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# Heat transfer enhancement using non-Newtonian nanofluids in a shell and helical coil heat exchanger

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## ABSTRACT

The current investigation examines heat transfer using three different non-Newtonian nanofluids comprising of $Fe_2O_3$, $Al_2O_3$ and CuO nanoparticles in aqueous carboxymethyl cellulose (CMC) base fluid. The studies were carried out to determine enhancement in heat transfer compared to base fluid (aqueous CMC solution) in a shell and helical coil heat exchanger. Non-Newtonian nanofluids containing nanoparticles in the concentration range of 0.2–1.0 wt% were prepared. Nanofluid and water were used on shell side and tube side respectively. The thermal analysis was carried out to determine overall heat transfer coefficient and shell-side Nusselt number, at different conditions such as flow rate of cold water (0.5–5 lpm), shell side fluid (nanofluid) temperature (40–60 °C) and stirrer speeds (500–1500 rpm). The results show that the Nusselt number increases with increasing nanofluid concentration, shell side fluid temperature, Dean number (flow rate of coil-side water), and stirrer speeds. It was found that the CuO/CMC-based nanofluid showed better heat transfer than the other two types of fluid ($Fe_2O_3$ and $Al_2O_3$). The heat transfer performance of non-Newtonian nanofluids was significantly enhanced at higher nanofluid concentrations, shell-side temperatures, stirrer speeds and Dean numbers.

## 1. Introduction

Nanofluids are stable suspensions containing particles of less than 100 nm, in conventional base fluids such as water, ethylene glycol, propylene glycol, oil and other liquids. Nanofluid exhibits higher thermal conductivity compared to the base fluids. Higher thermal conductivity of nanofluids results in enhancement in heat transfer rates [1–4]. This intensification of heat transfer can help in meeting the main challenge of designing a compact heat exchanger.

Heat enhancement techniques can be divided into three groups: active, passive and compound techniques. The active techniques require external actions like use of mechanical aids, surface vibrations, fluid vibration, electric field, injection-suction and jet impingement. The passive techniques require special surface geometry or fluid additives (e.g., nanoparticles). In the compound technique, one or more techniques can be used simultaneously. The passive technique generally uses geometrical modifications to the flow channel by incorporating inserts (e.g., fins) or modifying the geometry (e.g., coils). In coiled tubes (e.g., helical coil), the centrifugal force due to the curvature of the tube results in the development of secondary flows which assist in mixing the fluid and enhance the heat transfer. Several studies have mentioned that helical coil tubes are superior to straight tubes when employed in heat transfer applications [5–10].

Helically coiled tubes are effective as heat transfer equipment due to their compactness and increased heat transfer coefficients in comparison with straight tube heat exchangers [5–8,11–13]. Shell and helical coil tube heat exchangers use single channel technology. One fluid (cold/hot fluid) is placed on the shell side and the other fluid (cold/hot fluid) enters through the helical coil tube and moves towards the center. Secondary flow in helical tubes results in higher heat transfer rates compared to a straight tube [14]. Helical coiled tubes for heat transfer have received considerable attention because of its practical importance, and find application much in refrigeration and air conditioning, food and dairy industry, chemical plants, natural gas processing, petrochemical plants, power plants and petroleum refineries [15,16]. Another passive technique for enhanced heat transfer is the addition of nanoparticles to the base fluid to obtain nanofluid which has higher thermal conductivity than the base fluid.

The last decade has seen a spurt in the research activity on heat transfer enhancement studies involving nanofluids. Water has been most widely used as the base fluid in these studies [17–22]. Water-based nanofluids follow Newtonian behavior. However, certain applications such as food industries, chemical industries, polymer, oil industries, biochemical and pharmaceuticals, involve flow of non-Newtonian fluids [16].

The following is an account of investigations reported involving

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**Nomenclature**

| | |
|---|---|
| $Re$ | Reynolds number |
| $d_i$ | inside diameter of tube (m) |
| $d_o$ | outside diameter of tube (m) |
| $d_a$ | diameter of stirrer (m) |
| $v$ | velocity (m/s) |
| $\rho$ | density (kg/m$^3$) |
| $\mu$ | viscosity (kg/m s) |
| $De$ | Dean number |
| $R_c$ | curvature radius of the coil (m) |
| $Q$ | heat transfer rate (W) |
| $m$ | mass flow rate (kg/s) |
| $c_p$ | specific heat of water (J/kg K) |
| $U$ | overall heat transfer coefficient (W/m$^2$ K) |
| $A_o$ | surface area of tube (m$^2$) |
| $T_h$ | shell-side fluid temperature (K) |
| $T_{ci}$ | inlet temperature of water (K) |
| $T_{co}$ | outlet temperature of water (K) |
| $x_w$ | thickness of the coil (m) |
| $k_w$ | thermal conductivity of coil tube (W/m K) |
| $\overline{D_L}$ | logarithmic mean diameter |
| $Pr$ | Prandtl number |
| $Nu$ | Nusselt number |
| $h_i$ | tube-side heat transfer coefficient (W/m$^2$ K) |
| $h_o$ | shell-side heat transfer coefficient (W/m$^2$ K) |

non-Newtonian nanofluids. Ding et al. [23] have experimentally studied aqueous-based nanofluids of carbon nanotubes, titania and titanate, which show the shear thinning (non-Newtonian) behavior. Their results demonstrated that the convective heat transfer coefficient enhancement exceeds, by a large margin, the extent of the thermal conduction enhancement. He et al. [24] have used water based dry Titanate nanotubes (TNT) nanoparticles and Carbon nanotubes (CNT) non-Newtonian nanofluids in a straight pipe. Their results suggest that the non-Newtonian character of nanofluids influences the heat transfer enhancement.

