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Analysis and Optimization of Spiral Plate Heat Exchanger using Computational Fluid Dynamics

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Abstract: Heat exchanger is the mostly used device all over the world for heat recovery and heat removal. Many types of heat exchangers are there according to various applications, commonly use heat exchanger is shell and tube heat exchanger, but they are more likely prone to fouling and cannot handle highly viscous fluids efficiently. The Spiral plate heat exchangers are the circular compact structures made by rolling two long metal plates around a central core to form two concentric flow passages one for each fluid, so they are less prone to fouling and can handle highly viscous fluids efficiently. Present work shows the CFD analysis of spiral plate heat exchanger to optimize the number of turns for given width. Analysis is done on three different models with 5, 6 and 7 number of turns, pure water and Al_2O_3 nanofluid (1%by vol) is taken as working medium in two different cases. Nusselt number and overall heat transfer coefficient are investigated numerically.
Keywords: Spiral plate heat exchanger, SPHE, Heat exchanger, Numerical modelling

I. INTRODUCTION

The most important part of a thermal system is the heat exchanger that is device used for the transferring of thermal energy from one media to another in any physical state without intermixing of the fluids, actually there is enthalpy exchange in both the fluids. Heat exchanger is the mostly used device in industries these are the tools providing the possibilities for heat transfer between two or more fluids heat transfer can be done in arrangements of liquid-liquid, liquid-gas, gas-gas. Heat exchanger are used in wide verity of applications such as in power plant, refineries, petrochemical, industrial, food and drugs industries. Common examples of heat exchangers are plate type, shell and tube type, these heat exchanger causes high pressure drop they have very low heat transfer coefficient occupy more space and are very costly. The heat exchangers exist in the boilers, condensers and radiators, the classification of heat exchanger is based on the transfer of heat, heat transfer coefficient, pressure drop, baffles and fouling are responsible for the efficiency of the heat exchanger. The material which is depositing on the inner sides of the tube is responsible for the formation of fouling, the fouling rate can be reduced by pre- treatment of fluid (water). the appropriate cleaning of the heat exchanger can lessen the effect of fouling.

One of the most promising and important type of heat exchanger is spiral plate heat exchanger these are the circular units which are made by rolling two long circular plate around a central core in order to form a two long circular concentric flow passages.

These heat exchangers are convenient compressed and have very good performance. They can easily prevent fouling due to its specific spiral geometry, which continuously alter the flow direction, thus intensifying local turbulence and reducing fluid stagnant zone. the demand for high heat-transfer performance is increasing day by day, and wide investigations have been led on the heat transfer enhancement of spiral-plate heat exchangers; some methods are proposed to improve heat transfer include by changing the geometry of the heat exchanger and by using different types of working fluids. Spiral plate heat exchangers do not suffer from fouling and clogging these heat exchangers are circular unit containing two spiral flow channels one for each fluid the different media flow counter currently in these channels without risk of intermixing one fluid enters the centre of the unit and flows towards the periphery and move towards the centre its single flow passage induced high shear rates that scrub away deposits as they form. The self-cleaning effect reduces fouling and makes spiral heat exchanger and ideal for handling tough fluids such as process slurries, sludge and media with suspended solid or fibres from application point of view spiral heat exchanger is an optimum solution for various reasons such as less space requirement, compact designed, no choking of threats. Among different type of heat exchanger that are used for cooling and heating the fluids in industries. Among different type of heat exchanger that are used for puling and heating the fluids in industries spiral heat exchanger has special place it consists of two sheets that are rolled around the central rod and therefore two separated constrict channels are made. The ends of the channel are sealed through welding.

II. LITERATURE REVIEW

Dongwu 2003 [1] In their studies they work on the project that is related to the spiral plate heat exchanger they read the geometrical calculations for semi-spiral in spiral plate heat exchanger they divided the spiral path into two semicircles by partitioning the spirals they gave many calculations in various parameters and relates the number of turns with the other dimensions as per the width of the metal plate what should be the minimum numbers of turns.

