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An experimental study on the proper criterion to judge the thermal performance of the nanofluids

R. Sajedi [a,*], M. Jafari [a], Sh. Nasirivatan [b], B. Osanloo [a]

[a] Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

This work is dedicated to finding a suitable measure to judge thermal performance of nanofluids. The importance of this issue arises from misleading claim of excess heat transfer of nanofluids compared to the base fluid, neglecting the hydraulic effects such as increase in pressure drop. To clarify the issue, the experimental setup with capability to create constant Reynolds number and constant pumping power is constructed. Thermal behavior of nanofluids of silicon oxide/water and aluminum oxide/water and distilled water in developing region of laminar flow regime is investigated. In this regard, the convective heat transfer coefficient within the finned tube heat exchanger is evaluated. According to the results, the concentration of nanoparticle in the base fluid will have a significant impact on the amount of deflection of these two criteria, so that by increasing the nanoparticle's concentration the difference between these two measures becomes greater.

1. Introduction

Since the need for cooling in the industry has been one of the major concerns of engineers, and development of industries increases the amount of heat generation per unit area, investigators are trying to use different methods to reach the maximum possible cooling in the minimum space. In this context, the use of nanofluids is of great interest for researchers.

Li and Xuan [1,2] performed an experimental study to investigate the rate of heat transfer and properties of copper/water nanofluid flowing in a pipe in the laminar and turbulent regimes with constant heat flux boundaries. Research results showed that the nanoparticles significantly improve the rate of heat transfer, while the friction coefficient of the nanofluids has not been changed much compared to the base fluid. Thermal behavior of the graphite nanofluids under the laminar regime in the circular pipe is experimentally investigated by Yang [3]. Results showed that the nanoparticles increase the rate of heat transfer in the laminar regime. But the increase was much less than expected values based on the static measurement of thermal conductivity. In an experimental study, the convective heat transfer coefficient of the base fluid of water and nanofluid of alumina/water were investigated under conditions of constant wall temperature in a pipe by Zeinali Heris et al. [4]. Six volume concentrations in the range of 0.2%–2.5% and different Reynolds number in the range of 700 to 2050 have been tested for the alumina nanofluids. Results indicated that the common relationships for anticipation of convective heat transfer coefficient in a pipe with constant temperature boundaries fails to use in the nanofluid. It is also necessary to mention that all the results in this paper are provided for the same Peclet Number of base fluid and nanofluid. Anoop et al. [5] presented an experimental study to investigate the effects of nanoparticle's size on the convective heat transfer coefficient of nanofluid of alumina/water in the laminar and developing regions. In this work, alumina nanoparticles in two sizes of 45 and 150 nm are used. Based on the results, the use of smaller nanoparticles has greater increase in convective heat transfer coefficient of nanofluid relative to the base fluid. They also concluded that addition of nanoparticles in the developing zone further increases the convective heat transfer coefficient, compared to the developed zone. Another interesting result of this study was the ability of single-phase relations to predict the convective heat transfer coefficient in the nanofluid. Also in this article all results have been reported for the constant Reynolds number. Hwang et al. [6] measured the pressure drop and heat transfer coefficient of the nanofluid of alumina oxide/water in a circular heat pipe in the laminar regime and fully developed zone. The experimental results showed that the friction coefficient of nanofluid can be computed using analytical equation of Darcy for single-phase flows. On the other hand, the convective heat transfer coefficient for nanofluid in the volume concentration of 0.3% showed an increase of 8% compared to the base fluid which could be estimated by equation of Shah.

Recently Esmailzadeh et al. [7] experimentally studied heat transfer properties of aluminum oxide nanoparticles in the water. They applied the constant heat flux along a meter pipe to compute the convective

* Corresponding author at: Faculty of Mechanical Engineering, University of Tabriz, 5166616471, Iran.
E-mail address: ramin_sajedi91@ms.tabrizu.ac.ir (R. Sajedi).

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Nomenclature

Latin symbols

P	Pressure [pa]
V	Velocity [m/s]
Re	Reynolds number [−]
Pr	Prandtl number [−]
T	Temperature [°C]
$\dot{v}$	Flow rate [L/S]
K	Thermal conductivity [W/m K]
C_p	Specific heat [J/kg∗K]
h	Heat transfer coefficient [W/ m^2∗k]
Q	Heat transfer rate [Watt]
$\overline{Nu}$	Nusselt number [−]
mW	Mili Watt

Greek symbols

μ	fluid dynamic viscosity [Pa.s]
ρ	fluid density [kg/ m^3]
φ	volume concentrations

Subscript

nf	nano fluid
bf	base fluid
p	nanoparticle
f	fluid
tub	tube
in	inlet
out	outlet
b	bulk
w	wall

heat transfer coefficient at different Reynolds numbers in the laminar regime. They also studied the pressure drop in the presence of different nanoparticle. They found that by increasing the percentage of nanoparticles heat transfer coefficient increases and the increase of heat transfer at the entrance of the pipe is much more intuitive. Also they examined the heat transfer and friction factor characteristics of γ-Al_2O_3/water through circular tube with twisted tape [8].

