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Stable colloidal copper nanoparticles for a nanofluid: Production and application

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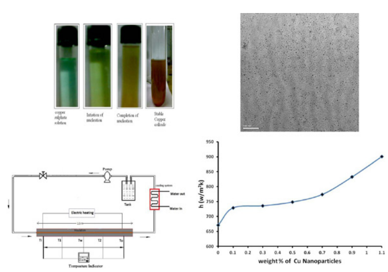
HIGHLIGHTS

- A layer of PVP is coated onto copper nanoparticles to minimize their agglomeration.
- Stable colloidal copper nanoparticles were prepared and used to prepared a nanofluid.
- Convective heat transfer properties of a colloidal copper nanofluid were studied.
- The heat transfer coefficient increases with concentration of colloidal copper nanoparticles.
- Enhancement in the heat transfer coefficient was observed at different Reynolds numbers.

GRAPHICAL ABSTRACT



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ABSTRACT

The present study deals with the synthesis of water based stable colloidal nanoparticles and the study of their heat transfer characteristics. Heat transfer analysis at different loading (0–1.1 wt%) of copper nanoparticles in water was carried out at fixed Reynolds number. Enhancement in the heat transfer coefficient was also studied at different Reynolds numbers by keeping the wt% of copper nanoparticles in the range of 0.7–1.1 wt%. The heat transfer analysis of the copper nanofluid was carried out in a copper tube at constant heat flux. Established correlations were used for the determination of thermal properties in the laminar flow regime. The results showed that the heat transfer coefficient increases with an increase in the concentration of colloidal copper nanoparticles and Reynolds number. For a 1.1 wt% copper nanofluid, a 34% increase in the heat transfer coefficient was observed as compared to the base fluid (pure water).

1. Introduction

Nanoparticles are of great interest in the chemical, electronic, and optoelectronic industries because of the novel properties afforded by their small size and high surface to volume ratio [1]. Nanofluids are a new class of fluids, which are prepared by dispersing nanometer size particles (nanoparticles) in a base fluid. It is important to note that one of the dimensions of the nanoparticle should be in the range of nanometer preferably 1–100 nm ranges [2,3]. The addition of thermally conducting nanoparticles in base fluids enhances the thermal transport and thermal properties of the resulting nanofluid. These tiny conducting particles enhance the surface area, thereby increasing the heat transfer coefficient. However, the reduction in the particle size has the issue of colloidal stability and hence, it affects the final performance of the nanofluid [4,5]. A number of metal and metal oxide nanoparticles has been used in nanofluid preparation which are reported in the literature, e.g. copper nanoparticles [6], nanosize aluminum oxide (Al_2O_3) [7], etc. Many researchers have reported on the use of titanium

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dioxide (TiO_2), zinc oxide (ZnO) and copper oxide (CuO) nanoparticles as conducting solids in the formulation of nanofluids [8,9]. In most cases the dispersion is prepared using a nanodry powder and base fluid such as water or ethylene glycol in presence of surfactant. However, the agglomeration and instability of nanoparticles leads to faster settling, which is undesirable in the case of practical nanofluid use [10,11]. The reason for the instability of a nanofluid is related its surface charge. Some reports mention the use of surfactants and sonication technique for making stable nanofluids: it was found that sonication affected the colloidal stability of the fluid and gave an enhancement in performance [12,13].

Nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, and convective heat transfer coefficients as compared to those of base fluids like oil or water. Various experimental investigations have been performed on the understanding that the convective heat transfer of nanofluids by laminar flow. Liu et al. [14] investigated the forced convective heat transfer characteristics in quartz micro tubes with inner diameters of 242, 315 and 520 μm. The Reynolds numbers ranged from 100 to 7000. The results showed that the experimental Nusselt number tends to be in good agreement with that of the theoretical correlations, when the flow regime was laminar. Heris et al. [15] investigated the effect of volume fraction of nanoparticles on convective heat transfer of nanofluids using Al_2O_3/water. They observed that a 41% enhancement of the heat transfer coefficient is possible at 2.5 vol % of nanoparticles. Brisco et al. [16] also examined the convective heat transfer of nanofluids using graphite/water, finding a, 22% enhancement of the heat transfer coefficient at 2.5 vol% nanoparticles. Chen et al. [17] reported the effect of increasing the nanoparticles concentration and aspect ratio of TiO_2/water nanoparticles on the convective heat transfer coefficient. They reported a remarkable increase in the convective heat transfer coefficient. Ding et al. [18] examined a CNT/water nanofluid for convective heat transfer and observed a remarkable enhancement of the heat transfer coefficient. Attempts were made for improving heat transfer by the addition of millimeter and/or micrometer sized particles to fluids, which results in a pressure drop. Nanofluids, on the other hand, do not cause pressure drop because of the small size of the nanoparticles. A nanofluid behaves like a neat fluid [19,20].

Copper metal nanoparticles have attracted applications due to their improved catalytic, thermal, optical, and electrical properties at the nanolevel. Copper nanoparticles find various applications, in heat transfer, electronic devices such as lithium batteries, industrial cooling and heating, mass transfer enhancement, energy storage devices. Copper nanoparticles are highly reactive and hence oxidation takes place rapidly. Pure copper metal nanoparticles are not easy to stabilize. Copper gets oxidized to copper oxide, hence there are changes in structural and thermal properties. Therefore, it is worthwhile to use a protective layer on the metallic particles to avoid oxidation. To stabilize the nanometer size of the particles, they have generally been encapsulated by different organic or inorganic agents [21,22].

In this study, copper nanoparticles are prepared in a batch process. Prepared colloidal copper nanoparticles are found to be stable without undergoing oxidation. The enhancement in convective heat transfer properties of a colloidal copper nanofluid was studied with the base fluid water.