Rangasamy et. al. [2] They experimentally and numerically investigated the heat-transfer performance of a spiral-plate heat exchanger over a wide range of operating conditions. The results showed that the heat-transfer coefficient increased with increased flow rate but decreased with increased spiral length and plate spacing. They studied heat transfer analysis on spiral plate heat exchanger in which they investigated the heat transfer coefficient, they constructed and tested a model which had plate of width 0.315m, thickness of plate 1mm and mean hydraulic diameter is 10mm besides they proposed new correlations for the calculation of Nusselt number

Shree Satya saya et. al. [5] Analysed heat transfer in spiral plate heat exchanger using experimental and computational fluid dynamics. their analysis had been carried out in both parallel and counter flow arrangement after more and more analysis and experimentations they concluded that heat transfer rate is obtained in case of parallel inward flow conditions was higher, they also observed from the analysis that for particular range of Reynolds number the heat transfer rate almost become stagnant they also suggested that the heat transfer rate in spiral plate exchanger is enhanced by cascading the heat exchanger by doing so heat transfer rate can be increased by 26.25% in single stage that means increasing the number of stages in spiral plate heat exchanger heat transfer rate increases.

Manoj V. et al. [4] In their studies they investigated heat transfer enhancement by using nanofluid in spiral plate heat exchanger nano particles in conventional fluid called nanofluid have been the subject of interesting study in the research field since the discovery of the anomalous thermal behaviour of these fluids. Their study they used aluminium oxide water as nanofluid and they compare those result obtained by using nanofluid with that of conventional fluid also they used numerical analysis by considering without Brownian motion and with Brownian motion. They designed fabricate and tested the spiral plate heat exchanger studied heat transfer coefficient for water for different mass flow rate using physical model also enhancing the heat transfer rate by using nanofluid for different mass flow rate finally they compared heat transfer coefficient of conventional fluid and nanofluid.

Venkateswara Rao et al.[7] They investigated thermal design of spiral plate heat exchanger through numerical modelling they explained numerical modelling approach and investigated the temperature variations along the heat exchanger they also studied heat transfer rate and finally they concluded that numerical approach is cost effective to choose the ideal fluid system or spiral plate heat exchanger they observed the length of spiral plate finds good agreement with that of geometrically considered length with an error of 2.5%.

Sufyan Memon et. al. [9] They design and tested spiral plate heat exchanger for textile industry they perform the experiment by keeping the mass flow rate of hot fluid and cold fluid constant that was 3000kg/hr. and varying the inlet temperature of hot fluid from 42°C to 82°C and corresponding outlet temperature of hot fluid and inlet and outlet temperature of cold fluid was noted down. They found that when the mass flow rate of hot fluid was 3024kg/hr. and cold fluid was 3000kg/hr. the overall heat transfer coefficient obtained was 558w\m^{2}k even when the mass flow rate of hot and cold fluid was increased above 3000 kg/hr. the overall heat transfer coefficient remains constant as the heat exchanger were design for mass flow rate capacity 3000kg/hr.

S. Sathiyan et.al. [10] : They proposed a new correlation for heat transfer to immiscible liquid-liquid mixture in spiral plate heat exchanger their study were carried out in spiral heat exchanger for the water-octane, water-Kerosene and water-dodecane system by varying the mass flow rate of cold fluid by keeping the hot fluid and fluid inlet temperature constant they observe that heat transfer coefficient of the two phase liquid is strongly dependent on the composition of liquid mixture they also developed new correlations using experimental data with composition of cold fluid as an explicit variable those correlation are used in designing compact heat exchanger for handling two phase water organic mixtures regression analysis was perform and as the resultant correlations faithfully reproduce the variations observed in the experiment predicting the experimental heat transfer behaviour within +- 1.5%.

Sara Rostami, [13] They Studied the effect of different channel spacings in SPHE filled with cu-zno-co water Hybrid nano-fluid to find optimum thermal-hydraulic performance They analysed effect of different flow velocities namo particles and channel spacing values and they presented results on Nusselt No outlet temp, pressure drop. They observed that an increase in inlet flow velocities leads to lower heat transfer rate between cold and hot channels They concluded that reducing channel spacing is more effective than volume fraction increases on outlet temperature improvement at the expense of pressure drop channel spacing values more than 5 mm pressure drop has not increases significantly.

Emerson et.al. [11] In their study they present an optimization of SPHE by using wind driven optimization the variables used for the optimization are spacing channels for hot and cold streams width length and thickness of the heat exchanger. They presented two case studies in which maximization of overall heat transfer coefficient and minimization of cost were implemented. For the cost the reduction was about 4 46 and 23%. were obtained proposed technique showed better results in all the simulation. In some cases, with GA the Statistic distribution inserted for self-adaptation of the evolution para meters showed satisfactory results.

