Intensification of Natural Convection using non-Newtonian Nanofluids in Unsteady State Condition

B. Anil Kumar Naik and A. Venu Vinod*

Department of Chemical Engineering,
National Institute of Technology-Warangal, Warangal-506004, Telangana, India
* Corresponding author: *avv122@yahoo.com*

ABSTRACT

Nanofluids have gained much attention due to excellent thermal properties. In this study, natural convection heat transfer behavior of three different types of non-Newtonian nanofluids in a shell and helical coil heat exchanger has been investigated experimentally under unsteady state conditions. Nanofluids were prepared by dispersion of Al_2O_3, Fe_2O_3 and CuO nanoparticles in an aqueous solution of carboxymethyl cellulose (CMC) (base fluid). Nanofluids of different concentrations (0.2, 0.4, 0.6, 0.8 and 1.0 wt%) were prepared by dispersing Al_2O_3, Fe_2O_3 and CuO nanoparticles in base fluid using probe sonication process. In the present study, the effect of shell-side nanofluid concentration, tube-side fluid (heating medium) temperature and flow rate parameters on heat transfer has been investigated.

Results indicated that the addition of nanofluid has intensified heat transfer as indicated by the higher temperature of nanofluid when compared to base fluid. Out of the three materials used in the study, CuO nanofluid attained the highest temperature because of its higher thermal conductivity. Heat transfer rate decreased with time continuously for all the experimental conditions. Enhancement in heat transfer initially was higher compared to later times. A maximum enhancement in heat transfer rate of 23% has been obtained initially. At longer time the enhancement is less due to the lower buoyancy forces prevailing due to lower driving force. The effect of nanofluid concentration on heat transfer rate with time exhibited different behavior compared to the effect of inlet temperature and flow rate.

Keywords: natural convection; helical coil; heat exchanger; nanofluid; non-Newtonian; unsteady state.

1. INTRODUCTION

The current trend toward component miniaturization or intensification by enabling the design of compact, smaller and lighter heat exchanger systems can be realised by employing nanofluids. Modification of the geometry of the heat exchangers is one more technique of enhancing heat transfer. Helical coils promote heat transfer because of the secondary flow through the coil tube, compared to a straight tube. Helically coiled tube heat exchangers are effective as heat transfer equipment due to their compactness and increased heat transfer coefficients in comparison with straight tube heat exchangers [1]. Helical coils are used in various fields of applications such as air conditioning, nuclear power, refrigeration, and chemical engineering for heat exchange [2]. Helical coil heat exchanger has received significant attention in heat transfer intensification using various types of nanofluids [2,3–8].

Putra et al. [9] reported natural convection heat transfer with Al_2O_3 /water and CuO/water nanofluids inside a horizontal cylinder. They found that natural convective heat transfer was more pronounced for the water–CuO nanofluids compared to the water–Al_2O_3 nanofluid and also their results show that unlike forced convection a definite deterioration in natural convective heat transfer occurs which was dependent on the particle density, concentration, and the aspect ratio of the cylinder. Eiyad Abu-Nada [10] investigated effects of variable viscosity and thermal conductivity of Al_2O_3–water nanofluid on heat transfer enhancement in horizontal annuli in natural convection. Different viscosity and thermal conductivity models were used to evaluate heat transfer enhancement in the annulus. Abu-Nada et al. [11] examined the effects of using different models for thermal conductivity, viscosity and aspect ratio on the natural convection of two nanofluids (Al_2O_3 / water and CuO / water) in a rectangular cavity. They found that for Al_2O_3/water nanofluids, the average Nusselt number is maximized at high Rayleigh numbers when the nanofluid concentration reaches 5% while particle loading at low Rayleigh numbers leads to a little increase in Nusselt number. For CuO / water nanofluid, adding nanoparticles to the base fluid results in a decrease of Nusselt number at high Rayleigh numbers whereas at low Rayleigh numbers the changes in concentration have no visible effect on the Nusselt number. Numerical simulations related to natural convection heat transfer were conducted by different investigators considering Newtonian nanofluids [3,5–7] and non-Newtonian nanofluids [12–17].

