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Thermal Investigation of Nanofluids in Heat Exchanger Tubes using Two-Phase Approach

M Mubashir Farid [a] *, Samia Sadaf [a], M Shahid Farooq [a], Ussama Ali [a]

[a] *Department of Mechanical Engineering, University of Engineering and Technology Lahore, Pakistan*

Abstract

This paper investigates the effect of nanofluids in a flat-tube heat exchanger on the heat transfer under the influence of constant heat flux using computational fluid dynamics (CFD) analysis. Two nanofluids: Titanium Oxide (TiO2)/water and Aluminum Oxide (Al2O3)/water were used with nanoparticles of diameter 10 nm. A two-phase approach with a mixture model is adopted in the CFD analysis. The heat transfer coefficient was evaluated at Reynolds number of 1750 utilizing various volume concentrations of nanoparticles (1%, 3%, 5%, and 7%). It was observed that an increase in the concentration of the nanoparticles resulted in an increase in the value of heat transfer coefficient. The results observed at 7% volume concentration, using two-phase approach, showed 5% and 8% enhancement in the heat transfer coefficient for TiO2/water and Al2O3/water, respectively, when compared with the results of single-phase technique.

Keywords: *Flat tube; Heat transfer coefficient; Two-phase approach; Nanofluids*

1. Introduction

Traditionally, two approaches are used to improve the heat transfer process categorized as active and passive. Enhancement in the heat transfer can be done by active techniques. However, due to the addition of external equipment and forces, system become complex and operating costs increase. The technique of modifying geometry of flow or thermo-physical properties of the working fluid by adding nanoparticles is another effective way to increase the heat transfer [1]. For enhanced heat transfer purpose, generally different shape tubes with fins are being used with base fluid as heat transfer medium to analyze the effect on heat transfer rate and pressure drop due to curvature, concentration of nanofluids, and hot water temperature [2].

The natural convection heat transfer rate is enhanced significantly in the Al2O3 and TiO2 nanofluids when nanoparticle volume loading increases [3]. With the help of nanoparticles and base fluid mixture, compactness in size of heat exchanger can be optimized. In order to achieve better thermal properties, nanoparticles can be mixed with base fluid. TiO2, ZnO, CuO, and Al2O3 showed excellent thermal properties and are chemically stable [4, 5]. These studies [4, 5, 6] show the improved thermal properties of base fluid with the help of TiO2, ZnO, CuO, and Al2O3 as nanoparticles in base fluid of ethylene glycol, water, and oil. Enhancement in thermal properties is directly related to nanoparticles concentration and size, and other heat exchanger design factors as well. To study the coefficient of heat transfer through convection, Huminic and Huminic [7] considered a radiator with flattened tube with laminar flow. They used the nanofluid CuO/ethylene-glycol through the single-phase technique. It was observed that the heat transfer coefficient was increased by 19% upon increasing concentration of CuO nanoparticles by 4%. They proved the direct relation of heat transfer rate and nano particles volume concentration. Also, flat tubes show better enhancement in result rather than elliptical and circular tubes.

Experiment was done by Srinivas and Vinod [8] to study the application of nanofluids on convection. During the experiment, a heat exchanger with turbulent flow was considered and Al2O3/water, CuO/water, and TiO2 were used. The experiment showed an increase in the heat transfer rate. Also, CuO showed higher heat transfer rather than Al2O3 and low heat transfer rate was noted for CuO. Razeghi et al. [9] used CFD analysis by using Al2O3/water nanofluid in rectangular curved micro-channel and a comparison study was made with single and multiphase approaches using Eulerian mixture model. They observed an increase in the pressure drop and Nusselt number with an increase in the nanoparticles concentration. Also, low pressure drop in multiphase model was noted as compared to single-phase model. Another interesting study was done by Qi et al. [10] to study the relation between bubble size and

* Corresponding author. Tel.: +923346037272
E-mail: mubashirfarid25@gmail.com

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concentration of nano particles on the heat transfer rate. They obtained optimum results when 2% of TiO2/water was used as nanofluid. While the higher concentration of nanofluid resulted in reduced heat transfer because of high viscosity and small bubble size.

