, thermocouples and an electrical power input and measurement system. Whereas a compressor, a test section, two volumetric flow meters, a data acquisition system (Keithley 2700), pressure gauges, thermocouples, an electrical power input and measurement system were use for air system.

The test section was made up of bronze particles sintered to a thin copper plate which was placed in the stainless steel channel. The test section is shown in Fig. The sintered bronze material was 89/11 copper/tin mix with a typical 0.3% phosphorous content. The nominal particle sizes of the sintered porous plates were 0.5–0.71, 1–1.4 and 1.4–2 mm. The sintered porous plates were 210 mm in length and 120 mm wide, and the thicknesses of the three sintered porous plates were 11.73, 10.87 and 10.22 mm with porosities of the sintered porous plates were 0.402, 0.444 and 0.463. The test channel received a constant heat flux, qw, while the bottom and side plates were insulated. The average flow velocity were u0 and temperature kept constant.

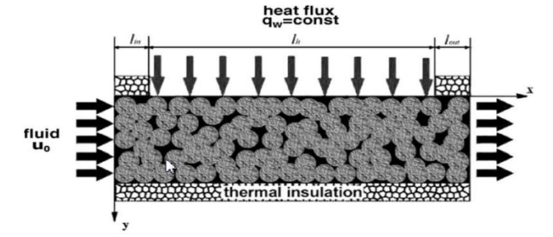

Figure 1: Porous medium

Convection heat transfer coefficients in an empty plate channel were studied. It was found that as compared to the empty channel the porous media greatly increased the heat transfer coefficient for both water and air. The average heat transfer coefficient enhanced 7–14 times for water and 3–36 times for air by using sintered bronze porous media depending on the mass flow rate. Also it concluded that Heat transfer enhancement for air increased sharply with increasing flow rate, while gradually increased for water with increasing in flow rate.

Table 1: Heat transfer enhancement in sintered porous media

Fluid	Particle diameter (mm)	Re_D					
		200	500	1000	2000	5000	10,000
Water	1.4–2.0	7.35	8.55	9.59	10.75	12.50	14.02
	1.0–1.4	8.17	9.05	9.79	10.58	11.73	12.67
	0.5–0.71	6.93	7.96	8.84	9.82	11.28	12.52
Air	1.4–2.0	2.71	4.80	7.40	11.39	20.17	31.06
	1.0–1.4	2.31	4.41	7.18	11.69	22.27	36.27
	0.5–0.71	3.19	5.51	8.34	12.62	21.81	33.00

An experimental result shows pressure drop for water and air in the sintered porous plate channels as a function of Reynolds number.