2. Experimental

2.1. Materials

Preparation of the copper nanofluid was carried out by using copper sulfate ($CuSO_4$, AR grade) and ascorbic acid ($C_6H_8O_6$, AR grade) which were procured from SD Fine Chemicals Ltd., Mumbai. Polyvinyl pyrrolidone (PVP, $(C_6H_9NO)_n$) was procured from Merck specialties, Mumbai. The purity of the all chemicals used was above 98%. Pure water (<1 μS/cm conductivity) from Millipore was used for the preparation of aqueous solutions of the precursors.

2.2. Preparation of colloidal copper nanofluids

An aqueous solution of copper sulfate was prepared by adding 1.59 g of copper in 100 mL water. Aqueous solutions of ascorbic acid and PVP were prepared separately by taking 4.36 g ascorbic acid and 1 g of PVP in 100 mL water. Ascorbic acid was used as a reducing agent whereas PVP was used as a surfactant. Aqueous solutions of copper sulfate, ascorbic acid and PVP were mixed and agitated with the use of a magnetic stirrer and the reaction mixture was maintained at 80 °C temperature. Copper sulfate was reduced by ascorbic acid which results in the formation of copper nanoparticles. In general, copper nanoparticles are highly unstable as they tend to form copper oxide. However, due to reducing properties of ascorbic acid, formation of copper oxide is inhibited resulting in the formation of stabilized copper nanoparticles [23,24]. As soon as the cooper nanoparticles were formed, PVP formed a layer of coating the copper particles, which prohibits further agglomeration. Formation of copper nanoparticles were confirmed when the color of reaction solution turned brick red. The formed copper nanoparticles were characterized using XRD, UV and TEM analysis.

Initially, in water $CuSO_4$ dissociates to Cu^{2+} and ${SO_4}^{2-}$ and Cu^{2+} ions are hydrolysed into $Cu(OH)_2$ as a precursor. Further reduction of $Cu(OH)_2$ takes place in presence of ascorbic acid to form Cu_2O. Finally, Cu_2O was again reduced to form Cu nanoparticles [25]. The overall reduction process can be represented as follows:

$$CuSO_4 \rightarrow Cu^{2+} + {SO_4}^{2-} \quad \text{(Rx 1)}$$

$$2H_2O \rightarrow 2H^+ + 2OH^- \quad \text{(Rx 2)}$$

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2 \quad \text{(Rx 3)}$$

$$2Cu(OH)_2 + C_6H_8O_6 \rightarrow Cu_2O + C_6H_6O_6 + 3H_2O \quad \text{(Rx 4)}$$

$$Cu_2O + C_6H_8O_6 \rightarrow Cu + C_6H_6O_6 + H_2O \quad \text{(Rx 5)}$$

$$2H^+ + {SO_4}^{2-} \rightarrow H_2SO_4 \quad \text{(Rx 6)}$$

2.3. Experimental setup for heat transfer studies of nanofluid

The heat transfer studies were carried out using a copper tube of 1.5 m length and 9.5 mm diameter. Four PT-100 thermocouples and a temperature display were used in order to measure the temperature at different places in the copper tube (test section). The experimental setup consisted of a copper tube (test section), four thermocouples, pump, condenser, water sink, etc. Schematic of the experimental setup for heat transfer studies is given in Fig. 1. Experiments were carried out at different weight fractions of copper nanoparticles in the nanofluid and at different volumetric flow rates of the nanofluid. In order to study the effect of weight fraction of Cu nanoparticles on the heat transfer characteristics, experiments were carried out for 0 wt% (pure water) to 1.1 wt% of copper nanoparticles in nanofluid at a $12.5 \times 10^{-6}\ m^3/s$ volumetric flow rate. Aqueous dispersions of copper nanoparticles, i.e., nanofluid was prepared in 3 L pure water. The test section was heated by a heating coil placed around the copper tube and connected to dimmerstat which was set to 120 V. The experiments were carried out under constant heat flux conditions. Nanofluid from the sink was pumped through the copper pipe using a 0.5 HP pump. Nanofluid

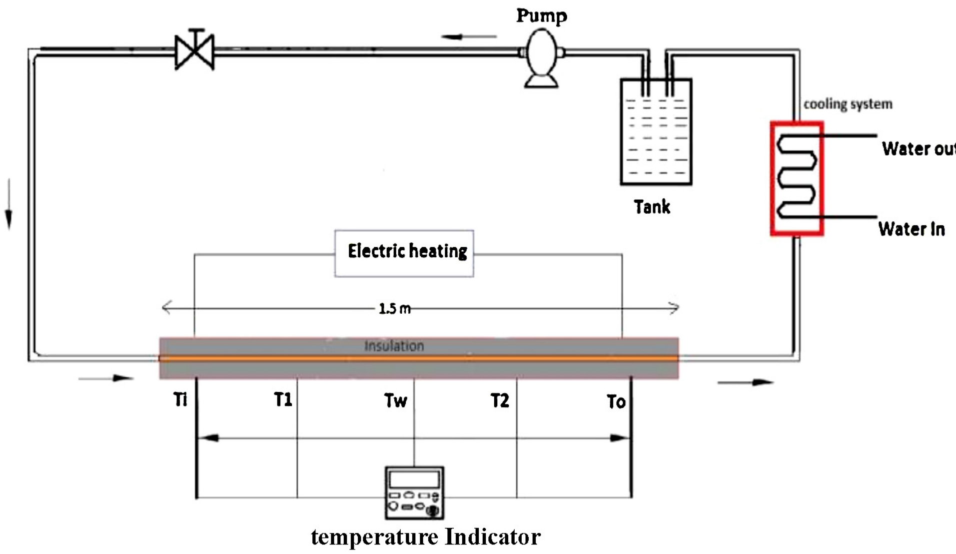

Fig. 1. Schematic diagram of the experimental setup for heat transfer analysis of nanofluids containing colloid copper nanoparticles.

temperatures were measured using the thermocouples placed at equal distance on the copper tube. In order to get the desired inlet temperature of for the nanofluid, cooling was provided to the sink. Once steady state was reached, the inner copper tube wall temperature, fluid temperature at different locations in the copper tube and sink temperature were measured. Experiments were carried out to study the effect of weight fraction of Cu nanoparticles in the nanofluid and varying flow rates of nanofluid. Further, experiments were performed by keeping the weight fraction of Cu nanoparticles (0.7 and 1.1 wt%) constant and varying the volumetric flow rate (Reynolds numbers 2000, 1517, 1197 and 878).

