

Chapter 29

Numerical Simulation of Heat Transfer to TiO₂-Water Nanofluid Flow in a Double-Tube Counter Flow Heat Exchanger

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Abstract Recently, the means of improvement of heat transfer has been rapidly studied. One of the methods that enhance the heat transfer is by changing the heat exchanging fluids. The poor heat transfer coefficient of common fluids compared to the most solids becomes the primary obstacle to design high compactness and effectiveness of heat exchanger. The primary objective of this chapter is to conduct the study of the heat transfer between the water and nanofluid. Both of the fluids were flowed in the horizontal counter flow heat exchanger under the turbulent flow condition. The flow velocity of the fluids varied with Re between 4,000 and 18,000. Literature review states that the heat transfer coefficient of nanofluid is higher than the water by about 6–11 %. Heat transfer to the nanofluid and water is investigated using a computer fluid dynamics software. Ten percent heat transfer augmentation is observed utilizing nanofluid as heat exchanging fluid compared to water. The results also showed the enhancement of the Reynolds number increases the heat transfer to the nanofluid studied in this investigation.

Keywords Numerical simulation • Heat transfer • TiO₂ • Nanofluid • Heat exchanger

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Nomenclature

Pr	Prandtl number
Re	Reynolds number
d	Diameter, m
f	Friction factor
k	Thermal conductivity, W/m ³ K
Q	Heat transfer rate, W/m ²
C_p	Heat capacity, kJ/kg °C
T	Temperature, °C
Nu	Nusselt number
h_x	Heat transfer coefficient
Pe	Peclet number

Greek Letters

ϕ	Volume fraction
μ	Viscosity, kg/ms
ϵ	Surface roughness, m
ρ	Density, kg/m ³
f	Friction factor

29.1 Introduction

Nowadays, the usage of Computational Fluid Dynamic (CFD) has been widely used in industrial and nonindustrial areas. CFD is the software for the analysis system involving fluid flow, heat transfer, and associated phenomena by means of computer-based simulation [1]. One of the examples of CFD usage is in the field of turbo machinery where the CFD is used to simulate the flow inside rotating passage, diffuser, etc. and it is due to the cost for conducting the simulation is lower than performing an experiment. Back in the 1960s, the aerospace industries used CFD software to design, conduct research and development (R&D), and manufacture the body of the aircraft.

Present research has been carried out to study the heat transfer characteristic in counter flow heat exchanger. Armaly et al. had experimented flow separation with the laser-Doppler anemometer to define the quantitatively variation of separation length with Reynolds number [2]. In the experiment, both side of the channel wall showed multiple regions of separation downstream of backward facing step. The separation and reattachment region has strong influence on the heat transfer characteristic.

Heat transfer enhancement can also be achieved by enhancing the thermo physical properties of the fluid itself. Today, the study regarding improving the thermal conductivities of fluids is by using the nanofluid where small solid particles

are suspended in the fluid [3]. Recently, a lot of researches were conducted by using nanofluids to investigate the heat transfer characteristic with various geometries [4–6]. Most of the studies of heat transfer have been focusing on ducts and circular pipe flow whereas a little research has conducted in annular passage [7, 8].

This chapter is focused on simulation for the nanofluid and showed the validity of the Nusselt number of previous investigation such as the work of Duangthongsuk and Wongwises [9]. Nanofluid can be defined as the suspension of ultrafine particles in a conventional base fluid, where it can increase the heat transfer characteristics of the original fluid [10]. Moreover, the nanofluid is suitable for practical applications as their use incurs little or no penalty in pressure drop because the particle of the nanofluid is ultrafine. Hence, the nanofluid looks like more to be single-phase rather than a solid–liquid mixture. Generally, the nanoparticles commonly available are: aluminum oxide (Al₂O₃), copper (Cu), Titanium oxide (TiO₂), copper oxide (CuO), gold (Au), silver (AgO), silica nanoparticles, and carbon nanotube [10]. The base fluid could be the water, acetone, decene, and ethylene glycol. The nanoparticle can be produced by several processes such as gas condensation, mechanical attrition, or chemical precipitation techniques [11]. There are two factors why the nanoparticle has been selected for making nanofluids which are capable of increasing the heat transfer. Firstly, the nanoparticles in the fluid can increase the thermal conductivity of the fluids. Secondly, the chaotic movement of the nanoparticles in the fluid causes the turbulence in the fluid that increases the energy exchange process. Many experiments have been conducted using the nanofluids, where it showed much higher thermal conductivity. In the experiment that carried out by Wen and Ding, they proposed the nanoparticles that enhanced the thermal conductivity of the fluid [12]. This is because the nanoparticles in the fluid have changed the properties of the base fluid such as water, oil, and ethylene glycol to a better suspension of higher thermal conductivity. In addition, an experiment carried out by Lee et al. where the CuO and Al₂O₃ have been used to enhance the heat transfer of the fluid. They proposed that the enhancement of the heat transfer is caused by the chaotic movement of the nanoparticles in the fluid. Moreover, they also suggested that the enhancement of heat transfer is also affected by the size and shape of the particles.

