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CFD Analysis on Twisted Tape Heat Exchanger with Hybrid Nano Particle

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Abstract: Heat exchangers are the most commonly used devices for the transfer of heat among hot and cold fluids. Hence, for the better exchange of heat between the fluids, there is a need in modifications in the design of heat exchangers. There are different methods to increase the heat transfer rate such as increasing the surface area by adding fins, inserts in the tube like twisted tapes, wire coils, baffles etc. In the present analysis, a single tube heat exchanger with the twisted tape insert is used. The twisted tapes of three different H/D ratios are inserted and change in rate of heat transfer is observed for various twisted tape inserts. With the use of nanofluid, there is an increase in heat transfer rate. Here, carbon nanotubes (CNT)-Fe_3O_4 hybrid nanofluid of three different volume concentrations are used as working fluid.
Key words: twisted tape inserts hybrid nano particle, augmentation techniques, CFD modeling and analysis

I. INTRODUCTION

The flow of a fluid in tube is classified into three types: Laminar flow, Transition flow, Turbulent flow. The flow in a pipe is laminar, transitional, or turbulent provided the Reynolds number is “small enough,” “intermediate,” or “large enough.” It is not only the fluid velocity that determines the character of the flow—its density, viscosity, and the pipe size are of equal importance. These parameters combine to produce the Reynolds number. The Reynolds number of a flow gives a measure of the relative importance of inertia forces (associated with convective effects) and viscous forces. If the applied boundary conditions do not change with time the flow is steady. This regime is called laminar flow. In the final state the flow behaviour is random and chaotic. The motion becomes intrinsically unsteady even with constant imposed boundary conditions. The velocity and all other flow properties vary in a random and chaotic way. This regime is called turbulent flow. The only randomness and mixing take place on the molecular scale and result in relatively small heat, mass, and momentum transfer rates.

An internal flow, such as flow in a pipe, is one for which the fluid is confined by a surface. Hence the boundary layer is unable to develop without eventually being constrained. The internal flow configuration represents a convenient geometry for heating and cooling fluids used in chemical processing, environmental control, and energy conversion technologies. A nanofluid is a fluid containing nanometer -sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nano tubes. Common base fluids include water, ethylene glycol and oil. Nanofluids have novel properties that make them potentially useful in many applications in heat transfer including microelectronics, fuel cells, pharmaceutical processes, and hybrid powered engines, engine cooling/vehicle thermal management, domestic refrigerator, chiller, heat exchanger, in grinding, machining and in boiler flue gas temperature reduction. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid. Knowledge of the rheological behavior of nanofluids is found to be very critical in deciding their suitability for convective heat transfer applications. Nanofluids are produced by several techniques.

Direct Evaporation (1 step)
Gas condensation/dispersion (2 step)
Chemical vapour condensation (1 step)
Chemical precipitation (1 step)

Several liquids including water, ethylene glycol, and oils have been used as base fluids. Nano-materials used so far in Nano fluid synthesis include metallic particles, oxide particles, carbon nanotubes, grapheme nano-flakes and ceramic particles.

A. Augmentation

The process of improving the performance of a heat transfer system is referred as the heat transfer enhancement technique. Augmentation techniques increase convective heat transfer by reducing thermal resistance in a heat exchanger. A decrease in heat transfer surface area, size, and hence weight of heat exchanger for a given heat duty and pressure drop.

B. Augmentation Techniques

The heat transfer can be increased by the following different augmentation techniques

1) Passive Techniques
2) Active Techniques
3) Compound Techniques

Passive Techniques generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. These techniques do not require any direct input of external power; rather they use it from the system itself which ultimately leads to an increase in fluid pressure drop.

C. Twisted Tapes

Twisted tape is a historically well-known heat transfer enhancement product. The enhancement is achieved by inducing swirl flow of the tube side fluid, resulting in higher near wall velocities and mixing of fluids thereby enhancing the heat transfer coefficient. A reasonable flow velocity is required in order to induce effective swirl flow, for that reason twisted tapes are most effective in turbulent flows with limited pressure drop. Under laminar flow conditions the improvements achieved are limited. The heat transfer and pressure drop characteristics can be varied by changing the twist pitch of the device. Typical twist pitch ratios possible to manufacture (360o twist pitch / tape width) are between 6 and 18. The width of the tape is specified to allow a small gap between the tape and the tube wall.

