Numerical Study of Heat Transfer Characteristics for Turbulent Flow in Circular Corrugated Profile Tube Using Tio_2-Water Nano-Fluid

Mahendra Pratap Pal[*1] **& Lokendra Kumar**[2]
[*1&2]Department of Mathematics, Jaypee Institute of Information Technology, Noida India

Abstract:
There are a number of methods for improving heat transmission, but one of the most recent is to utilise nanofluids. Here, with the popular professional "Computational Fluid Dynamics" (CFD) programme "ANSYS Fluent", we report the results of a numerical analysis of turbulent induced convection in a Circular corrugated profile tube. Internal dimensions for the flowing of fluid include both length and diameter of the tube investigated in the research has dimensions of 200mm x 12 mm has a 3mm diameter circular corrugated profile at the outside of the flowing fluid and an aluminium pipe of outer diameter 20mm through which fluid is flowing which have a uniform heat flux of 1000W/m2 near the wall's outer edge. To investigate this, we run a 3D simulation using a Realizable k-ε turbulence model that incorporates a more thorough wall treatment into the investigation. When TiO_2- water-based nano-fluid is permitted to move at a constant speed according to the respective Reynolds no. Assume no-slip conditions and a consistent temperature of 300 K at the inlet. Variable in heat transfer like the coefficient of heat conduction and fluid dynamics factors like the "Convective Heat Transfer Coefficient" and outlet temperature. TiO_2- water-based nano-fluid with varying volume fractions (1, 2, 3, 4, and 5 %) for a wide Reynolds number range from 5 000 to 30 000 at an interval of every 5000 were calculated. The result demonstrates that when the volume fraction grows, the heat transfer coefficient also increases.
Keywords: Nanofluid, corrugated profile, pipe, channel, heat transfer characteristics, thermodynamic analysis, no-slip condition, Ansys simulation, Reynolds no. TiO_2-water nano-fluid.
DOI: 10.24297/j.cims.2022.11.068

1. Introduction

Today, heat transfer is one of thermal engineering's most pressing concerns because of the widespread impact it has on our daily lives and because of the many ways in which thermal energy and heat are generated, created, characterised, transformed, and exchanged across different physical systems. Energy production, maritime transfer, industrial processes, climate control, cooking, chilling, lubrication, etc. all face the same difficulty: how to efficiently remove or add heat as it moves from one process stream to another. Fluid is used for transporting energy in various easy and cheap ways other than conduction. The fluid in a variety of systems transfers energy in air conditioning, vehicles, heat exchangers, cooling, fridges, machining systems, etc. However, fluid is the primary phenomenon that regulates heat transfer activity (Gürdal et al., 2022). Several techniques have emerged during recent years for enhancing energy exchange rates, thermodynamic conduction, and outlet temperature while simultaneously minimising the amount of energy required to maintain the system. Illustrations of such methods include using microfluidic devices, and fins, applying motion to the thermal energy exchange interface, and so on. The operating fluid’s thermodynamic conductance can be improved to speed up the transfer of energy. Thermal energy exchange substances such as seawater, propylene, and lubricating oil are commonly utilised, however, their heat transfer capability is low in comparison to that of solids. When a little number of solid fragments are added to the core or thermal conduction fluid, the fluid's thermal efficiency may be dramatically increased. “Choi and Eastman (1995) revisited their suspensions of nanoscale metallic particles and carbon nanotubes at Argonne National Laboratory”. Several fluids have been attempted by Choi (1998) and Choi et al., (2001) to suspend nanoparticles of metals and metal oxides, and the results have been encouraging. As they dug further, they found that many of these nanofluids provide significantly less heat loss and frictional loss between any physical systems.