Das et al. have done the analysis of turbulent flow and heat transfer of different nanofluids; CuO, Al₂O₃, and SiO₂ in ethylene glycol and water mixture at constant heat flux in circular tube [13]. Through their research, they found that the smaller the particle, the higher the viscosity and Nusselt number. Other than that, the higher the volume concentration of nanofluids and Reynolds number, the heat transfer coefficient will increase. However, the increasing of volume concentration of nanofluids and Reynolds number caused the pressure loss.

On the other hand, there were several reports about inconsistency of nanofluids behavior in terms of heat transfer coefficient. Pak and Cho reported that for the forced convective heat transfer, the Nusselt number for the Al₂O₃-water and TiO₂-water nanofluids is increased with the volume fraction of suspended nanoparticles and Reynolds number [14]. Moreover, Yang et al. report the similar observation for the graphite nanofluids in laminar flow regime [15].

29.2 Methodology

The numerical simulation has been conducted to verify the accuracy of the heat transfer experimentally. Figure 29.1 shows the pipe drawn and meshed by using the CFD software. The inner diameter of the copper pipe is set at 8.13 mm and the outer diameter is 9.2 mm. The thickness of the copper pipe is about 0.7 mm. The temperature of the water in the copper pipe is 40 °C, and the flow rate is 3 L/min. On the other hand, the outer pipe is made up of PVC, where the nanofluid flows through outer pipe. The dimension of the inner diameter of PVC pipe is 27.2 mm whereas the outer diameter is 33.9 mm. The nanofluid flows in the counter direction of the water with 27 °C. The annular passage is considered in the simulation, where the Reynolds number varied between 4,000 and 18,000. Figure 29.1 shows the schematic diagram of the counter flow heat exchanging equipment.

29.2.1 Computational Fluid Dynamics Simulation

The aim of this research is to investigate the heat transfer, typically Nusselt number and understand the phenomena of flow in annular pipe. Thus, the finite volume-based flow solver of computational dynamics software (FLUENT) is chosen in this investigation. The geometry is drawn in the CFD software. Moreover, the K-epsilon viscous model has been chosen for the iteration based on the energy equation and Reynolds averaged Navier Stokes equations. The flow condition in the pipe between the base fluid (i.e., water) and the nanofluid is assumed to be in thermal equilibrium and no slip occurs between them [16].

In the simulations, the initial information of the study such as geometry, dimension, input and initial values, dependent and independent variables of the study have been determined. Then, based on these data gained in case study and according to literature review the geometry considered for the simulation can be simplified. This case is simplified by using 2-dimensional pipe and the pipe is cut into half to make it

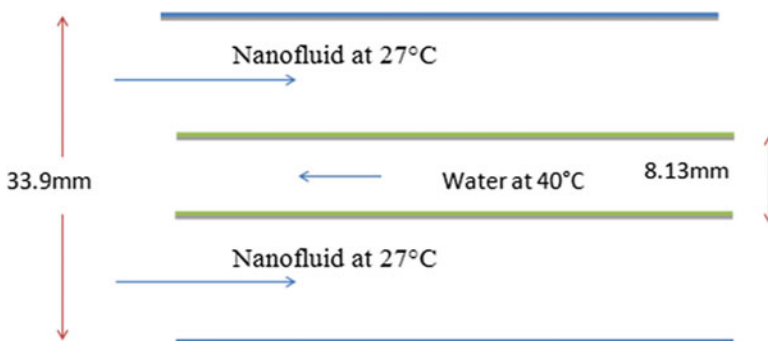


Fig. 29.1 Counter flow heat exchanger drawing

symmetry. Fluid flow in a physical domain is governed by the laws of conservation of mass and momentum.

Upon meshing, the governing equations including some partial differential equations are derived and discretized by one of the existing methods such as finite element, infinite element, and finite volume to be converted into algebraic equations. In addition, the boundary conditions, material properties, and initial values were obtained to solve the iteration. These steps are called preprocessing steps. Once the preprocessing part is completed, governing equations are solved during several iterative algorithms. The measure of convergence error and the problem initialization are specified before running the solution algorithms.

After the preprocessing step, the post-processing step takes place where the result is obtained. During post-processing step, all the data including temperature, velocity, and pressure can be obtained. The accuracy of the results is then verified. Furthermore, the Nusselt number is then calculated from the temperature data.

