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Comparison study of performance and heat leak factor of three types of heat exchangers operated with nanofluid

Esam I Jassim[1,a *] and Bashar I Jasem[2,b]

[1]College of Engineering, Prince Muhammad Bin Fahd University, 31952 Al-Khobar, Kingdom of Saudi Arabia

[2]Department of Computer Technology, Al-Hadba University College, Mosul, Iraq

[a]ejassim@pmu.edu.sa, [b]adamalzuhairee@gmail.com

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Abstract. Nanofluid are categorized under class of fluids that have extreme potential to enhance the heat transfer in heat exchangers. However, the interaction between the exchanger and the ambient (heat leak) is an essential issue since it could deteriorate the exchanger performance. The quantity of the heat loss is directly related to the temperature of the hot fluid, the Reynolds number, and the type and volume fraction of the nanoparticle. The experimental study presents the heat leak when distilled water is mixed with different concentration of Al_2O_3 (range from 1% to 3%) and streamed into three different types of heat exchangers, namely concentric, shell and tube, and plate type. The results emphasize that presence of nanoparticles improves the Nusselt number (convection coefficient) and the NTU number (exchanger performance). The analysis also shows that heat leak factor augments with the increase in VoF of nanofluid in all types. However, plate type exchanger has the lowest losses to the ambient, followed by shell and tube and finally concentric type.

Introduction

Heat exchangers are type of equipment that are commonly used in numerous industries such as petrochemical sector, ore refining sector, power plants and so on. Heat exchangers can be customized based on geometric structure suitability, maintenance feasibility, and operation durability [1]. Although shell and tube heat exchangers are most commonly used in this field, other types such as double pipe and plate heat exchangers are still in demand for many applications.

Recently, numerous research studies were implemented on the impact of utilization nanometallic on the performance of energy equipment such as the heat exchanger [2, 3, 4] and engine lubricant [5].

R. Dharmalingam [6] summarized the experimental study of the forced convective heat transfer and flow characteristics of a nanofluid consisting of water as base fluid and 1% Al_2O_3 (volume concentration) nanoparticle flowing in a parallel flow, counter flow, and shell and tube heat exchanger under laminar flow conditions. He proved that shell and tube exchanger provides more enhancements in heat transfer coefficient than the other two flow arrangements. Nusselt number was also shown to be augmented for the Al_2O_3/water nanofluid, which eventually enhances the convective heat transfer coefficient.

Jaafar Albadr [7] investigated experimentally the thermal performance of propylene glycol/water with a fixed concentration of (10/90) % and Al_2O_3/water nanofluid with a various concentration (0.1, 0.4, 0.8, 1.5, and 2.5) % by volume under turbulent flow inside a horizontal shell and tube heat exchange. The researcher reported that thermal conductivity and viscosity increase due to the dispersion of the nanoparticles into the base liquid. However, friction factor augments with the increase of a particle volume concentration.

Wael I.A. Aly [8] studied the heat transfer and pressure drop characteristics of water-based Al_2O_3 nanofluid flowing inside coiled tube-in-tube heat exchangers. The design parameters of the

CFD modelling were in the range of 0.5%-2.0% VoF, coil diameters 0.18-0.3 m, inner tube and annulus sides flow rates from 2 to 5 LPM and 10 to 25 LPM, respectively. The results obtained showed a different behavior depending on the parameter selected for the comparison with the base fluid. Also for same Re or Dn, the heat transfer coefficient increases by increasing the coil diameter and nanoparticles volume concentration. The friction factor, on the other hand, increases with the increase in curvature ratio.

D. Madhesh a,b, R. Parameshwaran b,c, S. Kalaiselvam [9] study to address the heat transfer and rheological characteristics of HyNF were investigated experimentally using a tube in-tube counter flow heat exchanger. The conclusions explained that the convective heat transfer coefficient of nanofluids increased with HyNC concentration and the Reynolds number. the Nusselt number, and the overall heat transfer coefficient were enhanced by 52%, 49% and 68%, respectively. The authors also noticed that the friction factor and pressure drop of HyNF obtained for 1% up to 2.0% volume concentration were 1.7% and 14.9% respectively.