Devireddy et al. [11] undertook the study related to the effect of nanoparticles TiO2 in 40:60 percent ethylene-glycol/water using flat tubes radiator. They also observed a direct relation between increase in percentage of TiO2 nanoparticles in base fluid to the heat transfer rate. Heris et al. [12] also did a similar study but they used different fractions of Al2O3/water as nanofluid and considered a circular tube with laminar flow conditions. They also obtained results showing an increase in the heat transfer with the increase in the nanofluid concentration. While Duangthongsuk and Wongwises [13] used a double tube horizontal radiator with counter flow for a similar study. For this purpose, they used 0.2% TiO2/water as a nanofluid. They were able to show 6% – 11% surge in convective heat transfer rate. Ali et al. [14] also did a similar experiment but on an automobile radiator. For their experimentation, they used 0.2% volume concentration of nanofluid ZnO/water. It was observed that heat transfer rate was increased up to 46% in contrast with the base fluid alone. Hussein et al. [15] carried out a study using CFD analysis for forced connection in automobile radiator by using 2.5% volume concentration of nanofluid SiO2/water. Their results showed 56% enhancement in Nusselt number. Momin et al. [16] conducted experiments for analysis of car radiator using nanofluids and studied the relationship with heat convection. The results revealed that the rate of heat transfer increased 30% – 47% at 0.5% – 1.5% volume concentrations respectively. Zhao et al. [17] numerically investigated the heat transfer coefficient in flat tubes under laminar flow by using Al2O3/water nanofluid.

Hejazian and Moraveji [18] numerically analyzed the convective heat transfer by using TiO2/water nanofluid in a horizontal circular tube. Both the single-phase and two-phase mixture approaches were considered. Enhancement in heat transfer was noted with increase in concentration of nanofluid and also with increase in Reynolds number (Re). Two-phase approach showed better arguments with experimental results as compared to single-phase approach. Behzadmehr et al. [19] studied two-phase approach for turbulent forced convection by using nanofluid in a circular tube. Their results were more accurate as compared to the single-phase approach and were in good agreement with the experimental results of Li and Xuan [20]. Lotfi et al. [21] used three different approaches: single-phase approach, two-phase Eulerian approach, and two-phase mixture model approach by using nanofluids in a horizontal circular tube. Results showed two-phase mixture approach was more precise as compared to other two approaches and had a good agreement with experimental results. Delavari and Hashemabadi [22] undertook a study to establish a relation of nanofluids and heat rate transfer using two approaches — single-phase and two-phase. In their experiments, they used Al2O3/water and Al2O3/ethylene-glycol as nanofluids. Results showed that two-phase approach had better result than a single-phase approach.

From the cited literature it is observed that the two-phase approach is much better in evaluating the performance of nanofluids numerically compared to the conventional single-phase approach. Therefore, this work is also dedicated to the two-phase approach where the performance of nanofluids (TiO2/water and Al2O3/water) is analyzed in flat tube heat exchanger with varying concentrations.

2. Methodology

This section provides the methodology carried out to perform this work.

2.1. Geometry

Fig. 1 below shows schematic diagram for a flat tube car radiator. It has a height (*H*) of 3mm, width (*W*) of 9mm, and length (*L*) of 345mm for each flat tube. The model geometry and mesh are created in commercial software Ansys/Fluent. Discretized mesh is created for better solution convergence.

