Original Article

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Thermal performance of the seal oil cooler of the RFCC MCB Pump by using CNT-water nanofluids

S. Masoud Hosseini [1], Abdolreza Moghadassi[2,*], Leila Vafajoo [3], Javad Moradi [2]

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[1] Process Engineering Department of RFCC Unit, Shazand Oil Refining Company, Iran
[2] Department of Chemical Engineering, Faculty of Engineering, Arak University, Arak, Iran
[3] Department of Chemical and Environmental Engineering, Islamic Azad University, South Tehran Branch, Tehran, Iran

Abstract

In this article, the water-based Carbon nanotube (CNT) nanofluid in various CNT concentrations was used in an industrial shell and tube cooler as a cooling fluid. The heat transfer factors have been analyzed, such as Reynolds number, Nusselt number, overall heat transfer coefficient, and heat transfer rate. The cooling fluid flows on the tube side, and the hot fluid flows on the shell side. The CNT concentrations were 0.0055%, 0.055%, 0.111% and 0.278% volume fraction. The results represented that the heat transfer properties increased with CNT volume fraction as 0.278 CNT volume fraction enhanced the Nusselt number and the convection heat transfer coefficient about 47% and 59.3%, respectively, for example. Likewise, heat transfer was enhanced with the increment of the nanofluid mass flow rate for all the CNT volume concentrations.

Keywords: CNT nanofluid, Shell and tube cooler, Heat transfer coefficient, CNT volume fraction, Nanofluid Mass flow rate

1. Introduction

Nanofluids are suspensions provided from dispersing various nanoparticles in base fluids to enhance thermal properties. Nanoparticles could be metals such as Cu [1], Au [2], and Ni [3]; metal oxide as Al_2O_3 [4], CuO [5], and ZnO [6]; and nonmetals such as Carbon nanotubes (CNTs) [7]. Nanofluids are the next generation of heat transfer fluids in heat exchangers since it was proven that nanofluids have better thermal properties than conventional fluids [8]. One of the categories of nanofluids applicable to the heat transfer processes is CNT-provided ones. Carbon nanotubes have excellent thermal conductivity, which enhances the thermal properties of the nanofluids [9]. Recently, much research has been done on using nanofluids as heat transfer fluids in the heat exchangers such as plate, double tube and shell, and tube heat exchangers. These researches demonstrate the enhanced heat transfer performance of the heat exchangers [10]. Shell and tube heat exchangers are among the most utilized types of heat exchangers in the industry, with numerous applications in power plants, oil and gas, food, and others. The shell and tube heat exchanger is a type of heat exchanger that allows for larger surface contact than other heat exchangers. The investigations illustrate that using nanofluids as working fluids in this type of heat exchanger enhances heat transfer performance noticeably [11, 12]. In the current study, the thermal performance of the seal oil cooler of an MCB (main column bottom) pump in the RFCC (residue fluid catalytic cracking unit) unit [18] has been investigated while CNT-water nanofluid was used in this heat exchanger as cooling fluid in low nanoparticle concentrations. RFCC is utilized for upgrading heavy feedstock (residue) to light products such as high octane number gasoline, LPG, Propylene, and diesel. The main column bottom (MCB) is also a heavy product of this unit produced in the fractionation column bottom. MCB is discharged at a high temperature (average 300 ºC) by a pump. A circulated oil fills the clearance between the mechanical seal and shaft to prevent pump fluid from leaking outside (Fig.1) [19].

Corresponding Authors: Abdolreza Moghadassi
a-moghadassi@araku.ac.ir

This temperature rise makes the mechanical seal hotter, and consequently, the seal oil outlet from the mechanical seal gets hotter. Thus, the shell and tube cooler could not efficiently cool the oil. This problem could gradually hurt the mechanical seal. Enhancing the thermal properties of water is one of the methods for solving this problem. With this goal, water-based nanofluid containing carbon nanotubes in this heat exchanger has been analyzed numerically. The heat exchanger has been manufactured by EagleBurgmann company. This work was performed through ASPEN heat exchanger design and rating simulation software.

