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Enhancement of cooling rate using nanofluid and hybrid nanofluid in cooling hot titanium plate

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ABSTRACT

Ceramic based nanoparticles are having great potential to improve the thermo physical properties of nanofluids for heat transfer applications. Hot Titanium grade-9 ($Ti_3Al_{2.5}V$) plate is quenched in two different fluids, namely aluminium oxide (Al_2O_3)/water nanofluid (NF) and aluminium oxide - titanium oxide (Al_2O_3-TiO_2)/water hybrid nanofluid [HyNF] to remove high heat flux. The performance of nanofluids was analyzed through cooling rate determination. High energy planetary ball milling technique was used to prepare Al_2O_3 and TiO_2 nanoparticles. A K-type thermocouple was embedded on the bottom surface of the plate to measure the temperature. The time–temperature data were recorded by the help of a data acquisition system. Experimental results revealed that the nanofluid as well as hybrid nanofluid surprisingly enhanced the cooling efficiency of titanium plate. Al_2O_3-TiO_2/water hybrid nanofluid shows significantly higher value of cooling rate (around 15%) as compared to the conventional cooling fluids. Also hybrid nanofluid exhibit marginally higher efficiency compared to Al_2O_3/water nanofluid.

Selection and Peer-review under responsibility of the scientific committee of the 2nd International Conference on Nanoscience and Nanotechnology.

1. Introduction

Cooling is one of the foremost necessary technical challenges faced by industries such as automobiles, manufacturing and electronics. New technological developments are required for quicker cooling of hot surfaces. In materials science, quenching is the quickest cooling technique of a work piece in a medium such as water, oil or air to attain specific material properties. Quenching has a high cooling potential and is one of the effective cooling techniques specifically in processes such as steel manufacturing, metallurgy, microelectronic device making and thermal management. Nanofluids are new type of quasi single phase medium containing stable colloidal dispersion of nanometer sized metallic or ceramic particles, fibers, wires, rods, sheets or droplets in base fluids include water, organic liquids, oils and lubricants, bio-fluids, polymeric solutions and other general liquids. These nanofluids have great potential to enhance heat transfer for various applications [1–5]. Huang et al. investigate the effect of hybrid nanofluid mixture in plate exchanger for enhanced heat transfer characteristics [1]. L.S. Sundar et al. indicated that hybrid nanofluids are more effective heat transfer fluids than single nanoparticles based nanofluids or conventional hybrid fluids [5]. The review also demonstrates that hybrid nanofluids were exhibiting higher thermal conductivity than individual nanoparticle (Fe_3O_4) based nanofluid. The thermal properties, such as thermal conductivity of hybrid nanofluids exhibit higher values compared to single nanofluid. Kim et al. conducted detailed analysis of nanofluids exhibiting significantly higher nucleate boiling critical heat flux compared to pure base fluid [6]. The characteristics of critical heat flux augmentation in nanofluids were examined according to the properties of boiling parameters. Efforts to reveal the key factors prominent to nanofluid critical heat flux augmentation are summarized.

Nanofluids are one of the efficient categories of heat transferring fluids that utilize dispersion of fine scaled metallic particles during a heat transport liquid in acceptable size and volume fractions to derive a significant improvement in the effective heat transfer coefficient of the mixture. Nanofluids consists of dispersion of non-metric metallic particles with considerable reduced sized and volume fraction then offers higher effectiveness of heat transfer, as compared to micron sized fluids. A mixture of Al_2O_3 and MWCNT hybrid was used as effective heat transfer fluid.

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The heat transfer characteristic of hybrid nanofluid was higher than that of Al_2O_3/water nanofluid and water. Baghbanzadeh et al. investigated heat transfer characteristics of a hybrid nanofluid mixture containing silica nanospheres and MWCNT. The enhancement in thermal conductivity nanofluid is in between MWCNT (23.3%) and silica nanospheres (8.8%) [7]. There were various investigations on the effective thermal conductivity enhancement of nanofluids and hybrid nanofluids with different parameters [8].