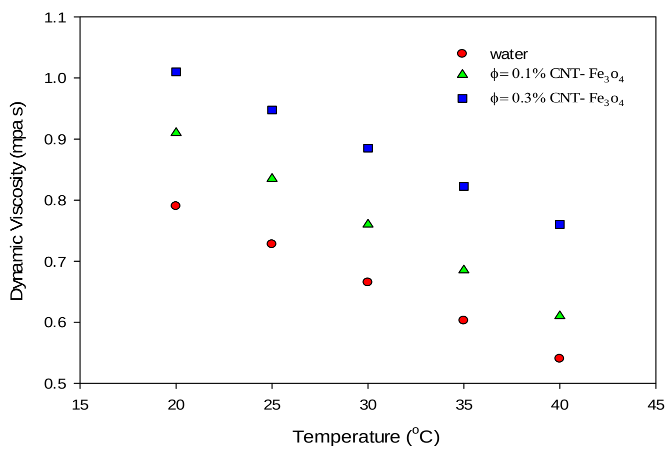

Fig 1.1 Variation of dynamic viscosity with temperature

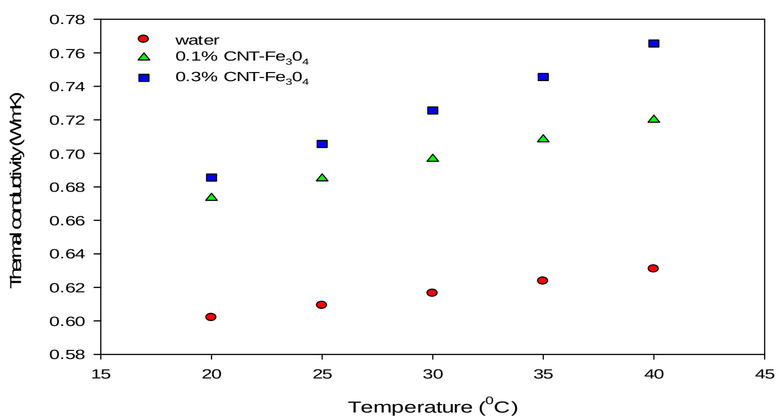

Fig. 1.2 Variation of thermal conductivity with temperature

Volume 5 Issue IV, April 2017
ISSN: 2321-9653

Twisted tapes are used in the present CFD analysis with carbon nanotubes based nanofluid. Twisted tapes of different ratios 5<H/D< 15 are considered with nanofluids of volume concentration 0.1 and 0.3 respectively. The tube with the twisted tape and the flow are modeled using CATIA and simulation is done using CFD. The specifications of the model designed are as follows. The length of the tube is 1100mm and thickness is 1mm. The inner diameter of tube is 14mm and outer diameter of tube is 16mm.

In a single pipe heat exchanger under constant heat flux condition with inserts in the tube creates turbulence which enhances the heat transfer rate. The twisted tape is made of aluminium strip of thickness 1mm and width 13mm. The twisted tapes of various H/D ratios are used in this analysis. The H/D ratios considered in this study are 5, 10 and 15. Finally, the simulations are done using ANSYS FLUENT Solver software to study the influence of nanofluids and twisted tape inserts on heat transfer characteristics in the test section.

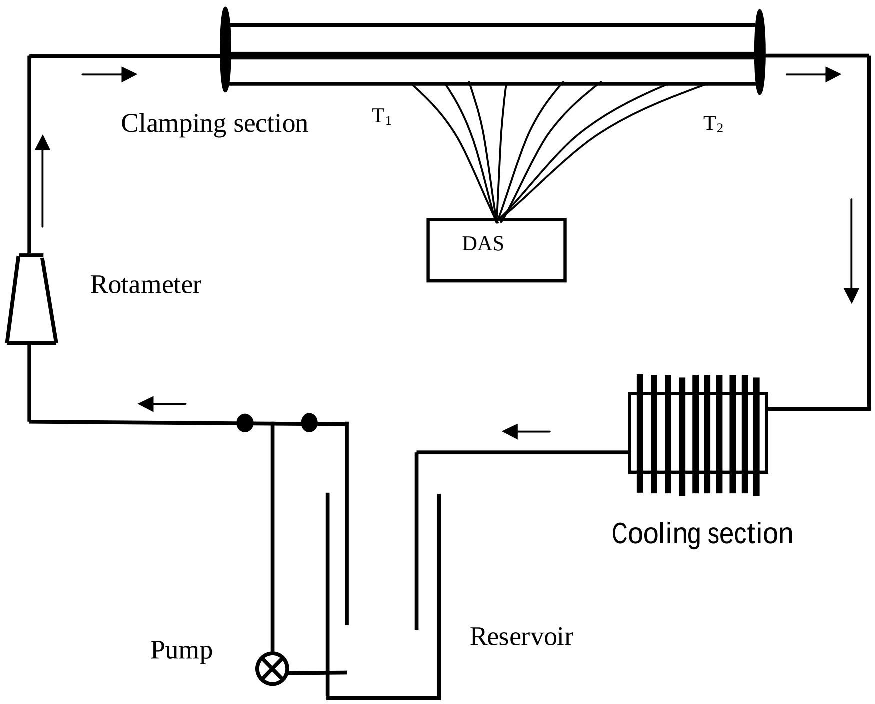

Fig 1.3 Schematic diagram of experimental setup

D. Modelling of Twisted Tape

In this case, study has to be done on a pipe with three various types of twisted tape inserts. The thickness and width of the twisted tape is 1mm and 13mm respectively. Here, twisted tapes are modelled with three different H/D ratios 5, 10 and 15 respectively.

