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Heat Transfer Analysis of Shell and Tube Heat Exchanger using Al_2O_3/SiC Nanofluid

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ABSTRACT

Heat exchanger plays a major role in the industrial process heating. Heat is transferred between fluids by convection and conduction through the walls of the heat exchanger. Heat transfer fluids have low thermal conductivity that greatly limits the heat exchanger efficiency. Various research works are carried out to enhance the thermal properties of the fluids by adding thermally conductive solids into liquids. Liquid mixed with nanoparticles known as 'nanofluid', exhibit substantially higher thermal conductivity than those of the corresponding base fluids. In this work a new nanofluid system has been developed by synthesizing aluminium oxide and silicon carbide nanoparticles with water and applied in a shell and tube heat exchanger. The thermal transport properties of this nanofluid, including thermal conductivity and heat transfer coefficient are characterized. The results show that this nanofluid possesses higher thermal transport properties and it has been experimentally proved that this nanofluid has the potential to be used as advanced heat transfer fluid. Experimental data have been generated in shell and tube heat exchanger using nanofluid and Li and Xuan correlation was used for the verification of the experimental data. The results also predict that Al_2O_3 act as a better nanoparticle in comparison to SiC due to high thermo-physical properties of the mixture, yield in the increase in heat transfer. Experimental results show that application of Al_2O_3/SiC based nanofluid enhances coefficient of heat transfer at 0.3% concentration by volume and a flow rate of 5 LPM respectively.

Keywords: Thermal conductivity, Nanoparticles, Nanofluid, Shell and tube heat exchanger, Li and Xuan correlation

INTRODUCTION

Various methods that have been used to enhance heat transfer include modifying surface roughness as turbulence promoter, flowing fluids through micro channels, and using nanofluids. A decade ago, with the rapid development of modern nanotechnology, particles of nanometre-size (normally less than 100 nm) are used instead of micrometre-size for dispersing in base liquids, and they are called nanofluids. This term was first suggested by Choi [1] in 1995, and it has since gained in popularity. In the past 20 years, many researchers have been investigating the heat transfer performance and flow characteristics of various nanofluids with different nanoparticles and base fluid materials. The base fluid used the same as traditional heat transfer fluids, e.g. water, oil, and ethylene glycol, hydrocarbons, and fluorocarbons. Nanofluids are actually dilute liquid suspended nanoparticles which have only one detracting dimension smaller than ~100 nm. The major reason behind the exploration of this divine fluid is that this new type of material possesses high rated properties and behaviour associated with heat transfer [1-2], mass transfer [3-4]. The thermal behaviour of nanofluids could provide a basis for a colossal modernization for heat transfer, which is of considerable importance to number of industrial sectors including transportation, micro-manufacturing, thermal therapy for cancer treatment, power generation, chemical and metallurgical sectors, as well as heating, cooling, ventilation and air-conditioning [5]. Nanofluids are also important for the production of nanostructured materials [6], for the engineering of complex fluids [7], as well as for cleaning oil from surfaces due to their excellent wetting and spreading behaviour [8]. The twenty-first century is an era of technological development and has already seen many changes in almost every industry. The introduction of nanoscience and technology is based on the famous phrase 'Theres Plenty of Room at the Bottom' by the Nobel Prize-winning physicist Richard Feynman in 1959 [9]. Feynman proposed this concept using a set of conventional-sized robot arms to construct a replica of themselves but one-tenth the original size then using that new set of arms to manufacture even smaller set until the molecular scale is reached [10].

We already know that heat exchanger is an integral part of every chemical processing industry in today's era [11]. It is nothing but a device which transfers the energy from a hot fluid medium to a cold fluid medium with maximum rate, minimum investment and low running costs [12]. The heat transfer in a heat exchanger involves convection on each side of fluid and conduction taking place through the wall which is separating the two fluids [13]. In a heat exchanger, the temperature of fluid keeps on changing as it passes through the tubes and also the temperature of the dividing wall located between the fluids varies along the length of heat exchanger [14]. Examples include boilers, superheaters, re-heaters, air preheaters, radiators of an automobile, oil coolers of heat engine, refrigeration of gas turbine power plant, waste recovery heat system. There are two major types of heat exchangers namely direct contact type heat exchanger and non-contact type heat exchanger. There are three possible directions of motion of fluid viz. parallel flow, counter current flow and mixed flow [15]. There are four possible methods in nanofluids which may contribute to thermal conduction [16]:

- Brownian motion of nanoparticles
- Ballistic nature of heat transport in nanoparticles
- Nanoparticles clustering in nanofluids
- Liquid layering at the liquid/particle interface

Various researchers have published articles related to nanofluids which increase the heat transfer coefficient of nanofluids in comparison to other fluids because of improved thermal conductivity and flow behaviour of fluids. [17] reported the thermal performance of a counter-flow shell and tube heat exchanger using nanofluids as the working fluids. They used Finite volume method to solve the three dimensional steady, turbulent developing flow and conjugate heat transfer in a shell and tube heat exchanger. The nanofluids used were Ag, Al_2O_3, CuO, SiO_2, and TiO_2 and the performance was compared with water. The thermal performance and flow of the shell and tube heat exchanger was analyzed using different nanofluids. Temperature profile, heat transfer coefficient, and pressure profile were obtained from the simulations. The results were evaluated in terms of effectiveness, heat transfer rate, and overall heat transfer coefficient. [18] studied the thermal conductivity of copper (Cu) nanofluids in water. [19] studied nanofluids of Cu in water and transformer oil. Thermal conductivity of Cu-ethylene glycol nanofluid was measured by [20]. All these studies reported enhanced thermal conductivity despite to different extents. Several factors were investigated by these authors such as particle concentration and size. Other metals investigated include iron (Fe) [21], gold (Au) [22,23] and silver (Ag) [22]. Despite the high percentage of thermal enhancement observed by earlier research, a different scenario was observed in a work by [24]. The nanofluids containing ~0.001 volume % gold nanoparticles did not show significant enhancement (<2%). This is a direct conflict of results measured by [22] where 5%-21% thermal conductivity enhancement was observed for particle concentration of 0.00026 by volume.

The difference results obtained in these researches may be due to different technique employed in the nanofluids production and different physical properties of surfactant. For example, [18] employed the VEROS technique, [19] utilized the sonication method while [22] applied the citrate reduction method. The accuracy and reliability of our study results are unknown as they are not being reported. The temperature at which the data were taken was also slightly different between these results. The error estimated in these results is approximately 5%-10%. The thermal conductivity of nanofluids containing metal oxide nanoparticles was also measured by many researchers. The three oxide nanoparticles that are very commonly investigated are Al_2O_3, CuO and TiO_2. An earlier work by [18] have demonstrated that the thermal conductivity of CuO-water nanofluids could be enhanced by 60% by adding 5 volume % of nanoparticles. The enhancement was also observed for Al_2O_3-water nanofluids, although less significant than that of CuO. A similar work was also conducted by [25]. These works showed that the thermal conductivity of nanofluids increased linearly with particles loading. [26] observed that even at very low volume fraction (0.1%), the thermal conductivity of Cu-EG nanofluids was increased by 2.6%. [27] measured the thermal conductivity of Al_2O_3 (28 nm diameter) and CuO (20 nm diameter) that are dispersed in several fluids; water, vacuum pump liquid, engine oil and ethylene glycol (EG). The results showed that the effective thermal conductivity for all the nanofluids measured were higher than that of the respective fluids. The experimental data were compared to those of [2] and [25] results. The comparison indicated a possible relation between the effective thermal conductivity and the nanoparticle size. The thermal conductivity was observed to increase with increasing particles size. The experimental data measured were found to be lower than the thermal conductivities values predicted by several existing models. This indicates that there are deficiencies in the models and therefore are insufficient to describe the heat transfer behaviour of nanofluids. Thus new model is needed which should account for factors such as motion and structuring of nanoparticles. [28] and [29] studied the heat conduction of water-based nanofluids containing CuO (28.6 nm) and Al_2O_3 (38.4 nm) over a temperature range of 21˚C to 51˚C. The thennal conductivity of the nanofluids was enhanced as a function of both volume fraction and temperature. The data were compared with the Hamilton Crosser model, a mathematical model that predicts the thermal conductivity of solid liquids mixture [30]. At room temperature, the Al_2O_3-water nanofluids agree with the Hamilton-Crosser (H-C) prediction whereas at other temperature they did not agree. It would somewhat be accidental since [31] observed a contradict results where the thermal conductivity of Al_2O_3-water nanofluid, measured at room temperature failed to agree with H-C prediction. [32] observed that the thermal conductivity of nanofluids was enhanced with increasing temperature and decreasing particle size. For such occurrences, the Brownian velocity is believed to be the key mechanism on the temperature dependence of nanofluids thermal conductivity.

