Investigation on Flow and Heat Transfer of Supercritical CO2 in Helical Coiled Tubes at Various Supercritical Pressures

N. Thiwaan Rao[1, *], *Ahmed. N.* Oumer[1, †], *G.* Devandran[1], *M. M.* Noor[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.

Abstract. Supercritical carbon dioxide (scCO2) has unique thermal properties with better flow and heat transfer behavior. However, the flow and heat transfer behavior of scCO2 using helical coil geometries have not fully documented yet. Therefore, the main purpose of this study is to investigate the flow and heat transfer characteristics of scCO2 in helical coiled tubes for heating process using computational fluid dynamics (CFD) method. For the simulation, commercial CFD software called ANSYS FLUENT is used. Helical coiled tube of inner and outer diameter 9.0 mm and 12.0 mm, respectively, with total length of 5500 mm, pitch distance of 32.0 mm and 6 turns of coils is considered. The model is intended to analyze the pressure drops, friction factor, Nusselt number, and goodness factor of scCO2. Three different inlet pressures (8.00 MPa, 9.03 MPa and 10.05 MPa) with three different uniform heat fluxes (20.5 kW/m², 50.5 kW/m² and 80.5 kW/m²) at constant inlet temperature of 27°C are considered. The numerical results are compared with experiment results from previous study to validate the developed model. The wall temperature results from the numerical analysis are in good agreement with the experimental data. From the numerical analysis, the Nusselt number increased significantly when the inlet mass flow rate and heat flux increased. Moreover, it was observed from the simulation results that an increment of average pressure drop by 900 Pa (19.57%) and average friction factor coefficient by 0.1536 (33.85%) when the pressure inlet increased from 9.03 MPa to 10.05 MPa. Hence, the results obtained from this study can provide information for further investigation of scCO2 for industrial applications

1 Introduction

Carbon dioxide (CO_2) gas is an environmental friendly gas that have been reintroduced as it has zero ozone depleting potential (ODP) and zero effective global warming potential (GWP). Furthermore, there are few advantages of using CO_2 such as it is non-toxic and safe to humans, abundant and non-combustible [1]. Hence, the idea of using scCO_2 can be ideal replacement for these non-environmental friendly refrigerants with the suitable thermo physical properties and appropriate model of heat exchanger design.

* Corresponding author: thiwaan@hotmail.com
† Corresponding author: ahmnur99@gmail.com

In other hand, supercritical carbon dioxide ($scCO_2$) fluid that exits in neither liquid nor gas when the pressure applied is 7.39 MPa at temperature of 31.1°C [2]. At the point where $scCO_2$ reaches near to critical point, the physical properties shows extremely rapid variations with a change in temperature and pressure which is getting more attention by many researchers nowadays as it has high demand in many engineering applications [3]. It is used as working refrigerators fluid in air conditioning system The type of heat exchanger used to study the characteristics of $scCO_2$ by researches are mostly in the form of vertical and horizontal tubes, miniatures, plates, fins and coils. Most of the heat exchangers are made up of stainless steel material which has been used by previous researchers in their experimental studies [4]. Many studies and experiments were done by researchers on $scCO_2$ using one or two parameters for cooling or heating process for both numerical and experimental studies [5]. However, a numerical simulation of developed mesh independent of circular helical coiled tube for $scCO_2$ using three parameters which are inlet pressure, inlet mass flow rate and surface heat flux at constant inlet and outlet temperatures that uses air as medium fluid flow around the coil for heating process haven't fully documented yet. Therefore, intensive research is carried out to fully understand the behavior of $scCO_2$ in circular helical coiled tubes with all the aforementioned specific boundary conditions applied. The thermo physical properties of $scCO_2$ such as density (ρ), specific heat capacity (C_p), viscosity (μ) and thermal conductivity (k) are obtained from the chemistry web book of National Institute Science and Technology (NIST) [6].

