Evaluation of γ-Al_2O_3/n-decane Nanofluid Performance in Shell and Tube Heat Recovery Exchanger in a Biomass Heating Plant

N. Bozorgan*
Department of Mechanical Engineering,
Islamic Azad University, Abadan Branch, Abadan, Iran
E-mail: N.bozorgan@gmail.com
*Corresponding author

M. Shafahi
Department of Mechanical Engineering,
California State Polytechnic University, Pomona, California, USA

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Abstract: The performance of a γ-Al_2O_3/n-decane nanofluid shell-and-tube heat exchanger in a biomass heating plant is analyzed to specify the optimum condition based on the maximum heat transfer rate and performance index for wide range of nanoparticle volume fraction (0–7%). Compared with pure n-decane, the obtained results in this research show that by using γ-Al_2O_3/n-decane nanofluid as the coolant at optimum values of particle volume concentration for maximum heat transfer rate (ϕ=0.021) and for maximum performance index (ϕ=0.006), the heat transfer rate and pumping power increased by 10.84%, 13.18% and 6.72%, 2.3%, respectively. Increasing particles concentration raises the fluid viscosity, decreases the Reynolds number and consequently decreases the heat transfer coefficient. As a result, determining the optimum value of the particle volume fraction of nanofluid as the working fluid, can improve the performance of shell-and-tube heat exchangers.

Keywords: Heat transfer, Nanofluid, Pressure drop, Shell and Tube Heat Exchanger

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Biographical notes: N. Bozorgan is currently instructor at the Islamic Azad University of Abadan, Iran. He is currently working on the improvement of the heat exchangers performance with the application of nanofluids. **M. Shafahi** is an assistant professor in mechanical engineering department at California State Polytechnic University. Her research interests are aquaponics, nanofluid heat pipe, drug delivery, bioheat and sustainable energy.

1 INTRODUCTION

Heat recovery systems utilize heat exchangers to recover the waste heat. Amount of heat recovered is highly dependent on fluid properties, particularly temperature and flow rate. The poor heat transfer properties of the utilized fluids in industries are obstacles for using different types of heat exchangers. A recent advancement in nanotechnology has introduced nanofluids with enhanced thermal properties to be utilized in thermal applications. Nanofluids were first innovated by Choi and Eastman [1] in 1995 at the Argonne National Laboratory. Nanofluids proved to be more efficient coolants in heat exchangers. They have attracted attention as the new generation of heat transfer fluids in heat exchangers, chemical plants and automotive cooling applications, due to their excellent thermal performance.

Recently there have been considerable research findings highlighting superior heat transfer performances of nanofluids. Sarkar [2] modeled the nanofluid cooled shell and tube gas cooler and showed that use of nanofluid as coolant improves the gas cooler effectiveness, cooling capacity and COP with nearly the same pump power. Author reported that the maximum cooling COP improvement of transcritical CO_2 cycle of 26.0% is obtained for Al_2O_3-H_2O, whereas that was 24.4% for TiO_2-H_2O, 20.7% for CuO-H_2O and 16.5% for Cu-H_2O. Mohammed et al., [3] studied the effects of using nanofluid on the performance of a square shaped microchannel heat exchanger (MCHE) numerically. Their results demonstrated that Al_2O_3 and Ag nanoparticles have the highest heat transfer coefficient and lowest pressure drop among all nanoparticles tested. Saeedinia et al., [4] applied CuO-base oil particles varying in the range of 0.2-2% inside a circular tube. Their results showed that the CuO nanoparticles suspended in base-oil increases the heat transfer coefficient even for a very low particle concentration of 0.2%.

Vajjha et al., [5] numerically investigated the heat transfer augmentation by application of two different nanofluids consisting Al_2O_3 and CuO nanoparticles in an ethylene glycol and water mixture circulating through the flat tubes of an automobile radiator. Their results showed that at a Reynolds number of 2000, the percentage increase in the average heat transfer coefficient over the base fluid for a 10% Al_2O_3 nanofluid is 94% and that for a 6% CuO nanofluid is 89%. Strandberg et al., [6] theoretically analyzed the performance of hydronic finned-tube heating units with nanofluids. They observed that the finned tube with 4% Al_2O_3/60% EG (40% water) has the lowest liquid pumping power at a given heating output of all the fluids modeled.