2.4. Characterization

To determine the size of the copper nanoparticles TEM images were taken on a Philips Tecnai 20 model electron microscope, which has resolution of 2 Å at an acceleration voltage of 200 kV with magnification of 7,50,000×. XRD patterns of the synthesized copper nanoparticles were taken by X-ray diffractometer (Philips PW 1800). Absorbance measurements were made using UV a spectrophotometer (SHIMADU 160 A).

Zeta Potential analysis of the nanoparticles was carried out using Malvern Zeta Analyzer.

2.5. Physical properties determination using model correlations

Thermo physical properties such as density (ρ), thermal conductivity (k), viscosity (μ), and specific heat (Cp) of nanofluids, used for the determination of the heat transfer coefficient of the nanofluid, were determined using theoretical values reported in the literature [14]. For copper: thermal conductivity = 385 W/m K, Specific Heat Cp = 0.39 J/g °C and density 8.96 g/cm^3 was used for calculating nanofluid properties. The density of nanofluid is calculated using Equation (1)

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \tag{1}$$

where ρ_{nf} is density of nanofluid, ρ_{bf} density of base fluid, ρ_p density of nanoparticles and φ is nanoparticle volume fraction. The specific heat capacity of nanofluids is calculated using Eq. (2).

$$Cp_{nf} = (1-\varphi)Cp_{bf} + \varphi Cp_p \tag{2}$$

where Cp_{nf} is specific heat capacity of nanofluids, Cp_{bf} specific heat capacity of base fluid and Cp_p specific heat capacity of nanoparticles.

The thermal conductivity enhancement ratio is defined as the ratio of thermal conductivity of the nanofluid to the thermal conductivity of the base fluid (k_{nf}/k_{bf}). The effective thermal conductivity calculation for a two-phase mixture consisting of a continuous and discontinuous phase was carried out by using Eq. (3) reported in the literature [4]. In Eq. (4), Maxwell assumed that the discontinuous phase should be spherical in nature. Thermal conductivity depends upon two important factors, namely, sphericity of the copper nanoparticles and the volume fraction of the copper nanoparticles to water as base fluid [16].

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\varphi(k_p - k_{bf})}{k_p + 2k_{bf} - \varphi(k_p - k_{bf})} k_{bf} \tag{3}$$

where k_{bf} is the thermal conductivity of the base fluid, k_p is the thermal conductivity of the particle, φ is the particle volume fraction.

For predicting effective viscosity of suspensions, the Einstein correlation was used, Eq. (4) [14]. Einstein's formula is valid for low particle volume fractions. Based on the assumption of a linearly viscous fluid containing dilute, suspended, spherical particles Eq. (4) can be used.

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\varphi \tag{4}$$

where μ_{nf} is the viscosity of the nanofluid and μ_{bf} is the viscosity of the base fluid.

2.6. Convective heat transfer measurement

Convective heat transfer coefficient characteristics were calculated by measuring the heat energy supplied q, when the fluid flows with mass velocity m, and the differential heat energy is given by

$$dq = C_p \times m \times dT \tag{5}$$

where C_P is the specific heat capacity and dT is the temperature difference.

$$q = h \times S \times (T_S - T_f) \tag{6}$$

where h, S, T_S and T_f are heat transfer coefficient, area of convective heat transfer, wall temperature and fluid temperature, respectively, it can be calculated as

$$dq = 2\pi rh \times (T_W - T) \times dx \tag{7}$$

$$\ln\frac{T_W - T_2}{T_W - T_1} = -\frac{2\pi r\Delta L}{C_P m}\bar{h} \quad (8)$$

$$h = -\frac{C_P m}{2\pi r\Delta L}\ln\frac{T_W - T_2}{T_W - T_1} \quad (9)$$

where T_1 is the inlet temperature, T_2 is the outlet temperature and T_W is wall temperature

Reynolds number, Re, was derived from $Re = (\rho u D/\mu)$, where ρ, u and μ are the density, the flow rate, and the viscosity of the fluids, respectively [19–20]. D is the diameter of the tube.

3. Results and discussion

A schematic of the reaction for the synthesis of copper nanoparticles is given in Fig. 2a and b. The proposed mechanism of formation of Cu nanoparticles is shown in Fig. 2a. Accordingly, the synthesis of Cu nanoparticles was carried out using ascorbic acid as reducing agent and PVP as a particle stabilizer. During the process of formation of Cu nanoparticles, homogeneous nucleation and growth of particles occur. In this stage, reduction of metal ions occurs by ascorbic acid (Reactions (1)–(6) (Fig. 2b). As the reaction proceeds, the initial blue color of solution became greenish yellow. Photographs of the color changes observed during the reduction of copper ions to form copper nanoparticles are shown in Fig. 2c. During the reaction, the concentration of the ascorbic acid in the solution was kept in excess to avoid oxidation of copper nanoparticle. The color of the final product was red, which remained almost stable for days [26].

During the synthesis process, excess ascorbic acid is essential to avoid the oxidation of copper nanoparticles. The antioxidant property of ascorbic acid is due to its ability to scavenge free radicals and reactive oxygen molecules, accompanying the donation of electrons to give the semi-dehydroascorbate radical and dehydroascorbic acid [27]. Therefore, ascorbic acid plays a dual role as reducing agent and as antioxidant of copper nanoparticles (Reactions (1)–(6)). In the present study, in place of sodium borohydride, ascorbic acid has been used to prevent further oxidation to copper oxide [27,28].