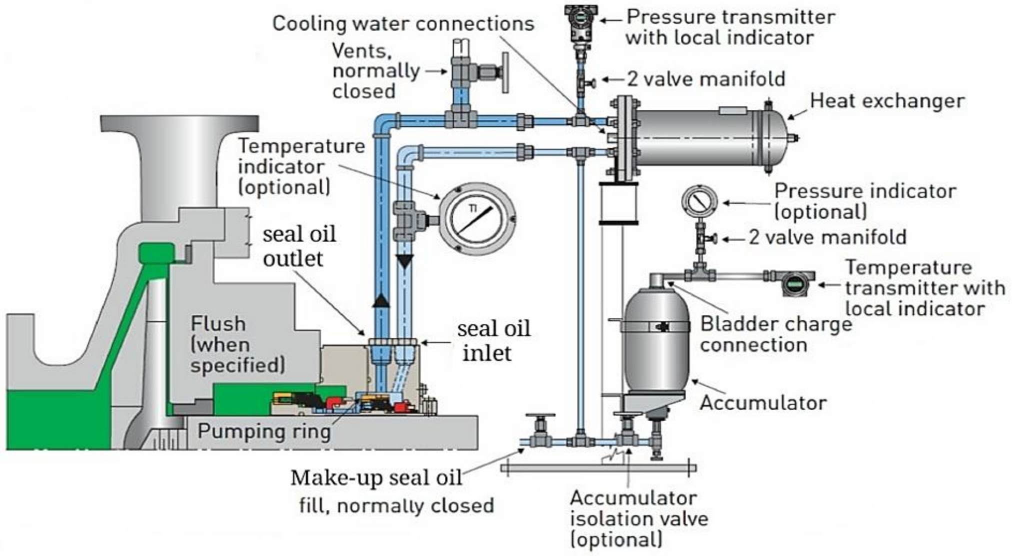

Fig. 1. Schematic of sealing system and seal oil circulation for the pumps [19]

2. Modeling

Aspen EDR (Exchanger Design & Rating) V11- ASPENONE software was applied for this work. This software has been known as the most operational one in the heat exchanger field. This software has four calculation modes to meet its user's needs: Design (sizing), Rating & Checking, Simulation, and finding fouling. In the current study, Simulation mode was considered to simulate the shell and tube heat exchanger, described in Fig.1, when using CNT-water nanofluids as coolant and analyzing the heat transfer performance. Also, Fig. 2 shows the real shell and tube cooler of the circulation seal oil of the RFCC MCB pump, which has been considered to be modeled.

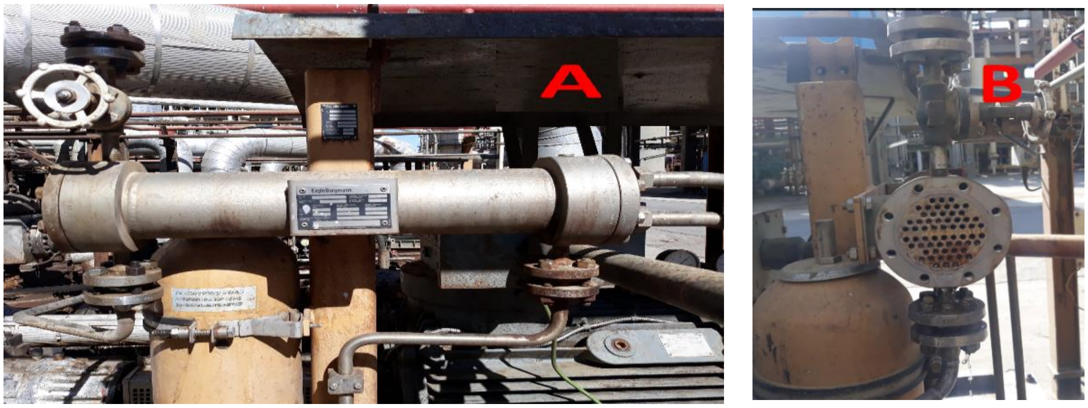

Fig. 2. A: Real shell and tube cooler of the circulation seal oil of the RFCC MCB pump that has been modeled B: Tube sheet of the heat exchanger.

Within this simulation, the operational condition of the shell side and tube side fluids of the heat exchanger, specification of the heat exchange, and thermophysical properties of the shell side and tube side fluids are entered into the software as inlet data. After running the software, the outlet process condition of the fluids and the heat transfer factors are available. In this study, CNT-water nanofluids were considered as cooling fluids on the tube side. For thermophysical properties of the CNT-water nanofluids, experimental data from Halelfadl et al. [20,21] were used for volume fractions 0.0055%, 0.055%, 0.111%, and 0.278% (Fig. 3a, 3b, 3c and 3d).

