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Performance of an agitated helical coil heat exchanger using Al_2O_3/water nanofluid

T. Srinivas, A. Venu Vinod *

Department of Chemical Engineering, National Institute of Technology, Warangal 506004, India

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ABSTRACT

The performance of an agitated helical coil heat exchanger using Al_2O_3/water nanofluid has been evaluated in terms of the energy consumed to heat another fluid. The comparison has been made when nanofluid and base fluid (water) are used as heating medium. The studies have been carried out using Al_2O_3/water nanofluid of different concentrations, flow rates, stirrer speeds and shell-side fluid (heating medium) temperatures. It has been observed that, energy savings are more in laminar and turbulent conditions of flow than transition regime, and percentage savings increase with increase in nanoparticle concentration. Higher stirrer speed and shell-side fluid temperature also resulted in more energy savings. In addition, use of nanofluid resulted in heating the coil-side fluid (water) to higher outlet temperature. Maximum energy savings of 10.65% have been obtained in the presentstudy.

1. Introduction

In chemical industries heat is removed from one fluid and transferred to another fluid in heat exchangers. Heating or cooling enhancement results in energy savings and increases the efficiency of the process. Heat transfer can be enhanced by employing various techniques and methodologies, such as increasing either the heat transfer surface or the heat transfer coefficient between the fluid and the surface that allow high heat transfer rates in a small volume e.g. helical coil heat exchangers [1–3]. In the recent years heat transfer intensification has been reported due to the use of nanofluids [4–6]. Fluids with nanoparticles suspended in them are called nanofluids. The addition of nano-sized solid metal (Cu, Au, Fe) or metal oxide (CuO, Al_2O_3, TiO_2) particles to the base fluids shows an increment in the thermal conductivity of resultant fluids [7–12].

Heat transfer studies involving nanofluids in different types of heat exchangers have been reported. Kumar et al. [13] carried out experiments on shell and helically coiled heat exchanger using nonmetallic Sisal nanofluids of 0.1–0.5% volume concentration and reported that the overall heat transfer coefficient increases with Reynolds number. In a theoretical study, Akbarinia [14] examined the simultaneous effects of buoyancy force, centrifugal force and volume fraction of Al_2O_3 nanoparticles in the base fluid on heat transfer augmentation using nanofluids in horizontal curved tubes. It was reported that the nanoparticle volume concentration does not affect the secondary flow, axial velocity and skin friction factor. Duangthongsuk and Wongwises [15,16] investigatedthe forced convective heat transfer and flow characteristics of a nanofluid consisting of water and 0.2% volume TiO_2 nanoparticles in a double tube counter flow heat exchanger. The results showed that the convective heat transfer coefficient of nanofluid is higher than that of the base liquid by about 6–11%. Farajollahi et al. [17] investigated on the heat transfer characteristics of γ-Al_2O_3/water and TiO_2/water nanofluids for turbulent flow in a horizontal stainless steel shell and tube heat exchanger. The results for both nanofluids indicate that the heat transfer characteristics of nanofluids improve with Peclet number significantly. Mahrood et al. [18] reported that increasing the nanoparticle concentrations of Al_2O_3 and TiO_2 nanofluids above 1.0% and 0.5%volume respectively deteriorates the natural convection heat transfer of non-Newtonian nanofluids. They found that both nanofluids have an optimum nanoparticle concentration at which the heat transfer enhancement passes through a maximum. The optimum concentrations of Al_2O_3 and TiO_2 nanofluids were about 0.2% and 0.1% volume respectively.

Firouzfar et al. [19] have investigated a methanol/silver nanofluid filled thermosyphon heat exchanger and compared the effectiveness as well as energy saving with pure methanol. They reported that using methanol/silver nanofluid, leads to energy saving around 8.8–31.5% for cooling and 18–100% for reheating the supply air stream in an air conditioning system.

Hashemi and Behabadi [20] have studied the heat transfer and pressure drop characteristics of nanofluid flow inside horizontal helical tube under constant heat flux. Kannadasan et al. [21] reported the comparison of heat transfer and pressure drop

* Corresponding author. Tel.: +91 870 2462621.
E-mail address: avv@nitw.ac.in (A. Venu Vinod).