The efficiency of heat transfer of nanofluids depends on various factors. The thermal physical properties of nanofluids vary with temperature, sonication time, base fluid's properties, particle size, particle shape and nature of material. Nanofluids have been extensively studied for improving heat transfer characteristics for past decades [9–18]. In order to perform the quantification of influence of nanoparticles on the heat-transfer performance, the convective heat transfer is a vital thermal parameter because the range of analysis performed on thermal characteristics depends on the thermo-physical properties of nanofluids. Wen et al. have studied Al_2O_3/water nanofluid heat transfer in laminar flow under constant wall heat flux and reported an increase in nanofluid heat transfer coefficient with Reynold's number and nanoparticle concentration, particularly at the entrance region [15]. It is concluded that the thermal developing length for nanofluid was greater than pure water. The reason for heat transfer enhancement of nanofluids is the reduced thermal boundary-layer thickness due to non-uniform distribution of thermal conductivity and viscosity resulting from the Brownian motion of nanoparticles [15]. Putra et al. have reported suppression of natural convection heat transfer by nanofluid of Al_2O_3/water and CuO/water and concluded that this could be due to several factors such as nanoparticle settling and velocity difference between nanoparticles and base fluid [16]. J. Sarkar has reviewed most of the experimental studies and reported that the pressure drop of the nanofluids properly matches with the values predicted from conventional correlations of base fluid for both laminar and turbulent flows[17].

The major objective of the investigation is to carry out the heat transfer characteristics of water based nanofluids such as Al_2O_3/water and their hybrid Al_2O_3-TiO_2/water in cooling of hot titanium grade-9 ($Ti_3Al_{2.5}V$) plate, which is widely used in aircraft components. There are only a few investigations on enhanced cooling efficiency of Al_2O_3-TiO_2 hybrid in hot titanium grade-9 ($Ti_3Al_{2.5}V$). Both nanofluids and hybrid nanofluid are used to quench hot titanium grade-9 test plate to remove high heat flux and their performances were compared. The efficiency of cooling of hot titanium surface by DI water based nanofluids and their hybrids were performed and analyzed.

2. Materials and experimentation details

2.1. Materials

The ceramic materials used in this investigation are aluminium oxide (Al_2O_3) and titanium oxide (TiO_2). The micron sized Al_2O_3 and TiO_2 powders were procured from NICE chemical private limited, India. The deionized (DI) water is used as dispersant medium for dispersing nanofluids.

2.2. Preparation of nanoparticles

Nanoparticles were prepared by ball milling of micron sized Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid powders. Nano-sized Al_2O_3, TiO_2 powders were prepared by mechanical milling using high energy planetary ball mill as shown in Fig. 1(a) and Fig. 1(b) at 300 rpm. with ball to powder ratio 10:1 (wt/wt) [19–21]. µm-

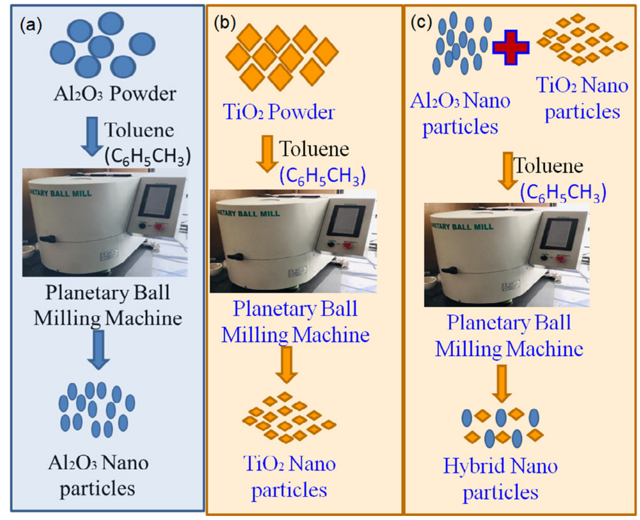

Fig. 1. (a) Preparation of Al_2O_3 nanoparticles; (b) Preparation of TiO_2 nanoparticles; (c) Preparation of Al_2O_3-TiO_2 hybrid nanoparticles; (d) Tungsten carbide balls.

sized aluminium oxide and titanium oxide powders were used as the starting precursor for mechanical milling. Hardened steel jars and tungsten carbide balls were used as the media for mechanical milling while toluene was used for avoiding oxidation of powders. The millings of Al_2O_3 and TiO_2 powders were carried out up to 3 h. A half an hour interval was introduced to avoid overheating of the milling media. The morphologies of Al_2O_3 nanoparticle, TiO_2 nanoparticle and Al_2O_3-TiO_2 hybrid (1:1 wt/wt) nanoparticle prepared were characterized by high resolution transmission electron microscopy (HR-TEM).