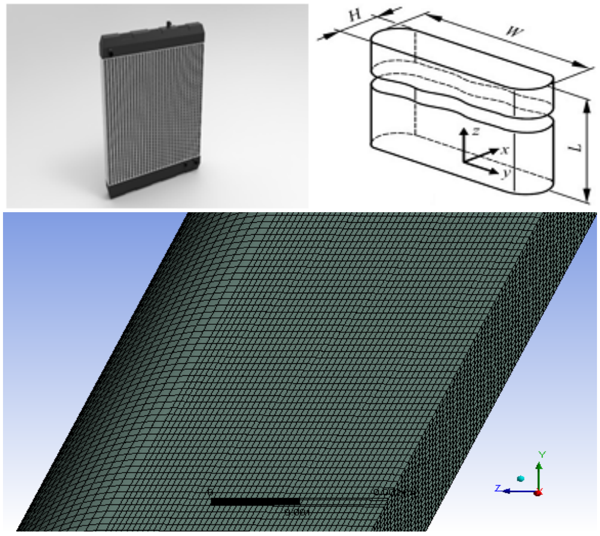

Fig. 1. Flat tube car radiator (top left), geometry of a single flat tube (top right), and the discretized mesh of the single flat tube (bottom)

2.2. Governing Equations

Followings are the conservation equations [23] that are being solved by the Fluent which is a finite volume solver:

Continuity Equation:

$$div(\rho\vec{V}) = 0 \quad (1)$$

Momentum Equation:

$$div(\rho\vec{V}\vec{V}) = -grad(P) + \nabla \bullet (\mu\nabla\vec{V}) \quad (2)$$

Energy Equation:

$$div(\rho\vec{V}C_pT) = div(kgradT) \quad (3)$$

where ρ is the fluid density, $\vec{V}$ is the velocity vector, P is the pressure, μ is the viscosity, C_p is the specific heat, T is the temperature, and k is the thermal conductivity of the fluid.

While using the above-mentioned equations, a few assumptions were made, which are mentioned below:

- Flow is incompressible
- Flow regime is laminar
- Viscous dissipation effects are assumed to be negligible
- Multiphase (two-phase) approach has been used

The equations (Eq. 1 – 3) were solved by the control volume approach using Ansys/Fluent. To discretize all quantities and convection variables, a first order upwind scheme was adopted. Also, staggered grid scheme was adopted in the computation.

While in order to solve the pressure-linked equations, a pressure-velocity coupling along with coupled scheme was used.

To implement the two-phase approach, a mixture model was used. Continuity equation, momentum equation, and energy equations were solved by the mixture approach. Slip velocity was kept zero along with zero mass transfer. Velocity magnitude for both phases was 0.4755 m/s.

2.3. Thermophysical Properties of Nanofluids

The effective thermo-physical properties of nanofluids were calculated by Corcoine [24]. Assuming that flow is incompressible, steady state, and uniform concentrations of nanoparticles in whole process, properties like viscosity, density, specific heat, and thermal conductivity were calculated from the following correlations:

Density:

$$\rho_{nf} = \phi_v \rho_{np} + (1-\phi_v)\rho_{bf} \tag{4}$$

Specific heat:

$$(\rho C_p)_{nf} = \phi_v (\rho C_p)_{np} + (1-\phi_v)(\rho C_p)_{bf} \tag{5}$$

Dynamic viscosity:

$$\mu_{nf} = \mu_{bf}\left(\frac{1}{\left(1-34.87\left(\frac{d_{np}}{d_{bf}}\right)^{-0.3}\phi_v^{1.03}\right)}\right) \tag{6}$$

Thermal conductivity:

$$k_{nf} = k_{bf}\left[1+4.4Re_{np}^{0.4}Pr_{bf}^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_{np}}{k_{bf}}\right)^{0.03}\phi_v^{0.66}\right] \tag{7}$$

where

$$d_{bf} = 0.1\left(\frac{6M}{N\pi\rho_{bf}}\right)^{1/3} \tag{8}$$

$$Re_{np} = \frac{2\rho_{bf}K_B T}{\pi\mu_{bf}^2 d_{np}} \tag{9}$$

Different properties of the various parameters used for the study are given in the Table 1.