In this research, TiO₂ nanoparticles mixed with the water by 0.2 % were used to investigate the heat transfer characteristic with different variables such as Reynolds number and temperature of the flowing nanofluid and mass flow rate. The simulation conditions used in this study are as follows:

- The Reynolds number of the nanofluid varied from 4,000 to 18,000
- The temperature of the nanofluid is 27 °C
- The mass flow rates of the hot water are 3 LPM and 4.5 LPM
- The temperature of the hot water is 40 °C

29.2.2 Mathematical Model

The thermal physical properties of the nanofluid can be calculated utilizing the following equations.

Pak and Cho calculated the density by using Eq. (29.1) [14]:

$$\rho_{nf} = \phi\rho_p + (1 - \phi) \cdot \rho_w \quad (29.1)$$

where ρ_{nf} the volume fraction of nanoparticles is, ρ_p is the density of the nanoparticles, and ρ_w is the density of the base fluid.

Donald and Stephen calculated the viscosity by using well-known Einstein equation (29.2) which is applicable to spherical particles in volume fractions of less than 5 % [17].

$$\mu_{nf} = (1 + 2.5\phi) \cdot \mu_w \quad (29.2)$$

The μ_{nf} is referred to the viscosity of the nanofluid, and the μ_w referred to the base fluid which is water.

Thermal conductivity of the nanofluid is obtained using Eq. (29.3) as suggested by Yu and Choi [18].

$$k_{nf} = \left[k_p + 2k_w + 2(k_p - k_w)(1 + \beta)^2 \phi \right] / \left[k_p + 2k_w - (k_p - k_w)(1 + \beta)^2 \phi \right] \quad (29.3)$$

where k_{nf} is the thermal conductivity of the nanofluid, k_p is the thermal conductivity of the nanoparticles, k_w is the thermal conductivity of the base fluid. Moreover, the Nusselt number is calculated from Gnielinski equation and Colebrook equation and then compared to the simulation results. The Gnielinski equation (29.4) and Colebrook equation (29.5) are as follow [19, 20]:

$$Nu = [(f/8)(Re - 1000)Pr] / \left[1 + 12.7(f/8)^{0.2} (Pr^{1/2} - 1) \right] \quad (29.4)$$

The Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number, and f is the friction factor.

Next, the Colebrook equation is defined as:

$$F^{(-1/2)} = -2 \text{Log} \left[(\epsilon/3.7D) + (2.51/Re \cdot f^{0.5}) \right] \quad (29.5)$$

The temperature of the inlet and outlet of copper tube were calculated to obtain the heat transfer rate from the water to the nanofluid through the copper tube. The heat transfer rate is calculated using the Eq. (29.6) which is suggested by Duangthongsuk and Wongwises [21].

$$Q_w = m \cdot C_{p_w} (T_{in} - T_{out})_w \quad (29.6)$$

The Q_w is the heat transfer rate for the hot water, and m is the mass flow rate of the water.

Next, the local heat transfer is calculated using the convection heat flux as used by Oon et al. [22]:

$$h_x = q_c / T_b \quad (29.7)$$

where q_c is the heat transfer from water to nanofluid, and the T_b is the temperature different between the outlet temperature and the inlet temperature. The value of the Nusselt number is calculated from the equation:

$$Nu = h_x \cdot d / k_{nf} \quad (29.8)$$

where the value of d is the hydraulic diameter, and the k_{nf} is the thermal conductivity of the water.

Then, Pak and Cho and Xuan and Li correlations are utilized to predict and compare the Nusselt number of TiO₂ nanofluid. The Pak and Cho correlation is shown in Eq. (29.9) [14, 23]:

$$Nu_{nf} = 0.021 \cdot Re_{nf}^{0.8} Pr_{nf}^{0.5} \tag{29.9}$$

The Xuan and Li correlation is shown in Eq. (29.10):

$$Nu_{nf} = 0.0059(1 + 7.6286\phi^{0.6886} Pe_{nf}^{0.001}) Re_{nf}^{0.9238} Pr_{nf}^{0.4} \tag{29.10}$$

where Pe_{nf} is the Peclet number. Table 29.1 shows the thermophysical properties of the water, nanoparticles, and the nanofluid calculated from the equations above.

29.3 Results and Discussion

Figure 29.2 shows the heat transfer coefficient increases with the increase of Reynolds number. The data obtained from simulation is compared with the Gnielinski equation for water in turbulent flow. The simulation result obtained is slightly higher than the Gnielinski equation partly due to turbulent flow. The value

Table 29.1 Thermal physical properties

Property	Fluid phase (water)	TiO ₂ particles	TiO ₂ -water (0.2 %)
Density, ρ (kg/m ³)	998.2	4,250	1,004.7
Heat capacity, Cp (J/kg K)	4,182	686.2	4,175
Thermal conductivity, k (W/m K)	0.6	8.9538	1.0677