Heydar Maddah, Nahid Ghasemi [10] experimentally investigated the heat transfer efficiency of water and iron oxide nanofluid in a double pipe heat exchanger equipped with a typical twisted tape. Experiments were conducted under the laminar and turbulent flow for Reynolds numbers in the range of 1000 to 6000. Three the concentration by weight of nanofluid was selected, namely: 0.01, 0.02 and 0.03 wt%. They reported that heat transfer efficiency increases as opposed to that of water (the base fluid). Numerically speaking, at Reynolds number was equal to 3000 and 45 °C, the heat transfer efficiency value for nanofluid was enhanced approximately by 21%. At identical Reynolds number and temperature, the heat transfer efficiency was ameliorated up to 25.9%.

Jassim et al [11, 12] are separately investigated the thermal performance of two types of heat exchangers when operate at concentration of 1%, 2%, and 3% of titanium dioxide–water (TiO_2–water) nanofluids by dispersing 20 nm diameter nanoparticles in distilled water. They also experimentally compared the overall heat transfer coefficient and NTU of water vs. nanofluids in laboratory-scale plate and shell-and-tube heat exchangers. Experimental results showed both augmentation and deterioration of heat transfer coefficient for nanofluids depending on the flow rate and nanofluid concentration through the heat exchangers.

Alireza Falahat, Mohsen Shabani, Mohsen Maleki [13] examined theoretically the effects of water- Al_2O_3 nanofluid on exergy destruction, exergy efficiency and pumping power in the helically coiled tube heat exchanger under turbulent flow and subjected constant wall condition. The main parameters considered in this study are nanoparticles volume concentration, nanoparticle size, Reynolds number, curvature ratio and dimensionless inlet temperature. It is found that when the Reynolds number increases, dimensionless total exergy destruction decreases. It is observed that by increasing the nanoparticles volume concentration from 2% to 6%, the dimensionless thermal exergy destruction reduces by 3.64% to 20.21 % compared to pure water. Also, it is seen that when nanoparticles dimensions increases, the exergy efficiency increases and pumping power decreases. Finally, the exergy efficiency increases with increasing of curvature ratio and pumping power decreases with increasing of curvature ratio.

There are ample researches on employing nanofluid in heat exchanger; however, studies on the exchanger/ambient energy interaction are still scarce. This work attempts to fill the gap by emphasizing on the energy interaction of three types of heat exchangers with the environment.

Theory

Nanofluid properties are formulated as a function of the concentration of nanoparticles. Density and heat capacity of the nanofluid is computed from Eqs. 1 and 2, respectively:

$$\rho_m = (1-\phi)\rho_f + \phi\rho_p \quad (1)$$

$$(\rho Cp)_m = (1-\phi)(\rho Cp)_f + \phi(\rho Cp)_p \quad (2)$$

Maxwell correlation is employed for nanofluid thermal conductivity while Batchelor empirical model is considered to evaluate the nanofluid viscosity, as listed below:

$$k_m = \frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)} k_f \tag{3}$$

$$(\mu)_m = (1+2.5\phi+6.2\phi^2)\mu_f \tag{4}$$

k_p, k_f are the thermal conductivity of the nanoparticle material and the base fluid, respectively. k_m is the effective thermal conductivity of the nanofluid. μ_m is the nanofluid viscosity, μ_f is the fluid viscosity, and ϕ is the volume concentration of the suspended particles.
to convert mass fraction into volume fraction of the nanofluid, the following expression stated below is adopted:

$$\text{\% volume concentration, } \phi = \left[\frac{\left(\frac{W_{CuO}}{\rho_{CuO}}\right)}{\left(\frac{W_{CuO}}{\rho_{CuO}}+\frac{W_{bf}}{\rho_{bf}}\right)}\right] \times 100 = \left[\frac{\left(\frac{W_{CuO}}{6300}\right)}{\left(\frac{W_{CuO}}{6300}+\frac{100}{1000}\right)}\right] \times 100 \tag{5}$$