The objective of this work is to characterize the energy performance of a shell and tube heat recovery system using a nanofluid based coolant in a biomass heating plant. It focused on the recovering heat from hot n-hexane to pre-heat n-decane based nanofluid fuel containing suspended 20nm-γ-Al_2O_3 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 [7]. Besides heating and cooling purposes, nanofluids can also be applied in the field of combustion and fuels. Energetic nanoparticles such as γ-Al_2O_3 offer high reactivity, fast ignition, and fast energy release [8]. When mixed with liquid fuels such as n-decane, they can increase the volumetric energy density of the fuel, which is the most important parameter of fuel for high-speed propulsion systems. The nanofluid-type fuels comprise a new class of fuels and have been rarely studied.

Jackson et al., [9] dispersed nano-aluminum particles in n-dodecane and showed that the addition of nanoparticles could substantially decrease the ignition delay time in a shock tube. Tyagi et al., [10] using a simple hot-plate experiment, reported that the ignition probability for fuel mixtures that contained aluminum nanoparticles was significantly higher than that of pure diesel fuel. The applicability of nanotechnology towards liquid fuels with a stable suspension of nonometer-sized particles should be considered as future work. In this investigation, the thermophysical properties of γ-Al_2O_3/n-decane nanofluid are calculated by using the well-known correlations developed from experiments.

2 METHODOLOGY

2.1. Prediction of Thermophysical Properties of nanofluid

The shell and tube heat exchanger considered in this study is illustrated in Figure 1, whereas the dimensions of shell and tube heat exchanger, operating conditions, some properties of γ-Al_2O_3 nanoparticles, base fluid (n-decane) and hot n-hexane are tabulated in Tables 1 and 2. The nanofluid flows through the tubes and the hot n-hexane flows through the shell. The following assumptions have been made in the analysis:

i. The flow is incompressible, steady-state, and turbulent.
ii. The effect of body force is neglected.
iii. Heat transfer with the ambient is negligible.
iv. Only single-phase heat transfer occurs for nanofluid.

In order to investigate the heat transfer performance of nanofluids and use them in practical applications, it is necessary to study their thermophysical properties such as density, specific heat, viscosity and thermal conductivity. In this study, to validate the numerical results, thermal properties of γ-Al_2O_3/n-decane nanofluid are determined by employing well-known empirical correlations.
Nanofluid density can be calculated as follows [11]:

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

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 nanofluids is given by the following equation [12]:

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

Where $c_{p,p}$ and $c_{p,bf}$ are the specific heat of the nanoparticles and base fluid, respectively.
The transport properties of nanofluid: thermal conductivity and dynamic viscosity are not only dependent on volume fraction, but also highly dependent on the other parameters such as particle shape, mixture combinations and slip mechanisms. Over the past decade, various theoretical and experimental studies have been conducted and various correlations have been proposed for these properties of nanofluids.
In the present study, the thermal conductivity and dynamic viscosity for n-decane nanofluid, k_{nf} and μ_{nf}, have been estimated based on two semi-empirical equations presented by Corcione [13]:

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

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

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 which can be calculated as follows [13]:

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

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.
Reynolds number of the suspended nanoparticles can be calculated as follows [13]:

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

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

2.2. Mathematical Modeling

This research attempts to investigate heat transfer and energy performance of a shell and tube heat exchanger using n-decane-based γ-Al_2O_3 nanofluid as a coolant.

