

Experimental Investigation of Thermal Enhancement using CuO-Water Nanofluid in a Tube Equipped with Helical Turbulators

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Abstract

Nanofluids and turbulators have gained significant interest because they improve heat transfer. Experimental investigations were performed using 12 mm and 18 mm pitch helical coil turbulator along with CuO-water nanofluids on counter flow concentric heat exchanger. CuO nanoparticles were synthesized using sol-gel process and two-step process was used to prepare CuO-water nanofluids of 0.025% volume concentration. The concentric heat exchanger was designed, where hot fluid at 70° C flowed at 5.01 LPM and cold fluid at 25° C circulated through the inner tube at 5.60-10.4 LPM. Experimental findings reveal that dispersing CuO nanoparticles in water led to enhancements in heat transfer. Overall heat transfer coefficients for CuO-nanofluid is increased by 5-8.64 % across flow rates 5.60-10.4 LPM compare to pure water. The study shows that 12 mm turbulator enhanced more heat transfer than 18 mm turbulator in pure water and nanofluids. Overall heat transfer coefficients for 18 mm turbulator and 12 mm turbulator increased by 24.66-31.18%; 36-47.08 % respectively and pressure drop increased by 309.09-560%; 454.55-716 % respectively across flow rates ranging from 5.60-10.4 LPM compare to water without turbulator. The highest overall heat transfer coefficients was found 51.01 % for CuO-water nanofluids with 12 mm turbulator at 10.4 LPM compare to CuO-water nanofluids without turbulator. Overall, the findings indicate that smaller-pitch helical turbulator intensify turbulence and CuO nanoparticles improves thermal properties of water thereby improving heat transfer, although it results in a noticeable rise in pressure losses.

Keywords: Nanofluids, nanoparticles, turbulator, Heat transfer, Pressure drop

1. Introduction

The modern world is growing rapidly which is possible due to conventional as well as renewable sources of energy. To cope with environmental impacts, limited energy resources, focus on the optimization of the component of the system to reduce energy consumption is necessary. One effective method to achieve this is by optimizing heat exchangers. A heat exchanger transmits heat from one fluid (liquid or gas) to another without mixing them. Heat exchangers are essential components in many industrial sectors such as power plants, chemical industries, and heating-cooling systems. Heat exchangers are the important part of the many machines because of its role of heating and cooling fluids according to the application.

Concentric heat exchangers consist one pipe inside another, are widely recognized for their simplicity, ease of maintenance, and efficiency. However, as the desire for higher efficiency and more compact designs develops, existing heat transfer mechanisms in concentric heat exchangers are being challenged to their limitations. This has led the development of new heat transfer strategies targeted at improving the thermal performance of these systems.

The efficiency of a heat exchanger can be improved by optimizing design parameters, utilizing fluids with high thermal conductivities etc. One promising method used to increase effectiveness of heat exchanger is to use hybrid nanofluids. Nanofluids can enhanced the thermal performance of heat exchanger systems (Akyürek et al., 2018). Nanofluids, produced through one-step and two-step methods, are stable and highly conductive but face issues with nanoparticle agglomeration, which is a crucial issue (Said et al., 2022).

Nanofluids increase temperature difference due to Brownian motion and agglomeration. Dispersing nanoparticles in base fluids leads to Brownian motion, increasing thermal conductivity. The aggregation of nanoparticles depends on the synthesis method and purity of the nanoparticles. Green synthesis is a promising cost-effective and eco-friendly method for nanofluids, with potential applications in engineering (Narayanan and Rakesh, 2019).

The sol-gel process is generally used to synthesize metal oxide nanoparticles. In this process, the precursor is dissolved in water/alcohol which is heated to convert into a gel. The gel is then dried, powdered, and calcined. The properties of nanoparticle depend on the drying method of gel. (Bokov et al., 2021).

Another popular way for improving heat exchanger performance is to employ a turbulator. Turbulators are often employed in heat exchangers to interrupt the fluid's laminar flow, which improves heat transmission. To maintain a constant heat transfer area in heat exchangers while improving heat transfer performance, a range of turbulators are used. However, the pressure drop is significant and varies with the type of turbulator and flow conditions (Çelik and Erbay, 2021).

Rajendra et al., (2016) presents a technique to improve the efficiency of shell and tube heat exchangers by increasing heat transfer surface area through rough surfaces and grooved tubes, as well as strategies to promote turbulence within heat exchanger tubes using inserts.

Shabi et al., (2024a) performed an experimental study on shell and helical coiled heat exchanger incorporating Al_2O_3 nanoparticles. The research revealed that nanoparticles greatly enhanced the rate of heat transfer within the helically coiled tube. Shahmohammadi & Beiki, (2016) conducted a numerical study of Al_2O_3 water nanofluids in a shell and tube heat exchanger. The research found that both heat transfer and pressure drop rose with increased mass flow rate and a greater number of baffles.

Ghashim, (2021) conducted CFD simulations on nanofluids in pipes with uniform heat flux. The addition of Al_2O_3 -Cu particles restrict thermal boundary layer growth, increasing bulk temperature and heat transfer coefficient. The study shows that the Nusselt number (Nu) ratio of Al_2O_3 -Cu-water increases with concentration of nanoparticles in the water.

