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Improvement of Plate-Type Heat Exchanger Performance by Employing Metallic Oxide Nanofluid

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***Abstract* -** Plate-type heat exchangers are characterized as compact and highly efficient type for their ability to operate at higher pressure in comparison to the conventional heat exchanger. Further enhancement of such type can be implemented by augmenting the thermal properties of the base fluid such as the thermal conductivity and the heat transfer convention coefficient. This could be achieved by adding additive in nano-sized to the fluid. The present research addresses the influence of utilizing Aluminium Oxide and Titanium oxide on the performance and energy interaction with the environment of plate-type heat exchanger. Different volume fractions of the abovementioned nanofluid are experimentally investigated to reveal the relation of the exchanger effectiveness with the concentration of the nanofluid. Effect of Reynolds number of nanofluid is also reported. The results confirm that existence of nanofluid does enhance the performance of the heat exchanger remarkably. The exchanger effectiveness also ameliorates with augmentation in VoF of nanoparticle. Analysis of the results ascertains that the exchanger performance shows better enhancement when Aluminium Oxide is employed in comparison to Titanium oxide, particularly at large Reynolds number. The outcome of the analysis reports that 13% increment in the exchanger effectiveness when 3% of TiO_2 nanofluid is used. In return, using same amount of Al_2O_3 nanofluid upgrades the exchanger performance by 23%.
For the system/environment energy interaction, the results shows that 3% of Aluminium oxides augments the heat leak factor by 40% when Re ~12000 while the increment in the leak factor approach 45% for the case of Titanium oxide. Increasing the nanofluid flowrates to Re = 14000 results in ameliorating in the heat interaction for both nanofluid, though TiO_2 is barely touch 50%.

***Keywords*:** nanofluid; heat-environment interaction; effectiveness; heat leak factor; Plate Heat Exchanger

1. Introduction

Heat exchangers based on nanofluids offer excellent heat transfer characteristics and may be used in a variety of industries, including automotive, chemical, and power plant [1]. Scholars are widening the current topic of nanofluids study. Hybrid base fluids have also been explored to improve heat transfer. The influence of magnetic characteristics of nanofluids created with an induced magnetic dipole is another intriguing subject under investigation. The impact of modifying viscosity on hydrodynamic nanofluid has also been explored numerically by many scholars [2], [3], [4].

Nanofluids might play a critical role in improving the efficiency of heat exchangers, according to a review of their properties and the intelligent approaches used in heat exchangers. In a similar vein, various empirical investigations of heat exchanger with different kinds of nanofluids like aluminium oxide, titanium oxide, carbon-acetone, graphene, kaolin, multiwall carbon nano tubes, and silicon carbide were observed in recent literature. The influence of hybrid nanofluids on heat exchanger efficiency is also fascinating. Recent articles, however, have looked at the influence of changing geometrical aspects. Spiral shape of double pipe, changes in baffle arrangement, shell with helix coils, and longitude direction fin are among these modifications [5-11].

Shirzad et al. [12] quantified the influence of geometric variables on efficiency of heat exchanger designed as pillow type. The elevation of pillow plates, as well as the transverse and longitudinal spacing for welding locations, were all addressed in their research. For improved heat exchanger efficiency, a bigger cushioning elevation and greater transversal spacing for welding zones were proposed. Arsenyeva et al. [13] carried out a thorough case study on plate heat exchangers, making comparisons of pillow and chevron types. Heat exchanger configuration of pillow type showed superior performance compared to chevron type for varying flow rates. Zhang introduced a capsules type plate heat exchanger, which is a new design for a heat exchanger. Reynolds number was changed from 500 to 12470 in his numerical calculations. A bigger Nusselt number was obtained for capsule type configuration. Jamzad et al. [14] invented and tested a new kind of heat exchanger using embossed graphite sheets. In comparison to a standard stainless steel heat exchanger, the efficiency of this generated graphene sheet heat exchanger was examined. Because of its higher thermal conductivity, the graphene sheet heat exchanger was recommended as a preferable option.

Zhang et al. [15] conducted a thorough performance analysis of plate heat exchangers. A wide range of boosting methods were investigated. The most important parameter for improving the efficiency of a chevron heat exchanger was reported to be the chevron angle. When geometrical changes and/or improvement tactics are used, it has been shown that plate heat exchangers function more effectively at low Reynolds numbers. The capsules kind embossing surface and use of nanofluids were suggested as viable enhancing alternatives.