Ferrouillat et al. [9] studied the impact of shape factor in the silicon oxide and zinc oxide nanoparticles in the water-based fluid. They worked at temperatures of 20 and 50 °C and at Reynolds numbers ranging from 200 to 15,000. Results indicated a slight increase in Nusselt number of nanofluid compared to the based fluid of water. An energy performance evaluation criterion was defined based on the increase of the rate of heat transfer and pumping power. It was observed that the zinc oxide nanoparticles with a larger shape factor of 3 have reached to a high level of energy performance the same as water. Azmi et al. [10] presented an experimental study on the forced heat transfer and frictional losses in the turbulent flow regime in the presence of oxide silicon nanoparticles. Their results were reported in the Reynolds number between 5000 and 27,000 and bulk temperature of 30 °C. According to the results, it was seen that in the presence of nanoparticles with a volume fraction of 3% the increase in the heat transfer coefficient and frictional losses increase 32.7% and 17.1%, respectively. Darzi et al. [11] experimentally worked on the heat transfer and fluid properties of nano silica in the turbulent flow regime in the pipe with a spiral strip. They used 30 nm silica nanoparticles. They implemented tests for a simple pipe and five pipes with different peach and height values. The results showed that the use of spiral pipes with low angles of helix and high altitude has significant impact on the increase of heat transfer compared to negligible frictional losses. Javadi et al. [12] studied the thermo-physical and heat transfer properties of nanofluids in a plane heat exchanger. They compared the thermo-physical and heat-transfer properties of nanofluids containing nanoparticles of silicon oxide, titanium oxide and aluminum oxide in a plate heat exchanger with water-based fluid. According to the results, aluminum oxide and titanium oxide enhance the rate of heat transfer more than silicon oxide. Ebrahimi et al. [13] presented an experimental study on the forced heat transfer characteristics of silicon oxide nanoparticles in the automobile radiators. They investigated the effects of inlet temperature; flow rate and volume concentrations of different nanoparticles. Results showed that by increasing the inlet temperature, Reynolds number and volume concentration of the nanoparticles, the Nusselt number will grow.

Researchers at Argonne national laboratory [14] examined the issue of the proper criterion of comparison between the base fluid and nanofluids. In this paper three criteria are studied to measure the effectiveness of nanofluids instead of base fluid for increasing the heat transfer. According to the results, using the criteria of the constant Reynolds number between the base fluid and nanofluid to judge the increase of heat transfer is incorrect. But, the use of constant velocity could be picked up as an acceptable criterion. Also, they introduced the use same pumping power between nanofluids and base fluid as a proper criterion of comparison.

Haghighi et al. [15] investigated the effectiveness of nanofluids in increasing the heat transfer using four criteria of the constant Reynolds number, constant velocity, constant mass flow rate and the constant pumping power. In this study, three nanofluids of alumina/water, titanium oxide/water and selenium oxide/water were tested in the mass concentration of 9%. According to the results, the equation of Shah which predicts the Nusselt number of the laminar flow under constant heat flux boundaries, could successfully anticipate the convective heat transfer coefficient for all three nanofluids. The same conclusion is valid for Darcy equation to predict the coefficient of friction for the nanofluids. Also this paper rejects the criterion of the constant Reynolds number to measure the heat transfer coefficient of nanofluid and base fluid and states that the criterion of the constant pumping power would be the best comparable measure.

This work, tries to obtain and highlight a proper comparative measure, using results of constant pumping power and constant Reynolds number. Silicon oxide and aluminum oxide nanoparticles in the water based fluid in the developing region of laminar flow regime are tested. Experimental results for nanofluids of alumina oxide/water and silicon oxide/water in four concentrations are compared with base fluid of distilled water in four different temperatures.

2. Experimental apparatus

Testing equipment to measure the convective heat transfer coefficient is shown in Fig. 1. Equipment used in the experiment consists of a pump, a finned tube exchanger, risers, a reservoir tank, heater, dimmer and a main tank. A vertical external extended finned heat exchanger is an aluminum finned with height of $H = 500$ mm, inner radius of $r_i = 3.5$ and outer radius of $r_o = 22.5$ mm. Owing to symmetry, cross sectional view of half part of the heat exchanger is shown schematically in Fig. 2. As depicted in this figure fin's thickness t is 2 mm and length is $l = 12.5$ mm. Also this heat exchanger has 20 fins with $S = 1.14$ mm distance in the roots. A 2.5-l plastic tank is used as a principal reservoir. Fluid pumped from the main tank into the system. Pump has maximum flow rate of 5200 l per hour and head of 3.5 m. In order to control the flow rate, a return line with a valve at the outlet of the pump is installed. A 2000 W heater is installed in the upper tank and adjusting is done with a dimmer. Upper tank is connected to the heat exchanger with a copper pipe. As it is shown in Fig. 3, ten temperature sensors of SMT-160 with confidence limits of ±0.5 °C are installed in the longitudinal direction to achieve wall temperature of the heat exchanger. Inlet and outlet temperatures are measured by the thermocouples