III.GEOMETRICAL MODELLING

A. Geometrical Specifications

Fig.1 shows the CAD model of spiral plate heat exchanger modelled in CATIA V5 the heat exchanger under study is investigated as counter current arrangement and the detailed geometrical specifications are shown in table no. I

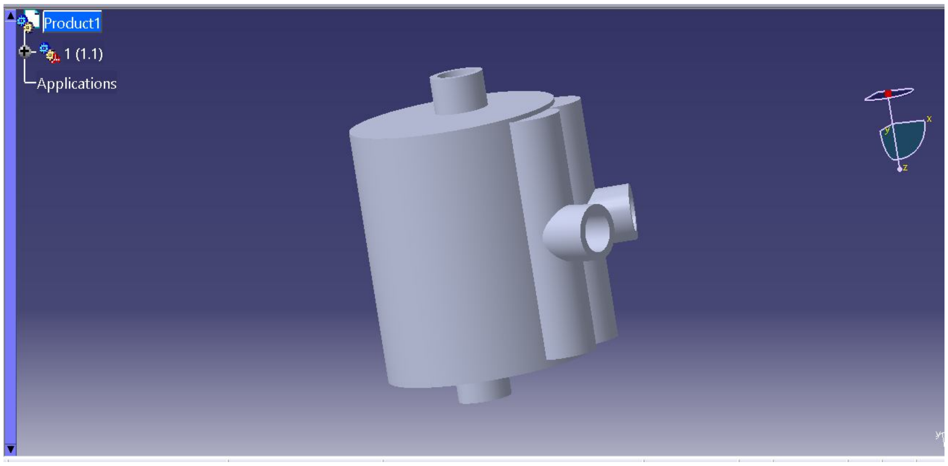


Fig. 1 CAD model of spiral plate heat exchanger

Table I Geometrical specification

Specifications	Value
Core Diameter	170 mm
Plate Width	300 mm
Channel Spacing	4 mm
Material	Stainless Steel

B. Thermal Analysis of Spiral Plate Heat Exchanger

The total heat transfer area of spiral plate heat exchanger can be calculated as

$$A_s=2BL$$

Heat transfer from hot side can be calculated as,

$$Q = m_h c_h(T_{hi}-T_{ho})$$

Heat transfer from cold side can be calculated as,

$$Q = m_c c_c(T_{co}-T_{ci})$$

The overall heat transfer coefficient can be calculated as,

$$\frac{1}{U}=\frac{1}{h_c}+\frac{1}{h_h}+\frac{l}{K_s}$$

Nusselt number can be calculated as,

$$N_u=\frac{hDe}{K}$$

IV. NUMERICAL MODELLING

Spiral plate heat exchanger used in the present work is studied as counter current arrangement and the numerical solution of the SPHE is described in detailed with following steps,

1) *Step1:* Fig. 2 illustrate the fluid domain of spiral plate heat exchanger created in CATIA stainless steel Is taken as the material. CFD software 16.0 is used for the prediction of pressure and temperature variations, the inlet temperatures of hot and cold fluid are kept constant and the outlet temperatures are calculated by software, also mass flow rate of hot fluid is kept constant and for cold fluid it is varied between 0.3-0.9 for the interval of 0.2 kg/s. A data of temperature and heat transfer coefficient at various points along the length of the spiral plate heat exchanger are recorded.

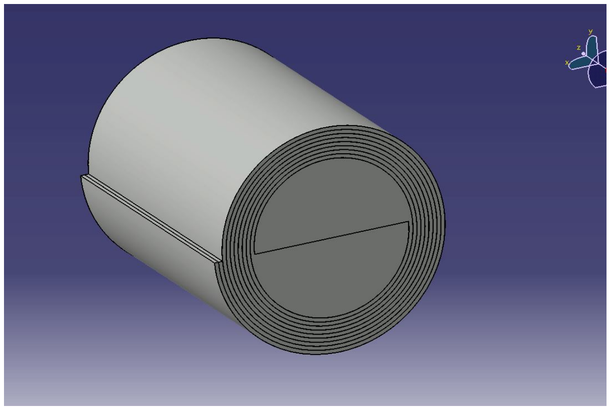


Fig. 2 Fluid domain of spiral plate heat exchanger

2) *Step 2:* Meshing is used to divide geometric structure into finite number of elements a greater number of elements ensures higher accuracy uniform course tetrahedral mesh is used with size 4mm in all three geometries. 3D mesh CFD model for 5 number of turns is shown in fig 3. The detailed mesh metrics for all three models is shown in table no. II