Although heat transfer studies involving nanofluids has received significant attention, the literature is scarce on natural convection studies and non-Newtonian fluids. Further, no study could be found in literature on unsteady state heat transfer involving nanofluids. Experiments were carried out using non-Newtonian nanofluids in a shell and helical coil heat exchanger in unsteady state conditions and natural convection. 0.5 wt% CMC-based Fe_2O_3, $Al_2O_3$and CuO nanofluids and hot water have been used as the shell-side fluid (cold fluid) and the coil-side fluid respectively.

2 MATERIALS AND METHODS

2.1 Preparation of nanofluids

In this study, 0.5 wt% CMC based - Fe_2O_3, Al_2O_3 and CuO non-Newtonian nanofluids were used. The complete details of preparation methodology, measurements of viscosity and thermal conductivity of non-Newtonian nanofluids were reported in our previous study [18].

2.2 Experiment Setup

Fig. 1 shows the schematic diagram of the shell and helical coil heat exchanger set-up. The setup consists of a shell, helical coil tube, heaters, rotameter, data acquisition system and pumps. The dimensions of the shell and helical coil tubes are given in Fig. 1.

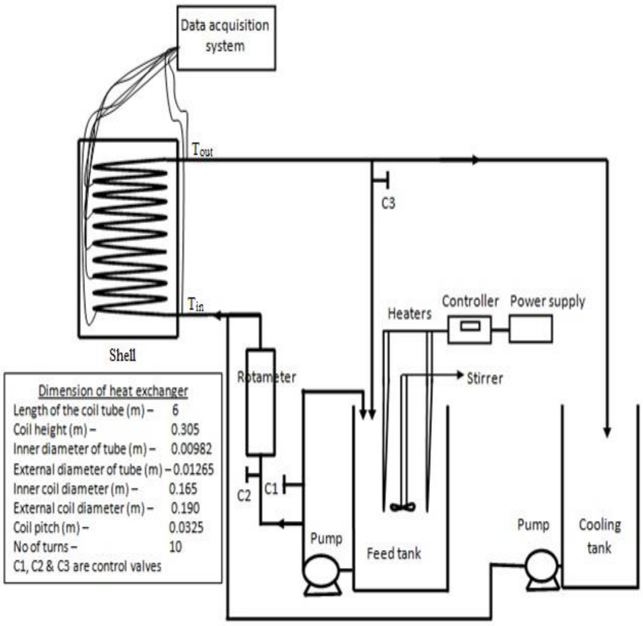

Fig. 1. Schematic diagram of the experimental setup.

The shell is made of steel (SS304) and is insulated with glass wool. Two 3 kW electrical heaters, controller and stirrer were used to maintain the required temperature of the feed water (hot fluid). PT-100 type RTD sensors were used to measure the temperature of inlet and outlet temperature of the hot fluid, shell-side fluid temperature, coil surface (at five equi-spaced locations along the length). All RTD sensors are connected to data acquisition system (make: ACE Instruments, model: AI-800D, 0.1ºC resolution) to record all temperature measurements. A rotameter (flow range 0.5 to 6 lpm) was used to measure the flow rate of hot water through the coil.

2.3 Experimental procedure

In natural convection, the cold fluid (base fluid / nanofluid) is placed on theshell side. Hot fluid (water) is pumped through the coil. Heat transfer occurs by natural convection from the coil to the fluid on the shell side. The experimental procedure is as follows:

i. The shell is initially filled with 0.5 wt% CMC base fluid and the initial temperature is set to at 25ºC. Feed tank (water; hot fluid) temperature is maintained constant 40ºC.
ii. Pump is switched on and the flow rate of hot fluid through the helical coil is set at 1 lpm using rotameter and the experiment is allowed to run for 90 minutes.
iii. The outlet temperature of the coil-side fluid (water) and temperature at the two different locations of the shell side fluid were recorded continuously using data acquisition system.
iv. Heat transfer occurs by natural convection from the coil surface to the shell-side fluid. Further the heat transfer occurs under unsteady state conditions as the shell-side fluid is continuously heated by the coil-side fluid and there is no provision for heat removal. After 90 minutes of operation the experiment was stopped.
v. Steps (i) to (iv) were repeated in the increments of 1 lpm till coil-side flow rate reached 5 lpm.
vi. The experiments were repeated for feed water temperatures 50 and 60ºC.
vii. The procedure was then repeated with non-Newtonian nanofluids (CMC-based Fe_2O_3, $Al_2O_3$and CuO) as the shell-side fluid for 0.2, 0.4, 0.6, 0.8 and 1.0wt% concentrations.

2.4 Data reduction

Heat transfer occurs from the hot fluid (coil-side, hot water) to the cold fluid (shell-side; initially base fluid, subsequently nanofluid). Heat transfer occurs under natural convection due to buoyancy forces generated due to the temperature difference between the coil surface and shell-side fluid. Heat transfer rate (Q) to the shell-side fluid was calculatedfrom temperature rise $\left(T_{s,m} - T_{s,o}\right)$as the heat gained by it in time t since the beginning of the experiment, using the following equation:

$$Q = mc_{p,nf}\left(T_{s,m} - T_{s,o}\right)/t \tag{1}$$

Where m and $c_{p,nf}$ are the mass and specific heat of shell-side fluid respectively. $T_{s,m}$ and $T_{s,o}$ are the average shell-side mean temperature (average of temperatures of two RTD sensors in the shell) and shell-side fluid initial temperature. The properties of the nanofluid were determined using the following models.

Density:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \tag{2}$$

Specific heat:

$$\rho C_{p\,nf} = (1-\phi)\left(\rho C_p\right)_{bf} + \phi\left(\rho C_p\right)_{np} \tag{3}$$

where ϕ is volume fraction of nanoparticles, subscripts *nf, bf* and *np* refer to nanofluid, base fluid and nanoparticle respectively.

3. RESULTS AND DISCUSSION

The base fluid and nanofluids used in the present study exhibited non-Newtonian (shear thinning – pseudoplastic) behavior. Rheological behavior and thermal conductivity of the nanofluids used in the present study were reported previously [18].

Heat transfer enhancement studies were carried out with base fluid followed by nanofluids as shell-side fluid. Heat transfer by natural convection occurred from hot surface of coil tube to the stationary nanofluid in the shell. The shell-side fluid temperature rises continuously with time due to the unsteady state conditions prevailing in the system (no heat is removed from the shell-side).

3.1 Effect of nanofluid concentration on heat transfer rate

Heat gained by the shell-side fluid was calculated using equation (1). Fig.2 shows the effect of CuO nanofluid concentration on heat transfer rate to the shell-side fluid as a function of time. It can be observed from the figure that the use of nanofluid has resulted in intensification of heat transfer as indicated by the increased heat transfer rates compared to base fluid. For small times (< 15 minutes) the enhancement in heat transfer is more and the same can be clearly observed from the figure. At longer times, the enhancement is relatively less due to the smaller driving force between the coil-side and shell-side fluid. Initial enhancement in heat transfer rate was in the range of 14 – 23 % for nanofluid compared to that of base fluid. Subsequently it decreases with time.