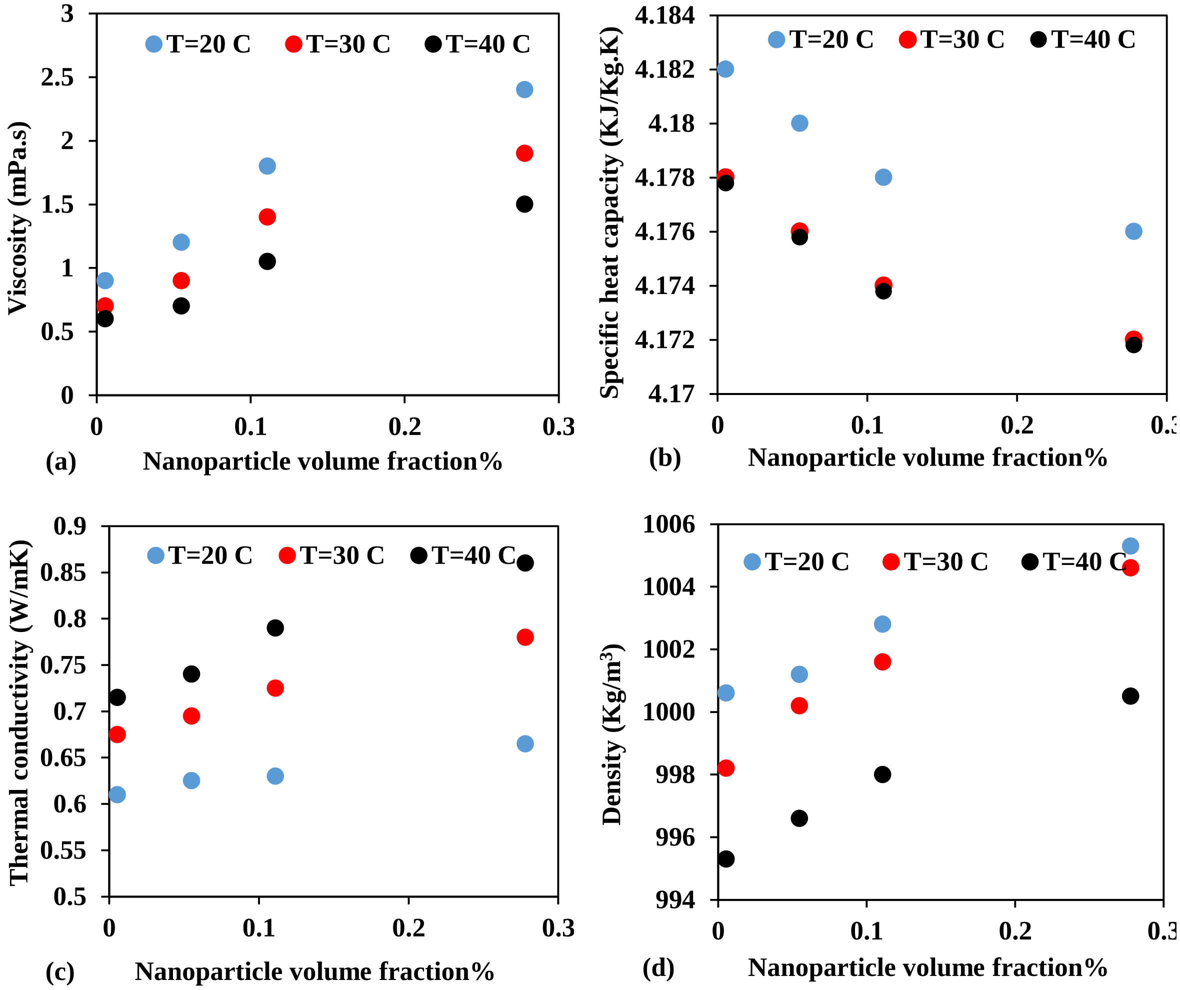

Fig. 3. (a, b, c, d) Influences of temperature and CNT volume fraction on the thermophysical properties of the CNT-water nanofluids [20, 21].

Likewise, thermophysical properties of the seal oil (manufactured by BEHRAN oil Co. of Iran) have been measured experimentally as thermal conductivity by catalog method, density by standard ASTM D4052, specific heat by NETZSCH DSC, and viscosity by Anton Paar rheometer. Fig. 4a, 4b, 4c and 4d show the measured experimental data of the seal oil thermophysical properties. It is mentionable that the fluid viscosities were considered in low shear rates because of laminar flow conditions. Table1 also presents data for heat exchanger geometry, which is needed for the simulation process. At first, simulation was performed based on water as a cooling fluid to ensure the results' validity. After that, the nanofluid simulations were carried out.

Table 1. Specification of the shell and tube cooler as well as the operational condition of both fluids in the shell side (the seal oil) and tube side (the coolants)

Parameter	Amount/type	Parameter	Amount/type
Shell inner diameter/ *mm*	110.3	Baffle type	Single-segment
Shell outer diameter /*mm*	123.41	Baffle spacing (center–center) (*mm*)	60
Tube number		Baffle cut %	45
Tube passes per shell	2	Mass flow rate of fluid in shell side (the seal oil) (kg s^{-1})	0.1389
Tube length/*mm*	64.5	Mass flow rate of tube-side fluid (cooling water and the nanofluid) (kg s^{-1})	0.225
Outer diameter of tube/*mm*	7.5	Shell-side fluid inlet temperature (°*C*)	80
Thickness of tube/*mm*	0.56	Tube-side fluid inlet temperature (°*C*)	25
Tube pitch/*mm*	9.38	Shell-side fluid inlet pressure (*bar*)	7.5
Tube pattern	30-Triangular	Tube-side fluid inlet pressure (*bar*)	3.7