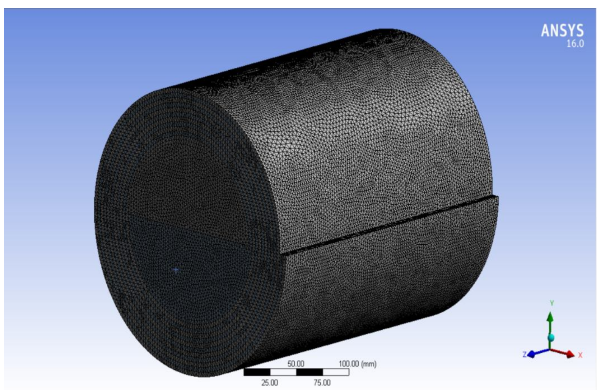


Fig. 3 Mesh CFD model for 5 turn

Table II Mesh metrics

Parameters	5 Turn	6 Turn	7 Turn
Nodes	102774	120569	132316
Elements	347768	395579	425916
Quality of element	0.89998	0.89165	0.87811
Orthogonal quality	0.82931	0.81779	0.79946
Skewness	0.27004	0.28165	0.29999

3) *Step 3:* For any CFD analysis it is very critical to specify realistic boundary conditions at both inlets of SPHE uniform temperature and at the outlets atmospheric pressure condition is applied also adiabatic and no slip condition for wall is considered since the flow is turbulent K-ϵ model is used.
4) *Step 4:* In first case simulation is performed using water as both hot and cold medium by keeping mass flow rate of hot fluid is constant and by varying mass flow rate of cold fluid same way in second case Al_2O_3 is used as cold medium and water as hot medium. Inlet temperature of hot fluid is 343K and for cold fluid 303K is taken. The performance characteristics of spiral plate heat exchanger can be assessed by solving following equations,

Conservation of mass:

$$\nabla\cdot(\rho v) = 0$$

Momentum conservation:

$$\nabla\cdot(\rho v v) = -\nabla P + \nabla\cdot(\mu\nabla v)$$

Conservation of energy:

$$\nabla\cdot(\rho v c p T) = \nabla\cdot(k\nabla T)$$

V. RESULTS AND DISCUSSION

In this study three models of spiral plate heat exchanger with 5, 6 and 7 number of turns are investigated in order to optimize number of turns, Nusselt number and overall heat transfer coefficient has also been investigated for each case. in first case pure water is used as both hot and cold medium whereas in second case Al_2O_3 Nanofluid is used. In both the cases mass flow rate of hot fluid is kept constant, inlet temperature for hot fluid is 343K and inlet temperature of cold fluid is 303K is taken. Variations in Nusselt number and Overall heat transfer coefficient with Reynold number for different values of mass flow rate is illustrated in fig. 4 and 5 respectively. From fig. 4 and 5 it is observed that overall heat transfer coefficient and Nusselt number keep on increasing with Reynolds number for different values of mass flow rate but these values are nearly same for 5 and 7 number of turns models however significant change from the very beginning even for lower Reynolds number can be seen for 6 number of turns model there is 23.9% increment in overall heat transfer coefficient and 10.8% increment in Nusselt number.