Some of these techniques include using microchannels, fins, vibration applied to the heat transfer surface, using an expanded surface of the physical system, etc. “Increasing the thermal conductivity of the working fluid is another way to boost heat transmission. Water, ethylene glycol, and motor oil are often used as heat transfer fluids, but these fluids have relatively poor thermal conductivity compared to the thermal conductivity of solids, thus researchers are focusing on enhancing the thermal conductivity of working fluids (Rahmati and Derikvand 2020). Increasing the thermal conductivity of a fluid may be as simple as mixing a few sold particles into the base or working fluid. Nano scale metallic particle and carbon nanotube suspensions were re-examined by Choi and Eastman (1995) at Argonne National Laboratory. Nanoparticles of different metals and metal oxides have been successfully suspended in a variety of fluids by Choi (1998) and Choi et al., (2001)”. Based on their findings, Choi and Eastman have coined the name "Nano fluid" to describe suspensions of Nano-structured materials, about which much remains unknown. Nano fluids have several uses; for example, inside a diesel electric engine as a coolant, which was studied in depth by Kulkarni et al., (2008). (DEG). Specific heat of aluminium oxide molecules of varying sizes was tested, and it was shown to decrease with increasing temperature and concentration (Moradi et al., 2020). Heat transmission properties of a circular profiled curved tube are invested in an Ansys model, as shown in Fig 1.

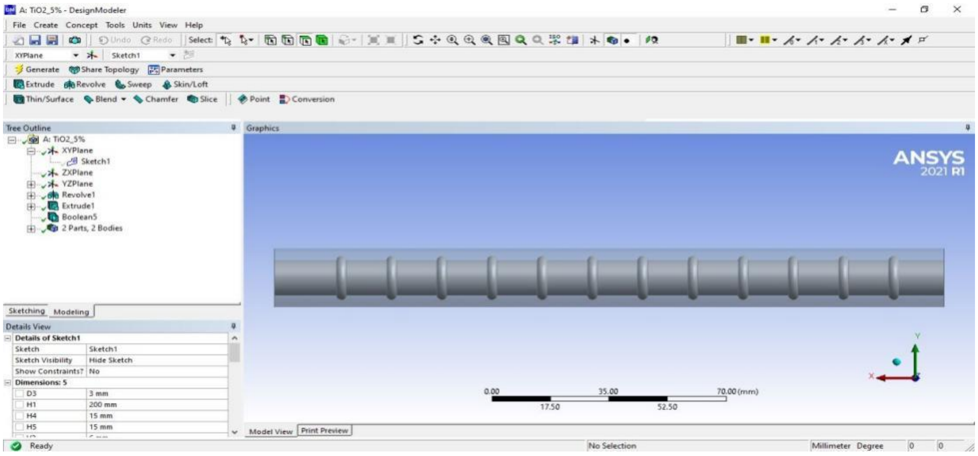


Fig 1: Designed Circular Profile Corrugated Pipe

Nano fluids' effectiveness as cooling agents was initially studied by Pantzali et al., (2009). The outcomes clearly showed how the base fluid's thermophysical properties were considerably changed by the addition of nanoparticles. As such, a CuO solution with a 4% concentration in water is chosen for. The presented tests highlight how the exchanger flow also affects coolant sufficiency. The viscosity of the liquid is hence the deciding element. Therefore, Nanofluids are not a suitable replacement for high-volume components. Meyer and Albolabrin (2018) did a recent study in which they used multiwall carbon nanotube suspensions in water to observe their transport through a straight tube. The study found that in the turbulent region, weight loss is 3% more than that of the water stream at the same normal stream speed, regardless of fixation. The losing weight for 0.33 vol. % fixation is 10% higher than the water stream within the laminar area, and for 0.75 vol. % fixing, it is 20% higher. Aqua with Al2O3 and Aqua with CuO Heris et al. conducted experiments on nanofluids in which the fluids flowed laminarly through a triangular conduit heated at a constant rate of flux (2013). Results demonstrated that Al2O3 nanoparticles are preferable to CuO nanoparticles inside a laminar restricted convective heat transfer scenario, at similar values as nanoparticle volume division or Reynolds number. The improvement in heat exchange in laminar flow using nanofluids was demonstrated to be better at such a Reynolds Numbers, as well as the Nusselt number of the nanofluid increases as molecular fixation increases as molecule width drops. The heat transfer characteristics of a new class for Nanofluids made from mango wood were identified by means of numerical modelling and investigation of turbulence through with a twin tube heat exchanger by Onyiriuka et al (2019). When considering particle sizes between 100 nm and 1,000 nm, a variety of volume fractions were evaluated. The finite-volume method was utilised to resolve the mixture model's continuity, momentum, energy, or volume fraction equations. At a Rayleigh number of 5,000, the Nusselt number has increased by 68%, and at a Rayleigh number of 13,000, the increase was 45%. The authors conclude that now the coefficient of heat transfer of a nan fluid was around double that of the base fluid. It was also shown that there are various plots that show areas of increased heat transmission, which, if used in the design, would result in higher heat transfer yet avoid other areas with low heat exchange. This was shown to be the case within a specific Reynolds number range when the average coefficient of heat transfer of the nanofluid underwent a complete reversal of a trend. Future heat exchanger thermal design may benefit from these results (Javid et al., 2020).