In this study, the various parameters of the concentric heat exchanger will be changed to see the effect of changes in heat transfer and flow behaviour inside the tube such as changing the size of turbulators and incorporating nanoparticles into conventional fluids. The results are anticipated to support the design of more compact and efficient heat exchangers by enhancing the thermal behavior of conventional fluids and boosting the heat-transfer performance of nanofluids used with various turbulator configurations.

2. Methodology

2.1 Synthesis of Nanoparticles

CuO nanoparticles were synthesized using the Sol-Gel process in the chemistry lab in the Department of Applied Sciences and Chemical Engineering, Pulchowk Campus. The chemicals used to synthesize CuO were: $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, NaOH, Citric acid and distilled water and following the process explained by (Radhakrishnan & Beena, 2014).

2.2 Nanofluid Preparation

For this study, thermophysical properties used for CuO Nanoparticles are shown in Table 1. (Alosious et al., 2017).

Table 1: Properties of CuO nanoparticles

Material	CuO
Diameter	<50nm
Purity	99%
Density	6510 kg/m ³
Specific Heat Capacity	540 J/kgK
Thermal Conductivity	33 W/mK

A two-step method was used to prepare nanofluid. The fixed volume concentration of nanoparticles was taken i.e. $\phi = 0.025\%$. The required amount of CuO was precisely weighed using digital electronic balance and added to the beaker containing distilled water and it was stirred with a magnetic stirrer for 5 minutes. After that, the beaker was transferred to the ultrasonic cleaner with ultrasonic frequency of 40 KHZ. To blend the mixture properly the sonication process was done for 90 minutes. After the process, no agglomerations of particles were seen. To prevent agglomerations of particles, the experiment was conducted within 5/6 hours from the sonication process. Fig. 1 shows the CuO water nanofluid after sonication process.



Fig. 1: CuO-water nanofluid after sonication

2.3 Properties of Nanofluid

Testing the thermal properties of nanofluids is critical for understanding their behavior and possible uses, particularly in heat transfer and cooling systems. Specific heat capacity, thermal conductivity, and density were calculated theoretically.

a) Density

The nanofluid density (ρ_{nf}) is determined through the physical mixture rule, considering the densities of the base fluid (ρ_f) and nanoparticles (ρ_{np}) along with the volume concentration ϕ (Alosious et al., 2017)

$$(\rho)_{nf} = \phi (\rho)_{np} + (1 - \phi) (\rho)_f \quad (1)$$

b) Specific heat capacity

The specific heat capacity of nanofluid ($c_{p,nf}$) is also calculated using the physical mixture rule, which provides a good agreement with the experimental works (Xuan & Roetzel, 2000).

$$(\rho c_p)_{nf} = (1 - \phi)(\rho c_p)_f + \phi(\rho c_p)_{np} \quad (2)$$

Where, $(\rho)_{np}$, $(c_p)_f$ and $(c_p)_{np}$ and is density of nanoparticles, specific heat capacity of base fluid and nanoparticles respectively.

c) **Thermal conductivity**

The thermal conductivity is determined via Maxwell model.

$$k_{nf} = \frac{K_{bf} (K_{np} + 2K_{bf} + 2 \phi (K_{np} - K_{bf}))}{(K_{np} + 2K_{bf} - \phi (K_{np} - K_{bf}))} \quad (3)$$

Where K_{bf} is thermal conductivities of base fluid K_{np} , K_{nf} are thermal conductivities nanoparticles and nanofluids respectively.

2.4 Nanoparticle Characterization Technique

In X-ray diffraction and crystallography, the Scherrer equation is a relation that links the dimensions of sub-micrometer crystallites within a material to the widening of a peak in a diffraction pattern. The Scherrer equation applies only to nano-scale crystallites, or more specifically, the size of the coherently scattering domain, which may be less than the crystallite size. The Scherrer equation is written as:

$$D = \frac{k\lambda}{(\beta \cos\theta)} \quad (4)$$

Where, D , K , λ , β , θ represent crystalline size, crystalline shape factor, X-ray wavelength, FWHM of the diffraction peak, and Bragg angle respectively

2.5 Overall Heat Transfer Coefficient

In heat transfer analysis, it's essential to assess the overall heat transfer coefficient (U), which is calculated using the formula below.

$$U = \frac{Q}{A * LMTD} \quad (5)$$

$$Q_{hot} = q * (\rho C_p)_f * (Th1 - Th2) \quad (6)$$

$$Q_{Cold} = q * (\rho C_p)_{hnf} * (Tc2 - Tc1) \quad (7)$$

$$Q = \frac{Q_{hot} + Q_{cold}}{2} \quad (8)$$

$$LMTD = \frac{(Th1 - Tc2) - (Th2 - Tc1)}{\ln(Th1 - Tc2) / (Th2 - Tc1)} \quad (9)$$

Where, $Th1$, $Th2$, $Tc1$, $Tc2$ is inlet and outlet temperatures of hot fluid and cold fluid respectively. A is surface area of inner tube and $LMTD$ represents Logarithmic mean temperature difference (K).