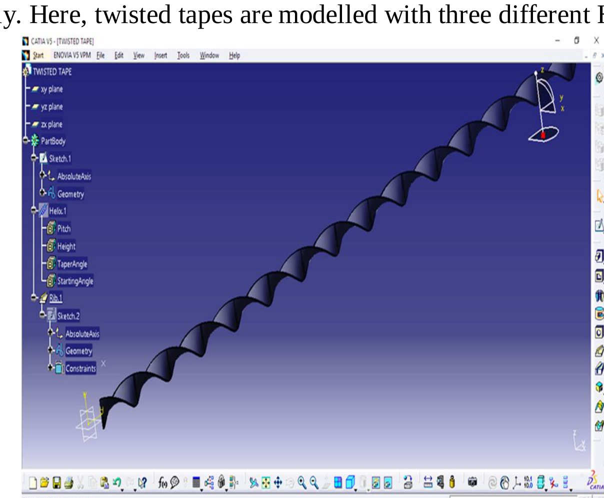

Fig 1.4 Twisted tape of H/D=5

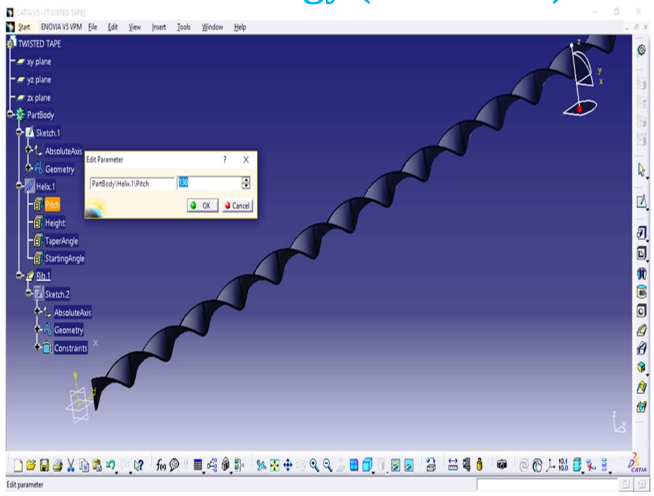

Fig 1.5 Specification of pitch for H/D=10

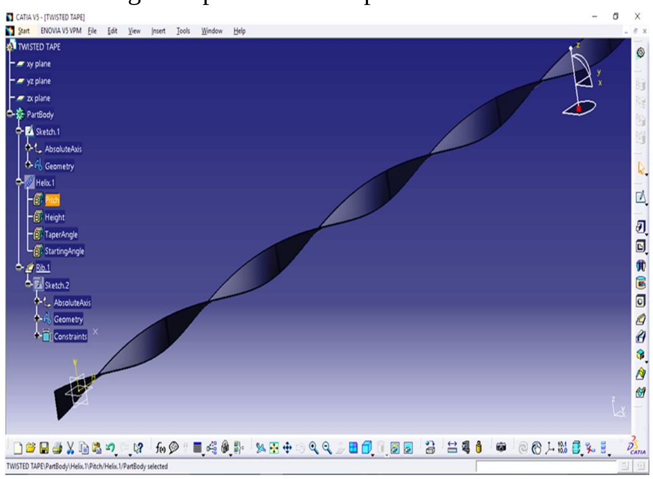

Fig 1.6 Twisted tape of H/D=15

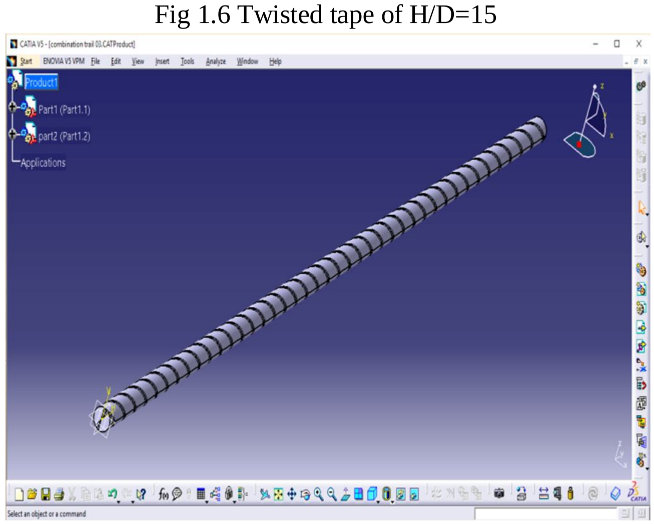

Fig 1.7 Assembly of twisted tape and tube

II. TURBULENCE MODELS FOR REYNOLDS-AVERAGED NAVIER–STOKES(RANS) EQUATIONS

Prior to the applicationof numerical methods the Navier–Stokes equations are time averaged(or ensemble averaged in flows with time-dependent boundaryconditions). Extra terms appear in the time-averaged (or Reynoldsaveraged)flow equations due to the interactions between variousturbulent fluctuations. These extra terms are modelled with classical turbulence models: among the best known ones are the k–ε model andthe Reynolds stress model. The computing resources required forreasonably accurate flow computations are modest, so this approachhas been the mainstay of engineering flow calculations over the lastthree decades.

A. The K-E Model

In two-dimensional thin shear layers the changes in the flow direction arealways so slow that the turbulence can adjust itself to local conditions. In flows, where convection and diffusion cause significant differences between the production and destruction of turbulence e.g., in recirculating flows, a compactalgebraic prescription for the mixing length is no longer feasible. The wayforward is to consider statements regarding the dynamics of turbulence. The$k$–ε model focuses on the mechanisms that affect the turbulent kinetic energy.

The instantaneous kineticenergy$k(t)$ of a turbulent flow is the sum of the mean kinetic energy $K = 1/2\ (U^2 + V^2 + W^2)$ and the turbulent kinetic energy $k = 1/2(\ u^2+v^2+w^2)$

$$k(t) = K + k$$

B. The K-E Model Equations

The exact ε-equation, however, contains many unknown and unmeasurableterms. The standard k–ε model(Launder and Spalding, 1974) hastwo model equations, one for k and one for ε, based on our best understandingof the relevant processes causing changes to these variables.

We use k and ε to define velocity scale ϑ and length scale ℓrepresentativeof the large-scale turbulence as follows:

$$\vartheta = k^{1/2} \quad \ell = \frac{k^{3/2}}{\varepsilon}$$

Applying dimensional analysis we can specify the eddy viscosity as follows:

$$\mu_t = C\rho\vartheta\ell = \rho C_\mu \frac{k^2}{\varepsilon} \qquad \text{Eq 5.2}$$

Where $C_\mu$is a dimensionless constant

The standard k–ε model uses the following transport equations for $k$and ε:

$$\frac{\partial(\rho k)}{\partial t} + \operatorname{div}(\rho k\mathbf{U}) = \operatorname{div}\left[\frac{\mu_t}{\sigma_k}\operatorname{grad} k\right] + 2\mu_t S_{ij} \,.\, S_{ij} - \rho\varepsilon \qquad \text{Eq 5.3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \operatorname{div}(\rho \varepsilon\mathbf{U}) = \operatorname{div}\left[\frac{\mu_t}{\sigma_\varepsilon}\operatorname{grad} \varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t S_{ij} \,.\, S_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad \text{Eq 5.4}$$

In words the equations are

$$\begin{matrix} \text{Rate of} & & \text{Transport} & & \text{Transport} & & \text{Rate of} & & \text{Rate of} \\ \text{change of} & + & \text{of } k \text{ or } \varepsilon \text{ by} & = & \text{of } k \text{ or } \varepsilon & + & \text{production} & - & \text{destruction} \\ k \text{ or } \varepsilon & & \text{convection} & & \text{by diffusion} & & \text{of } k \text{ or } \varepsilon & & \text{of } k \text{ or } \varepsilon \end{matrix}$$

The equations contain five adjustable constants: Cμ, σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$. Thestandard$k$–ε model employs values for the constants that are arrived at bycomprehensive data fitting for a wide range of turbulent flows:

$C\mu=0.09$, $\sigma_k=1.00$,$\sigma_\varepsilon=1.30$, $C_{1\varepsilon}=1.44$,$C_{2\varepsilon}=1.92$

C. Governing Equations

The problem under consideration is three dimensional, steady and turbulent. To derive the governing equations, the following assumptions are considered.