To improve convective heat transmission, scientists have been experimenting with Nanofluids in a variety of corrugated geometries. In this investigation, TiO_2-water-based nanofluids are used to achieve a fast heat transfer rate however this increases material handling complexities. The purpose of this research is to determine how changing the volume ratio of TiO2-water Nano - fluids inside a circular concave tube will affect the results, with Reynolds numbers ranging from 5000 to 25000. Finally, the volume fraction for which Nano fluid is the optimal operating condition is established, and the results are compared to those obtained using water as a heat transfer fluid.

2. Literature Review

In order to examine the heat transfer properties and ideal working conditions employing nano fluids, various investigations were conducted, and their methods and results were covered in this section.

Variyenli (2019)studied a variety of sectors rely heavily on plate heat exchangers due to their efficiency and reliability. When used in a heat transfer also as working fluid, nanofluids dramatically increase the efficiency of the system. The results of an experimental and computational investigation into the consequences of utilising a fly ash nanofluid in a plate heat exchanger are presented here. Plate heat exchanger heat transfer properties were simulated using ANSYS FLUENT software. The nanofluid was created using fly ash nanoparticles with average diameters of 14 nm. The 2% (wt/wt) nanoparticle concentration of the ready-made nanofluid was impressive. The experimental findings demonstrated an increase in heat transmission efficiency of 6-20% when employing the fly ash nanofluid. Moreover, there is a strong concordance between theoretical predictions and experimental findings.

Rahi and Kareem (2021) discussed that spiral solar collectors are a specific kind of solar collector that consists of a pipe with several twists that is permanently attached within a solar collector box. Numerical simulations utilising the commercial software ANSYS-FLUENT are used to forecast the temperature distribution and solar collector of the spiral type's thermal effectiveness. Water is assumed to be the working fluid, and the (K-ε) model is used to solve the transient 3D energy equation under the conditions of a steady-state, incompressible, turbulent flow. When comparing calculated values with those obtained from an actual test conducted on a model of a spiral-type solar collector constructed from a copper pipe with a diameter of 7.75 mm and a length of 23 metres, the two sets of data show excellent agreement. This spiral pipe is attached to a flat copper board that is 65 square centimetres in size (cm2), which is then placed within a 77 square centimetre (cm2) wooden box that has one sheet of glass on top and fibreglass insulation on the bottom. A D.C. pump is linked to a cork water storage tank that can hold 17.8 litres. This pump receives its electricity supply from a solar cell that generates 100 watts. The results showed that the best thermal efficiency (82.5%) was achieved at a rate of flow of 0.0625 lit/sec running in a manner such that the fluids entry port is located in the middle of a spiral pipe. When the flow velocity is held constant but the entry port is reshaped to have a larger diameter, thermal efficiency is improved by 34.6% compared to the worst scenario.

Aljabair (2022) With the use of a nanofluid flow (CuO, Al2O3/distilled waters) and twisted tape (standard twisted tape, using twist ratios (TR=9.2)), it was examined to present the findings of an experimental and mathematical study into the improvement of heat transfer inside a horizontal circular tube. Concentrations of (=0.6), (1.22), and 1.8% (by volume) of the hybrid nanofluid were examined in fully developed turbulent flow with uniform heat flux. All the necessary tools to analyse the improvement in heat transmission are included in the experimental test setup. A constant heat flux (13217.5 W/m2) and a Reynolds number range of 3560-8320 were used for all the experiments. The tube was then loaded with the twisted tape, which was made from polylactic acid (PLA) using 3-dimensional printing technology. The turbulent forced convection flow through the tube was modelled in this numerical investigation using the finite volume technique (CFD) process. Maximum thermal performance factor improvement for a twisted hybrid nanofluid was 2.18 at = 1.8%, whereas for twisted water in a tube, the improvement was just 1.6%. (2.04). Concentrations of 1.8% produced a high Nusselt number and improved heat transmission by around 6.70% compared to water.

