CuAg and AuAg bimetallic nanoparticles for catalytic and heat transfer applications

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Abstract

Bimetallic nanoparticles (BNPs) have drawn significant attention due to their numerous applications. They demonstrate enhanced optical, electrical, thermal, and catalytic properties due to the synergistic effects of monometals present in them. In this work, CuAg and AuAg BNPs have been synthesized using a facile and economical chemical reduction method. Optical characterization was carried out using UV–visible spectroscopy, and effect of pH on optical absorbance was studied. For CuAg and AuAg BNPs, optimum pH was observed to be at 9.4 and 6.39, respectively. Morphological investigation confirms the average diameters of CuAg and AuAg BNPs were to be 65 nm and 30 nm, respectively. Photocatalytic property illustrates the reduction of 4-nitrophenol to 4-aminophenol with a 92% conversion percentage in the presence of CuAg BNPs in 4 min, and rate constant for the reaction was measured to be $8.98 \times 10^{-3} \text{ s}^{-1}$. But for the AuAg BNPs, the conversion percentage was 97% in 8 min and rate constant was found to be $7.95 \times 10^{-3} \text{ s}^{-1}$. Thermal conductivity and viscosity measurements of the nanofluids obtained with CuAg and AuAg BNPs have ascertained them to be efficient candidates for the heat transfer and catalytic applications.

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Graphic abstract

Keywords Bimetallic nanoparticles · Thermal conductivity · Viscosity · Catalytic activity · Optical properties · Gold · Silver

Introduction

Nanostructured materials have prevailed superior characteristics over their bulk counterparts in the contemporary times owing to their unique and exceptional properties. They possess potential applications in various fields such as catalysis, optoelectronics, antibacterial activity, and electronics (Srinoi et al. 2018). Among them, BNPs are well known and gained great importance and interest with their enhanced optical, electrical, and catalytic properties compared to the single-component nanoparticles (NPs) due to their composition and synergistic effects (Sharma et al. 2015; Suwannarat et al. 2018). In comparison with the metal NPs, the BNPs are cost-effective, provided the materials, synthesis, and characteristics are leveraged well with their potential usage in electrical, catalytic, and heat transfer applications. Therefore, there is an increasing demand for the low-cost and applicative BNPs Au–Ag (Ferreira et al. 2020), Cu–Ni (Kim et al.

2016; Hashemizadeh and Biglari 2018), and Pt–Pd (Wang et al. 2018) in which the synthesis method such as thermal decomposition, chemical reduction, hydrothermal, micro-emulsion, microwave irradiation, sol–gel, sonochemical, and radiolytic plays a vital role.

One of the well-known applications of NPs is catalysis, where NPs are used to enhance the rate of the reaction. Aromatic nitro compounds are of great importance in industries, since most of the dyes, drugs, pesticides, etc., are manufactured using these compounds. Still, the reduction of aromatic nitro compounds to amino compounds before their disposal to the environment is also equally crucial since aromatic nitro compounds are toxic (Suwannarat et al. 2018). Metallic NPs are successfully used in the catalytic reduction of 4-nitrophenol to 4-aminophenol to a certain extent of success. Comparatively, BNPs have good catalytic activity than monometallic NPs because the work function or electronic levels of two elements align together to enhance

the electronic charge shift, which is responsible for catalysis. Thus, the combinatorial effect of two elements in BNPs yields better catalytic activity than their corresponding monometallic NPs (Toshima 2008).