In the present work, the authors examine the effect of metallic nanofluid and the role of volume fraction on the performance of plate type heat exchanger. The present work is part of continuous research [16], [17], [18] done by the authors towards the application of nanofluids in thermal systems.

2. Theory

The experimental data are used to calculate heat transfer parameters like the overall heat transfer coefficient, the Nusslet number, the number of transfer unit, the exchanger performance or efficiency, and the environment/system heat interaction. The traditional expression employed to calculate the rate of heat transfer of hot fluid is given by:

$$\dot{Q}_h = \rho_w \dot{V}_h C_p (T_{hi} - T_{ho}) \tag{1}$$

Where ρ is the density, $\dot{V}_h$ is the hot fluid flow rate in m^3/s, and T_{hi}, T_{ho} are, respectively, the inlet and exit temperatures of the hot fluid.

On the other side, the rate of heat transfer in the outer tube (the cold nanofluid stream) is calculated by:

$$\dot{Q}_c = \rho_{nf} \dot{V_{nf}} C_{pnf} (T_{co} - T_{ci}) \tag{2}$$

Where nf refers to the nanofluid flow and T_{ci} and T_{co} are the inlet and outlet temperatures of the nanofluid, respectively.

To compute the thermal properties of the nanofluid, an expression of well-known mixture correlations is employed:

$$\rho_{nf} = (1 - \emptyset)\rho_p + \emptyset \rho_p \tag{3a}$$

$$Cp_{(nf)} = \frac{(1 - \emptyset)(\rho Cp)_f + \emptyset (\rho Cp)_p}{\rho_{nf}} \tag{3b}$$

$\emptyset$ stands for the fraction of the nanofluid mixed with the water in volume basis.

The overall heat coefficient based on the area U_o is determined using Eq. (4):

$$U_o = \frac{\dot{Q}_{ave}}{A_o \Delta T_{lm}} \tag{4}$$

Where A_o is the effective outer surface area and ΔT_{lm} is the logarithmic mean temperature difference which depended on the relative directions between the streams of the hot-side distilled water and the cold-side nanofluid

The number of transfer unit (NTU) and the minimum heat capacity ratio ($c_{\min}$) are evaluated by:

$$NTU = \frac{(UA)_o}{C_{min}} \tag{5a}$$

$$c_{min} = min\left(CR, \frac{1}{CR}\right) \tag{5b}$$

The heat capacity rate ratio *CR* between the cold-side nanofluid stream and the hot-side water is given as:

$$CR = \frac{\left(\rho\dot{V}Cp\right)_{nf}}{(\rho V^{\cdot}Cp)_w} = V_r\left(\frac{(\rho V^{\cdot}Cp)_{nf}}{(\rho V^{\cdot}Cp)_w}\right) \tag{6}$$

V_r is the flowrate ratio of the cold (nanofluid) to the hot (water) streams.

The experimental data are used to compute the exchanger effectiveness (Eq. 7):

$$\varepsilon = \frac{Q_{ave}}{\left(\rho\dot{V}Cp\right)_{min}(T_{hi} - T_{ci})} \tag{7}$$

The energy interaction of the exchanger and atmosphere is characterized by Heat Leak factor α, reported by [16]:

$$\alpha = \frac{\left|\dot{Q}_h - \dot{Q}_c\right|}{\max(\dot{Q}_h, \dot{Q}_c)} \tag{8}$$

The exchanger effectiveness calculated from Eq. (7), which will henceforth be referred to as Model I, is compared with the following expression (Model II) for validation purposes [17]:

$$\varepsilon = \frac{1 - exp(-NTU[1 - c_{min}])}{1 - c_{min} \times exp(-NTU[1 - c_{min}])} \tag{9}$$

