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Performance of Helical Coil Heat Recovery Exchanger using Nanofluid as Coolant

Nanofluids are expected to be a promising coolant condidate in chemical processes for heat transfer system size reduction. This paper focuses on reducing the number of turns in a helical coil heat recovery exchanger with a given heat exchange capacity in a biomass heating plant using γ-Al2O3/n-decane nanofluid as coolant. The nanofluid flows through the tubes and the hot n-hexane flows through the shell. The numerical results show that using nanofluid as coolant in a helical coil heat exchanger can reduce the manufacturing cost of the heat exchanger and pumping power by reducing the number of turns of the coil.

Keywords: *Nanofluid, Coil heat exchanger, Overall heat transfer coefficient, Number of turns in helical coil.*

1. Introduction

Coiled tubes are effective heat transfer equipment because of their high heat transfer coefficient and smaller space requirement compared with straight tubes. Heat exchangers with helical tubes are used in chemical and petrochemical industries, heat recovery processes, HVAC systems, cryogenic process, food industries and many other engineering applications. They provide a large surface area per unit volume. But the low thermal property of the heat transfer fluid is a primary limitation to the development of high compactness and effectiveness of them. To overcome the limited heat transfer capability of these fluids, the use of nanosized metals and metal oxides as an additive suspended into the base fluid is a technique for heat transfer enhancement. Fluids with incremented particles of nanometer dimensions are called nanofluids, this term was proposed by Choi [1] in 1995 at the Argonne National Laboratory, U.S.A. Compared with traditional solid-liquid suspensions containing millimeter or micrometer sized particles, nanofluids used as coolants in the heat exchangers have shown better heat transfer performance because of the small size of incremented solid particles. This is due to the fact that nanofluids have a behavior similar to base liquid molecules. So far, few studies have been done on heat transfer characteristics of nanofluids in helical coil heat exchanger [2-10]. To the best of our knowledge, no study has been done to reduce the number of turns in a helical coil heat recovery exchanger using nanofluid as coolant. The objective this work is to characterize the energy performance of a helical coil heat recovery exchanger using a nanofluid based coolant in a biomass heating plant. It focused on the recovering waste heat from hot n-hexane to preheat n-decane based nanofluid fuel containing suspended 20nm-γ-Al2O3 nanoparticles. N-hexane can be produced in the plant biomass from the fermentation of sugars using specific natural bacteria or yeast that produce specifically butyric acid as a single product. The butyric acid is then subjected to Kolbe dimerization electrolysis to form n-hexane. The single n-hexane product also requires further refinement in order to be used as a transportation fuel. So that n-hexane can be converted to ethane and n-decane as the major products.

In this investigation, first the thermophysical properties of γ-Al2O3/n-decane nanofluid are calculated by using the well-known correlations developed from experiments.

2. Methodology

2.1. Prediction of Thermophysical Properties of Nanofluid

Heat transfer performance of a helically coiled heat exchanger (Fig. 1) is studied in this paper. The nanofluid flows through the tubes and the hot n-hexane flows through the shell. The dimensions of helical coil heat recovery heat exchanger, operating conditions, some properties of γ-Al2O3 nanoparticles and base fluid (n-decane) which have been used for assessing nanofluid properties and thermophysical properties of hot n-hexane are tabulated in Tables 1 and 2. The analysis has been carried out by using the existing formulas available in the literatures. γ-Al2O3/n-decane nanofluid with 1–7% particle volume concentration were used during the analysis. The nanofluid thermophysical properties had been computed by applying following equations.

Density of nanofluid [11]:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \tag{1}$$

where ρ_p and ρ_{bf} are the densities of the nanoparticles and base fluid, respectively and ϕ is volume concentration of nanoparticles.

The specific heat of nanofluid is calculated as follows [12]:

$$c_{p,nf} = \frac{(1-\phi)\rho_{bf}c_{p,bf} + \phi\rho_p c_{p,p}}{\rho_{nf}} \tag{2}$$

where $c_{p,p}$ and $c_{p,bf}$ are the heat specifics of the nanoparticles and base fluid, respectively.