1) The properties of fluid are constant.

Volume 5 Issue IV, April 2017
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

2) Fluid is isotropic, incompressible and continuous.
3) he working fluid is Newtonian.
4) The effect of gravity is negligible.

Equations of continuity, momentum and energy for the fluid flow are given below in tensor form.

Continuity equation

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad \text{Eq 5.5}$$

Momentum equation

Energy equation

$$\frac{\partial}{\partial x_i}(\rho u_j C_p T - k\frac{\partial T}{\partial x_i}) = u_i \frac{\partial \rho}{\partial x_i} + \left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

Boundary Conditions

The boundaries in the computational domain fall in to one of the two categories, namely Solid or fluid. The copper thickness section is considered as a solid part on which heat interaction between nichrome heater and cold water is done. Turning on the fluid boundaries, there are two of these, namely water inlet (Velocity inlet) and water outlet (outflow). Each of these boundaries now considered in turn.

Velocity of the fluid at inlet is varied for each simulation to obtain the results at various Reynolds number. Outflow is considered at outlet and remaining surfaces are considered as walls. In case of twisted tape insert, it is considered as another solid domain and surfaces are retained as wall which is coupled with adjacent fluid domain. All the flow variables at the outlet boundary, including temperature, were determined from the interior of the domain by extrapolation. The 3-D numerical simulations were carried out using the commercial software ANSYS FLUENT. The steady state pressure based solver with standard k-ε turbulence model with Reliazable is considered with second order upwind scheme available in ANSYS FLUENT was used for all the calculations. The SIMPLE scheme for pressure – velocity coupling is used for all the calculations.

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

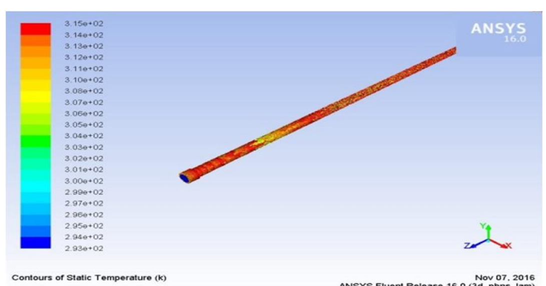


Fig 2.1 Temperature distribution in a plain tube with water

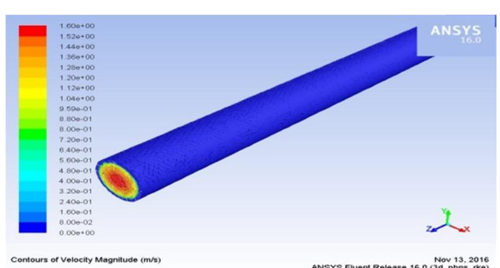


Fig 2.2 Velocity distribution in a plain tube with water

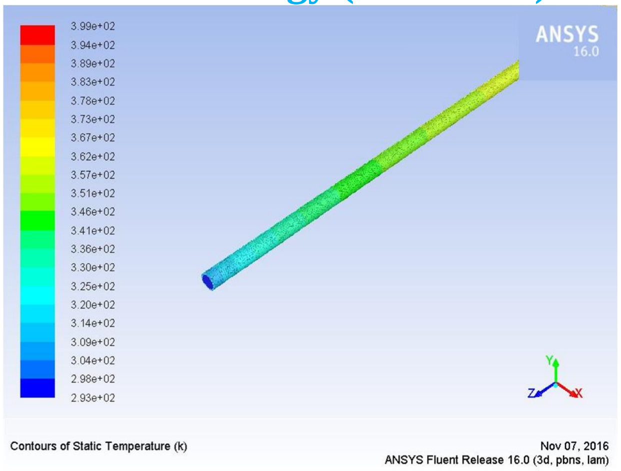


Fig 2.3 Temperature distribution in a tube with twisted tape H/D=10 and 0.3% CNT-Fe_3O_4nanofluid

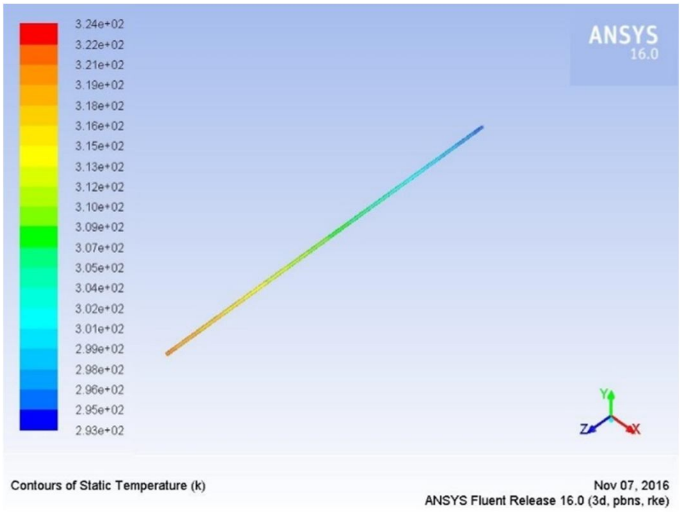


Fig 2.4 Temperature distribution in a tube with twisted tape H/D=15 and 0.3% nanofluid