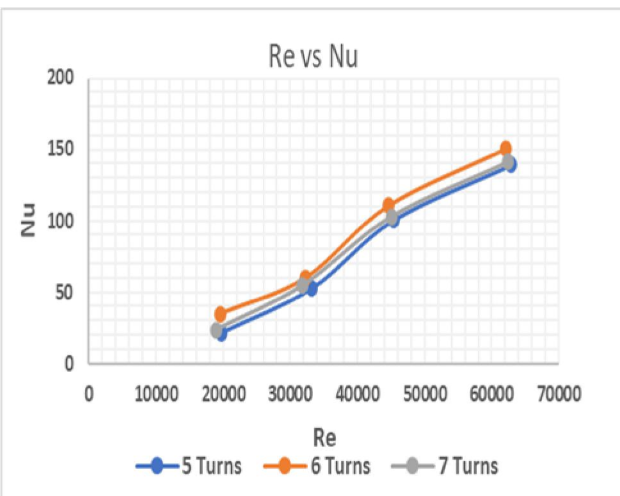


Fig. 4 Reynold no. vs Nusselt no. for pure water

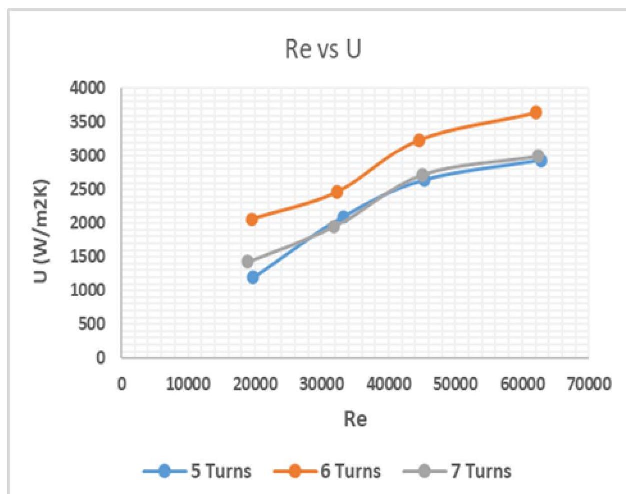


Fig. 5 Reynold no. vs Overall heat transfer coefficient for pure water

Similarly, variations in Nusselt number and overall heat transfer coefficient with Reynolds number for Al_2O_3 nanofluid is shown in fig. 6 and 7 respectively. From fig. 6 and 7 it is observed that overall heat transfer coefficient and Nu number is significantly high for 6 number of turns model compare to 5 and 7 number of turns there is 31.2% increment in overall heat transfer coefficient and 30.38% increment in Nusselt number. Overall heat transfer coefficient and Nusselt number values are much more for 6 number of turns model when compared with pure water as working medium.

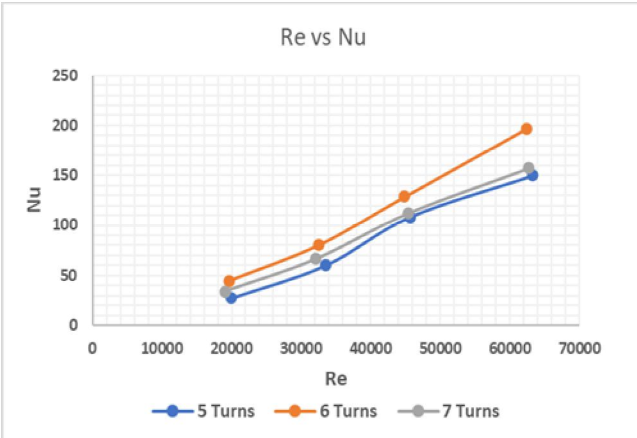


Fig. 6 Reynolds no. vs Nusselt no. for Al_2O_3

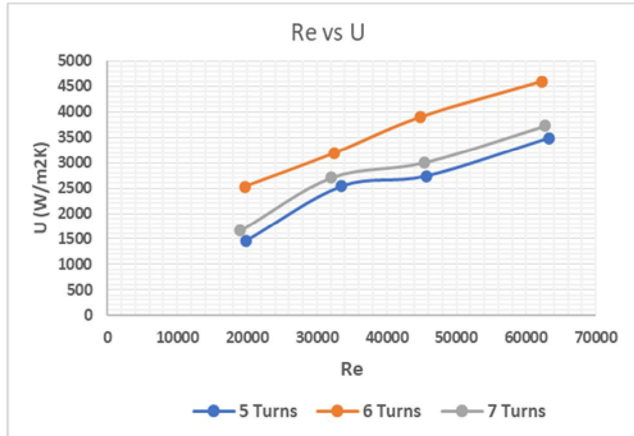


Fig. 7 Reynolds no. vs Overall heat transfer coefficient Al_2O_3

Fig 8A-C shows the final temperature contours for pure water as both hot and cold fluid with 0.5 kg/s mass flow rate for both hot and cold medium. From fig 8A-C it clearly seen that rate of heat transfer is more with 6 number of turns model, inlet temperature of hot fluid is 343K and for cold fluid is 303K is taken.

