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Enhanced Jet Cooling Application Using Zinc/Aluminum Layered Double Hydroxide Nanofluid

Ibtisam A. Hasan

Department of Electromechanical Engineering, University of Technology, Baghdad, Iraq.

*Corresponding Author Email: 50255@uotechnology.edu.iq

ABSTRACT

In this study, a comprehensive heat transfer investigation of steel plate using zinc/aluminum layered double hydroxide (Zn/Al-LDH) nanofluid in jet cooling application is reported. Continuously, a robust correlation between the thermal conductivity and heat transfer was established with respect to the Zn/Al-LDH nanofluid concentration. In details, the highest cooling rate was observed to be 129 oC/s at 150 ppm nanofluid concentration. Surface heat flux maximum value of 2.4 MW/m2 was acquired. Simultaneously, the resultant Zn/Al-LDH nanoparticles were characterized using powder X-ray Diffraction technique (PXRD), Fourier Transform-Infrared Spectroscopy (FT-IR), and Field Emission Scanning Electron Microscopy (FESEM). Particularly, the particle features using FESEM technique was found to be of a plate-like shape and diameter of 43 nm. In conjunction with the aforementioned, it was found that the present study represents a cost-effective and eco-friendly nanofluid for high surface flux applications.

KEYWORDS

Zn/Al-LDH nanofluid, co-precipitation, heat transfer, and heat flux

INTRODUCTION

In steel industries, a variety of cooling techniques have been conventionally proposed where by laminar jet cooling procedure being the most convenient method[1]. However, the existing cooling system, laminar jet cooling, has revealed some drawbacks. One of these drawbacks is the low cooling rate (30-80℃/s), which can be attributed to the impinged water on the targeted plate at low pressure[1, 2].Another major disadvantage of laminar jet cooling system for increased surface temperature is Leiden frost effect[2]. This singularity creates isolating vapor thin film resulting in heat transfer blocking from the hot surface and subsequently leads to low heat removal rate. In contrast to laminar cooling system, forced jet cooling is proposed to demonstrate greater value of cooling rates[3]. The cooling rate value relies on a number of factors such as nature of jet, surface condition of the specimen, and most importantly the thermo-physical features of the coolant [3, 4].

Therefore, scientific research has anticipated a promising additive which is micro-sized particles; this presumably provides improvement in cooling rates[5]. The use of conventional micro-sized particles suspension as a cooling environment is thought to be well-verified yet undesired option due to some negative aspects such as clogging tendency, poor heat capacity, poor stability and noticeable pressure drop increment throughout pumping[6, 7]. Thus, in view of the restricted heat transfer potential of standard coolants alongside the prospect of thermal efficiency required improvement, the invention of nanofluids have attracted a world-wide heat transfer industries emphasis[7, 8]. Nanofluid concept is an innovative strain of energy efficient cooling environment which is acquired via homogeneously dispersed nano-size particles (at least one dimension ranging from 1-100 nm) in the pure fluid[8]. Nanoparticles demonstrate remarkable features in the cooling system; among these are: high mobility, enhanced thermal conductivity, great stability, reduced erosion and pumping cost and high surface area[8-12]. Different types of nanoparticle forms such as carbon nanotubes (CNT), Al_2O_3, TiO_2, CuO, ZnO ...etc. have been developed as an additive to the conventional coolants (water, poly-α-olefin oil and ethylene glycol)[9, 12-15].

The aforementioned methodologies which focus on nanofluid heat transfer mainly used commercially existing forms of nanoparticles. However, a promising nanoparticles structure in the field of heat transfer namely layered double hydroxide (LDH) has been introduced in the current study. LDH is a class of binary dimension anionic layered clays which made of two trivalent and divalent metallic ions. LDH is defined by the formula, $[M_{1-x}^{II}M_{x}^{III}(OH)_2(A^{n-})_{\frac{x}{n}}.mH_2O\ ]$, in which constants M^{III} and M^{II} signify both trivalent and divalent metallic ions (such as Zn^{2+}, Al^{3+}, Cu^{2+}, Mg^{2+}, Mn^{3+}) respectively; *A* and *n* are the interlayer anion and charge on interlayer ion, respectively. While the cation molar ratio is represented by the coefficient *x*[16]. LDHs have established a number of attractive properties for wide-range of applications including photo-catalyst, micro-container, drug delivery, photo-response and dye-sensitized photodetectors [16-19].

