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# Synthesis of Cu-Al LDH nanofluid and its application in spray cooling heat transfer of a hot steel plate

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ABSTRACT

In the current study, authors have synthesized Cu-Al Layered Double Hydroxide nanofluid at different molar ratios of Cu and Al by using co-precipitation technique and utilized this as a coolant in a pressure atomized spray to achieve high cooling rates in the temperature range of 900–600 °C for a 6 mm thick steel plate. The study initially focuses on the effect of Cu: Al molar ratio variation on thermal conductivity, stability as well as its heat transfer potential in steel quenching. Post thermal conductivity and stability analysis, spray cooling experiments were conducted in two parts. The first part involves optimization of Cu: Al molar ratio by varying the ratio (Cu: Al = 2:1, 4:1 and 6:1) at a fixed nanofluid concentration (120 ppm) to select the best Cu: Al molar ratio based on heat transfer results. The results show that the highest cooling rate and average heat flux were achieved at a Cu and Al molar ratio of 4:1 among all molar ratio combinations. Once, the optimized molar ratio is selected, the second part of the spray cooling experiments was performed to study the effect of nanofluid concentration variation (40–240 ppm, at an optimized molar ratio of Cu: Al = 4:1) on spray cooling results. With respect to concentration optimization, the maximum cooling rate of 168.6 °C/s was attained at a concentration of 160 ppm which is 26% higher than what was achieved by normal water spray. Results obtained from the spray cooling experiments were further verified by the thermal conductivity analysis where highest enhancement of 15.17% was also observed at 160 ppm nanofluid concentration.



## 1. Introduction

Production of high strength multipurpose steel is the need of the modern civilization. In order to produce such high quality, high strength steel, alloying of steel is one of the most commonly used methods. However, the process is a costly option. In order to attain high mechanical properties, controlling the cooling rate on the run-out table (ROT) of steel rolling mill gives an inexpensive option. Cooling rate achieved at the ROT (temperature: 900°–600 °C) aids to attain required metal microstructure which is essential for having improved mechanical properties [1]. Transformation of steel from austenite to martensite, pearlite, and bainite is desirable in terms of the mechanical properties of steel. Using conventional cooling techniques (laminar cooling, cooling rate 30–80 °C/s) and conventional coolants (such as water, alcohol, ethylene glycol etc.), it is very difficult to attain high cooling rates required for producing desired microstructure. Therefore, the ultrafast cooling technique is implemented to achieve the needful. According to the definition, a cooling can only be termed as ultrafast cooling when the multiplication of cooling rate and plate thickness (for the present case, thickness of the steel plate is 6 mm) surpasses 800. Ultrafast cooling can be achieved by a combination of advanced cooling technique such as forced jet, or spray, or an air-atomized cooling technique along with the additive based cooling scheme. Alteration in surface tension by the addition of different surfactants can lead to improvement in droplet spreading and wettability which in turn improves the heat transfer rates. Reduced surface tension can play a significant role in increasing nucleate boiling and can give rise to a number of bubble generation and nucleation site. Several researchers have worked with different surfactant based additives and achieved significant improvement in heat transfer rates in their corresponding cooling processes [2–4]. However, the present study is focused on the use of nanofluid on spray cooling heat transfer. Nanofluids due to its enhanced thermal properties can be used as the efficient alternative to conventional coolants.

With the advancement in nanotechnology in past decade, the synthesis of the nanoparticle is now a reality. Application of nanotechnology stretches from material manufacturing, medical science, separation process, thermal engineering, and electronics to many more sectors. However, the focus of our current work is based on the thermal engineering aspect of nanotechnology especially metal quenching. A

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particle is called a nanoparticle when at least one of its dimensions is <100 nm in size. Due to its higher surface to volume ratio, nanoparticle suspended in a base fluid (such as water, ethylene glycol, ethanol, transformer oil etc.) can be used to extract heat in a more efficient way. The nanoparticle suspension in base fluid is known as nanofluid [5]. Nanofluid provides us a smart and easy alternative to replace conventional coolant which has a low thermal conductivity value. The low thermal conductivity of the quenching medium can directly affect the heat extraction process. However, using of a millimetre and micron sized particle suspension in the base fluid can increase the heat extraction but can also give rise to several other problems such as poor stability, excessive deposition on flow channel, higher pressure drop and higher pumping cost. However, when the particle size is reduced to nanometer level then all of the above mentioned problems seemed to drastically reduce while giving a higher thermal conductivity enhancement at a much lower concentration [6]. The most attractive and intriguing feature of nanofluids is its high thermal conductivity value as compared to any conventional coolants. The thermal conductivity enhancement of nanofluid is dependent on several other factors such as Brownian motion [7,8], particle aggregation [9,10], liquid layering surrounding nanoparticle [11], particle size [12], particle shape [13,14], effect of micro convection and turbulence [6,12] etc. However, there is some debate on the actual mechanism behind thermal conductivity enhancement but scientists are in agreement with its incredible potential as a coolant.