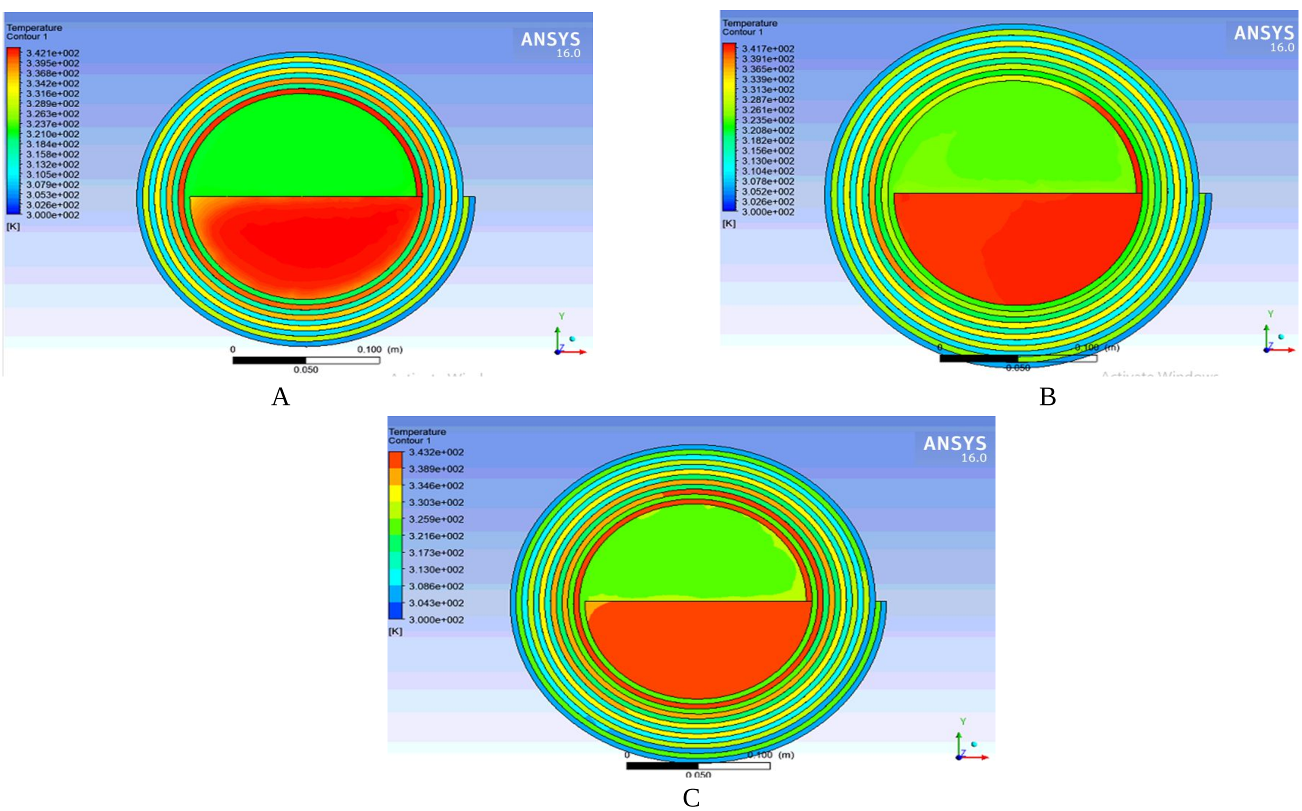
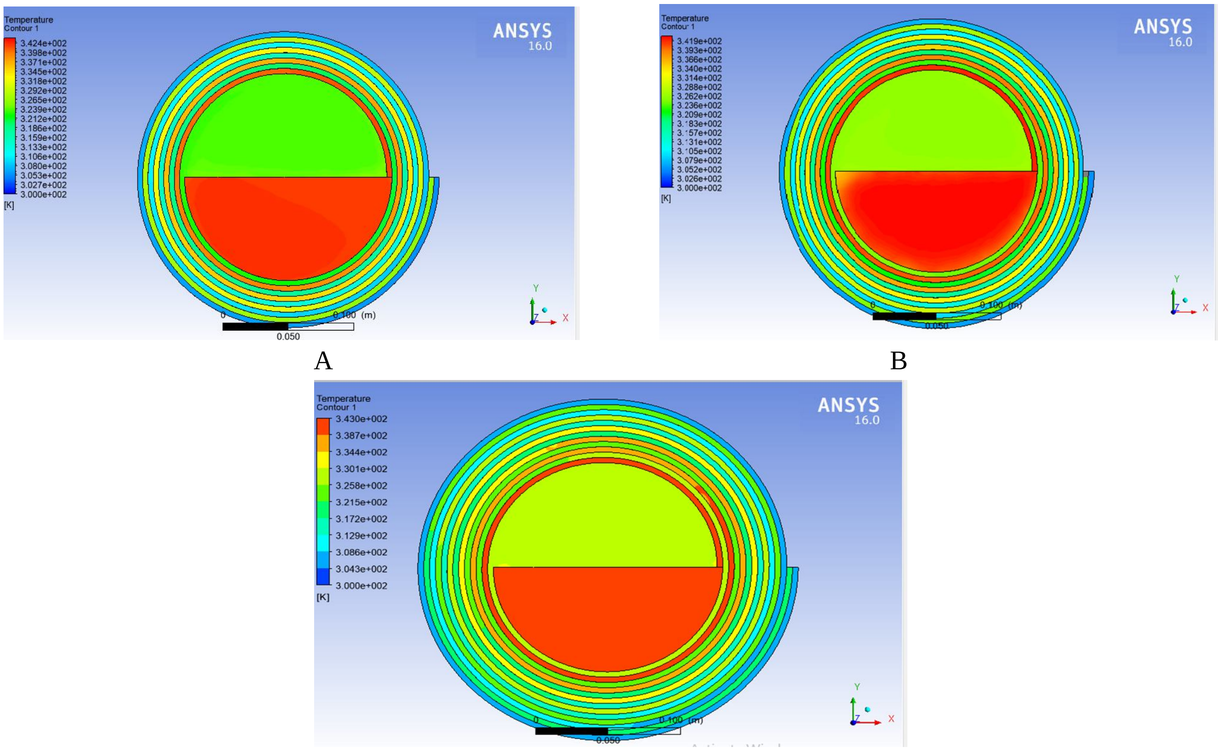