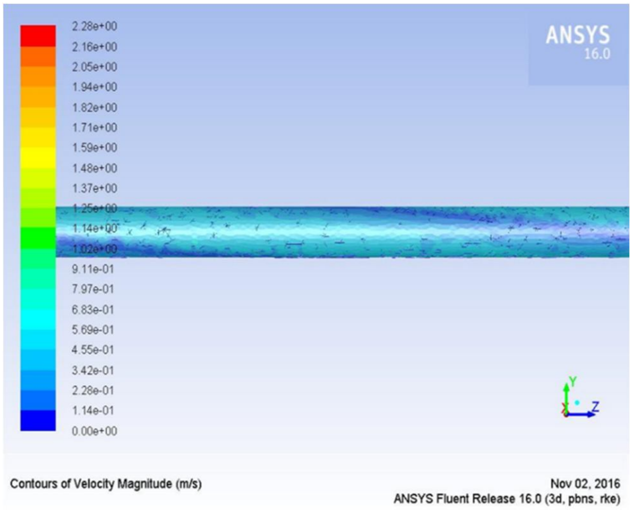


Fig 2.5 Velocity distribution in a tube with twisted tape H/D=15 and 0.3% nanofluid

Volume 5 Issue IV, April 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

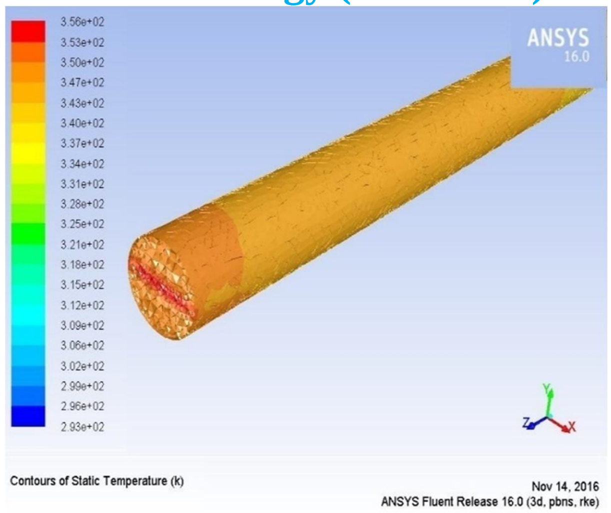


Fig 2.6 Temperature distribution in a tube with twisted tape H/D=5 and 0.3% nanofluid

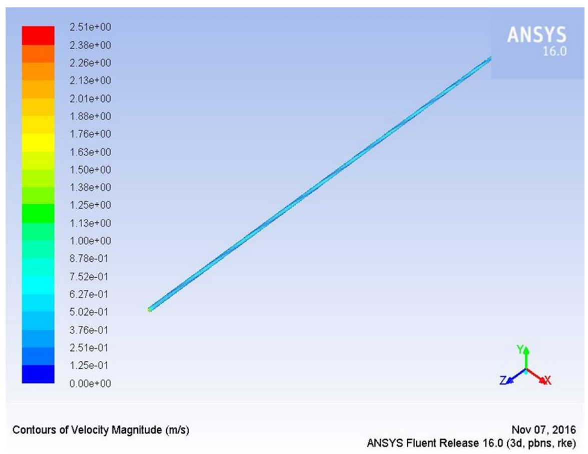


Fig 2.7 Velocity distribution in a tube with twisted tape H/D=5 and 0.3% nanofluid

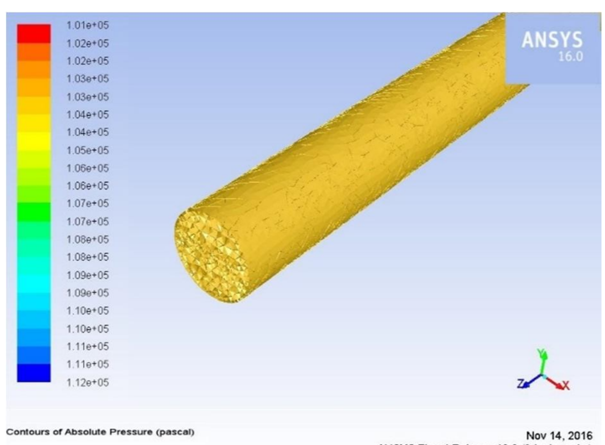
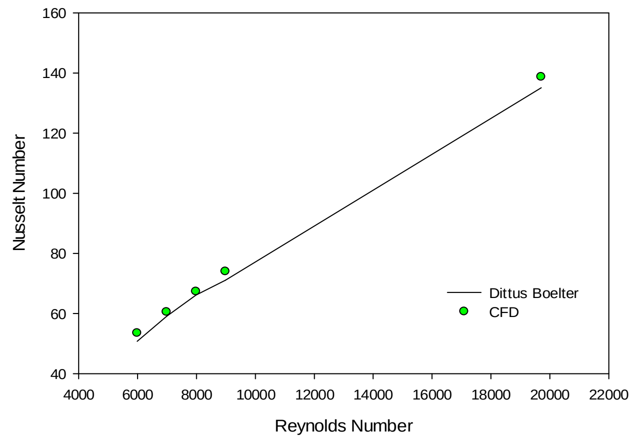


Fig 2.8 Pressure distribution in a tube with twisted tape H/D=5 and 0.3% nanofluid

D. Validation

The simulation was done using the CFD software. The Nusselt number estimated from CFD was compared with expression developed by DittusBoelter and is shown in Fig. 2.9. The results were found to be in close agreement with DittusBoelter. The developed model was further used to analyze the influence of nanofluid for different volume concentration on forced convection heat transfer. Fig 2.9Validation of CFD mode



III. RESULTS AND DISCUSSION

The analysis is further extended for nanofluids of two different volume concentrations; the analysis is presented in Fig 6.1. It is found that the presence of nanoparticle in the base fluid contributes to improvement of heat transfer and the trend as observed in Fig 6.1. The Reynolds number is found in the range of 6000<Re<20000. The Nusselt number is found to exist in the range of 50<Nu<160. This shows that as the volume concentration of nanoparticle increases in the base fluid Nusselt number is found to increase.