Debnath and Pradhan (2022) Shell & coil tube heat exchangers (SCTHX) have been used in heating and cooling systems, chemical reactors, solar water heating, and steam power plants to transfer heat energy from one material to another. Helical tubes have been widely used in industry as a passive heat transfer enhancement technology in heat exchangers because of their greater heat transfer rate and ease of fabrication. Helical coils have a higher heat transfer coefficient than straight pipes, and this has been extensively used in the industry. This secondary flow of nanofluid forms for a purpose. The dean vortex acts as a driver, forcing its way into the major flow. This study aims to enhance the heat transfer convective contact between the fluid and a helical coil's solid surface. The results of a state-of-the-art review suggest that the shape of SCTHX and other aspects influencing its fluid properties may be tweaked to provide better results in future studies. The impact on superhydrophobic surfaces, bubble generation from a rough surface heating surface, and polymer additions in nanofluids could all boost heat transmission. Finally, this study presents novel methods for maximising heat transfer efficiency and minimising production costs and footprint.

3. Methodology

a. Governing Equations

The following are the continuity, momentum, and equation for induced airflow in a turbulence-dominated stable condition:

- Continuity Equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

- Momentum Equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

- Energy Equation:

$$\frac{\partial}{\partial x_i}(-\rho u_i T) = \frac{\partial}{\partial x_j}\left[(\Gamma + \Gamma_t)\frac{\partial T}{\partial x_j}\right] \tag{3}$$

Here $\Gamma$is the temperature-dependent diffusivity of molecules$\Gamma_t$is the thermal diffusivity in turbulent flows, and it has an expression as:

$$\Gamma = \frac{\mu}{Pr'} \text{ and} \tag{4}$$

$$\Gamma_t = \frac{\mu_t}{Pr_t'} \tag{5}$$

- Turbulent Kinetic Energy (KE)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{6}$$

Turbulent dissipation rate:

$$\frac{\partial}{\partial y}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{7}$$

Where,

$$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = S\frac{k}{\varepsilon} \; and \; S = \sqrt{2S_{ij}S_{ij}} \tag{8}$$

"Here Gk represents the generation of turbulent kinetic energy due to the mean velocity gradients, Gb is the generation of turbulent kinetic energy due to buoyancy, YM represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, and σk and σε are the turbulent Prandtl for k and ε respectively".

- The Reynolds number is expressed as:

$$Re = \frac{\rho_{nf}U_{av}D_h}{\mu_{nf}} \tag{9}$$

- Nusselt No is expressed as:

$$Nu = \frac{h_c D_h}{K_{nf}} \tag{10}$$

- Pressure drop is defined as:

$$\Delta P = \frac{fL\rho U_{av}^2}{2D_h} \tag{11}$$

b. Thermal Properties of Nano fluids

- Density

$$\rho_{nf} = \rho_p\varphi + \rho_{bf}(1-\varphi) \tag{12}$$

- Specific heat

$$C_{nf} = (1-\varphi)C_w + \varphi C_p \tag{13}$$

- Thermal Conductivity

$$K_{nf} = K_{bf}(1.0021 + 7.3349\varphi) \tag{14}$$

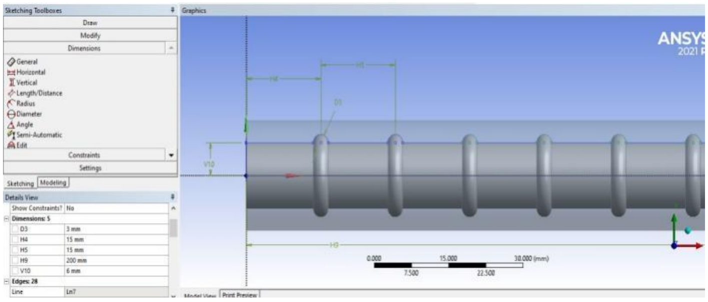
- Dynamic viscosity

$$\mu_{nf} = \mu_f(1 + 7.3\varphi + 123\varphi^2) \tag{15}$$

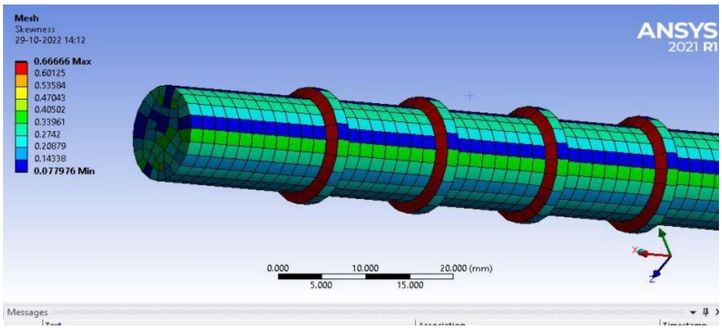
c. Physical Model and Boundary Conditions