In nanofluid applications, LDH has shown a promising features for its enhanced thermal conductivity properties [6, 20, 21]. Nanofluid have been used as an efficient way to increase the heat transfer in different applications [22-27].it was establised that the nanofluids aid to improve the coefficient of heat transfer when nanofluid was used. The effect of the concentration of nanofluid has been discussed with Reynolds number value and with the velocity of fluid. It was found that the increases in the velocities service the nanofluid with the increases of the heat transfer. In this attempt, this manuscript reports a heat transfer study using a series of Zn/Al-LDH concentrations as additive for the coolant (water) whereby both zinc and aluminum exhibit high value of thermal conductivity as compared to other cost-effective materials [21, 28]. The results suggest that a robust correlation between the thermal conductivity and heat transfer can be established. This is achieved by the observation of the thermal conductivity enhanced value at the optimum nanofluid concentration (150 ppm) which in turn demonstrates similar trend in the heat transfer profiles.

PREPARATION AND PROPERTIES ANALYSIS OF ZN/AL-LDH COOLANT

Preparation of Zn/Al-LDH nanofluids

The preparation of Zn/Al-LDH nanofluids was performed using co-precipitation method [29]. In a typical procedure, zinc nitrate, $Zn(NO_3)_2.6H_2O$ (Aldrich, 99 %), was consistently mixed with aluminum nitrate, $Al(NO_3)_3.9H_2O$ (Merck Co., 99.3%), in 200 mL of distilled water under 700 r.p.m. stirring rate. The molar ratio used in this experiment is 3:1. To empower an accurately precise growth procedure (pH=7.5 ±0.5), drop wise addition of 1.25 molar of sodium hydroxide (NaOH, Aldrich, 99%) was supplemented to the mixture under nitrogen gas (N2) environment, in order to abolish the undesired formation of carbonate compound. Consequently, the resultant mixture was exposed to growth process at 70 °C for 12 h in air oven. The attained white precipitate mixture was then proceeded to a multi-cycle washing and centrifuging process. The obtained powder was then dried at 75 °C for 24 h and later grinded using mortar and pestle to obtainsatis factory fine nanoparticles powder. Finally, variety of nanoparticles amount were mixed with distilled water and subsequently sonicated for 3 h to form uniform Zn/Al-LDH nanofluids at different concentrations (50, 100, 150, 200, 250, and 300 ppm).

Characterization of Zn/Al-LDH nanofluids coolant

Structural analysis

As presented in Figure 1, room temperature powder X-ray diffraction (PXRD) of the prepared Zn/Al-LDH nanofluid sample was performed on PXRD; Model X'PERT-PRO PANALYTICAL) with CuKa radiation and wavelength of λ = 0.154nm, the scanning rate was0.07/s ranging from 5º to 70º.In general, diffraction pattern in Figure 1 is indexed to Zn/Al-LDH (JCPDS No.38-0486). In details, there are three pronounced peaks perceived in the spectrum which can be correlated to the basal planes and high-order reflection of (003), (006) and (009) at 2θ 9.9º, 19.9º and 30º, respectively; while another non-basal plane of (110) at 2θ 60.6º in Zn/Al-LDH matrix. Furthermore, additional detected peaks in Figure 1 (highlighted peaks) can be correlated to ZnO hexagonal Wurtzite structure of JCPCS No. 36-1451 [29].