Nusselt number of nanofluid can be determined from the following expression:

$$\boldsymbol{Nu_m} = \frac{\boldsymbol{h_o D_h}}{\boldsymbol{k_m}} \tag{6}$$

where h_o is the convection heat transfer coefficient of the nanofluid evaluated from Eq.7:

$$\frac{1}{h_o} = \frac{1}{U_o} - \left\{\frac{D_o}{D_i}\times\frac{1}{h_i} + \frac{D_o ln(D_o/D_i)}{2k_w}\right\} \tag{7}$$

the overall heat transfer coefficient U_o, is based on outer surface area and is calculated using the LMTD method:

$$U_o = \frac{Q_c}{A_o \times \left(\frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}\right)} \quad ; \ \Delta T_1 = T_{h,i} - T_{c,o} \text{ and } \Delta T_2 = T_{h,o} - T_{c,i} \tag{8}$$

The surface area A_o is calculated from different expressions, depending on the type of the heat exchangers, [11, 12, 14]

$\boldsymbol{T_{ci}}$ and $\boldsymbol{T_{co}}$ are the inlet and outlet mean temperature of the nanofluid; and D_i, D_o, D_h are the inner, outer, and hydraulic diameter, respectively.

The heat transfer coefficient of the hot fluid streamed through the tube-side is evaluated from the Dittus-Boelter empirical correlation:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3} \tag{10}$$

where $$\mathrm{Pr} = \frac{\mu \times C_p}{k} \tag{11}$$

Experimental Set-up

The experimental setup, illustrates in Fig.1 consists of two units namely, the base unit and the heat exchanger unit which are computer controlled through PLC-SCADA data logging and process monitoring system, Fig.(2). The dimensions of the base unit are 1100 x 650 x 400 mm. The water in the hot fluid tank is heated by means of an electric heating element to a prescribed temperature and is then streamed to the the heat exchanger unit by means of an impeller pump. The second fluid which is the nano fluid in the cold fluid tank is pumped into the heat exchanger unit by means of another impeller pump. Two flowmeters and valves are located along the hot and cold circuits to control and measure the flow rates of hot and cold fluids. Al_2O_3 /water nanofluid is circulated in the annulus cold zone. The major components and specifications of the base unit is listed in Table 1.

Table 1: Components and Specifications of Base Unit

Component	Sub-components	Specification
Tank	1. Electric heating element 2. Level switch 3. Temperature sensor 4. Drain valve	Tank material : Stainless Steel Tank capacity: 30 liter Heater power: 3000W
Impeller Pump	Range: 0 - 2.5 liter/min	
Pressure Regulation Valve	Maximum pressure: 0.7 bar	
Flow Sensors	Quantity: 2 Range: 0 – 6.5 liter/min	
Ball Valves	Quantity: 6	
Flexible Tubes	Quantity: 4	

Figure 1. Base unit includes: hot fluid tank, sensors, valves, pump and pressure regulator

Figure 2. PLC-SCADA Data recording and process monitoring system

Results and discussion

Fig. (3) depicts the variation of Nusselt Number with the Volume Fraction of Al_2O_3 nanofluid for the three types of heat exchangers. Observation shows that Nu is augmented as the VoF of nanofluid increases. This can be attributed to the enhancement in the convection heat transfer coefficient of the nanofluid due to the presence of metallic nanoparticles. The figure also illustrates that magnitude of Nu of the plate type of heat exchanger is the largest and the concentric type in the lowest regardless of the nanofluid VoF.