2.3. Preparation of nanofluid and hybrid nanofluid

Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid (1:1 wt/wt) nanoparticle based fluids were prepared by employing the two-step methodology, as depicted in Fig. 2. The procedure followed to prepare both the nanofluids was similar. A measured amount of nanoparticles (0.1 gm) was mixed with specific amount (500 ml) of DI water. In order to improve the dispersion of nanoparticle in water, high energy probe sonicator is utilized. The nanofluid mixture was ultra-sonicated for 3 h using probe sonicator. The solution was

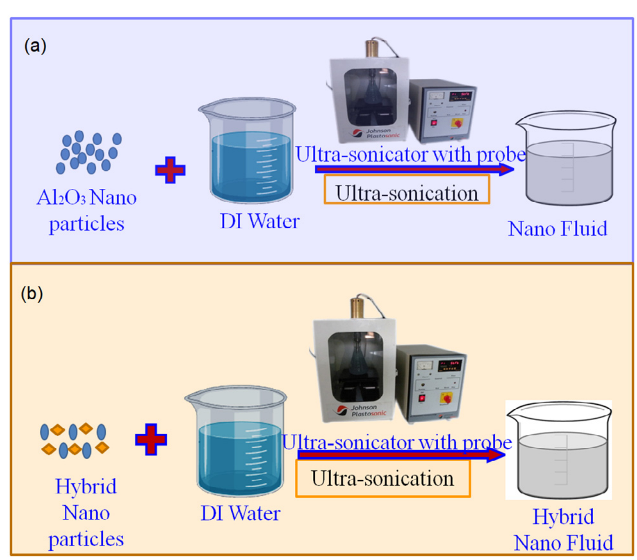

Fig. 2. (a) Preparation of nanofluid; (b) Preparation of hybrid nanofluid.

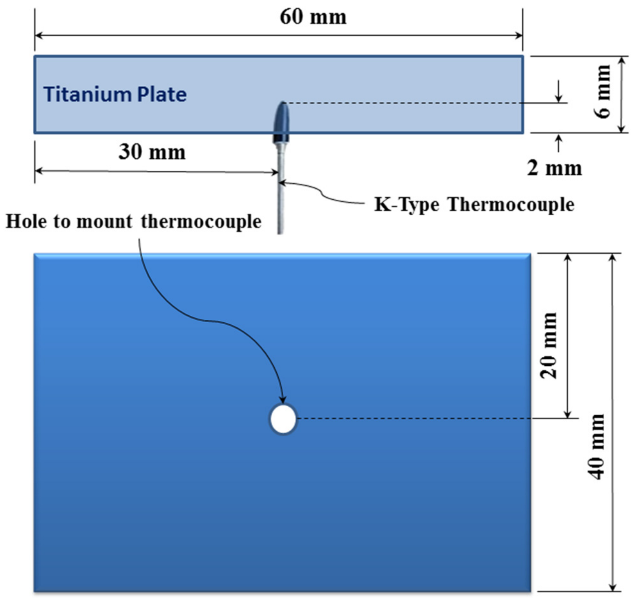

Fig. 3. Mounting and location diagram of thermocouple.

then kept for 24 h to measure the stability. The weight/volume percentage of the nanofluid and hybrid nanofluid was calculated as 0.02%(w/v %) by using Eq. (1).

$$\frac{weight}{volume}\% = \frac{weightofsolute}{volumeofsolution} \times 100, \% \tag{1}$$

During the preparation of nanofluids, no surfactant was added because additions of any surfactants bring changes to the surface property of such colloidal solutions. After the preparation of a standard solution, the stability of nanofluids and hybrid nanofluid was measured by zeta potential. The detailed process flow diagram for preparation of nanofluids and hybrid nanofluid was depicted in Fig. 2.