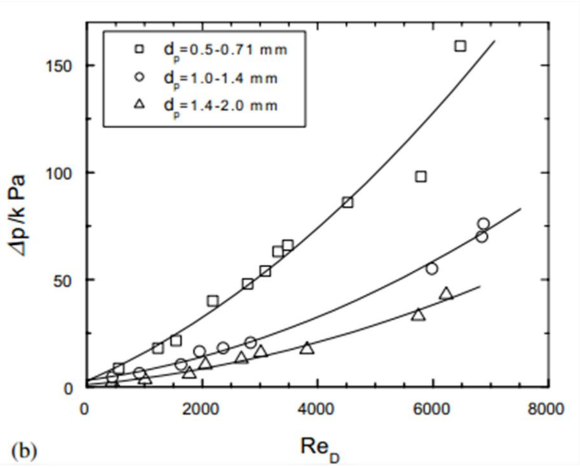

Figure 2: Pressure drop for air in the sintered porous plate channel

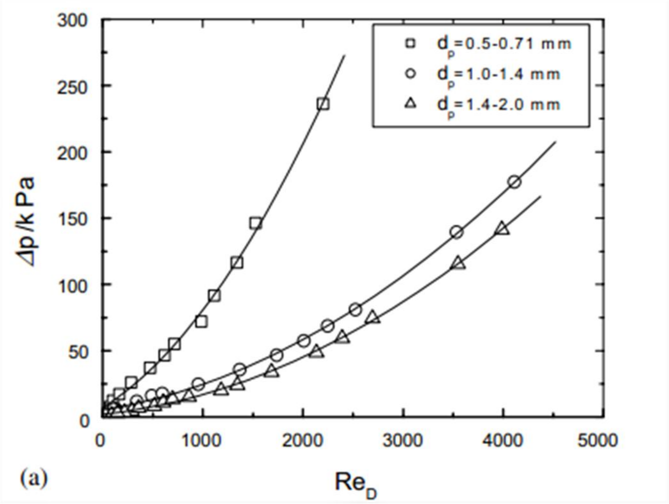

Figure 3: Pressure drop for water in the sintered porous plate channel

The result obtained from experimental study it was observed that the sintered bronze porous media enhanced the local heat transfer coefficient 15-fold for water and up to 30- fold for air depending on the mass flow rate. Higher heat transfer rate and effective thermal conductivity take place in sintered porous material than non-sintered porous material.

B. Case study- II

G. Hetsroni et.al. [5] Investigated Heat transfer and pressure drop in a rectangular channel with sintered porous inserts. In this experiment stainless steel sintered material with different average pore diameter of 20 µm and 60 µm were studied. The major aim of this study was to cool high power mini devices.

Filtered water was used in it as the coolant. The water was supplied to the test section from the entrance tank, 1, by a gear pump, 2. The experimental set up comprises 3. Control valve, 4. Temperature and pressure measurements ports, 5. Sample of porous medium, 6. Top of test section, 7. Housing. 8. Copper rod, 9. heaters, 10. Insulation, 11. Exit tank, 12. Electronic scales, 13. Thermocouple.

The rectangular channel of cross section 5 X 1 mm and the length of 70 mm were used. The channel was filled with porous insert of width 5 mm, length 2 mm and of 1 mm thickness. The heat was supplied to the porous sample through a copper rod.

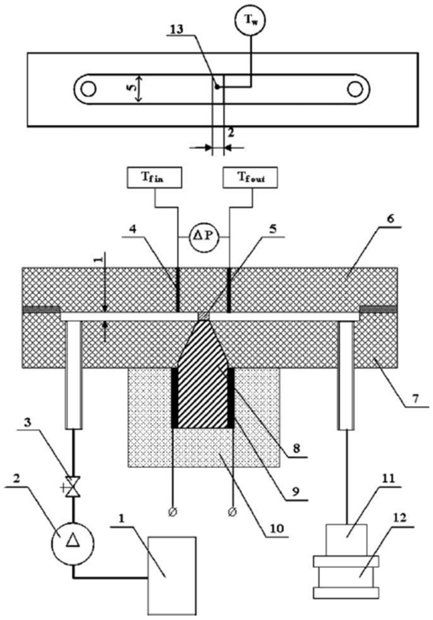

Figure 4: Schematic diagram of the experimental setup

The experiments were carried out in the range of average liquid velocity 0 .2 ≤ U ≤ 1.5 m/ s in the channel with the porous insert. The range of heat flux was 0.1≤ q ≤ 0.6 kW/cm2.

Pressure drop per the unit length for the two porous inserts were depicted in the fig. It cleared that the pressure drop in the porous material with 20 µm pore diameter is more than twice as large as that for the porous material of 60 µm. Also it concluded that up to 6000 kW/ m2 heat flux was removed by using porous samples with porosity 32% and average pore diameter 20 µm.