Fig. 8 Temperature contours of spiral plate heat exchanger for pure water A,5 Turns; B, 6 Turns; C, 7 Turns

Fig 9A-C shows the final temperature contours for Al_2O_3 (1% by vol.) as cold medium with 303K temperature and the pure water as hot medium with 343K temperature. From fig. 9A-C it is clearly seen that heat transfer rate is more with nanofluid as compared to pure water, the main reason is nanofluids exhibits high effective thermal conductivity and higher heat transfer rates.



A B C

Fig. 9 Temperature contours of spiral plate heat exchanger for Al_2O_3 A, 5 Turns; B, 6 Turns; C, 7 Turns

VI. CONCLUSIONS

In the present work overall heat transfer coefficient and Nusselt number have been investigated for three different models having 5,6 and 7 number of turns and also two different working mediums are used. In first case pure water is used as both hot and cold medium whereas in second case hot medium is water and cold medium as Al_2O_3 nanofluid is taken, following conclusions have been drawn from this numerical analysis

1) Among 5,6 and 7 number of turns models, model with 6 number of turns showed very good thermal performance.
2) As the number of turns are increased from 5 to 6 overall heat transfer coefficient increased by 23.9% and the Nusselt number increased by 10.8%, when water is used as working medium, on further increment in turns overall heat transfer coefficient and Nusselt number keep on decreasing.
3) In case of nanofluid Al_2O_3 (1% by vol.) concentration overall heat transfer coefficient and Nusselt number for 6 number of turns increased by 31.2% and 30.38% respectively.
4) Al_2O_3 nanofluid exhibits better thermal performance as compared to pure water this is because nanofluids exhibits high effective thermal conductivity and higher heat transfer rates.
5) On comparing the enhancement in parameters in case of pure water and Al_2O_3 nanofluid for 6 number of turn model there is 26.2% in overall heat transfer coefficient and 30.57% in Nusselt number is noted.
6) Numerically obtained values of overall heat transfer coefficient and Nusselt number are compared with experimental data from the literature which shows reasonable fit.

