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Heat transfer through heat exchanger using Al_2O_3 nanofluid at different concentrations

Jaafar Albadr [a,*], Satinder Tayal [a], Mushtaq Alasadi [b]

[a] Department of Mechanical Engineering, Maharishi Markandeshwar University, Mullana-Ambala, Haryana, India
[b] Refrigeration Department, South Oil Company, Ministry of Oil, Basra, Iraq

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ABSTRACT

This article reports an experimental study on the forced convective heat transfer and flow characteristics of a nanofluid consisting of water and different volume concentrations of Al_2O_3 nanofluid (0.3–2)% flowing in a horizontal shell and tube heat exchanger counter flow under turbulent flow conditions are investigated. The Al_2O_3 nanoparticles of about 30 nm diameter are used in the present study. The results show that the convective heat transfer coefficient of nanofluid is slightly higher than that of the base liquid at same mass flow rate and at same inlet temperature. The heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate, also the heat transfer coefficient increases with the increase of the volume concentration of the Al_2O_3 nanofluid, however increasing the volume concentration cause increase in the viscosity of the nanofluid leading to increase in friction factor.

1. Introduction

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. Many researchers have investigated the heat transfer performance and flow characteristics of various nanofluids with different nanoparticles and base fluid materials. Several following existing published articles which associate with the use of nanofluids are described in the following sections. Abu-Nada, et al. [2] used an efficient finite-volume method to study the heat transfer characteristics of natural convection for CuO/EG/water nanofluid in a differentially heated enclosure. His results show that the dynamic viscosity and friction factor increased due to dispersing the alumina nanoparticles in water. Chein and Chuang [3] reported experimentally on microchannel heat sink (MCHS) performance using CuO–water nanofluids as coolants. The thermal and physical properties of nanofluids were calculated using the following equations: the Brinkman equation [4] for viscosity, the Xuan and Roetzel equation [5] for specific heat, and the Hamilton and Crosser model [6] for thermal conductivity. The results showed that the presence of nanoparticles creates greater energy absorption than pure water at a low flow rate and that there is no contribution from heat absorption when the flow rate is high. Duangthongsuk and Wongwises [7,8] investigated the effect of thermophysical properties models on prediction of the heat transfer coefficient and also reported the heat transfer performance and friction characteristics of nanofluid, respectively. The 0.2 volume concentration TiO_2

* Corresponding author. Tel.: +964 7801771277.
E-mail address: jnalbader@yahoo.com (J. Albadr).

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Nomenclature

Cp	specific heat, J/kg K
d	nanoparticle diameter, m
D	tube diameter, m
f	friction factor
U	overall heat transfer coefficient, W/m^2 K
K	thermal conductivity, W/mK
$\dot{m}$	mass flow rate, L/s
Nu	Nusselt number
Re	Reynolds number
Pe	Peclet number
Pr	Prandtl number *Q* heat transfer, W
T	temperature, °C
V	mean velocity, m/s

Greek symbols

υ	kinematic viscosity, m^2/s
$\varnothing$	volume concentration, %
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
μ	viscosity, kg/ms
ΔT	°C

Subscripts

wi	water inlet
wo	water outlet
ni	nanofluid inlet
no	nanofluid outlet
in	inlet
out	outlet
n	nanofluid
f	base fluid
ρ	nanoparticles

