Enhancement of heat transfer by water—Al₂O₃ and water—TiO₂ nanofluids jet impingement in cooling hot steel surface

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ABSTRACT
Two different nanofluids, namely water—Al₂O₃ and water—TiO₂, were impinged in the form of jet on hot steel surface to remove high heat flux, and their performance was compared. The dimension of the test steel sample was 120 mm × 120 mm and 4 mm thickness. Four K-type thermocouples were embedded on the bottom surface of the plate to measure the transient temperature distribution. The time-temperature data were recorded by the help of a data acquisition system (make: CHINO, model: KR2000), and the results were analysed by ZAILA application software. Effect of impinging nanofluids with weight concentrations of 0.01%, 0.03%, 0.05% and 0.07% Al₂O₃ and TiO₂ nanoparticles on heat transfer from the hot surface was tested. The surface heat transfer coefficient (HTC) was computed from the time-temperature history recorded during experimentation. Experimental results revealed that addition of nanoparticles to the base fluid (water) surprisingly enhanced the heat transfer rate and HTC as expected. The heat transfer rate increased up to certain limit of nanoparticle concentrations, and then declined. Application of nanofluids for the steel strip cooling was found very effective in terms of heat transfer phenomena as compared to the conventional fluid cooling methods.

1. Introduction
Impingement of heating and cooling was found to be one of the great challenges in most of the industrial applications like metal manufacturers, power plants, transport sectors and electronics. Various methods including extended surfaces, pulsed hot surfaces and fluid impingement can be used to improve heat transfer. Nanofluids are new type of quasi single phase medium containing stable colloidal dispersion of nanometre metallic or ceramic particles, fibres, wires, rods, sheets or droplets in base fluids include water, organic liquids, oils and lubricants, biofluids, polymeric solutions and other general liquids. These nanofluids have great potential of application to enhance heat transfer.
Combination of liquid jet impingement and nanofluids technology was attempted to explore advantages of both and enhance the heat transfer.

Impinging jets have got significant consideration because of its inherent qualities of accomplishing generally high rate of cooling from relatively small surface range. Impinging jets are frequently utilised as a part of different mechanical applications, specifically, drying of food items, textile, film and papers, preparing of a few metals and glass, cooling of gas, cooling of turbine blade and outer wall of combustion chamber and cooling of electronic device. The heat transfer rate for jet impinging is strongly affected by the different parameters, for example, Reynolds number, jet to plate distance, radial separation from stagnation point, Prandtl number, target plate inclination, nozzle geometry, curvature of target plate, and roughness of the plate and turbulence force at the nozzle exit. Different heat transfer regimes are recognised in water jet impingement, for example, film boiling, transition boiling, nucleate boiling and forced convection are recognised during impinging jet with water as coolant.[1-7]

The research of the heat transfer characteristics of nanofluids has been limited to pool boiling experiments. As illustrative, various concentrations of nanoparticles in pool boiling experiments have shown increase in critical heat flux and heat transfer coefficient in comparison with pure water.[8-17] Also, the critical heat flux reached a plateau after certain concentrations which also depended on the type of nanoparticles.[18,19] It has also been reported that the size of the particles used can affect the heat transfer properties of the fluid. Anoop et al. reported that smaller particles have greater heat transfer coefficient compared to larger particles in the developing region of internal flow.[20] There is almost no experimental data available in the open literature on cooling of hot surfaces by fluids with suspended nanoparticles in the film boiling regimes. For nucleate boiling, Bang and Chang [11] presented that particle concentrations performed poorly on a plain surface and the nanoparticles deteriorated the boiling mechanism by changing the surface characteristics as concentration increased.

Nguyen et al. [21] investigated experimentally the heat transfer characteristic of a 36 nm Al2O3-water nanofluids with different volume fraction ranging from 0% to 6% in a confined and submerged impinging jet on a flat, horizontal and circular heated surface. The highest surface heat transfer coefficients can be obtained with an intermediate nozzle-to-surface distance of 5 mm and a 2.8% particle volume fraction nanofluid. In the confined impinging jet configuration condition, the nanofluids with high particle volume fractions, i.e. 6% or higher are not suitable for the heat transfer enhancement. Vajjha et al. [22] numerically studied the performance of the flat tubes of an automotive radiator by using two different nanofluids consists of aluminium oxide (Al2O3) and copper oxide (CuO) nanoparticles, dispersed in ethylene glycol and water mixture under a three-dimensional turbulent flow condition. The results showed that under the basis of equal pumping power, Al2O3 and CuO nanofluids up to 3% and 2% particle volumetric concentrations, respectively, provide higher heat transfer coefficients than that of the base fluid.

Tie et al. [23] experimentally investigated the heat transfer characteristics of CuO-water nanofluids of volume fraction varying from 0.17% to 0.64% flowing through the multiple jet arrays impingement cooling system. The addition of nanoparticles can remarkably improve the heat transfer behaviours of the base fluid and the heat transfer coefficient increases with the increasing of volume fraction of nanoparticles. However, the combination of 0.17% volume fraction nanofluids results an adverse effect on heat transfer.
coefficient. Lelea and Laza [24] used finite volume method for numerical simulations of water based Al₂O₃ nanofluids flowing through a micro tube heat sink with five inlet jets configurations. The results showed that except specific heat, both the thermal conductivity and viscosity of nanofluids are higher than the base fluid water. Mitra et al. [25] studied the boiling heat transfer aspect of water—TiO₂ and water–multiwalled carbon nanotubes (water—MWCNT) nanofluids based on laminar jet cooling of horizontal heated steel plate. The cooling rate was enhanced by using 0.1 % wt. water—TiO₂ and 0.01 % wt. water—MWCNT nanofluids as compared to the base fluid. The development of nanoadsorption layer on the heated surface during spray impingement cooling by using nanofluids drastically affected the thermal performance of cooling system. With an increase in nanoparticle concentration, the adsorption layer thickness increased and absorbed the nanofluid droplets due to capillary action and, thus, reduced the contact angle.[26,27] The adsorption for nanoparticles was highly dependent on the size of the nanoparticle and was linearly correlated with the enhancement of the thermal conductivity.[28]