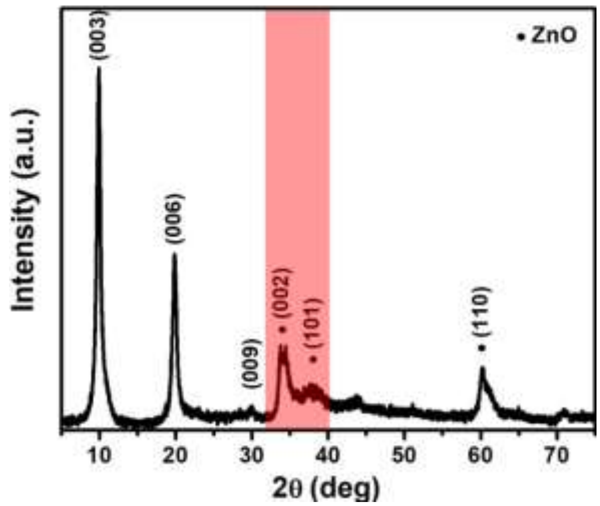

Figure 1. XRD patterns of the prepared Zn/Al-LDH nanofluid.

Fourier Transform-Infrared Spectroscopy (FT-IR) analysis

As depicted in Figure 2, the compact char surface Fourier Transform Infrared Spectroscopy (FT-IR) was recorded on a Thermo Nicolet Nexus in the range of 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1} for Zn/Al-LDH nanofluid sample. The unexpected broad band at around 3390 cm^{-1} is mainly attributed to O-H hydroxyl group stretching. In the meanwhile, the nitrate, which is intercalated between the Zn/Al-LDH interlayers, was found at around 1338 cm^{-1}. Finally, peaks acquired at values below 800 cm^{-1} is due to metal-oxygen vibrations, ν(M-O-H) bending, and ν(M-O) stretching [30].

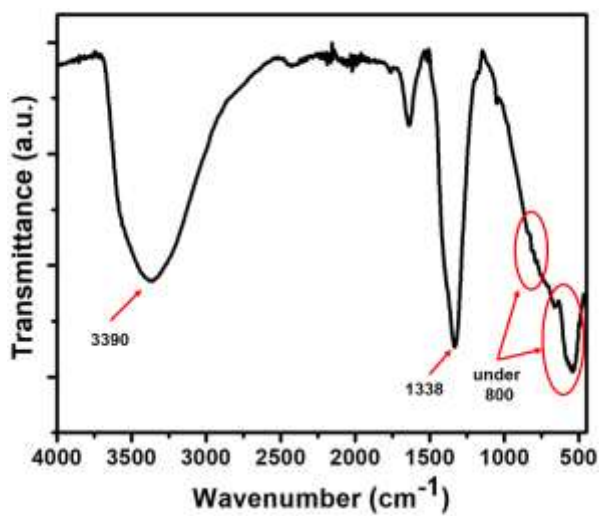

Figure 2. FT-IR analysis of the prepared Zn/Al-LDH nanofluid.

Surface morphology analysis

The morphology evaluation of Zn/Al-LDH nanofluid sample was investigated using Field Emission Scanning Electron Microscopy (FESEM, Hitachi, SU8030) at 5.00 KV, the obtained images are presented in Figure 3 (a and b). It can be clearly noticed that the formation of nanoparticles with plate-like hybrid structures (red circle as illustrated example) in the prepared sample is acquired under FESEM analysis which can be indirectly attributed to the induced phase segregation throughout LDH crystal formation during the one-step co-precipitation method (Figure 3,a).

Interestingly, Figure 3 (b) reveals a clear investigation of the LDH nanoparticles average diameter in which it was estimated to be 43 nm, using Image j software.