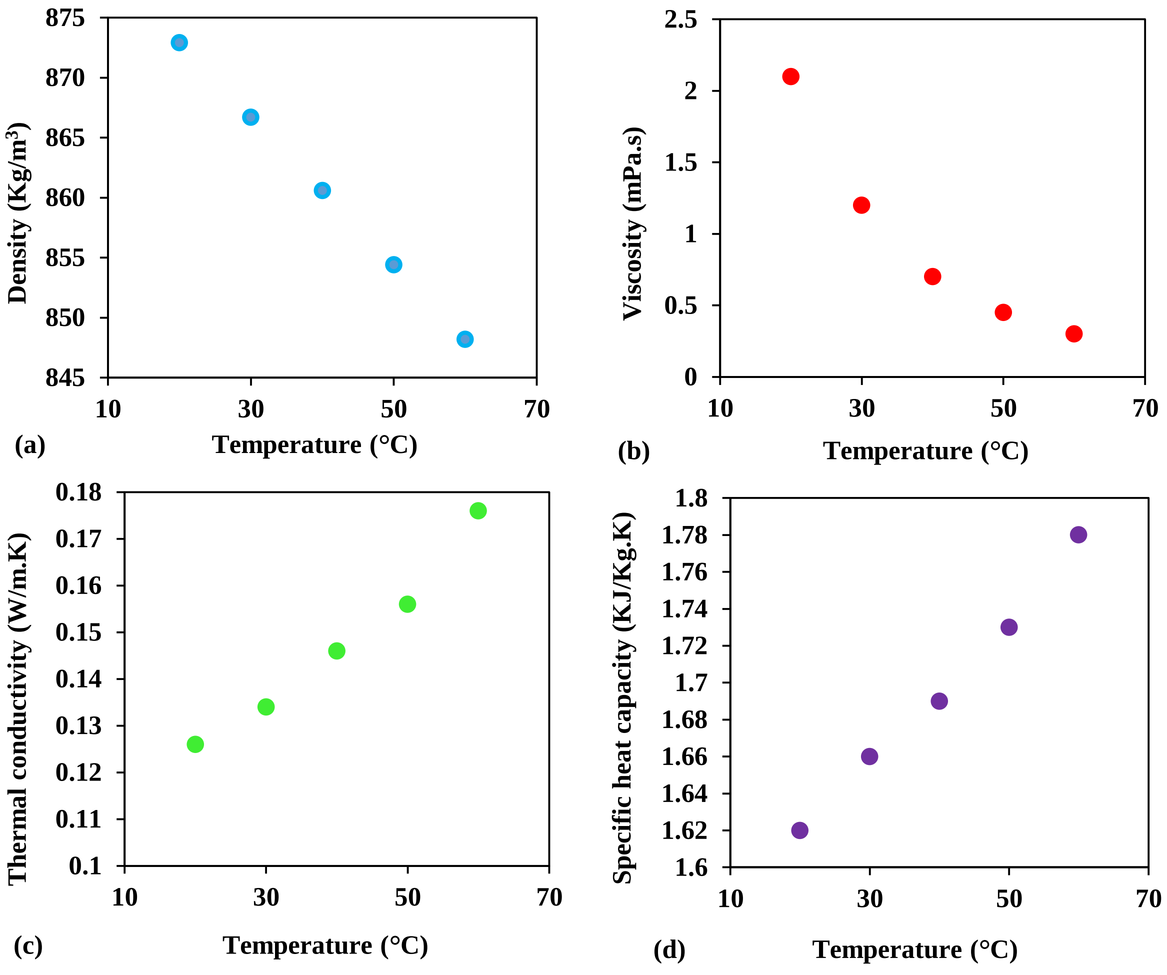

Fig. 4. (a, b, c, d) Measured experimentally thermophysical properties of the seal oil.

3. Results analysis

Fig. 5 depicts that the Reynolds number decreases with the CNT volume fraction. The viscosity of the nanofluids rises with the increase of the nanoparticle volume fraction (Fig. 3). According to Eq. 1, by increasing the viscosity, the Reynolds number decreases. Also, it is clear from Fig.5 that the range of the tube side Reynolds number relates to the laminar flow condition.

$$Re_{nf} = \frac{m_{nf} d}{A_t \mu_{nf}} \qquad (1)$$

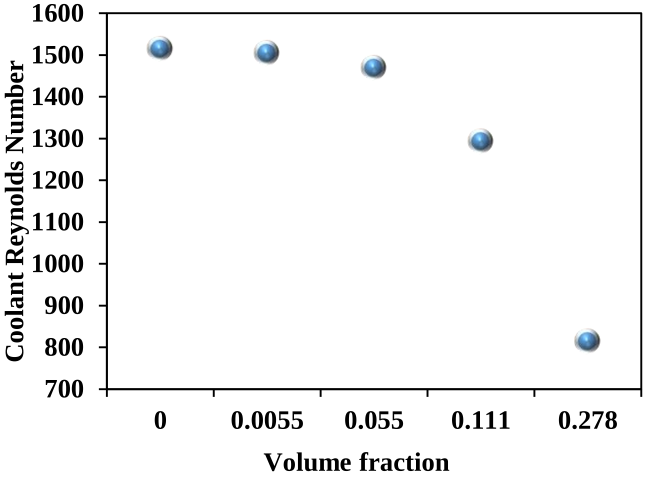

Fig. 5. Reynolds number of the coolant as a function of CNT volume fraction.

