Increasing the Heat Transfer Performance of a Turbulator Equipped Concentric Gas-liquid Heat Exchanger Using Al_2O_3 – Water Nanofluid

Seyed Soheil RahimHosseini[1], Seyyed Masoud Seyyedi[2*], Mehdi Hashemi-Tilehnoee[3*]

Abstract– In this study, the turbulent fluid flow and heat transfer performance of a concentric two-tube (air-nanofluid) heat exchanger with a helical turbulator is studied using STAR-CCM+. First, the computational code is validated according to the related experimental data and its simulation results for air and water. Then, the heat transfer performance and the effect of the different pitches of the helical turbulators are analyzed by replacing nanofluid instead of water for heat removal. The results show that the turbulator and nanoparticle have a high impact on heat transfer capability of the heat exchanger. The result shows that the heat transfer is increased using turbulators in comparison with a smooth tube for pitches of 15, 30, and 45 mm, respectively. In addition, the STAR-CCM+ is a proper tool for simulation of complex geometries in three-dimensional.

Keywords: STAR-CCM, turbulators, nanofluid, smooth tube, turbulent

1. Introduction

Given the fact that heat exchangers can be used between two fluids at different temperatures separated by a solid wall, they have become prevalent in the industry. They are used in thermal engineering applications such as power plants, chemical plants, food industries, cooling heating systems, airplanes, automobiles, solar water heaters, thermal rooms, heat recovery processes, and so on. Heat transfer coefficient and pressure drop are indispensable parameters in reducing the size and cost of a heat exchanger, which decreases during energy consumption.

The heat transfer coefficient and pressure drop are the most important parameters to determine in reducing the size and cost of a heat exchanger. Heat transfer enhancement techniques for the design of more compact heat exchangers can be divided to two groups: active and passive methods [1]. active methods require extra external power sources, such as mechanical aids, surface, and fluid vibration, electrostatic fields, injection or suction of fluid, and jet impingement. Passive methods, on the other hand,

Perform without additional external power, by means of surface coating, rough surfaces, extended surfaces, displaced enhancement devices, turbulent or swirl flow devices, coiled tubes, and additives for liquids and gases[2]. In this respect, several types of tubulator's, replacing a finned surface, have been used in gas to liquid heat exchangers in boiler applications[3]. The tubulator's improve heat transfer efficiency; however, they cause a pressure drop. Some series of studies have been investigated experimentally and numerically heat transfer and pressure drop characteristics in a circular tube with different design and considering tubulator's, conical-nozzle, V-nozzle, twisted-tape, and screw-tape. In 1998, Yildiz et al.[4] experimentally analyzed the heat transfer and pressure drop for a concentric double-pipe heat exchanger with and without twisted narrow metallic strips in the inner pipe. It was observed that the heat transfer increases up to 100% at a cost of about 130% increase in pressure drop for the tube with twisted strips inside. In 2004, Durmuş [5]studied the effect of cut-out conical turbulators on the heat transfer rates and entropy generation were placed in an air-water heat exchanger tube at constant outer surface temperature. The experiments were conducted for turbulent airflow and some empirical correlations expressing the results were also derived and discussed. Zhnegguo et al.[1] experimentally studied the rate of heat transfer and pressure drop of helically baffled heat exchanger combined with petal-shaped finned tubes for oil cooling with water. The results show that the shell side heat transfer coefficient based on the actual outside surface area of tube bundle and pressure drop increase with increasing volumetric flow rate of oil.

Dmitri Neshumayev et al. [2] investigated the heat

1 Department of Mechanical Engineering, Aliabad katoul Branch, Islamic Azad University, Aliabad Katoul, Iran. Galaxysoheilh@gmail.com

2,3*Correspoding Authors: Department of Mechanical Engineering, Aliabad katoul Branch, Islamic Azad University, Aliabad Katoul, Iran. Email: mehdi.hashemi.t@gmail.com , s.masoud_seyedi@yahoo.com

Received: 2022.08.09; Accepted: 2022.12.13

transfer augmentation by various turbulator inserts (twisted-tape insert, the straight-tape insert, and the combined turbulator insert) in gas-heated channels of fire-tube boiler. The results showed that the mean heat transfer of the combined turbulator is higher than the mean heat transfer for the twisted tape and the helical-wire-coil insert cases. Kenan Yakut and Bayram Sahin [3] experimentally examined the flow-induced vibration characteristics of conical-ring turbulators used for heat transfer enhancement. It was found that the Nusselt number and friction factor increase with the increasing Reynolds number and the maximum heat transfer is obtained for the smallest pitch arrangement. Eiamsa-rad and Promvonge[6] experimentally evaluated the influence of helical tapes inserted in a tube on heat transfer enhancement in a range of Reynolds number between 2300 and 8800. The full-length helical tape with a rod provides the highest heat transfer rate about 10% better than that without a rod but it increased the pressure drop. Kurtbaş et al. [7] examined the effects of propeller-type turbulators located in the inner pipe of co-axial heat exchanger on heat transfer, entropy generation rate, and exergy loss rate. They concluded that the Nusselt number and exergy loss rate were proportional with blade angle, inter-turbulator distance and propeller diameter where the increase in the heat transfer results in an increase in entropy generation rate. Güla and Evin [8] presented an experimental study of heat transfer and friction characteristics in decaying turbulent swirl flow generated by a short helical tape placed at the entrance of the test section. The results confirmed that, the use of a helical tape inserted to the tube leads to a higher heat transfer rate than the non-swirling flow. In 2007, Piroozeh Zamankhan [9] compared the simulation results using SIMPLE algorithm with an experimental test in literature to investigate the heat transfer augmentation in a circular tube with a helical turbulator in turbulent conditions. Comparisons with experimental data showed reasonable agreement with large eddy simulation results. In 2008, Smith Eiamsa et al.[10] experimentally investigated the heat transfer and friction characteristics in a concentric tube heat exchanger with louvered strips. Experimental results confirmed that the use of louvered strips leads to a higher heat transfer rate over the plain tube where the use of the louvered strip with backward arrangement leads to better overall enhancement ratio than that with forward arrangement. In 2011, Naphon and Suchana [11]conducted a study on increasing heat transfer and pressure drop in a concentric horizontal tube with twisted wires inside it. In short, Twisted wire brushes insert has a large effect on the enhancement of heat transfer, however, the pressure drops also increase. In 2012, Emre Turgut et al. [12] studied the optimum design parameters of the concentric heat exchanger with injector turbulators using Taguchi experimental design method. The Reynolds Number in this study is between 10,000 and 17,000. The heat transfer performance and friction characteristics of a concentric tube heat exchanger with different cross-section area and pitches of helical turbulators were investigated experimentally and numerically for a Reynolds number range from 3000 to 17 000[13-14]. The numerical tool was Ansys Fluent with k-ε turbulence model. In 2020, Karouei and Mousavi Ajarostaghi [15] numerically studied the heat transfer and fluid flow in a double□coil heat exchanger with an innovative swirl generator with a curved structure in the inner channel (hot side) using Ansys Fluent CFD software. Besides ordinary fluid, the researchers try to consider the effect of adding nanoparticle in the fluids of the heat exchangers numerically and experimentally. Yadav and Singhai[16] simulated the heat transfer enhancement in a double pipe heat exchanger using a bio-nano fluid and Al2O3-water using Ansys Fluent CFD code. The main purpose of this study is to investigate the heat transfer behavior in a concentric type heat exchanger with a turbulator by considering the addition of Al_2O_3 nano particle with a concentration of 0.002% into the cooling water. In this regard, we intend to add turbulator and nano particle to check the amount and intensity of heat transfer, pressure drop and other parameters inside the pipe Using STAR-CCM+ CFD software.

Methods and Material

2.1 Experimental data

Fig. 1 shows the schematic of the overall system used for data comparison, which includes the acquisition system, thermocouples, measurement equipment, heat exchanger, and other items [13]. These tests were carried out in steady-state and completely flowing conditions.