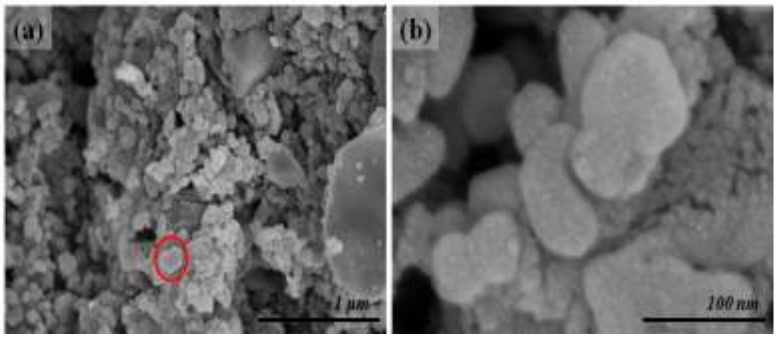

Figure 3. FESEM images of the prepared Zn/Al-LDH nanofluid with scale bar of (a) 1 µm, and (b) 100 nm.

Stability observation

As reported in the literature, nanoparticles agglomeration phenomenon, whereby a layer could be formed on the surface, is of undesired effect on the heat transfer final efficiency. Additionally, this phenomenon could result in corrosion and clogging of metallic tubes inner surface [8, 31]. Therefore, visual monitoring method is conducted to examine the stability of the prepared Zn/Al-LDH nanofluid, as pre-recommended in the literature [31]. Visual monitoring method of the prepared Zn/Al-LDH nanofluid with concentration of 150 ppm is demonstrated in Figure 4 (a, b, c, and d) to explore the phase separation of the Zn/Al-LDH nanofluid solution. As depicted in Figure 4, the prepared nanofluid at the optimum concentration (150 ppm) persisted stable even after 3 days, which ensure the consistency of the solution.

Figure 4. Stability observation of the prepared Zn/Al-LDH nanofluid at 150 ppm; (a) as-synthesized, (b) 1h, (c) 1 day, and (d) 3 days.

Thermal conductivity measurement

Thermal conductivity of the prepared Zn/Al-LDH nanofluid was conducted using needle probe technique (KD3, USA). A variation of the prepared nanofluid thermal conductivity at different concentrations is presented in Table 1. As tabulated in Table 1, an increase in the thermal conductivity is observed as the concentration of the prepared Zn/Al-LDH nanofluid increased to 150 ppm which can be due to higher value of thermal conductivity of the prepared nanoparticles as compared to pure water. The thermal conductivity increment was followed by a decrease in its values as the concentration of the prepared nanoparticles was further increased in the solution. This phenomenon could be mainly attributed to uniform suspension of nanoparticles as well as Brownian motion [6, 32].

Table 1. Thermal conductivity of the prepared Zn/Al-LDH nanofluid at different concentrations.

Concentration (ppm)	Thermal conductivity (W/mk)
0 (water)	0.57

50	0.60
100	0.61
150	0.64
200	0.63
250	0.62
300	0.61

Jet-cooling experimental set-up

A detailed schematic illustration of the jet-cooling system setup and component is demonstrated in Figure 5 (a).AISI 304 grade stainless steel plate with dimensions of 10 cm× 10 cm×0.6 cm was employed in this experiment. In addition, K-type thermocouples namely T-01, T-02 and T-03 with diameter of 3 mm were injected to the stainless steel plate in order to obtain the temperature measurements (dimensions are demonstrated in Figure 5, b). A jet nozzle with circular shape was employed in this experiment for the purpose of hot steel plate quenching. A muffle furnace (maximum heat capacity of 1500 ºC) was used to heat up the steel plate up to 950 º C. Subsequently, the steel plate with targeted temperature (950ºC) was placed on an enclosure while the data of the transient temperature history was observed using data acquisition component (NI DAQ 9174)in conjunction with the aforementioned thermocouples. Hereinafter, a pump was used to supply water while a rotameter was used to control the flow rate ($26 \times 10^{-5} m^3/s$).The water flow through the jet nozzle switching on was well-ordered by the valve. Jet nozzle to steel plate distance was optimized at 40 cm during the experiments [3].Each experiment was repeated three times for each individual Zn/Al-LDH nanofluid solution concentrations (50, 100, 150, 200, 250, and 300 ppm) to reduce measurement uncertainty.