The heat transfer rate and the related pumping power can be evaluated most simply in a curved channel with a comfortable temperature flow on its allow. The commercial commercial cfd tool ANSYS Fluent has been used to numerically analyse the behaviour of Nanofluid inside a corrugated tube. Fig2(a) depicts an model that is used in 3D simulations for the purpose of examining various parameters; the model's matching mesh is seen in Figure 2(b) and fig 2(c) for fluid domain and pipe domain correspondingly and fig 2(d) shows the Mesh quality report. A corrugated tubes with a 20mm wall delivers a constant heat flow of 5000 W/m2 and 12mm outer and inner diameter correspondingly and 3mm diameter outward circular corrugated profile and 200 mm in length to create turbulence. The research uses a k- ε turbulent model that is realistic and includes improved wall treatment. Assuming a nonslip condition at the tube's intake, a uniform velocity and temperature of 300 K are applied to the Nano fluid. After hydrodynamic and thermal enhancement of the fluid stream, all the parameters pertaining to the stream's dynamics and heat exchange are extracted; in this example, all the measurements are collected beyond a length of x/D=10.

(a)



(b)



(c)

(d)

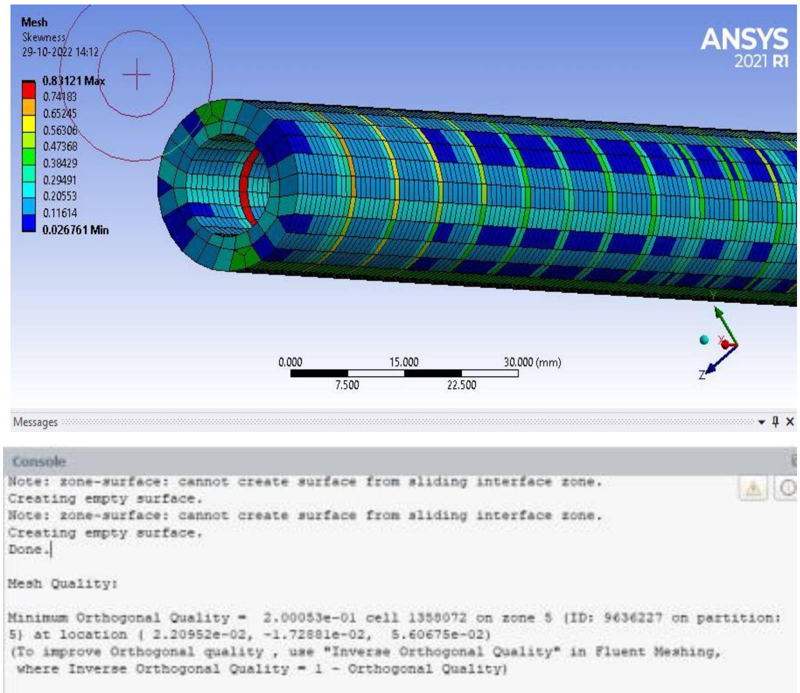
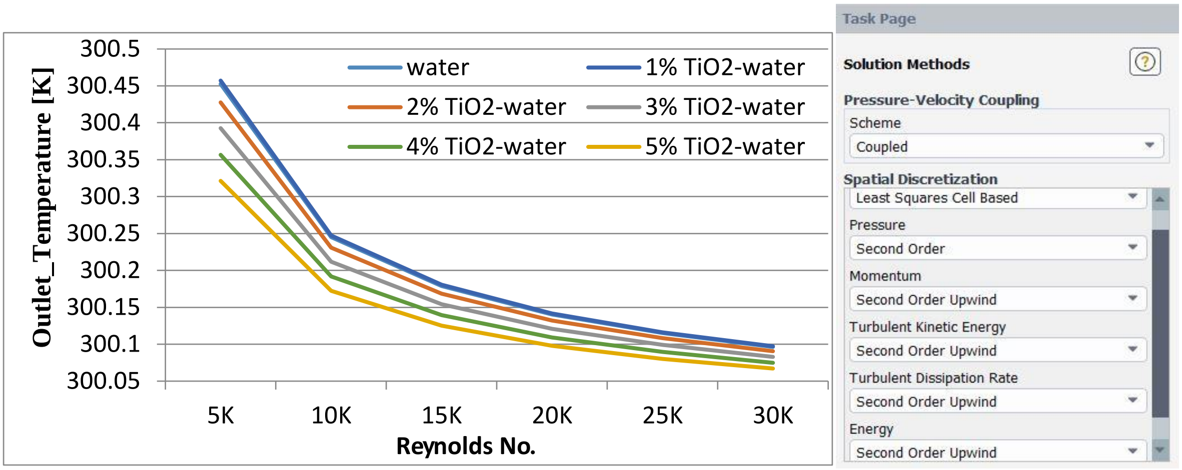