Thermal conductivity of TiO_2-water nanofluids was studied by [33]. Two morphologies of nanoparticles were investigated: i) spherical shape of 15 nm diameter and ii) rod-like shape with 10 nmx40 nm dimension. The investigation showed that the thermal conductivities of TiO_2 nanofluids are higher than the base liquid. For a particle volume fraction of 5%, the enhancement achieved was 27.9% for nanofluids consisting of spherical particles and 32.8% enhancement was observed for cylindrical particles. The thermal conductivities were also affected by the morphology of the nanoparticles where the thermal conductivity of spherical shape nanoparticles was always higher. The results were compared with several models. It was found that the experimental results were higher than those predicted by the models. An earlier work on TiO_2-water nanofluids observed 10% enhancement for a particle loading of 4.35 volume % [2]. Nanofluids containing other compound of metal such as carbides were also studied in several works. [34] and [35] measured the thermal conductivity of SiC nanofluids where EG and water were utilized as the base liquids. Two types of SiC nanoparticles were investigated; one having a spherical shape with 26 nm average diameter and the other is cylindrical shape with average diameter of 600 nm. The experiments showed that even at small amount of particle loading (4.2 volume %), the thermal conductivities of the nanofluids systems were significantly higher than that of the respective base liquids and the enhancement increased linearly with particle volume fraction. The results were compared with the Hamilton-Crosser model. It was found that the model fitted well for large particle (600 nm) but inadequate for nanofluids made of smaller nanoparticles. A recent work on $Al_{70}Cu_{30}$ alloy in ethylene glycol observed a sigmoidal nature of thermal conductivity enhancement. A very significant increase (>200%) was reported for 1.5 volume % of particles [36]. The thermal conductivity of carbon nanotubes (CNTs) nanofluids also received much attention in the literature. CNTs were first discovered by a Japanese physicist [37]. Since then, a lot of reports on the thermal conductivity of CNTs were published. Experimental measurements have indicated that CNTs possess high thermal conductivity [38-40]. Many studies on thermal conductivities of nanofluids have reported a significant enhancement. Fundamentally, the thermal conductivity of nanoparticles depends on their size, which may be even much lower than the bulk value because of the boundary scattering of phonon and electrons. Therefore, with this argument, the thermal conductivity of nanoparticles suspension would then be reduced if particles are smaller than the mean free path of the energy carrier. In most publications, the thermal conductivity of the bulk material is often used since there is very limited data on the thermal conductivity of nanoparticles. These results suggest that there is an urgent need to develop new measurement techniques that takes into account these factors and able to predict nanofluid thermal conductivity.

Table -1

(a) The Relevant Research about the Thermal Conductivity of Nanofluids

Researcher	Base fluid	Nanoparticle
Masuda et al. [2]	DIW	Al_2O_3, TiO_2
Xie et al. [34]	DIW	SiC
Putra et al. [29]	DIW	Al_2O_3, CuO
Zhang et al. [41]	DIW	Al_2O_3, TiO_2, CuO
Timofeeva et al. [42]	DIW, EG	Al_2O_3

(b) The Relevant Research About the Viscosity of Nanofluids

Researcher	Base fluid	Nanoparticle
Masuda et al. [2]	DIW	Al_2O_3, TiO_2
Pak and Cho [43]	DIW	Al_2O_3, TiO_2
Wang et al. [27]	DIW, EG	Al_2O_3
Putra et al. [44]	DIW	Al_2O_3
Maré et al. [45]	DIW	Al_2O_3
Nguyen et al. [46]	DIW	Al_2O_3

MATERIALS AND METHODS

Materials

The Nano Labs India supplied the nanoparticles used for this study. The average particle sizes of nanoparticles Al_2O_3 and SiC were 30-50 nm and 40-60 nm in diameter respectively. The Avantor Performance Materials India Limited supplied the surfactant Sodium Dodecyl Benzene Sulfonate (SDBS) which was used as a mixing agent.