2.2.1. 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 [14]:

$$h_h = \frac{0.36k_h}{D_e}\mathrm{Re}_h^{0.55}\mathrm{Pr}_h^{\frac{1}{3}}\left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14} \quad (7)$$

Where *h* and *nf* denote the relevant parameters of hot n-hexane and nanofluid coolant and D_e is the equivalent diameter which is expressed in the following form [14]:

$$D_e = \frac{4(P_t^2 - \frac{\pi d_o^2}{4})}{\pi d_o} \quad (8)$$

In equation (7), the Reynolds and Prandtl numbers are calculated considering the hot n-hexane properties as follows:

$$\mathrm{Re}_h = \left(\frac{\dot{m}_h}{A_{cf}}\right)\frac{D_e}{\mu_h} \quad (9)$$

$$\mathrm{Pr}_h = \frac{c_{p,h}\mu_h}{k_h} \quad (10)$$

Where $\dot{m}_h$ is the hot n-hexane mass flow rate and A_{cf} is the cross-flow area which is defined as follows [14]:

$$A_{cf} = (D_s - N_{CL}d_o)B \quad (11)$$

2.2.2. Nanofluid Side Calculation

(a) The heat transfer coefficient of the nanofluid as coolant flowing through the tubes can be calculated using the turbulent Nusselt number as follows [15]:

$$\frac{h_{nf}\,d_i}{k_{nf}} = \mathrm{Nu}_{nf} = 0.0059\left(1.0 + 7.6286\phi^{0.6886}\,\mathrm{Pe}_d^{0.001}\right) \times \mathrm{Re}_{nf}^{0.9238}\,\mathrm{Pr}_{nf}^{0.4}\left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14} \quad (12)$$

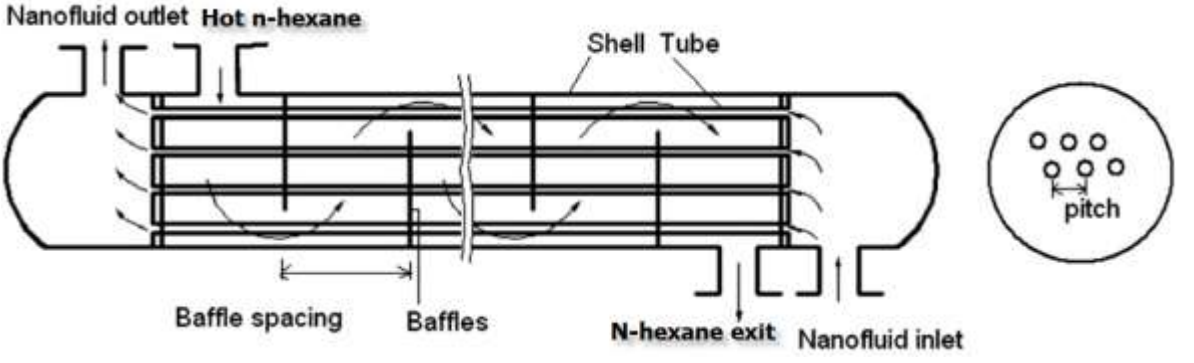

Fig. 1 Shell and tube heat exchanger configuration

Table 1 Shell and tube heat exchanger geometry and operating conditions

Description	Type/value
Type of heat exchanger	Two-tube passes (n=2), type AES
Tube inner diameter (d_i)	0.0157 m
Tube outer diameter (d_o)	0.019 m
Tube length (L)	4.267 m
Number of tubes (N)	414
Number of tubes in the central row (N_{CL})	21
Tube layout pitch (P_t)	0.0254 m
Shell inner diameter (D_s)	0.609 m
Baffle spacing (B)	0.234 m
Nanofluid mass flow rate	38.88 kg/s
Hot n-hexane mass flow rate	33.33 kg/s
Nanofluid inlet temperature	40 °C
N-hexane inlet temperature	104 °C

Table 2 Thermophysical properties of n-decane, n-hexane and γ-Al_2O_3 nanoparticle

Property	n-decane	n-hexane	γ-Al_2O_3
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 Reynolds number and the particle Peclet number for nanofluid are defined respectively as [14]:

$$\mathrm{Re}_{nf} = \frac{\dot{m}_{nf}\,d_i}{a_t\,\mu_{nf}} \quad (13)$$

$$a_t = \frac{\pi d_i^2}{4}\left(\frac{N}{n}\right) \quad (14)$$

$$\mathrm{Pe}_d = \frac{u_{nf}\,d_p}{\alpha_{nf}} \quad (15)$$

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf}\,c_{p,nf}} \quad (16)$$

Where a_t is the total flow area for the tubeside nanofluid, d_p is the diameter of the nanoparticles and α_{nf} is the nanofluids thermal diffusivity.