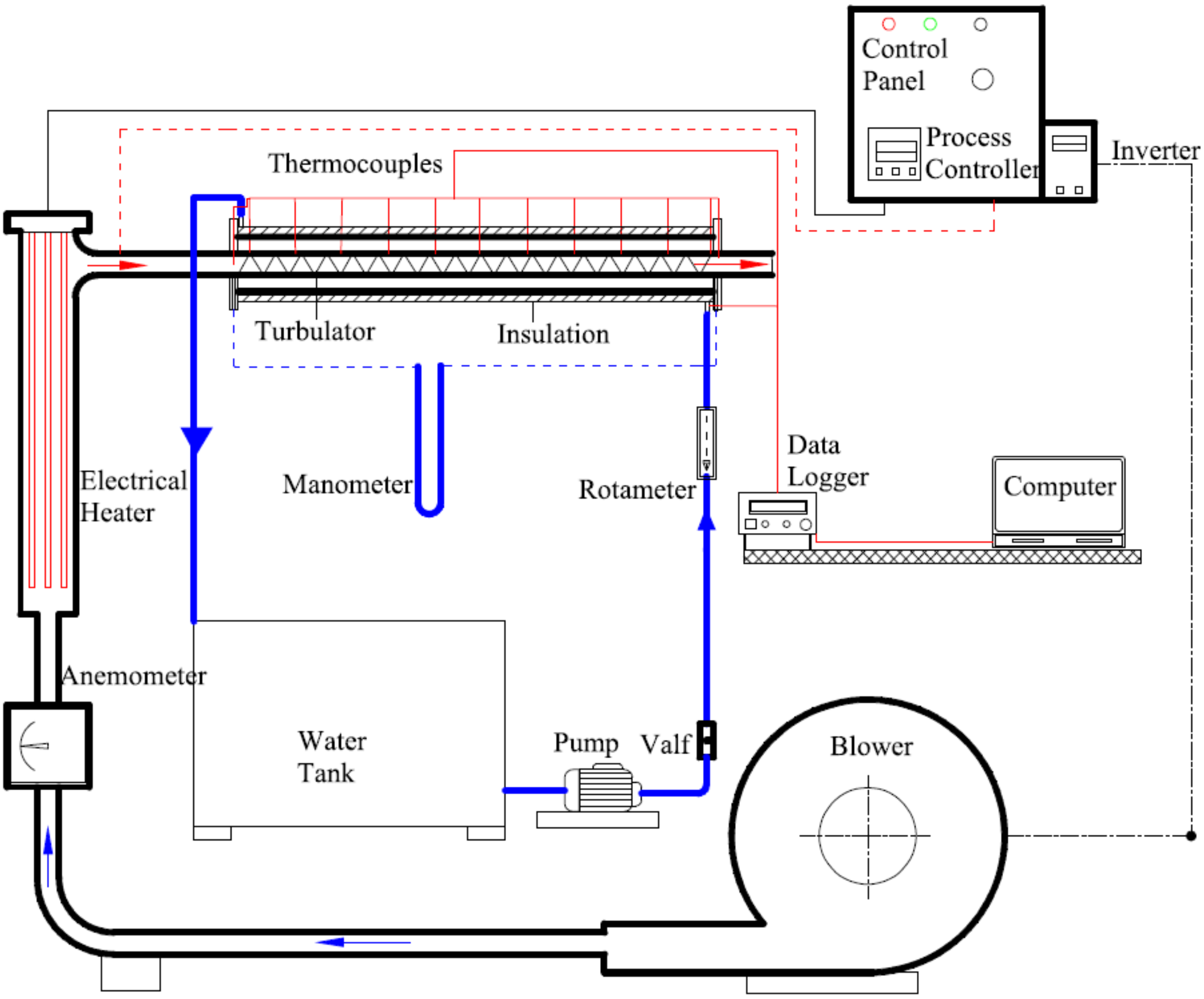

Fig 1: Schematic diagram of the experimental setup [13]

The inlet bulk air at 22 C from the laboratory room was directed through a blower adjusted flow rate. The air was heated up to 100 C by an electrical heater. The heated air velocity was measured by a digital anemometer. The pressure drop of the hot air across the test section was measured by U-type manometer with water. The inlet hot air temperature was heated to 100 C and the cold water was at 23 C during the experiments. The cold water in the tank was circulated through the annulus by a pump. The flow rate of the water was controlled by an adjusting valve and measured by a calibrated rotameter. The K-type thermocouples save the temperature measurements [13-14]. The system consists of two concentric pipes (Fig. 2) made of copper and stainless steel that run from inside to outside and contain two fluids.

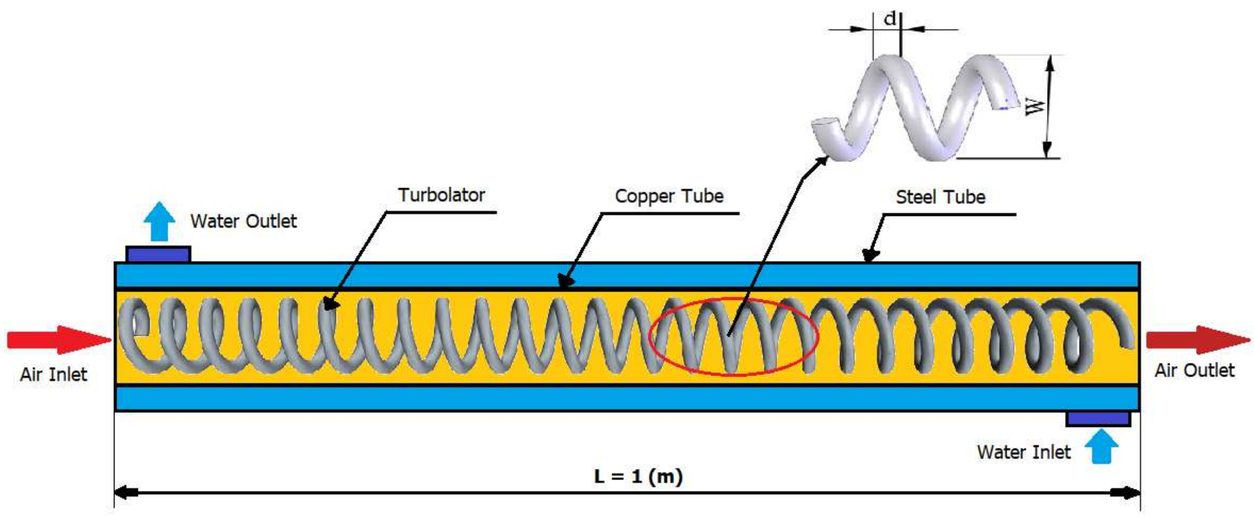

Fig2: A concentric two-tube heat exchanger with turbolator

The diameters of the inner tube and outer tube are 40 mm and 69 mm, respectively. The length of tube (L) is 1000 mm (for fully developed flow), the inner tube is made of copper and its thickness is 1 mm. The outer tube is made of steel, thickness is 3.5 mm. The helical turbulator was inserted into the inner tube for turbulent flow. The helical turbulator is made of stainless steel with different pitches of the helical turbulator were used in the experiments. The dimensions of the helical turbulator are W=37 mm and d =6.5 mm. The fluids are hot air and cold water, which later will be replaced with nanofluid. The fluids enter the system in opposite directions and travel a certain distance along the pipe's path before exiting. It's worth noting that the outside stainless tube was designed to be adiabatic. Specific boundary condition sets, such as input and output conditions for both air and water, are also examined. The experiments were operated at steady-state conditions and fully developed flow for hot air and Re number ranging from 3000 to 17000.

2.2 Numerical method

Numerical analysis was performed using commercial CFD software, STAR-CCM+.

The continuity, momentum and energy equations for the numerical calculation can be written as follows.

$$\frac{\partial}{\partial xi}\ (\rho ui = 0) \tag{1}$$

$$\frac{\partial}{\partial xi}(\rho uiuj) = \frac{\partial}{\partial xi}\left(\mu\frac{\partial uj}{\partial xi}\right) - \frac{\partial p}{\partial xj} \tag{2}$$

$$\frac{\partial}{\partial xi}(\rho uiT) = \frac{\partial}{\partial xi}\left(\frac{k}{Cp}\frac{\partial T}{\partial xi}\right) \tag{3}$$

Where **ρ** is the density, **u** is the velocity, **μ** is the dynamic viscosity, **p** is the pressure, **k** is thethermal conductivity, **T** is the temperature and **Cp** is the specific heat.

The 400,000 Polyhedral meshed cells with a precision of 4.8 mm are used in calculations (Fig. 3). The Wall Y + on the inner tube wall is below 4 to solve the problem of boundary layer in turbulent regime.

