ENHANCED THERMAL PERFORMANCE OF A DOUBLE PIPE HEAT EXCHANGER USING MONO AND HYBRID NANOFLUIDS: A CFD STUDY

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Abstract

Heat exchangers play a very crucial role in thermal system, and they are common in industrial, power generation, and HVAC operations. Nevertheless, the thermal efficiency of traditional double pipe heat exchanger (DPHE) tends to be impaired by low thermal conductivity of low thermal conductivity of base fluids like water. This paper elaborates a numerical research on the thermal and hydraulic characteristics of a counter-flow DPHE with the help of mono and hybrid nanofluids. The MXene, CuO, and hybrid CuO-SiO 2 nanofluids are subjected to simulations on their heat transfer at low volume concentrations of 0.02 per cent and 0.04 per cent in computational Fluid Dynamics (CFD). The findings prove that nanofluids have great heat transfer capabilities when compared with pure water. Out of all the cases the maximum overall heat transfer coefficient and heat transfer rate are at 0.04% of CuO -SiO2 hybrid nanofluid. As small a pressure drop increase is noted, however the gain in thermal performance overrides the hydraulic penalty. The results lead to the evidence of the promising character of progressed nanofluids in enhancing energy efficiency in heat exchanger systems.

Keywords

Double Pipe Heat Exchanger, Nanofluids, Hybrid Nanofluids, MXene, CFD, Heat Transfer Enhancement

1. Introduction

The heat exchangers are important in thermal engineering use in that they facilitate a very good heat transfer between fluids at varying temperatures. There are many types, the most common is the double pipe heat exchanger (DPHE) since it is a simple design, can be created easily and offers flexibility in operation. In a normal DPHE, both fluids are passing through the inner pipe whereas the other fluid is passing through the annular space where the heat exchange occurs through the pipe wall. Counter-flow set up is normally desired because it delivers greater temperature difference and enhanced thermal effectiveness [7][8].

Nevertheless, these benefits have been gained at the cost of poor thermal conductivity, which has limited the heat transfer ability of conventional DPHEs which use base fluids like water and oil. Such a weakness creates the need to use larger heat exchanger sizes and consume more energy. Nanofluids have been proposed in order to resolve this problem as a new-generation heat transfer media. The idea of nanofluids was initially introduced by Choi (1995) in which it was revealed that nanoparticles greatly increase thermal conductivity with their addition [1].

It has been observed in the subsequent studies that nanofluids enhance convective heat transfer and Nusselt number as well as thermal performance [2][3]. Moreover, nanofluids composed of a blend of more than two nanoparticles (hybrid nanofluids) have also exhibited better performance through synergies (e.g. greater micro-convection and higher dispersion stability) [6]. This paper presents the analysis using CFD to obtain the working capacity of mono and hybrid nanofluids in a DPHE system.

2. Literature Review

Application of nanofluids in heat transfer has gained a lot of research. Eastman et al. (2001) found a huge increment of thermal conductivity of nanofluids to base fluids [2]. Equally, Keblinski et al. (2005) described the nature of enhancement of thermal behavior of nanofluids based on Brownian movement and particle-fluid interaction [11].

Do et al. (2010) noted that nanofluids improved the performance of heat pipes, where the level of thermal resistance was reduced, and the heat transfer was enhanced [3]. Huminic and Huminic (2015) also showed that nanofluids enhance the performance of thermosyphons with respect to enhanced nucleation site and surface modification effects [12].

Prakash and Kumar (2015) indicated that the use of Al2O3 nanofluids improved the heat transfer coefficient in DPHE by 10 percent [4], whereas Nusselt number increased by 12 percent when TiO2 nanofluids were used [5]. Even better improvement has been accomplished with hybrid nanofluids. According to Qasim et al. (2021), the heat transfer was found to be improved by 14.8 percent with the help of Al2O3-Fe2O3 hybrid nanofluids [6].

New materials that have been researched have included graphene and MXene. Li et al. (2013) showed that there was improved thermal conductivity of graphene nanofluids [13], whereas Baby and Ramaprabhu (2011) observed increased boiling heat transfer [14]. It has been established that MXene nanofluids are also promising as they are highly thermal conductive and stable [15].