It shall be noted that the viscosity correction factor is defined as the ratio of viscosity of the nanofluid at the mean temperature of inlet and outlet conditions to that one at the mean temperature of wall tube. The mean temperature of wall tube, T_w, cannot be calculated explicitly. Therefore, as a first approximation, it is assumed to be equal to 1 and the first values of heat transfer coefficients (h_h and h_{nf}) are calculated using equations (7)-(16). Then, T_w is calculated by equating the heat transfer rates at both sides of the tube wall as follows:

$$q''_{conv} = h_{nf}(T_w - T_{ave}) = h_h(T_{ave} - T_w) \quad (17)$$

By having T_w, the exact value of viscosity correction factor is calculated and the previous values for h_h and h_{nf} are modified.

(b) The pressure drop (Δp_{nf}) and pumping power (PP) for γ-Al_2O_3/n-decane nanofluid used as a coolant in a shell and tube heat exchanger are calculated with Poiseuille's law as follows [16]:

$$\Delta P_{nf} = \left(\frac{128 \mu_{nf} L \dot{V}_{nf}}{\pi d_i^4} \right) \times N \times n \quad (18)$$

$$PP = \dot{m}_{nf} \frac{\Delta P_{nf}}{\rho_{nf}} \quad (19)$$

Where L is the length of the tube, $\dot{V}_{nf}$ is the volumetric nanofluid flow rate.

2.2.3. Total heat transfer area and coefficient calculation

(a) Knowing h_h and h_{nf}, the total heat transfer coefficient can be calculated as follows:

$$U = \left(\frac{1}{h_h} + \frac{1}{h_{nf}} \times \frac{d_o}{d_i} + Rf \right)^{-1} \quad (20)$$

Where the fouling resistance (Rf) is assumed to be 0.0009 m^2KW^{-1}.

(b) Total tubes heat transfer area, A_{real}, can be determined with its geometric dimensions as follows:

$$A_{real} = N \pi d_o L \quad (21)$$

(c) In this work, the calculated area, A_{calc}, is computed from the following equation [14]:

$$A_{calc} = \frac{q}{U \times F \times LMTD} \quad (22)$$

$$q = \varepsilon C_{min}(T_{h,i} - T_{nf,i}) \quad (23)$$

$$\varepsilon = 1 - \exp[(\frac{1}{C^*})(NTU)^{0.22}\{\exp[-C^*(NTU)^{0.78}] - 1\}] \quad (24)$$

Where

$$C^* = \frac{C_{min} = (\dot{m}_{nf}\, C_{p,nf})}{C_{\max} = (\dot{m}_h\, C_{p,h})}\ ;\ NTU = \frac{UA_{real}}{C_{\min}} \quad (25)$$

Where q is the heat transfer rate, F is the temperature correction factor which is assumed to be 0.967, ε is the heat exchanger effectiveness, NTU is the number of heat transfer units.

3 RESULTS AND DISCUSSIONS

Results are reported in terms of k_r (k_{nf}/k_{bf}), h_r (h_{nf}/h_{bf}), h_{nf}, U, q, ΔP_{nf} and PP as a function of volume concentration ϕ. As mentioned previously, the Corcione model has been applied to predict the thermal conductivity of the γ-Al_2O_3/n-decane nanofluid. In all cases the particle size is considered equal to 20 nm. Figure 2 and Table 3 show k_r and h_r parameters for the γ-Al_2O_3/water nanofluid at various concentrations (0-7%).