2.6 Experimental Setup

The experimental setup for a counter-flow concentric heat exchanger was developed to investigate its performance under different operating conditions. In a counter-flow system, heat and cold fluids move in opposite directions. Counter-flow heat exchangers was selected because they are more efficient than parallel-flow heat exchangers. They maintain a greater temperature difference between fluids throughout their length, resulting in a higher $LMTD$ and more heat transfer (Krasniqi et al., 2018).

The pressure drops and temperature difference across the heat exchanger at different flow rates are measured for pure water, CuO-nanofluid with and without various turbulator size. The setup consists of primary and secondary heat exchanger, three pumps, two pressure sensor, four thermocouples, two flow sensors, hot water collector etc. The detailed view is shown in Fig. 2.

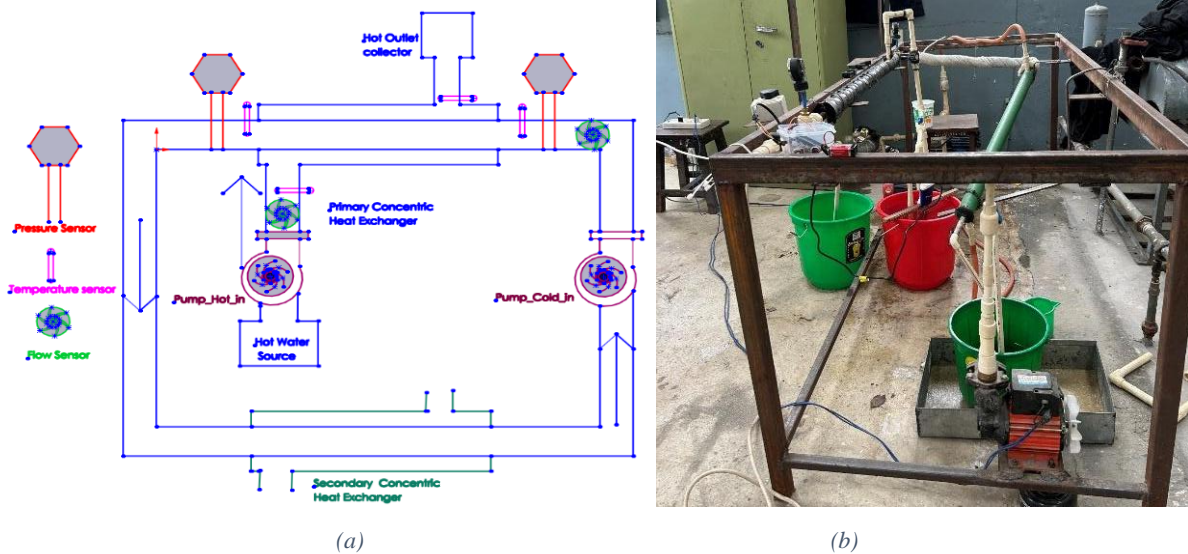


Fig. 2: (a) Experimental layout (b) Fabricated Experimental Setup

Primary Concentric heat exchanger is the main part of the experimental system, temperature, pressure, flow rates etc. are measured across this section. The inner tube is fabricated using copper, whereas the outer shell is fabricated with CPVC material pipe. The shell has external diameters of 35 mm and internal diameters of 27 mm. The shell is covered with the insulator to prevent heat loss to the surrounding. The tube has external and interior diameters of 13 mm and 10 mm, respectively. The length of the shell and tube is 1000 mm and 1060 mm respectively. Secondary Concentric heat exchanger is used to maintain the inlet temperature of the cold nanofluid since nanofluid was re-circulated across the system. Three pumps are installed in the system to circulate fluid.

Four thermocouples are positioned to measure the temperatures of incoming and outgoing cold fluids and hot water. Two pressure gauges are positioned at the entrance and exit of the copper tube to assess the initial pressure of the nanofluid and the pressure decrease following heat transfer in the heat exchanger. At the inlet area of the copper tube and external shell, two flow sensors are placed to measure the flow rate of cold fluids and hot water. Flow readings were recorded using a computer and Arduino, and average values were used for analysis. Two different size of helical coil turbulator are fabricated using mild steel wire of diameter 1 mm. The diameter of coil is 9 mm and pitch is 12mm and 18 mm. Turbulators are used to experiment pressure drop across the system. To heat the water, immersion water heater rod with 1500 W capacity was installed in the system.

2.7 Experimental Procedure

After the fabrication of experimental setup, experimental procedure began. The water tank for secondary heat exchanger is filled, all the pumps, sensor etc. are checked. The Hot water is pre-heated at the temperature of 70°C . The cold fluid at the temperature of 25°C is collected in the collector. The flow sensors are connected to the arduino, the temperature sensors and pressure gauge are observed. All three pumps are run simultaneously and ball valve are adjusted according to the desire flow rate. After the system reached in steady state conditions. The major data such as inlet outlet temperature for cold and hot fluid, pressure and flow rate are measured for the steady state condition. The identical process was repeated by adjusting the operating conditions.

3. Results and Discussion

3.1. Characterization of CuO

CuO nanoparticles was produced using the sol-gel process and assessed for physical and structural properties prior to blending to base fluid. The crystalline structure and phase were studied

through X-ray diffraction (XRD), which revealed the presence of sharp peaks which demonstrate a high degree of crystallinity. The Miller Indices obtained from XRD results of CuO are -111, 111, -202, 202, -113, 022 and 220 is shown in Fig. 3 are in good concordance with the data obtained by (Sagadevan et al., 2017; Radhakrishnan & Beena, 2014). No other peaks were seen, which indicates the formation of pure CuO nanoparticle. The average size of the synthesized nanoparticle was 33 nm.