2.4. Characterization techniques

The morphological analyses of Al_2O_3, TiO_2, and Al_2O_3-TiO_2 hybrid powders were carried out using HR-TEM. Nanoparticle morphologies were then observed under a JEOL 3010 HRTEM at 300 kV. The stability of nanofluid and hybrid nanofluid were determined by zeta potential measurements. The zeta potential measurement of nanofluids and hybrid nanofluid were carried out using Brookhaven Instruments Corporation, UK.

2.5. Cooling set-up

The experimental test set-up in the present experiment comprises of a liquid (pure water or nanofluids) loop and a hot grade-9 titanium plate. The titanium plate (dimension: 130 mm × 60 mm and 6 mm thick) was cut into three pieces of dimension 60 mm × 40 mm × 6 mm each. They were heated inside a furnace up to 400 °C. A K-type thermocouple was embedded at center on the base surface of the plate to measure transient temperature data. The thermocouple data were recorded by using a data acquisition system (CDAC-9171 manufactured by National Instruments) and analyzed through software. Water or nanofluids was taken in a container in which the quenching experiment needs to be done. The hot titanium plate was connected with K–type thermocouples at the center where a hole of 2 mm was drilled. The heated titanium plate is immersed in the nanofluid to cool the plate. The mounting and location of thermocouple in the titanium plate were mentioned in Fig. 3.

The change in temperature is recorded by the thermocouple and is analyzed by the data acquisition system. K-type thermocouples made by Techno Instruments (Gujarat, India) were used to measure the plate temperatures at different desired locations.

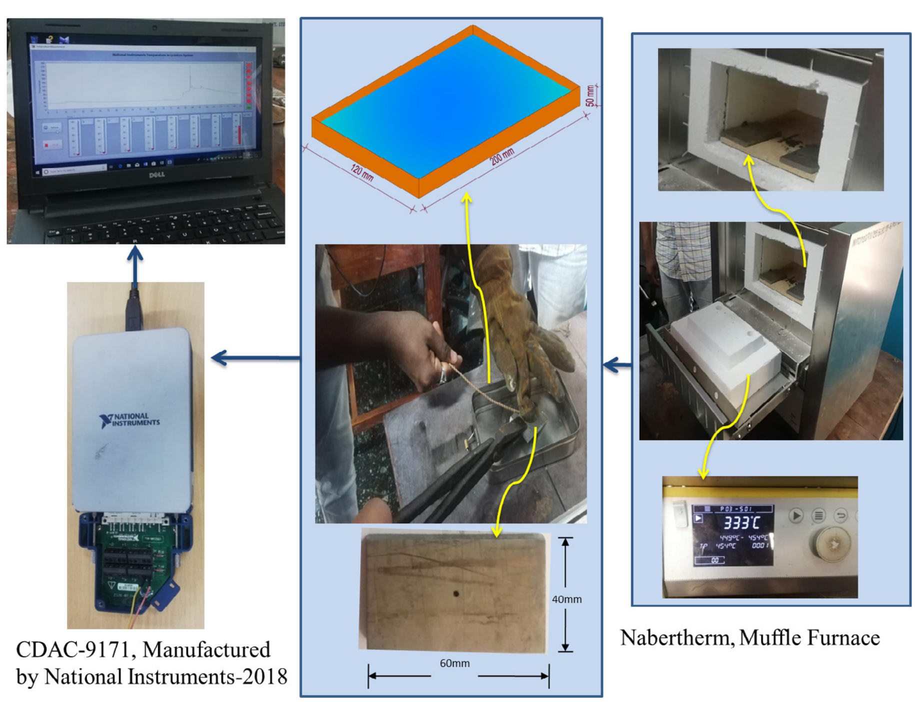

Fig. 4. Experimental set up for cooling experiment.