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Nomenclature

d	diameter (mm)
De	Dean number = Re $(d_i/2R_c)^{0.5}$
E	energy consumption in kW h
R_c	curvature radius of coil (mm)
Re	Reynolds number = $d_i v\rho/\mu$
v	velocity (m s^{-1})

Greek symbols

μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

i	inner
w	water
n	nanofluid

characteristics of CuO/water nanofluids in a helically coiled heat exchanger held in horizontal and vertical positions. Their experimental results showed that there is no much difference between horizontal and vertical arrangements in the enhancement of convective heat transfer coefficient and friction factors of nanofluids compared to water. Behabadi et al. [22] investigated heat transfer using Multi-Walled Carbon Nanotubes (MWCNT) dispersed in heat transfer oil flow in a vertical helical coil. Their experimental investigations showed that nanofluid flows showed much higher Nusselt numbers compared to the base fluid flow.

Corcione et al. [23] have reported reduction in pumping power when nanoparticle suspensions were used as heat transfer fluids. They further reported that optimal particle loading leads to reduction in the operating cost.

Most of the studies have focused on enhancement in heat transfer under different experimental conditions. Very few have reported on the energy savings due to the use of nanofluids. Though there have been studies on helical coil heat exchangers, there have not been any reports of agitated helical coil heat exchangers. This paper presents energy savings when Al_2O_3/water nanofluid is used as a heating medium in an agitated helical coil heat exchanger at different concentrations of nanopowder and other experimental conditions.

2. Materials and methods

2.1. Experimental setup

The schematic diagram of the experimental set-up is shown in Fig. 1. Helical coil is made of copper tube and is 6 m long. The number of turns in the coil is 10. The coil tube has 0.00982 m (9.82 mm) inner diameter and 0.01262 m (12.62 mm) outer diameter. The pitch circle diameter (PCD) of the coil is 0.165 m (165 mm) and tube pitch is 0.0325 m (32.5 mm). The pitch is the distance between the centerline of the tube coil for two subsequent turns. A cylindrical shell made of stainless steel is used to house the coil. The shell is 0.42 m (420 mm) in height and 0.275 m (275 mm) in diameter. Two 3 kW electrical heaters are used to heat the shell-side liquid. Shell side temperature is maintained constant using a temperature controller. The shell is insulated with glass wool. Temperature measurements are made using PT-100 type RTD sensor. Five sensors are placed at equally spaced locations along the coil length to measure the coil-side fluid temperature. Stirrer is used to (i) transfer heat from the shell-side fluid to the coil-side fluid (water) and (ii) maintain the uniform temperature in the shell. The stirrer is axial turbine type stirrer (Make: Remi Laboratory Instruments, model: RQ-121/D). The details of the stirrer and its location in the exchanger are shown in Fig. 2. The speed of the stirrer can be set at required value using a controller. Water from feed tank is pumped through the coil using a centrifugal pump. Feed water temperature in all the runs has been maintained constant at 27 °C. Flow rate of the waterthrough the coil is measured using rotameter (range: 0.5–5 lpm; made of glass, SS-316 float, accuracy ±2%, Make: CVG Technocrafts India). The set-up is provided with a data acquisition system (accuracy: 0.3%; make: Ace Instruments, www.aceinstrumentshyd.com, model: Al-800D) with a capacity of 8 analog input channels to record all temperatures (inlet and outlet temperatures of water, shell-side fluid temperature). Energy is consumed to maintain steady-state conditions in the experiment. As water flows through the coil, heat is transferred from the shell-side fluid to water in the coil. The controller maintains the shell-side fluid temperature (by switching on/off the heaters when the shell-side fluid temperatures decreases/increases from the set point temperature). The energy consumed in a particular period in maintaining the steady-state conditions is recorded by an energy meter (Shenzhen Star Instruments Co. Ltd., China; Model: DDS26D, single phase).

