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Influence of Y-Shape Ribs Provided on Heat Transfer and Flow Characteristics of a Solar Air Heater

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Abstract: A numerical analysis of the solar air heater employed with the Y shape ribs over the absorber plate, arranged transverse to the direction of flow has been carried out to determine its influence on the thermal and hydraulic performance of the solar air heater.The computational analysis was carried out with a broad rectangular heater duct whose walls were heated and flow occurring through it was considered turbulent and hence the Reynold number range was assumed 4000-16000, which had been found most relevant condition for solar air heater.By comparing the predictions made by different low Reynold number turbulence models with the experimental results which are provided in literature, it has been found that SST k-omega model gives most closer results to that of experimental results. With the use of selected model, a detailed analysis of variation of heat transfer within the inter rib region is done. From the analysis, it has been observed that local heat transfer coefficient had highest value at the reattachment point of the separated flow. The results obtained with Y shape ribs were compared with the rectangular ribs and a duct having smooth surface. The results shows that the Y shape ribs gives better thermal performance than rectangular ribs.

Keywords: Solar air heater; Turbulence; Heat transfer; Friction; Ribbed roughened duct.

I. INTRODUCTION

The thermal efficiency obtained with solar air heater is considerable low due to low heat transfer coefficient between the absorber plate and the flowing fluid. This is due to the formation of laminar sub layer at the region near the walls of the absorber plate when ~~the flow~~ through solar air heater duct is turbulent. Laminar sub layer behaves as an insulation to the heat transfer phenomenon. Therefore it become necessary to break the laminar sub layer at the vicinity of wall and this can be done by providing some artificial roughness at the wall which will create excessive turbulence in the flow. However, providing roughness at the wall will improve thermal efficiency but it will also increase the frictional losses and pumping power requirements, therefore the roughness is provided only in the laminar sub layer zone to neglect these losses with considerable enhancement in heat transfer efficiency. The artificial roughness can be provided at the solar air heater wall by using ribs, baffles, protrusion wires etc, of different shapes and sizes. Enhancement of heat transfer efficiency of a rectangular solar air heater duct by using different shapes ribs has been a common practice in the recent years.

The most common shape of a solar air heater used for various application is a rectangular duct consisting an absorber plate on the top, a back plate, insulated wall over the back plate, a glass cover exposed to solar radiation, and a passage for the flow of air between the absorber and bottom plate .

From the recent experiments, it has been observed that the best thermal energy transfer in a solar air heater is obtained when the Reynold number for the air flowing through duct lies in the range 3000-21000 [2]. In this range, turbulent flow inside the duct occurs. Due to this reason, all the research experiment related to the improvement of performance characteristics of a solar air heater is carried out by considering the value of Reynold number lying in the above range. Hence, all the experiments carried out to improve the performance characteristics of solar air heater consider turbulent flow through duct. all the research work pertaining to the design of an effective solar air heater involves turbulent flow. Since the heat transfer coefficient and friction factor in a turbulent flow are highly affected by the surface condition of the passage through which fluid flow will take place [5] , therefore it is necessary to keep in view that the solar air heater must be provided with artificial roughness in such a way that higher heat transfer with low roughness to air flow is obtained. This can be done by proper selection of shape, size, patterns of the artificial roughness provided on solar air heater. Many scientists and authors carried out research which involves the use of different shapes, sizes and patterns of artificial roughness and performed experiments to find out the correct value of the parameters at which solar air heater gives optimum results. Some scientist develops important set of correlations based on the results of the experiment carried out which are useful to determine friction factor and nusselt numbers pertaining to experiment.

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II. SOLUTION DOMAIN

A solar air heater duct having rectangular section was selected with reference to the experimental details given by Tanda[19]. Solution domain consist three sections, test section having length L_2, inlet section of duct having length L_1 and the outlet section having length L_3. The numerical simulation was performed on 2-dimensional solution domain. This is due to reason that because Chaube et al. [1] did not found any considerable difference between the 2-dimensional and 3-dimensional results on performing numerical simulation on a solar air heater duct of same geometry having aspect ratio 7.5. The geometry of the solution domain considered is same to that taken by Tanda [19] rectangular solar duct. They considered a rectangular duct having length 640 mm, width 100 mm and height 20 mm having the length of test section 280 mm.Thickness of the absorber plate wastakenonly 1 mm. Rib height (e) was 3.4 mm and rib width was 5.8 mm.

