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Design and mathematical analysis of a concentric Triple Tube Heat Exchanger for better heat transfer

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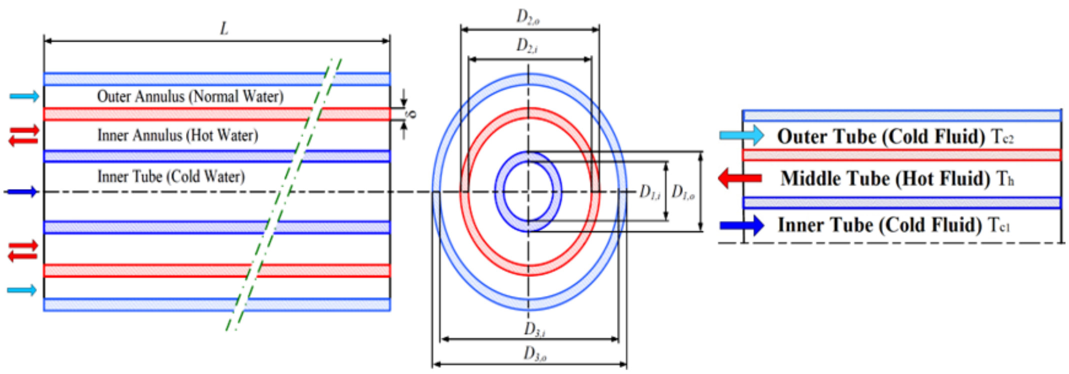
ABSTRACT



In the present work, mathematical analyses have been performed for different designs of a concentric triple tube heat exchanger for the enhancement of thermal performance. The main objective of the present work is to perform mathematical analysis of triple concentric tube heat exchanger has to be designed for the various conditions using graphene nanoplatelets–platinum nano-fluid. Concentric triple tube heat exchanger used without baffle, straight baffle and inclined baffles with the inclination angle of 45°, 60° and 75°. For this analysis of concentric triple tube heat exchanger are divided into three different domains such as two cold fluids in the inner and outer tube and one hot fluid in the middle tube at different nano-fluid concentration including 0.0, 0.02, 0.06 & 0.1%. Results show that triple tube heat exchanger with inclined baffle at 75° gives maximum outlet temperature for nano-fluid of 20.77 °K for ø = 0.1which is 21.71% greater than without baffle, 33.56 % greater than straight baffles and 20.58% greater than baffles inclined at 60°. The heat transfer rate of 17.98% higher than without baffle, 27.79% higher than straight baffle and 17.04% higher than baffles inclined at 60°, while the maximum overall heat transfer coefficient of 0.9832 for ø = 0.1 have been observed. Hence concentric triple tube heat exchanger with inclined ribs at 75° recommended for better heat transfer.

Keywords: Triple tube heat exchanger, Thermal performance, Nano-fluid, Concentration ratio, heat transfer rate.

INTRODUCTION

Triple tube heat exchanger consists mainly three sections which are inner tube, inner annulus and outer annulus. It is required to flow the objective fluid whose temperature differences is of main concern for application fulfillment in the inner annulus for taking maximum benefit of the heat exchanger. The other two compartments which are inner tube and outer annulus have to be filled with appropriate temperature fluid as per the application requirement. The inner annulus has two heat exchange surfaces (inner tube outer surface and outer tube inner surface) which increases the heat exchange area of heat exchanger marginally compared to double tube heat exchanger (has only one heat exchange surface) subsequently increases the rate of heat exchange. It also in terms increases the efficiency of heat exchanger. Therefore, it also decreases the length of heat exchanger for the same temperature difference compared to double tube heat exchanger.

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WORKING PRINCIPLE OF TRIPLE CONCENTRIC TUBE HEAT EXCHANGER

A schematic diagram of the triple concentric-tube heat exchanger configuration is shown in figure 1. Three fluids being considered which are chilled water in the inner tube, hot water in the inner annulus, and normal tap water in the outer annulus of the heat exchanger.

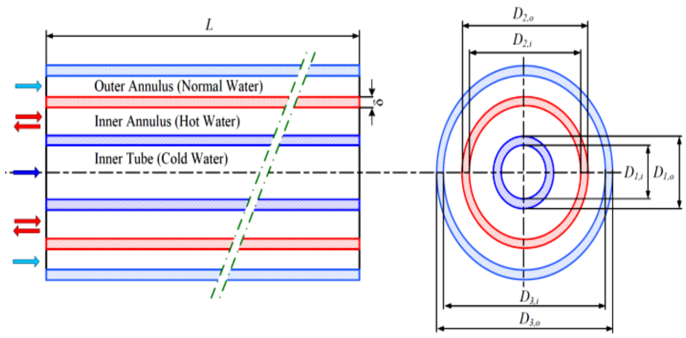

Figure 1. Schematic diagram of the triple concentric-tube heat exchanger

Possible flow patterns on triple concentric tube heat exchanger

Possible four flow arrangements as shown in figure 2 where Position A to D of the three fluids inside the triple tube heat exchanger including the counter-current, co-current, counter-current with co-current and co-current with counter-current flow.