Table 1. Thermal properties of nanoparticles and base fluids

Material	Specific heat capacity C_p (J/kg.K)	Thermal conductivity k (W/m.K)	Density ρ (kg/m^3)	Dynamic viscosity μ (Pa.s)
Al2O3	826.2	40.3	3890	-
TiO2	696	8.38	4138.3	-
Water	4182	0.611	998.8	0.00089

2.4. Average Heat Transfer Coefficient

Heat transfer rate can be calculated by given formula called Newton's law of cooling, depending upon surface area (A_s), heat transfer coefficient (h), and change in temperature (ΔT):

$$Q = h_{avg} \times A_s \times (T_b - T_s) = h_{avg} \times A_s \times \Delta T \tag{10}$$

Hydraulic diameter (D_h) of flat tube depends upon following two parameters:

- Perimeter (P_m)
- Cross sectional area of the flat tube (A)

It can be obtained by given formula:

$$D_h = (4 \times A) / P_m \tag{11}$$

Following formula was used to calculate the cross-sectional area of flat tube. Cross sectional area depends upon its width (W) and height (H):

$$A = (\pi \times H^2)/4 + (W - H) \times H \tag{12}$$

Also, perimeter of flat tube is obtained by the following given formula:

$$P_m = \pi \times H + 2 \times (W - H) \tag{13}$$

Bulk temperature is found from average value of inlet temperature and outlet temperature of flat tube.

$$T_b = (T_{in} - T_{out})/2 \tag{14}$$

Heat transfer rate depends upon area, velocity, density, specific heat capacity and change in temperature. Following relationship was used to calculate the heat transfer rate:

$$Q = \rho \times A \times V \times C_p \times (T_{in} - T_{out}) \tag{15}$$

Following given formula is used to calculate the average heat transfer coefficient that depends upon number of parameters:

$$h_{avg} = \rho \times A \times V \times C_p \times (T_{in} - T_{out}) / (A_s \times DT) \tag{16}$$

Reynolds number is calculated by given formula as below, which depends upon viscosity of working fluid, density, hydraulic diameter of flat tube, and velocity of fluid flow.

$$\mathrm{Re} = (\rho \times V \times D_h)/\mu \tag{17}$$

3. Results and Discussion

This section presents the results of this study. The symmetry option is being used for the analysis here the overall computational domain is divided into four sections and only one of these sections is considered for the analysis. A quarter portion of tube is being used for simulation. This reduces the computational load and time. A mesh independence study is carried out for average heat transfer coefficient (h_{avg}) and pressure drop (dp) as shown in Fig. 2. It is observed that the mesh size of 20,000 elements is optimal for this study as further increasing the mesh size does not affect dp as much. This mesh size is compromise between accuracy and solution time. The convergence criterion for all the parameters is set as 10^{-6} for the residuals and solution convergence is reached when this criterion is met, as shown in Fig. 3.