Pangkita Deka et. al. employed in situ generated Cu NPs as a catalyst for the reduction of 4-nitrophenol to 4-aminophenol in the presence of NaBH_4 very efficiently at room temperature with good recyclability up to four cycles (Deka et al. 2014). Tanur Sinha and M. Ahmaruzzaman reported the green synthesis of Cu NPs using fish scales of *Labeo rohita* for the catalytic degradation of methylene blue (96%) from aqueous solution (Sinha and Ahmaruzzaman 2015). Sijo Francis et. al. synthesized Ag and Au NPs using the herb *Naregamia alata* by microwave-assisted reduction, and NPs have efficiently reduced the dyes such as eosin Y, methyl red, and 4-nitrophenol in the presence of NaBH_4 (Francis et al. 2017). Nikesh Gupta et. al. prepared gold, silver, and platinum NPs using tannic acid as reducing agent. Silver NPs showed enhanced photocatalytic activity toward the degradation of methyl orange when compared to the gold and platinum NPs in the presence of NaBH_4 (Gupta et al. 2011). Nurafaliana Berahim et. al. studied the photocatalytic property of the Au–Ag BNPs prepared via seed colloidal technique. Size-dependent enhanced catalytic reduction of 4-nitrophenol into 4-aminophenol is observed compared to corresponding their monometallic NPs (Berahim et al. 2018). Muhammad Ismail et. al. synthesized ginger rhizome powder-based bimetallic photocatalysts, i.e., copper–silver (Cu–Ag/GP), copper–nickel (Cu–Ni/GP), and nickel–silver (Ni–Ag/GP) for the reduction of 2-nitrophenol (2-NP), 4-nitrophenol (4-NP), methyl orange (MO), congo red (CR), and rhodamine B (RhB). Cu–Ag/GP and Cu–Ni/GP displayed excellent catalytic activity for the reduction of all tested organic compounds, and the prepared NPs can be used for the reduction of mixture of dyes (Ismail et al. 2018).

Along with the catalytic applications, heat transfer applications are very common in chemical processing industries by adapting several fluids (liquids) to carry out the process. These applications mainly depend on the fluid properties such as thermal conductivity, density, viscosity, and specific heat (Yu and Choi 2003; Garg et al. 2008; Hamed Mosavian et al. 2010). Water, ethylene glycol, polypropylene, polyvinylpyrrolidone, and mineral oils are some of the base fluids. Thermal conductivity of base fluid can be enhanced by the inclusion of metal NPs, whereas its heat transfer ability is boosted by incorporating the BNPs. However, other fluid properties such as density, viscosity, and specific heat should be taken care of.

Garg, J. et al. reported that 2 vol% copper in ethylene glycol would lead to a 38% enhancement in the thermal conductivity of ethylene glycol (Garg et al. 2008). Saterlie et al. showed that there was a 48% enhancement in the thermal conductivity of deionized water when 1.0 vol% copper

nanofluid was inserted in it (Saterlie et al. 2011). L. Godson et. al. showed that thermal conductivity of water can be increased by 80% by adding 0.9 vol% silver nanofluid at an average temperature of 70 °C (Godson et al. 2010). They witnessed that enhancement of thermal conductivity and viscosity is holding a proportional relationship at elevated temperatures for silver nanofluid. Nevertheless, the viscosity enhancement was less compared to the thermal conductivity, which is a necessary factor for the heat transfer application. Natallia Shalkevich et. al. have produced gold nanofluid with a wide range of particle sizes, i.e., 2–45 nm, and concentrations, i.e., 0.0025–1 vol%, observing significant enhancement in thermal conductivity of water reaching its highest value of 1.4% for NPs size 40 nm with particle concentration of 0.11% (Shalkevich et al. 2010). Jisha John et. al. followed a green synthesis approach for the preparation of gold nanofluids using the plant extracts *Piper nigrum*, *Cinnamomum verum*, and *Syzygium samarangense* leaf (John et al. 2015). Increased thermal conductivity of the base fluid (water) was observed in case of star-shaped particles, followed by bean and spherical NPs with the decrease in the specific heat capacity. Min-Sheng Liu et. al. prepared copper NPs by the chemical reduction method, and it efficiently improved the thermal conductivity of water (Liu et al. 2006). There was 23.8% enhancement in thermal conductivity when the volume concentration of Cu–water nanofluids was 0.1%. M. Meena Kumari et. al. carried out a green synthesis technique for the preparation of Au–Ag BNPs using fruit juice of pomegranate (Meena Kumari et al. 2015). Both core–shell and alloy-like nanostructures were formed based on the different molar ratios of gold and silver ions. There was an enhancement in thermal conductivity of base fluid (water) from 21 to 72% when the volume concentration of nanofluid increases from 25 to 100% at 303 K. Sujoy Das and M M. Ghosh synthesized Ag–Cu alloy NPs via wet chemical method at room temperature and dispersed them in water and ethylene glycol (Das and Ghosh 2019). Thermal conductivity of the nanofluid increased almost linearly with wt% recording thermal conductivity enhancement as 9.6% at 0.26 wt% loading, and for ethylene glycol-based nanofluids, it is as 24.2% at 1.5 wt% loading. Moreover, both water and ethylene glycol-based nanofluids are stable in static condition for at least 35 days.