naoparticles are used to disperse in the water. The results showed that the various thermophysical models have no significant effect on the predicted values of Nusselt number of the nanofluid. The results also indicated that the heat transfer coefficient of nanofluid is slightly greater than that of water by approximately (6–11)% and use of nanofluid has little penalty in pressure drop. Hwang et al. [9] through experimental investigation of flow and convective heat transfer characteristics of Al_2O_3/water nanofluid, with convective heat transfer characteristics of Al_2O_3/water nanofluid with particles varying in the range of 0.01–0.3% in a circular tube of 1.812 mm inner diameter with the constant heat flux in fully developed laminar regime reported improvement in convective heat transfer coefficient in the thermally fully developed regime. Li and Xuan [10] and Xuan and Li [11] studied experimentally the convective heat transfer and flow features for Cu–water nanofluids flowing through a straight tube under laminar and turbulent flow regimes with a constant heat flux. The experimental results showed that addition of nanoparticles into the base liquid remarkably enhanced the heat transfer performance of the base liquid. Moreover, the friction factor of nanofluids coincided well with that of the water. They also proposed new convective heat transfer correlations for calculating the heat transfer coefficients of the nanofluid for both laminar and turbulent flow conditions. Mapa and Mazhar [12] performed a similar study using commercially available equipment. The results showed that a number of factors increase the thermal conductivity of the nanofluid and the presence of nanoparticles reduces the thermal boundary layer thickness. Mirmasoumi and Behzadmehr [13] have studied the effects of nanoparticle mean diameter on the heat transfer and flow behavior into a horizontal tube under laminar mixed convection condition. Their calculated results demonstrate that the convection heat transfer coefficient significantly increases with decreasing the nanoparticles means diameter. However, the hydrodynamics parameters are not significantly changed. They also showed that the non-uniformity of the particles distribution augments when using larger nanoparticles and/or considering relatively high value of the Grashof numbers. Pak and Cho [14] investigated experimentally the heat transfer performance of Al_2O_3 and TiO_2 nanoparticles dispersed in water flowing in a horizontal circular tube with a constant heat flux under turbulent flow conditions. The results showed that the Nusselt number of nanofluids increased with increasing Reynolds number and the volume concentration. However, they still found that the convective heat transfer coefficient of the nanofluids with 3 volume concentration nanoparticles was 12% lower than that of pure water at a given condition. Finally, a new heat transfer correlation for predicting the convective heat transfer coefficient of nanofluids in a turbulent flow regime was proposed. Putra et al. [15] poured Al_2O_3/water and CuO/water nanofluids into a horizontal circular tube. Under the same aspect ratio, the natural convective heat transfer coefficient of nanofluid was lower than that of base liquid, revealing that the natural convective heat transfer coefficient of nanofluid fell with the increase of particle concentration, aspect ratio and density. The experimental data showed that nanofluids were of no help to the natural convective heat transfer. Xuan and Roetzel [5] used single-phase fluid and solid–liquid two-phase fluid to induce the prediction of heat convection performance of nanofluid. They thought that higher heat convection performance of nanofluid was caused by the higher thermal conductivity of nanofluid and the disordered movement of nanoparticles. Zamzamian et al. [16] investigated the effects of forced convective heat transfer coefficient with Al_2O_3/EG and CuO/EG nanofluid in double pipe and plate heat exchangers. Their results indicate that increasing the nanoparticle concentration and temperature could enhance the convective heat transfer coefficient of nanofluid, leading to a 2–50% enhancement in convective heat transfer coefficient of the nanofluid. This thesis is aimed at studying the heat transfer enhancement and flow characteristics of Al_2O_3–water nanofluids at a low concentration flowing in a horizontal shell and tube heat exchanger under a turbulent flow condition.

2. Experimental setup

To design a project that could be used to transfer heat from hot water in a heat exchanger to nanofluid stored in a separate tank and make temperature calibrations for the same by employing two thermocouples. Also, flow meters will be installed in the pipes carrying nanofluid to check its flowing rate. The complete system will be very dynamic and easy to use. Mechanical structure design is shown is Fig. 1.

It consists of two flow loops, a heating unit to heat the nanofluid or the distilled water, and temperature measurement system. The two flow loops carries heated nanofluid or distilled water and the other cooling water. Each flow loop includes a pump with a flow meter, a reservoir and a bypass valve to maintain the required flow rate. The shell and tube heat exchanger is of stainless steel type 316 L, 248 mm long consisting of 37 tubes. The tube diameter is 2.4 mm with a tube wall thickness of 0.25 mm, having a designed heat transfer area of 0.05 m^2. Two J-type thermocouples with removable bulbs are inserted on the heat exchanger to measure the bulk temperatures of inlet and outlet fluid streams. The pumps are used with maximum delivery rate of 18.3 L/min.