3.1. Characterization colloidal nanoparticles used in preparation of nanofluids

The UV–vis absorption spectrum of a copper nanoparticle solution was recorded in the range of 200–700 nm in the absence and presence of PVP. As shown in Fig. 3a, an intense peak observed at 265 nm in the absence of PVP is due to a interband electronic transition of copper which is almost unstable in nature. Initially a color change from blue to a bluish yellow tint was observed, while after some time (after 1 h of synthesis), the original blue color was regained, which indicates that the colloidal copper nanoparticles are unstable in nature. Further as shown in Fig. 3b, with the addition of PVP, a major peak is observed at 600 nm, which is attributed to the surface plasmon absorption of copper [28,29]. The variation of the absorption coefficient of copper nanoparticles as a function of wavelength is shown in Fig. 3. A maximum absorbance of 0.53 was observed at 600 nm. Further to confirm the stability of copper nanoparticles, Zeta potential analysis was carried out for the copper nanofluid. The value of the Zeta potential was −28.5 mV, which indicates that the nanoparticles are stable in nature.

A XRD pattern of prepared copper nanoparticles is depicted in Fig. 4. Three peaks at 2θ values of 43, 50, and 74° corresponding to (1 1 1), (2 0 0), and (2 2 0) planes, respectively were observed and compared with the standard powder diffraction card of JCPDS No. 04-0836. The XRD measurement confirmed the formation of copper nanoparticles. In addition to these peaks, one major peak is observed at 74° corresponding to 3 1 1 planes of cubical Cu_2O. These results are in good agreement with the UV spectrophotometer analysis. However, the peak obtained at 74° indicates the oxidation of copper nanoparticles which may occur after some days. In such cases, the copper nanoparticles are polymorphous in nature. The major peak obtained at 43° indicates that the copper colloidal nanoparticles have FCC structure.

The FTIR spectrum of nanocolloids of copper is reported in Fig. 5. Intense characteristic peaks reported in the range 3549–3298 cm^{-1} are assigned to —OH stretching modes and the characteristics peak at 1624 cm^{-1} corresponds to —OH bending. The peak centered at 688 cm^{-1} corresponds to the vibration mode of Cu—O [26]. The characteristic peak of PVP is observed in the range of 1600–2070 cm^{-1}, which indicates the coating of PVP on to Cu nanoparticles.

The TEM images of prepared copper nanoparticles using transmission electron microscopy are shown in Fig. 6a and b. A uniform distribution of Cu nanoparticles is clearly observed from the TEM images. The particle sizes of Cu nanoparticles were measured from TEM analysis and found to be in the range of 3–10 nm. In the TEM images, dark black spots are copper nanoparticles, whereas black stains show the presence of PVP. The average particle size of prepared Cu nanoparticles, as revealed from XRD and TEM results, are less than 10 nm. The role of a particle stabilizer, e.g. PVP, is for controlling the growth of copper nanoparticles with spherical shape [28–30]. Spherical structures of prepared colloidal Cu nanoparticles with size ranging from 3 to 10 nm were sufficiently stable in aqueous solution, when formed in the presence of PVP (1 g/100 mL)/ascorbic acid (4.36 g/100 mL) and copper sulphate (1.59 g/100 mL).

3.2. Effect of weight fraction of copper nanoparticles onto enhancement in heat transfer coefficient

Several literature reports have shown that the concentration of nanoparticles in a fluid enhances the heat transfer coefficient efficiently. In order to study the effect of concentration of copper nanoparticles, heat transfer experiments were carried out under different loading of copper nanoparticles, i.e. 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1 wt% in nanofluid and at different flow rates of nanofluid corresponding to Reynolds numbers of 878, 1200, 1517 and 2000. The weight fractions of nanoparticles loaded in the base fluid has a notable effect on the heat transfer coefficient. Palm et al. [26] have used various weight fractions from 1% to 4%, where no linear relationship between the nanoparticle concentration and heat transfer coefficient was found. It was reported that above 4 wt%, a decrease in the heat transfer coefficient was observed.

Fig. 7 shows the convective heat transfer coefficients for nanofluids with various weight fractions of copper nanoparticles at a Reynolds number of 2000. Enhancement in the heat transfer coefficient is observed for increasing wt% of copper nanoparticles in the nanofluid. For the base fluid (water), the heat transfer coefficient value was estimated to be 670 W/m^2 K. It is found that the heat transfer coefficient increases with an increase in the concentrations of copper nanoparticle. For 0.1 wt%, there is sudden rise in the heat transfer coefficient (h) value and it shows exponential growth. At 1.1 wt% concentration of Cu nanoparticles in the basefluid, the heat transfer coefficient is found to be 900 W/m^2 K. It can be seen that with an addition of only 0.1 wt% of copper nanoparticles into the base fluid, there is an increase in the heat transfer coefficient of about 8% in comparison with the pure base fluid (water). A 34% enhancement in the heat transfer coefficient was observed for a 1.1 wt% concentration in the base fluid compared to pure water. The percentage enhancement in the heat transfer coefficient with an increase in the concentration of copper nanoparticles in the base fluid at constant Reynolds number for nanofluids is depicted