Fig. 6 demonstrates the trend for the Prandtl number with CNT volume fraction. The Prandtl number decreases for the lower CNT volume fractions (0.0055% and 0.055%) while increasing for the higher ones (0.111% and 0.278%). Referring to Eq. 2, the effects of C_P and k are higher than μ for the lower concentrations since the nanofluids viscosities in these concentrations are close to water.

$$Pr_{nf} = \frac{C_{p_{nf}} \mu_{nf}}{k_{nf}} \qquad (2)$$

Increasing the CNT volume fraction intensifies the μ effect on the Prandtl number; thus, the Prandtl number increases for the higher concentrations.

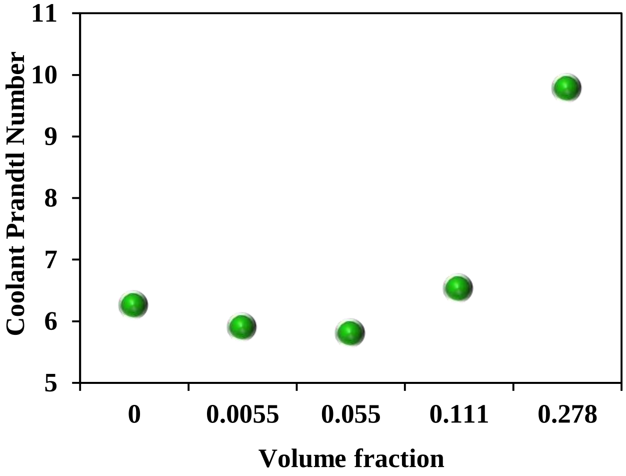

Fig. 6. Prandtl number of the coolant as a function of CNT volume fraction.

Fig. 7 presents an increasing Nusselt number with CNT volume fraction based on Li and Xuan model [22], expressed as Eq. 3.

$$Nu_{nf} = 0.4328(1 + 11.258\varphi_{nf}^{0.754} Pe_{nf}^{0.218}) Re_{nf}^{0.333} Pr_{nf}^{0.4} \quad (3)$$

Peclet number in this equation is also calculated as Eq. 4.

$$Pe_{nf} = Re_{nf} Pr_{nf} \quad (4)$$

The increase of Nusselt number for 0.0055%, 0.055%, 0.111%, and 0.278% CNT volume fractions are about 2.2%, 18.7%, 30%, and 47% respectively.

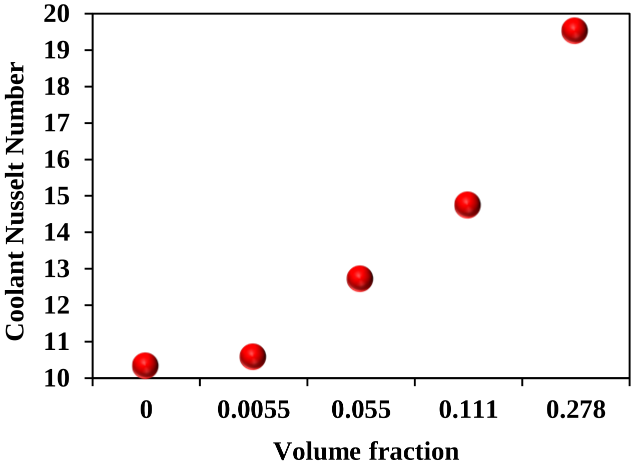

Fig. 7. The coolant Nusselt number as a function of CNT volume fraction.

As expressed by Eq. 5, fluid thermal conductivity and Nusselt number are directly related to the convection heat transfer coefficient; the convection heat transfer coefficient increases with the Nusselt number and thermal conductivity of the fluids (Fig. 8) about 12.5%, 28.85%, 41.58% and 59.3% for CNT volume fractions of 0.0055%, 0.055%, 0.111%, and 0.278%, respectively.

$$h_{nf} = \frac{Nu_{nf} k_{nf}}{d_i} \quad (5)$$

Moreover, an increase in the convection heat transfer coefficient leads to an enhancement of the total heat transfer coefficient (Fig. 9), as shown in Eq. 6.

$$\frac{1}{U} = \frac{1}{h_{hot}} + \frac{d_o \ln(\frac{d_o}{d_i})}{2k_w} + \frac{1}{h_{nf}} \frac{d_o}{d_i} \quad (6)$$

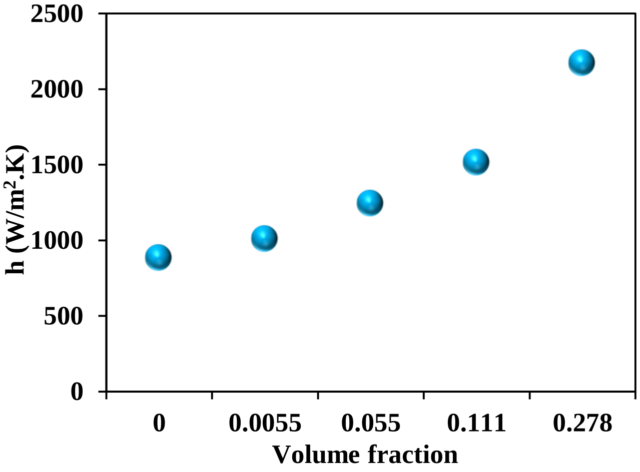

Fig. 8. Convection heat transfer coefficient of the coolants as a function of CNT volume fraction.