In our work, we have employed chemical reduction process to synthesize CuAg and AuAg BNPs by simply controlling the composition, size, shape, and structure of the NPs by altering the pH, temperature, reducing agent, stabilizing agent, and precursor. Here, reducing agents are meant to reduce the metal ions to its zero-valent state (Natsuki et al. 2015). We have analyzed its catalytic behavior by reducing 4-nitrophenol to 4-aminophenol as a model reaction for the reduction of aromatic compounds. Owing to the physical, chemical, and thermal properties of copper, gold, and silver

NPs, we have tested the thermal conductivity and viscosity of CuAg and AuAg BNPs to know the combined effect of monometallic NPs in the enhancement of the thermal conductivity of the base fluid.

Experimental section

Materials

Copper sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 99%), polyethylene glycol (PEG), sodium hydroxide (NaOH, 98%), silver nitrate (AgNO_3 , 99%), trisodium citrate (99%), and 4-nitrophenol (98%) were procured from Loba Chemie Pvt. Ltd. Ascorbic acid (99%) and sodium borohydride (NaBH_4 , 98%) were purchased from Sigma-Aldrich. Tetrachloroauric acid (HAuCl_4) was procured from Spectrochem Pvt. Ltd. All the chemicals were used without any further purification.

Synthesis of CuAg BNPs

CuAg BNPs were prepared using seed synthesis method. Here, polyethylene glycol (PEG) (0.02 M), ascorbic acid (0.02 M), and NaOH (0.1 M) were added sequentially to $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (0.01 M) solution under continuous stirring for one hour, followed by the addition of NaBH_4 (0.1 M). A yellow-colored solution which turned black after some time indicates the formation of Cu NPs. An aqueous solution of AgNO_3 (0.01 M) was added to the seed solution and stirred for 10 min to form CuAg BNPs.

Synthesis of AuAg BNPs

AuAg BNPs were synthesized by the seed colloidal technique (Ko and Chang 2014; Berahim et al. 2018). For this, we have added 1 ml sodium citrate (38.8 mM) to 10 ml aqueous solution of HAuCl_4 (1 mM) under vigorous stirring at 100 °C temperature. The appearance of dark red color indicates the formation of Au NPs, but the stirring and heating were continued for 10 more minutes to complete the reduction reaction. 2.5 ml of Au seed solution was added to 8 ml of distilled water, and then, 1 ml of sodium citrate (38.8 mM) was added to the resulted solution with stirring at room temperature. After 10 min of stirring, 1.2 ml of silver nitrate (10 mM) and 0.4 ml of ascorbic acid (100 mM) were added in sequence, and the stirring was continued for 30 min.

Characterization

Optical studies of the prepared samples were carried out using a Shimadzu-1800 UV–Vis spectrophotometer.

Morphological and elemental analysis was carried out using a field emission scanning electron microscope and an energy-dispersive X-ray diffraction analyser (FESEM; Carl Zeiss; EVO-18), accordingly. Structural analysis was performed by an X-ray diffractometer (XRD) (Rigaku Miniflex 600).

Catalytic reaction

The catalytic activity of these BNPs was studied by the reduction of 4-nitrophenol. One milligram of bimetallic nanopowder was dispersed in 4 ml of distilled water out of which 400 μl of solution was added to 3 ml of distilled water along with 40 μl aqueous solution of 4-nitrophenol (0.01 M) in a quartz cuvette. The sample was analyzed immediately after adding 200 μl of NaBH_4 (0.5 M) to the cuvette with the spectrophotometer. The progress of the reaction was periodically checked until the solution turned transparent, which indicates the completion of the reduction process.

Thermal conductivity and viscosity measurements

Thermal conductivity measurement was taken using KD2 Pro setup from Decagon Devices, Inc., which works on the hot-wire principle. Initially, the instrument was calibrated using glycerin, and then, the thermal conductivity of water and other samples (0.3 volume fraction, 0.6 volume fraction, and 1.0 volume fraction) was measured. The maximum error in measurement was 5%. The viscosity of the samples was measured using a MCR rheometer from AntonPaar with a shear rate of 600 s^{-1} . The reactions that may occur during the synthesis of CuAg BNPs are as follows (Trinh et al. 2015):

The reactions that occur during the synthesis of AuAg BNPs are as follows (Kumar et al. 2007; Suriati and Mariatti 2014):