The present results are similar to that observed by Esfe et al., [17] and Jwo et al. [18]. They showed the heat transfer coefficient ratio (h_r) of 1.36 for 1.0% concentration of MgO nanoparticles in water at Re=7331. Our numerical results show that h_r=1.5728 for 1.0% concentration of γ-Al_2O_3 nanoparticles in n-decane at Re=21659.6 (Table 3). Enhancement of heat transfer by nanofluids may be resulted from the following aspects: (i) nanoparticles had higher thermal conductivity, so a higher concentration of nanoparticles resulted in a more obvious heat transfer enhancement. (ii) Nanoparticles collided with the base fluid molecules and the wall of the heat exchanger, thus strengthening energy transmission. (iii) The nanofluid increased friction between the fluid and the wall, improving heat exchange.

Increasing particles concentration raises the fluid viscosity, decreases the Reynolds number and consequently decreases the heat transfer coefficient (Table 3). The results reveal that as the concentration increases, $h_r > k_r$ is up till a volume fraction of 0.019. After this concentration level, h_r ratio is less than k_r ratio. It can also be seen in Table 3 that increasing particles concentration increases the h_r ratio up till ϕ=0.039. The present results are similar to the observation of Lelea et al. [19]. They reported that the Al_2O_3/water nanofluid with $\phi = 3\%$ has the lower heat transfer coefficient compared with $\phi = 1.33$ and 2%.

According to Figure 3, the total heat transfer coefficient shows a consistent trend with the heat transfer coefficient. The present results are similar to the observation of Jwo et al., [18]. They experimentally confirmed that nanofluid offers higher total heat transfer performance than the base fluid as well. As can be seen in Figure 4, the heat transfer rate is calculated by Equation (23) by computing *U*, *NTU*, C^* and Ɛ for γ-Al_2O_3/ n-decane nanofluid at various concentrations. The results show that the best volume fraction for maximum heat transfer rate is equal to ϕ=0.021.

As the nanoparticles loaded into the base fluid increase, the viscosity and density of the base fluid also increases; causing higher friction factor and pumping power. The pressure drop and pumping power are closely related. Figure 5 clearly shows that the pressure drop of γ-Al_2O_3/ n-decane nanofluid increases with the increasing volume concentrations. Pantzali et al., [20] and Kabeel et al. [21] found the same results. From the experimental data of Pantzali et al., [20], Kabeel et al. [21] and present work it can be seen that the pressure drop is increased about 40%, 45% and 44.4%, respectively, at $\phi = 4\%$.

In this study, the ratio of the heat transfer rate and pumping power is defined as the performance index [22].

$$\eta = \frac{q}{PP} \tag{26}$$

Figure 6 shows that the optimum concentration for maximum performance index is ϕ=0.006.

Table 3 Summary of numerical results

ϕ	k_r	h_r	μ[kg m^{-1} s^{-1}]	ρ_{nf} (kg/m^3)	h_{nf} (W/m^{2}K)	U (W/m^{2}K)	PP (W)	Re
0	1	1	0.62×10^{-3}	716	1448.1776	418.0364	1067.6574	24552.17
0.01	1.5410	1.5728	0.7×10^{-3}	745.84	2277.6807	478.0097	1115.3371	21659.6
0.019	1.8264	1.8206	0.8×10^{-3}	772.696	2636.6146	494.8649	1187.7758	18949.42
0.02	1.8548	1.8416	0.82×10^{-3}	775.68	2666.9803	496.1296	1197.8695	18645.46
0.03	2.1171	1.9907	0.97×10^{-3}	805.52	2882.8757	504.5265	1329	15583.67
0.039	2.3283	2.0347	$1{,}18\times10^{-3}$	832.376	2946.6408	506.8472	1515.2	12801
0.04	2.3507	2.0342	1.22×10^{-3}	835.36	2945.9646	506.8279	1541.7702	12490.52
0.05	2.5650	1.9652	1.62×10^{-3}	865.2	2845.9308	503.2554	1915.1236	9373.85
0.06	2.7651	1.7564	2.44×10^{-3}	895.04	2543.5748	491.0228	2689.0412	6238.2887
0.07	2.9542	1.3313	4.93×10^{-3}	924.88	1928.0601	457.4705	5089.1950	3086.9383

A further inspection of Figures 4 and 6 shows that the optimum concentration for maximum performance index is lower than that for maximum heat transfer. This observation is consistent with the experimental results presented by Tiwari et al., [23]. Compared with pure n-decane, the obtained results in this research show that by using γ-Al_2O_3/ n-decane nanofluid as coolant at optimum values of particle volume concentration for maximum heat transfer rate (ϕ=0.021) and for maximum performance index (ϕ=0.006), the heat transfer rate and pumping power increased by 10.84%, 13.18% and 6.72%, 2.3%, respectively.