3. Experimental Setup

The test equipment employed in this investigation was supplied by the Edibon manufacturing company. The dimensions are 400 x 1100 x 550 mm (Height x Width x Depth). It includes of something like a basic station and an exchanger module. A hot water tank in the base unit allows hot water to pass across to the heat exchanger. A cold fluid tank is made available on the ground surface and a connection is established with the exchanger. A set of parallel-laid stainless-steel plates constitute the heat exchanger unit. The arrangement includes a total of 20 plates. The space between the plates offers channels for fluids to move through. The two fluids are designated to move in opposing direction. A flexible hose unites the two components allowing hot and cold streams to flow between the two units. Pumps and regulatory valves have been used to control fluid flow. Concurrent flow and countercurrent combinations may be generated by simply altering the valves that come with the basic device. Four thermocouples were inserted at the heat exchanger module's entrance and exit locations, providing for the surveillance of cold and hot fluid entry and exit temperatures. A PLC-SCADA system oversees the complete facility, offering data collection, control, and monitoring of the full system. The setup can be used for investigating nanofluid impact on heat transfer and determining efficiency of heat exchanger.

Figure 1: Plate heat exchanger experimental facility

4. Validation of the Data Processing

The Number of Transfer Unit (NTU) and the effectiveness (ε) are plotted against the Reynolds number of the nanofluid for both models. As seen in Fig. (2), model II suggests better improvement in the NTU with the augmentation in Re than model I. Fig. (3) also readily proves that model II appropriately present the enhancement in the heat exchanger performance in comparison to model I albeit both present direct proportion between the exchanger effectiveness with the nanofluid Reynolds number

The error in NTU and effectiveness predicted by two models is illustrated in Fig. (4). It is evaluated that the deviation in NTU predicted by the two models ranges between 5-25%. However, alteration in the exchanger effectiveness does not pass 10%.

Since model II involves the geometry, shape, and architecture of the plate heat exchanger in the NTU and effectiveness expressions, it is decided to adopt it during the experiment data analysis.

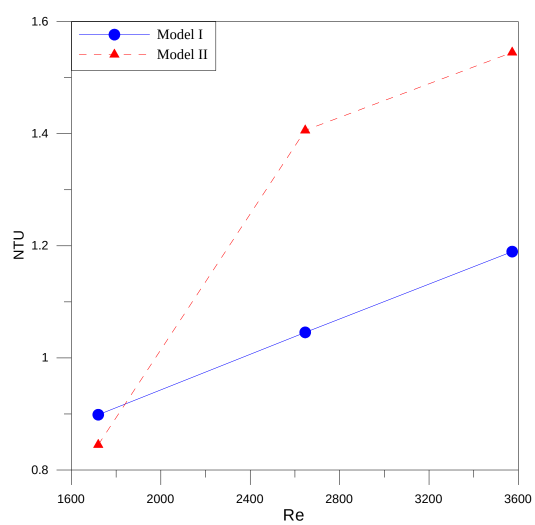

Figure 2: Comparison of exchanger NTU predicted by Model-I and Model-II

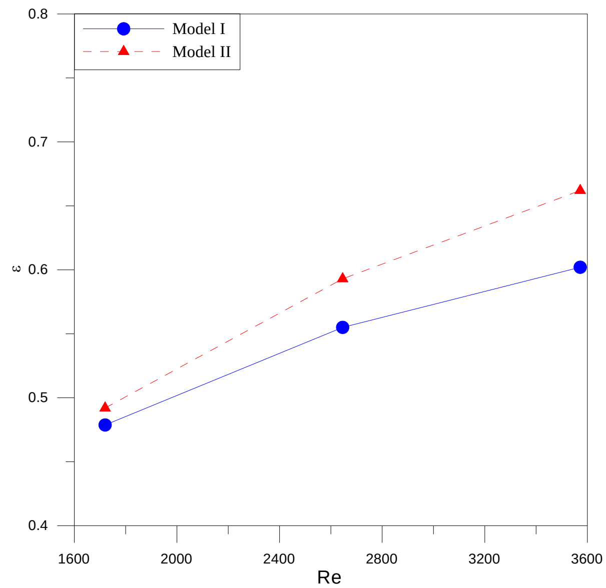

Figure 3: Comparison of exchanger effectiveness predicted by Model-I and Model-II