The main purpose of this study is to determine the thermo-fluid properties of $scCO_2$ namely Nusselt number, Colburn factor, pressure drop and friction factor for three different inlet pressures. This study is expected to provide better knowledge on $scCO_2$.

2 Mathematical Formulations

2.1 Governing Equations

In this study, the flow field is assumed to be incompressible, steady and non-isothermal. Therefore, the governing equations for the continuity, momentum and energy can respectively be expressed as [7-10]:

$$\vec{\nabla} \cdot \vec{V} = 0 \tag{1}$$

$$\rho \frac{D\vec{V}}{Dt} = \rho \left[\frac{\partial \vec{V}}{\partial t} + \left(\vec{\nabla} \cdot \vec{V} \right) \vec{V} \right] = -\vec{\nabla} P + \rho g + \mu \vec{\nabla}^2 \vec{V} \tag{2}$$

$$\rho C_P \left(\frac{\partial T}{\partial t} + \vec{V} \cdot \vec{\nabla} T \right) = k \vec{\nabla}^2 T + \dot{\gamma} \cdot \tau \tag{3}$$

where $\vec{\nabla}$ is divergence operator and V is velocity vector of the fluid (m/s), ρ is density of the fluid (kg/m^3), t is time (seconds), P is the hydrostatic pressure (Pa), g is gravitational acceleration (m/s^2) and μ in the fluid viscosity (kg/m.s). C_p is the specific heat (J/kg.K), and k is the thermal conductivity (W/m.K). The term $\dot{\gamma}$ represents the shear rate, and τ is the total stress tensor.

2.2 Data reduction

The friction in the tube causes pressure loss when a fluid flows through it. The friction factor can be calculated with the pressure drop (ΔP) equation [7]. The general equation of f is:

$$f = \frac{2D\Delta P}{\rho V^2 L} \tag{4}$$

where ΔP is pressure drop (Pa), L is length the tube (m), and D is diameter of the tube (m). Meanwhile, Reynolds number is calculated with following formula:

$$\text{Re} = \frac{\rho VD}{\mu} \tag{5}$$

In addition to the friction factor, the convective heat transfer rate ($\dot{Q}_{conv}$) can also be calculated with the following Newton's Law of Cooling expression [11]:

$$\dot{Q}_{conv} = hA_S\left(T_S - T_\infty\right) \tag{6}$$

where $\dot{Q}_{conv}$ is convection heat transfer rate (W), h is convection heat transfer coefficient (W/m^2 ºC), A_S is surface area (m^2) , T_S is surface temperature (ºC) and T_∞ is fluid temperature (ºC). The Nusselt number (Nu) was calculated using the following equation:

$$Nu = \frac{hD}{k} \tag{7}$$

3 Numerical Analysis

3.1 Computational Domain and Boundary Conditions

In order to conduct numerical simulation for this project, a circular type of helical coil tube was sketched and designed in 3D model using SolidWorks 2014 software as shown in Figure 1.

The helical coil tube is considered and designed using single inlet and outlet diameter with all the dimensions in mm according to the experimental work of Xu. J. et.al. [12]. The material used for the helical coiled tube is stainless steel as this material is used by previous researchers in their experimental studies. Table 1 shows the dimensions used to design the numerical model of the helical coiled tube.