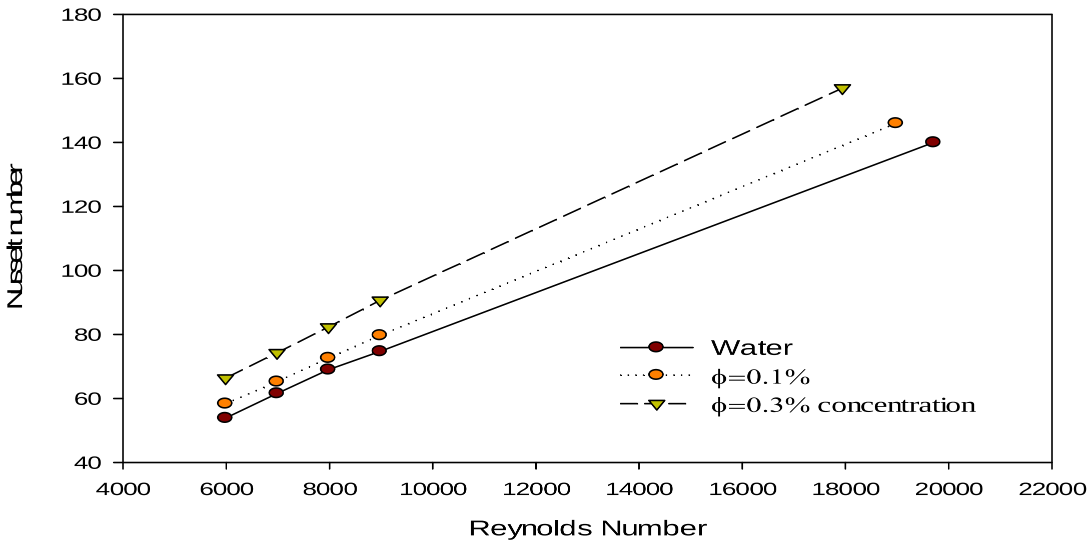


Fig 3.1 Variation of Nusselt number in a plain tube with various concentrations of nanofluid

The developed model was analyzed with flow path modification along the inner tube with twisted tapes of different H/D ratios. Three different H/D ratios were selected for the study namely (5, 10 and 15). The combined influence of nanoparticle in the base fluid with twisted tapes on heat transfer is presented in subsequent Figs 3.1 and 3.2. With the application of twisted tapes there is an enhancement in heat transfer. The Nusselt number increases with the decrease in twist ratio. The inserts in the test section contributes to early transition in flow along the test section incrementing turbulence and Nusselt number. Nusselt number is found to be higher for H/D=5 and lower for H/D=15. The variation of Nusselt number for the various twist ratios at the corresponding Reynolds numbers are shown in Fig. 3.2. Nusselt number is found to increase with the increase in the volume concentration of nanoparticle in the base fluid. It is found that the thermo-physical .of the nanofluid contributes to a larger extent in improving the rate of heat transfer with introduction of nanoparticles in the base fluid.

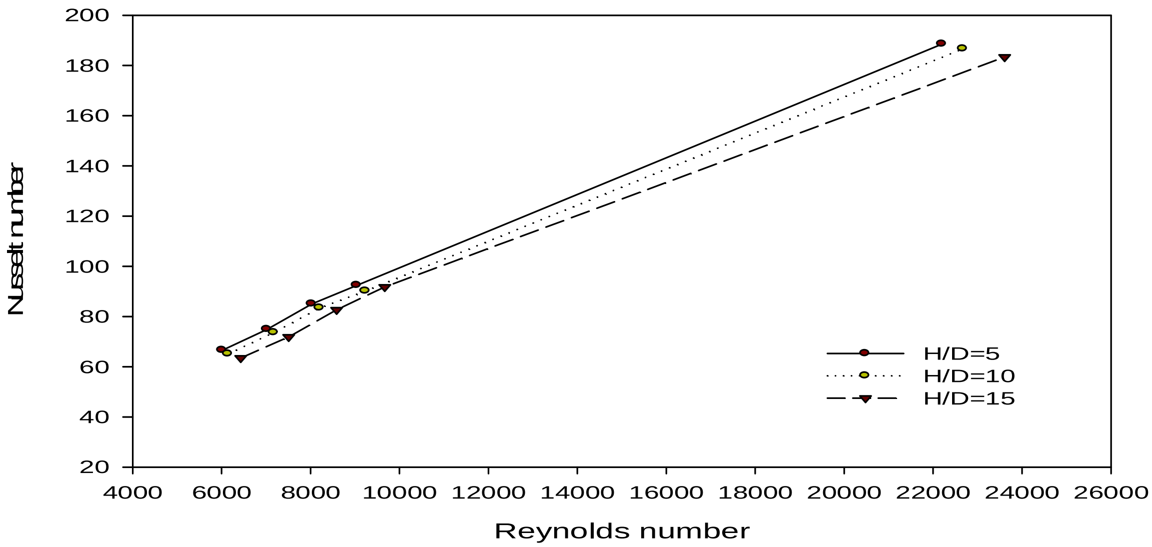


Fig 3.2 Comparison of Nusselt number for various H/D ratios at 0.1% CNT-Fe_3O_4

A. *Influence of Concentration*

The combined influence of twisted tape with 0.1% volume concentration of CNT-Fe_3O_4 nanofluid is shown in Fig. 3.2. It is found that there is a significant improvement in Reynolds number consequently an increment in Nusselt number by virtue of presence of twisted tapes and nanofluid flowing through the test section. The Reynolds number is found to be in the range of 6000<Re<24000 with Nusselt number in the range of 60<Nu<190 with an average increment of 21.36%. Literature reveals that swirl flow generated in the presence of twisted tape enhances heat transfer coefficient. It is further reported that with decrease in H/D ratio, the wall shear resistance is found to be higher at the wall with maximum dissipation of energy leading to lower local velocities in flow.