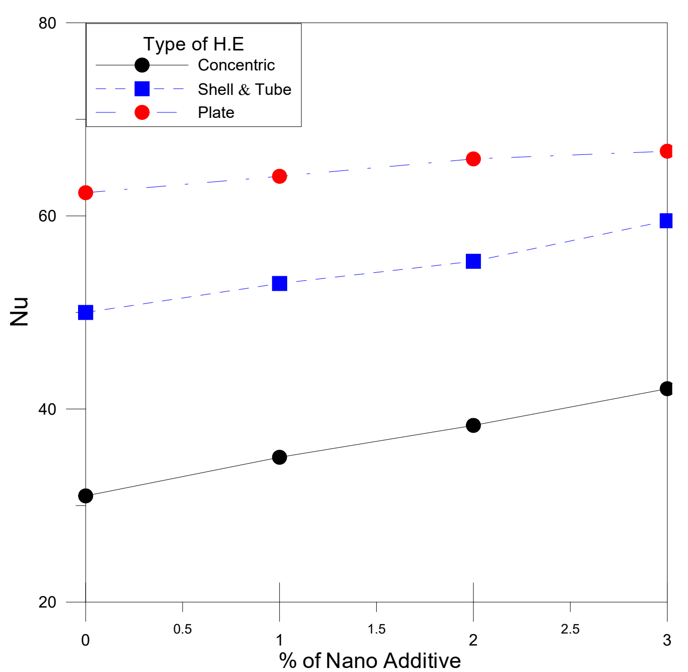

Figure 1: Variation of Nu with nanofluid VoF for Al_2O_3 volume fraction

The NTU is a prominent tool that frequently utilized to assess and evaluate the performance of any heat exchanger. Plate type is shown to operate at higher performance compared to the other types and its performance even enhances exponentially with the presence of nanofluid, figure (4). Shell and tube type enhancement is observed to be slight but always better than the concentric type.

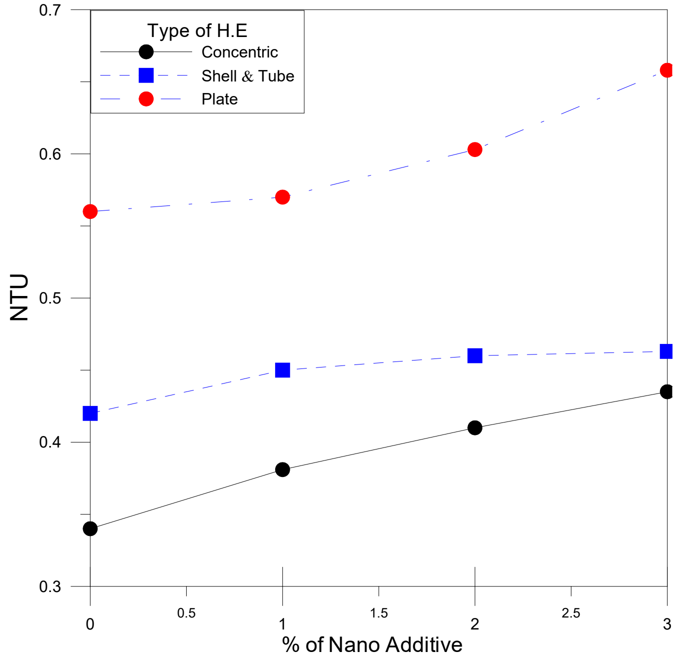

Figure 4: Variation of NTU with nanofluid VoF for Al_2O_3 volume fraction

Jassim and Ahmed [11] proposed a new parameter, so called "Leak Factor", as a benchmark to feasibly assess such the exchanger/environment inteeaction. Defined as the ratio of the heat rate lost to the ambient from the entire system to the actual rate transferred from the hot fluid, the leak factor is plotted against the Reynolds number of the nanofluid for the three selected volume fractions. Fig. (5) illustrates the variation of the leak factor with the Reynolds number at various volume fractions of Al_2O_3 for shell and tube exchanger. The higher the Reynolds number, the larger the leak factor. Also, the figure concludes that leak factor is substantially elevated with the presence of nanoparticle, particularly at high Reynolds number.