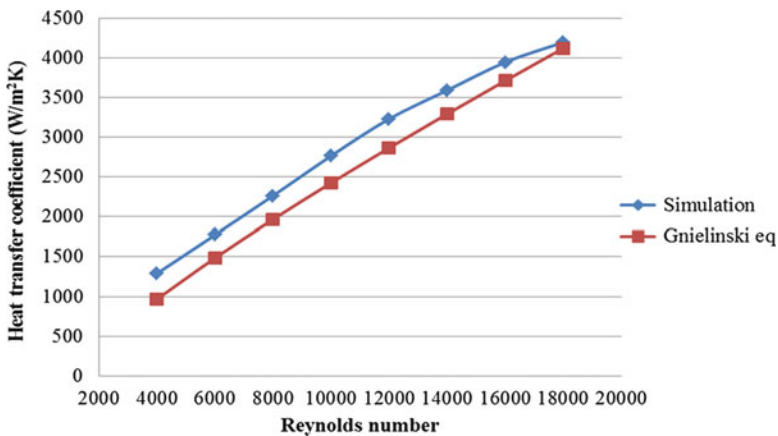


Fig. 29.2 The comparison between the heat transfer coefficients against Reynolds number for water

obtained from the simulation is compared with the Gnielinski equation. Hence, the same parameter used in the computational study can be extended for simulation of TiO₂-water nanofluid.

Figure 29.3 shows the simulation values of Nusselt number of TiO₂-water nanofluids which are closer towards Pak and Cho correlation than the Xuan and Li correlation. This is simply because Xuan and Li correlation was established from the data of Cu-water nanofluids while the Pak and Cho correlation was established from the data of TiO₂-water nanofluids.

Figure 29.4 shows the results for different variables such as change of mass flow rate of hot water from 3 LPM to 4.5 LPM for the 0.2 % TiO₂-water nanofluid.

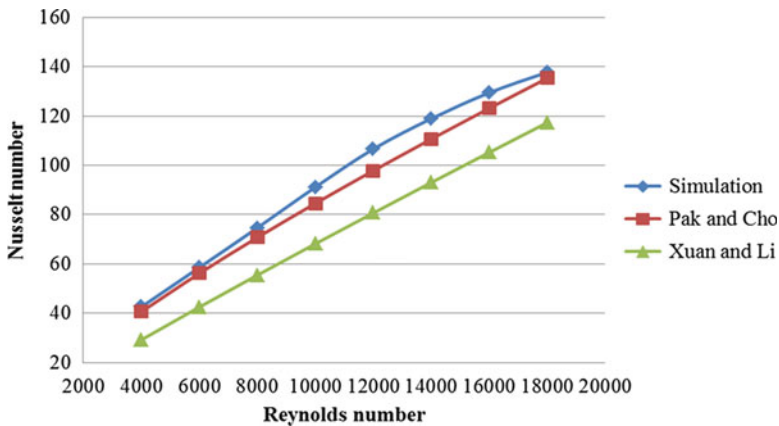


Fig. 29.3 The comparison of Nusselt number between the TiO₂

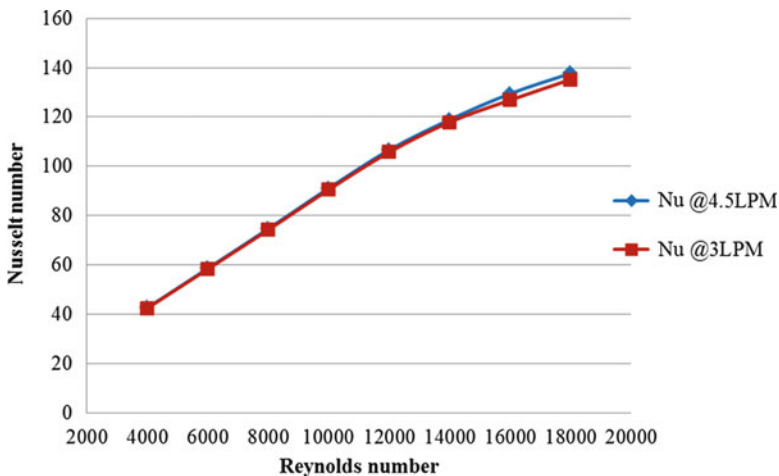


Fig. 29.4 The comparison of Nusselt number of TiO₂ between 3 LPM and 4.5 LPM water flow rate

It is clearly seen that the 4.5 LPM flow rate shows higher heat transfer compared to 3 LPM flow rate. The result also shows that the heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate of the hot water.

29.4 Conclusion

The numerical simulation has shown that the increasing in Reynolds number also causes the heat transfer to increase. The higher Reynolds number contributes to greater heat transfer from the water to the nanofluid. In addition, the numerical simulation results agree with the Pak and Cho correlation as both of the results are in compliance. Finally, with the development of computational software it has become easier to provide a fare and comparable result as in the present case.

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