3. Data processing

The nanofluid presented equation are calculated by using of the Pak and Cho [14] correlations, which are defined as follows:

$$\rho_{nf} = (1-\varnothing)\rho_f + \varnothing\rho_p \tag{1}$$

where ρ_{nf} is the density of the nanofluid, $\varnothing$ is the particles volume concentration, ρ_f is the density of the base fluid and ρ_p is the density of the nanoparticles.

The specific heat is calculated from Xuan and Roetzel [5] as following:

$$(\rho Cp)_{nf} = (1-\varnothing)(\rho Cp)_f + \varnothing(\rho Cp)_p \tag{2}$$

where Cp_{nf} is the heat capacity of the nanofluid, Cp_f is the heat capacity of the base fluid and Cp_p is the heat capacity of the nanoparticles.

Heat transfer rate can be defined as

$$Q = \dot{m}Cp\Delta T \tag{3}$$

where Q is the heat transfer rate, $\dot{m}$ is the mass flow rate and ΔT is the temperature difference of the cooling liquid.

The logarithmic mean temperature difference:

$$\Delta T_{lm} = \frac{(T_{wi}-T_{no})-(T_{wo}-T_{ni})}{Ln((T_{wi}-T_{no})/(T_{wo}-T_{ni}))} \tag{4}$$

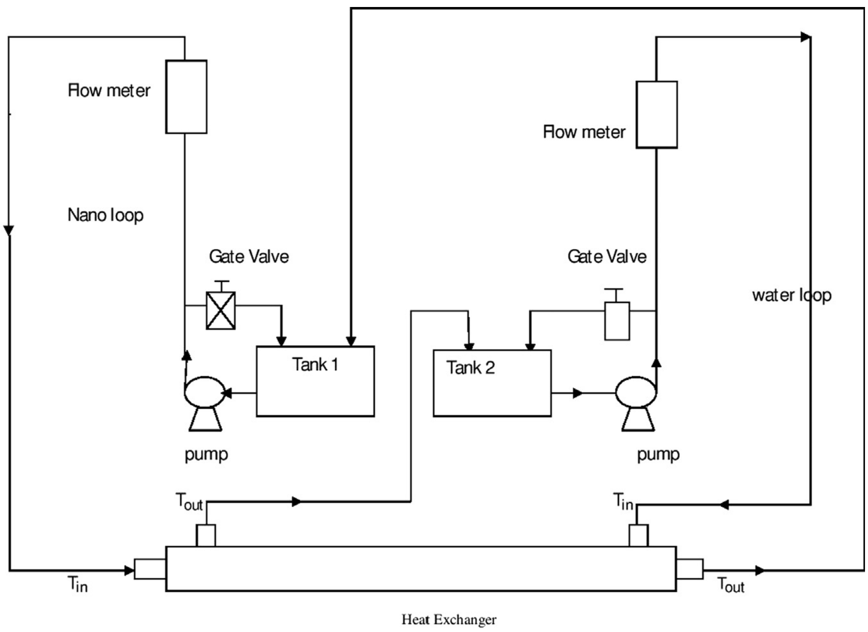

Fig. 1. System diagram.

where ΔT_{lm} is the logarithmic temperature difference, T_{wi} is the inlet temperature of the water, T_{wo} is the outlet temperature of water, T_{ni} is the inlet temperature of the nanofluid and T_{no} is the outlet temperature of the nanofluid.

The overall heat transfer coefficient is

$$Q = UA_s \, \Delta T_{lm} \tag{5}$$

where U is the overall heat transfer coefficient and A_s is the surface temperature.

3.1. Thermal conductivity

An alternative formula for calculating the thermal conductivity was introduced by Yu and Choi [17], which is expressed in the following form:

$$K_{nf} = k_f \frac{(K + 2K_f - 2\,\phi(K_f - K\,)}{K + 2K_f + \,\phi(K_f + K)} \tag{6}$$

where K_{nf} is thermal conductivity of the nanofluid, K_ρ is thermal conductivity of the nanoparticle and K_f is the base fluid thermal conductivity.

