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Measurement of Forced Convective Heat Transfer Coefficient of Low Volume Fraction CuO-PVA Nanofluids under Laminar Flow Condition

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Abstract Experimental investigations of forced convective heat transfer coefficient of CuO-PVA nanofluids under uniform and constant heat flux are reported in this paper. Different nanofluid samples at different volume concentrations (0.05, 0.1 & 0.2%) were prepared by dispersing CuO NPs with an average size of 32.50 nm in 4 wt% PVA solution using ultrasonication and magnetic stirring. The forced convective heat transfer coefficient of the CuO-PVA nanofluids was measured with the help of vertical shell-and-tube heat exchanger where spiral circular copper tube was used. All the experiments were performed under laminar conditions ($Re \leq 2300$). The results under laminar flow conditions showed considerable enhancement of convective heat transfer with the use of nanofluids. There was increase in heat transfer coefficient of nanofluids CuO-PVA when compared with their base fluids. The increase is significant even though the concentration is less.

Keywords: *nanofluid, shell-and tube heat exchanger, forced convective heat transfer coefficient*

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1. Introduction

In recent times, nanotechnology has gained much attention for its vital pioneering role in manipulating materials at the atomic and molecular levels to dramatically alter the product properties. Materials reduced to the nanometric scale display significantly different properties compared to what they display at the macroscale or microscales. Because of their unique properties, nanomaterials are widely used in a variety of applications. Small amounts of nanoparticles can play a vital role in developing the properties of materials. Nanoparticles are becoming more and more important day by day as they play a beneficial role in a wide variety of scientific fields. In general, the size of a nanoparticle spans the range between 1 and 60 nm. Nanotechnology comprises the design, construction and utilization of functional structures with at least one characteristic dimension measured in nanometers. Currently nanoparticles are widely using in many fields [1-9].

Heat transfer enhancement is an active and important field of engineering research. Heat transfer fluids play an important role in many industries such as power generation, transportation, and newer electronic systems which have higher thermal requirements. Poor thermal conductivity is the main limitation in the development of energy efficient heat transfer fluids required for modern heat transfer equipment. The enhancement of heating or cooling in an industrial process may create a saving in energy, reduce process time, raise thermal rating and lengthen the working life of equipment. Most of the heat transfer fluids that are used in various applications have low thermal conductivity. Conventional fluids, such as refrigerants, water, engine oil, ethylene glycol, etc. have poor heat transfer performance and therefore high compactness and effectiveness of heat transfer systems are necessary to achieve the required heat transfer [10].

Generally metals, metal oxides and nanotubes are used in the preparation of nanofluids to enhance the thermal conductivity of the nanofluid by increasing conduction and convection coefficients [11,12]. Compared to other metal oxides oxides of copper have high thermal conductivity [13,14]. Copper oxide nanofluid shows reduced weight loss, enhanced thermal stability and thermal conductivity when compared to other fluids [15].

Thermal conductivity of commonly available and economically viable metal oxide nanoparticles is in the range of 10-40 W/m-K which is still two orders of magnitude higher than the thermal conductivity of water [16]. Thus, creating stable dispersions of nanoparticles in base fluids to improve thermal properties and thus heat transfer performance seems a logical approach.

Over the last decade, the use of nanofluids as advanced heat transfer fluids for various heat transfer applications has been a topic of profound research. Nanofluid is a new kind of heat transfer medium, containing nanoparticles (1–100 nm) which are uniformly and stably distributed in a base fluid. These distributed nanoparticles, generally a metal or metal oxide greatly enhance the thermal conductivity of the nanofluid, increases conduction and convection coefficients, allowing for more heat transfer [17,18].

Many researches are carried out to improve the heat transfer rate of base fluids using nano fluids. A number of studies to evaluate the heat transfer behavior of nanofluids have been reported. In the present investigation, we have chosen CuO–PVA nanofluid. Initially, CuO nanoparticles are synthesized through chemical route and characterized by XRD and SEM. Later on, CuO nanofluid is synthesized using 4 wt% PVA with the help of ultrasonicator and magnetic stirrer. This thesis is aimed at measuring the forced convective heat transfer coefficient of low volume fraction CuO-PVA nanofluids under a constant heat flux and laminar flow condition using a vertical shell-and-tube heat exchanger.