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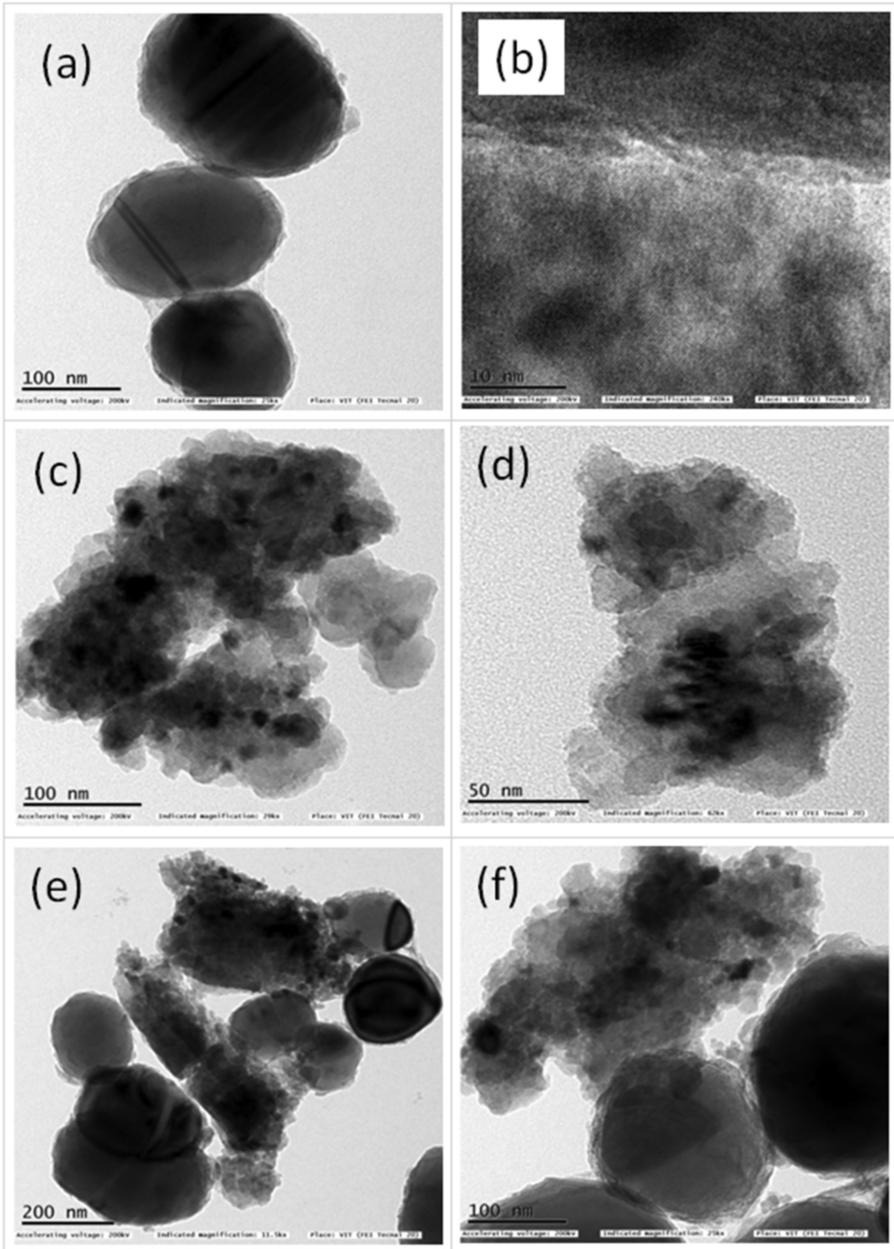

Fig. 5. HRTEM images of (a&b) Al_2O_3 nanoparticles, (c&d) TiO_2 and (e&f) Al_2O_3-TiO_2 hybrid.