As mentioned previously, present results are in good agreement with results of several researches [17-21]. To validate the numerical code, the calculated area (A_{calc}) is computed using the numerical code and compared with the total effective area of the shell and tube heat exchanger (A_{real}) for pure n-decane as coolant. The difference between A_{calc} obtained by code and A_{real} is about 4.5% (A_{calc}=100.71m^2 and A_{real}=105.445 m^2). This difference is acceptable.

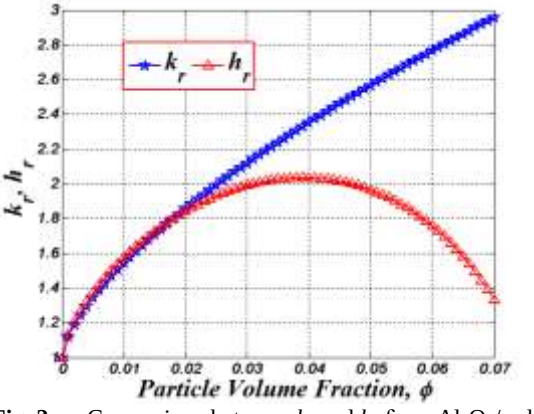

Fig. 2 Comparison between k_r and h_r for γ-Al_2O_3/n-decane nanofluid flowing through tubes

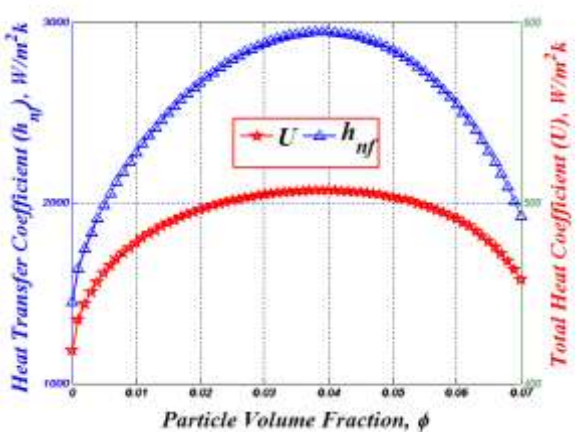

Fig. 3 Heat transfer coefficient and total heat transfer coefficient for γ-Al_2O_3/n-decane nanofluid at various concentrations

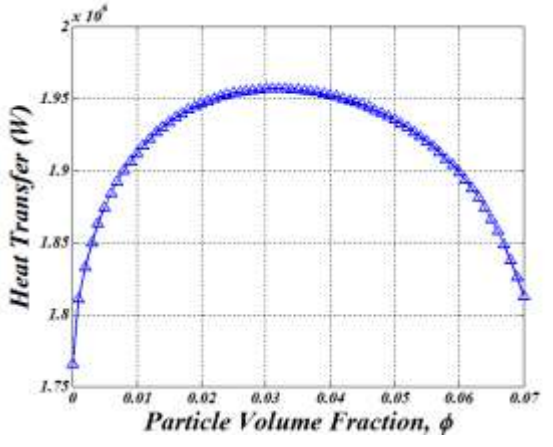

Fig. 4 Heat transfer rate for nanofluid at different particle concentration level