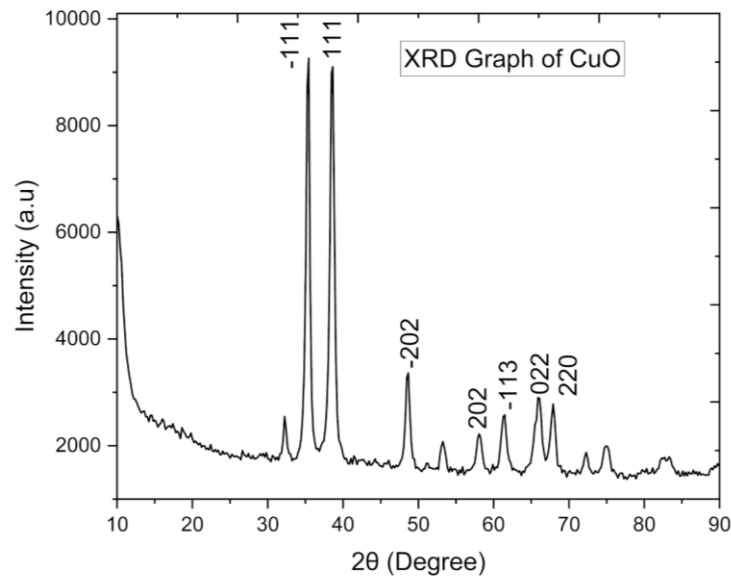


Fig. 3: XRD Graph of CuO

3.2. Comparison of overall heat transfer coefficient at various flow rates for both pure water and nanofluid

When CuO nanoparticles at a volume concentration of 0.025% were introduced to pure water, the overall heat transfer coefficients for CuO-nanofluid increased by 5% to 8.64% at flow rates between 5.60 LPM and 10.4 LPM compared to pure water. This improvement in the overall heat transfer coefficient results from the increased thermal conductivity and surface area offered by the nanoparticles added (Fares et al., 2020). Fig. 4 shows overall heat transfer coefficients in relation to various flow rates for both pure water and nanofluid.

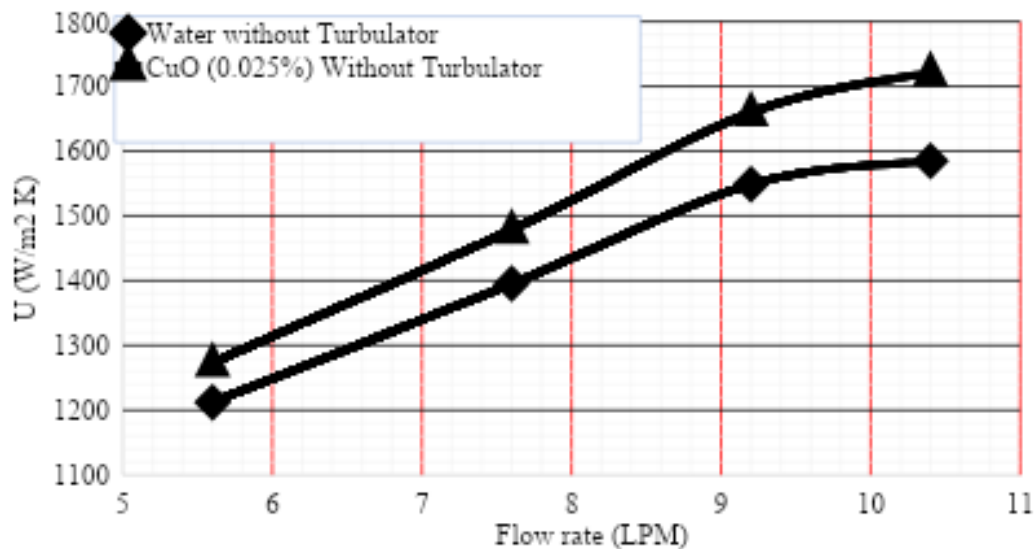


Fig. 4: Overall heat transfer coefficient vs different flow rate for pure water and nanofluid

3.3. Comparison of overall heat transfer coefficient using various turbulators for pure water

Adding 18 mm pitch helical coil turbulator in the inner tube where cold fluid was flowing, overall heat transfer coefficients increased by 24.66 % to 31.18%; across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without turbulator. Replacing 18 mm pitch with smaller pitch turbulator which is 12 mm, overall heat transfer coefficients increased by 36 % to 47.08 % across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without turbulator. Helical coil turbulator with reduced pitch size increases turbulence, thereby improving heat transfer, in agreement with earlier studies (Akyürek et al., 2018). Figure 5 presents the overall heat transfer coefficient in relation to various flow rates with different turbulator.