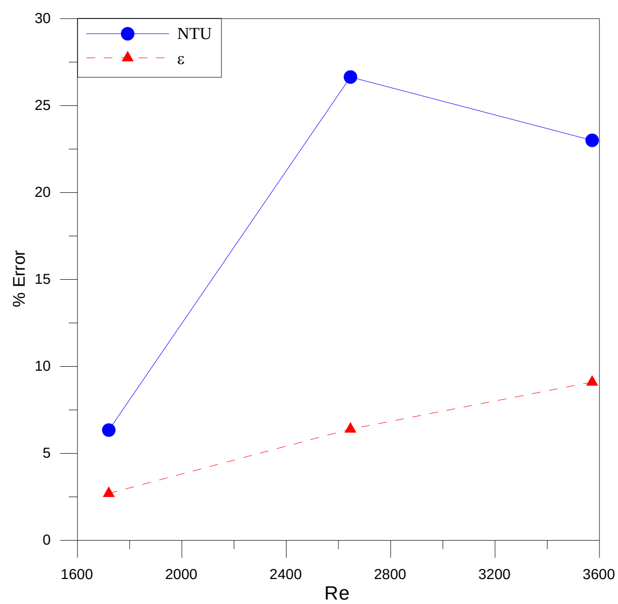

Figure **4**: Deviation in NTU value and effectiveness predicted by the two models at different nanofluid flowrate

5. Results and Discussion

TiO_2 nanofluid at different volume fractions is compared with the case of conventional water to present the improvement in the exchanger performance when nanofluid is employed. Fig. (5) depicts the exchanger effectiveness versus nanofluid Reynolds number at three volume fractions of TiO_2. As expected, nanofluid does enhance the exchanger performance particularly at high Re. Augmentation in the nanoparticle concentration in the base water would also increase the heat transfer interaction between the hot and the cold fluid, resulting further improvement in the effectiveness.

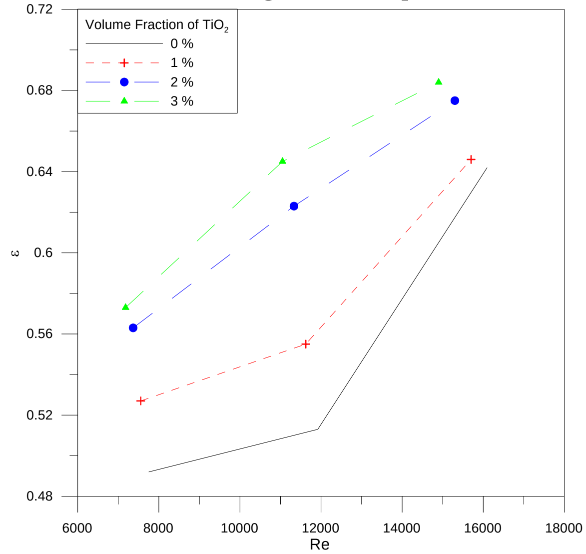

Figure **5**: Exchanger performance against Reynolds number at different volume fractions of TiO_2

Similar trend occurs for the case of Aluminium Oxide nanofluid as seen in Fig. (6). Remarkable amelioration in the exchanger effectiveness, particularly at VoF 2% and up, one can conclude.

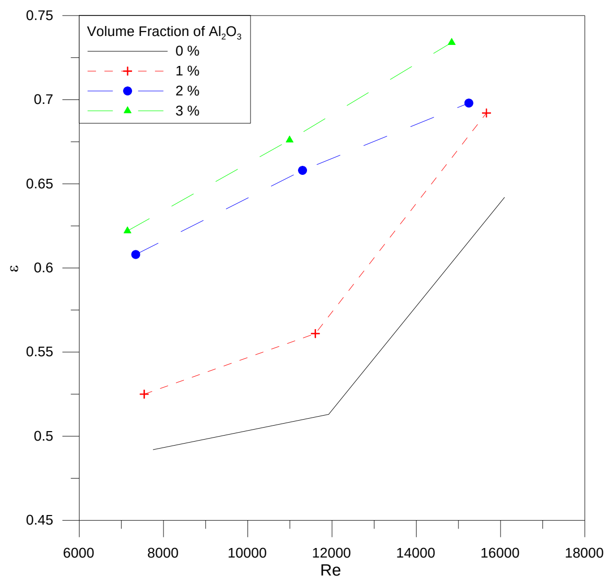

Figure **6**: Exchanger performance against Reynolds number at different volume fractions of Al_2O_3

The heat leak factor proposed by [17] and expressed in Eq. 8 is prominent since it describes the energy transfer between the system and the surrounding. It can be used as a benchmark to evaluate the exergy balance as well as the second law efficiency of the thermal system. In the present study, the leak factor is evaluated at different nanofluid flowrates for various volume fractions of TiO_2 (Fig. 7) and Al_2O_3 (Fig. 8). It is concluded that the leak factor augments with the increase in the Reynolds number for TiO_2 case. Moreover, the more the nanofluid concentration in the base water, the larger the leak factor obtained.