The viscosity of the nanofluid Drew and Passman [18] suggested the well-known Einstein′s equation for calculating viscosity, which is applicable to spherical particles in volume fractions less than 5.0 vol%, and is defined as follows:

$$\mu_{nf} = (1 + 2.5\varnothing)\mu_w \tag{7}$$

where μ_{nf} is the nanofluid viscosity and μ_w is the water viscosity.

The properties of the nanofluid shown in the above equations are evaluated from water and nanoparticles at room temperature.

4. Results and discussions

To evaluate the accuracy of measurements, experimental system has been tested with distilled water before measuring the heat transfer characteristics of different volume concentration of Al_2O_3/water.

From the experimental system, the values that have been measured are, the temperatures of the inlet and outlet of the hot water as well as the inlet of the distilled water and the different concentrations of nanofluids at different mass flow rates.

Friction factors and Nusselt numbers for single phase flow has been calculated from the Gnielinski equation [19]. The Gnielinski equation is defined as

$$f = [1.58 \ln \mathrm{Re} - 3.82]^{-2} \tag{8}$$

where f is the friction factor and Re is Reynolds number.

Finding Nusselt number [19]

$$Nu = \frac{(0.125f)(Re - 1000)pr}{1 + 12.7(0.125f)^{0.5}\,(Pr^{2/3} - 1)} \tag{9}$$

where Nu is Nusselt number and Pr is Prandtl number.

Friction factor for each flow rate for nanofluid can be found with the help of Duangthongsuk and Wongwises correlation [20] as Gnielinski equation [19] for single phase flow cannot be used for calculating Friction factor as well as Nusselt number.

$$f = 0.961Re^{-0.375}\varnothing^{0.052} \tag{10}$$

Nusselt number is calculated from Duangthongsuk and Wongwises correlation [20] as follows:

$$Nu = 0.074{Re_{nf}}^{0.707}{Pr_{nf}}^{0.385}\varnothing^{0.074} \tag{11}$$

The Kinematic viscosity can be calculated from:

$$\upsilon = \frac{\mu}{\rho} \tag{12}$$

Calculation of Reynolds [21], Peclet and Prandtl numbers [22] are as follows:

$$Re = \frac{VD}{\upsilon} \tag{13}$$

where V is the fluid velocity and D is the tube diameter.

$$Pe = \frac{V\,D}{\alpha_{nf}} \tag{14}$$

where Pe is peclet number and α_{nf} is thermal diffusivity.

$$Pr = \frac{\upsilon_{nf}}{\alpha_{nf}} \tag{15}$$

Thermal diffusivity is given by

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} Cp} \tag{16}$$

In order to apply the nanofluids for practical application, in addition to the heat transfer performance of the nanofluid it is necessary to study their flow features. Study with 0.3, 0.5, 0.7, 1 and 2 volume concentrations suspended nanoparticles are used to calculate the friction factor for each volume concentration and for all the mass flow rates. Fig. 2 shows the calculated friction factor for a measured value of Reynolds number.

The results show that the friction factor increases with the increase in volume concentration of the nanoparticles for a given mass flow rate and decreases with increase in Reynolds number. The heat transfer rate of distilled water increases with the increase in mass flow rate till the amount of 0.01083 L/s and the heat rate starts to decrease at the mass flow rate of 0.0125 L/s. The same results are shown in Mapa and Mazhar [12]. The addition of nanofluid increases the heat rate with the increase in mass flow rate as well as the increase in volume concentration. The maximum enhancement ratio of 1.375 is calculated at the maximum mass flow rate and at 2% volume concentration of nanofluid.