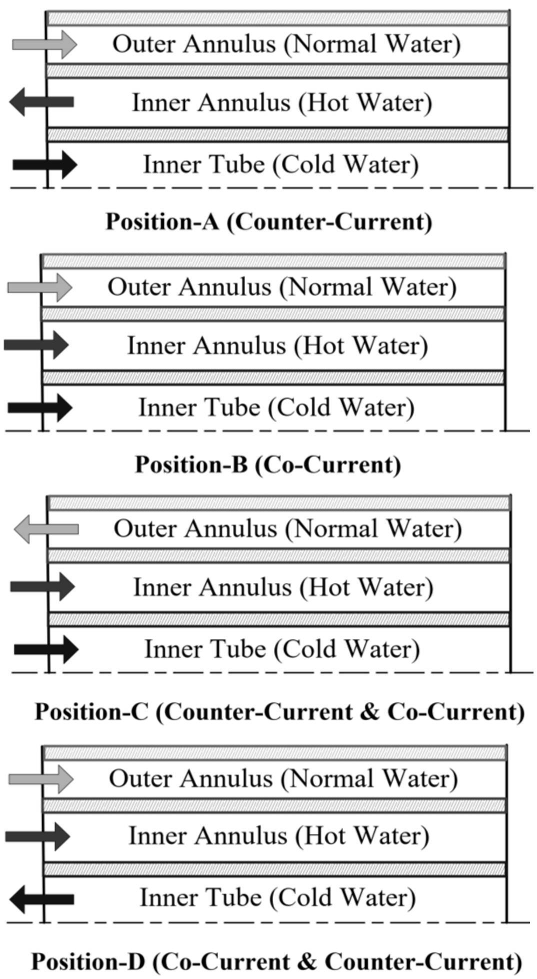

Figure 2. Possible flow patterns on the triple tube heat exchanger; A (Counter-current), B (Co-current), C (Counter-Current & Co-current) & D (Co-Current & Counter-Current)

The heat transfer surface area associated is more with intermediate temperature water side than the same with chilled water side leading to better heat transfer rate. It can be seen from the figure that the effectiveness decreases with the increase of Reynolds number for all flow pattern arrangements. The highest values of the effectiveness is obtained for position (A) followed by position (D) followed by position (C) while the position (B) has the lowest effectiveness values.

The main objective of the present work is to perform mathematical analysis of triple concentric tube heat exchanger has to be designed for the various conditions using graphene nanoplatelets–platinum nano-fluid.

Literature review

Experimental investigation on triple concentric tube heat exchanger.[1] A numerical investigation on Effects of water-aluminum oxide nanofluid on double pipe heat exchanger.[2] A two-phase analysis on performance enhancement of a triple-tube heat exchanger through heat transfer intensification using novel crimped-spiral ribs and nanofluid.[3] Thermal characterisation on the thermal performance of triple tube heat exchanger equipped with different inserts with WO3/water nanofluid.[4] Performance and exergy analysis of different perforated rib designs of triple tubes heat exchanger employing hybrid nanofluids.[5] Performance enhancement of PCM latent heat thermal energy storage system utilizing a modified webbed tube heat exchanger.[6] Experimental study of a triple spirally coiled tube heat exchanger thermofluid characteristics.[7] Evaluation of cooling efficiency improvement of the simple office for small factories using heat dissipation with cold water circulation.[8] Work on charging/discharging mechanism of Wavy channels triple-tube LHS unit.[9] Experimental study on the flow and heat transfer characteristics of nanofluids in double-tube heat exchangers based on thermal efficiency assessment.[10] Investigate Optimal diameters of triple concentric-tube heat exchangers.[11] Work on Factorial experimental design for the thermal performance of a double pipe heat exchanger using Al2O3-TiO2 hybrid nanofluid.[12] Work on Enhancement of cooling characteristics and optimization of a triple concentric-tube heat exchanger with inserted ribs.[13] Establish Simple heat transfer correlations for turbulent tube flow.[14] Work on Thermal performance of a counter-current double pipe heat exchanger working with COOH-CNT/water nanofluids.[15] Case study, on Prediction of the outlet temperatures in triple concentric—tube heat exchangers in laminar flow regime.[16] Numerical study due to mixed convection nanofluid flow with the effect of velocity slip and thermal conductivity across curved stretching surface.[17] A study on the characteristics of Cooling Load due to the heat absorption of cold water circulating inside the Ocher Walls of small Cabins of one person.[18] Experimental investigation of the performance of a triple concentric pipe heat exchanger.[19] Heat transfer enhancement and development of correlation for turbulent flow through a tube with triple helical tape inserts.[20] Study of Heat transfer characteristics in double tube helical heat exchangers using nanofluids.[21] A computer based solution to check the drop in milk outlet temperature due to fouling in a tubular heat exchanger.[22] Milk fouling simulation in helical triple tube heat exchanger.[23] Develop an analytical method for determining transient temperature field in a parallel-flow three-fluid heat exchanger.[24] Numerical simulation of triple concentric-tube heat exchangers.[25] Case studies of theoretical analysis of triple concentric-tube heat exchangers.[26] It has been observed from the above works of literature that there is a lot of work has been carried out and still going on to improve the performance of triple tube heat exchangers. Most of the research is available on Shell and tube, Double & Triple tube heat exchangers using nanofluid, ferrofluid, etc. Various Experimental, Numerical, and Computational fluid dynamic analyses were investigated to improve the thermo-hydraulic behavior by changing its design and various geometrical parameters.

METHODOLOGY

The mathematical analysis of concentric triple tube heat exchanger has been conducted in present work involved for cooling. The cold fluids flow in the inner tube and outer tube at a temperature of $T_{c1(in)}$ and exits at temperatures $T_{c1(out)}$ where $T_{c2(out)}$ in the inner tube and outer tube, respectively. The hot fluid which has to be cooled enters from the inner annulus of the triple tube heat exchanger at a temperature of $T_{h(in)}$ and exits at a temperature of $T_{h(out)}$ as shown in figure 3.