2.2. Preparation of nanofluid

Al_2O_3/water nanofluid (particle size 20–30 nm; Sisco Research Laboratories Pvt. Ltd. India) of required particle concentration is prepared by dispersing the nanopowder in ultrapure water (Millipore). The SEM image of the nanopowder is shown in Fig. 3. The nanofluid is subjected to ultrasonic pulses using an Ultrasonicator (Hielscher, UP200H; 200 W, 24 kHz) for 3 h to get the uniform dispersion and stable suspension. The nanofluid with Al_2O_3 nanoparticles of concentrations 0.15%, 0.3%, 0.45%, 0.6% and 0.75% by weight are prepared.

2.3. Experimental process

I. The shell is filled with ultrapure water.
II. Stirrer (axial turbine) is switched on and the speed is set at a particular value (500, 1000 and 1500 rpm).
III. Heaters are switched on to heat the shell side fluid to required temperature (40, 45 and 50 °C).
IV. Centrifugal pump is switched on and the flow rate of water through the helical coil is set at 0.5 lpm using rotameter.
V. Shell side temperature is maintained constant using temperature controller and the experiment is allowed to run in steady state (as indicated by constant shell-side fluid temperature).
VI. At steady state, energy consumed in a given time period is noted.
VII. The flow rate of the water through the coil is increased to 1 lpm and steps (v) and (vi) are repeated.
VIII. The procedure is repeated up to 5 lpm in the increments of 0.5 lpm.
IX. Now the steps from (ii) to (viii) are repeated with nanofluid of different concentrations on shell-side.
X. The experiment is repeated for other stirrer speeds and shell-side fluid temperatures.

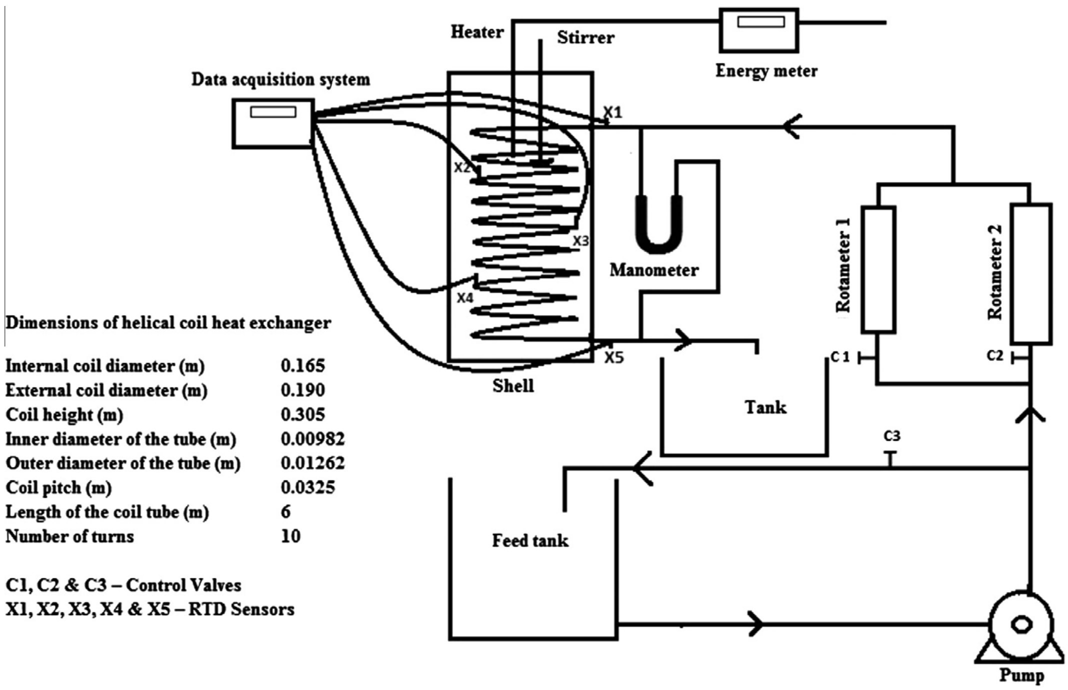

Fig. 1. Schematic diagram of the experimental set-up.