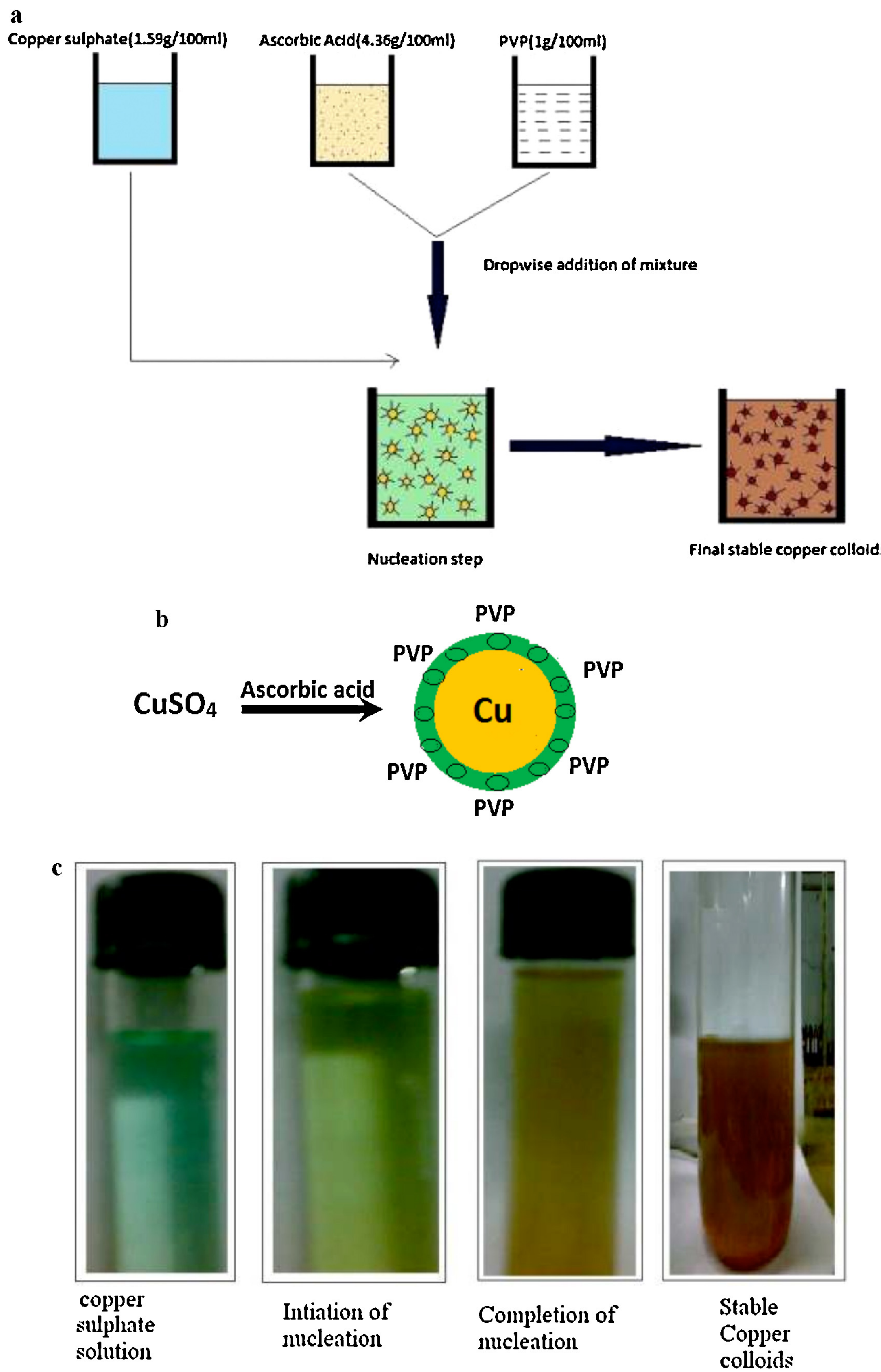

Fig. 2. (a) Reaction and formation of stable copper nanoparticles during synthesis. (b) Synthesis of copper colloid nanoparticles. (c) Stages of formation of stable colloids of copper nanoparticles.

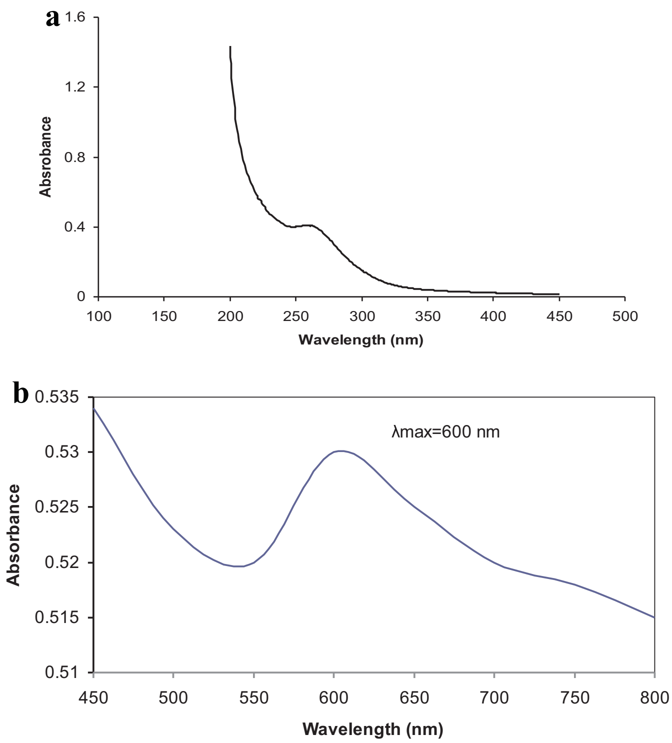

Fig. 3. (a) UV spectra of reaction mixture without addition of PVP [unstable colloids]. (b) UV spectra of copper nanoparticles with addition of PVP particle stabilizer at end of reactions (stable colloid particles are red in color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

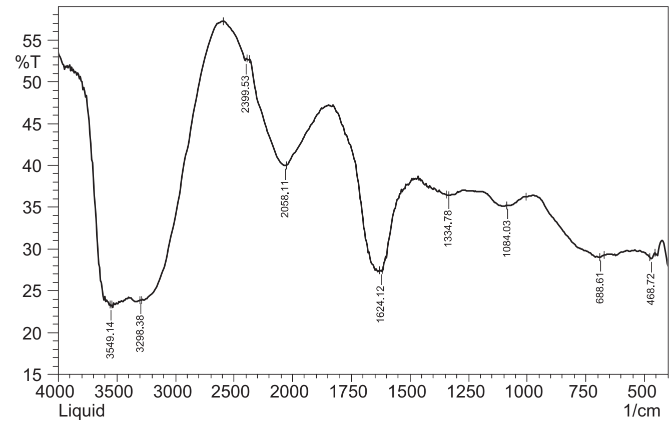

Fig. 5. FTIR spectra of colloid copper nanoparticles in the presence of PVP.