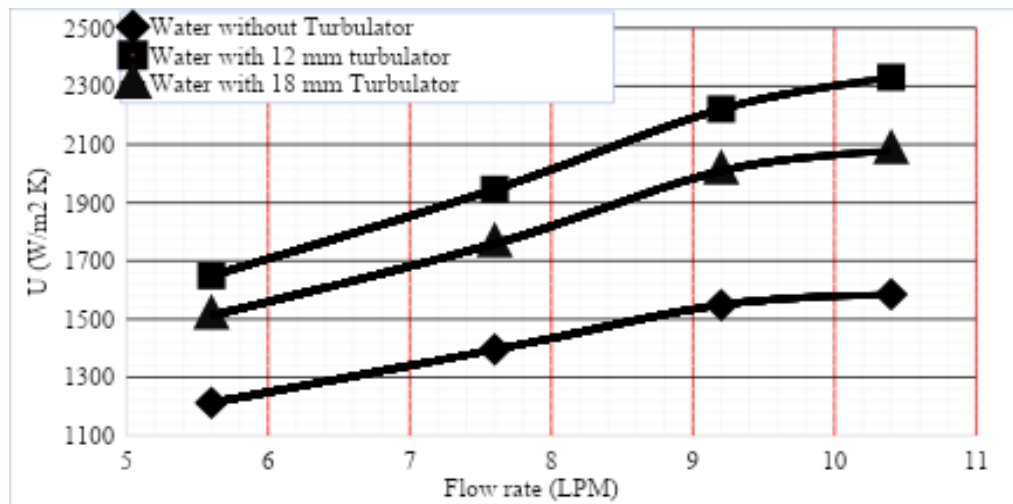


Fig. 5: Overall heat transfer coefficient vs different turbulators for pure water

3.4. Comparison of Overall heat transfer coefficient with different turbulators for CuO-water nanofluid

Overall heat transfer coefficients for 18 mm turbulator and 12 mm turbulator increased by 25.42 % to 33.19 %; 37.49 % to 51.01 % respectively across flow rates ranging from 5.60 LPM to 10.4 LPM compare to CuO-water nanofluid without turbulator. Fig. 6 shows the overall heat transfer coefficient versus different flow rate with different turbulator.

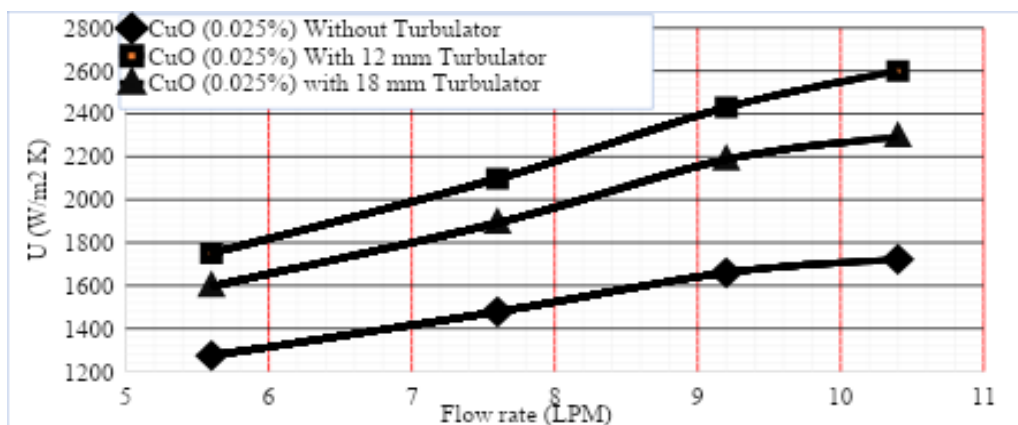


Fig. 6: Overall heat transfer coefficient vs different turbulators for nanofluid

3.5. Comparison of Overall heat transfer coefficient with 18 mm turbulators for pure water and nanofluid

The overall heat transfer coefficients for CuO nanofluid rose by 5.65% to 10.31% across flow rates between 5.60 LPM and 10.4 LPM using an 18 mm pitch turbulator when compared to pure water with an 18 mm turbulator. Fig. 7 shows the Overall heat transfer coefficient versus different flow rate with 18 mm turbulator.

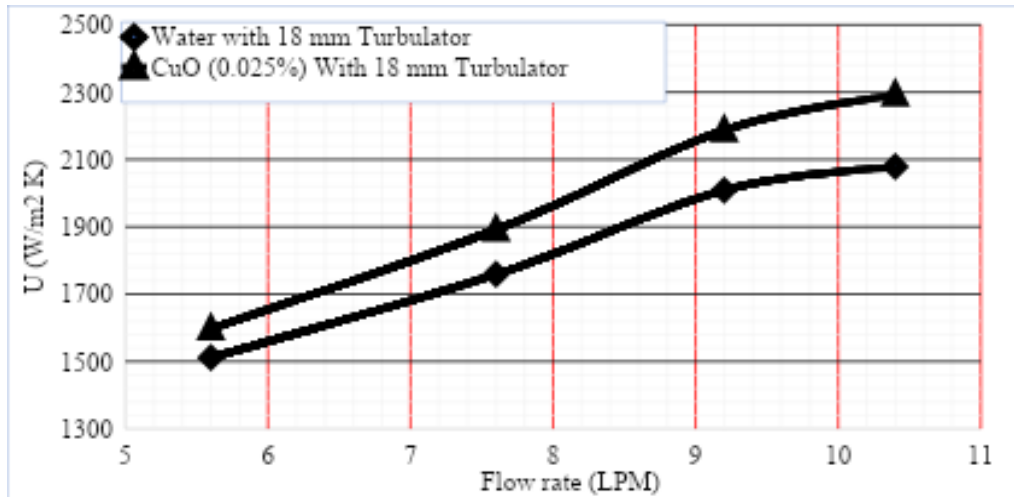


Figure 7: Overall heat transfer coefficient vs different flow rate with 18 mm turbulator