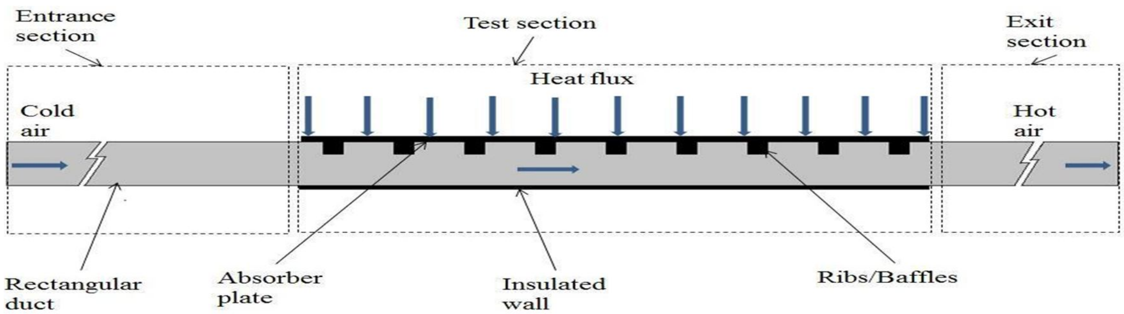
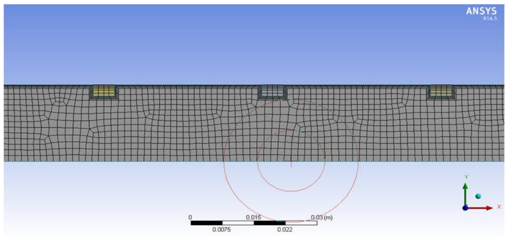


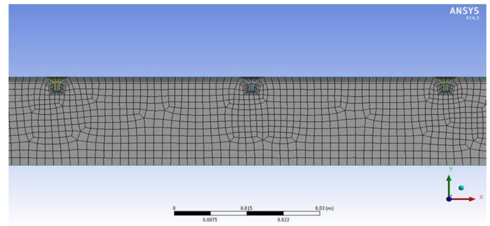
Fig. 2.1 Sketch of solution domain

According to the guidelines given by ASHRAE (American Society Of Heating, Refrigeration and Air conditioning Engineers) for the establishment of fully developed flow and to prevent the losses the length at the entrance and exit section of the solution domain must be more than $5\sqrt{WH}$ and $2.5\sqrt{WH}$ respectively

Table 3.1: Geometrical and Operating parameters used for CFD analysis

Operating and Geometrical parameters	Value / Range
Length of test section of duct, L_2	280 mm
Length of entrance section of duct L_1	245 mm
Exit section length of duct L_3	115 mm
Duct height, H	20 mm
Duct width, W	100 mm
Duct hydraulic diameter, D_h	33.33 mm
Aspect ratio of the duct, W/H	5
Constant heat flux, q	1100 W/m^2
Range of the Reynolds number	4000-16000





(a) (b)

Fig 2.2 meshed test domain with (a) rectangular ribs and (b) Y shape ribs

III. SELECTION AND VALIDATION OF MODEL

For determining the best turbulent model which would give most accurate numerical results, the following method was chosen. The selection of the model is done by comparing the results obtained from different low Reynold number models that are available in literature. The model selected is then validated by comparing its heat transfer predictions for the inter rib regions with the experimental results obtained by Tanda[19]. Therefore, the CFD simulations were carried out on a solar heater duct with smooth walls (without ribs) and the results of variation of the friction factor and the Stanton number with reynold number results were obtained. Then, these outputs were compared with the experimental results obtained by Tanda [19]. For the regions adjacent to wall, low Reynold number models are used because high Reynold number do not give good results in these regions, however they work well in outer flow regions. For example, Reynold Stress Model (RSM) and standard k- omega model do not perform well in regions near the walls as k & omega approaches to zero. When k becomes zero, it become tedious to solve € equation. Similarly, large eddy simulation model (LES) do not catch small eddies formaton near the wall. Considering the problem associated with these models, low Reynold number models has been developed. Therefore, three different low Reynold number turbulent flow models, RNG-k-epsilon, Realizable-k-epsilon and SST k-omega models were selected and their corresponding results were compared with the experimental results in terms of variation of Stanton number with the Reynolds number.