The Nusselt number is found to be higher for H/D=5 with 0.1% volume concentration of nanofluid and lower for the twisted tape of H/D=15 with base fluid. The average enhancement of Nusselt number for H/D=5 with 0.3% volume concentration of nanofluid is found to be 26.2% as compared to the base fluid.

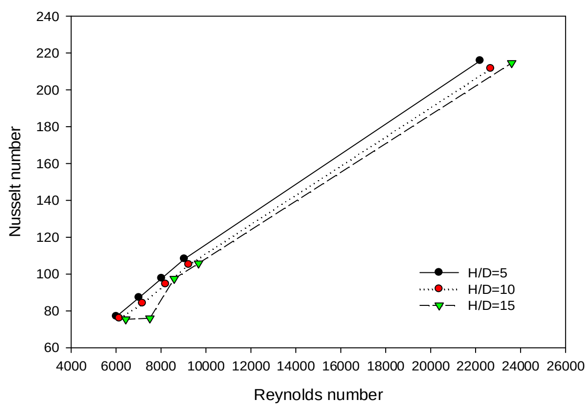


Fig 3.3 Comparison ofNusselt number for various H/D ratios at 0.3% CNT-Fe_3O_4 concentration

The variation of Nusselt number with different H/D ratios at 0.3% volume concentration of CNT-Fe_3O_4 nanofluid is shown in Fig. 3.3. The average enhancement of Nusselt number for H/D=5and for 0.3% concentration of nanofluid is 32.3%, as compared to the base fluid in a plain tube.

B. *Influence of Friction Factor*

The friction factor varies with change in the volume concentration of nanofluid and with the inserts of twisted tapes of various H/D

Volume 5 Issue IV, April 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

ratios.

The influence of friction factor on Reynolds number is shown in Fig 3.4 for different H/D ratios of twisted tapes used in the test section. The friction factor is found to increase with decreasing H/D ratio for Reynolds number in the range of 6000<Re<24000.

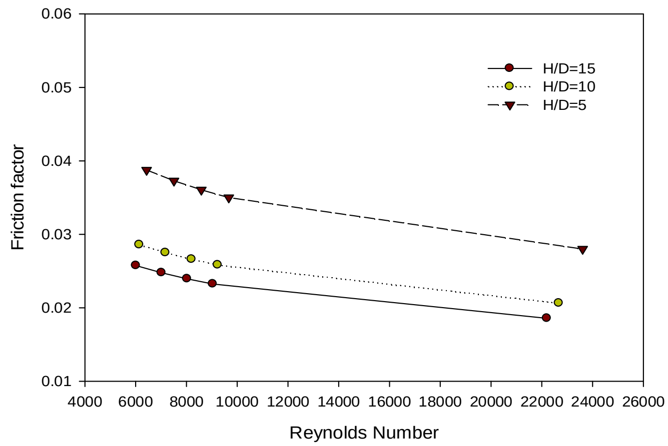


Fig 3.4 Comparison of friction factor for different H/D ratios at 0.1% CNT-Fe_3O_4 concentration

The influence of friction factor with addition of nanoparticle to the base fluid is found to follow thesame trend as observed in Fig 3.4. The friction factor is found to exist in the range of 0.01< f <0.04 and with 1.9 times increment over water in plain tube.

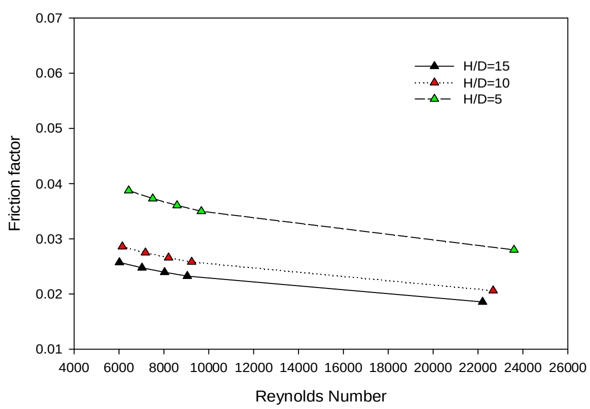


Fig 3.5 Comparison of assumption factor for different H/D ratios at 0.3% CNT-Fe_3O_4concentration

The friction factor was 1.14 times the value of the base fluid in plain tube for the twisted tape insert of H/D ratio 15 with the 0.3% concentration of nanofluid at Reynolds number of 6000.

The friction factor increased with the decrease in twist ratio. It is for twisted tape insert of H/D=5 when compared with the twisted tape insert of H/D=15. The friction factor also increases with the increase in the Reynolds number. The variation of friction factor for various twist ratios and different Reynolds numbers at 0.3% concentration of CNT-Fe_3O_4nanofluid is shown in fig 3.5.

C. Formulation of New Regression Equation

The influence of twisted tape and presence of CNT-Fe_3O_4 nanoparticles contributes to enhancement of Nusselt number. A general regression equation is formulated to estimate Nusselt number with 45 data points using FORCE program with an average deviation of 1.29% and standard deviation of 2.23% is furnished below.

$$Nu = 0.032(Re)^{0.8}(Pr)^{0.3069}\left(1+\frac{H}{D}\right)^{0.0317}(1+\Phi)^{0.6202}.$$

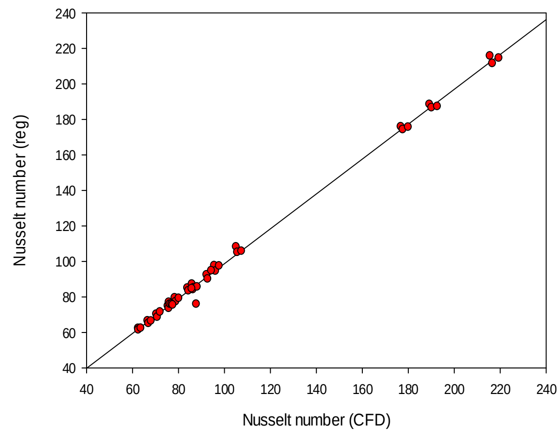


Fig 3.6 CFD vs Regression Nusselt number values

The formulated regression equation data is used in Fig 3.6 to plot a graph with Nusselt number as obtained from CFD analysis.