Implementation of this engineered coolant (nanofluid) can improve the thermal performance of any heat transfer system. Due to its high thermal conductivity value, it can extract heat from a heat source not only at a faster rate but also by using a lesser amount of coolant. Nanofluid is widely used for heat extraction from electronic chips, automobile engine, welding equipment, industrial heat exchanger, nuclear power plant etc. The immense potential of nanofluid as a coolant can also be utilized for metal quenching process like in the present case of steel manufacturing. Nanofluids can be classified into three main types based on the nature of the nanoparticle, a) metal based (Cu, Fe, Ag, Au etc.) [6,15–17], b) metal-oxide/non-metal based (CuO, $Al_2O_3$, $SiO_2$, $TiO_2$, $Fe_3O_4$, SiC etc.) [18–27], c) carbon based (SWCNT, DWCNT, MWCNT) [28,29]. In recent years, different types of nanofluid have found application in several fields of research. Li et al. [30] investigated on the thermo-physical properties and dielectric constant of waste oil based SiC/$TiO_2$ nanofluid. Authors found that addition of nanoparticles in base fluid has a beneficial effect on both thermal conductivity and dielectric constant value. Both the synthesized nanofluid can also be used to reduce frictional heat loss in industrial machines due to its lubricating nature. The positive environmental effect and waste recyclability potential are other beneficial attributes of this nanofluid. Water and ethylene glycol based SiC nanofluid has also been used as an engine coolant [31]. It was found that increase in nanofluid volume fraction leads to increase in thermal conductivity and viscosity value. The overall effectiveness of SiC nanofluid coolant was 1.6 times (at 0.2 vol%) greater than what achieved by normal car coolant. Patra et al. [32] have used alumina-water nanofluid to quench vertical metal rod (made of stainless steel) which resembles nuclear fuel rod. They have observed that deposition of nanoparticle on the metal surface enhances the surface wettability. The heat transfer rate and heat transfer coefficient value increased in case of $Al_2O_3$ nanofluid compared to water based quenching. Scientists have also used water based $Al_2O_3$ nanofluid as an engine coolant and found augmentation in convective heat transfer coefficient value by nanoparticle addition [33]. In a recent work, thermo-physical properties of Ag modified $TiO_2$ nanofluid have been investigated to check its suitability for application in crystallizer cooling system [34]. Other researchers have used CNT based nanofluid for the purpose of steel quenching to check the effect of nanofluid on mechanical and surface properties [35]. Tiara et al. [36] have used alumina nanofluid to enhance the heat transfer performance of hot steel plate using jet impingement cooling. In this study, authors have observed that increase in surface roughness due to nanoparticle deposition and augmentation in thermal conductivity of the quenching medium directly influences the heat transfer performance. It is quite obvious from the literature review that bulk of the recent research on nanofluid is focused on metal-oxide and carbon based nanofluid. However, in the present study, authors have used a new kind of nanofluid for extracting heat from a hot steel plate (above 900 °C). Layered Double Hydroxide (LDH) is anionic clay which has a versatile chemical formula enabling it to combine two different metal ions of higher thermal conductivity (such as $Cu^{2+}$, $Al^{3+}$, $Zn^{2+}$) without calcination. According to Wang et al. [37], the general chemical formula for LDH is $[M^{2+}{}_{1-x}\ M^{3+}{}_x(OH)_2]^{x+}(A^{m-})_{x/m}$ x, $yH_2O$, where, $M^{2+}$and $M^{3+}$ are divalent (such as $Cu^{2+}$,$Zn^{2+}$), and trivalent (such as $Cr^{3+}$, $Al^{3+}$) cations, respectively. A is defined as an interlayer anion with m- charge, whereas x and y represent the fraction constants. Chakraborty et al. [38] first investigated the thermo-physical properties (i.e. thermal conductivity, surface tension) of Cu-Al LDH nanofluids. They have observed moderate increase (16.1%) in thermal conductivity value as compared to base fluid. In their later work [39], authors have carried out forced jet cooling of hot steel plate using by Cu-Al LDH (molar ratio of Cu and Al is 2:1) nanofluid and achieved a maximum cooling rate of 154 °C/s. However, changing the Cu and Al molar ratio (4:1 or 6:1) can further enhance the heat transfer potential of Cu-Al LDH nanofluid. Therefore, in this present study authors have used three different molar ratios of Cu and Al (2:1, 4:1 and 6:1) to synthesize Cu-Al LDH nanofluid and carried out spray cooling heat transfer study on hot steel plate to evaluate the best possible molar ratio for this nanofluid based on the cooling rate and heat flux values.

The current work is divided into two parts; first part involves synthesis and characterization (XRD analysis, FTIR analysis) of Cu-Al LDH nanoparticle and measurement of particle size, thermo-physical properties (thermal conductivity, viscosity, and surface tension) of Cu-Al LDH nanofluid. The second part includes spray cooling study of hot steel plate (above 900 °C) by using aforementioned nanofluid. Surface cooling rate, average heat flux, and average heat transfer coefficient values of spray cooling study(for a 6 mm thick steel plate kept at an initial temperature above 900 °C)were measured between 900 and 600 °C at different (Cu: Al) molar ratio and nanofluid concentration.

## 2. Material and methods

### 2.1. Materials

For nanofluid preparation, emplura grade nitrate salts of copper ($Cu(NO_3)_2 \cdot 3H_2O$), aluminium ($Al(NO_3)_3 \cdot 9H_2O$) and sodium ($NaNO_3$) were obtained from Merck, India. Sodium hydroxide pellets (NaOH) of emplura grade were also purchased from Merck, India. Distilled water was used as the base fluid for nanofluid preparation.

### 2.2. Synthesis of Cu-Al LDH nanofluid

In the current work, copper nitrate, aluminium nitrate, and sodium nitrate are mixed with water in three different molar ratios of 2:1:2, 4:1:2, 6:1:2, respectively to prepare aqueous solutions (Solution A) for three cases. 2 M (M) NaOH solution (Solution B) is then added to Solution A in order to increase the pH of resultant solution to 10.7. NaOH acts as a precipitating agent. 2 M NaOH (Solution B) was prepared by dissolving 80 g of NaOH pellets into 1 l of water. The remaining steps of Cu-Al LDH nanofluid preparation method were kept similar to the methods used in our earlier works. The remaining steps of Cu-Al LDH nanofluid preparation method were kept similar to the methods used in our earlier works [38,40]. The reaction mechanism and synthesis scheme have been depicted in Fig. 1(a–b).