Results and discussion

Optical studies

It is well known that the surface plasmon resonance (SPR) of the NPs depends on the size, shape, and type of the material. The optical behavior of the prepared BNPs was studied using a UV–visible spectrometer. The absorbance spectrum of CuAg BNPs is shown in Fig. 1a. CuAg BNPs showed absorbance peak at 389 nm, while Cu and Ag NPs are exhibiting at 574 and 410 nm, respectively (Pellarin et al. 2015; Cao et al. 2019; Jolly et al. 2021). The influence of pH on the optical properties of CuAg BNPs is depicted in Fig. 1b. The pH of the solution was varied by adding different amounts of NaOH during the preparation of BNPs. This study analyzes the effect on the absorbance spectra of the synthesized BNPs. Variation of the λ_{max} and maximum absorbance with pH are shown in Fig. 1c, d, and it is observed that the optical properties of NPs tuned with the variation in pH of the solution, where the CuAg BNPs showed maximal absorbance at pH 9.4. However, the absorbance intensity decreases with a further increase in the pH value. Oxidation reaction and aggregation of NPs may occur for the pH below and above 10, respectively. Hence, the pH range between 8 and 9 is desirable in order to synthesize the NPs anticipated for designated applications. Within this pH range, electrostatic repulsion between the nanoclusters increases by reducing the aggregation tendency of the nanoclusters (Alqadi et al. 2014; Anigol et al. 2017).

The optical absorbance spectra of AuAg BNPs and their effect with respect to the pH on optical spectra are depicted in Fig. 1e, f. Absorbance peak is traced out at 420 nm for BNPs (Yang et al. 2008), while individual NPs are displaying at 522 nm and 410 nm, respectively (Meena Kumari et al. 2015). Variation of λ_{max} with pH is shown in Fig. 1g. λ_{max} was found to be blue shifted, indicating that with the increase in pH the particle size decreases (Park et al. 2019). This is because the solution becomes alkaline as electrostatic repulsion between the nanoclusters increases, which reduces the aggregation tendency of the nanoclusters (Anigol et al. 2017). As shown in Fig. 1h, maximum absorption at a particular wavelength was decreased and also the broadening of the curve was detected over pH 6.39. It may be due to the formation of non-uniform NPs with different sizes absorbing light of different wavelengths.

Morphological studies

SEM images of both AuAg (Fig. 2a) and CuAg (Fig. 2b) BNPs in comparison with their individual NP entities reveal

their surface morphology as shown in Fig. 2. Their uniform distribution accounts for the active role of surfactant polyethylene glycol preventing the agglomeration of NPs. The average diameter of AuAg and CuAg BNPs is 30 and 65 nm, whereas the Au (Fig. 2c), Ag (Fig. 2d), and Cu (Fig. 2e) NPs possess the values as 20, 50, and 56 nm, correspondingly. These tiny NPs are expected to contribute optimal thermal conductivity allowing them to be potential candidates for the heat transfer applications. The EDS mapping of CuAg in Fig. 2f and AuAg in Fig. 2g confirms the presence of

Fig. 1 Optical absorption spectra of CuAg (a–d) and AuAg (e–h) BNPs. (a) Absorbance of Cu, Ag, and CuAg BNPs and (b) absorbance with pH variation. pH dependence of (c) λ_{max} and (d) maximum absorbance. Similar to CuAg, (e) absorbance of Au, Ag, and AuAg BNPs and (f) absorbance with pH variation. pH dependence of (g) λ_{max} and (h) maximum absorbance

Fig. 2 FESEM images of (a) AuAg, (b) CuAg, (c) Au, (d) Ag, and (e) Cu BNP. EDS images of (f) CuAg and (g) AuAg BNP with weight percentages

respective elements with respect to their weight percentages in BNP that are present in the nanofluid.