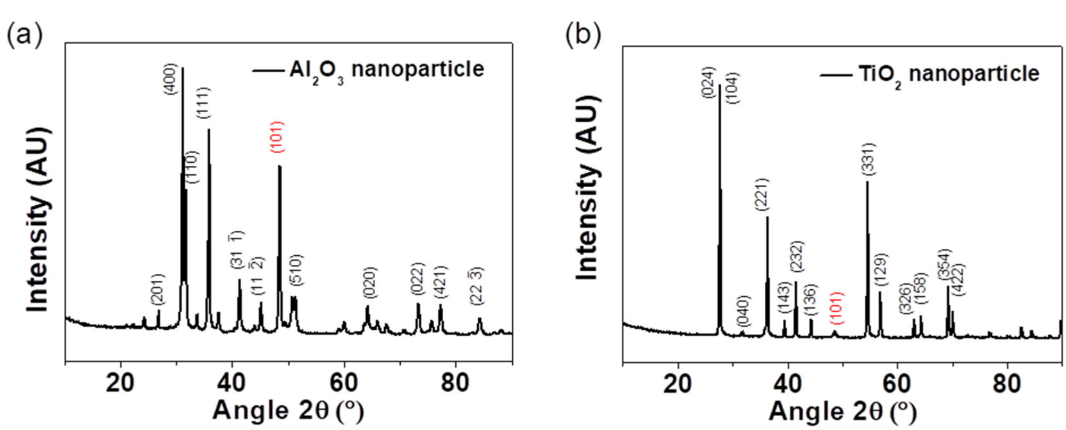

Fig. 6. X-ray diffraction of (a) Al_2O_3 and (b) TiO_2 nanoparticles.

Table 1
Comparison of Zeta potential measurement of nanofluids and hybrid nanofluid.

Sample name	Zeta potential (m V)
Al_2O_3/DI water (Nanofluid)	−17.6
TiO_2/DI water (Nanofluid)	−24.5
Al_2O_3-TiO_2/DI water (Hybrid Nanofluid)	−23.7

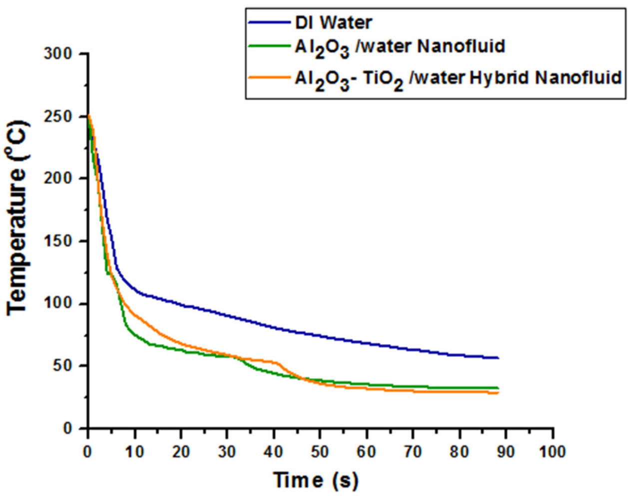

Fig. 7. Measured cooling curve with temperature vs. time curve of DI water, nanofluid and hybrid nanofluid.

The thermocouples were of insulated junction and sheathed by stainless steel of 0.5 mm outside diameter.

2.6. Quenching of titanium plate

When a hot plate is in touch with the liquid quenchant, usually there are three stages of quenching occurs. The three stages of quenching are:

- Vapor stage (vapor blanket stage).
- Boiling stage (nucleate boiling stage).
- Convection stage.

The titanium plate of dimensions 130 mm × 60 mm × 6 mm was cut into 3 plates of dimensions 40 mm × 60 mm × 6 mm and each one of the plate was heated to temperature range of 400 °C. It was allowed to rest these plates inside the Muffle furnace (Nabertherm, Germany) for 15 min. Simultaneously a dish of dimension 120 mm × 200 mm × 50 mm is filled with each solution in the order. Initially the distilled water, then Al_2O_3/water nanofluid and finally Al_2O_3-TiO_2/water hybrid nanofluid respectively.

After rest time of 15 min each plate were taken out of the furnace and is connected with the K-thermocouple at the hole drilled at the center of the plate. The thermocouple is connected with data acquisition system (National Instrument Temperature Acquisition System, at NIT Calicut) and the graph is plotted using recorded values by thermocouples. The quenching must be done carefully using a long arm holder and a pair of thick gloves for hand protection from this high temperature. When the plate is heated to a temperature of 400 °C and now opens the furnace and takes the plate using tongs and connects the thermocouple using clay to the plate, at the point of the drill. Press the thermocouple to the drill hole and apply some clay for proper attachment. The experimental setup for quenching of titanium plate is clearly illustrated in Fig. 4.

3. Results and discussion

3.1. Morphological analysis

The morphology of Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid nanoparticles were determined by HRTEM. Fig. 5(a) and 5(b) shows HRTEM micrograph of ball milled Al_2O_3 nanoparticle with an average dimension of 80–100 nm. Fig. 5(c) and 5(d) shows the HRTEM micrograph of ball milled TiO_2 nanoparticle with an average dimension 30–40 nm. It is seen that the Al_2O_3 nanoparticle have nearly spherical geometry, whereas TiO_2 exists as highly clustered particle with irregular structure.