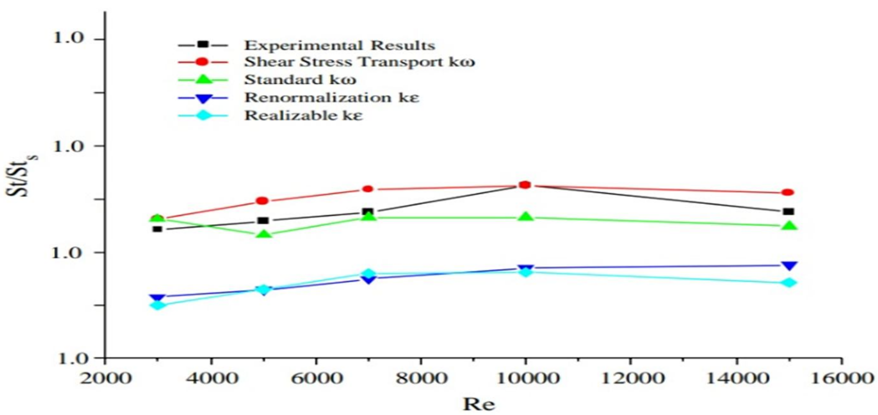


Fig 3.1 Comparison of different low turbulent models with the experimental results

The increment in heat transfer obtained in experiment was compared with the computational result obtained with different models by drawing a graph between the ratio of Stanton number of ribbed duct and the smooth duct versus Reynold numbers shown in fig 3.1.By comparing the results obtained with different models with the experimental results, it has been found that SST k-omega model gives more closer results to that of experimental results. Therefore, SST k-omega model was selected for thenumerical analysis of the present work.

IV. DETAILED ANALYSIS

Commercially available ANSYS FLUENT v 14.5 was the CFD software employed to solve the concerned general differential equations numerically. This software numerically simulates using FINITE VOLUME METHOD.

The meshing of the solution domain was performed on the commercially available meshing software of ANSYS. The created geometrical model of the test domain was imported to the ANSYS meshing. The number of the divisions and type of "bias"

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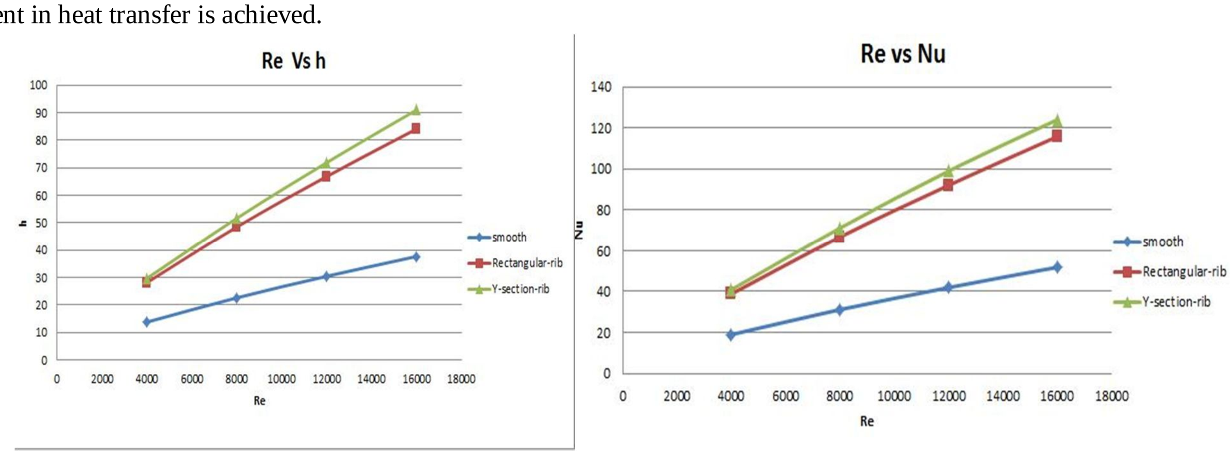
required to each edge were assigned. For obtaining the mesh cells of regular rectangular shape mesh cells having best orthogonal quality, mapped facing option was selected. After that, the 'Generate Mesh' option was selected to get the meshed structure of the test domain. The grid convergence for present work was carried out at Re = 12000 because the thickness of the viscous laminar sub layers was observed to be minimum at this Reynolds number. Separate test of grid independence was carried out for test domain containing different shapes of ribs. For the test domain with rectangular ribs , the best grid size obtained was 254714 while with Y shaped rib it was 269386. Hence, determining the correct grid dimensions at this Reynolds number would predict the grid size that would results in more accurate value of heat transfer for the entire range of the Reynolds number considered in present simulation (Re = 4000-16000).