in Fig. 8. This enhancement in the heat transfer coefficient can be explained by the following mechanism. An increase in the weight fraction of the nanoparticles enhances the interaction and collision of the nanoparticles and also the effective diffusion rate which results in an enhancement in the heat transfer coefficient. Relative movement of these particles near the walls also leads to a fast heat transfer from the walls to the nanofluid. This enhancement would only be expected to occur within a very narrow region of Reynolds numbers. Once the base fluid transitioned to turbulent flow, similar heat transfer performance would be expected [30]. A second reason, which might explain this observed enhancement, is associated with rheological properties of the fluid. Because the nanofluid is shear-thinning and the shear rate is highest near the wall, better fluid flow performance should be realized near the wall. Thus, the non-uniform distribution of the viscosity field across the tube cross-section might also explain this enhancement [31–33].

It can be seen from Fig. 9 that Nusselt number of the nanofluid is found to be increased as compared with pure water. When compared with the base fluid, it shows that up to 0.5 wt% copper containing nanofluid, the Nusselt number does not show much enhancement compared to that for the base fluid but it is found to be increased for 0.7 wt% copper nanofluid. Significant enhancement in the Nusselt number is observed for 1.1 wt% as compared to water. For 1.1 wt% of copper nanoparticles the Nusselt number value is 13.58 and for pure water it is 10.12. As discussed earlier, the copper particles are very small in size, 5–10 nm, whereas adding PVP ensured the particles remained separated in the dispersion. Hence, a very small wt%, i.e. 1.1 wt% still shows good heat transfer enhancement. As reported by Yang et al. [34], copper nanoparticles of 2 vol% showed a 23% improvement.

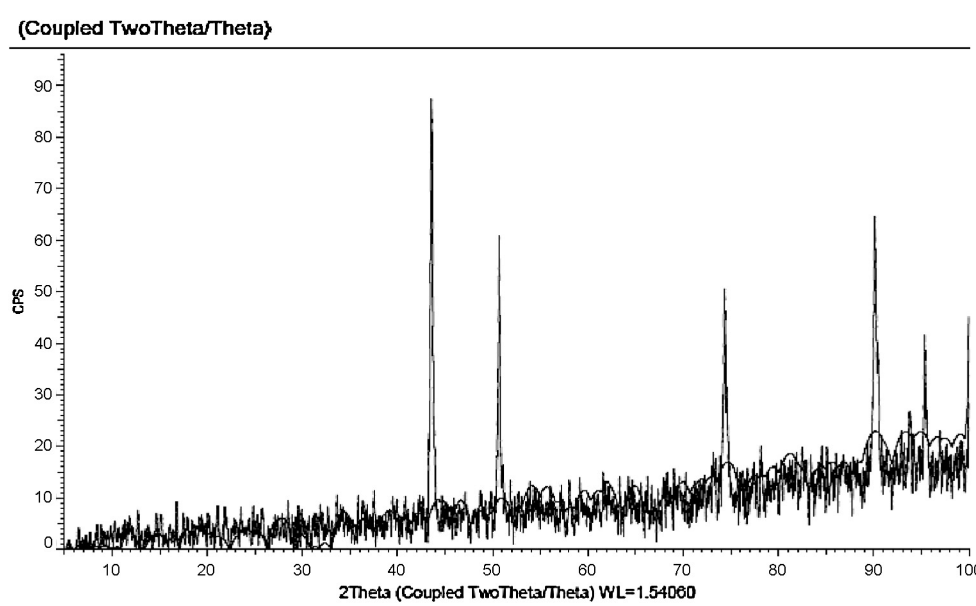

Fig. 4. X-ray diffraction pattern of copper nanoparticles.

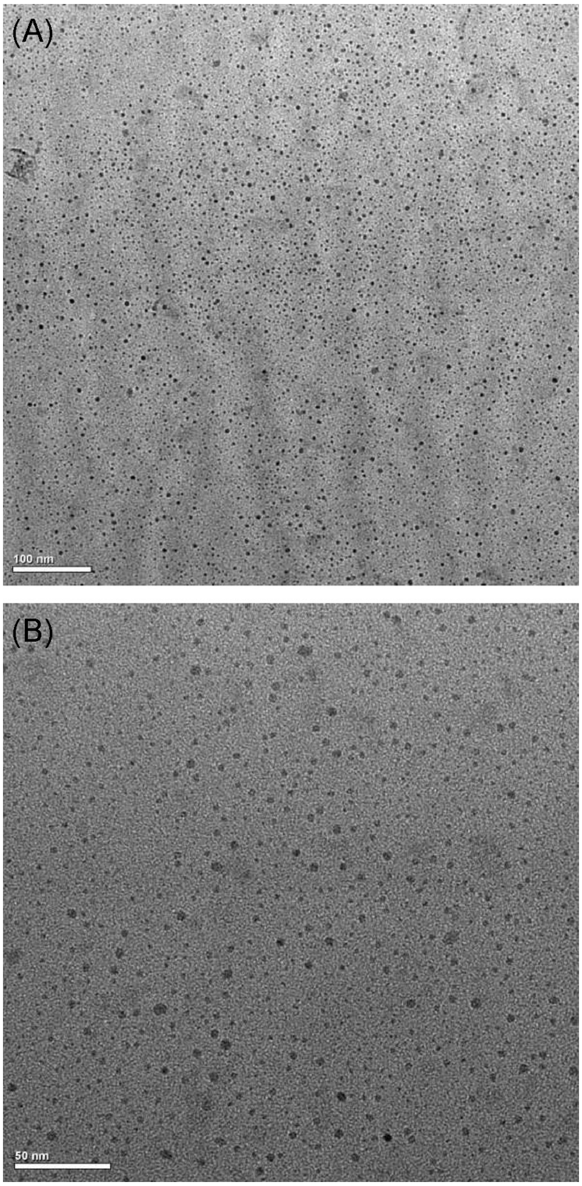

Fig. 6. TEM images of copper nanoparticles.