Nanofluid Preparation

The successful production and synthesis of nanofluids are crucial in obtaining optimum thermal properties. A lot of efforts have been put on to the synthesis of nanofluids since the research begun approximately a decade ago. Studies to date have reported that various type of nanoparticles which include metal nanoparticles such as aluminium (Al), copper (Cu), iron (Fe), gold (Au), nickel (Ni), and titanium (Ti) have been utilized in the production of nanofluids. Oxide nanoparticles and other metal compound such as copper oxide (CuO), silica (SiO_2), and titanium dioxide (TiO_2) also received much attention in the synthesis of nanofluids. In addition, nanotubes such as carbon and titania nanotubes as well as diamond nanoparticles have also been used to make nanofluids. The formulations of nanofluids have been a real challenge due to various factors such as morphology of nanoparticles/nanotubes, strong interparticle forces and surface properties of nanoparticles. Particles in the liquid move through Brownian motion and collide with each other. Therefore, the stability of the suspension is mainly determined by the interactions during the collision. The particles are either attractive or repulsive to each other depending on the solution chemistry and surface properties of particles. When particles are attractive, they will form aggregates and even strong agglomerates, which have to be overcome during nanofluid production. In this study, nanofluids were prepared by dispersing Al_2O_3 and SiC nanoparticles with different volume concentrations ranging from 0.1%-0.3% in distilled water as a base fluid. The mechanical mixer (magnetic stirring) and ultra-sonication was used for dispersing nanoparticles for 30 minutes and 60 minutes respectively. The solutions of Al_2O_3-water and SiC-water nanofluids were prepared by the equivalent weight of nanoparticles according to their volume and was measured and gradually added to distilled water while being agitated in a flask. No sedimentation was observed for 3 days in the low concentrations used in this study.

Experimental Set-Up

The experimental system used for this study is shown in Figure 1, which comprises of a test section (straight steel), outer tube, pump and reservoir tank. The tube side dimensions are d_o=12.7 mm and d_i=10 mm and the shell side dimensions are D_o=125 mm and D_i=120 mm. Length of the tube is 500 mm. The total number of tubes are 14. The variation of flow of fluid is from 1-5 LPM. Heated fluid was recirculated to keep constant temperature at the inlet of the test section. The material of construction is SS-304. The experiments were done using a counter-current flow mode in a horizontal shell and tube heat exchanger, with hot nanofluid flowing inside the inner tube while cold water flows through the annulus. The temperature of the nanofluid at the inlet was maintained at 50˚C. The stainless steel outer tube was thermally isolated using Aeroflex tube. Four K-type thermocouples were mounted at differential longitudinal positions on tube surface of the wall, two K-type thermocouples were inserted into the flow at the entrance and exit of the test section to measure the bulk temperatures of nanofluid and two K-type thermocouples were measured the flow the entrance and exit of the cold water flows in the annular temperatures. The electric heater with a PID controller was installed to keep the temperature of the nanofluid constant. The cooler tank with a thermostat is used to keep the nanofluid temperature constant. The nanofluid flow rate and cold water were controlled by adjusting the bypass flow valve, which was measured by Dakota rotameters. To create constant wall temperature boundary condition, the cool water was circulated with high flow rate. During all experiments, the inlet and outlet temperature of the nanofluid, the wall temperature at the various positions were measured and recorded using the thermocouple data acquisitions module (Omega TC-08). The average of all data was used in the present study.

Fig. 1 Experimental Set-up of shell and tube heat exchanger

Table -2 Thermo-Physical Properties of Water, Al_2O_3 and SiC Nanoparticles

Sample	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal Conductivity (W/m·K)
Water	988.02	4182	0.6435
Al_2O_3 nanoparticles	3890	880	35
SiC nanoparticles	3216	610	15

Table -3 Thermo-Physical Properties of Al_2O_3-Water Sample

Sample	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal Conductivity (W/m·K)	Viscosity (kg/m·s)
Water	988.02	4182	0.6435	0.000547
Water+0.1% Al_2O_3	990.893	4169.1663	0.6453	0.0005484
Water+0.2% Al_2O_3	993.812	4156.204	0.6472	0.000549
Water+0.3% Al_2O_3	996.6998	4143.4542	0.649	0.000551