Structural studies

Figure 3a,b represents the XRD patterns of AuAg and CuAg BNP revealing the formation of well-crystalline nature closer to nano-realms. Distinguishing the Au and Ag XRD peaks is impracticable as their lattice parameters barely mismatch. However, in the above morphological studies by FESEM-EDS, we can clearly observe the respective metallic concentrations. The XRD patterns

of AuAg (Fig. 3a), CuAg (Fig. 3b) BNP are indexed by their corresponding powder diffraction files of Cu (PDF# 89–2838) and Ag (PDF# 04–0783). Simultaneously, the two diffraction peaks of Cu (at 42° , 73.4°) and four peaks of Ag (at 37.84° , 44.04° , 64.22° , 77.22°) denoted in the figures are confessing the face-centered cubic crystalline orientation. The presence of the peaks at $2\theta = 36.22^\circ$ and $2\theta = 61.64^\circ$ corresponding to the respective (111) and (220) planes is due to the presence of oxidized phase of Cu NPs (Cuprous Oxide JCPDS # 65–3288). The structural and morphological studies of these high crystalline BNP make them competent enough

Fig. 3 XRD patterns of (a) AuAg and (b) CuAg BNP

for heat transfer applications offering optimum thermal conductivity (Chen et al. 2013; Holden et al. 2014).

Catalytic studies of CuAg BNPs

Catalysis is one of the major applications of the NPs, and we have carried out the catalytic activity of prepared CuAg BNPs for the reduction of 4-nitrophenol in the presence of NaBH_4 . Figure 4a shows the UV–visible absorption spectra for the reduction of 4-nitrophenol in the presence of NaBH_4 alone. The decrease in intensity of absorption peak observed at 400 nm is attributed to the reduction of 4-nitrophenol in the presence of NaBH_4 , demonstrating 23% reduction of 4-nitrophenol after 60 min as shown in Fig. 4b (Berahim

et al. 2018). Next, Fig. 4c portrays the absorption spectra for the reduction of 4-nitrophenol in the presence of CuAg BNPs as a catalyst and NaBH_4 as reducing agent. In the presence of these BNPs, the reduction from 4-nitrophenol to 4-aminophenol was observed in 4 min and the color of the solution turned from yellow to colorless. The new peak at 300 nm is attributed to the absorption peak of 4-aminophenol (Berahim et al. 2018). Rate constant of the chemical reactions was calculated from $\ln(A_0/A_t)$ versus time plot for both NaBH_4 and (NaBH_4 + CuAg catalyst), as shown in the inset of Fig. 4b and in Fig. 4d. The rate constant of NaBH_4 alone was found to be $6.99 \times 10^{-5} \text{ s}^{-1}$, and in the presence of CuAg, it was $8.98 \times 10^{-3} \text{ s}^{-1}$. Figure 4e shows the conversion percentage of nitrophenol to aminophenol in the presence

Fig. 4 (a) UV–visible spectra of reducing the 4-nitrophenol in the presence of NaBH_4 , (b) reduction percentage of 4-nitrophenol with $\ln(A_0/A_t)$ versus time plot. (c) Reducing the 4-nitrophenol in the presence of CuAg BNPs. (d) Reduction percentage of 4-nitrophenol with $\ln(A_0/A_t)$ versus time plot. Rate constant of the reactions (b inset, e) is shown as $\ln(A_0/A_t)$ versus time plot. (f) Color change from yellow (before reduction) to transparent (after the completion of reduction)

of CuAg BNPs, and Fig. 4f depicts the color of the solution before (4-Nip + NaBH₄) and after reduction (4-Amp). There was 92% conversion of 4-nitrophenol to 4-aminophenol using CuAg BNPs. The conversion efficiency of CuAg + NaBH₄ is significantly higher, indicating that the BNPs can be effective catalysts for the dye reduction.

Catalytic studies of AuAg BNPs

Similar to the CuAg, the catalytic activity of AuAg BNPs was studied by catalyzing the reduction of 4-nitrophenol to 4-aminophenol. Figure 5a shows the absorption spectra of the reduction of 4-nitrophenol in the presence of AuAg BNPs. At the beginning of the reduction process, the peak was observed at 400 nm, which is attributed to the absorption peak of 4-nitrophenolate. The intensity of the peak at 400 nm was found to decrease with time and a new peak was formed at 300 nm. Color change from yellow to transparent indicates the completion of reduction process. The rate constant of the chemical reaction was calculated from $\ln(A_0/A_t)$ versus time plot shown in Fig. 5b, and the corresponding value was found to be $7.95 \times 10^{-3} \text{ s}^{-1}$. Figure 5c shows the conversion percentage of nitrophenol to aminophenol in the presence of AuAg BNPs yielding about 97% conversion in 8 min permitting them to effectively reduce the aromatic nitro compounds.