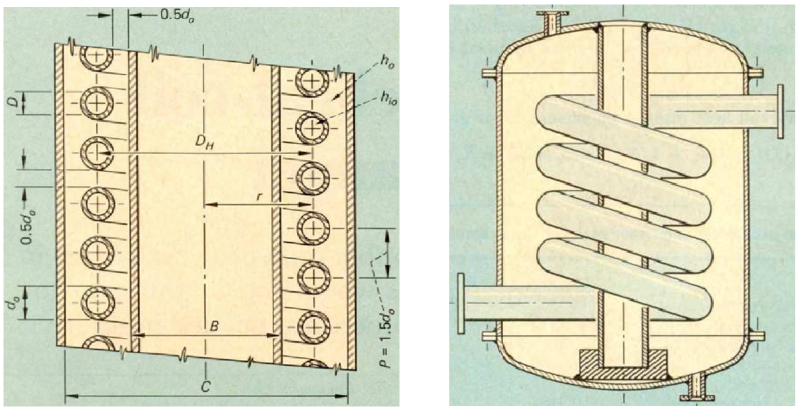

Figure 1. Schematic diagram of helical coil heat exchanger [13].

Table 1. Helical coil heat exchanger geometry and operating conditions.

Outside diameter of inner cylinder (*B*)	0.340 m
Inside diameter of outer cylinder (*C*)	0.46 m
Inside diameter of coil (*D*)	0.025 m
Average diameter of helix (D_H)	0.4 m
Inside diameter of helix (D_{H1})	0.37 m
Outside diameter of helix (D_{H2})	0.43 m
Outside diameter of coil (d_o)	0.03 m
Shell inner diameter (D_s)	0.609 m
Baffle spacing (*B*)	0.234 m
Thermal conductivity of coil wall (k_c)	16.28 W/mK
Nanofluid mass flow rate	0.375 kg/s
Hot n-hexane mass flow rate	0.6 kg/s
Nanofluid inlet temperature (T_1)	40 °C
Nanofluid outlet temperature (T_2)	61 °C
N-hexane inlet temperature (t_1)	104 °C
N-hexane outlet temperature (t_2)	85 °C

Table 2. Thermophysical properties of n-decane, n-hexane and γ-Al2O3 nanoparticle.

Property	n-decane	n-hexane	γ-Al2O3
c_p [J kg^{-1}K^{-1}]	2140	2640	880
ρ [kg m^{-3}]	716	578	3700
k [Wm^{-1}K^{-1}]	0.129	0.0917	46
μ[kg m^{-1} s^{-1}]	0.62×10^{-3}	0.16×10^{-3}	

The thermal conductivity and dynamic viscosity are estimated based on two semi-empirical equations presented by Corcione [14] as follows:

$$\frac{k_{nf}}{k_{bf}} = 1 + 4.4 Re^{0.4} Pr_{bf}^{0.66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{k_p}{k_{bf}}\right)^{0.03} \phi^{0.66} \quad (3)$$

$$\mu_{nf} = \frac{\mu_{bf}}{1 - 34.87(d_p / d_{bf})^{-0.3}\phi^{1.03}} \quad (4)$$

where k_{bf} is the thermal conductivity of the base fluid, Re is the nanoparticle Reynolds number, Pr_{bf} is the Prandtl number of the base fluid, T is the nanofluid temperature, T_{fr} is the freezing point of the base fluid, k_p is the thermal conductivity of the nanoparticles, μ_{bf} is the dynamic viscosity of the base fluid, d_p is the diameter of the nanoparticles and d_{bf} is the equivalent diameter of a base fluid molecule, as stated in Ref. [14], can be calculated as follows:

$$d_{bf} = 0.1\left(\frac{6M}{N\pi\rho_{bf0}}\right)^{1/3} \quad (5)$$

where M and N are respectively the molecular weight of the base fluid and the Avogadro number (6.022×10^{23} mol^{-1}) and ρ_{bf0} is the mass density of the base fluid calculated at T_0=293 K.
In more detail, the Reynolds number of the suspended nanoparticles can be calculated as follows [14]:

$$Re = \frac{2\rho_{bf} k_b T}{\pi \mu_{bf}^2 d_p} \quad (6)$$

wherein k_b=1.38066×10^{-23} J/K is the Boltzmann constant.