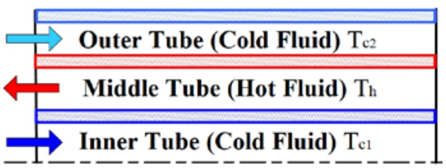

Figure 3. Arrangement of fluid flow in triple tube heat exchanger

Modeling of the heat transfer in a triple tube heat exchanger is not the same for the case where the hot fluid flows in the same direction as the cold fluid and the case where the hot fluid flows in the opposite direction as the cold fluid. Therefore, the formulations for these two different arrangements are analyzed separately.
There are some assumptions have been considered for simplicity:
The system is at steady state.
Both fluids are incompressible.
Fluid properties are constant.
Phase change does not occur at any point in the heat exchanger.
The heat exchanger is insulated from the surroundings.

Table 1. Dimensions of Ribbed concentric triple tube heat exchanger

Parameter	Value
Rib heights H (mm)	9
Rib pitches λ (mm)	50
heat exchanger length *l* (mm)	500
thickness of the walls (t_b) (mm)	2.77
diameters of the inner tubes (mm)	13.51
diameters of intermediate tubes (mm)	45.26
outer tube diameter (mm)	70.66
Ribs thickness (t_R) (mm)	2
material of both tubes and ribs	Aluminum
Thermal conductivity (W/mK)	200

HEAT TRANSFER RATE OF THE HOT NANOFLUID, COLD FLUID AND NORMAL FLUID

$$q_{nf} = \dot{m}_{nf} . c_{p,nf}\left(T_{nf,in} - T_{nf,out}\right)$$
$$q_{cold} = \dot{m}_{cold} . c_{p,cold}\left(T_{cold,out} - T_{cold,in}\right)$$
$$q_{normal} = \dot{m}_{normal} . c_{p,normal}\left(T_{normal,out} - T_{normal,in}\right)$$

Where q_{nf}, q_{cold} &q_{normal} are heat transfer rate of the hot nanofluid, cold fluid and normal fluid, $\dot{m}_{nf}, \dot{m}_{cold}$& $\dot{m}_{normal}$ are mass flow rate of the hot nanofluid, cold fluid and normal fluid, $c_{p,nf}, c_{p,cold}$ & $c_{p,normal}$ are specific heat of the hot nanofluid, cold fluid and normal fluid, $T_{nf,in}$is temperature of hot fluid at inlet, $T_{nf,out}$ is temperature of hot fluid at outlet, $T_{cold,out}$ is temperature of cold fluid at outlet, $T_{cold,in}$ is temperature of cold fluid at inlet, $T_{normal,out}$ is temperature of normal fluid at outlet, $T_{normal,in}$ is temperature of normal fluid at inlet.

Overall heat transfer coefficient of the concentric triple tube heat exchanger

$$U = \frac{q_{\square}}{A_{cross,inner} \times LMTD_{avg}}$$

Where U is overall heat transfer coefficient, $A_{cross,inner}$ is Inner tube area
Average logarithmic mean temperature differences

$$LMTD_{avg} = \frac{LMTD_{\square ot\,\&\,cold} + LMTD_{\square ot\,\&\,nf}}{2}$$

Where $LMTD_{avg}$ is Average logarithmic mean temperature differences, $LMTD_{\square ot\,\&\,cold}$ is Logarithmic mean temperature differences of hot & cold fluid, $LMTD_{\square ot\,\&\,nf}$ is Logarithmic mean temperature differences of hot & nano-fluid

$$LMTD_{\square ot\,\&\,cold} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

And

$$LMTD_{\square ot\,\&\,nf} = \frac{\Delta T_3 - \Delta T_4}{ln\left(\frac{\Delta T_3}{\Delta T_4}\right)}$$

Where

$$\Delta T_1 = T_{\square ot,in} - T_{cold,out}$$
$$\Delta T_2 = T_{\square ot,out} - T_{cold,in}$$
$$\Delta T_3 = T_{\square ot,in} - T_{nf,out}$$
$$\Delta T_4 = T_{\square ot,out} - T_{nf,in}$$

Effectiveness of concentric triple tube heat exchanger

$$Effectiveness = \frac{q_{\square}}{q_{max}}$$

Where $q_{\square}$ is heat transfer rate for hot fluid, q_{max} is Maximum possible heat transfer rate.

Bulk mean temperature of cold fluid

$$T_{b,cold} = \frac{T_{cold-1,in} + T_{cold-1,out}}{2}$$

Where $T_{b,cold}$ is bulk mean temperature of cold fluid, $T_{cold-1,in}$ is inlet temperature of cold fluid, $T_{cold-1,out}$ is cold temperature of cold fluid.

Bulk mean temperature of hot fluid.

$$T_{b,\square ot} = \frac{T_{\square ot,in} + T_{\square ot,out}}{2}$$

Where $T_{b,\square ot}$ is bulk mean temperature of hot fluid, $T_{\square ot,in}$ is inlet temperature of hot fluid & $T_{\square ot,out}$ is outlet temperature of hot fluid.

Liner velocity of nano fluid

$$v_{nf} = \frac{\dot{m}_{nf}}{\rho_{nf} A_{cross\ mid}}\ m/sec$$

Where v_{nf} is liner velocity of nano fluid, $\dot{m}_{nf}$ is mass flow rate of nano-fluid, ρ_{nf} is density of nano-fluid & $A_{cross\ mid}$ is cross section area of middle tube.

Liner velocity of cold water

$$v_{cold} = \frac{\dot{m}_{cold}}{\rho_{cold} A_{cross\ inner}}\ m/sec$$

Where v_{cold} is liner velocity of cold water, $\dot{m}_{cold}$ is mass flow rate of cold water, ρ_{cold} is density of cold fluid & $A_{cross\ inner}$ is cross sectional area of inner tube.