Fig. 5 (a) UV–visible spectra of reduction of 4-nitrophenol in the presence of AuAg, (b) $\ln(A_0/A_t)$ versus time plot, (c) percentage conversion versus time plot, (d) color change from yellow (before reduction) to transparent (after complete reduction)

Thermal conductivity and viscosity studies of CuAg

Thermal conductivity and viscosity of CuAg nanofluid were measured at room temperature by varying the concentration of CuAg nanofluid from 0 to 100% in the base fluid water. Figure 6 illustrates the plot of thermal conductivity and viscosity at a different volume fraction, and it is found to increase proportionally with the concentration of NPs in the base fluid. Table 1 provides the thermal conductivity as well as viscosity values at a different volume fraction of nanofluid.

Increasing the nanofluid concentration from 30 vol% to 100 vol%, we can evidence the enhancement in thermal conductivity is from 2 to 8%, whereas the increment in viscosity is in the range of 21% to 72%. The increment in thermal conductivity can be attributed to the Brownian motion of NPs, but the change in viscosity is because of their suspension in nanofluid. These results indicate that CuAg BNPs are potential candidates for the heat transfer applications.

Thermal conductivity and viscosity studies of AuAg

In analogy to CuAg, thermal conductivity and viscosity of AuAg nanofluid were measured at room temperature by varying the concentration of AuAg nanofluid from 0 to 100%. The plot of thermal conductivity and viscosity at a

Fig. 6 (a) Thermal conductivity at different volume fractions, (b) viscosity at different volume fractions, for the CuAg BNPs

Table 1 Values of thermal conductivity and viscosity at different volume percents of CuAg nanofluid

Vol % of nanofluid (with colloidal NPs)	Thermal conductivity (W/mK)	Viscosity (mPa.s)
0 (water)	0.560	0.742
30	0.595	0.901
60	0.606	0.983
100	0.633	1.274

different volume fraction of nanofluid is shown in Fig. 7. Both thermal conductivity and viscosity were found to increase with the concentration of nanofluid in the base fluid. However, after 0.6 volume fraction, thermal conductivity tends to decrease, which may be due to the agglomeration of NPs, which hampers the conduction [22].

Table 2 shows the thermal conductivity as well as viscosity values at different volume fractions of nanofluid. Nearly 7% enhancement was observed with thermal conductivity reaching a maximum at 60 vol% of nanofluid, and an increase in viscosity was found to be ~6% approximately. In resemblance to the CuAg BNPs, the increase in thermal conductivity can be attributed to the Brownian motion of NPs, while the viscosity to the suspension of

NPs enables them to be potential candidates for heat transfer applications.

Conclusion

In this work, the CuAg and AuAg BNPs were successfully prepared via chemical reduction method. CuAg BNPs showed a characteristic absorbance peak at 389 nm and the optimum absorbance has been attained at pH 9.4. In the case of AuAg BNPs, the absorbance peak was found at 420 nm, having maximum absorption at pH 6.39. Structural examination unveils their spherical nature and the presence of bimetallic composition is evinced by EDS analysis. The

Table 2 Values of thermal conductivity and viscosity at different volume percents of AuAg nanofluid

Vol % of nanofluid (with colloidal NPs)	Thermal conductivity (W/mK)	Viscosity (mPa.s)
0 (water)	0.560	0.769
10	0.573	0.855
30	0.597	0.752
60	0.625	0.819
100	0.595	0.821

Fig. 7 (a) Thermal conductivity at different volume fractions, (b) viscosity at different volume fractions, for the AuAg BNPs

catalytic activity of both BNPs realizes better reducing ability of nitrophenol to aminophenol, and the rate constants of the reaction were found to be $8.98 \times 10^{-3} \text{ s}^{-1}$ (CuAg) and $7.95 \times 10^{-3} \text{ s}^{-1}$ (AuAg), which is higher compared to either pure gold or silver NPs. Therefore, the prepared BNPs are optimal candidates for better and faster reduction of 4-nitrophenol. Thermal conductivity and viscosity of base fluid were found to increase with the concentration of nanofluid. Enhancement in thermal conductivity was found to be 8% for 100 vol% of nanofluid, and viscosity increased about 72% for CuAg BNPs. Thus, 7% enhancement in thermal conductivity was obtained for 60 vol% nanofluid in the presence of AuAg BNPs, and the viscosity has nearly attained 6%.

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