2.2. Hot n-hexane Side Calculation

The heat transfer coefficient of the hot n-hexane flowing through the shell under a turbulent regime can be calculated as follows ($50 \le Re_h \le 10000$) [15]:

$$h_h = \frac{0.6k_h}{D_e} Re_h^{0.5} Pr_h^{0.31} \quad (7)$$

where h denotes hot n-hexane conditions, and D_e is shell side equivalent diameter which is expressed in the following form:

$$D_e = \frac{4V_f}{\pi d_o L} \quad (8)$$

V_f is volume available for fluid flow in annulus and L is length of coil needed to form N turns which can be determined by using following formulations [13]:

$$V_f = (\pi/4)(C^2 - B^2)pN - (\pi/4)d_o^2 L \quad (9)$$

$$L = N\sqrt{(2\pi r)^2 + p^2} \tag{10}$$

D_e=0.0845 m is obtained by using Eqs. (8)-(10) in the presentstudy. In equation (7), the Reynolds and Prandtl numbers are calculated considering the hot n-hexane properties as follows:

$$Re_h = \left(\frac{\dot{m}_h}{A_a}\right)\frac{D_e}{\mu_h} \tag{11}$$

$$Pr_h = \frac{c_{p,h}\mu_h}{k_h} \tag{12}$$

where $\dot{m}_h$ is the hot n-hexane mass flow rate and A_a is the area for fluid flow in annulus which is defined as follows [13]:

$$A_a = (\pi/4)\left[(C^2 - B^2) - (D_{H2}^2 - D_{H1}^2)\right] \tag{13}$$

2.3. Nanofluid Side Calculation

The heat transfer coefficient of the nanofluid as coolant flowing through the tubes can be calculated with considering the turbulent Nusselt number presented by Li and Xuan [16] as follows:

$$\frac{h_{i,nf}D}{k_{nf}} = Nu_{nf} = 0.0059\left(1.0 + 7.6286\phi^{0.6886}Pe_d^{0.001}\right)\times Re_{nf}^{0.9238}Pr_{nf}^{0.4} \tag{14}$$

$h_{i,nf}$ is heat transfer coefficient inside straight tube. The heat transfer coefficient inside coiled tube ($h_{i,nf}$ corrected for coil) based on inside diameter can be calculated as follows [13]:

$$h_{ic,nf} = h_{i,nf}\times\left(1 + 3.5(\frac{D}{D_H})\right) \tag{15}$$

In Equation (14), the Reynolds number and the particle Peclet number for nanofluid are defined respectively as:

$$Re_{nf} = \frac{\dot{m}_{nf}\,D}{A_f\mu_{nf}} \tag{16}$$

$$A_f = \frac{\pi}{4}D^2 \tag{17}$$

$$Pe_d = \frac{u_{nf}d_p}{\alpha_{nf}} \tag{18}$$

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} c_{p,nf}} \quad (19)$$

where $\dot{m}_{nf}$ is the nanofluid mass flow rate, A_f is the cross-sectional area of coil, d_p is the diameter of the nanoparticles and α_{nf} is the nanofluids thermal diffusivity.

2.4. Total heat transfer area and coefficient calculation

(a) The total heat transfer coefficient is calculated by [13]:

$$U = \left(\frac{1}{h_h} + \frac{1}{h_{io,nf}} + \frac{x}{k_c} + R_t + R_a \right)^{-1} \quad (20)$$

where the tube side fouling factor (R_t) and the shell side fouling factor (R_a) are assumed to be 0.0007 m^2KW^{-1}. In Equation (20), the thickness of coil wall (x) and heat transfer coefficient inside coil based on outside diameter of coil ($h_{io,nf}$) are calculated respectively as:

$$x = (d_o - D)/2 \quad (21)$$

$$h_{io,nf} = h_{ic,nf}(D/d_o) \quad (22)$$

(b) The total heat transfer area of a helical coil heat exchanger, A, is computed from the following equation:

$$A = \frac{\dot{Q}_{given}}{U \Delta t_c} \quad (23)$$

In Equation (23), the heat load ($\dot{Q}_{given}$) and the corrected logarithmic mean temperature difference (Δt_c) with correction factor of 0.99 [13] are calculated respectively as:

$$\dot{Q}_{given} = \dot{m}_{nf} \, c_{p,nf}(T_1 - T_2) \quad (24)$$

$$\Delta t_c = 0.99 \frac{[(T_1 - t_1) - (T_2 - t_2)]}{\ln((T_1 - t_1) - (T_2 - t_2))} \quad (25)$$

2.5. Number of turns of coil

The number of turns of coil needed can be calculated by:

$$N = A / (\pi d_o (\sqrt{(2\pi r)^2 + p^2})) \quad (26)$$

2.6. Pressure drop modeling

The friction factor of nanofluid in helical coils in turbulent flow can be calculated using the formula presented as follows [17]:

$$f_{nf} = 0.304\,\mathrm{Re}^{-0.25} + 0.029\sqrt{(\frac{D}{D_H})} \tag{27}$$

In this paper, the pressure drop (Δp_{nf}) and pumping power (*PP*) for γ-Al2O3/n-decane nanofluid used as a coolant in a helical coil heat exchanger are calculated as follows:

$$\Delta p_{nf} = 2\frac{f_{nf} L \rho_{nf} u_{nf}^2}{D} \tag{28}$$

$$PP = \dot{m}_{nf}\frac{\Delta P_{nf}}{\rho_{nf}} \tag{29}$$

3. Results and Discussion

Results are reported in terms of $h_{io,nf}$, *U*, *A*, *N*, ΔP_{nf} and *PP* as a function of volume concentration ϕ. In all cases the particle size is considered equal to 20 nm. The findings are as follows:

(a) Increasing the particles concentration raises the fluid viscosity and decreases the Reynolds number and consequently decreases the heat transfer coefficient. But the results shown in Fig. 2 indicate that increasing in particles concentration raises the convective and total heat transfer coefficient up till ϕ=0.04. Therefore, it can be concluded that the change in the coolant heat transfer coefficient is more than the change in the fluid viscosity with increasing nanoparticles loading in the base fluid up to an optimum concentration.

(b) As shown in Fig. 3 the heat transfer area and the number of turns of helical coil are calculated up to optimum concentration (ϕ=0.04). The results showed that the total heat transfer area decreases with the increasing of volume concentration of nanoparticles and therefore can reduce the number of turns. For example, the reduction of the total heat transfer area at 0.04 volume concentration is about 24% with 50 turns compared with 62 turns for pure n-decane.

(c) As seen in Fig. 4, the nanofluid friction factor for flow in a coiled tube is greater than that of the pure n-decane. As the nanoparticles loaded into the base fluid increase, the viscosity and density of the base fluid also increase; causing higher friction factor and pressure drop. But Fig. 5 clearly shows that can decrease the pressure drop and the pumping power using nanofluid as coolant in a helical coil heat recovery exchanger with a given heat exchange capacity by reducing the length of helical coil needed to form *N* turns.

4. Conclusions

A numerical study has been carried out on the characteristics of 20 nm γ-Al2O3/ n-decane nanofluid with volume concentrations up to 7% in a Helical Coil Heat recovery exchanger under turbulent flow conditions. The nanofluid flows through the tubes and the hot n-hexane flows through the shell. The results confirm that nanofluid offers higher heat performance than n-decane up to an optimum concentration (▱=0.04) and therefore can reduce the total heat transfer area and also the length of helical coil for providing the same heat exchange capacity.