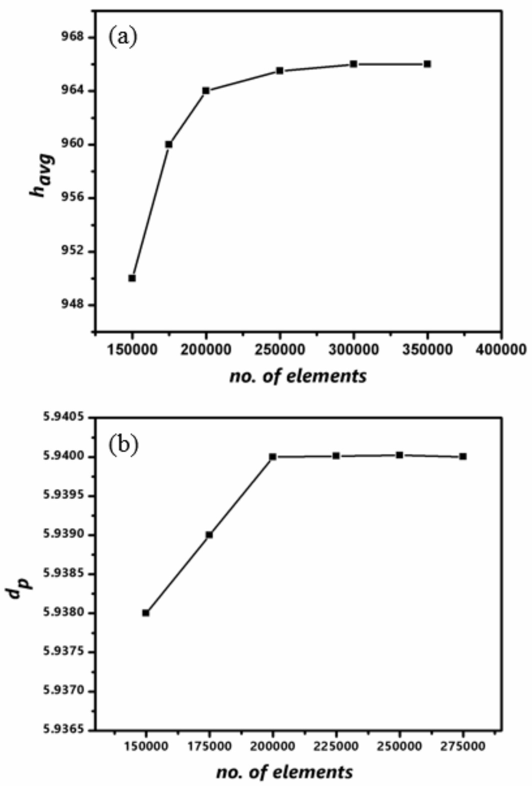

Fig. 2. Mesh independence study

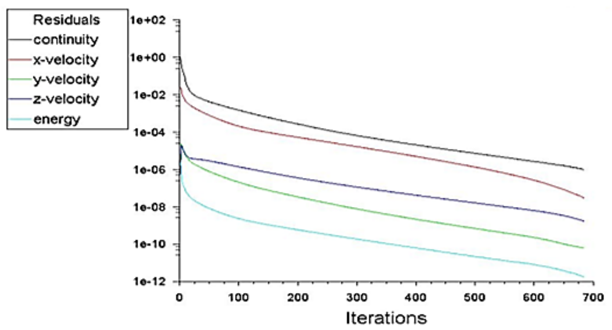

Fig. 3. Relative residual errors for the governing equations

The model validation is done by comparing the results obtained with those of Elsebay et al. [23] for the average heat transfer coefficient as shown in Fig. 4. Pure water was used as the cooling fluid. The maximum error of 2% appeared and the results showed good agreement with those of Elsebay et al. [23].

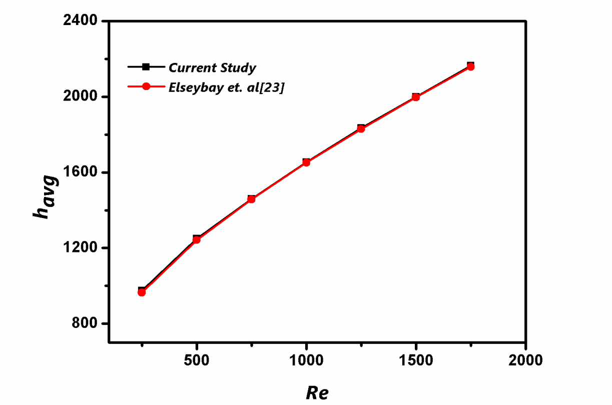

Fig. 4. Comparison of current results with those of Elsebay et al. [23] for pure water

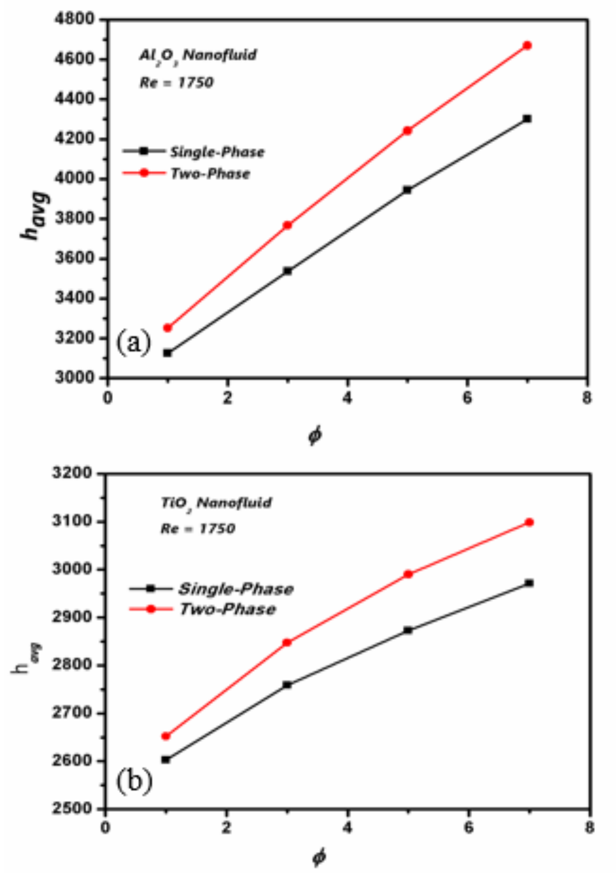

Fig. 5. The average heat transfer rate vs the nanoparticles concentration by volume for (a) Al2O3 and (b) TiO2