2. Experimental

2.1. Sample Preparation and Characterization

In this study CuO-PVA nanofluids were prepared using two-step technique [19]. At first, CuO NPs were prepared via chemical precipitation method by following the procedure applied by Pandey, Vimal, et al. [20]. Then the nanofluids of 0.05 vol.%, 0.1 vol.% and 0.2 vol.% were prepared by dispersing different quantity of CuO nanoparticles in base fluid. 4wt% PVA solution was used as a base fluid in this study. The nanofluids were sonicated continuously for 1 hour using a probe sonicator to disperse the nanoparticles uniformly. Following this, the nanofluids of different volume concentrations were stirred continuously for 3-4 hours using magnetic stirrer to obtain uniform dispersion of nanoparticles in base fluid.

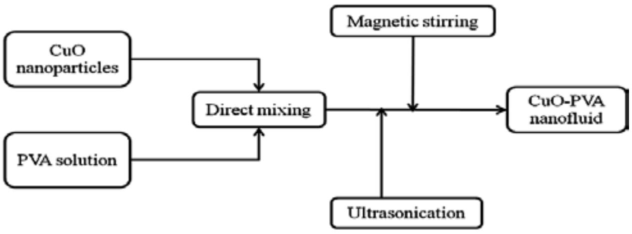

Figure 1. Preparation of CuO-PVA nanofluid

Figure 2 represents XRD patterns of CuO NPs along with the standard tenorite (CuO). This XRD pattern is almost completely matched with the monoclinic phase of CuO (tenorite) nanoparticles. No characteristic peaks any other phases were observed. The intensities and positions of peaks were in good agreement with that of reported values (JCPDS file no. 05–0661) [21].The present experimental result wasalso found to be in harmony with the reported diffraction patterns of CuO NPs prepared by Radhakrishnan et al [22].The average crystallite size of CuO NPs is 32.50 nm.

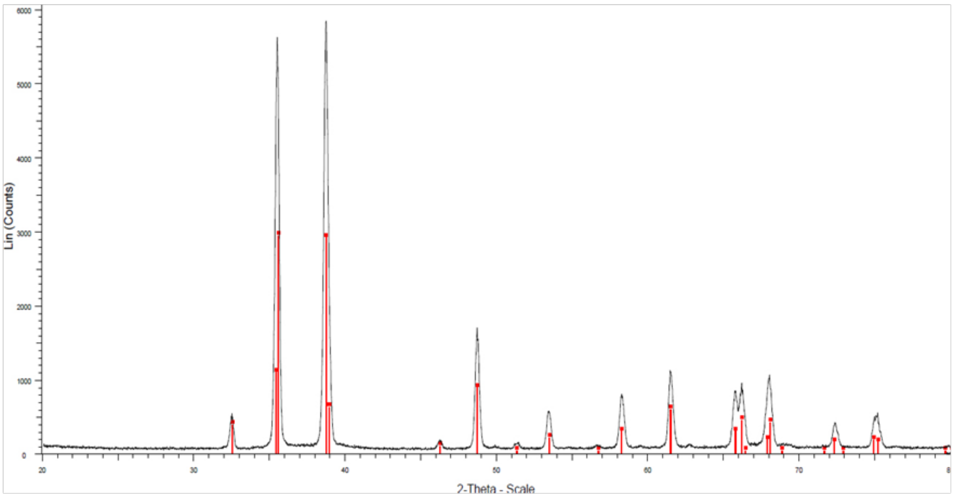

Figure 2. XRD pattern of CuO NPs. The (|) vertical lines indicate the position and relative intensity of 05-0661 JCPDS card file diffraction peaks for the monoclinic phase

Figure 3 represents the SEM image of CuO nanoparticles. The SEM image at 25,000× magnifications was collected. From the SEM image of CuO-NPs, it was observed that the particles are well-dispersed spherical, accompanying almost well defined and uniform crystalline structure. There was also a higher tendency of agglomerations. The SEM image supports the formation of regular polyhedron shape for the CuO-NPs. The island growth of the tightly packed spherical arrangement was clearly observed. In some regions, the big nanoparticles were surrounded by smaller nanoparticles. Similar SEM images of CuO-NPs were observed and reported [22].