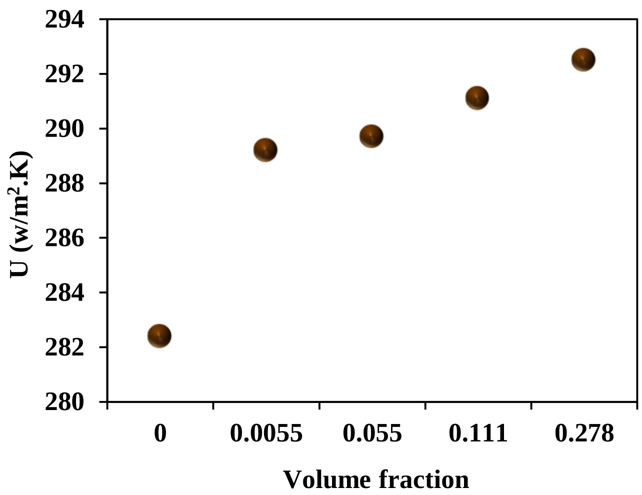

Fig. 9. Total heat transfer coefficient of the coolants as a function of CNT volume fraction.

Fig. 10 shows the increment of heat transfer rate with CNT volume fraction. It is observed in Eq. 7 that the heat transfer rate is proportional to the total heat transfer coefficient, as the heat transfer rate increases with the total heat transfer coefficient.

$$q = UA_s\Delta T_{LMTD} \qquad (7)$$

A maximum heat transfer rate of 8073 W occurs at φ = 0.278 vol% since the maximum total heat transfer coefficient occurs for this point.

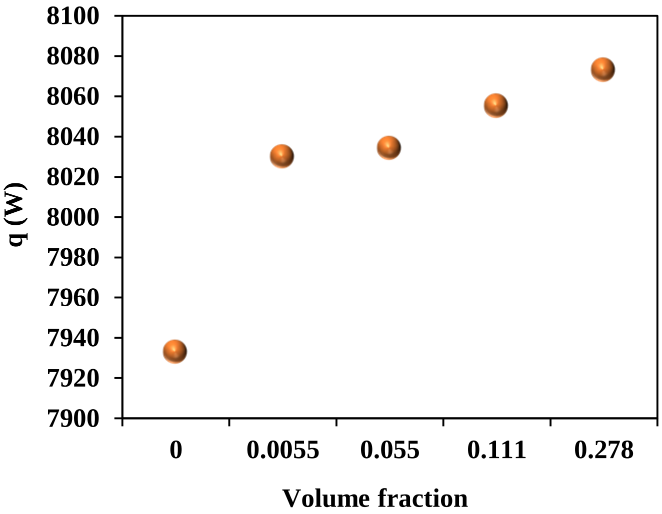

Fig. 10. Heat transfer rate of the coolants as a function of CNT volume fraction.

As shown in Eq. 1, the Reynolds number of the cooling fluid is a function of the mass flow rate at a constant nanoparticle volume fraction. Therefore, the Reynolds number rises when the nanofluid mass flow rate increases. This behavior is shown in Fig. 11.

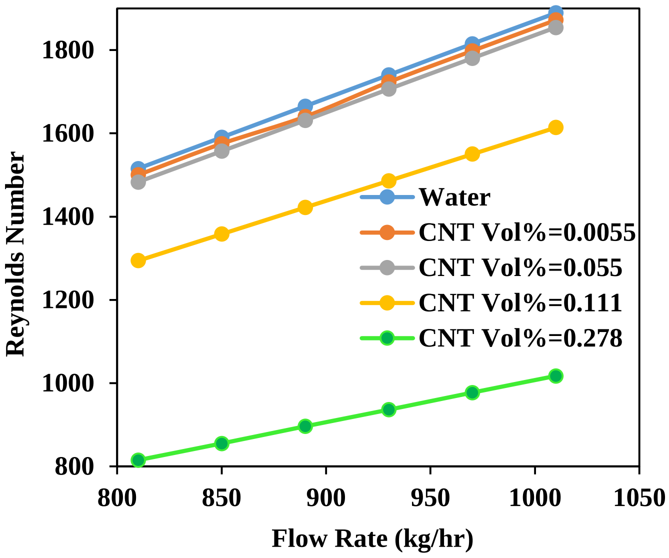

Fig. 11. Influence of the coolants mass flow rate on Reynolds number.

Fig. 12 also illustrates that the Prandtl number is almost constant regardless of the cooling fluid mass flow for each CNT volume fraction.