Table -4 Thermo-Physical Properties of SiC-Water Sample

Sample	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal Conductivity (W/m·K)	Viscosity (kg/m·s)
Water	988.02	4182	0.6435	0.000547
Water+0.1% SiC	990.225	4170.518	0.6452	0.0005484
Water+0.2% SiC	992.467	4158.897	0.6469	0.000549
Water+0.3% SiC	994.6838	4147.5475	0.6486	0.000551

Nanofluid Physical Properties

In this study, the thermo-physical properties considered for Al_2O_3, SiC and base fluid are tabulated in Table 2. Nusselt number and Reynolds number was determined using the experimental observations. The thermo-physical properties were calculated on mean bulk temperature of nanofluid. Effective viscosity, density, heat capacity and thermal conductivity were calculated using equation 1, 2, 3 and 4 and tabulated in Table 3 and 4.

1. Viscosity of nanofluid: Drew and Passman relation [47]

$$\mu_{nf} = (1 + 2.5\emptyset)\mu_{bf} \quad (1)$$

2. Density: Choi correlation [1]

$$\rho_{nf} = (1 - \emptyset)\rho_{bf} + \emptyset_{\rho_p} \quad (2)$$

3. Heat Capacity equation: Xuan and Roetzel [48]

$$C_{p_{nf}} = \frac{(1-\emptyset)\rho_{bf}C_{P_{bf}} + \emptyset_{\rho_p}C_{p_p}}{\rho_{nf}} \quad (3)$$

4. Effective thermal conductivity: Maxwell model [49]

$$K_{eff} = \frac{K_p + 2K_{bf} + 2(K_p - K_{bf})\emptyset_p}{K_p + 2K_{bf} - (K_p - K_{bf})\emptyset_p} K_{bf} \quad (4)$$

5. Validation of the experimental data was performed using:
   a. Li and Xuan correlation [50]

$$Nu = 0.4328(1 + 11.285\emptyset^{0.754}Pe^{0.218})Re^{0.333}Pr^{0.4} \quad (5)$$

   b. Xuan and Li correlation [51]

$$Nu = 0.0059(1 + 7.6286\emptyset^{0.6886}Pe^{0.001})Re^{0.9238}Pr^{0.4} \quad (6)$$

   c. Maiga correlation [52]

$$Nu = 0.28Re^{0.35}Pr^{0.35} \quad (7)$$

Procedural Steps

1. Take readings and find out $\Delta T1 = T1 - T4$ and $\Delta T2 = T2 - T3$
2. Find LMTD
3. Find area = $\pi D^2/4$
4. Take flow rate in kg/sec
5. Find $Q = m \times C_p \times \Delta T1$
6. Find $h = Q/(A \times \Delta T_{LMTD})$
7. Find $V = m/A$
8. Find $Re = (\rho \times V \times D)/\mu$
9. Find $Nu = (h \times D)/k$
10. Find $Pr = (C_p \times \mu)/k$
11. Find $Pe = Re \times Pr$

RESULTS AND DISCUSSION

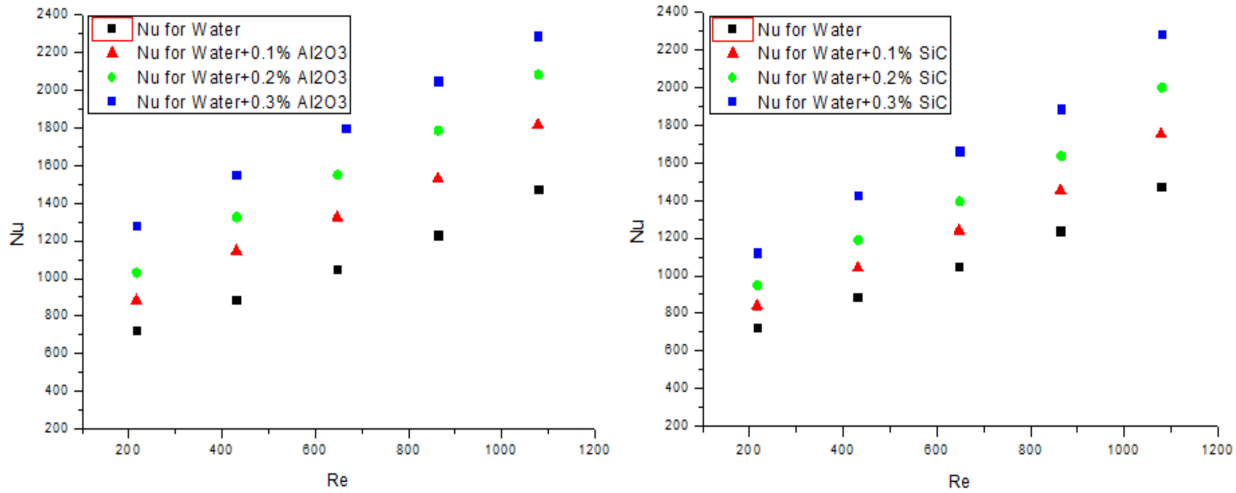
All the experimental analyses were performed by Al_2O_3/SiC-water nanofluids by varying the concentration of nano-particles from 0.1% to 0.3% by volume and different flow rate (1-5 LPM). The temperature was maintained at 50±3˚C for all runs. The observations from this study were summarized as below.