Liner velocity of normal water

$$v_{normal} = \frac{\dot{m}_{normal}}{\rho_{normal} A_{cross\ outer}}\ m/sec$$

Where v_{normal} is liner velocity of normal water, $\dot{m}_{normal}$ is mass flow rate of normal water, ρ_{normal} is density of normal water & $A_{cross\ outer}$ is cross sectional area of outer tube.

Reynolds No. of GNPs

$$R_{e,nf} = \frac{\rho_{nf} v_{nf} D_{mid}}{\mu_{nf}}$$

Where $R_{e,nf}$ is Reynolds number of nano-fluid, D_{mid} is diameter of middle tube, μ_{nf} is kinematic viscosity of nano-fluid.

Reynolds No. of cold water

$$R_{e,cold} = \frac{\rho_{cold} v_{cold} D_{inner}}{\mu_{cold}}$$

Where $R_{e,cold}$ is Reynolds number of cold water, ρ_{cold} is density of cold water & D_{inner} = diameter of inner tube.

Reynolds No. of normal water

$$R_{e,normal} = \frac{\rho_{normal} v_{normal} D_{out}}{\mu_{normal}}$$

Where $R_{e,normal}$ is Reynolds number of normal water, D_{out} is diameter of outer tube & μ_{normal} is kinematic viscosity of normal water.

Calculation of Nusselt no. of GNPs:

$$Nu_{nf} = \frac{\square_{nf} D_{\square,nf}}{k_{nf}} = 0.023 {R_{e,nf}}^{0.8} \times {Pr_{nf}}^{0.4}$$

Where Nu_{nf} is Nusselt number of nano-fluid, $\square_{nf}$ is convective coefficient of nanao-fluid, k_{nf} is thermal conductivity of nano-fluid, $D_{\square,nf}$ is hydraulic diameter of nano-fluid & Pr_{nf} is Prandelt number of nano-fluid.

Calculation of Nusselt no. of cold water:

$$Nu_{cold} = \frac{\square_{cold} D_{\square,cold}}{k_{cold}} = 0.023 \times {R_{e,cold}}^{0.8} \times {Pr_{cold}}^{0.4}$$

Where Nu_{cold} is Nusselt number of cold water, $\square_{cold}$ is convective coefficient of cold water, $D_{\square,cold}$ is hydraulic diameter of cold water tube & k_{cold} is thermal conductivity of cold water.

Calculation of Nusselt no. of normal water:

$$Nu_{normal} = \frac{\square_{normal} D_{\square,normal}}{k_{normal}} = 0.023 {R_{e,normal}}^{0.8} {Pr_{normal}}^{0.4}$$

Where Nu_{normal} is Nusselt number of normal water, $\square_{normal}$ is convective coefficient of normal water, $D_{\square,normal}$ is hydraulic diameter of outer tube & k_{normal} is thermal conductivity of normal water.

Heat transfer coefficient for nano-fluid, Normal and cold water:

$$\square_{nf} = \frac{k_{nf}.Nu_{nf}}{D_{\square nf}}\ W/_{m^2.k}$$

Heat transfer coefficient for cold water:

$$\square_{cold} = \frac{k_{cold}.Nu_{cold}}{D_{\square,cold}}\ W/_{m^2.k}$$

Heat transfer coefficient for Normal water:

$$\square_{normal} = \frac{k_{normal}.Nu_{normal}}{D_{\square,normal}}\ W/_{m^2.k}$$

Darcy-Weisbach factor for Newtonian fluids:

$$f_D = \frac{64}{Re}$$

Blasius friction factor for turbulent flow in circular tubes

Blasius developed an expression of friction factor in 1913 for $2100 < Re < 10^5$

$$f_{Blasius} = \frac{0.0791}{Re^{0.32}}$$

Koo friction factor

Koo introduced another explicit formula in 1933 for a turbulent flow for $10^4 < Re < 10^7$

$$f_{koo} = 0.0014 + \frac{0.125}{Re^{0.32}}$$

The expression for drop through both sides

Pressure drop for GNPs

$$\Delta p_{nf} = 4 f_{nf} \frac{L}{D_2} \rho_{nf} \frac{{\mu_{nf}}^2}{2}$$

Pressure drop for cold

$$\Delta p_{cold} = 4 f_{cold} \frac{L}{D_1} \rho_{cold} \frac{{\mu_{cold}}^2}{2}$$

Pressure drop for normal

$$\Delta p_{normal} = 4 f_{normal} \frac{L}{D_3} \rho_{normal} \frac{{\mu_{normal}}^2}{2}$$

$$\mathrm{L} = \frac{\mathrm{V_o}}{\Delta \mathrm{i_L f_s}}(1 - (\mathrm{D_{PV}} + \mathrm{D_{BT}} + \mathrm{D_{UC}}))$$

RESULT & DISCUSSION

For this analysis of concentric triple tube heat exchanger were divided into three different domains such as two cold fluids in the inner and outer tube and one hot fluid in the middle tube at different nano-fluid concentration including 0.0, 0.02, 0.06 & 0.1%.