3. Methodology

A 3D computer-aided design of counter-flow DPHE is created to mimic the performance of heat transfer. Hot fluid (water) will flow into the inner pipe with 340 K mass flow rate of 0.24 kg/s and cold fluid flow into the annulus at 319 K and the mass flow rate is 0.186 kg/s. The heat exchanger is 2.08 m in length and 4.266 cm and 7.474 cm in inner and outer diameters, respectively.

There are four working fluids that are used: pure water, CuO nanofluid, MXene nanofluid and hybrid CuO- SiO2 nanofluid. At 0.02 and 0.04 nanoparticles concentration, the simulations are conducted. The model consists of the governing equations, namely continuity equations, momentum equations, and energy equations, which are addressed in the steady-state conditions [7].

Table 1: Simulation Parameters

Parameter	**Value**
Heat Exchanger Length	2.08 m
Inner Diameter	4.266 cm
Outer Diameter	7.474 cm
Hot Fluid Temperature	340 K
Cold Fluid Temperature	319 K
Nanoparticle Concentration	0.02%, 0.04%
Fluids Used	Water, CuO, MXene, CuO–SiO_2

4. Results and Discussion

The outcome of the simulation shows that the thermal performance of the DPHE can be improved with nanofluids at a significant rate. The heat transfer rate is enhanced as the concentration of nanoparticles is enhanced because of the increase in thermal conductivity and the ability to increase the convective heat transfer [9][10]. The hybrid CuO-SiO2 nanofluid with a concentration of 0.04 is the most efficient fluid in terms of heat transfer rate and total heat transfer coefficient than any other fluid.

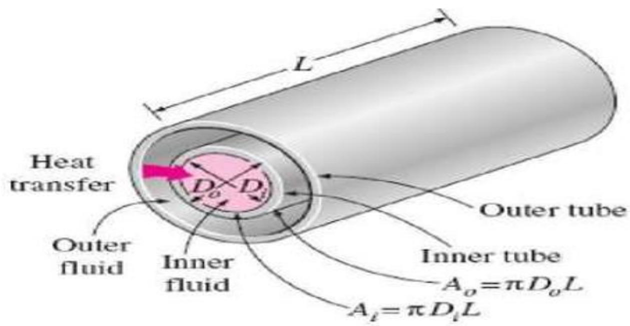
The growth in Nusselt number is an affirmation of a higher level of convective heat transfer. Various mechanisms that have led to the improvement include the Brownian movement, micro-convection, and nanoparticle interaction with the fluid [11]. The hybrid nanofluid also has a high performance because the actions of both CuO and SiO2 nanoparticles are synergistic.

Though there is some slight increase in the pressure drop that is caused by the increased viscosity, the net advantage of the thermal performance is greater than this drawback [12]. The findings are a clear indication that hybrid nanofluids perform optimally as compared to other fluids that were tested.

Table 2: Performance Comparison

Fluid Type	Concentration	Heat Transfer Rate	Performance
Water	—	Low	Poor
CuO	0.02%	Medium	Good
MXene	0.02%	High	Better
CuO–SiO_2	0.04%	Very High	Best

Figure 1: Schematic Diagram of Double Pipe Heat Exchanger.



The two heat transfer surface areas associated with a double-pipe heat exchanger (for thin tubes, $D_i \approx D_o$ and thus $A_i \approx A_o$).

Inherent counter-flowing fluid flow, the schematic layout of the counter-flow double pipe heat exchanger (DPHE) applied in the research is provided in Figure 1. This consists of two concentric pipes, wherein the hot moving fluid flows through the inner pipe and the cold moving fluid flows through the annular space in a reverse manner. This counter-flow method will guarantee an increased temperature gradient across the heat exchanger length, and hence, enhance thermal efficiency. The process of heat transfer takes place at the wall of the pipes between the two fluids and is mainly led by the conduction and convection mechanisms. It is also important to note that the figure shows the inlet and outlet limits of the two fluids and how is always an exchange of thermal energy through the length of the exchanger. This arrangement is much favored in industry because it is simple, easy to fabricate and has a better heat transfer capability than parallel-flow systems.