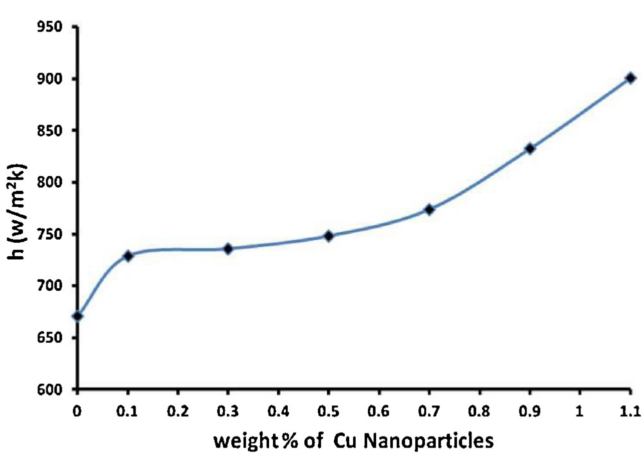

Fig. 7. Heat transfer coefficient versus wt% of copper nanoparticles (Re = 2000).

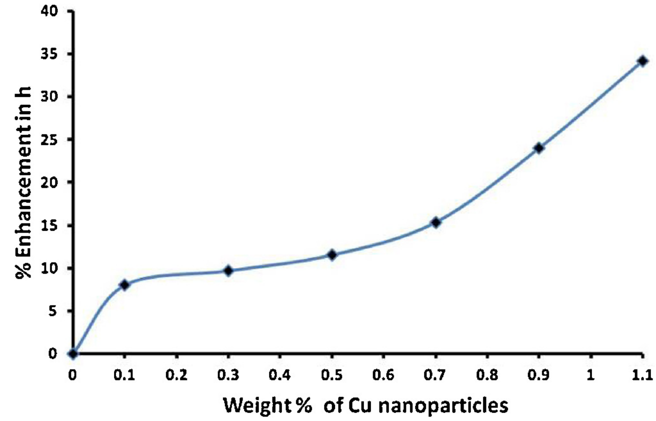

Fig. 8. Percentage enhancement in the heat transfer coefficient with increase in wt% (Re = 2000).

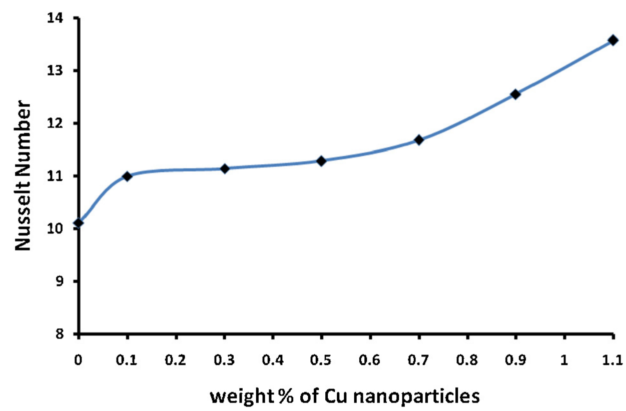

Fig. 9. Nusselt number versus wt% of copper nanoparticles (Re = 2000).

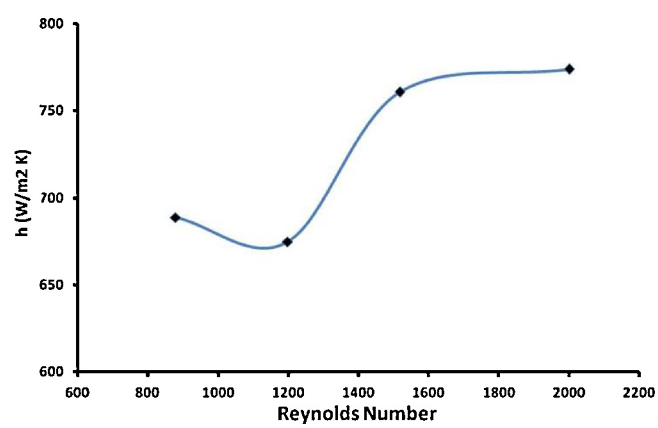

Fig. 10. Heat transfer coefficient versus Reynolds number (wt% of copper = 1.1%).

3.3. Effect of flow rate of colloidal nanofluid on heat transfer coefficient

In order to study the effect of nanofluid flow rate on the heat transfer coefficient, 0.7 wt% of copper nanoparticles in base fluid was selected. The effect of flow rate was studied at this concentration because for a constant flow rate value, the heat transfer coefficient has showed relatively higher values compared to other concentrations. Heat transfer characteristics are dependent on the flow behavior of a nanofluid to a significant extent. Increase in the flow rate generates turbulence and eddies in the flow which results in increasing the heat transfer rate. Heat transfer enhancement was

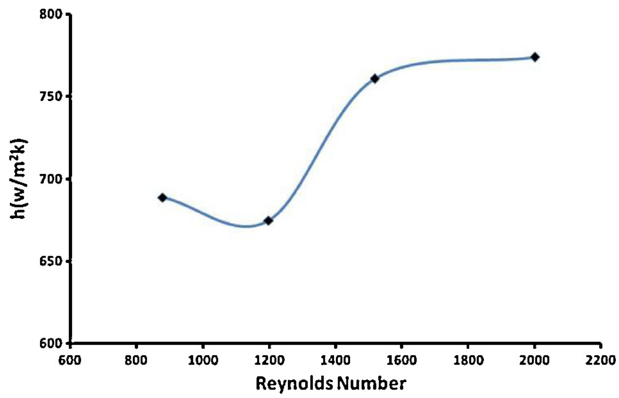

Fig. 11. Heat transfer coefficient versus Reynolds number (wt% of copper nanoparticles = 0.7%).