Table 2: Different calculated area of triple tube heat exchanger

Parameters	Area [m^2]
Lateral Surface Area outer tube = $2\pi r_3 l$	0.110992
End cross section of the outer tube= $\pi({r_3}^2 - {r_2}^2)$	0.002313
Lateral Surface Area intermediate tube = $2\pi r_2 l$	0.071094
End cross section of the intermediate tube = $\pi({r_2}^2 - {r_1}^2)$	0.001466
Lateral Surface of the inner tube $2\pi r_1(l + r_1)$	0.021508
cross section of the inner tube = $\pi {r_1}^2$	0.000143

Table 3: Liner velocity of nano fluid

φ (%)	Velocity (m/sec) $v = \dfrac{R_e \times \mu}{\rho \times D_{inner}}$	Mass flow rate $\dot{m} = \rho \times A \times v$ (Kg/Sec)	Viscosity (μ) (kg/ms)
0	0.1112-1.1847	0.017295	0.00038305
0.02	0.1306-1.3792	0.020344	0.00045058
0.06	0.1744-1.8752	0.027135	0.00060101
0.1	0.1774-1.8861	0.027627	0.00061189

Table 4: Heat transfer coefficient for nano-fluid

φ (%)	Thermal conductivity (W/mK)	Nusselt number	Heat transfer coefficient
0	0.697662-0.0057	3.4471-3.1638	75-7453-0.5680
0.02	0.897288-0.1689	25.9888-4.2844	734.4693-22.7915
0.06	0.9947-0.2336	23.5646-5.6254	738.2577-41.3888
0.1	1.0976-0.02646	11.7303-6.6353	405.5169-5.5298