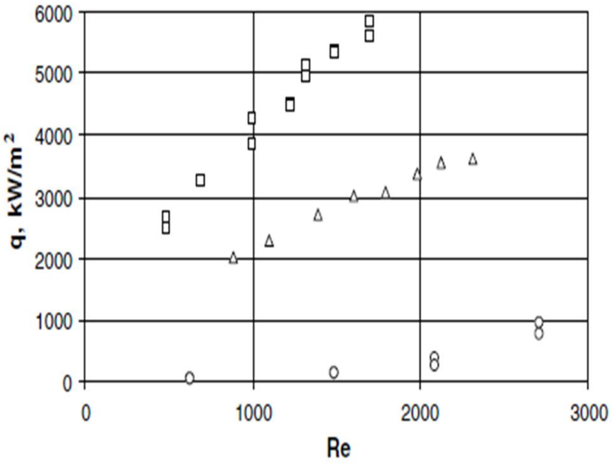

Figure 5: Heat flux as a function of the Reynolds number

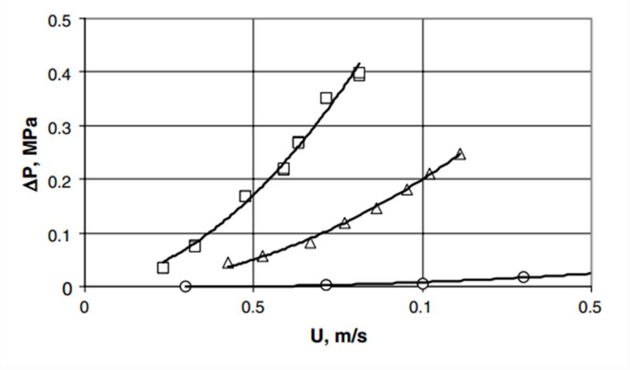

Figure 6: Pressure drops for the channels with two kinds of porous inserts and clear channel

C. Case study- III

Bogdan I. Pavel et.al.[6] Investigated the effects of porosity, pore diameter, pressure drop and thermal conductivity on heat transfer rate. The Investigation were carried out on copper pipe subjected to a constant and uniform heat flux and was filled with metallic porous material.

The porous media used for experiments were manufactured from commercial aluminum screen (wire diameter 0.8 mm, density 2770 kg/m3, thermal conductivity 177 W/m2K) cut out at various diameters Dp and then inserted on steel rods as shown in fig. The 12 different porous media, whose properties are presented in Table 1, were obtained by varying the screen diameter and the distance between two adjacent screens L

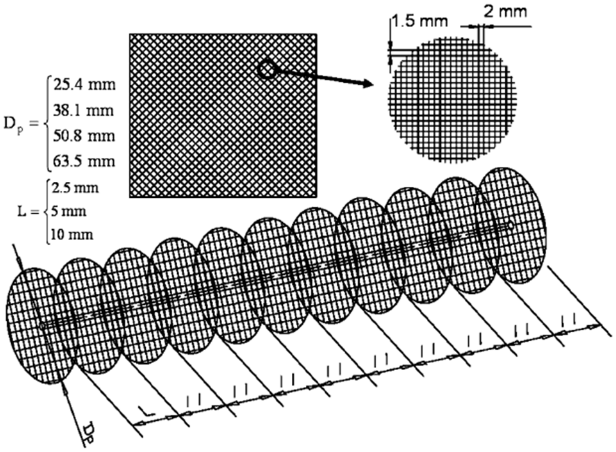

Figure 7: Porous medium manufactured from aluminum screens

Table 2: Porous medium characteristics

Porous medium	D (mm)	L (mm)	R_p	ε (%)	K (m^2)	F	Da
1	25.4	10	0.4	97.9 (large)	–	–	–
2	25.4	5	0.4	97.4 (medium)	–	–	–
3	25.4	2.5	0.4	96.6 (small)	–	–	–
4	38.1	10	0.6	98.8 (large)	9.409×10^{-7}	0.038	9.3341×10^{-4}
5	38.1	5	0.6	98.3 (medium)	5.947×10^{-7}	0.055	5.8897×10^{-4}
6	38.1	2.5	0.6	97.5 (small)	2.792×10^{-7}	0.069	2.7669×10^{-4}
7	50.8	10	0.8	99.1 (large)	–	–	–
8	50.8	5	0.8	98.6 (medium)	–	–	–
9	50.8	2.5	0.8	97.8 (small)	–	–	–
10	63.5	10	1.0	99.3 (large)	6.228×10^{-7}	0.032	6.1786×10^{-4}
11	63.5	5	1.0	98.8 (medium)	3.704×10^{-7}	0.046	3.6741×10^{-4}
12	63.5	2.5	1.0	98.1 (small)	1.954×10^{-7}	0.058	1.9384×10^{-4}

Tests were carried out for all porous media manufactured, at different mass flow rates of air and for the same power input 13.26 W so that the initial value of the Re number was around 1000. The temperature of the air at the inlet, the temperatures on the pipe surface along the heated section, the mass flow rate of air as well as the pressure drop were continuously monitored.

The figures depicted below concluded that the variation of the local Nusselt number for different values of Da = 10-2, 10-3, 10-4, 10-5, and 10-6. In all cases the employment of a porous material leads to an increase in Nu in comparison with the clear flow case. Thermal performance for the case where Da = 10-2 increases with the porous material diameter up to an Rp = 0.6. Further increase in Rp up to 0.8 and even more up to 1.0 leads to a decrease in Nu. This is not the case when the permeability of the porous material is decreased to a corresponding Da = 10-3 to 10-6. In the latter cases the heat transfer increases with Rp up to 0.8, which offers a far better thermal performance than all other cases. The same effect of poorer thermal performance can be observed for these cases when Rp is increased from 0.8 to 1.0.