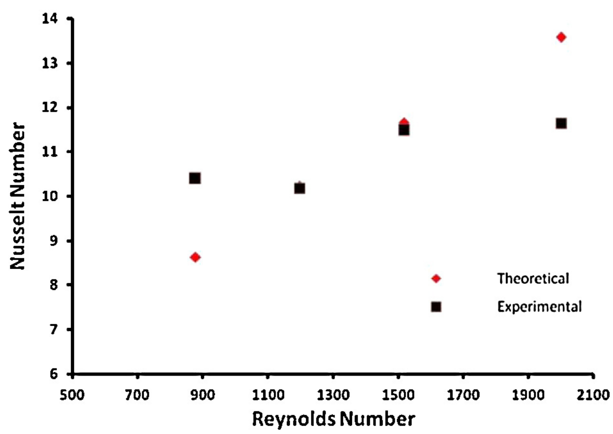

Fig. 12. Nusselt number versus Reynolds number (wt% of copper nanoparticles = 0.7%).

studied by keeping the wt% of copper fluid constant and varying the Reynolds number ranging from 878 to 2000. Effect of Reynolds number on the heat transfer coefficient was studied at concentration 0.7 wt%. The experimental results showed some inconsistency. At a Reynolds number equal to 878, the heat transfer coefficient was 688 W/m^2 K but it decreases at a Reynolds number 1197 to 674 W/m^2 K. Further, the heat transfer coefficient increases up to 774 W/m^2 K for a Reynolds number of 2000. For a concentration of 1.1 wt% and Reynolds number equal to 878, the value of the heat transfer coefficient is 663 W/m^2 K which is increased up to 900 W/m^2 K for a Reynolds number of 2000. Figs. 10 and 11 show the effect of Reynolds number on the heat transfer coefficient for 1.1 and 0.7 wt% of copper nanoparticles. Once the flow becomes fully developed hydrodynamically and thermally, the heat transfer coefficient value stabilizes for pure fluids as well as for nanofluids. A similar trend is observed for the nanofluid samples to a certain extent. A clear enhancement in the heat transfer coefficient was observed as the Reynolds number was increased.

Efficient heat transfer in laminar flow occurs in the thermal entrance region. The Average Nusselt Number for laminar flow in a circular tube with uniform surface temperature is given by Eq. (10). Theoretical values of Nusselt numbers, shown in Figs. 12 and 13, are calculated by Eq. (10).

$$\mathrm{Nu} = 1.86\,\mathrm{Re}^{1/2}\mathrm{Pr}^{1/2}\left(\frac{D}{L}\right)^{1/2} \tag{10}$$

The effect of the Reynolds number on the Nusselt number showed an increasing trend. Figs. 12 and 13 reports the comparative study of theoretical and experimental results for the Nusselt

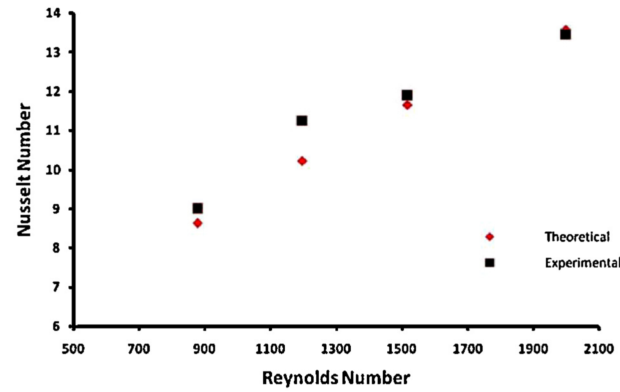

Fig. 13. Nusselt number versus Reynolds number (wt% of copper nanoparticles = 1.1%).

number at different Reynolds numbers for 0.7 and 1.1 wt% of copper nanoparticles respectively. For a concentration of 0.7 wt%, experimental and theoretical values at Reynolds numbers of 878 and 2000 are not matching. For Reynolds numbers equal to 1197 and 1517 values of the Nusselt number are almost same. For concentration of 1.1 wt% values of the theoretical Nusselt number are in good agreement with experimental values. At low Reynolds number, nanoparticles may agglomerate in the nanofluid flow. This will reduce the particle-particle interaction and hence the heat transfer enhancement at lower Reynolds numbers. However, at high Reynolds number, nanoparticles disperse uniformly which intensifies the mixing and the agglomeration effect is significantly reduced which results in a significant increase not only in the heat-transfer coefficient, but also in the Nusselt number. Nusselt numbers are calculated at different Reynolds numbers using correlation and these values are compared with those obtained from experimental results. Both set of values show an increasing trend: the Nusselt number increases as the Reynolds number increases [33–35].

4. Conclusion

In this work, convective heat transfer enhancement of water based copper nanofluids has been investigated. Colloidal copper nanoparticles were produced in a batch process from copper sulfate using ascorbic acid as reducing agent and PVP as a particle stabilizer. Stabilized copper nanoparticles suspensions were used for heat transfer studies. The effect of wt% of copper nanoparticles and Reynolds number were studied. It is concluded that the addition of nanoparticles to a base fluid can the increase heat transfer characteristics of the base fluid by a significant amount. With an increase in the concentration of copper nanoparticles in water, the heat transfer coefficient and Nusselt number values increased significantly. For 0.1 wt% copper nanoparticles an 8% enhancement was observed and for 1.1 wt% the enhancement observed was 34% (Reynolds number = 2000). Effects of different Reynolds numbers were also studied at 1.1 and 0.7 wt%. The Nusselt number and heat transfer coefficient were found to increase with an increase in the Reynolds number. This is attributed to a significant reduction in particle agglomeration and intensification of mixing due to the dispersion of the nanoparticles. Also the effect of Reynolds number on the heat transfer was found to be sufficient in the laminar flow regime.

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