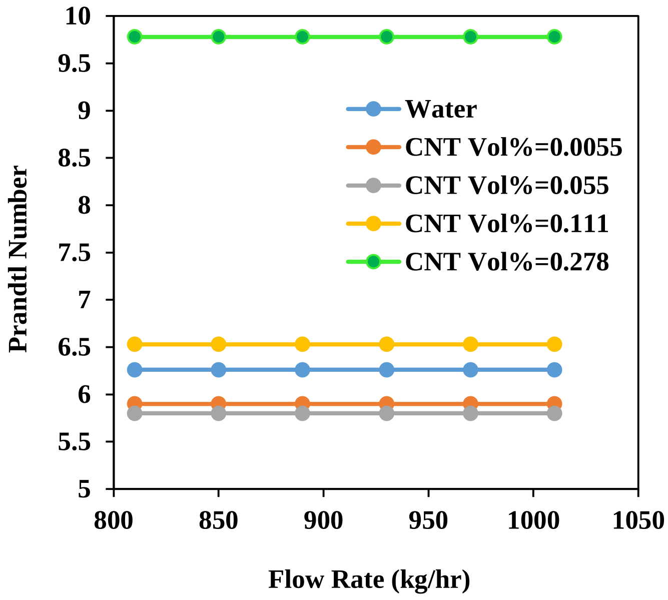

Fig. 12. Influence of the coolants mass flow rate on Prandtl number.

Fig. 13 represents the increase in Nusselt number due to the coolant mass flow rate rise for a constant CNT concentration. As can be seen, the highest Nusselt number occurs for $\varphi = 0.278\%$.

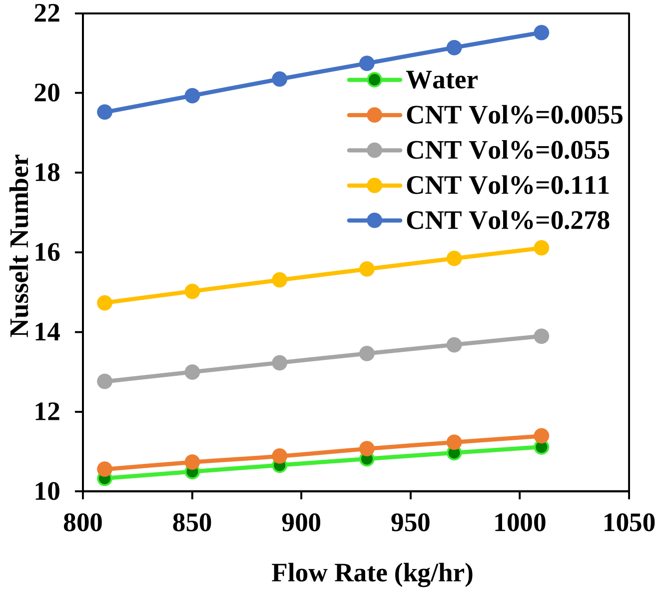

Fig. 13. Influence of the coolants mass flow rate on Nusselt number.

From Fig. 14, the convection heat transfer coefficient increases as the CNT nanofluid mass flow rate increases. Likewise, an increment in CNT concentration intensifies the increase of convection heat transfer coefficient with the mass flow rate (from 810 kg/hr to 1010 kg/hr, and for 0.278 vol%, an increase of 9.3% is observed in the convection heat transfer coefficient).

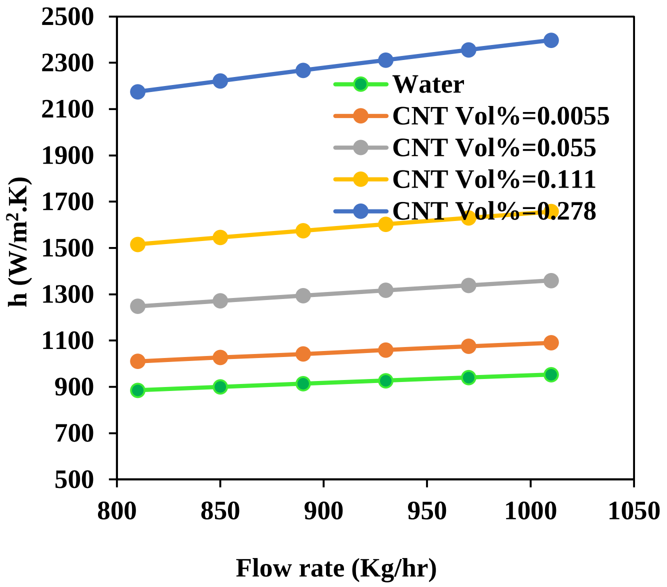

Fig. 14. Influence of the coolants mass flow rate on convection heat transfer coefficient.

Fig. 15 shows increasing total heat transfer coefficient trends versus the cooling fluid’s mass flow rates. Regarding the rise in total heat transfer coefficient with the mass flow rate, enhancing heat transfer rate also occurs when the mass flow rate increases (Fig. 16).