Effect of Concentration of Nanoparticles

Fig. 2 (a) and 2 (b) shows the effect of nanoparticle concentration on Nusselt number with Reynolds Number. From these figures, it can be concluded that changes in the concentration of nanoparticles increases the Reynolds number hence Nusselt Number. It was due to increase in heat transfer and Reynolds number on addition of nanoparticles in the fluid which improved thermo-physical properties of the mixture. Similar results were reported by [53-54]. The variation of Nusselt number with Reynolds number for 0.3% Al_2O_3 and 0.3% SiC nanofluid was represented in Fig. 3. This revealed that heat transfer enhancement was more in Al_2O_3 as compared to SiC for same volume concentra-tion. This may be due to more thermal conductivity of Al_2O_3 than SiC. Similar results were reported by [55-56].

Validation of Experimental Data and Correlation

Fig. 4 (a) and 4 (b) shows validation of experimental data at 0.3% by volume of Al_2O_3 and SiC nanofluid with corre-lations given by Li and Xuan, Xuan and Li and Maiga. It was observed that Xuan and Li correlation was best fitted with experimental results in comparison to other correlations.



(a) **(b)**

Fig. 2 (a) Variation of Nusselt number with Reynolds number for Al_2O_3 nanofluid (b) Variation of Nusselt number with Reynolds number for SiC nanofluid

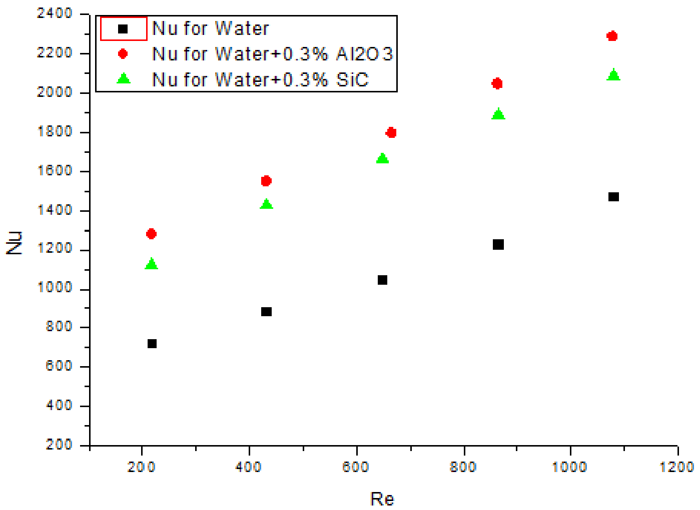
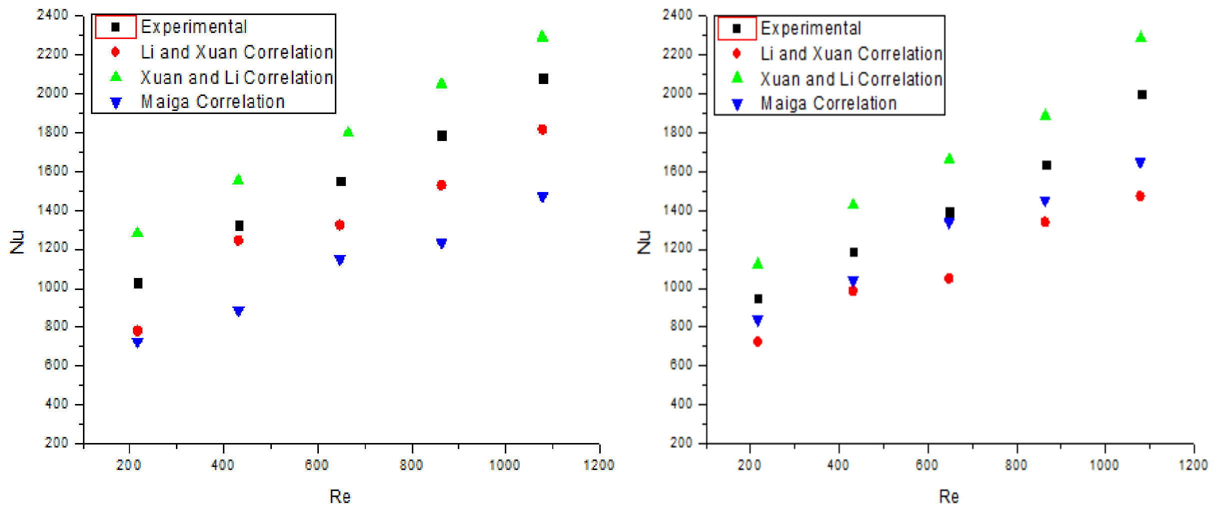