Fig2: (a) Numerical domain of the circular corrugated tube, and corresponding mesh for (b) Fluid domain (c) Pipe domain (not to scale) (d) Mesh quality report

4. Results and Discussion

a. Nano fluid Volume Fraction Influence on Outlet Temperature

When demonstrated in Fig. 3 (a), as the particle volume percentage and Reynolds number rise, the outlet temperature at the end of tube is reduces by the incorporation of nanoparticles into the base fluid. Fig 3(b) demonstrates the solution method incorporated during the simulation process. TiO_2-water Nano fluid with a 5% volume fraction has a least outlet temperature profile than water's at a Reynolds number of 30,000. Both the nano-fluid volume fraction and The Reynolds number increases heat transfer and lowers exit temperature as a result.



(a) (b)

Fig 3: (a) Outlet temperature with particle volume fraction (b) solution Method used for simulation

b. Volume Fraction's Impact on Heat Transfer

As the particulate volume percentage or Reynolds number rises, as illustrated in Fig. 4, the dispersion of nanoparticles to a base fluid considerably enhances the convection heat transfer. TiO2-water The heat transfer of a nano fluid with a 5% volume concentration is 21.44% more than that of water at a Reynolds numbers of 30,000. Reynolds number and nanofluid volume percentage both increase convective heat transport. No of the volume proportion, the conduct of nano fluids inside a corrugated tubes is consistent. As demonstrated in fig. 4, a corrugated tube's enhanced wall shear stress causes a convective transfer of heat. An increase in rate of heat transfer is influenced by both volume fraction or Reynolds number.

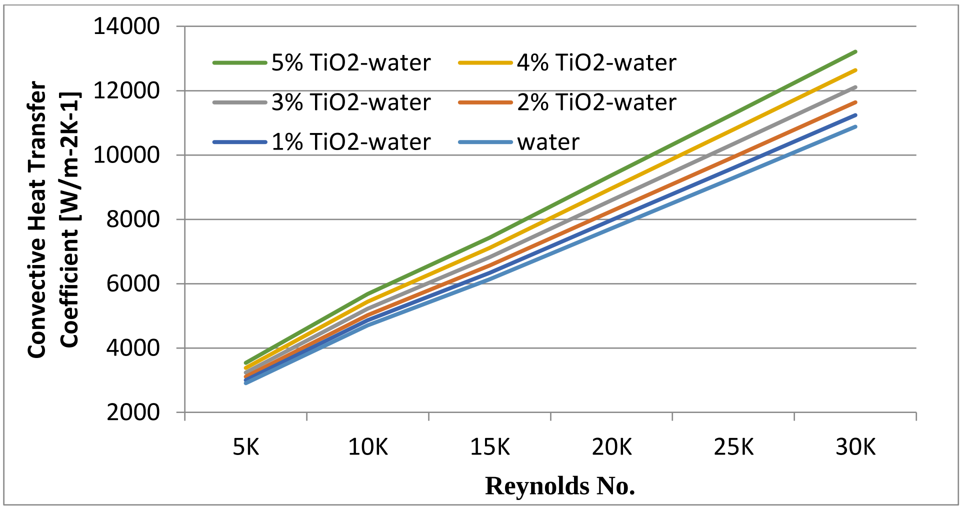


Fig 4: Use of corrugation for heat transfer enhancement for nano-fluid of different volume fractions

5. CONCLUSION

One of the unique methods to obtain a notable increase in heat transfer rate is to employ nano-fluid in a corrugated tube. Corrugation on the wall border not only increases the heat transmission rate, but also requires a great deal of pumping force. Up to a specific volume % of nano fluid, lower pumping power may be found. However, the heat transfer drastically rises whenever the Reynolds number as well as the layer thickness of a nano-fluid are elevated.