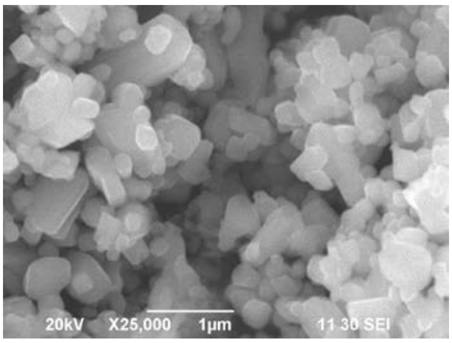

Figure 3. SEM image of CuO-NPs

2.2. Experimental Setup

The setup used in this experiment for measuring the convective heat transfer coefficient is shown schematically in Figure 4. This experimental setup consists of a reservoir shell of 350 ml volume in which hot water (100°C) was kept in a stagnant condition. 6 kW immercible heater (Watlow Ref. L14JX8B) is fitted in the shell to heat the water. A constant heat flux condition was maintained. A spiral tube made from smooth copper tubing with 0.44 mm outer diameter, 0.15 mm thickness and 0.29 mm inner diameter and a heat exchange length of 68.58 cm was incorporated into the shell. A centrifugal pump (Espa Ref. XVM8 03F15T) was used to circulate the nanofluids and base fluid through the test section. The fluids took heat from the hot water and then passed away from the tube. Hot fluids passed from the tube were collected in a beaker. To reduce the heat loss from the system the test section is perfectly insulated by using glass wool. The K- type thermocouples are used to measure the temperature at the shell and outlet side tube.

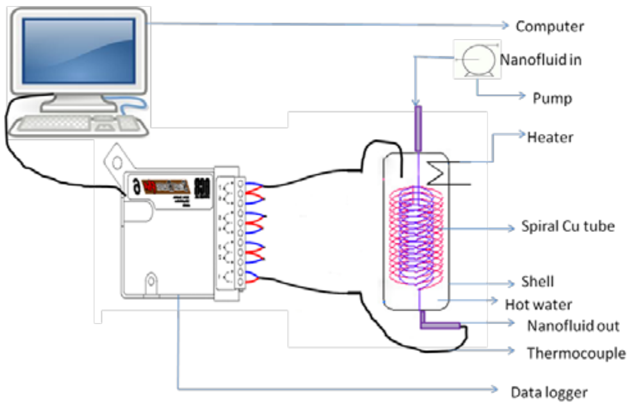

Figure 4. Experimental setup for the measurement of forced convective heat transfer coefficient of nanofluids

2.3. Data Analysis

Convective heat transfer between a moving fluid and a solid surface can be defined by the following relationship [[23]]:

$$\mathbf{Q = hA(T_s - T_f)\ or, Q = hA\Delta}\mathrm{T} \quad (1)$$

Where

Q is the rate of forced convection heat transfer (W)

T_s is the solid surface temperature (^{o}C)

T_f is the fluid temperature (^{o}C)

A is the area of the surface that is in contact with the fluid (m^2)

h is the convective heat transfer coefficient (W/m^2K)

Now, $Q = mS\Delta\theta$

Where

m = mass of hot water, kg

S = specific heat of water, J/kg.K

$\Delta\theta$ = difference in temperature of water before and after releasing temperature, K.