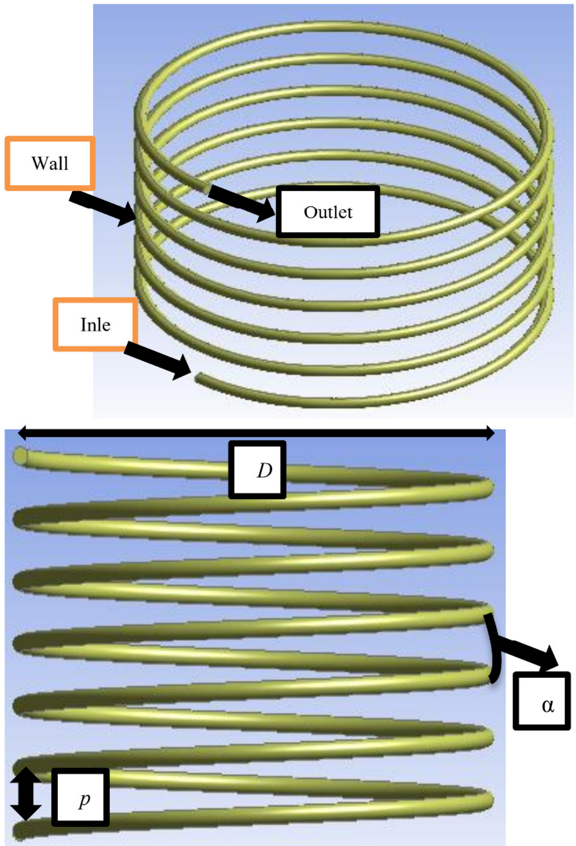

Fig. 1. Isometric and front views of helical coiled tube and its boundary conditions.

Table 1. Parameters.

Coil diameter, *D* (mm)	Inner tube diameter, *d* (mm)	uncoiled tube Length, L_T (mm)	Pitch, *p* (mm)	Ascending angle, α (°)	Number of coil turns
283	9	5500	32	3.2	6

For the numerical simulation of helical coil tubes, combination of various inlet parameters in terms of pressure, mass flow rate and heat fluxes have been applied to the boundaries of the circular helical coiled tube at constant inlet and outlet temperatures of 27 °C and 120 °C respectively.

The applied parameters were referred from the previous researcher's experimental case study. At the inlet of the helical tube, the $scCO_2$ inlet temperature was fixed at 27 ºC for all three different inlet pressures. Meanwhile, at the outlet, the temperature is fixed at 120 ºC with outlet pressure near to inlet pressure. Uniform heat flux was assigned at the wall of the coiled tube. There were 9 different sets of input parameters, which are labelled as Coil 1 until Coil 9. Table 2 shows the parameters that are obtained from the previous study, applied for the helical coiled tubes at constant inlet and outlet temperatures of 27°C and 120°C.

Table 2. Dimensions of numerical model of helical coiled tube.

Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6	Coil 7	Coil 8	Coil 9
$P_1 = 8.00$ MPa			$P_2 = 9.03$ MPa			$P_3 = 10.05$ MPa		
$Q_1 = 20.5$ kW/m^2			$Q_2 = 50.5$ kW/m^2			$Q_3 = 80.5$ kW/m^2		
$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$
0.0131	0.0151	0.0167	0.0131	0.0151	0.0167	0.0131	0.0151	0.0167
$\rho_{avg} = 366.01$ kg/m^3			$\rho_{avg} = 405.06$ kg/m^3			$\rho_{avg} = 453.27$ kg/m^3		

Table 3. The thermophysical properties of $scCO_2$ at three various pressure inlet [6].

	$P_1 = 8.00$ MPa			$P_2 = 9.03$ MPa			$P_3 = 10.05$ MPa	
Coil 1	T_1	300	Coil 4	T_1	300	Coil 7	T_1	300
	ρ_1	751.10		ρ_1	780.09		ρ_1	801.19
	Cp_1	3970.0		Cp_1	3322.2		Cp_1	2988.7
	μ_1	6.2855 E -05		μ_1	6.7392 E -05		μ_1	7.095 E -05
	k_1	0.082524		k_1	0.085921		k_1	0.088847
Coil 2	T_2	323	Coil 5	T_2	323	Coil 8	T_2	323
	ρ_2	219.18		ρ_2	287.41		ρ_2	390.29
	Cp_2	2512.5		Cp_2	3758.1		Cp_2	5907.3
	μ_2	2.0479 E -05		μ_2	2.3250 E -05		μ_2	2.8730 E -05
	k_3	0.032330		k_3	0.040597		k_3	0.053123
Coil 3	T_3	373	Coil 6	T_3	373	Coil 9	T_3	373
	ρ_3	127.74		ρ_3	147.69		ρ_3	168.34
	Cp_3	1248.1		Cp_3	1307.2		Cp_3	1370.5
	μ_3	2.1076 E -05		μ_3	2.1553 E -05		μ_3	2.2107 E -05
	k_3	0.029277		k_3	0.030306		k_3	0.031449