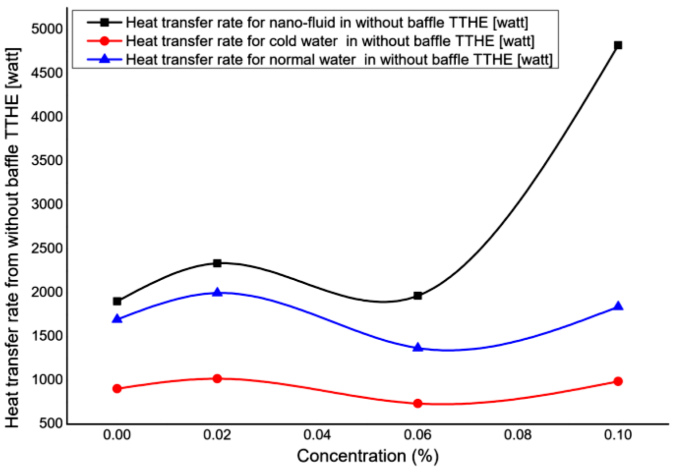

Figure 4: Heat transfer rate from without baffle TTHE

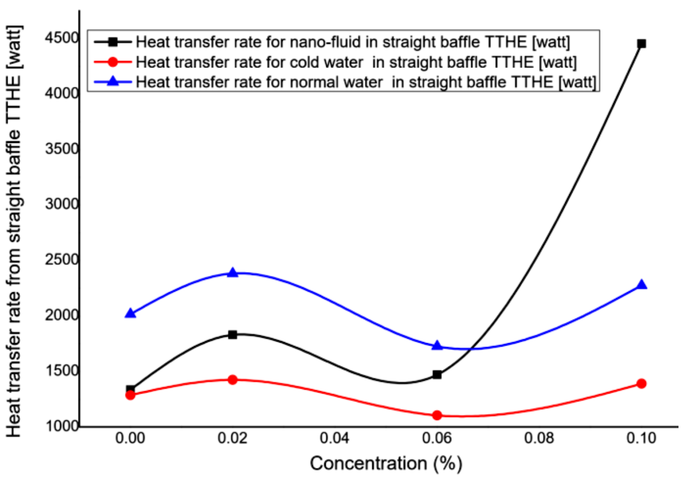

Figure 5: Heat transfer rate from straight baffle TTHE

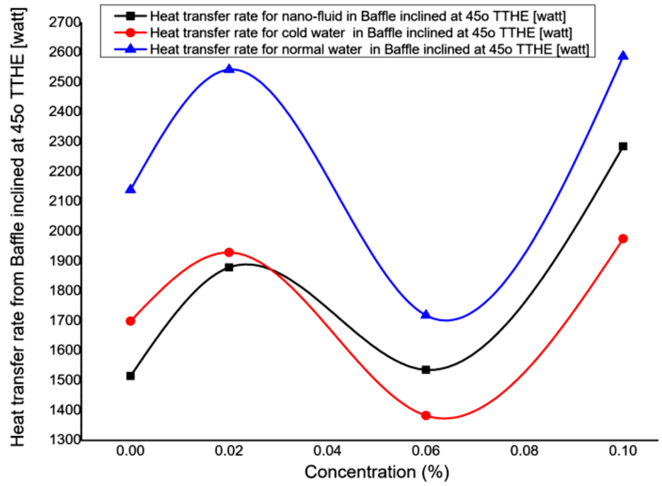

Figure 6: Heat transfer rate from baffle inclined at 45º TTHE

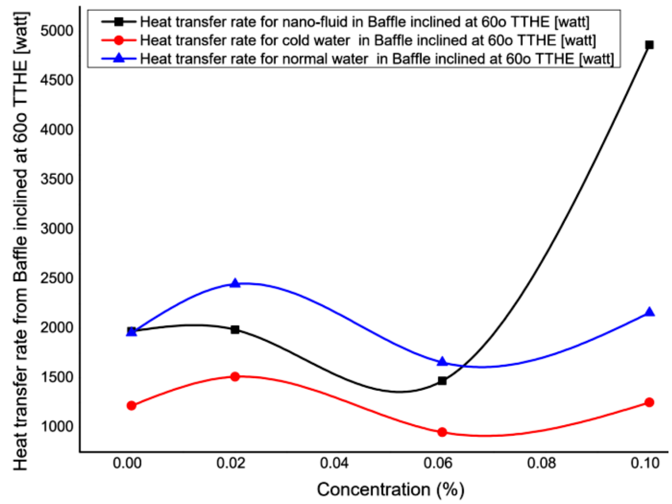

Figure 7: Heat transfer rate from baffle inclined at 60º TTHE

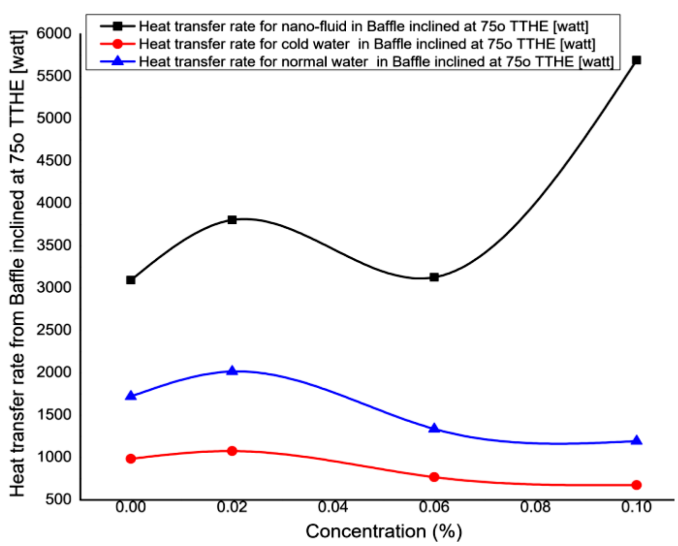

Figure 8: Heat transfer rate from baffle inclined at 75º THE

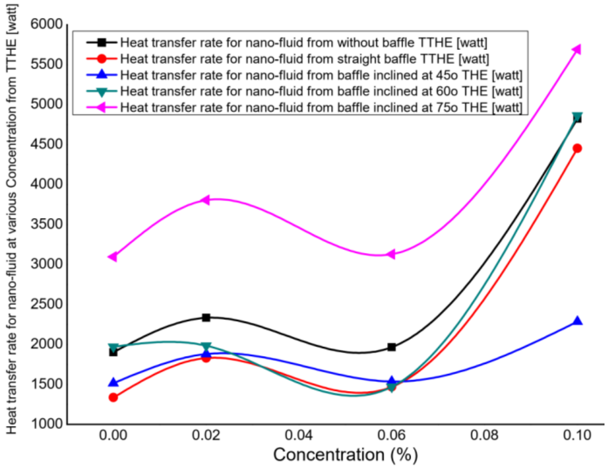

Figure 9: Heat transfer rate for nano-fluid at various concentrations from TTHE

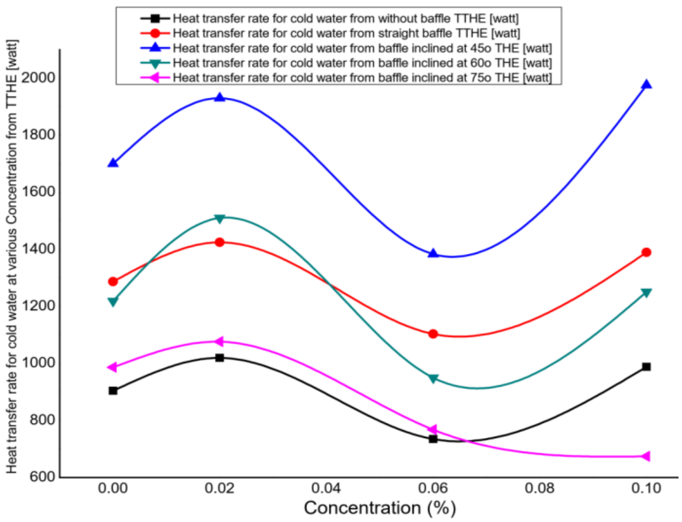

Figure 10: Heat transfer rate for cold water at various concentrations from THE

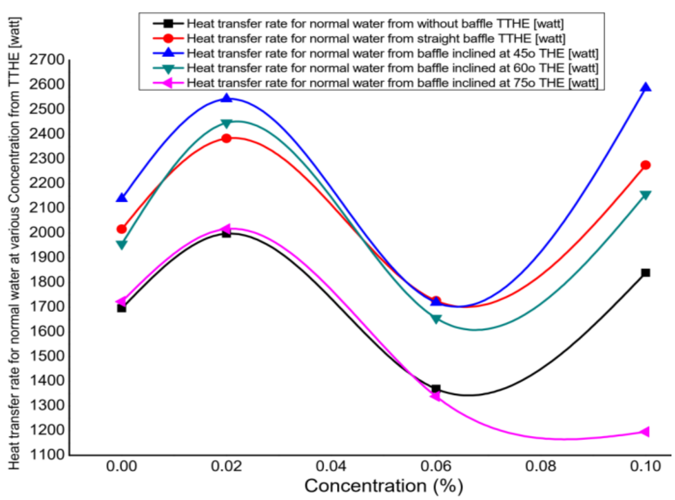

Figure 11: Heat transfer rate for normal water at various concentrations from TTHE

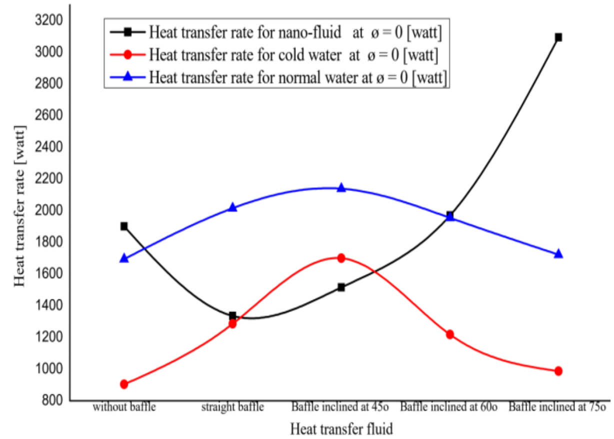

Figure 12: Comparative results of heat transfer rate for different design of TTHE at ø = 0.0