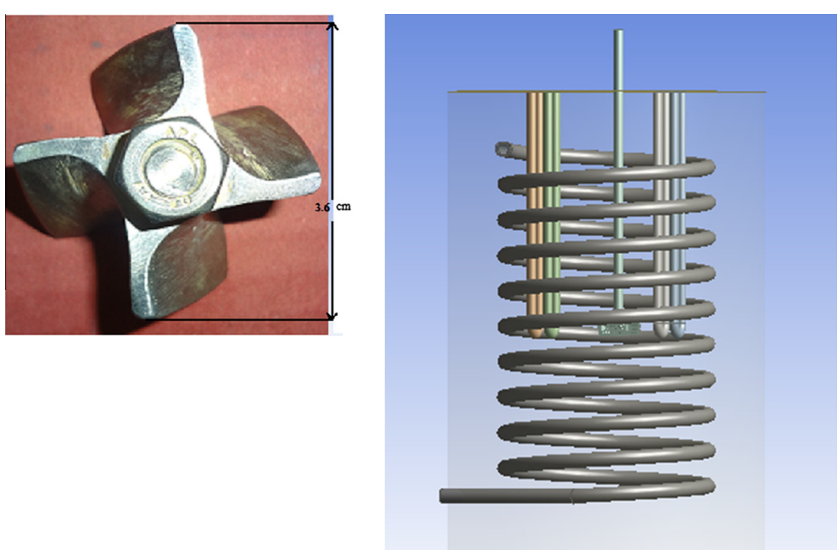

Fig. 2. Stirrer details and its location in shell.

2.4. Experimental studies

The effect of the following on energy consumed has been studied

(1) Effect of concentration of Al_2O_3 nanoparticles in nanofluid (0.15 wt.%, 0.3 wt.%, 0.45 wt.%, 0.6 wt.% and 0.75 wt.%).
(2) Effect of coil-side fluid flow rate.
(3) Effect of stirrer speed (500, 1000 and 1500 rpm).
(4) Effect of shell side temperature (40, 45 and 50 °C).

2.5. Energy consumption

To heat the fluid to a given temperature, nanofluid consumes less energy when compared to the base fluid (water). This is because of the fact that the nanopowder material (in the present study Al_2O_3) has less specific heat (c_p) compared to water (standard values of c_p of Al_2O_3 and water, at room temperature are 0.775 kJ/kg K and 4.2 kJ/kg K respectively [24,25]). The nanofluid which is a mixture of nanopowder and water has specific heat less than that of water [26,27], and therefore the nanofluid consumes

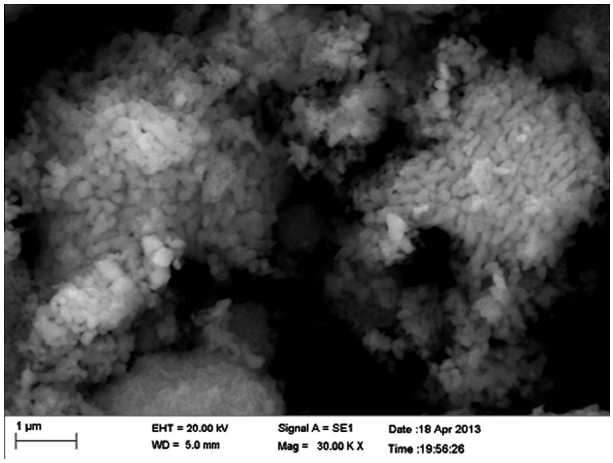

Fig. 3. SEM image of the Al_2O_3 nanoparticles.

less energy compared to pure water, when heated to a given temperature.

The same was observed in the present study. The resultant energy savings percentage is calculated from the following equations,

$$\begin{aligned}&(\text{Energy savings under steady state condition in 10 min}, \Delta E)\\&= (\text{Energy consumed when base fluid (water) is used on shell-side}, E_w)\\&\quad - (\text{Energy consumed when nanofluid is used on shell-side}, E_n) \end{aligned} \quad (1)$$

$$(\text{Energy savings percentage}) = \frac{(E_w - E_n)}{E_w} \times 100 \quad (2)$$

2.6. Dean number

It is a well-known fact that the flow through helical coil is characterized by Dean number. In the present study Dean number is calculated using the following equation:

$$De = \text{Re}(d_i/2R_c)^{0.5}$$

$$\text{Re} = d_i v \rho / \mu$$

where d_i is inner diameter, R_c is curvature radius of the coil and v velocity of the fluid through the coil. Viscosity (μ) and density (ρ) of the fluid have been evaluated at the average of inlet and outlet temperatures of the coil-side fluid. In the present study laminar flow is obtained for flow range 0.5–2.5 lpm ($340 < De < 1900$) and turbulent flow for 3–5 lpm ($2100 < De < 3500$).