3.2 Mesh Independency Test

The designed numerical model of helical coiled tube in SolidWorks is imported into the commercial computational fluid dynamics (CFD) software called ANSYS FLUENT 16.2. Since the mesh quality of any model plays an important role in numerical calculations, mesh independent test was conducted on a circular helical coiled tube for inlet pressure, flow rate and heat flux values of 8.00 MPa, 0.0131kg/s and 20.5 kW/m^2 respectively. This is to check the mesh sensitivity in terms of various numbers of elements produced in order to choose suitable mesh size for the model. for this three different mesh sizes (36468 , 53222 and 77140) were simulated at various tube ascending angles. Shown in Figure 2 is variation of wall temperature at with tube ascending angle at various number of mesh elements. As can be observed from the figure, considering the finest mesh as reference, the maximum percentage differences of the wall temperature T_w for 53222 and 36468 number of mesh elements are only 0.11% and 0.42%, respectively, which are well below the acceptable value.

This shows that any of the three mesh sizes can be used for the simulation. In this study, the 77140 numbers of elements is selected for the simulation and the meshed geometry is shown in Figure 2. Hence, the mesh independency test concludes that the final results from numerical analysis are not affected by the number of mesh elements.

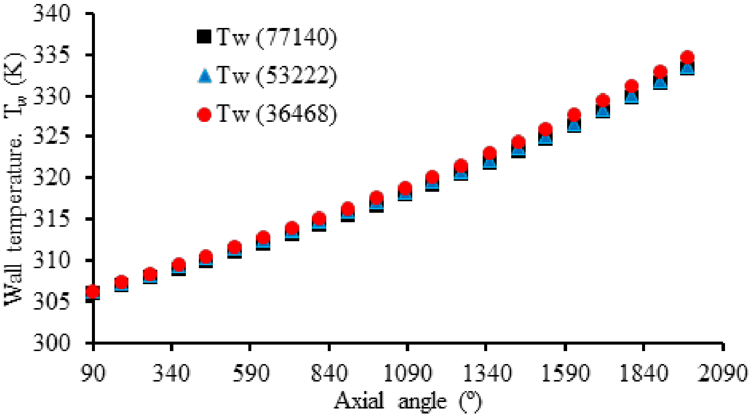

Fig. 2. Mesh independence test comparison for different number of mesh elements.

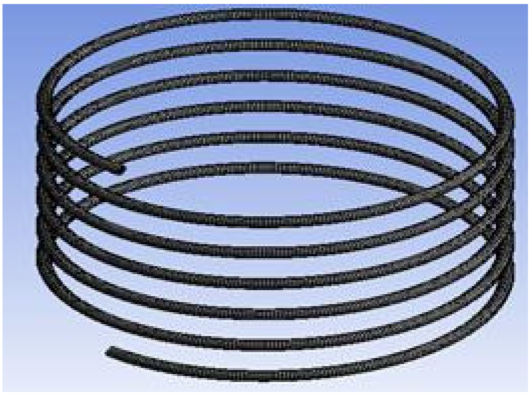

Fig. 3. The meshed circular helical coil tube.

4 Results and Discussions

The data readings taken from all the simulation results in terms of wall temperature (T_w), mean temperature (T_m), pressure drop (ΔP) and manually calculated values of Nusselt number, and friction factor are analyzed.