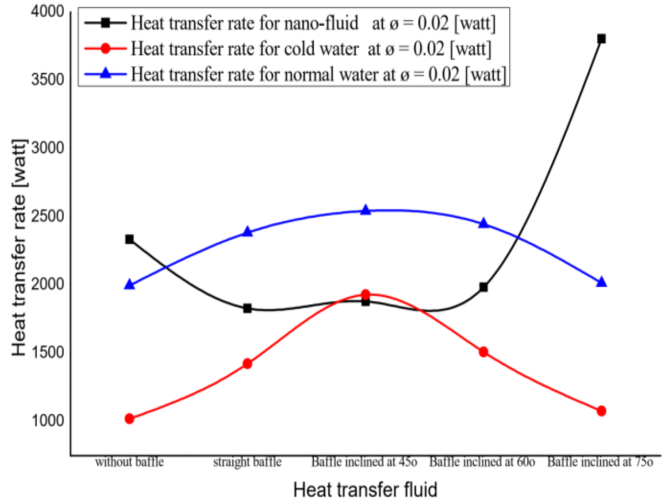

Figure 13: Comparative results of heat transfer rate for different design of TTHE at ø = 0.02

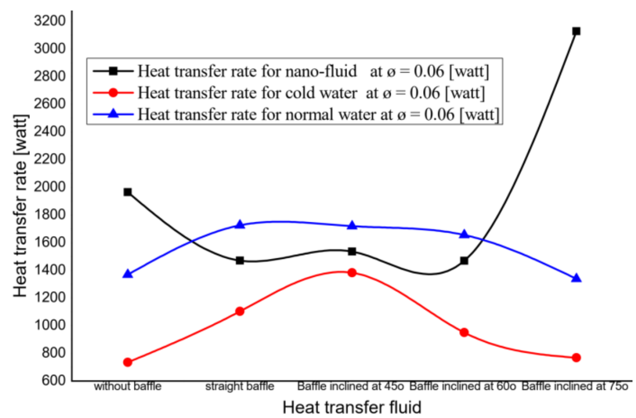

Figure 14: Comparative results of heat transfer rate for different design of TTHE at ø = 0.06

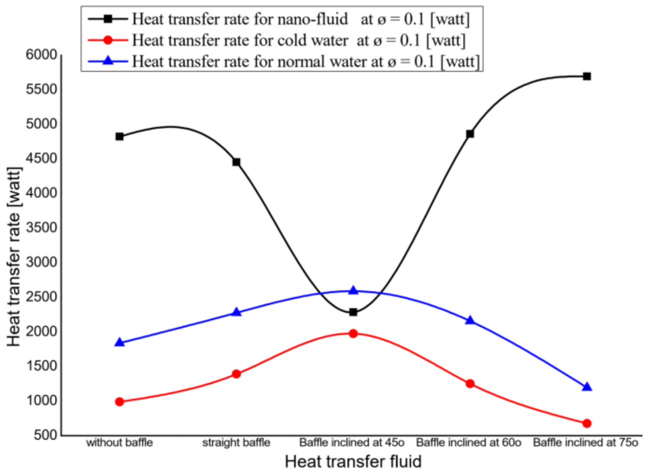

Figure 15: Comparative results of heat transfer rate for different design of TTHE at ø = 0.1

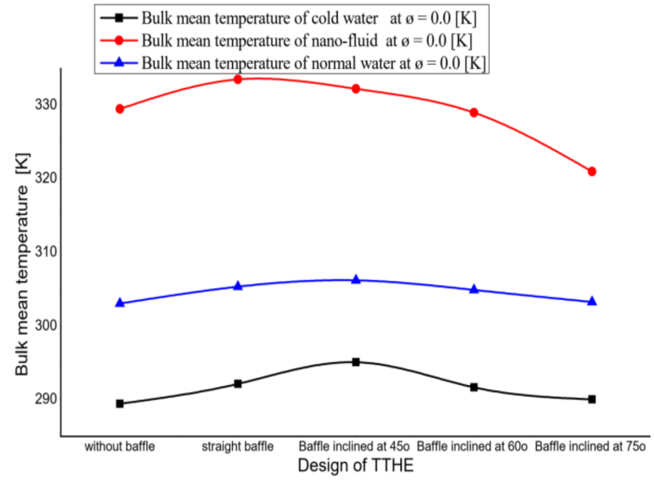

Figure 18: Bulk mean temperature for different design of TTHE at ø = 0.0

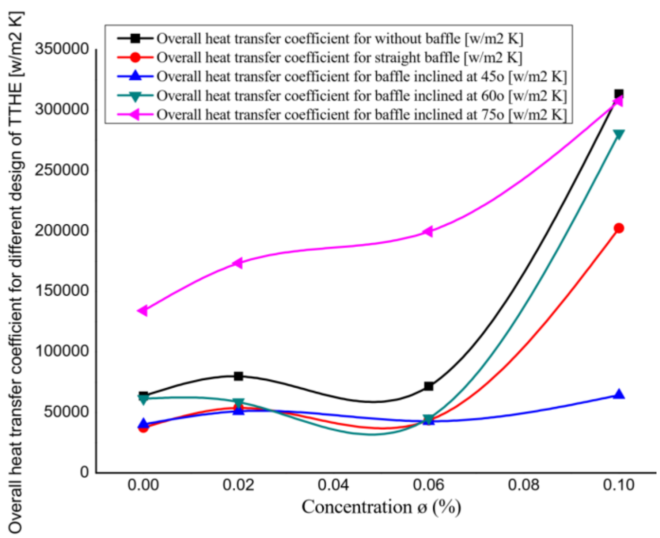

Figure 16: Overall heat transfer coefficient for different design of TTHE at various concentrations