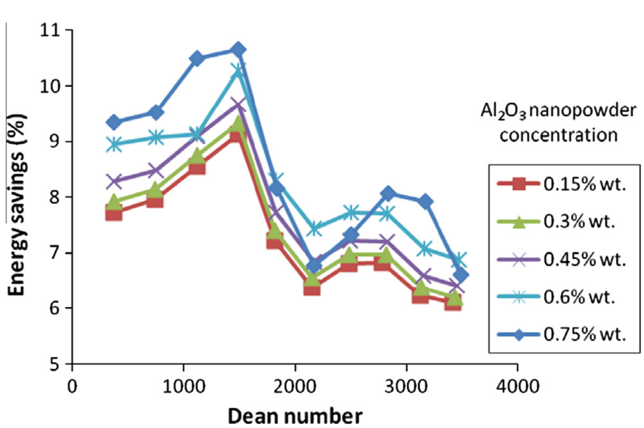

Fig. 4. Effect of nanopowder concentration on percentage energy savings (stirrer speed = 1500 rpm, shell-side fluid temperature = 50 °C).

2.7. Uncertainty analysis

Uncertainty analysis of the experimental data was carried out. Physical properties of water (coil-side fluid) were taken from the standard data [28]. Data of temperature and Dean number (dependent on velocity of water, an experimental value) were analyzed for relative uncertainty, and the values of relative uncertainty were found to be within 3%. For energy saving, the values of relative uncertainty were found to be within 4%.

3. Results and discussion

The effects of concentration of Al_2O_3 nanopowder, stirrer speed, shell-side fluid temperature and coil-side fluid flow rate on the performance of the heat exchanger have been investigated. The performance has been evaluated, under steady state conditions (constant shell-side fluid temperature and feed water temperature), in terms of (i) the energy consumed and (ii) higher water outlet temperature. Less energy was consumed when nanofluid was used on the shell-side, instead of water. The percentage savings in the energy, calculated using Eq. (2), are shown in Figs. 4–13. Figs. 4–6 show the effect of water flow rate at different nanoparticle concentrations. During laminar flow (<2.5 lpm, $De \leqslant 1900$), the percentage energy savings increase with flow rate. During transition regime (2.5–3 lpm, $1900 < De < 2100$) the

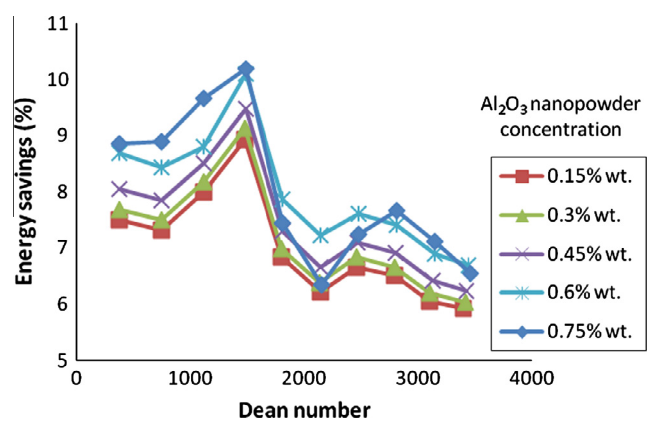

Fig. 5. Effect of nanopowder concentration on percentage energy savings (stirrer speed = 1000 rpm, shell-side fluid temperature = 50 °C).