Subsequent to the temperature data recording, INTEMP software was initialized to compute both the temperature of the surface and surface heat flux [33]. As pre-descried [34], a detailed geometry and governing equation were demonstrated. In general, the two-dimensional geometry of the steel plate used in this study has been taken realistically for the calculation of surface temperature and surface heat flux. The steel plate geometry using INTEMP software was divided into 7500 elements and 7780 nodes assuming the entire geometry in two dimensions (x = 10 cm and y = 0.6 cm). The surface under analysis is allocated into three different zones (x= 0 to 36 mm, y =6 mm; x= 36 to 64 mm, y =6 mm; and x=64 to 100 mm, y=6 mm). The transient temperature data history recorded by the thermocouple was used as impute to the nodes in INTEMP software. Positions of thermocouples are illustrated in details in Figure 5 (b).

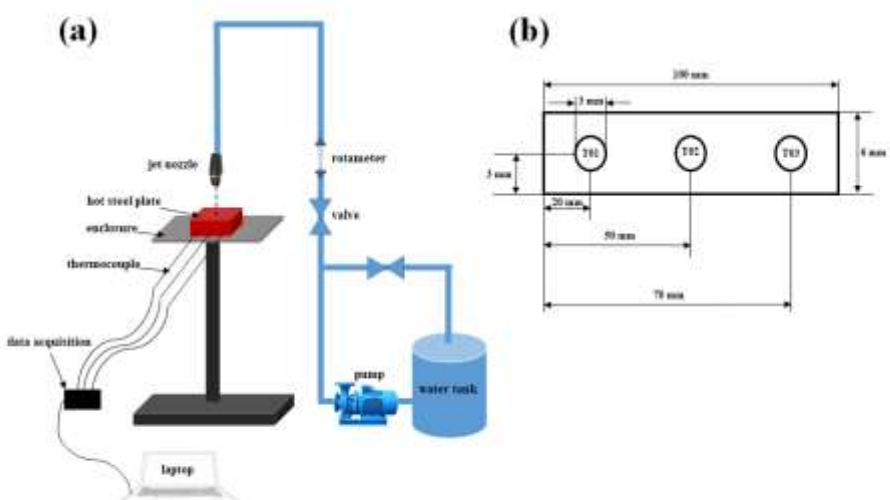

Figure 5. Experimental setup schematic diagram and thermocouple locations

RESULTS AND DISCUSSION

Cooling curve and cooling rate analysis

The cooling rate is retrieved using the transient temperature data history for all experiments as depicted in Figure 6 (a). It can be clearly observed from Figure 6(a) that the cooling curves for all Zn/Al-LDH nanofluid concentrations exhibited a similar trend as a function of cooling time (s). As illustrated in Figure 6 (a), a decrease in the cooling time was noticed as the concentration of Zn/Al-LDH nanofluid increased from 50 to 150 ppm. This phenomenon could be also due to the fact that the solid-liquid contact rises which in turn enhances the heat transfer effectiveness rate [6]. Subsequently, the cooling time augmented with concentration values higher than the optimum one (150 ppm). These findings are in a good agreement with the thermal conductivity profile of Zn/Al-LDH nanofluid (Table 1), whereby 150 ppm nanofluid presented the maximum thermal conductivity value as compared to other concentrations. Concurrently, the aforementioned cooling time decline profile could be because of that at low concentration of Zn/Al-LDH nanofluids, small quantity of LDH nanoparticles are placed on the plate surface resulting in a formation of a nucleation site.