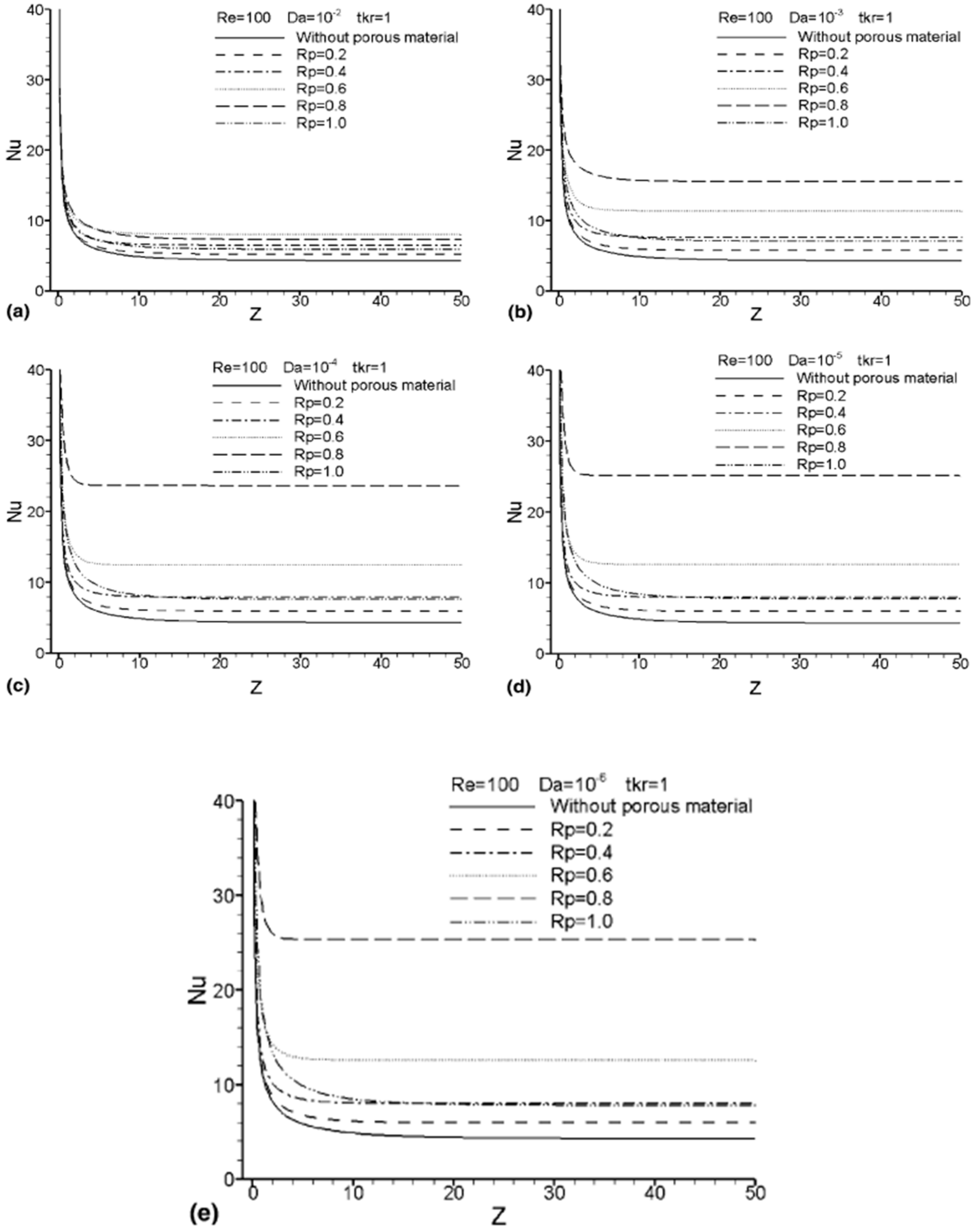

Figure 8: Influence of Rp on local Nu (a) Da=10-2, (b) Da= 10-3, (c)=10-4, (d) Da=10-5, (e) Da=10-6

From the experimental result it was observed that Heat transfer enhancement can be achieved using porous inserts

V. SUMMARY

From the above case studies it can be summarize that,
As the porosity of the sintered porous medium decreases, a higher heat-transfer rate takes place.
The specific contact surface of the fluid increases as the porosity decreases. This causes higher heat-transfer rate between the fluid and the solid phases for a constant flow-rate.