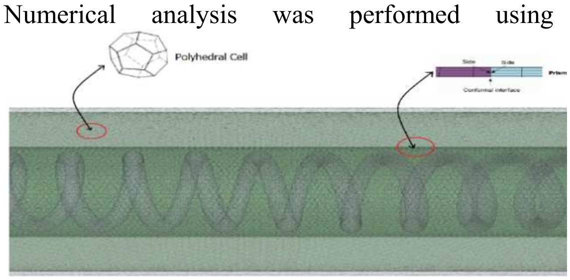

Fig. 3. Schematic of the computational domain

Table 1. shows the characteristics and properties of nanofluid Al_2O_3 (concentration of 0.02%) and water fluid. We have repeated the test for each test separately.

Table 1. Thermo-physical properties of nanoparticle and water fluid:

Unit	ρ (kg/m	C_p(J/kgK	k (W/mK	μ (pa-s
Al2O	3970	765	40	-
Wate	977	4179	0.6	8.8871E

Empirical correlations results for Nu number and friction factor were compared with the experimental and numerical results for the smooth tube, as follows:

Sieder – Tate: Nu = $0.027\times Re^{0.8}\times Pr^{0.33}\times(\frac{\mu}{\mu s})^{0.14}$ - *for Re* (4)

$$Petukhov: Nu = \frac{(\frac{f}{8})Re\times Pr}{1.07+12.7(\frac{f}{8})1/2(Pr-1)} \text{ - fo}$$ (5)

$10^4 < Re < 5 \times 10^6$

Gnielinski: Nu = $(f/8)(Re-1000)Pr / 1+ 12.7 (f/8)^{1/2} (Pr^{2/3}-1)$ - For $3000 < Re < 5 \times 10^6$ (6)

To calculate f or the Friction Factor, we use two methods by Moody and Petokhov:

Moody: $f = 0.31\times Re^{-1/4}$ For $Re < 2\times10^4$ for $Re \leq 2 \times 10^4$ (7)

Petukhov: $f = (0.790 \ln Re - 1.64)^{-2}$ - For $3000 < Re < 5\times10^6$ (8)

2.3 Mesh verification

In short, the higher the mesh accuracy, the larger the mesh cell, and the longer the settling period, the better the resolving accuracy. Mesh accuracy was evaluated in with a minimum of 10,000 mesh cells and a maximum of 500,000 mesh cells. The number of numerical variations in pressure drop was decreased from the range of 400,000 mesh cells, and we utilized the accuracy of 380,000 mesh cells with an accuracy of 4.8 mm to reduce the numerical calculations in less time, as shown in Figure 4:

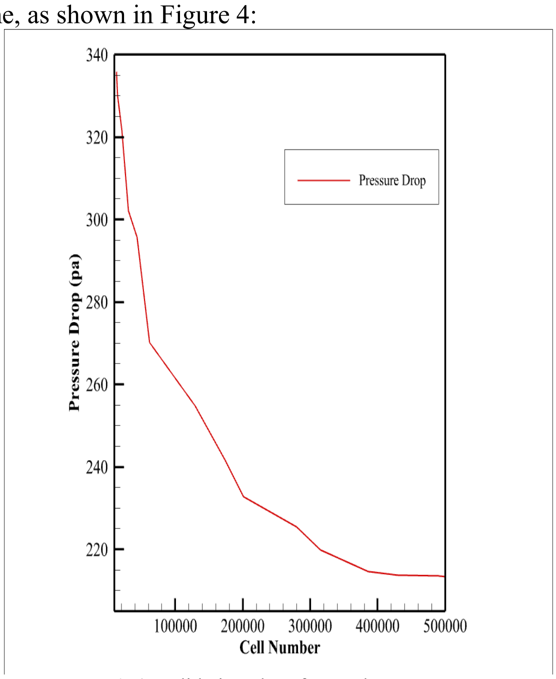

Fig4: Validation chart for mesh accuracy

We have the following figure (**Fig. 5**) in the area of comparing the Nusselt number in the anticipated condition through calculations, numerical and experimental results:

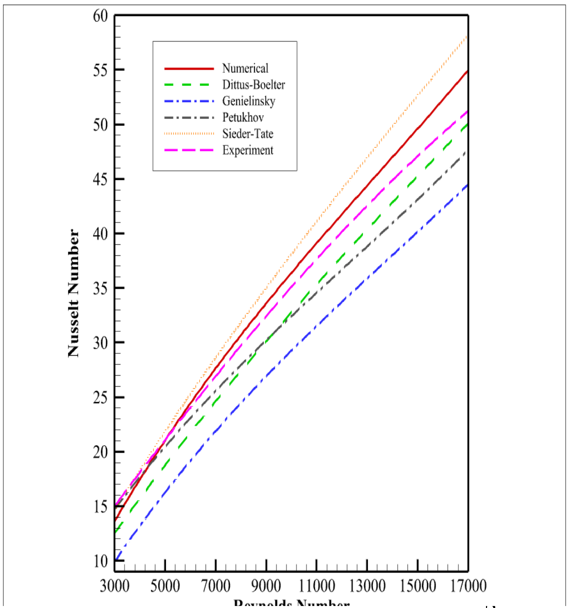

Fig 5: Variation numerical Nusselt number Vs. Reynolds number)

A correlation comparison of the anticipated Nusselt number range with experimental and numerical (Figure 5) findings can be seen in the diagram above. The Dittus-Boelter connection and the experimental, numerical results have a strong relationship.

2.4 Boundary conditions and Solving Method

- Air and Water were incompressible.
- the temperature and velocity of air and water at the inlet of the test section were taken from experiments. Also, air and water leave from the test section.
- The flow was steady-state and assumed to be fully developed turbulent in the model
- The material of tubulator's and outer tube were stainless steel and inner tube is copper.
- The thermo-physical properties of air and water were considered constant.
- The thermo-physical properties of the materials were taken as constant.
- The Steel Tube (outer tube) wall was assumed to be adiabatic.

The STAR-CCM+ uses the source derivatives in the linearization of the discrete, non-linear transport equations. Also, STAR-CCM+ provides an integral finite element solver for the solution of solid mechanics, fluid-structureinteraction, heat conduction, and thermal stress problems.

Results and discussion

3.1 Examining the temperature distribution

The temperature contour and heat transmission within the tube are examined in the accompanying figure 6, which shows the effect of having a turbulator in the system vs. not having one for all turns on the Reynolds 11500:

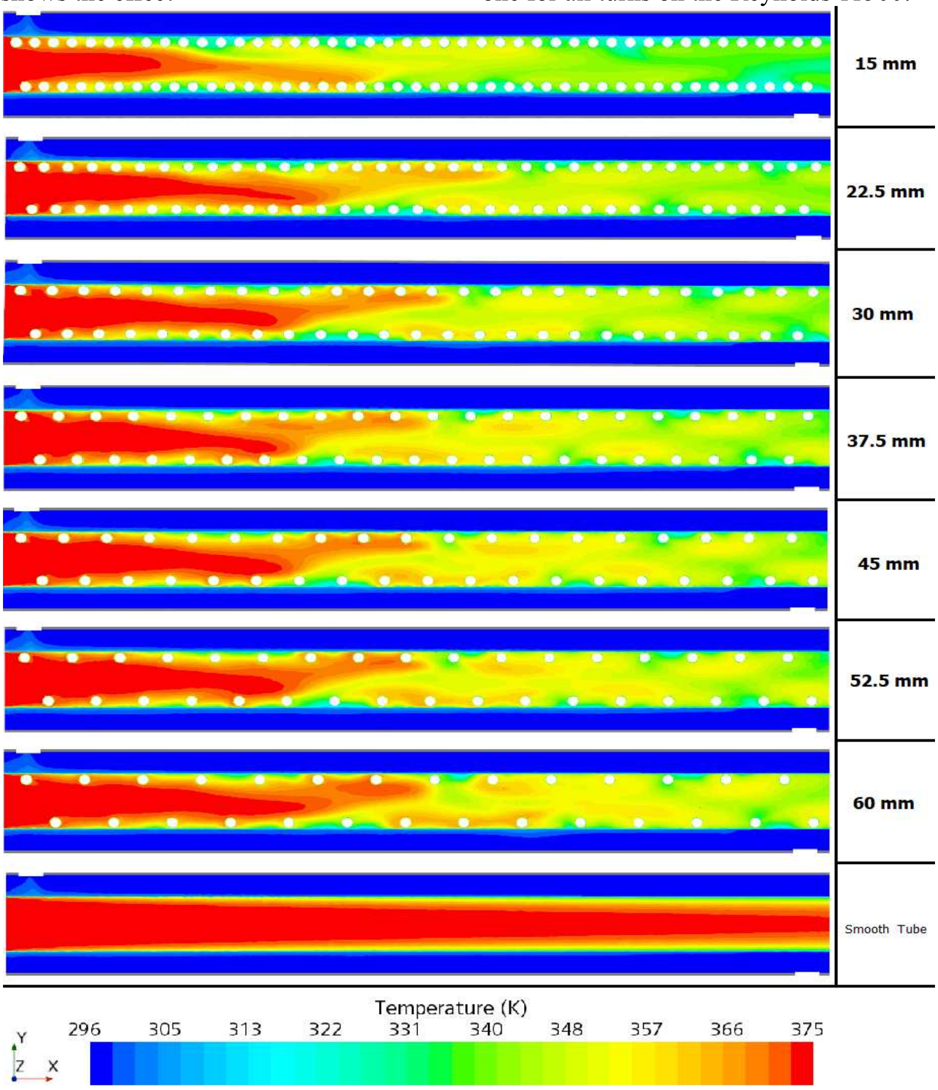

Fig 6: Temperature contour from top to bottom, with Turbulator distances of 15, 22.5, 30, 37.5, 45, 52.5, 60 mm and smooth tube

Another temperature connector (Figure 7) has also been prepared to better display the cooling state inside the pipe at various distances, as well as the heat transfer to the exterior of the pipe, as seen below:

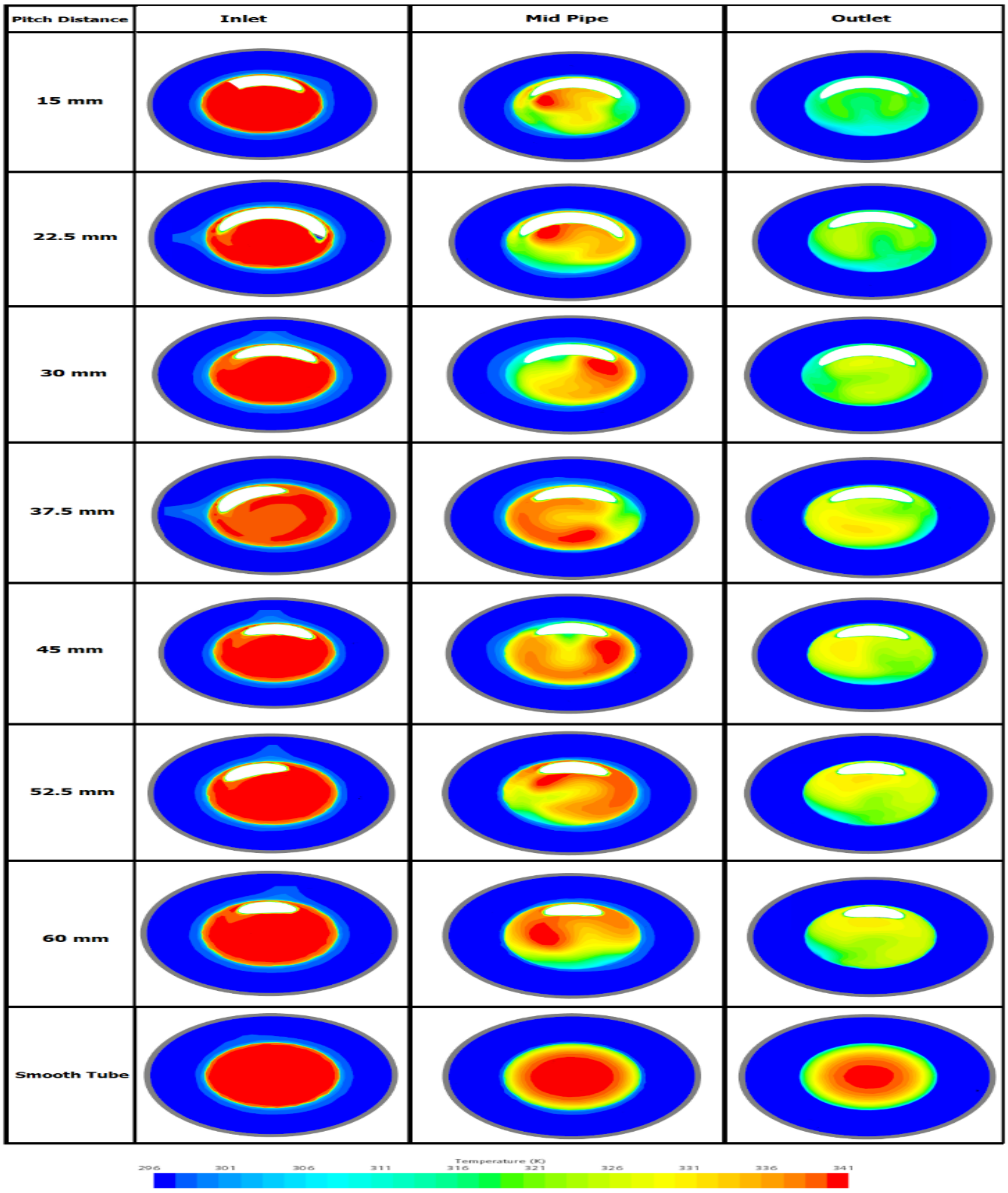

Fig7: HorizontalTemperature contour in Re 11500 from top to bottom, with Turbulator distances 15, 22.5, 30. 37.5, 45, 52.5, 60 mm and smooth tube

Fig. 6 and 7 Depcit the temperature distribution in a horizontal section for the Reynolds range 11500, with turns of 15, 22.5, 30, 37.5, 45, 52.5, 60 mm and no turbulator. The temperature-fluid distribution in each part clearly varies as the screw spacing changes. As the distance between the screws in the center and at the end of the pipe decreases, the internal temperature drops.

3.2 Investigating the Velocity Magnitude:

Figure 8 also shows the Velocity Magnitude in Reynolds 11500, which illustrates the effect of the presence of a turbulator in the system and its role in increasing heat transfer:

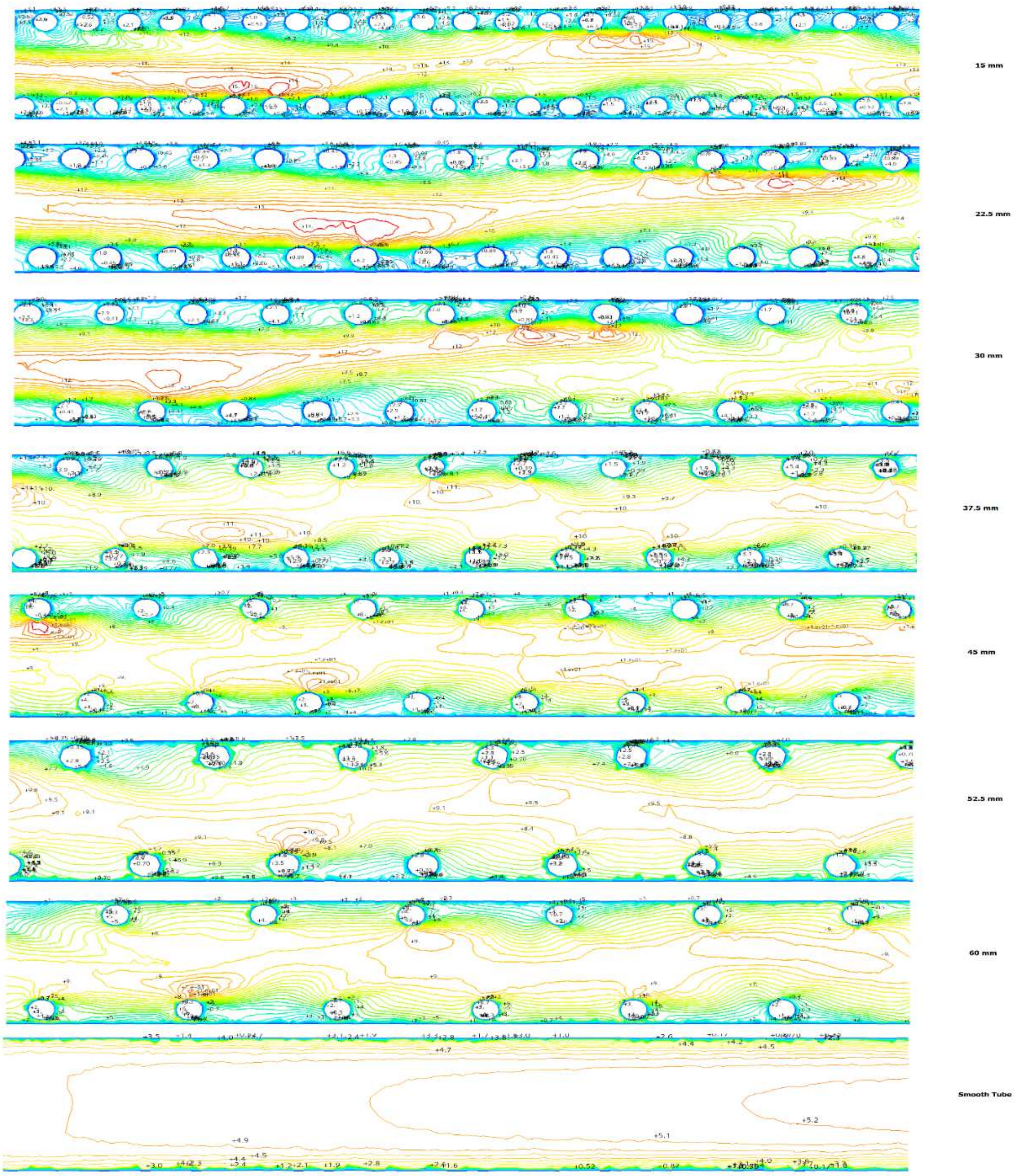

Fig8: Velocity Magnitude for Re 11500 in Selected Region a 15, 22.5, 30, 37.5, 45, 52.5, 60 mm and Smooth Tube

The magnitude of the velocity in a horizontal section (Fig. 8), for a smooth tube with a confounder at different distances (15, 22.5, 30, 37.5, 45, 52.5 and 60 mm) for the Reynolds range 11500 in the middle of the tube, shows that when the distance between the Turbulator Pitches as it decreases, more axial vortices appear, especially near the wall of the tube. Reducing the Turbulator Pitch distance causes turbulence flow, which explains the formation of vortices. In addition, the amount of velocity in the center of the tube reaches its maximum.

3.3 Numerical and Experimental Comparison

In this section, we see the results obtained for numerical data, including Pressure Drop (Fig. 9), Nusselt Number (Fig. 10) and Temperature Difference (Fig . 11):

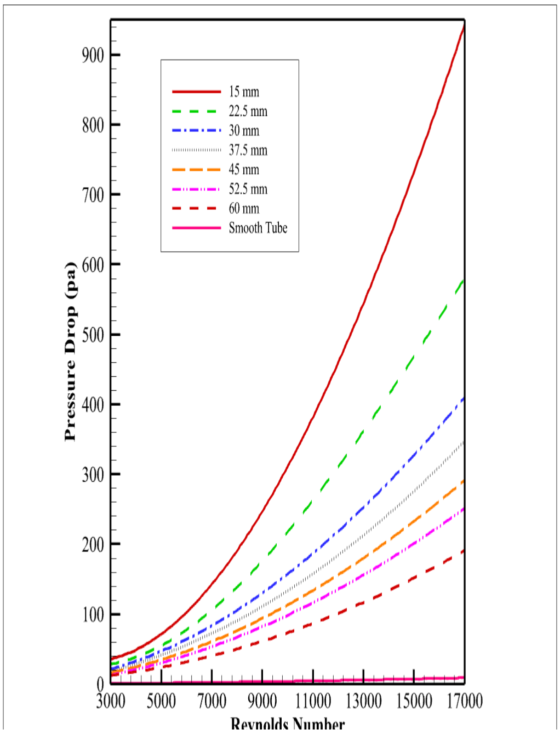

Fig9: pressure drop vs Reynolds for all distances with smooth tube

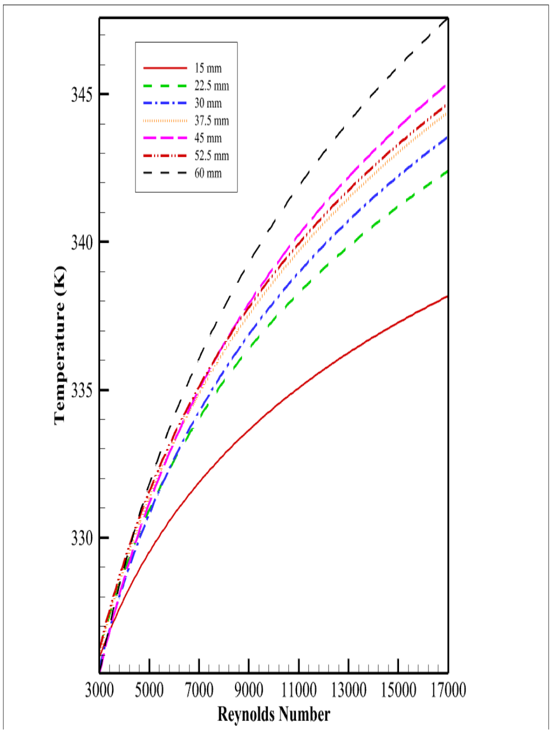

Fig11: Variation numerical Temperature Difference VS. Reynolds number

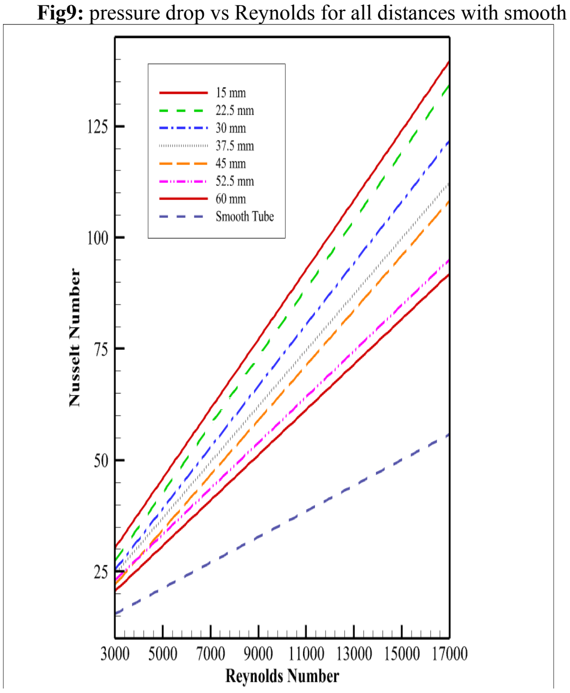

Fig10: Numerical results related to Nusselt number in terms of Reynolds number for all distances with smooth tube

Next, when a nanoparticle (Al_2O_3 with a concentration 0.002%) is introduced into the system is Increases TheNusselt. The results demonstrate that when nanofluid is introduced into the system, the Nusselt number rises. Between water fluid and nanofluid, the Nusselt number changes by around 1 to 1.5 percent on average.