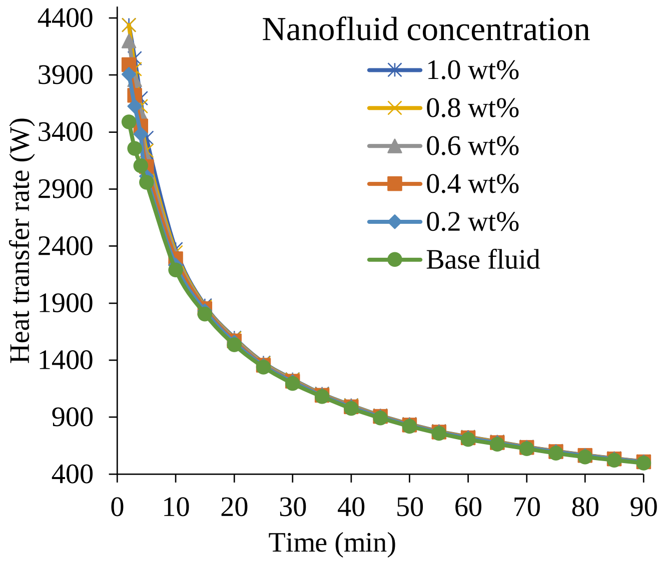

Fig. 2. Effect of CuO nanoparticle concentration on the heat transfer rate
(water inlet temperature = 60°C and flow rate = 5 lpm)

3.2 Effect of water inlet temperature

Fig. 3 shows the effect of water inlet temperature on the heat transfer rate number respectively for 1 wt% Al_2O_3 nanofluid at 5 lpm. Form Fig. 3 it can be observed that the heat transfer rate decreases with time due to the effect of decreasing driving force with the time. When the water inlet temperature is higher the heat transfer rate is higher due to greater driving force. The figure also shows the results for base fluid. The enhancement in heat transfer rate can be noticed for nanofluid over base fluid. The enhancement decreases with time.

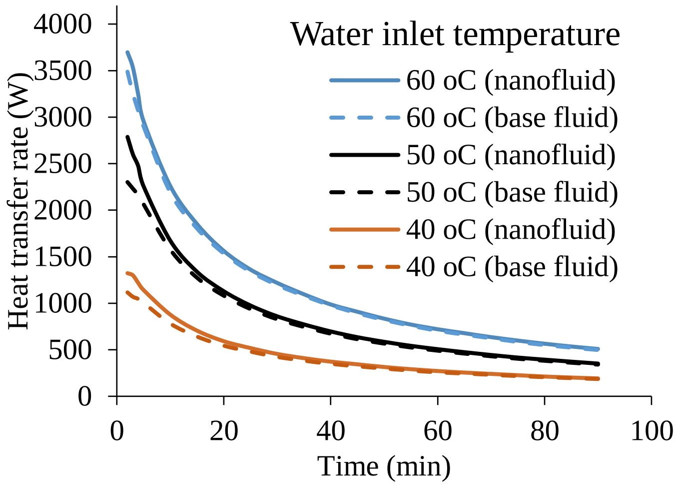

Fig. 3. Effect of water inlet temperature on the heat transfer rate.
(1.0 wt% Al_2O_3 nanofluid, flow rate = 5 lpm).

3.3 Effect of flow rate of water through coil-side

The effect of water flow rate through the coil tube on heat transfer was carried out at 1 – 5 lpm for base fluid (CMC solution and nanofluids). Fig. 4 shows the effect of water flow rate on heat transfer rate for 1 wt% Fe_2O_3 nanofluid for water inlet temperature of 60ºC. At higher flow rates the shell-side fluid temperature is higher, indicating the effect of forced convection through the coil tube though heat transfer from the coil surface is by natural convection. The difference in the shell-side fluid temperatures (for different flow rates) is initially low, increases with time and then decreases as the driving force at large times decreases as the shell-side fluid temperature approaches the water inlet temperature. For low flow rates, the shell-side fluid gets heated slowly, as indicated by the lower temperatures. Heat transfer rate is higher at high water flow rates, and it decreases with time, a trend similar to that shown in Fig. 2 (effect of nanofluid concentration). However, as can be seen from both the figures, the effect of water flow rate on heat transfer rate is more pronounced than that of the nanofluid concentration.