The morphology of Al_2O_3-TiO_2 hybrid nanoparticles was shown in Fig. 5(e) and 5(f). It is seen that in hybrid nanoparticle, Al_2O_3 and TiO_2 forms a continuous phase with TiO_2 found to be uniformly adsorbed on Al_2O_3 surface to form a homogeneous mixture. The nanoparticles were appeared to be slightly agglomerated due to Van der Waals forces of interaction. Thus while preparing nanofluid; it is necessary to sonicate using probe-sonicator for improved dispersion of nanoparticle in water.

3.2. X-ray diffraction studies of nanoparticle

Fig. 6(a) and (b) Shows the X-ray diffraction analysis Al_2O_3 and TiO_2 nanoparticles prepared by ball milling process. Al_2O_3 nanoparticles shows highest diffraction peaks at 2θ values 31.2°, 31.7° and 36.5° represent corresponding to planes (400), (110) and (111) respectively. The diffraction pattern of Al_2O_3 is compared to JCPDS database 00–120-0005. An additional peak at 48.4° corresponding to (101) plane from tungsten carbide (WC) traces, which arise during ball milling. TiO_2 nanoparticles shows highest intensity diffraction peaks at 2θ values 27.3°, 27.4°, 36.1° and 54.9° corresponding to planes (024) (104)(221) and (316) respectively. The diffraction pattern of Al_2O_3 is compared to JCPDS

Table 2
Percentage difference in cooling temperature using Al_2O_3/water nanofluid and Al_2O_3-TiO_2/water hybrid nanofluid.

Temperature after cooling 88 s (°C)		Difference in temperature (°C)	Difference in percentage
Using Al_2O_3/water nanofluid	Using Al_2O_3-TiO_2/water hybrid nanofluid		
32.4	29.2	3.2	11.02

Table 3
Determination of average value of cooling rate of DI water, nanofluid and hybrid nanofluid.

Average value of cooling rate (°C /s)			Increment in the cooling rate of hybrid nanofluid against Al_2O_3 nanofluid (%)	Increment in the cooling rate hybrid nanofluid against DI water (%)
Using DI water	Using Al_2O_3/water nanofluid	Using Al_2O_3-TiO_2/water hybrid nanofluid		
2.2	2.47	2.53	2.43	15

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database 00–154-7283. This also shows an additional peak at 48.4° corresponding to (1 0 1) plane from tungsten carbide (WC) traces, which arise during ball milling.

3.3. Stability of nanofluids and hybrid nanofluid

The stability of the nanofluid was analyzed by using zeta potential measurements. Table 1 shows the zeta potential values of Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid nanofluids in DI water. Al_2O_3 nanofluid shows a zeta potential of −17.6 mV, whereas TiO_2 and Al_2O_3-TiO_2 hybrid nanofluids showed higher stability in aqueous media with zeta potential of −24.5 mV and −23.7 mV respectively. Thus all the nanofluids show improved stability for further quenching application. Also it is observed that Al_2O_3 and TiO_2 nanofluids show negative zeta potential values.

3.4. Determination of cooling rate

In heat treating, the cooling curve test is usually used as a tool to compare quenchants or as a way to make sure that the quenchant being employed is appropriate for continuing use and can satisfy current necessities.

Experimental result was obtained from the time when the hot plate was placed on the test bed and quenching on the plate started as shown in Fig. 7. The data acquisition system had a sampling time of 88 sec during temperature measurement. The quenching time was recorded till the heated plate obtained ambient temperature. For each experiment, data were stored as excel format files and desired cooling curves were plotted from this recorded data. It is seen that temperature of Al_2O_3/water nanofluid shows a temperature 32.4 °C and Al_2O_3-TiO_2/water hybrid nanofluids shows a temperature of 29.2 °C. Thus hybrid nanofluid shows slightly higher cooling efficiency 11.02% after 88 s as shown in Table 2.

Table 4
Maximum cooling rate values of DI water, nanofluid and hybrid nanofluid extracted from the cooling rate curves.