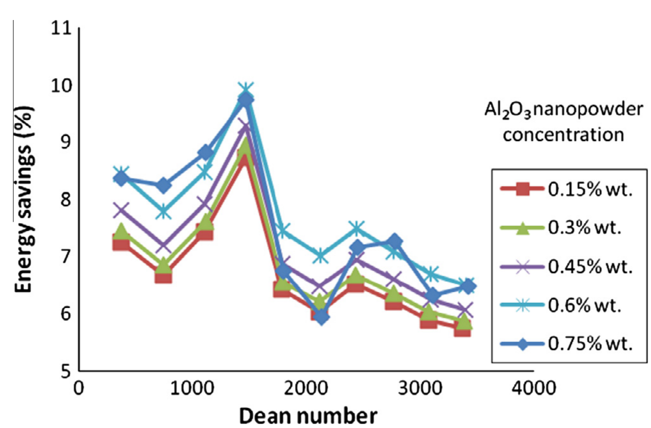

Fig. 6. Effect of nanopowder concentration on percentage energy savings (stirrer speed = 500 rpm, shell-side fluid temperature = 50 °C).

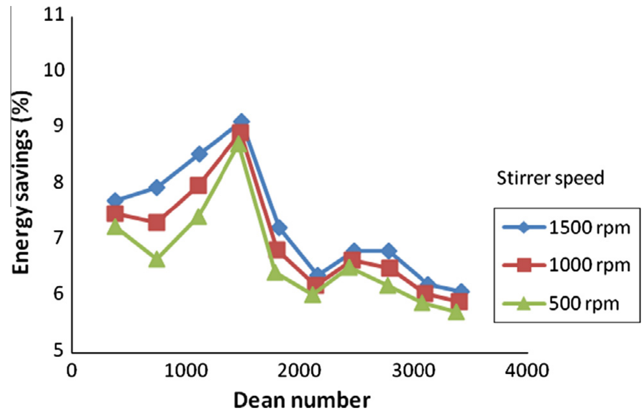

Fig. 7. Effect of stirrer speed on percentage energy savings (0.15 wt.% of Al_2O_3 nanopowder, shell-side fluid temperature = 50 °C).

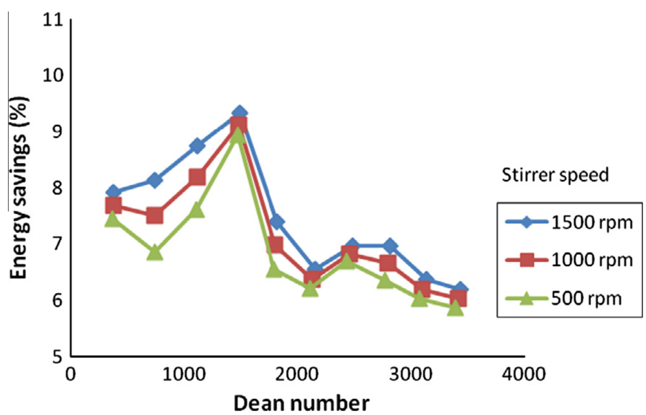

Fig. 8. Effect of stirrer speed on percentage energy savings (0.3 wt.% of Al_2O_3 nanopowder, shell-side fluid temperature = 50 °C).

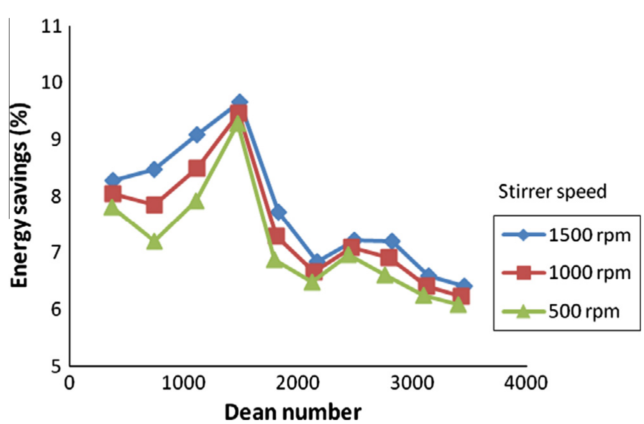

Fig. 9. Effect of stirrer speed on percentage energy savings (0.45 wt.% of Al_2O_3 nanopowder, shell-side fluid temperature = 50 °C).