3.6. Comparison of overall heat transfer coefficient with 12 mm turbulators for pure water and nanofluid

Overall heat transfer coefficients for CuO nanofluid increased by 6.15% to 11.54% across flow rates ranging from 5.60 LPM to 10.4 LPM with 12 mm pitch turbulator compare to pure water. Fig. 8 presents the Overall heat transfer coefficient in relation to various flow rates using a 12 mm turbulator.

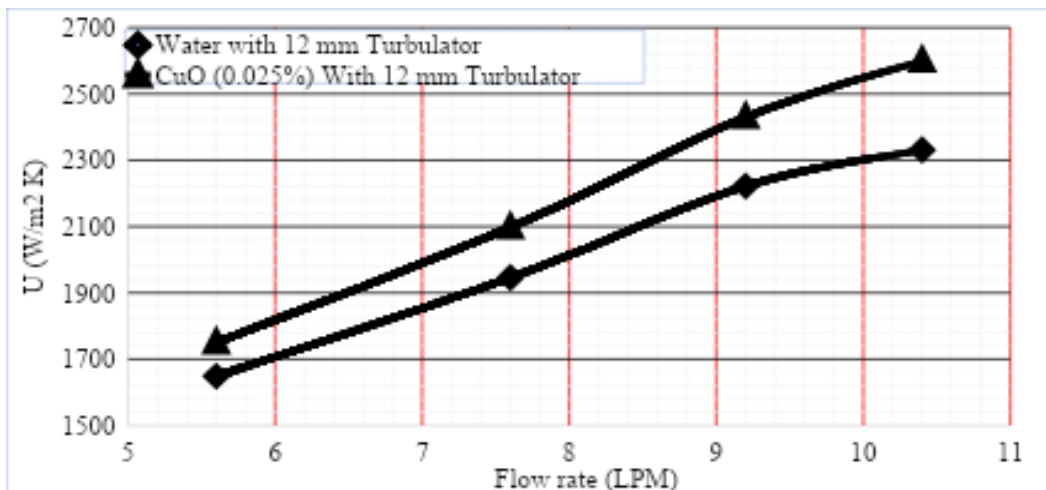


Fig. 8: Overall heat transfer coefficient vs different flow rate with 12 mm turbulator

3.7. Comparison of pressure drop at varying flow rates for pure water and nanofluid

After adding CuO (0.025 %) nanoparticles to the pure water, pressure drop for CuO-nanofluid is increased by 9.09 % to 20 % across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without any turbulator. According to Shabi et al. (2024) this rise in pressure drop results from a

nanoparticle concentration as well as increase in mass flow rate. Fig. 9 illustrate the pressure reduction against various flow rates for both pure water and nanofluid.

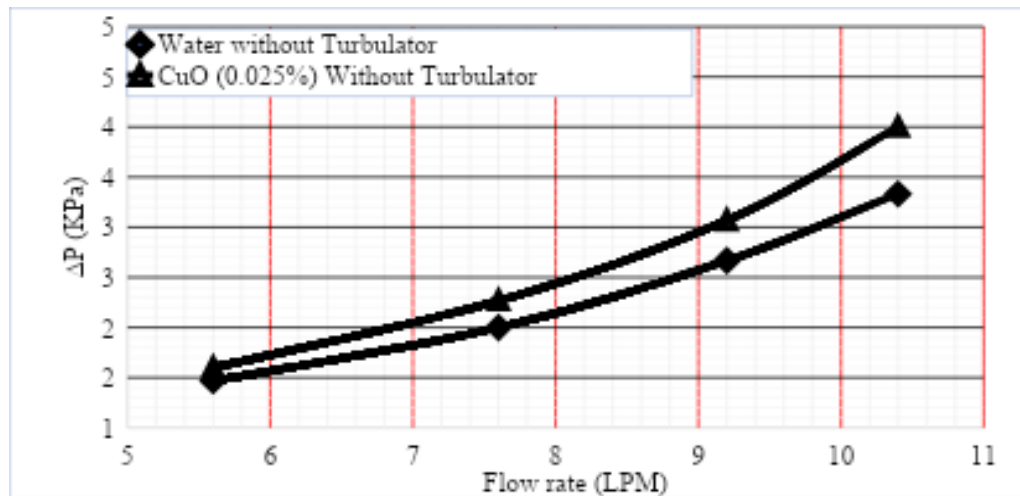


Fig. 9: Pressure drop vs different flow rate for pure water and nanofluid

3.8. Comparison of pressure drop with various turbulators for pure water

Adding 18 mm pitch helical coil turbulator, pressure drop increased by 309.09% to 560%; across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without turbulator. Replacing 18 mm pitch with smaller pitch turbulator which is 12 mm, pressure drop increased by 454.55 % to 716 % across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without turbulator. Lower pitch turbulator create more turbulence leading to more pressure drop. Figure 10 displays the Pressure drop in relation to various flow rates with different turbulators.