Different quenchants	Maximum cooling rate (°C /s)	Temperature at maximum cooling rate (°C)
DI water	25.2	193.6
Al_2O_3/water nanofluid	39.1	200.9
Al_2O_3-TiO_2/water hybrid nanofluid	40.7	197.7

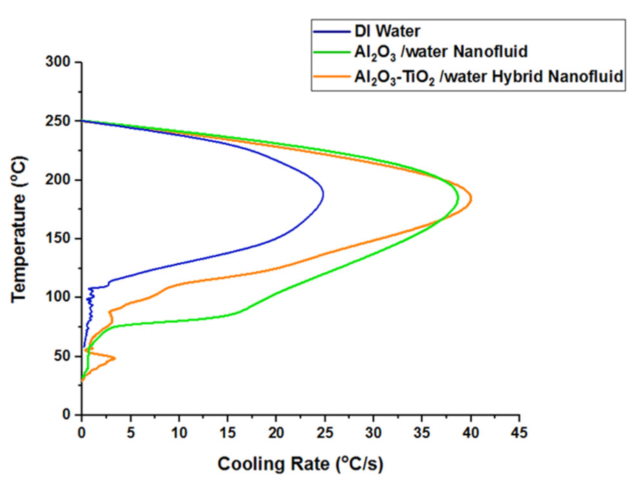

Fig. 8. Effect of hybrid nanofluid on cooling rates as compared to nanofluid and DI water.

From the obtained temperature distribution curves at each thermocouple on three different samples, the corresponding average value of cooling rates were computed by taking the peak values of temperature and time, and by using the following Eq. (2).

$$(CR_{Avg}) = \frac{T_1 - T_2}{t_2 - t_1}, C/S \tag{2}$$

where, CR_{Avg} is the average value of cooling rate in °C/s, T_1 and T_2 are the temperatures (in °C) at the start and end of quenching process, t_1 and t_2 are the initial and final cooling times (in seconds) during the cooling process.

Table 3 shows the average cooling rate values of Al_2O_3/water nanofluid and Al_2O_3-TiO_2/water hybrid nanofluid. It is seen that the hybrid nanofluids shown 2.37% higher cooling rate as compared to nanofluid. As compared to DI water hybrid nanofluid shows 13.3% higher cooling rate as calculate by Eq. (2).

Table 4 it is seen that the maximum cooling rate on the hot titanium surface using Al_2O_3/water nanofluid is 39.12 °C/s, whereas Al_2O_3-TiO_2/water hybrid nanofluid shows 40.72 °C/s. The cooling rate curve response of hybrid nanofluid and nanofluid shows an increased maximum cooling rate in comparison with the DI water is clearly depicted in Fig. 8. The extracted data of maximum cooling rate and temperature at maximum cooling rate is given in Table 4.

4. Conclusion

An experimental set-up was designed and fabricated to investigate the enhancement of cooling rate of nanofluid as well as hybrid nanofluid for cooling a 6 mm thick titanium plate. The morphologies of Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid nanofluid were analyzed using HRTEM. The stability of aqueous dispersion of Al_2O_3, TiO_2 and Al_2O_3-TiO_2 hybrid were analyzed using zeta potential measurement and found that all nanofluids showing higher stability. The hybrid nanofluid shows good stability with zeta potential of 24 mV. From the cooling experiment of nanofluids, it can be concluded that the Al_2O_3-TiO_2/water hybrid nanofluid as well as Al_2O_3/water nanofluid shows improved cooling rate. Al_2O_3-TiO_2/water hybrid nanofluid shows a significantly higher cooling rate as compared to Al_2O_3/water nanofluid. Hybrid nanofluid exhibited about 2.4% and 15% increase in average value of cooling rate as compared to Al_2O_3/water nanofluid and DI water respectively. The cooling efficiency of hybrid nanofluid is significantly higher than water. Application of hybrid nanofluid for the titanium plate cooling was found very effective in terms of heat transfer phenomena as compared to the conventional fluid cooling methods. The future scopes of nanofluids are specifically for energy storage devices such as fuel cells and solar panels. There are a few preliminary studies on applications in proton exchange membrane fuel cells and solar panel application [22–23].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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