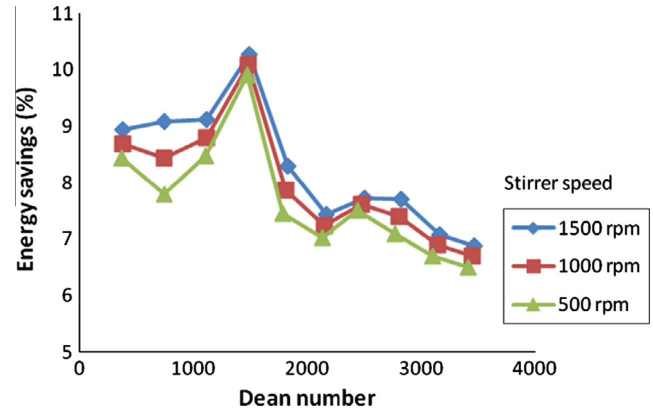

Fig. 10. Effect of stirrer speed on percentage energy savings (0.6 wt.% of Al_2O_3 nanopowder, shell-side fluid temperature = 50 °C).

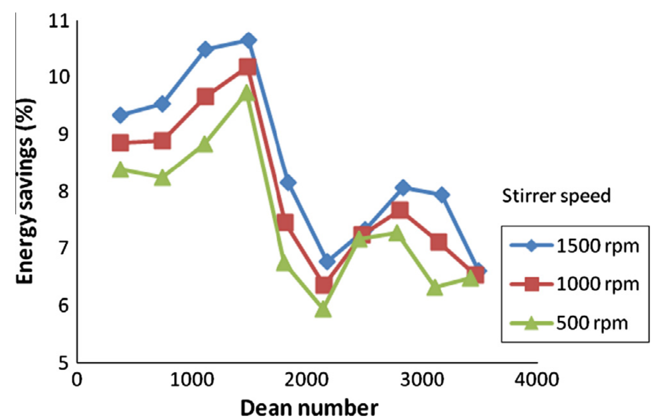

Fig. 11. Effect of stirrer speed on percentage energy savings (0.75 wt.% of Al_2O_3 nanopowder, shell-side fluid temperature = 50 °C).

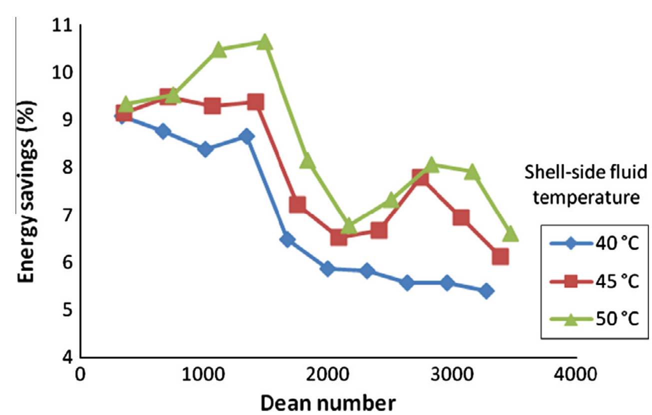

Fig. 12. Effect of shell-side fluid temperature on percentage energy savings (0.75 wt.% of Al_2O_3 nanopowder, stirrer speed = 1500 rpm).

percentage energy savings are reduced. It is a well-known fact that the heat transfer during transition regime is poor compared to laminar and turbulent regimes [28,29]. For a given nanofluid concentration, percentage savings are found to be more for laminar flow compared to turbulent flow (though actual savingsare of the same order in laminar and turbulent flows). Percentage energy savings increase with increase in nanoparticle concentration. A similar trend is observed in Figs. 7–11 for different stirrer speeds. At higher stirrer speeds more savings are observed. As the shell-side fluid temperature increases the percentage energy savings increase. Nanoparticle concentration has more significant effect on energy savings than stirrer speed and shell-side (nanofluid) temperature. This is shown in Figs. 12–14. In the range of conditions for the present study energy savings were found to be in the range of 2.23–10.65%. Highest savings of 10.65% have been observed corresponding to nanopowder concentration of 0.75 wt.%, flow rate of 2 lpm, stirrer speed of 1500 rpm,and shell-side fluid temperature of 50 °C.