Results indicate same trend of the heat rate for the overall heat transfer rate using distilled water as working fluid. This is because heat rate is directly proportional to the overall heat transfer coefficient. The overall heat transfer coefficient for distilled water increases with the increase in mass flow rate till the amount of 0.01083 L/s, after that the overall heat transfer coefficient starts to decrease till it reaches the amount of 0.0125 L/s because the value of the temperature difference decreases with the increase in mass flow rate. For the nanofluid, the overall heat transfer coefficient increases with the increase in all the values of the mass flow rates and with the increase in volume concentration of the nanofluid, the maximum value of the overall heat transfer coefficient indicated at the maximum flow rate and at 2% volume concentration of the nanoparticles with an enhancement ratio of 1.754, the reason is that the nanoparticles increase the thermal conductivity and a large energy exchange process resulting from the chaotic movement of the nanoparticles. Figs. 3 and 4 shows the increase in overall heat transfer coefficient for a given mass flow rate and a given Peclet number.

Nusselt numbers of the nanofluid are higher than the base fluid, and the numbers are increasing with the increase in Reynolds number as well as the particle volume concentration. The maximum value can be obtained at the maximum Reynolds number of 180,349.123 and at the volume concentration of 2%. Fig. 5 represent the calculated Nusselt number for distilled water as well as for different concentrations of the Al_2O_3/water nanofluid in relation to the calculated Peclet numbers and Reynolds numbers.

It was concluded that the heat transfer characteristics of the nanofluid increased. The trends shown by the nanofluid is due to the fact that the nanoparticles presented in the base fluid increase the thermal conductivity and the viscosity of the base liquid at the same time. The enhancement of thermal conductivity leads to increase the heat transfer performance as well as viscosity of the fluid which results into an increase in friction factor and the boundary layer thickness.

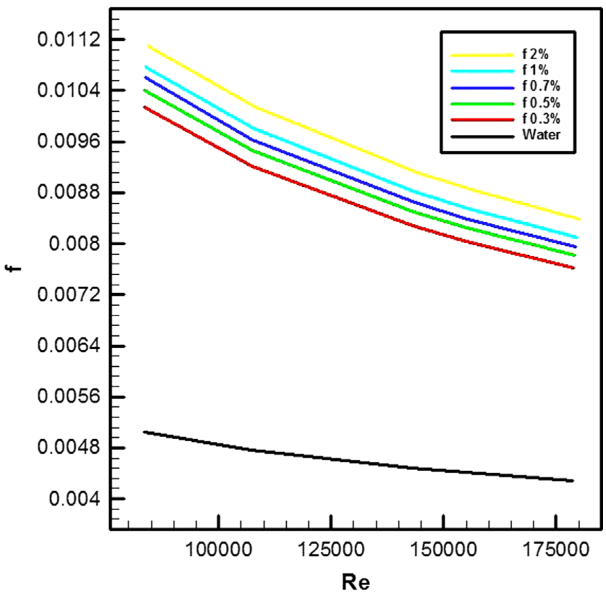

Fig. 2. Friction factor (f) versus Reynolds number (Re).

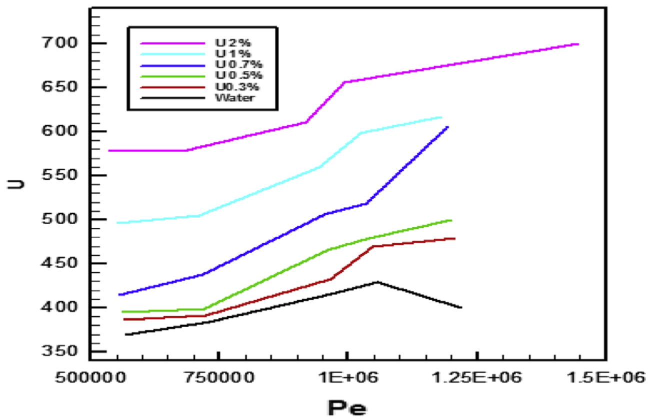

Fig. 3. Overall heat transfer coefficient (U) versus mass flow rate ($\dot{m}$).