V. TEST RESULTS

Using SST k-omega model, test domain containing no ribs, Y shaped ribs and rectangular shaped ribs has been analyzed for similar duct parameters . Reynold number is varied between 4000 and 16000.The result obtained from numerical simulation shows that the solar air heater duct provided with ribs gives increment in both heat transfer and friction factor values than that obtained with the solar air heater having smooth duct surface.

Fig. 5.1(b) shows the variation of Nusselt number with the Reynold number values for the different rib geometries. From fig. it is clear that the the nusselt number is higher in case of Y shaped ribs than that of solar air heater employing rectangular ribs. William and Watts present an explanation after observing the flow pattern occurring under different shapes ribs. They claimed that for a rib having square or rectangular shape , standing vortices are formed in the inter-rib regions that covers nearly two-third of the cavity and the energy exchange of this region with the main flow was only sufficient to cause vortex shedding occasionally. Thus, the propagation of the disturbance from the inter rib region to the main flow was very small. But with the chamfered or inclined ribs , the vortex developed between the the ribs was so strong that it grows up to the full cavity between the ribs and causes vortex shedding more frequently and hence in this case disturbance propagation to main flow is very high. In present study, the Y shaped ribs combines the effect of inclined and rectangular shaped ribs and hence disturbance propagation from inter rib region to main flow is higher in this case than that of rectangular ribs. Thus , Y shaped ribs have higher values of Nusselt number and friction factor as it causes the frequent propagation of disturbances and hence causes enhancement in the heat transfer characteristics and frictional losses. Fig.5.1(a) shows the variation of the convective heat transfer coefficient over the range of Reynold number for different rib geometries.

Fig. 5.2(b) shows the variation of friction factor over the range of Reynold number for different rib geometries employed in solar air heater. It has been observed that in almost all three cases, the value of friction factor is highest at the lower values of Reynold number. This is due to reason that the thickness of the laminar sub layer at lower Reynold number values is capable of submerging the roughness element provided on duct walls and the viscous forces are high enough to overcome the flow disturbances occurring due to the presence of the ribs on the wall.Thus, the disturbances could not flow to the main flow region. On the other hand at higher values of Reynold number. The laminar sub layer formed is thinner and therefore the rib height becomes equals or more than laminar sub layer thickness. When the height of the ribs are such that it can penetrate the laminar sub layer zone , optimum increment in heat transfer is achieved.



(a) (b)

Fig. 5.1 Variation of (a) Convective heat transfer coefficient ,and (b) Nusselt number with Reynold number for different rib geometries.

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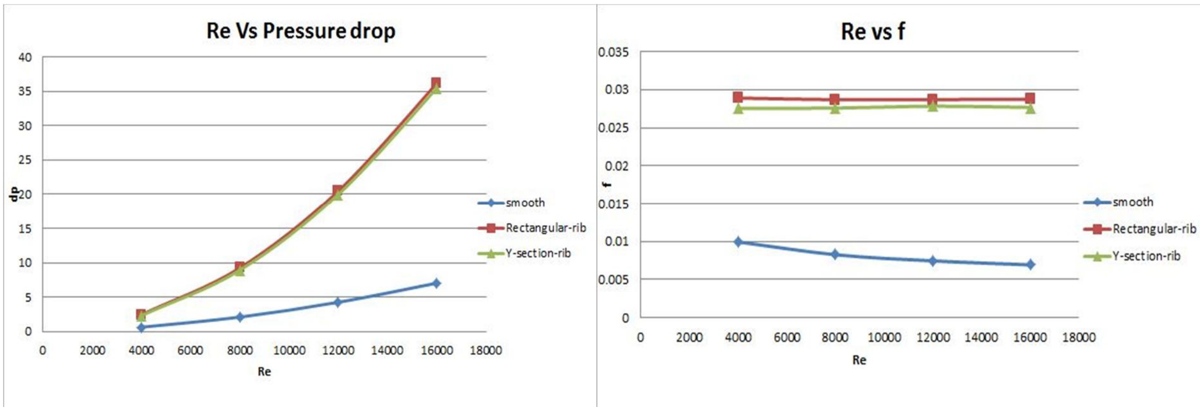
Fig 5.2(a) shows the variation of the pressure drop over the range of the Reynold number for the solar air heater duct provided with smooth surface, rectangular ribs and Y shape ribs. It has been observed from the results that the drop in pressure was smaller at low Reynold value as it was 0.6349 ,2.433 and 2.313 pascal at Reynold number value 4000 for smooth, rectangular ribbed and Y shape ribbed duct respectively. When an increment the Reynold number value occurs, an enhancement in the value of pressure drop has been observed for all ribs. It has also been seen that the pressure drop in rectangular ribbed duct was slightly more than that of Y shape ribbed duct for upto Reynold number value 12000 whereas at Reynold number value 16000 , the pressure drop in Y shaped ribbed duct are more than that of rectangular ribbed duct.