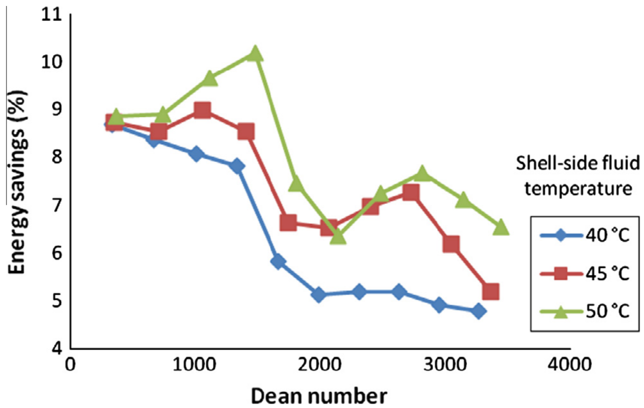

Fig. 13. Effect of shell-side fluid temperature on percentage energy savings (0.75 wt.% of Al_2O_3 nanopowder, stirrer speed = 1000 rpm).

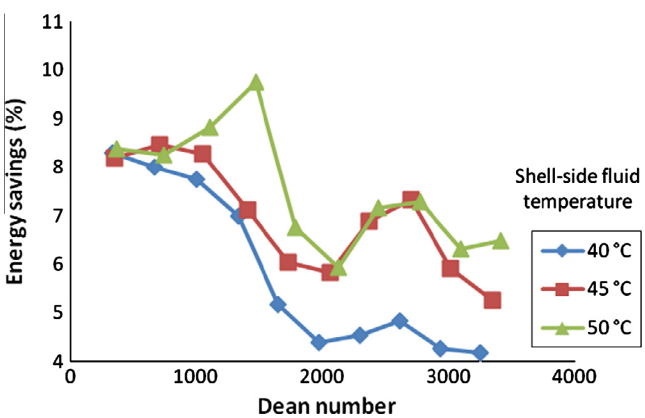

Fig. 14. Effect of shell-side fluid temperature on percentage energy savings (0.75 wt.% of Al_2O_3 nanopowder, stirrer speed = 500 rpm).

Table 1
Increase in coil-side fluid outlet temperature (nanofluid temperature 50 °C).

Coil-side fluid (water) flow rate (lpm)	Increase in coil-side fluid outlet temperature (°C) (1500 rpm) Nanofluid concentration				
	0.15 wt.%	0.3 wt.%	0.45 wt.%	0.6 wt.%	0.75 wt.%
0.5	0.1	0.1	0.1	0.1	0.1
1	0.2	0.5	0.5	0.6	0.8
1.5	0.2	0.6	0.6	0.6	0.8
2	0.6	0.7	0.7	0.8	0.9
2.5	0.7	0.7	1.0	1.1	1.3
3	0.7	0.7	1.2	1.2	1.4
3.5	0.7	0.7	1.2	1.3	1.4
4	0.9	1.2	1.3	1.5	1.6
4.5	0.9	1.2	1.7	1.9	2.0
5	0.9	1.2	1.5	1.7	2.3

3.1. Higher outlet temperature

For given conditions, use of nanofluid also resulted in higher outlet temperature of the coil-side fluid. The increase is in the outlet temperature varied between 0 and 2.3 °C. For lowest flow rate 0.5 lpm and lowest concentration 0.15% no increase in outlet temperature of the coil-side fluid was observed. But at higher the flow rates and higher concentrations of nanopowder, the increase is more. Corresponding to flow rate of 5 lpm and 0.75 wt.% nanopowder concentration highest increase of 2.3 °C is observed. This higher outlet temperature (Table 1) is an additional benefit, to the energy savings reported above.

4. Conclusions

In this work, the performance of in an agitated helical coil heat exchanger has been evaluated experimentally, in terms of energy savings when Al_2O_3/water nanofluid is used as heating medium. Less energy was consumed when nanofluid was used as the heating fluid compared to water. Increasing the concentration of nanopowder in the base fluid resulted in more energy savings. Further, higher stirrer speed and shell-side temperature also resulted in more energy savings. As the flow rate was increased, energy savings were found to increase during laminar and turbulent flow regimes. However, during transition flow regime the energy savings were comparatively less.

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