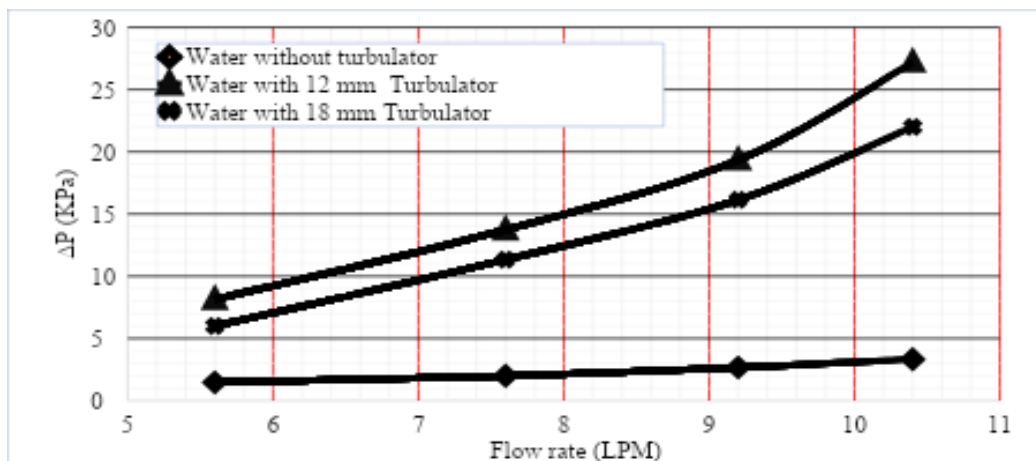


Fig. 10: Pressure drop vs different turbulators for pure water

3.9. Comparison of pressure drop with different turbulators for CuO nanofluid

Pressure drop for 18 mm turbulator and 12 mm turbulator increased by 316.67 % to 563.33%; 475% to 763.33% across flow rates ranging from 5.60 LPM to 10.4 LPM compare to CuO-water nanofluid without turbulator. Figure 11 shows the pressure drop versus different flow rate with different turbulator.

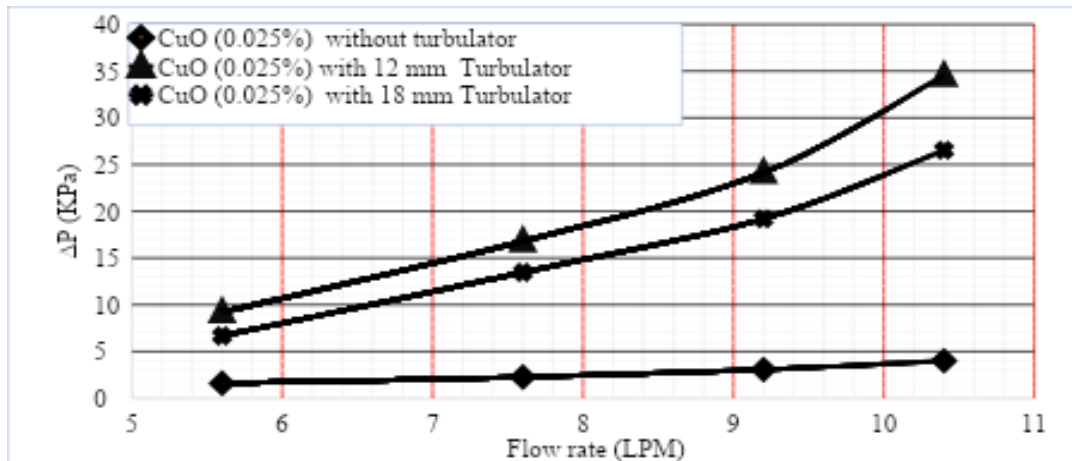


Fig. 11: Pressure drop vs different turbulators for CuO nanofluid

3.10. Comparison of pressure drop with 18 mm turbulators for pure water and nanofluid

Pressure drop for CuO-water nanofluid increased by 11.11% to 20.61% across flow rates ranging from 5.60 LPM to 10.4 LPM with 18 mm pitch turbulator compare to pure water. The increase in pressure drop is contributed by increased density and viscosity due to the addition of CuO nanoparticles in pure water. Fig. 12 shows the pressure drop versus different flow rate with 18 mm turbulator for nanofluid.