Therefore, we get the following equation,

$$h = (Q/A)/(\Delta T)\ \text{or, } h = mS\Delta T/(A.\Delta T) \quad (2)$$

Let,

heat transfer coefficient of base fluid = h_0

,, of 0.05% nanofluid = h_1

,, of 0.1% nanofluid = h2

,, of 0.2% nanofluid = h3

Difference in temp. of water before and after releasing temp. for base fluid = $\Delta\theta_0$

,, for 0.05% nanofluid = $\Delta\theta_1$

,, for 0.1% nanofluid = $\Delta\theta_2$

,, for 0.2% nanofluid = $\Delta\theta_3$

Difference between the temperature of water and PVA solution = ΔT_0

,, 0.05% nanofluid = ΔT_1

,, 0.1% nanofluid = ΔT_2

,, 0.2% nanofluid = ΔT_3

Table 1. Data required for the calculation of heat transfer coefficients

Parameters	Values
Mass of water, m	350g or 0.35 kg
Specific heat of water, S	4178 J/kg.K
Outer diameter of Cu-tube, d	0.065 m
Heat exchange length of Cu-tube, l	1.55 m
$\Delta\theta_0$ for base fluid	2 K
$\Delta\theta_1$ for 0.05% CuO-PVA nanofluid	4.5 K
$\Delta\theta_2$ for 0.1% CuO-PVA nanofluid	6.5 K
$\Delta\theta_3$ for 0.2% CuO-PVA nanofluid	7 K
ΔT_0 for base fluid	15 K
ΔT_1 for 0.05% CuO-PVA nanofluid	11.5 K
ΔT_2 for 0.1% CuO-PVA nanofluid	9 K
ΔT_3 for 0.2% CuO-PVA nanofluid	6.5 K

From these data, the forced convective heat transfer coefficients can be determined. Therefore, using equation (2) we get

h_0 = (4.6 103 X 2) / 15 = 615.70 $W/(m^2K)$

h_1 = (4.6 103 X 4.5) / 11.5 = 1800.00 $W/(m^2K)$

h_2 = (4.6 103 X 6.5) / 9 = 3322.22 $W/(m^2K)$

h_3 = (4.6 103 X 7) / 6.5 = 4953.84 $W/(m^2K)$

3. Result and Discussion

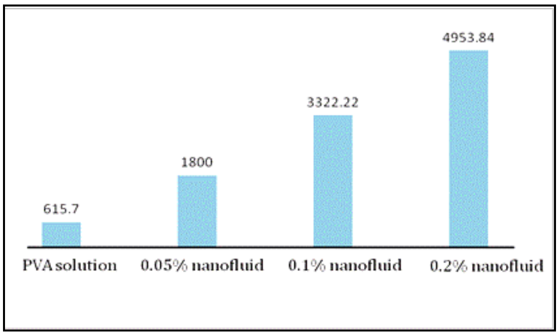

Figure 5. Forced convective heat transfer coefficient in $W/(m^2K)$ of PVA solution and CuO-PVA nanofluids

Figure 5 shows the enhancement of convective heat transfer coefficient at the low volume fractions (0.05, 0.1 & 0.2%) of CuO-PVA nanofluids under laminar flow conditions. This clearly proves that the presence of nanoparticles in the base fluid increases the convective heat transfer coefficient, and the increase is clearly seen even though the concentration is less. There are two possible reasons for the enhancement: i) the suspended particles increase the thermal conductivity of the two-phase mixture; and ii) the chaotic movement (Brownian movement) of ultrafine particles which accelerates the energy exchange process in the fluid. It is also observed that the increase in the measured heat transfer coefficient is because of the nanofluid thermo-physical properties and this has resulted in an increase in heat transfer rate [24]. Sivakumar et. al. (2015) and Senthilraja et. al. (2013) found similar results [25,26].

4. Conclusion

Experimental investigation on the forced convective heat transfer performance of low volume fraction of CuO-PVA nanofluid in laminar regime through a heat exchanger showed that the presence of nanoparticles increases the forced convective heat transfer coefficient of the original base fluid under the same Reynolds number. In conclusion, this study has provided a insight into the thermal behavior of a nanofluid under forced convective conditions. Further investigations are needed for better understanding of the underlying mechanisms for enhanced heat transfer characteristics of nanofluids. Moreover, these results found can be leveraged for various practical heat transfer and thermal applications to bring about a dynamic advancement in the field of nano scale heat transfer.

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