A. Nomenclature

A_s surface area for heat transfer (m^2)
B channel plate width (m)
D_e equivalent diameter of heat exchanger
h_h convective coefficient for heat transfer for hot fluid (W/m^2K)
h_c convective coefficient for heat transfer for cold fluid (W/m^2K)
k thermal conductivity ($W/m\ K$)
ks thermal conductivity of steel ($W/m\ K$)

L	flow length of the spiral plate (m)
m_h	mass flow rate of hot fluid (kg/s)
m_c	mass flow rate of cold fluid (kg/s)
Nu	Nusselt number
Q	rate of heat loss (W)
Re	Reynolds number
T	temperature (K)
t	thickness of channel plate (m)
U	overall heat transfer coefficient (W/m^2K)

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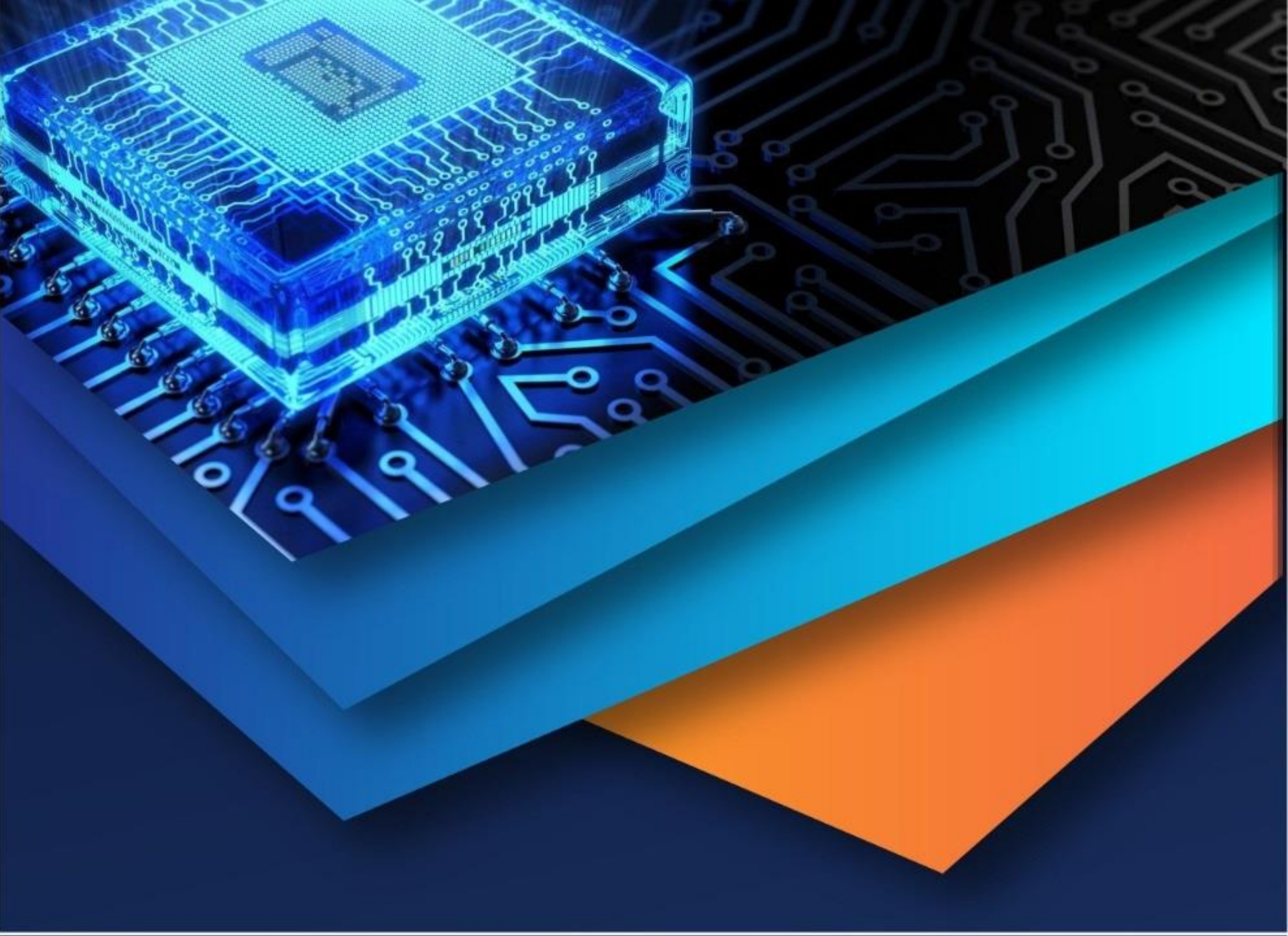

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