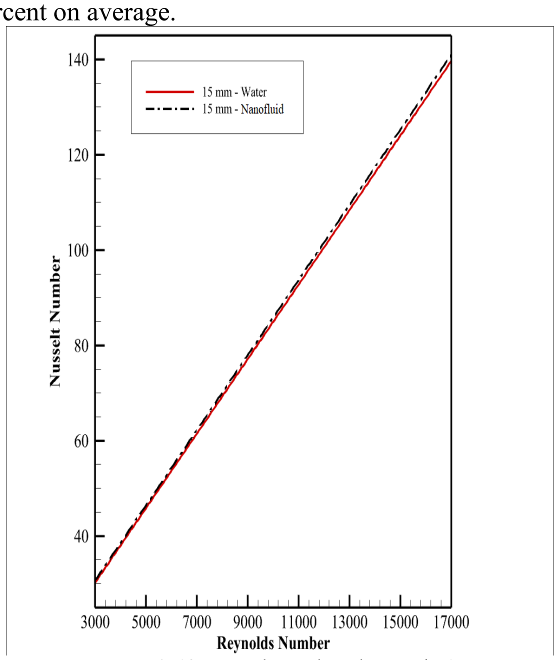

Fig12: Nusselt number changes in 15 mm

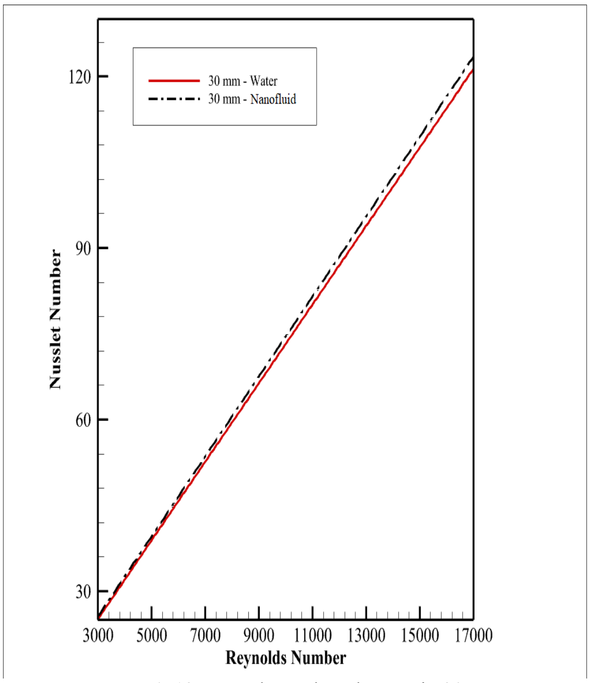

Fig13: Nusselt number changes in 30 mm

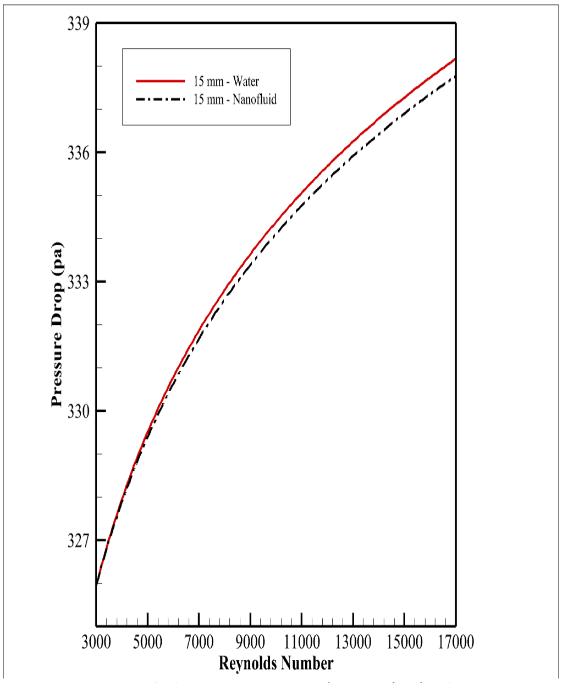

Fig15: Temperature changes in the 15 mm

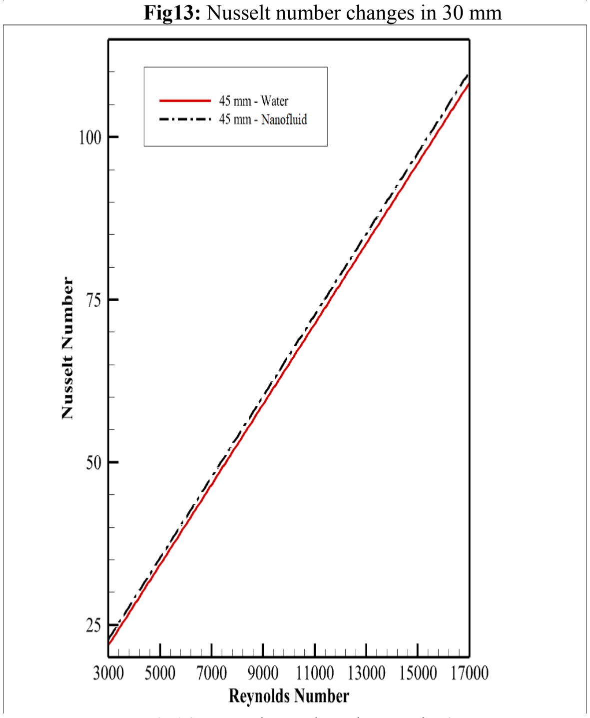

Fig14: Nusselt number changes in 45 mm

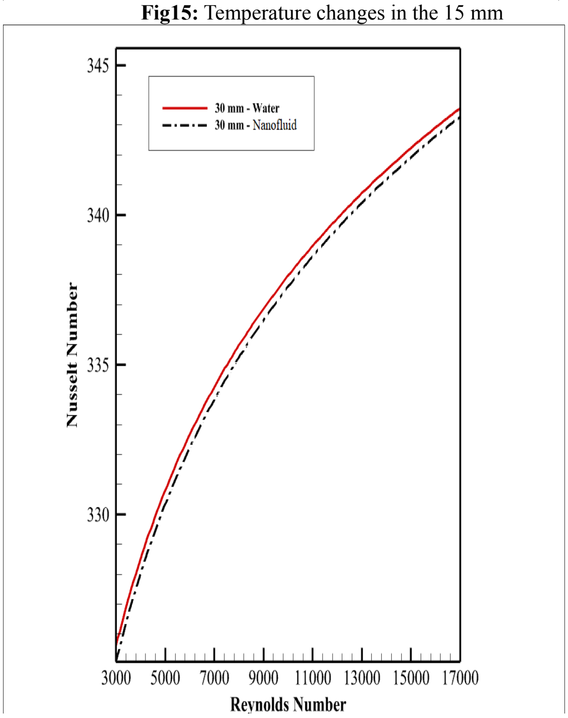

Fig16: Temperature changes in the 30 mm

Another change that occurs when nanoparticle (Al_2O_3 – 0.002%) is introduced into the system is a reduction in temperature. The temperature variations before and after the addition of nanofluids are depicted in the figures below:

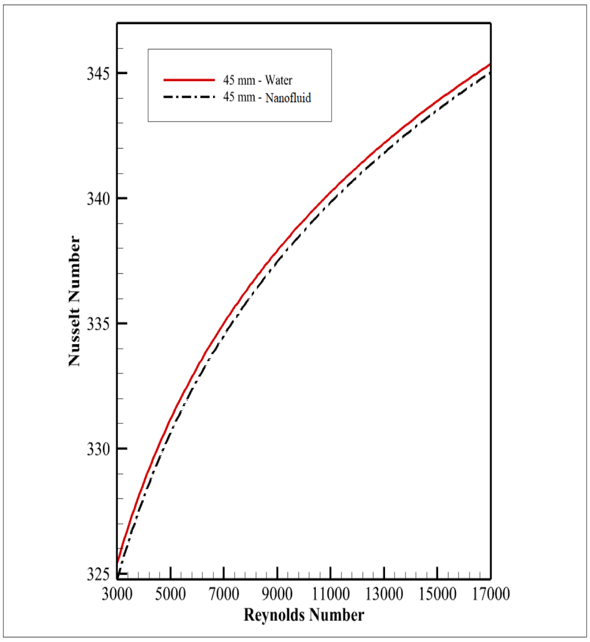

Fig17: Temperature changes in the 45 mm

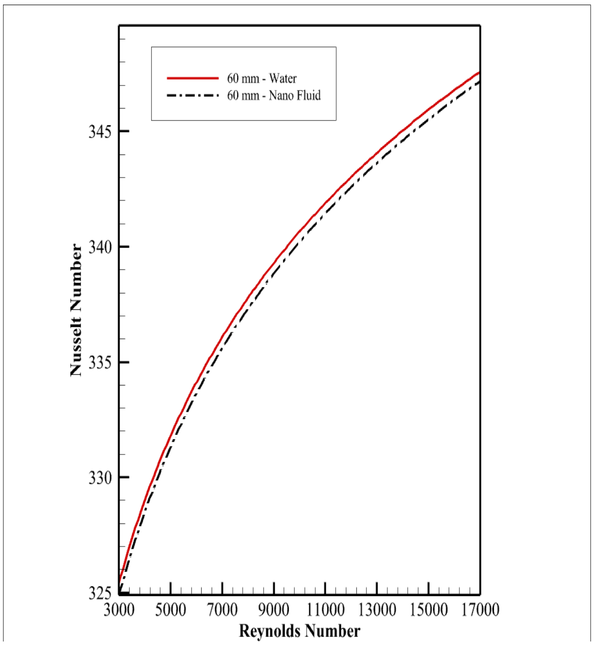

Fig18: Temperature changes in the 60 mm

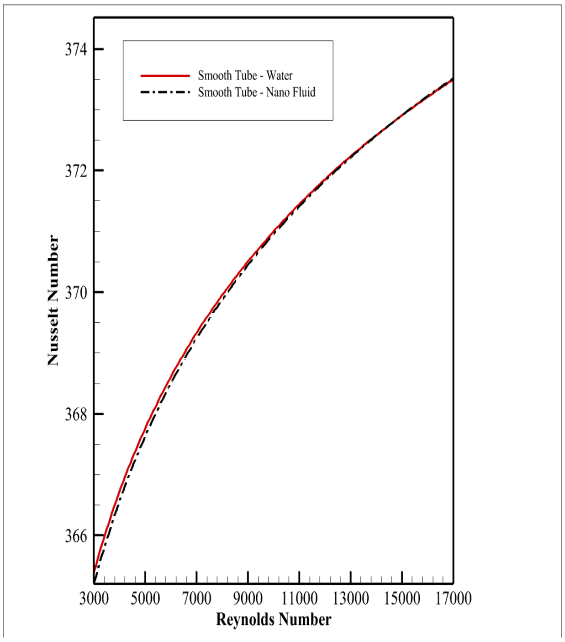

Fig19: Temperature changes in a Smooth Tube

The temperature lowers substantially with the addition of nanofluid, as seen in the figures above. It's worth noting that when the turbulator is removed from the system, we still notice a drop in temperature, but it's much less than when the turbulator is present. In general, adding nanofluid to a tube can lower the temperature inside it. Temperature differences between water and nanofluid ranged from 0.5 to 1%. Comparative diagrams of pressure drop versus Reynolds number for experimental and numerical results at four distances (15, 30 and 45 mm) can be seen in the following Figures. The results are almost well correlated, which somehow confirms our computational work with STAR-CCM + software. Comparison of numerical and experimental findings of Pressure Drop vs. Reynolds Number at 15, 30, and 45 mm Pitches. (Fig. 19-21):

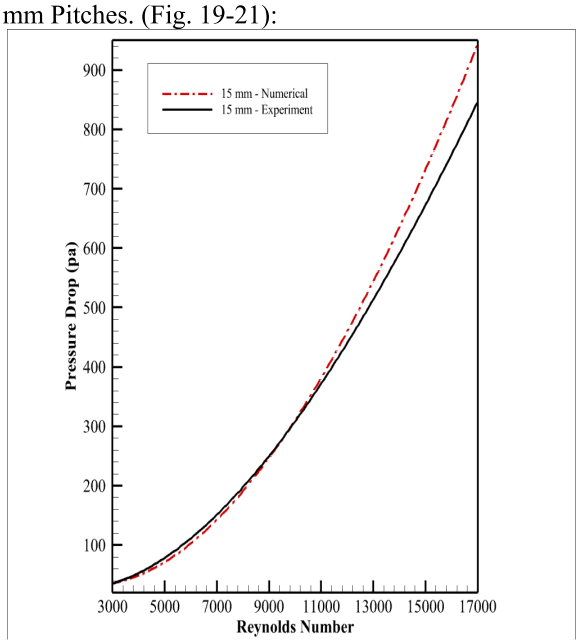

Fig20: Pressure Drop Changes in 15 mm

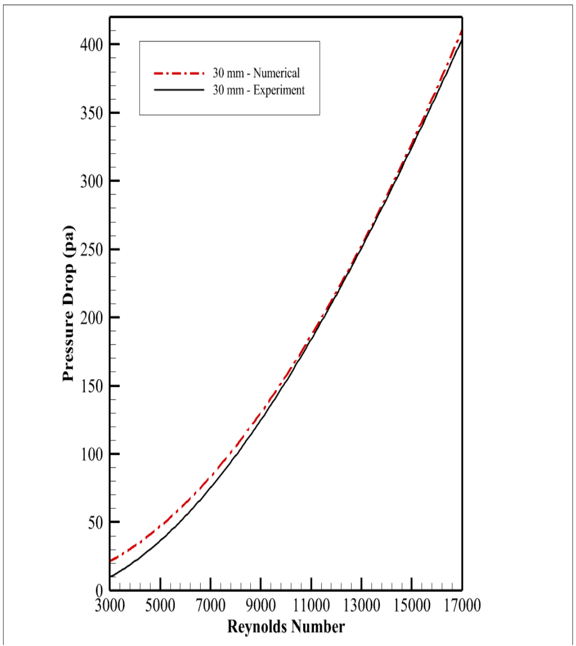

Fig21: Pressure Drop Changes in 30 mm

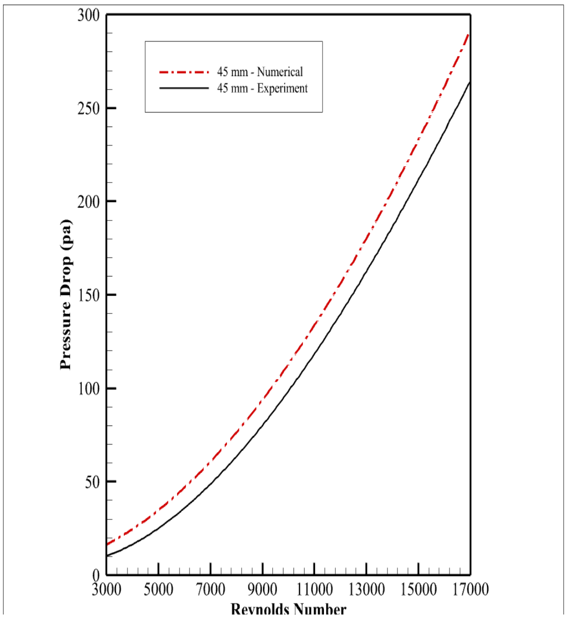

Fig22: Pressure Drop Changes in 45 mm

The aforementioned results demonstrate that experimental and numerical calculations are strongly connected and that this correlation is adequate for all three Pitches of 15, 30, and 45 mm. The accuracy of STAR-CCM+ software is superior to the article's numerical results in several areas.

The following graphs show a comparison of the Nusselt vs. Reynolds number for experimental and numerical findings at four distances (15, 30, 45 mm, and an Smooth tube). The results are nearly identical, confirming our computational work using the STAR-CCM + program.

Nusselt number VS Reynolds numerical and experimental findings at distances of 15, 30, and 45 mm (Fig. 22, 23, and 24):