4.1 Model Validation

Before analyzing the thermo-fluid properties of $scCO_2$ in heating process through coiled vertical tubes, the developed model needs to be validated first. For this, the results obtained from the present numerical model are compared with the experimental results from Xu, J. et.al [12]. The wall temperature (T_w) distribution along the helical coiled tube is compared with mathematical models of three different mesh sizes. Figure 4 shows the T_w variations along the helical coiled tube for 8.00 MPa inlet pressure with 0.0131 kg/s inlet mass flow rate, and heat flux of 20.5 kW/m^2. For all cases, the wall temperature increases as the coil ascending angle increases. The maximum percentage errors for Coil 1, Coil 2 and Coil 3 in comparison to the corresponding experimental wall temperature values are 4.9%, 1.7% and 2.6%, respectively. Hence, since the simulation results are within the acceptable error ranges, the developed model can be used to simulate the flow and heat transfer characteristics of $scCO_2$ through coiled tubes.

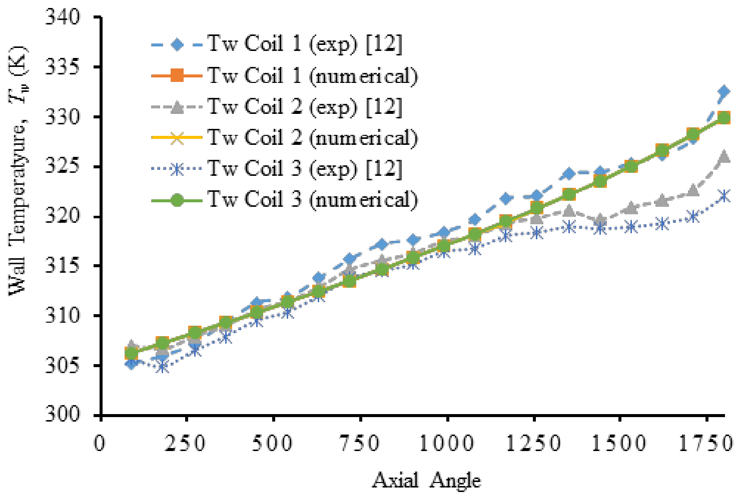

Fig. 4. Comparison of T_w from numerical results with experimental results for Coil 1, Coil 2, and Coil 3 at 8 MPa inlet pressure.

4.2 Nusselt number

Figure 5 shows the variation of the average Nusselt number (Nu_{avg}) with increasing mass flow rate for inlet pressures of 8 MPa, 9.03 MPa and 10.05 MPa with surface heat flux of 20.5 kW/m^2, 50.5 kW/m^2 80.5 kW/m^2, respectively. As can be clearly seen from the figure, at all pressure values the Nu_{avg} slightly decreased as the inlet mass flow flux increases. As expected, the 10 MPa inlet pressure produces the highest average Nu followed by the 9 MPa inlet pressure. The maximum average Nu increment from 8 to 9 MPa and from 8 to 10 MPa inlet pressure are around 1% and 43% respectively. This indicates that at points far from the sudo-critical point of carbon dioxide, the heat transfer is much higher than near the critical region. On the other hand, increasing the heat flux at near critical region will have little effect on the heat transfer performance of $scCO_2$.

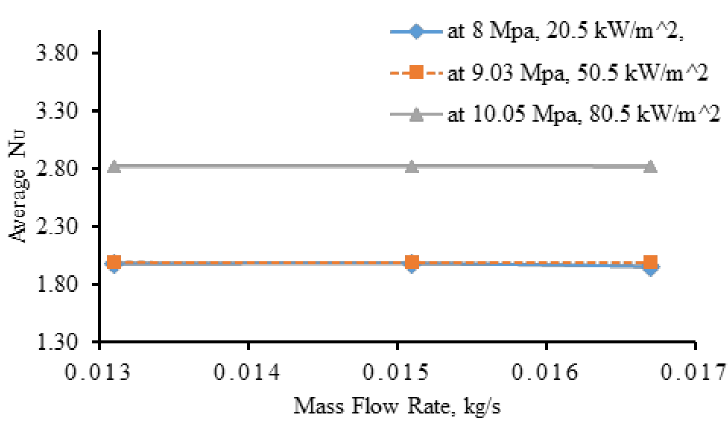

Fig. 5. Average Nusselt number results from numerical results for Coil to Coil 9.