Figure 2: Geometric design of double pipe heat exchanger.

The simulation of fluid flow and heat transfer within the double pipe heat exchanger was carried out using ANSYS Fluent, a powerful and widely adopted CFD software for analyzing thermal-fluid systems. ANSYS Fluent provides advanced solvers and robust numerical algorithms capable of handling single-phase and multiphase flow - making it ideal for studying the detailed performance of heat exchangers under various working fluid conditions.

Figure 3: Configuration of Hot and Cold Fluid Entry and Exit Points in a Double Pipe Heat Exchanger.

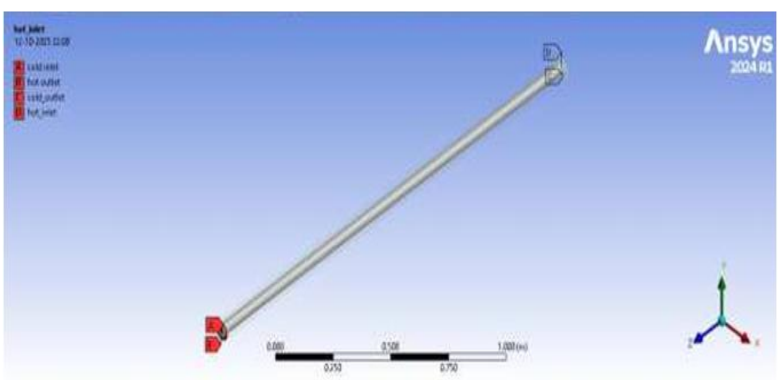


Figure 4: Overall Heat Transfer Coefficient (Uo) vs. Fluid Type

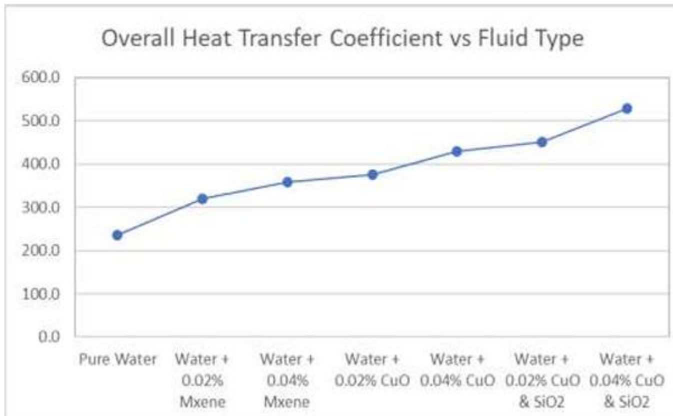


Figure 4 shows the change of the overall heat transfer coefficient (Uo) of various working fluids employed in the DPHE system. It is also clear that the use of nanofluids greatly improves the level of heat transfer as compared to ordinary water. All other tested fluids, the hybrid CuO–SiO_2 nanofluid at 0.04%is the most effective in terms of overall heat transfer coefficient, which represents superb thermal activity. This increase can be explained by the fact that there is a better thermal conductivity, the heat exchange surface area is augmented, and there is greater convectional heat transfer because of interactions between nanoparticles. The MXene and CuO nanofluid also exhibit significant improvements compared to base fluid but not as high as the hybrid nanofluid. Throughout the figure, it is evident that hybrid nanofluids are synergistic and can therefore be used in high efficiency heat exchanger application where high thermal efficiency is needed.

5. Conclusion

This paper has shown that mono and hybrid nanofluid integrations are a major advancement to thermal efficiency of the double pipe heat exchanger over the traditional base fluids. Nanoparticles enhance thermophysical characteristics, which leads to increasing the rates of heat transfer and efficient performance. The CuO-SiO2 hybrid nanofluid concentration of 0.04% gives the best performance in the test among the tested fluids since the nanoparticles will have synergistic effects.

Even though the pressure drop increase is minimal, the thermal gain is greater than the hydraulic penalty. The results validate the assumption that nanofluids present an appropriate solution when it comes to enhancing the efficiency and energy performance of heat exchangers in industries.

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