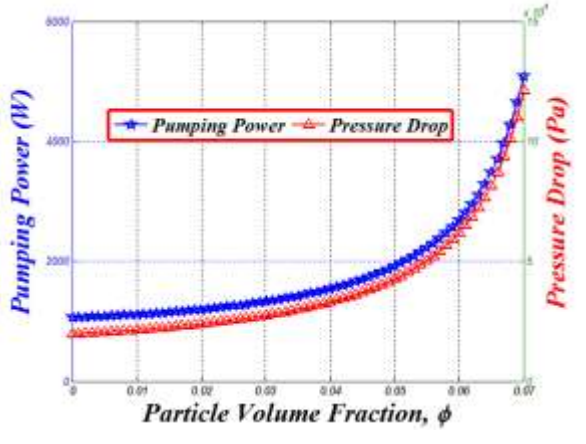

Fig. 5 Influence of γ-Al_2O_3 volume fraction on the pumping power and pressure drop

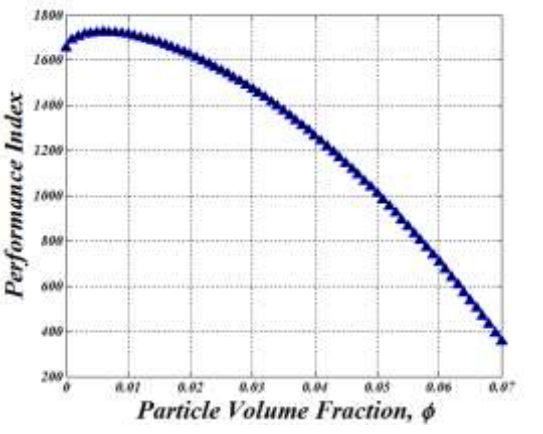

Fig. 6 Variation of performance index with particle volume fraction

4 CONCLUSION

Based on the analysis, the following conclusion could be drawn:

(1) $h_r > k_r$ is up till a volume fraction of 0.019. After this concentration level, h_r ratio is less than k_r ratio.
(2) Increasing particles concentration increases the h_r ratio up till ϕ=0.039.
(3) This study indicates that the optimum concentration for maximum performance index is lower than that for maximum heat transfer rate.
(4) Compared with pure n-decane, the obtained results in this research show that by using γ-Al_2O_3/ n-decane nanofluid as coolant at optimum values of particle volume concentration for maximum heat transfer rate (ϕ=0.021) and for maximum performance index (ϕ=0.006), the heat transfer rate and pumping power increased by 10.84%, 13.18% and 6.72%, 2.3%, respectively.

Nomenclature

A : total heat transfer area, m^2
A_{cf} : cross-flow area, m^2
B : baffle spacing, m
c_p : specific heat, J/kg K
D_s : shell inner diameter, m
D_e : equivalent diameter for heat transfer, m
d_i : tube inner diameter, m
d_o : tube outer diameter, m
d_o : tube outer diameter, m
d_{bf} : equivalent diameter of a base fluid molecule, m
d_p : diameter of the nanoparticle, m
F : *LMTD* correction factor, m
h : heat transfer coefficient, W/m^2 K

k : thermal conductivity, W/m K
L : tube length, m
$LMTD$: logarithm mean temperature difference
M : molecular weight of base fluid, kg mol^{-1}
$\dot{m}$: mass flow rate, kg/s
N_{CL} : number of tubes in the central row
Nu : Nusselt number
NTU : number of heat transfer units
N : number of tubes or number of tubes per shell
n : number of tube passes
Δp : pressure drop, Pa
Pe_d : Peclet number
Pr : Prandtl number
PP : pumping power, W
P_t : tube layout pitch, m
q : heat flow, W
Re : Reynolds number
Rf : fouling resistance, m^2K/W
T : temperature, °C
T_w : mean temperature of wall tube, °C
T_{fr} : freezing point of the base fluid, °C
U : total heat transfer coefficient, W/m^2K

$\dot{V}_{nf}$: volumetric nanofluid flow rate, m^3/s

Greek letters

ρ : density, kg/m^3
ϕ : volume concentration
μ : viscosity, kg/ms
α : thermal diffusivity, m^2/s
ε : heat exchanger effectiveness

Subscripts

ave : average
bf : base fluid
h : hot n-hexane
nf : nanofluid
p : particles
w : wall tube
wnf : nanofluid viscosity at the wall temperature

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