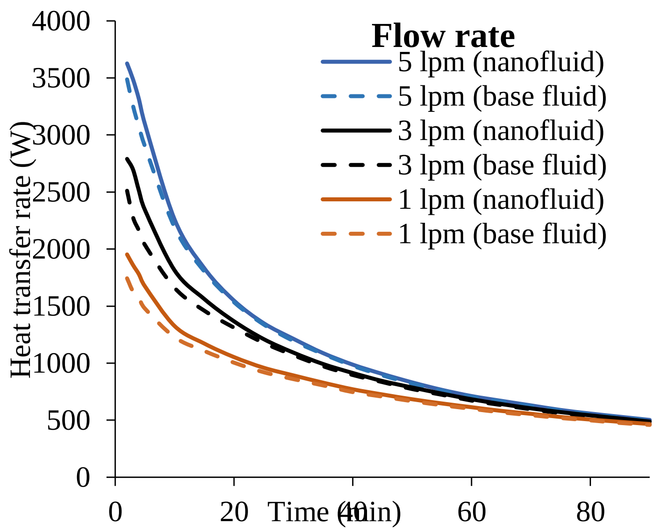

Fig. 4. Effect of flow rate on the heat transfer rate
(1.0 wt% Fe_2O_3 nanofluid, water inlet temperature = 60 ºC).

3.4 Effect of the nanopowder material

Nanofluids prepared from three different metal oxide nanopowders were used in the present study. Fig.5 shows the effect of nanopowder material on heat transfer rate at water inlet temperature of 60ºC and flow rate 5 lpm. At any given time, the heat transfer rate of CuO nanofluid is the highest and that of the basefluid lowest. The behavior follows the trend of the thermal conductivities of the respective materials. From Fig. 5 it can be observed that maximum heat transfer rate enhancement was 8.3%, 18.7% and 29.5 for 1.0 wt% concentration of Fe_2O_3, Al_2O_3 and CuO nanofluid respectively compared to the base fluid.

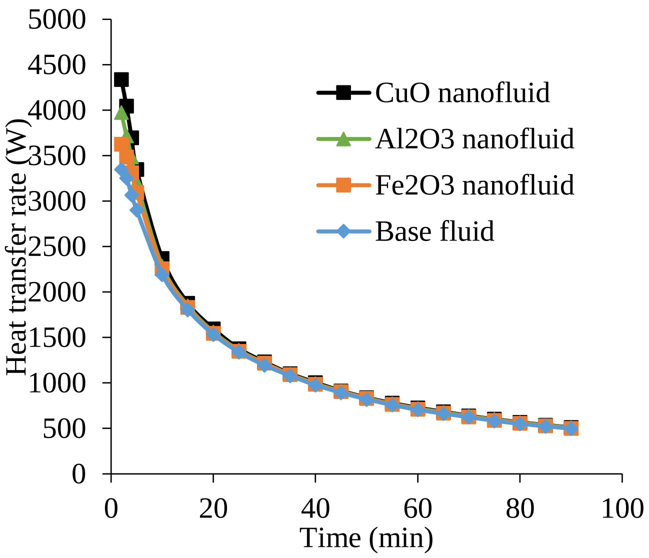

Fig. 5. Effect of nanopowder material on heat transfer rate
(water inlet temperature = 60°C, flow rate = 5 lpm, 1 wt% nanofluid concentration)

Natural convection plays an important role in the heat transfer since the nanoparticles will continuously move in the base fluid due to Brownian motion and thermophoresis (a phenomenon in fluids of mobile particles where the particle exhibit different responses to the force of a temperature gradient).

1. Conclusions

The following conclusions can be drawn from the study:

- The use of nanofluid has resulted in enhancement in heat transfer as indicated by the higher shell-side fluid temperature. The higher the nanofluid concentration, greater is the shell-side fluid temperature.
- CuO nanofluid exhibited performance because of its higher thermal conductivity.
- A maximum enhancement in heat transfer rate of 23% has been obtained initially. At longer time the enhancement is less due to the lower buoyancy forces prevailing due to lower driving force.
- As the water inlet temperature and flow rate increase, increase in heat transfer enhancement can be obtained.

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