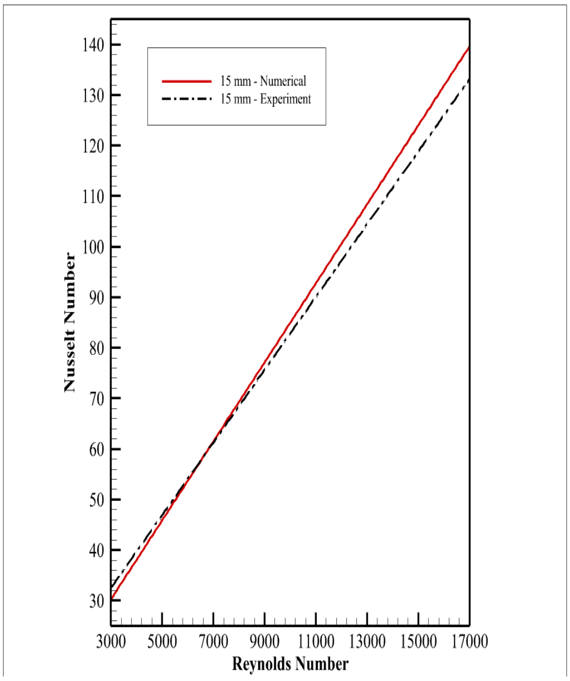

Fig23: Nusselt Number Changes in 15 mm

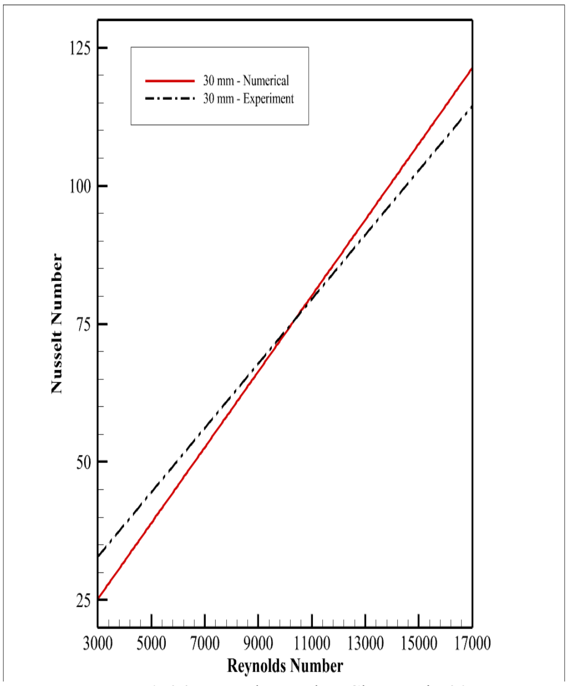

Fig24: Nusselt Number Changes in 30 mm

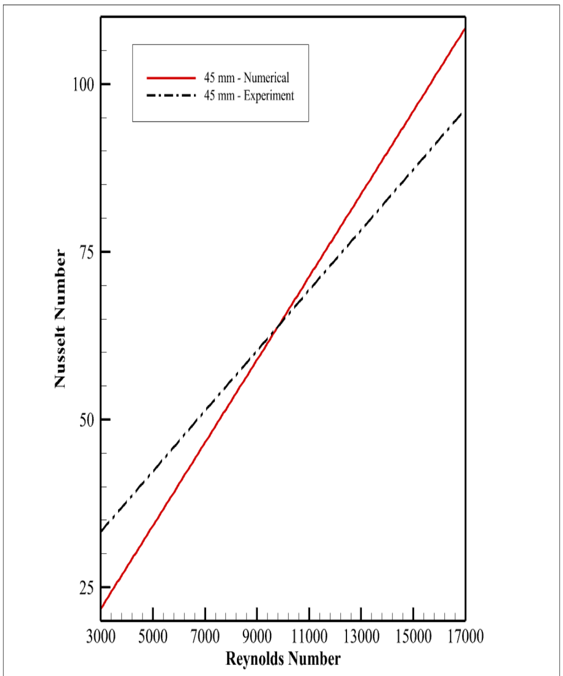

Fig25: Nusselt Number Changes in 45 mm

One more time, The aforementioned results demonstrate that experimental and numerical calculations are strongly connected and that this correlation is adequate for all three Pitches of 15, 30, and 45 mm. The accuracy of STAR-CCM+ software is superior to the article's numerical results in several areas.

4. Conclusion

- The effects of turbulator on heat transfer and pressure drop characteristics, Nusselt number, and velocity were investigated experimentally and numerically for a new type of concentric Type Heat Exchanger with turbulator at various distances. The following offers a summary:
- In a concentric tube heat exchanger with a turbulator, the STAR-CCM+ Code was effectively employed for heat transfer and pressure drop analysis.
- The STAR-CCM+ program effectively extracted data relating to pressure drop, Nusselt number, velocity, and other factors.
- We noticed a rise in the Nusselt number at all intervals for the turbulator.
- However, when the Reynolds number increases, the Nusselt number increases as well.
- When compared to enhanced heat transmission, pressure drop values are minimal.
- The addition of nanoparticle Al_2O_3 with 0.02% concentration lowers the temperature and, thus, raises the Nusselt number.
- The findings show an effective improvement in heat transfer performance as well as a reduction in heat exchanger size.
- Experimental testing may be made cheaper and faster by using numerical calculations.
- Experimental investigations give a more thorough understanding of heat transfer and current distribution than numerical simulations.
- The heat transmission is efficiently increased by increasing the number of pitches, according to numerical values computed using software for temperature decrease along the pipe. Heat transfer without a turbulator is minimal when compared to a flat tube.
- Numerical calculations obtained for Velocity Magnitude at three different distances showed that increasing speed is directly related to increasing Reynolds number.
- By checking the accuracy of the problems, time can be saved for solving and analyzing the study.

References

[1] Zhnegguo, Zhang, Xu Tao, and Fang Xiaoming. "Experimental study on heat transfer enhancement of a helically baffled heat exchanger combined with three-dimensional finned tubes." *Applied Thermal Engineering* 24, no. 14-15 (2004): 2293-2300.

[2] Neshumayev, Dmitri, ArvoOts, Jaan Laid, and Toomas Tiikma. "Experimental investigation of various turbulator inserts in gas-heated channels." *Experimental Thermal and Fluid Science* 28, no. 8 (2004): 877-886.

[3] Yakut, Kenan, and Bayram Sahin. "Flow-induced vibration analysis of conical rings used for heat transfer enhancement in heat exchangers." *Applied Energy* 78, no. 3 (2004): 273-288.

[4] Yildiz, Cengiz, Yaşar Biçer, and Dursun Pehlivan. "Effect of twisted strips on heat transfer and pressure drop in heat exchangers." *Energy Conversion and Management* 39, no. 3-4 (1998): 331-336.

[5] Durmuş, Aydın. "Heat transfer and exergy loss in cut out conical turbulators." *Energy Conversion and Management* 45, no. 5 (2004): 785-796.

[6] Eiamsa-ard, Smith, and PongjetPromvonge. "Enhancement of heat transfer in a tube with regularly-spaced helical tape swirl generators." *Solar energy* 78, no. 4 (2005): 483-494.

[7] Kurtbaş, İ., Durmuş, A., Eren, H. and Turgut, E., 2007. Effect of propeller type swirl generators on the entropy generation and efficiency of heat exchangers. *International Journal of Thermal Sciences*, *46*(3), pp.300-307.

[8] Gül, H. and Evin, D., 2007. Heat transfer enhancement in circular tubes using helical swirl generator insert at the

entrance. *International Journal of Thermal Sciences*, *46*(12), pp.1297-1303.

[9] Zamankhan, P., 2010. Heat transfer in counterflow heat exchangers with helical turbulators. *Communications in Nonlinear Science and Numerical Simulation*, *15*(10), pp.2894-2907.

[10] Eiamsa-ard, S., Pethkool, S., Thianpong, C. and Promvonge, P., 2008. Turbulent flow heat transfer and pressure loss in a double pipe heat exchanger with louvered strip inserts. *International Communications in Heat and Mass Transfer*, *35*(2), pp.120-129.

[11] Naphon, P. and Suchana, T., 2011. Heat transfer enhancement and pressure drop of the horizontal concentric tube with twisted wires brush inserts. *International Communications in Heat and Mass Transfer*, *38*(2), pp.236-241.

[12] Turgut, E., Çakmak, G. and Yıldız, C., 2012. Optimization of the concentric heat exchanger with injector turbulators by Taguchi method. *Energy conversion and management*, *53*(1), pp.268-275.

[13] Şahin, H.M., Baysal, E. and Dal, A.R., 2013. Experimental and numerical investigation of thermal characteristics of a novel concentric type tube heat exchanger with turbulators. *International journal of energy research*, *37*(9), pp.1088-1102.

[14] Şahin, H.M., Baysal, E., Dal, A.R. and Şahin, N., 2015. Investigation of heat transfer enhancement in a new type heat exchanger using solar parabolic trough systems. *International journal of hydrogen energy*, *40*(44), pp.15254-15266.

[15] HashemiKarouei, S.H. and Mousavi Ajarostaghi, S.S., 2021. Influence of a curved conical turbulator on heat transfer augmentation in a helical double□pipe heat exchanger. *Heat Transfer*, *50*(2), pp.1872-1894.

[16] Yadav, R.K. and Singhai, A., 2020. Heat Transfer Enhancement in a Double Pipe Heat Exchanger using Bio-Nano fluid (Mango-Bark) using CFD. *International Journal of Innovative Research in Technology*, *6*(9), 123-130.