The increment of Nu_{avg} initially for each coil is due to the effect of increment of $\dot{m}$which tends to increase the turbulence of the $scCO_2$ flow at extreme level in helical coiled tubes. The high heat fluxes applied for each increment of inlet pressure enhanced the heat transfer. This is due to continues increased of temperature difference between wall temperatures and mean temperatures (T_w-T_m) along the helical coil tubes.

4.3 Pressure Drop

The pressure drop (ΔP) for all three different inlet pressures: 8 MPa, 9.03 MPa and 10.05 MPa are registered to be 5540 Pa, 4600 Pa and 5500 MPa respectively. The different mass flux in each coil did affect the friction factor showing friction factor decrement with increasing mass flux as shown in Figure 6. However, higher friction factor is observed at 8 MPa compared to 9 MPa inlet pressure case. This might be due to the reason that the heat flux was doubled for the 9 MPa case which makes the temperature inside the tube increase, hence higher pressure drop. On the other hand, even though it produces highest heat transfer, the pressure drop for 10 MPa is the highest. Considering the friction factor at 8 MPa as reverence value, the average friction factor decreased by 8% at 9.03 MPa and increased by 22% at 10.05 MPa. The continuous decrement of friction factor coefficients is due to the viscosity of $scCO_2$ itself and the amount of inlet mass flow rate (velocity) applied which affects the frictions along the coil tubes.

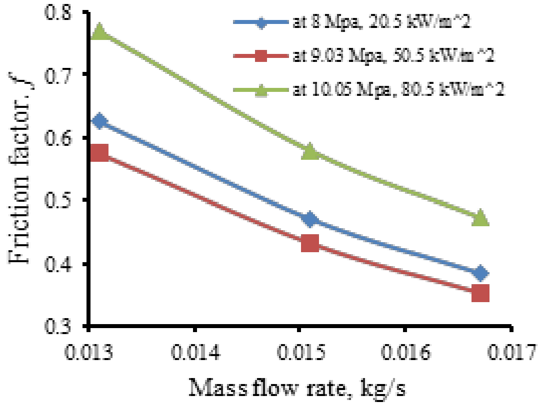

Fig. 6. Friction factor variation with mass flow rate at various critical inlet pressures.

4.4 Goodness Factor

In fact, the heat transfer enhancement can be obtained using a dimensionless number such as Nusselt number. Nevertheless, it provides a fractional indication of the overall performance. Thus, to see the overall performance of the heat exchanger, area goodness factor (*j/f*) needs to be examined. Meanwhile, the Colburn factor coefficient (*j*) is a dimensionless equation of parameter used to study the distribution of natural heat convection over the friction factor coefficient of the fluid flow. The equation of Colburn factor coefficient used is expressed as Eq. (8).

$$j = \frac{h}{\rho u_{mx} c_P} \Pr^{\frac{2}{3}} \tag{8}$$

Figure 7 shows variation of the area goodness factor with mass flow rate at various inlet supercritical pressures. It can be clearly seen that the *j*/*f* values increase with increasing of the mass flux. Therefore, among all the inlet pressures, the 10 MPa has the highest *j*/*f* vale for all inlet mass fluxes. The lowest goodness factor is obtained at 8 MPa. It can be concluded from the *j/f* results that high pressure inlet is recommended where high heat transfer is required. On the other hand, low inlet pressure is recommended where pumping power is a crucial issue