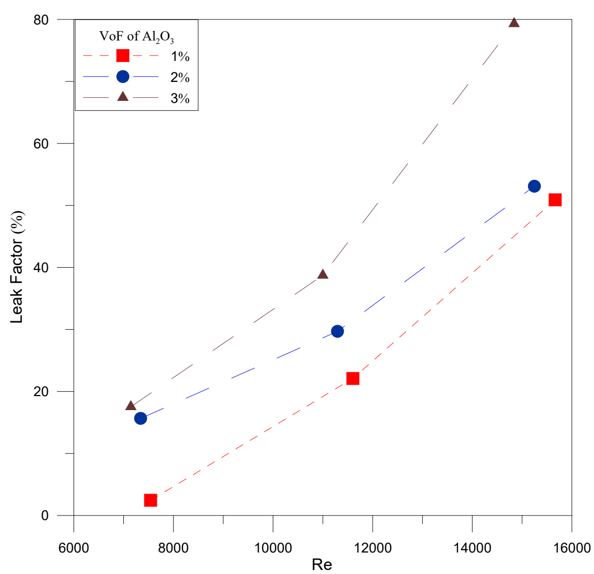

Figure 2: Variation of leak factor with Reynolds number for Al_2O_3 nanofluid, [11]

Heat leak factor is plotted against the concentration of Al_2O_3 for the three exchangers under study. Figure 6 summarizes that for all exchangers, the heat leak factor is proportion to the concentration of nanofluid. However, plate heat exchanger leak factor is observed to be the minimal. The heat loss factor predicted from the experiments increases with the increase of the concentration. The figure also concludes that using nanofluid intensifies the energy interaction of the exchanger with the surroundings.

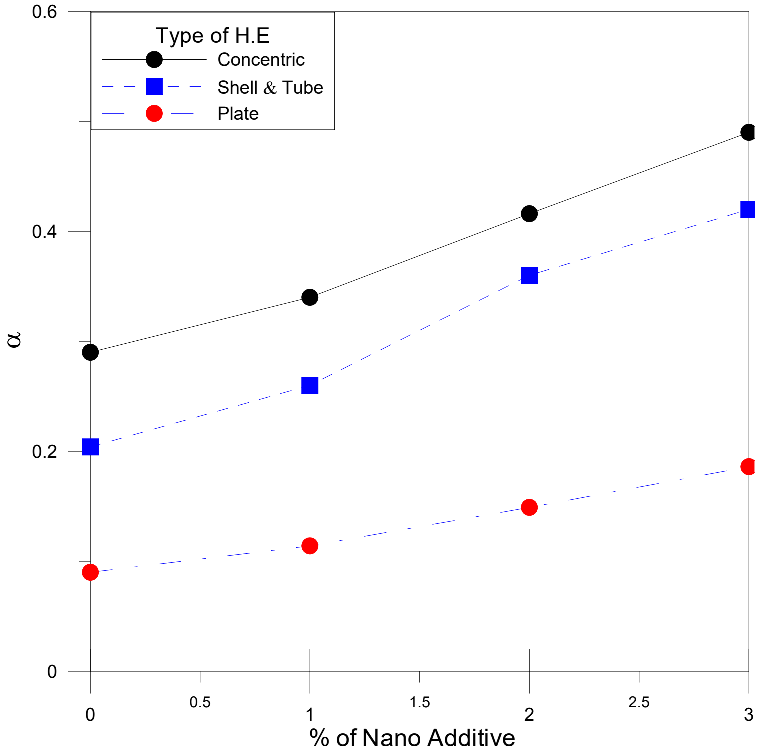

Figure 6: Heat Leak factor against nanofluid VoF for Al_2O_3 volume fraction

Conclusion

Experimental study on the behavior of Al_2O_3 nanometallic/water at various VoF for three types of heat exchangers are analyzed. Results indicated that the presence of nanofluid ameliorates the heat transfer characteristics significantly. Adding more nanoparticle to the base fluid enhances the Nusselt Number as well as the heat transfer performance.

By increasing the nanoparticle concentrations, the heat leak to the environment is shown to be augmented, resulting in reduction in the system availability.

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