The findings of the current study agree well with previous reports with respect to the nanofluids nature [6, 21, 35]. In the current article, the cooling rate is defined as the required time to cool down the temperature of the steel plate surface from 900 to 600 ^oC (Figure 6, b).The cooling rate curve demonstrated in Figure 6 (b) shows an obvious correlation of the effect of Zn/Al-LDH nanofluid concentration on the cooling curve, demonstrated in Figure 6 (a). As illustrated in the mentioned figure, it is clear to be perceived that the obtained cooling rate progressively rises alongside the LDH nanofluid concentration increment (150 ppm and cooling rate of 129 $^oC/s$), which was followed by a decline in the cooling rate as the concentration was further increased. This phenomenon clearly indicates an ultrafast cooling in which it can be attributed to the impactful jet impingement cooling system with Zn/Al-LDH nanofluid as an additive to water.

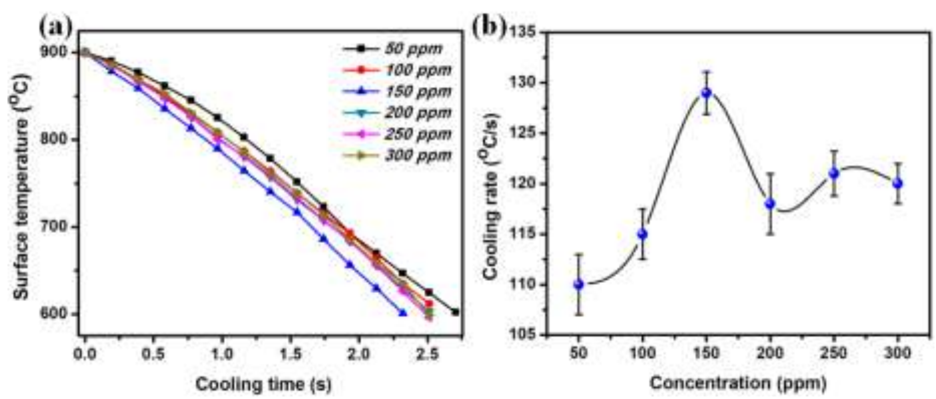

Figure 6. (a) cooling curve and (b) cooling rate at different Zn/Al-LDH nanofluid concentrations.

Boiling curve and critical heat transfer analysis

Figure 7(a) shows the boiling curves for different Zn/Al-LDH nanofluid concentrations at impingement zone. It can be evidently noticed that an increase in the heat flux was obtained until it reached a maximum at around 500 ^oC concentration of 150 ppm and thereafter followed by a sharp decline. The heat flux maximum increment is located below the transition-boiling regime. During such a singularity, coolant falls on the steel's hot surface followed by a rapid vanishing because of the high temperature of the surface, which results in intensifying the contact heat transfer. Concurrently, the surface heat flux extents to a peak significance, which is defined as critical heat flux (CHF, Figure 7 (b), and thereafter it declines as nucleate boiling starts. Values of CHF increased with increment of Zn/Al-LDH nanofluid concentration (Figure 7, b) until the optimum level (150 ppm) with a maximum CHF value of 2.4 MW/m^2 which is higher than that of pure water [36]. This can be explained by thermal conductivity profile of the prepared Zn/Al-LDH nanofluid (Table 1) which in turn can be due to excessive nanoparticle agglomeration and the formation of a thick nanoparticle layer on the steel plate surface. Because of this phenomenon, CHF values decreased upon further augmentation (beyond 150 ppm) of Zn/Al-LDH nanofluid concentration. A similar findings were reported in previous studies with respect to coolants additive formation [6, 21, 36].