The effect of two-phase approach and concentration by volume of nanoparticles (Al2O3 and TiO2) on average heat transfer coefficient at Re = 1750 is depicted in Fig. 5. It can be deduced that the heat transfer increased with an increase in the nanoparticles concentration. The two-phase approach showed higher heat transfer coefficient than single-phase approach. For Al2O3 at Reynolds number of 1750 and 10 nm diameter, the enhancement in h_{avg} for ϕ = 1%, 3%, 5%, and 7% is approximately 4%, 6%, 7%, and 8%, respectively, greater than that for single-phase approach. For TiO2 the corresponding enhancement are approximately 2%, 3%, 4%, and 5%, respectively.

Fig. 6 shows the effect of the type and concentration by volume of nanoparticle. It is observed that Al2O3 shows greater enhancement in the heat transfer as compared to TiO2 at Re = 1750 and 10 nm diameter. For instance, at Re = 1750 and ϕ = 7%, the heat transfer rate increased 8% for Al2O3 and 5% for TiO2.

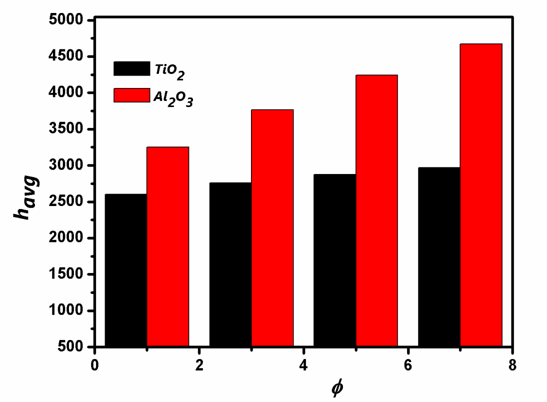

Fig. 6. Response of heat transfer coefficient for Al2O3 and TiO2 to the nanoparticles concentration on using two-phase approach

4. Conclusion

In this work, the convective heat transfer coefficient is evaluated for Al2O3/water and TiO2/water nanofluids using a flat tube of a radiator. The study was done computationally at constant heat flux boundary condition. The CFD analysis was done using mixture model and two-phase approach. Following conclusions are presented based on the results:

- TiO2 and Al2O3 nanoparticles in water can improve the efficiency of the heat exchanger, and the enhancement is directly related to the nanoparticle concentration.
- Up to 5% and 8% heat transfer improvement was observed (comparing the two-phase approach to the single-phase approach) for TiO2/water and Al2O3/water, respectively, at $\phi = 7\%$, Re = 1750, and 10 nm diameter of nanoparticles.
- The addition of nanoparticles results in enhancement of the heat transfer.
- Al2O3/water showed greater enhancement in heat transfer coefficient than TiO2/water.
- Depending upon the cooling capacity, size of the radiator can be reduced and upgraded by using nanoparticles. Compactness in design and smaller cooling systems can be obtained.

Nomenclature

A	Cross sectional area of the tube
C_p	Specific heat capacity
D_h	Hydraulic diameter
H	Height of flat tube
h	Heat transfer coefficient
k	Thermal conductivity
L	Length of the flat tube
M	Molar mass
P_m	Perimeter
p	Pressure
Q	Heat transfer rate
q	Heat flux
Re	Reynolds number
T	Temperature
V	Velocity
W	Width of the flat tube

Greek Symbols

ρ	Density
μ	Dynamic viscosity
ϕ	Particle volume concentration

Subscripts

avg	Average
s	Surface
b	Bulk
in	Inlet
out	Outlet
np	Nanoparticle
bf	Base fluid

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