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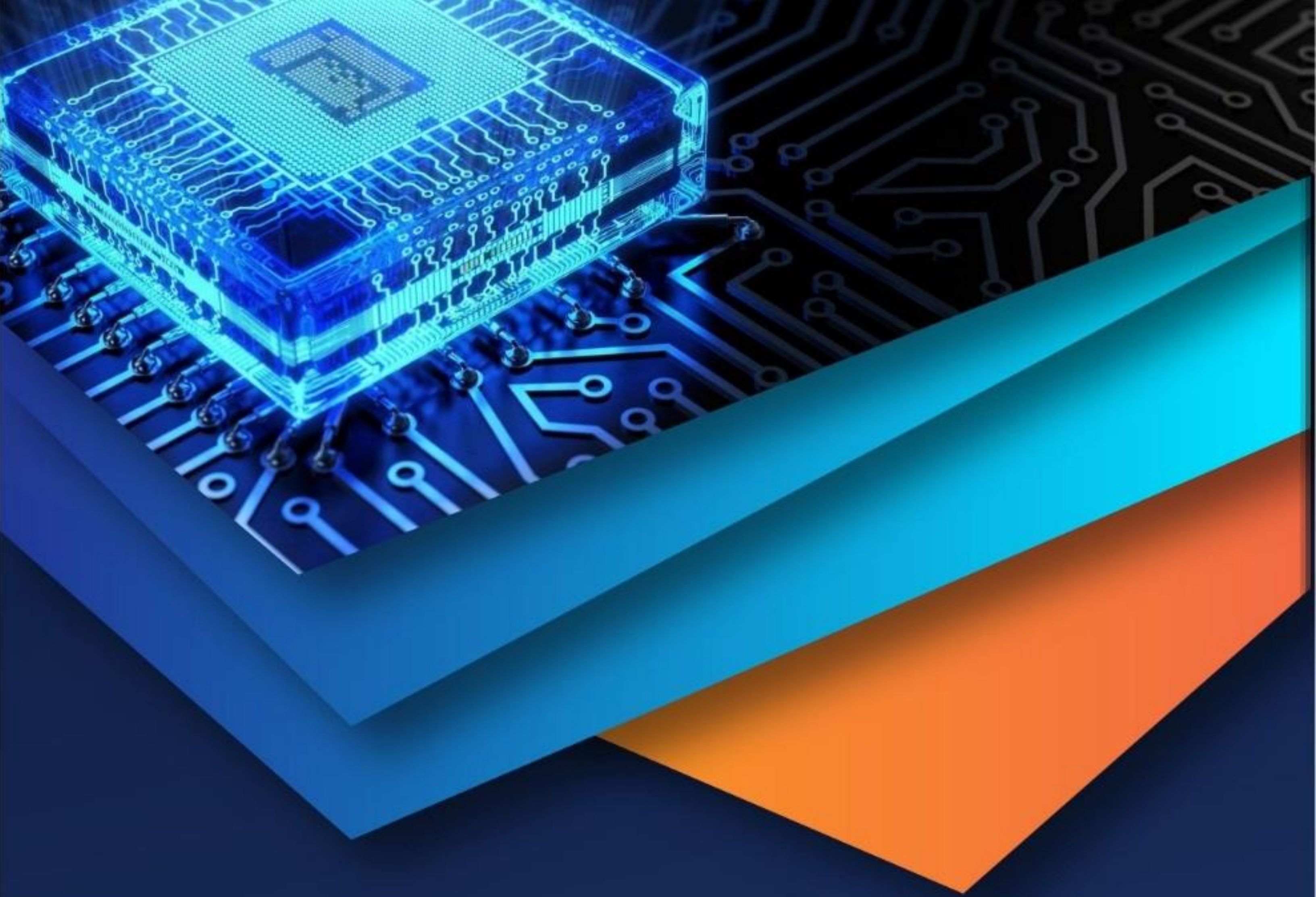

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