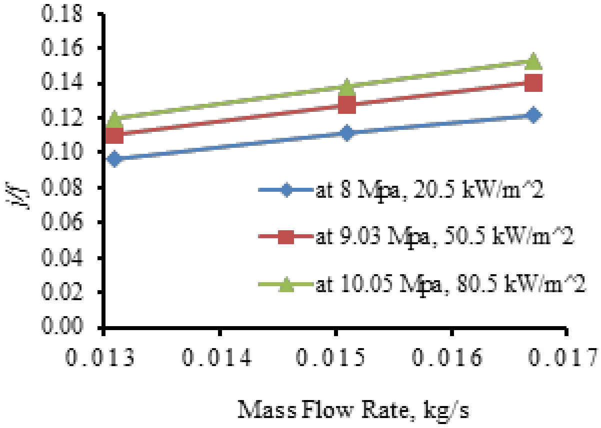

Fig. 7. Area goodness factor (*j/f*) variation with mass flow rate at various supercritical inlet pressures.

5 Conclusions

In conclusion, the numerical method of computational fluid dynamics (CFD) investigation of flow and heat transfer of $scCO_2$ through circular helical coiled tubes has been investigated. The developed numerical model of helical coiled tube has been validated successfully with published experimental results of helical coiled tube by comparing the wall temperature (T_w) for Coil 1, Coil 2 and Coil 3 at 8.00 MPa and 20.5 kW/m^2. Generally, the *Nu* increases with the increment of *Re* till to the certain point along the helical coiled tube, then after that, the *Nu* decreases continuously till to the end due to pressure drop (ΔP) and insufficient of mass flow rate (velocity) where the fluid flow is against gravity along the helical coiled tubes.

Meanwhile, the friction factor (*f*) decreased as the mass flow rate ($\dot{m}$) increased. However, the area goodness factor (*j/f*) increased as the mass flow rate ($\dot{m}$) increased. In general, it can be concluded from the simulation results that high pressure inlet is recommended where high heat transfer is required. On the other hand, low inlet pressure is recommended where pumping power is a crucial issue.

The authors would like to be thanking Universiti Malaysia Pahang for providing laboratory facilities and Ministry of Higher Education Malaysia for financial assistance under FRGS project no. RDU130132.

References

1. Zhang, W., et al., Appl. Therm. Eng., **88**: pp. 61-70. (2014)
2. Hagen, K.D., *Heat Transfer with Application*s. (Prentice Hall. 1999)
3. Liu, Z.B., et al., Appl. Therm. Eng., **70**: pp. 307-315 (2014)
4. Kim, T.H., et al., Nucl. Eng. Des., **288**: 110-118 (2015)
5. Rao, N.T., A.N. Oumer, and U.K. Jamaludin, J. Supercrit. Fluid., **116**: pp. 132-147 (2016)

6. Lemmon, E.W., M.O. McLinden, and D.G. Friend. *"Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69,* (P.J. Linstrom and W.G. Mallard. 2015)
7. Cengel, Y.A. and J.M. Cimbala, *Fluid Mechanics: Fundamentals and Applications*., (New York: McGraw-Hill, 2013)
8. Oumer, A., N. Hamidi, and I.M. Sahat. *Numerical prediction of flow induced fibers orientation in injection molded polymer composites. IOP Conference Series: Materials Science and Engineering*. (2015)
9. Oumer, A.N. and O. Mamat, Int. J. Comp. Sci. Eng., **9**(3): pp. 247-256 (2014)
10. Oumer, A.N. and O. Mamat, Compos. Part B-Eng., **43**(3): pp. 1087-1094 (2012)
11. 11. Cengel, Y.A. and A.J. Ghajar, *Heat and Mass Transfer: Fundamentals and Applications. 4th Edition ed*., (New York: McGraw-Hill Higher Education, 2011)
12. Xu, J., et al., Int. J. Heat Mass Tran., **80**: pp. 748-758 (2015)