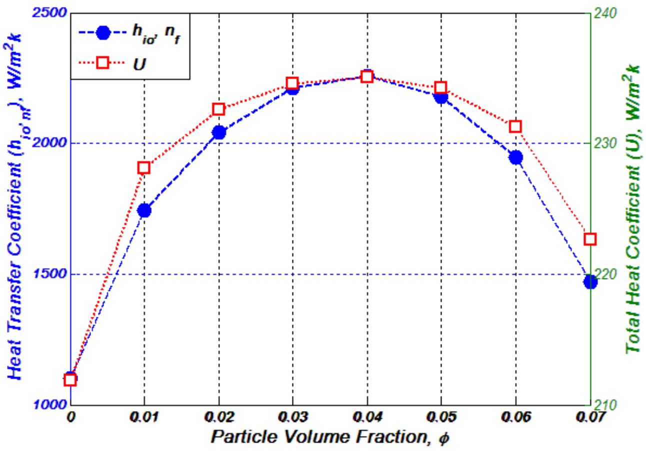

Figure 2. The convective and total heat transfer coefficient for γ-Al_2O_3/n-decane nanofluid at various concentrations.

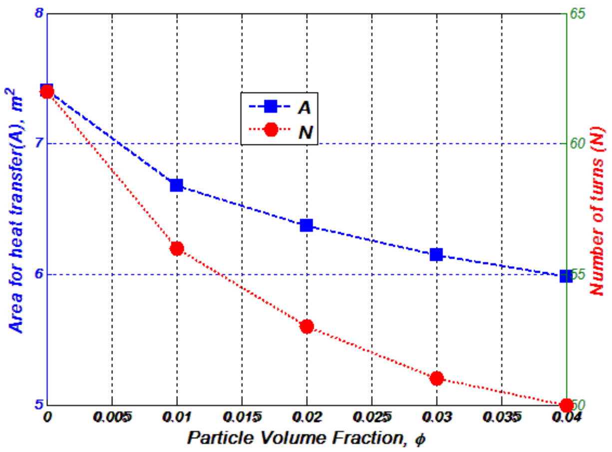

Figure 3. Area for heat transfer and number of turns at various concentrations.

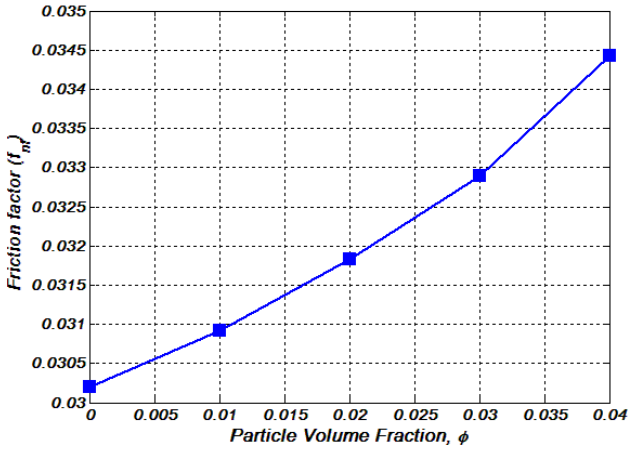

Figure 4. Friction factor of γ-Al_2O_3/n-decane nanofluid flowing in helical coils at various concentrations.

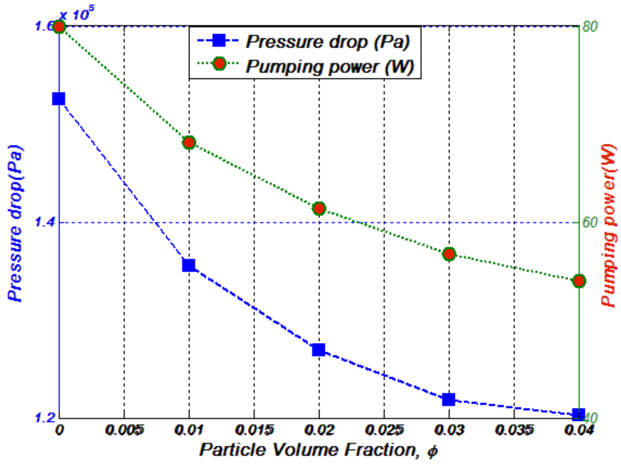

Figure 5. Pressure drop and pumping power of γ-Al_2O_3/n-decane nanofluid flowing in helical coils at various concentrations.

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