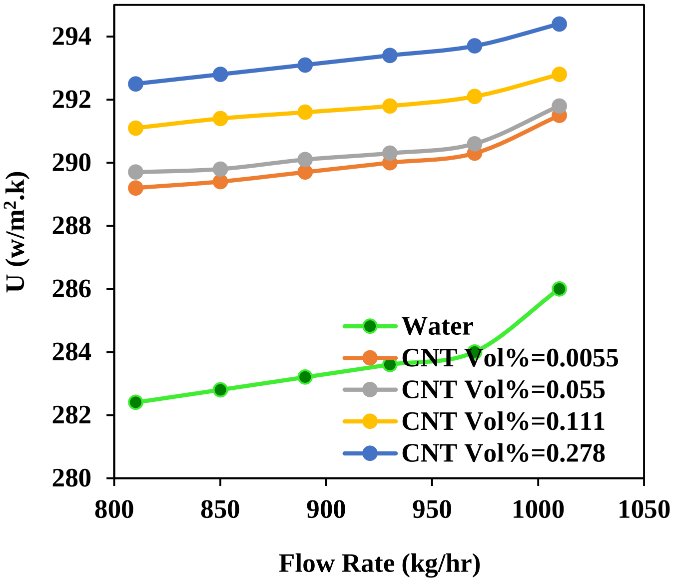

Fig. 15. Influence of the coolants mass flow rate on total heat transfer coefficient.

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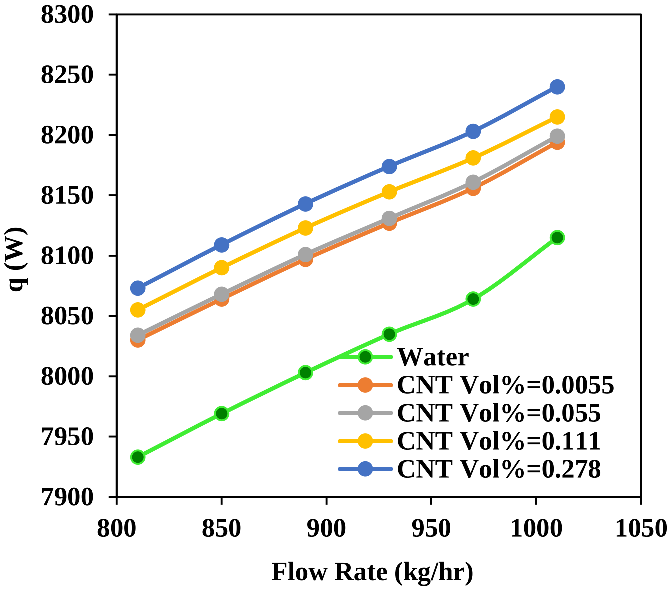

Fig. 16. Influence of the coolants mass flow rate on the heat transfer rate.

5. Conclusions

This investigation studied the thermal performance of the seal oil cooler of the RFCC MCB pump consisting of a shell and tube heat exchanger type through software simulation by using water base nanofluids loaded by CNT as cooling fluids. The results demonstrated that in very low viscosity and density, the pressure drop is negligible. Therefore, an increase in thermal conductivity and a decrease in specific heat capacity could enhance the thermal properties of the nanofluid and following that heat transfer performance of the heat exchanger. Also, all analyzed CNT concentrations improved the heat properties such as Nusselt number, convection heat transfer coefficient, total heat transfer coefficient, and heat transfer rate. The maximum rise in thermal properties belongs to the 0.278% CNT volume fraction as the Nusselt number increased by about 47%, and the convection heat transfer coefficient rose about 59.3% by using the 0.278% CNT volume fraction. Consequently, the heat performance of the heat exchanger is also enhanced from 7933 w for water to 8073 w for the maximum CNT concentration. The heat performance was also enhanced by increasing the mass flow rate of the nanofluids in all CNT volume fractions.

List of symbols

Re_{nf}	Nanofluid Reynolds number	U	Total heat transfer coefficient
m_{nf}	Nanofluid mass flow rate (Kg/s)	A_s	Total heat transfer area of tube outside (m^2)
μ_{nf}	Nanofluid viscosity (mPa.s)	K_w	Thermal conductivity of the tube
Pr_{nf}	Nanofluid Prandtl number	q	Heat transfer rate
C_P	Specific heat (KJ/Kg.K)	ΔT_{LMTD}	Log mean temperature difference
k_{nf}	Nanofluid thermal conductivity (W/m.K)	A_t	Flow area of tube side (m^2)
Pe_{nf}	Nanofluid Peclet number	d_i	Inner tube diameter (m)
φ_{nf}	Nanoparticle volume fraction	d_o	Outside tube diameter (m)
h_{nf}	Nanofluid convection heat transfer coefficient	Nu_{nf}	Nanofluid Nusselt number
h_{hot}	Convection heat transfer coefficient of hot fluid		

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Author information

*Corresponding Author: Abdolreza Moghadassi
E-mail addresses: a-moghadassi@araku.ac.ir

ORCID

Abdolreza Moghadassi: 0000-0003-0733-4540.

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