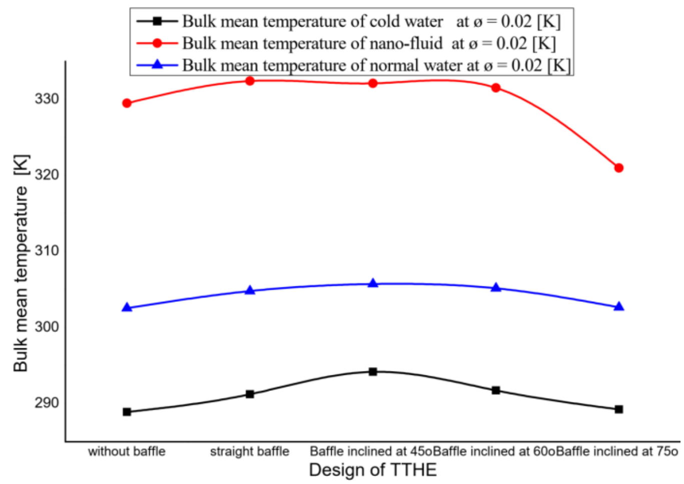

Figure 19: Bulk mean temperature for different design of TTHE at ø = 0.02

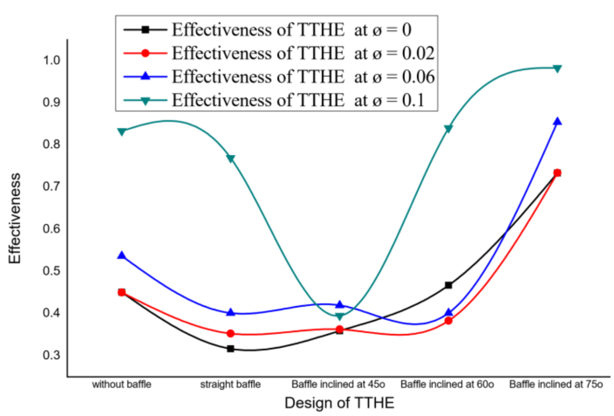

Figure 17: Effectiveness of the various design of TTHE at different concentration

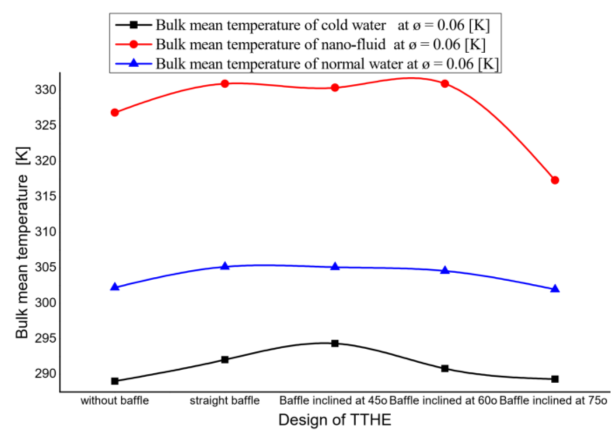

Figure 20: Bulk mean temperature for different design of TTHE at ø = 0.06

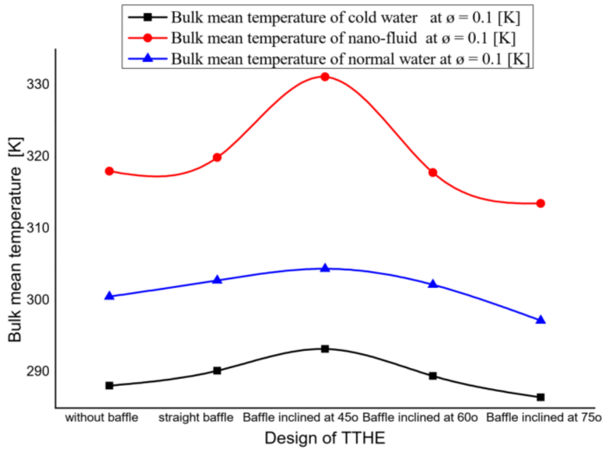

Figure 21: Bulk mean temperature for different design of TTHE at ø = 0.1

The momentum boundary condition with no slip is set for solid walls where the heat flux is set as zero for the outer tube wall to make adiabatic condition, while the inner tube walls and ribs is coupled. The inlets for the outer and inner tube sides are set as mass flow inlet; the outlets are set as pressure outlet. The fluent software is used to calculate the fluid flow and heat transfer in the computational domains. The governing equations are iteratively solved by the finite volume formulation with the SIMPLE algorithm. RNG k-epsilon model is used for turbulent flow because the swirling effect on turbulent flow having higher precision as compared with standard k-epsilon model and the second order upwind scheme is used for the momentum energy turbulence and its dissipation rate.

Conclusion

It has been observed from above result analysis of concentric triple tube heat exchanger with inclined baffle at 75° gives maximum outlet temperature for nano-fluid of 20.77 °K for ø = 0.1 which is 21.71% greater than without baffle, 33.56 % greater than straight baffles and 20.58% greater than baffles inclined at 60°. The heat transfer rate of 17.98% higher than without baffle, 27.79% higher than straight baffle and 17.04% higher than baffles inclined at 60°, while the maximum overall heat transfer coefficient of 0.9832 for ø = 0.1 have been observed. Hence concentric triple tube heat exchanger with inclined ribs at 75° recommended for better heat transfer.

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