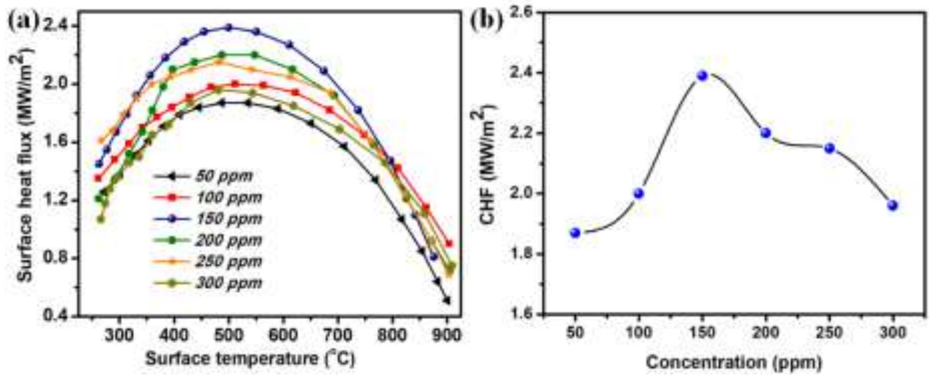

Figure 7. (a) surface heat flux and (b) critical heat flux at different Zn/Al-LDH concentrations.

Variation of heat transfer coefficient

The heat transfer coefficients variation as a function of steel plate surface temperature at different Zn/Al-LDH nanofluid concentrations is demonstrated in Figure 8. The heat transfer coefficient, which is measured in W/m^2. K, is estimated in accordance with the following equation:

$$h = q/(T - T_f) \quad (1)$$

where q is the calculated heat flux (W/m^2), while T and T_f are the surface and coolant temperature in ^{o}C, respectively. From the heat transfer coefficient profile (Figure 8), it can be clearly stated that the different values were acquired even at high surface temperature for all Zn/Al-LDH nanofluid concentrations. Simultaneously, the values of heat transfer coefficient increased as the temperature decreased with respect to the Zn/Al-LDH nanofluid concentration. This hypothesis may be attributed to the onset of nucleate boiling at small steel plate surface temperature. As the cooling process starts, the coolant evaporates on a rapid base upon becoming in contact with the hot surface, which in turn results in small amount of nanoparticles agglomeration on the surface. This leads to an increase of the mentioned agglomeration phenomenon, which subsequently results in hindering the heat transfer rate. Uninterruptedly, the heat transfer rate upsurges alongside the increment in Zn/Al-LDH nanofluid concentration until the optimum level (150 ppm) and then decreased. Similar trends in previous reports were found to be comparable to the current study findings [21,37, 38].

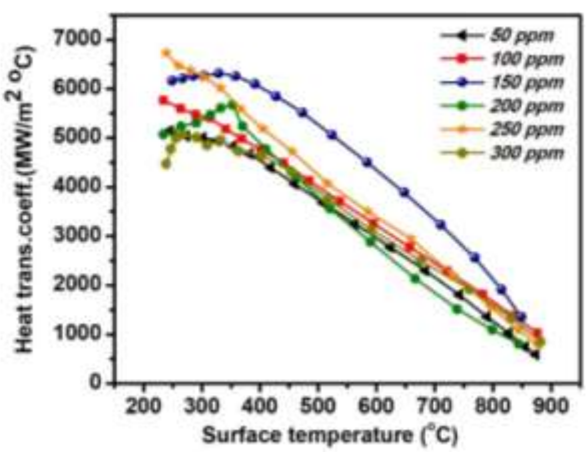

Figure 8. Heat transfer coefficient variation at different Zn/Al-LDH concentrations.

CONCLUSION

The heat transfer analysis of steel plate for jet cooling applications was successfully investigated using Zn/Al-LDH nanofluid as coolant. Particularly, it was found that the optimum thermal conductivity of the prepared nanofluid with concentration of 150 ppm has a direct relation to the heat transfer profile. Predominantly, cooling rate of 129 $^{o}C/s$ was found at 150 ppm concentration in which the highest thermal conductivity was acquired. Continuously, critical heat flux value of 2.4 $MW/m^2MW/m^2$ was noticed at the optimal nanofluid concentration which in turn evidences a low cost Zn/Al-LDH nanofluid for high surface flux applications. Further, FESEM analysis showed that a plate-like shape nanoparticle with diameter of 43 nm can be achieved via modified co-precipitation method.

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