Fig. 3 Variation of Nusselt number with Reynolds number for 0.3% Al_2O_3 and 0.3% SiC nanofluid



(a) (b)

Fig. 4 (a) Validation of results with theoretical correlation and experimental (0.3% Al_2O_3) (b) Validation of results with theoretical correlation and experimental (0.3% SiC)

CONCLUSION

Performance of heat exchanger (shell and tube) has been studied using experimental observation and numerical techniques. Results have been shown by highlighting the variation of flow rate and concentration of nanoparticles. Experimental results show that application of Al_2O_3/SiC based nanofluid enhances coefficient of heat transfer with concentration and flow rate (increase by 5%) respectively. Xuan and Li correlation found to be best fitted with the experimental observations. A theoretical and experimental result shows that distribution of nanoparticles in homogeneous and stabilized manner increases the coefficient of heat transfer significantly.

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Nomenclature

d_o = Outer diameter of inner tube of heat exchanger, mm
d_i = Inner diameter of inner tube of heat exchanger, mm
D_o = Outer diameter of outer tube of heat exchanger, mm
D_i = Inner diameter of outer tube of heat exchanger, mm
μ_{nf} = Viscosity of nanofluid, kg/m sec
ρ_{nf} = Density of nanofluid, kg/m^3
C_{pnf} = Heat capacity of nanofluid, J/kg K
K_{eff} = Effective thermal conductivity of nanofluid, W/m K
μ_{bf} = Viscosity of base fluid, kg/m sec
ρ_{bf} = Density of base fluid, kg/m^3
C_{pbf} = Heat capacity of base fluid, J/kg K
K_{bf} = Effective thermal conductivity of base fluid, W/m K
ρ_p = Density of particle, kg/m^3
K_p = Effective thermal conductivity of particle, W/m K
C_{pp} = Heat capacity of particle, J/kg K
C_p = Specific heat, J/kg K
k = Thermal conductivity, W/m K
T = Temperature, ˚C
m = Mass flow rate, kg/sec
T1 = Inlet temperature of hot fluid, K
T2 = Outlet temperature of hot fluid, K
T3 = Inlet temperature of cold fluid, K
T4 = Outlet temperature of cold fluid, K
Q = Rate of heat transfer, W
ΔT_{LMTD} = Log mean temperature difference, ˚C
A = Cross-sectional area of shell, mm^2
h = Heat transfer coefficient, W/m^2 K
D = Diameter of tube, mm
V = Mean velocity, m/sec
Nu = Nusselt number
Re = Reynolds number
Pr = Prandtl number
Pe = Peclet number
LPM = Litre per minute
DIW = Distilled water
EG = Ethylene glycol

Mathematical Symbols

< = Less than
% = Percentage

Greek Letters

ρ = Density, kg/m^3
ϕ = Volume concentration, %
μ = Viscosity, kg/m s
ΔT = ˚C

Subscripts

nf = Nanofluid
bf = Base fluid
LMTD = Log mean temperature difference
p = Particle
eff = Effective value