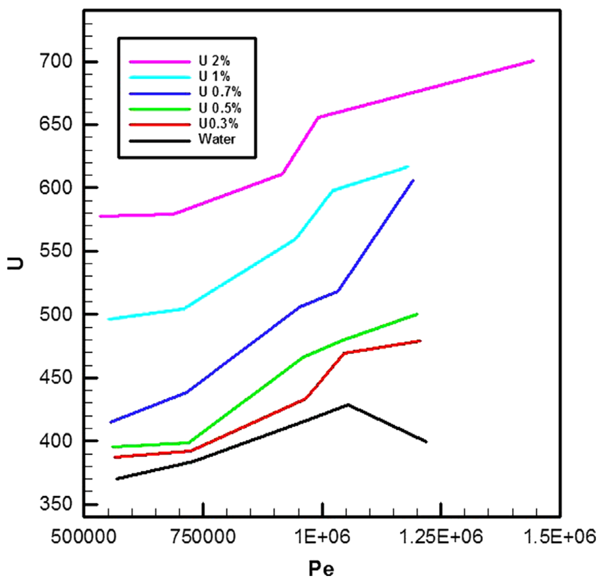

Fig. 4. Overall heat transfer coefficient (U) versus Peclet number (Pe).

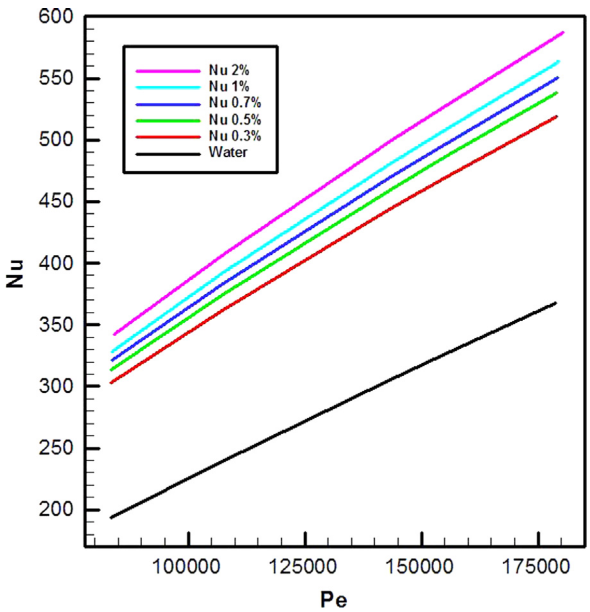

Fig. 5. Nusselt number (Nu) versus Peclet number (Pe).

5. Conclusion

The convective heat transfer performance and flow characteristics of Al_2O_3 nanofluid flowing in a horizontal shell and tube heat exchanger has been experimentally investigated. Experiments have been carried out under turbulent conditions. The effect of particle concentration and the Reynolds number on the heat transfer performance and flow behavior of the nanofluid has been determined. Important conclusions have been obtained and are summarized as following:

1. Dispersion of the nanoparticles into the distilled water increases the thermal conductivity and viscosity of the nanofluid, this augmentation increases with the increase in particle concentrations.
2. At a particle volume concentration of 2% the use of Al_2O_3/water nanofluid gives significantly higher heat transfer characteristics. For example at the particle volume concentration of 2% the overall heat transfer coefficient is 700.242 W/m^2 K and for the water it is 399.15 W/m^2 K for a mass flow rate of 0.0125 L/s so the enhancement ratio of the overall heat transfer coefficient is 1.754, this means the amount of the overall heat transfer coefficient of the nanofluid is 57% greater than that of distilled water. As for Nusselt number, the value of Nusselt number for 2% volume concentration is 587 and for the distilled water it is 367.759 so the maximum enhancement ratio at 0.0125 L/s is 1.596, this means that Nusselt number of the nanofluid is 62.6% greater than that of distilled water.
3. Friction factor increases with the increase in particle volume concentration. This is because of the increase in the viscosity of the nanofluid and it means that the nanofluid incur little penalty in pressure drop.

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