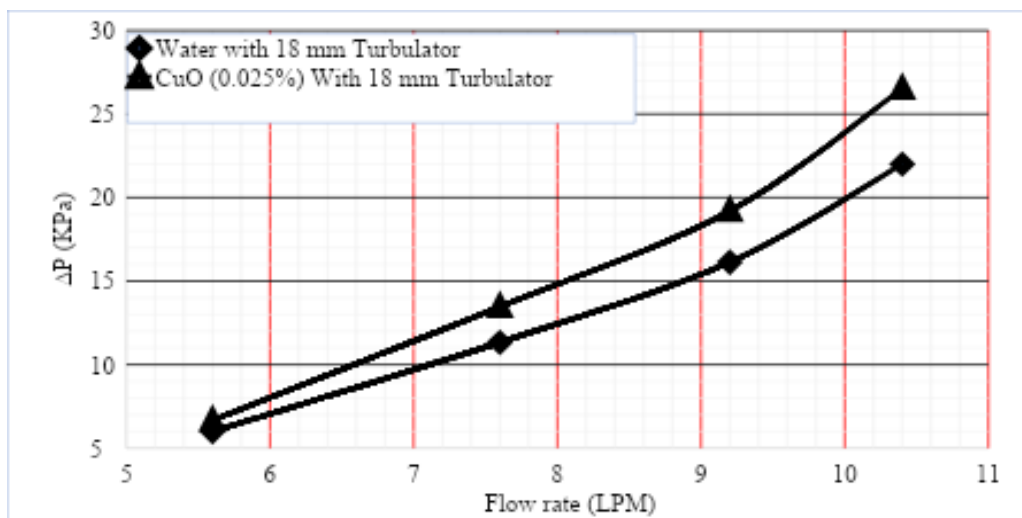


Fig. 12: Pressure drop vs different flow rate with 18 mm turbulator

3.11. Comparison of pressure drop with 12 mm turbulators for pure water and nanofluid

Pressure drop for CuO-water nanofluid increased by 13.11% to 26.96% across flow rates ranging from 5.60 LPM to 10.4 LPM with 12 mm pitch turbulator compare to pure water. Fig. 13 shows the pressure drop versus different flow rate with 12 mm turbulator for nanofluid.

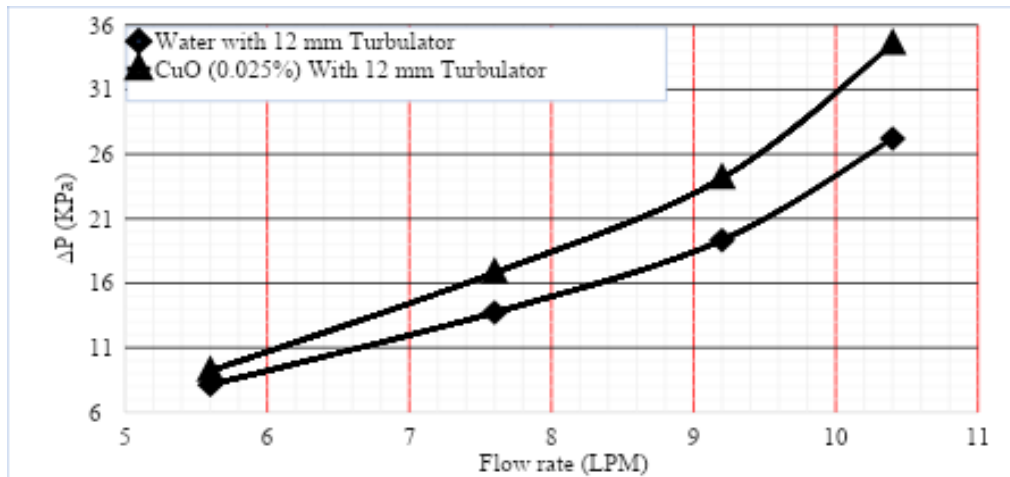


Fig. 13: Pressure drop vs different flow rate with 12 mm turbulator

4. Conclusion

Overall heat transfer coefficient and pressure drop were investigated experimentally using 12 mm and 18 mm pitch helical coil turbulator along with CuO-water nanofluids on counter flow concentric heat exchanger. Nanofluids with a volume concentration of 0.025% were prepared using CuO nanoparticles aiming to increase efficiency of concentric heat exchangers, energy consumption reduction and improve characteristics of conventional fluids. Experimental results show considerable improvements in the overall heat transfer coefficient with the addition of CuO nanoparticles to pure water. The study shows that helical coil turbulator with smaller pitch size intensify turbulence which in turn enhanced heat transfer. In expense of heat transfer adding nanoparticles in pure water and turbulator in tube increased the pressure drop.

The experimental study shows that the overall heat transfer coefficients and pressure drop increases with increasing the flow rate. The overall heat transfer coefficients for pure water without turbulator increased by 30.71% and pressure drop increased by 127.27% when flow rate increased from 5.60 LPM to 10.4 LPM.

Overall heat transfer coefficients for CuO-nanofluid increased by 5% to 8.64% and pressure drop increased by 9.09% to 20% across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water.

The study shows that the helical coil turbulator with 12 mm pitch enhanced more heat transfer and increased more pressure drop than 18 mm pitch turbulator in pure water and nanofluids. Overall heat transfer coefficients for 18 mm turbulator and 12 mm turbulator increased by 24.66% to 31.18%; 36% to 47.08% and pressure drop increased by 309.09% to 560%; 454.55% to 716% across flow rates ranging from 5.60 LPM to 10.4 LPM compare to pure water without turbulator.

The study shows that maximum overall heat transfer coefficients enhancement and increase in pressure drop is for CuO-water nanofluids and for turbulator with 12 mm pitch for 10.4 LPM flow rate. Overall heat transfer coefficients for CuO-water nanofluids increased by 51.01% and pressure drop increased by 763.33% for flow rates of 10.4 LPM compare to CuO-water nanofluids without turbulator.

Conflicts of Interest

The authors declare no conflict of interest.

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