Reza et al. [25] experimentally studied the natural convection heat transfer performance of 0.5 wt% CMC (carboxymethyl cellulose) -based $Al_2O_3$ and $TiO_2$ non-Newtonian nanofluids. Significant enhancements were observed at low particle concentrations. Increasing nanoparticle concentration had a contrary effect on the heat transfer of nanofluids, so at concentrations greater than 1 vol% of nanoparticles the heat transfer coefficient of nanofluids is less than that of the base fluid.

Cheng [26] studied the heat transfer over a truncated cone embedded in a porous medium saturated by a non-Newtonian power-law nanofluid with constant wall temperature and constant wall nanoparticle volume fraction. In this study, the effects of the power-law index, thermophoresis parameter, Brownian motion parameter, Lewis number, and buoyancy ratio on the heat transfer and fluid flow characteristics were studied. Hojjat et al. [27] have carried out heat transfer studies under laminar flow conditions experimentally for three types of CMC-based non-Newtonian nanofluids ($Al_2O_3$, CuO and $TiO_2$) in a circular tube with constant wall temperature. Results showed that the convective heat transfer enhancement was more significant when both the Peclet number and the nanoparticle concentration were increased.

Esmaeilnejad et al. [28] studied the effect of convection heat transfer and laminar flow of nanofluids with non-Newtonian base fluid in a rectangular microchannel. Their experimental results demonstrated significant enhancement of heat transfer particularly in the entrance region, and with increasing the volume fraction of non-Newtonian nanofluids. Li et al. [29] have investigated heat transfer using non-Newtonian nanofluids in a horizontal channel. Water and dilatant fluids were used as working base fluids. The results revealed that nanofluids based on dilatant flow are more sensitive to the heat flux than those based on pseudoplastic fluid.

Job et al. [30] considered unsteady magneto hydrodynamics (MHD) free convection flows of $Al_2O_3$-water and single-walled carbon nanotube (SWCNT)-water nanofluids within a symmetrical wavy trapezoidal enclosure. Their results showed that, for alumina-water nanofluid, the rate of heat transfer decreases through low values of Hartmann number (Ha), but increases through larger values of Ha. In the case of the SWCNT-water nanofluid, the rate of heat transfer increases with increasing Ha.

Tahiri and Mansouri [31] have theoretically investigated the laminar flow convective heat transfer in a circular duct considering $Al_2O_3$ based non-Newtonian nanofluid. Results have clearly revealed that the addition of $Al_2O_3$ nanoparticles has produced a remarkable increase in heat transfer compared to base fluid (pure water). Zhang et al. [32] have reported on surface wetting using functionalized carbon nanotubes (FCNT) for critical heat flux (CHF) enhancement.

Though there have been reports in the literature on heat transfer involving non-Newtonian nanofluids, there has not been any effort in investigating the enhancement in heat transfer considering non-Newtonian nanofluids in a shell and helical coil heat exchanger. To address this gap, in this study CMC-based nanofluids have been used experimentally in a shell and helical coil exchanger. The effect of nanoparticle concentration, nanoparticle material ($Fe_2O_3$, $Al_2O_3$ and CuO), Dean number (cold water flow rate), temperature of nanofluid and stirrer speed on heat transfer and overall heat transfer coefficient have been investigated.

## 2. Material and methods

### 2.1. Preparation of nanofluid

The base fluid required for preparation of nanofluid was prepared by dispersing 0.5 wt% carboxymethyl cellulose (CMC) powder in deionized water. The nanofluid was subsequently prepared from the base fluid by dispersing nanoparticles of the required concentration. A uniform and stable dispersion of nanoparticles in base fluid was obtained by ultrasonication for 2 h (Hielscher, UP200H; 200 W, 24 kHz). As the nanofluid obtained was stable for a period of two weeks no stabilizer (surfactant) was added. Nanofluids containing nanoparticles of $Fe_2O_3$, $Al_2O_3$ and CuO of required particle concentration (0.2, 0.4, 0.6, 0.8 and 1.0 wt%) were prepared separately. Base fluid concentration was maintained at 0.5 wt% uniformly throughout. Table 1 gives the details of the nanoparticles used.

### 2.2. Materials characterization

The crystalline phases of the $Fe_2O_3$, $Al_2O_3$ and CuO nanopowders were determined by X-ray diffraction (XRD) patterns. X-ray diffraction pattern of the dried nanoparticles was recorded by using X-ray diffractometer (Xpert PRO PANalytical, Holland; model: PW3040/80). X-ray diffraction pattern was taken by measuring 2θ values from 10° to 100° with a step size of 0.008356° and step time of 20.32 s. The voltage and current were recorded 45 kV and 30 mA respectively.

**Table 1**
Details of nanoparticles.

| Material | Size (nm) | Make |
|---|---|---|
| $Fe_2O_3$ | 30–60 | Sisco Research Laboratories Pvt. Ltd. India |
| $Al_2O_3$ | 20–30 | Sisco Research Laboratories Pvt. Ltd. India |
| CuO | 40 | Alfa Aesar, England |