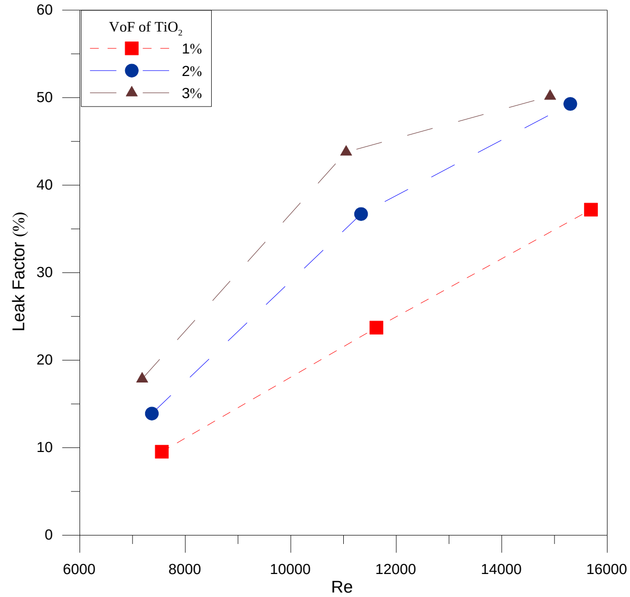

Figure **7**: Heat leak factor verses Reynolds number at various fractions of TiO_2

Al_2O_3 behaviour is similar to titanium oxide as seen in Fig. (8). However, comparison with TiO_2 trend concludes that substantial elevation in leak factor with the existence of nanoparticle is observed, especially at high Reynolds number.

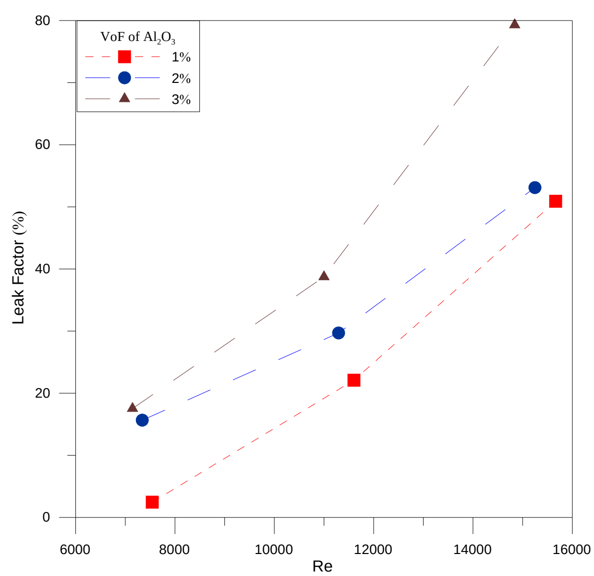

Figure **8**: Heat leak factor verses Reynolds number at various fractions of Al_2O_3

6. Conclusion

Mixing metallic oxide nano-sized particles with conventional fluid enhances the convection heat transfer of the fluid. Such improvement ameliorates the heat exchanger performance. However, the energy interchange between the plate heat exchanger and its surrounding augments as a result of boundary layer destruction. In the current study, two types of nanofluid at different concentrations are employed to observe and evaluate the deviation in the effectiveness of plate-type heat exchanger as well as the heat interaction with the surrounding.

Analysis of the results proved that exchanger effectiveness does enhance with the presence of nanoparticle, albeit Aluminium Oxide contribution to the enhancement of the exchanger has shown to be better than Titanium Oxide. Energy interaction of the exchanger with the atmosphere is also reported in the study. Analysis of the data confirmed that nanofluid stream increases the energy interaction with the surrounding atmosphere due to reduction in the exchanger's thermal resistance. The results showed that leak factor augments with the augmentation of nanofluid flowrate both metallic oxides that are utilized in the study. However, Aluminium Oxide was observed to cause higher leak interaction than Titanium Oxide. The study also concluded that adding more particles to the conventional fluid increases the leak up to 60% for TiO_2 and 80% for Ai_2O_3.

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