IV. CONCLUSIONS

A. The thermal conductivity is found to be increasing with increase in volume concentration of CNT-Fe_3O_4nano particle in water. The thermal conductivity is found to increase by 10.6% for 0.1% volume concentration and 12.2% for 0.3% volume concentration.

B. The dynamic viscosity is found to be increasing with increase in volume concentration of CNT-Fe_3O_4nano particle in water. The dynamic viscosity is found to increase by 13.19% for 0.1% volume concentration and 21.79% for 0.3% volume concentration.

C. The friction factor for 0.3% volume concentration of nanofluid and twisted tape insert of H/D=15 is 1.14 times the water in plain tube.

D. The value of the friction factor for 0.3% volume concentration of nanofluid and twisted tape insert of H/D=5 is 1.19 times the water in plain tube.

E. The rate of heat transfer is found to increase with the decrease in H/D ratio of twisted tapes. The rate of heat transfer is found to be 15.9% higher for H/D = 5.0 and 14.84% for H/D =10.0 and 14.434% higher for H/D = 15.0 with water as the working fluid.

F. With introduction of nanoparticles, the Nusselt number is found to increase significantly with combined effect of twisted tape in the test section. The Nusselt number is found to be 21.48% higher for H/D=5.0 with 0.1% volume concentration. The Nusselt number is found to be 20.44% higher for H/D=10.0 with 0.1% volume concentration. The Nusselt number is found to be 20.05% higher for H/D=15.0 with 0.1% volume concentration. In future, research can be extended using various nanofluids and with different volume concentrations of nanofluids. The present analysis is based on the twisted tape inserts with CNT-Fe_3O_4 hybrid nanoparticle. There are other augmentation techniques available in literature which can be used to study their influence on heat transfer.

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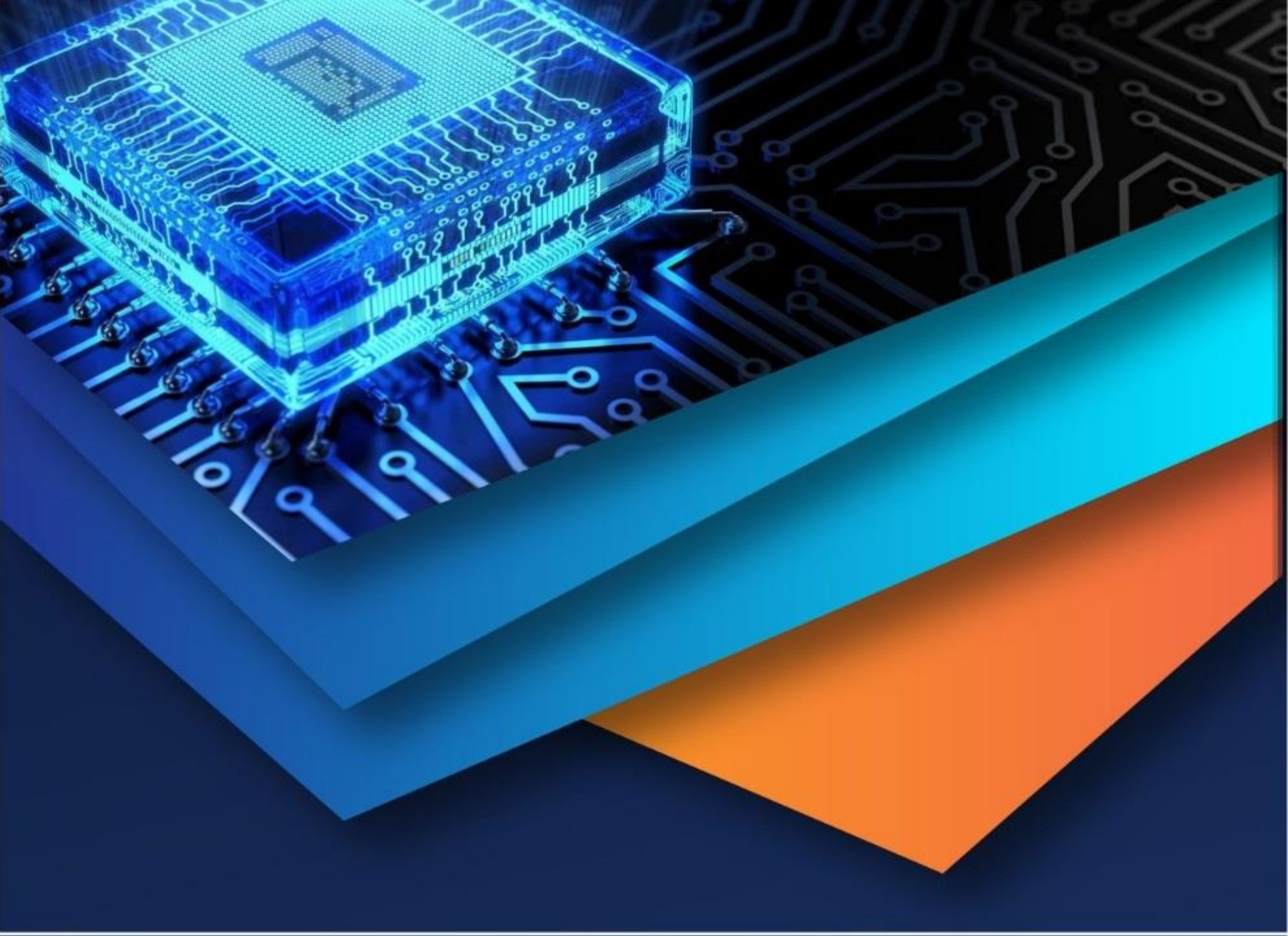

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