(a) (b)

Fig 5.3 Variation of (a) pressure drop, and (b) friction factor with Reynold number for different rib geometries.

In order to compare the performance of the solar air heater employing ribs of different geometries in which the pumping power requirement is same, equartion to calculate the performance index (η)is given as:

$$\eta = \frac{(Nu)_R / (Nu)_S}{(f_R / f_S)}$$

The Nusselt number in smooth duct is chhjkkkalculated by using Dittus – Boelter correlation which is given as:

$$Nu_S = 0.024\ Re^{0.8}\ Pr^{0.4}$$

Friction factor in smooth duct was calculated by using modified Blasius equation which is given as:

$$f_S = 0.085\ Re^{\ 0.25}$$

Fig. 5.5 shows the comparison of the performance index (η) behavior for ribs of different geometries over the considered range of the Reynold number (4000-16000) by drawing a graph between the Nusselt number ratio of ribbed duct and smooth duct versus Reynold number. The plot between the performance index and Reynold number shows that the best thermo hydraulic performance is obtained by employing Y shaped ribs on the solar air heater duct for the most of the values of Reynold number.

From fig 5.3, it has been observed that the value of performance index is highest at the lower values of Reynold number and decreases with increase in the value of Reynold number for both Y shaped ribs and rectangular ribs. This is due to reason that with the increase in Reynold number, turbulence in the inter rib region increases which causes the disturbances to propagate more frequently in main flow region causing enhancement in heat transfer but more frictional losses comparatively.

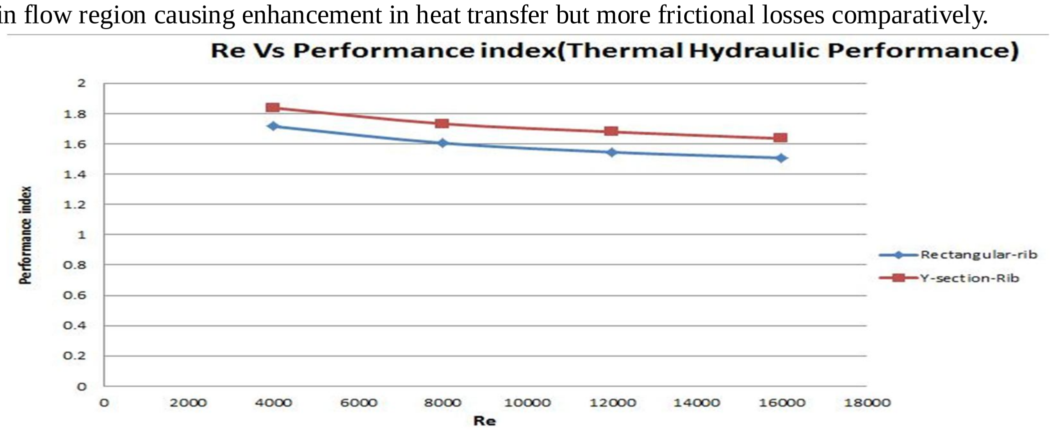


Fig 5.3 Variation of performance index over the range of Reynold number for different ribs

VI. CONCLUSION

Following conclusion has been drawn from the output of the present numerical simulation:

1) Y- shape ribs arranged transverse to flow direction gives higher thermal performance than that obtained with rectangular ribs for a given range of the Reynold number.
2) Peaks of friction factor are obtained at lower Reynold number and it follow small decrement with the increment in Reynold number.
3) The results predicts that the frictional losses are more in rectangular ribs than that in Y shape ribs.
4) Pressure drop between entrance and exit section of the duct is lower at the low Reynold number and increases with increase in value of Reynold number.
5) Out of all three arrangements, the best thermo hydraulic performance index was observed in Y shaped ribs.