References

1. Aljabair, Sattar. "Numerical and Experimental Investigation of Heat Transfer Enhancement by Hybrid Nanofluid and Twisted Tape." Engineering and Technology Journal 41, no. 1 (2022): 69-85.
2. Choi, S. U. S., Z. George Zhang, WLockwoodFE Yu, F. E. Lockwood, and E. A. Grulke. "Anomalous thermal conductivity enhancement in nanotube suspensions." Applied physics letters 79, no. 14 (2001): 2252-2254.
3. Choi, S. US, and Jeffrey A. Eastman. Enhancing thermal conductivity of fluids with nanoparticles. No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab.(ANL), Argonne, IL (United States), 1995.
4. Choi, Stephen U-S. Nanofluid technology: current status and future research. No. ANL/ET/CP-97466. Argonne National Lab.(ANL), Argonne, IL (United States), 1998.
5. Debnath, Pinku, and Mrinal Pradhan. "A recent state of art review on heat transfer enhanced characteristics and material selection of SCTHX." Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering (2022): 09544089221124463.
6. Gürdal, Mehmet, Hayati Kadir Pazarlıoğlu, Mutlu Tekir, Kamil Arslan, and Engin Gedik. "Numerical investigation on turbulent flow and heat transfer characteristics of ferro-nanofluid flowing in dimpled tube under magnetic field effect." Applied Thermal Engineering 200 (2022): 117655
7. Heris, S. Zeinali, Taofik H. Nassan, S. H. Noie, Hamideh Sardarabadi, and Mohammad Sardarabadi. "Laminar convective heat transfer of Al2O3/water nanofluid through square cross-sectional duct." International Journal of Heat and Fluid Flow 44 (2013): 375-382.
8. Javid, Khurram, Nasir Ali, and Muhammad Bilal. "A numerical simulation of the creeping flow of hybrid-nano-fluid through a curved configuration due to metachronal waves propulsion of beating cilia." The European Physical Journal Plus 135, no. 1 (2020): 49.
9. Kulkarni, Devdatta P., Ravikanth S. Vajjha, Debendra K. Das, and Daniel Oliva. "Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant." Applied Thermal Engineering 28, no. 14-15 (2008): 1774-1781.
10. Meyer, Josua P., and S. M. Abolarin. "Heat transfer and pressure drop in the transitional flow regime for a smooth circular tube with twisted tape inserts and a square-edged inlet." International Journal of Heat and Mass Transfer 117 (2018): 11-29.

11. Moradi, Abed, Masoud Zareh, Masoud Afrand, and Morteza Khayat. "Effects of temperature and volume concentration on thermal conductivity of TiO2-MWCNTs (70-30)/EG-water hybrid nano-fluid." Powder Technology 362 (2020): 578-585.
12. Onyiriuka, E. J., O. O. Ighodaro, A. O. Adelaja, D. R. E. Ewim, and S. Bhattacharyya. "A numerical investigation of the heat transfer characteristics of water-based mango bark nanofluid flowing in a double-pipe heat exchanger." Heliyon 5, no. 9 (2019): e02416.
13. Pantzali, M. N., A. A. Mouza, and S. V. Paras. "Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE)." Chemical Engineering Science 64, no. 14 (2009): 3290-3300.
14. Rahi, Sejjad Mousa, and Mishaal A. AbdulKareem. "Experimental and Numerical Investigation of the Thermal Performance of Spiral Type Solar Collector." Journal of Mechanical Engineering Research and Developments (2021): Vol. 44, No. 10, pp. 239-250
15. Rahmati, Ahmad Reza, and Mohammad Derikvand. "Numerical study of non-Newtonian nano-fluid in a micro-channel with adding slip velocity and porous blocks." International Communications in Heat and Mass Transfer 118 (2020): 104843.
16. Variyenli, Halil Ibrahim. "Experimental and numerical investigation of heat transfer enhancement in a plate heat exchanger using a fly ash nanofluid." Heat Transfer Research 50, no. 15 (2019).