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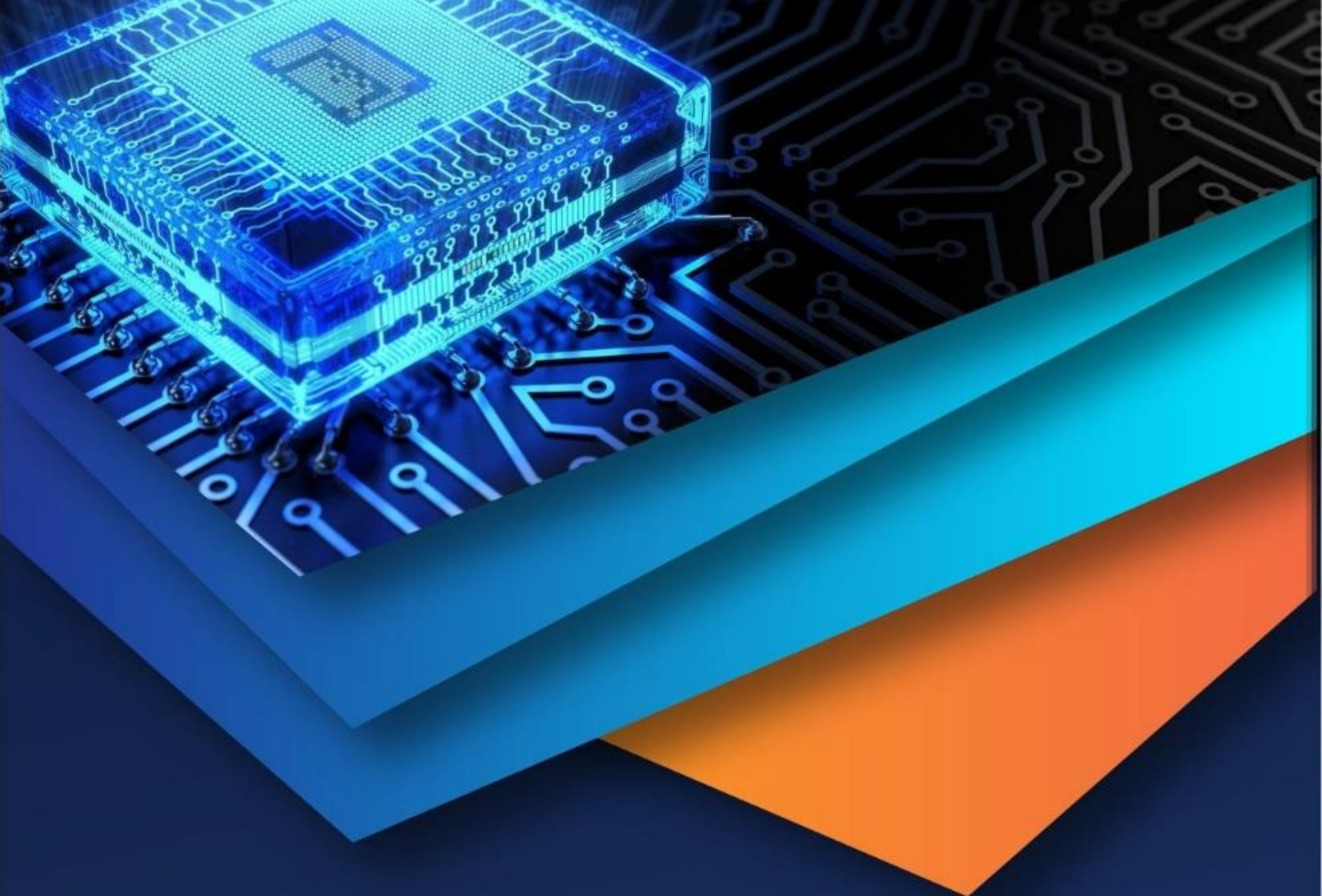

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