Although the effects of nanofluids have been investigated in pool boiling, there are very less experimental results available for film boiling regimes. The previous works include investigations on influence of types of nanofluids, change in nanoparticle type, size and concentration, change in base liquids, different jet set-up, distinctive initial surface temperature and extensive variety of Reynolds number. The present work is a comparative study between different nanofluids and distilled water in cooling of a hot stationary steel plate in the film boiling regimes. Two types of nanoparticles Al₂O₃ and TiO₂ with distilled water as base fluid are used in the experiment to investigate the heat transfer characteristics of jet impingement cooling system. The effect of different controlling parameters such as particle concentrations and jet pressures on surface heat transfer rate was thoroughly investigated.

2. Experimental set-up and procedure

2.1. Preparation of nanofluids

The nano-sized titania and aluminium oxide powders were prepared by mechanical milling using high energy planetary ball mill (Figure 1) at 250 rpm with ball to powder ratio 10:1. Micron-sized titania and aluminium oxide powders (the particle sizes: approximately 45 μm, 99.8% purity) were used as the starting precursor for mechanical milling. Hardened steel jars and balls were used as the media for mechanical milling while toluene was used for avoiding oxidation of powders. The millings of TiO₂ and Al₂O₃ powders were carried out up to 10 hours, with milling time of 2 hours. A half an hour was introduced to avoid overheating of the milling media. For TiO₂ powders, mass density and thermal conductivity values were measured as 4.23 g/cm³ and 11.7 W/m-K, respectively. Similarly, the mass density, molar mass and thermal conductivity values for Al₂O₃ powders were found to be 3.9 g/cm³ and 34 W/m-K. The TiO₂ and Al₂O₃ nano powders fabricated are shown in Figure 2(a,b). It was clearly observed from Figure 2(a,b) that the colour of Al₂O₃ nanoparticle is white and that of TiO₂ nanoparticle is greyish.

The scanning electron microscopy (SEM) micrographs and energy dispersive X-ray spectroscopy (EDX) analysis in Figure 3(a,b) show the typical morphology of the powders where the average particle size, estimated from the micrographs, is 20 nm. The micrographs indicate a fair amount of agglomeration of the particles which is typical of powders
Figure 1. The planetary ball milling machine.

Figure 2. (a) Al$_2$O$_3$ nanoparticles obtained ball milling and (b) TiO$_2$ nanoparticles obtained ball milling.
Figure 3. SEM and EDX micrographs of (a) Al$_2$O$_3$ nanoparticles and (b) TiO$_2$ nanoparticles.
produced by high energy ball milling. The average agglomerate size is about 100 nm. TiO$_2$ and Al$_2$O$_3$ nanoparticle based fluids were prepared by employing the two-step methodology, as depicted in Figure 4. The procedure followed to prepare both the nanofluids was similar. A measured amount of nanoparticles was mixed with certain amount of demineralised water. The mixture was then passed through a constant magnetic stirring of 1200 rpm speed for 3–4 hours. The solution was then kept for 24 hours to prepare the precipitation. A sample of solution was kept over a Petri dish. The Petri dish was then heated to dry out the solution completely, which provided the weight percentage of nanoparticle actually used to prepare a standard nanofluid. The weight percentage of the constituents was calculated by using Equation (1).

$$\frac{W_n}{W_f} = \frac{W_{p+n} - W_p}{W_f} \times 100, \quad \%$$

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 test was performed for each nanofluid with different nanoparticle concentrations. The nanofluid containing the highest (0.07% wt.) weight percentage particle remained stable for three days. However, after three days, clustering started to occur in the solution. Magnetic stirring was applied to breakdown the clusters. Similarly, for nanofluid with lowest (0.01% wt.) weight percentage particle, the particles were stable up to 10 days in both the TiO$_2$ and Al$_2$O$_3$ cases. In case of intermediate weight percentage particles (0.03% wt. and 0.05% wt.), the nanofluids were stable for seven and five days, respectively.

2.2. Jet impingement cooling set-up

The experimental test set-up in the present experiment comprises of a liquid (pure water or nanofluids) loop and a hot square steel plate as depicted in Figure 5. The square steel plate (dimension: 120 mm $\times$ 120 mm and 4 mm thick) was heated using an electrical coil.

Figure 4. The two-step preparation process of nanofluids.
heater of capacity 2.5 kW and operating voltage of 230 V. The heating element used was spiral stainless steel heating coils of 0.008 m diameter. High thermal conductivity ceramic base was used to hold the heating coil in its cylindrical gap housing. The energy of the heater was controlled using a variable transformer (made by Voltamp Controls Pvt Ltd., Mumbai, India). The voltage, current and the electric energy of the heater were measured by an energy meter (made by MetrixPlus Instruments, Pune, India). The uncertainties in measurement of voltage, current and energy were recorded as ±0.5, ±0.7 and ±1.5, respectively. Four K-type thermocouples were embedded at different locations on the base surface of the plate to measure transient temperature data. The thermocouple data were recorded by using a data acquisition system (made by CHINO, Mumbai, India) and analysed through ZAILA application software. Water or nanofluids was allowed to flow from the collecting tank through flexible tubes using a centrifugal pump with controlled flow rates. The liquid jet emerged from the two glass nozzles and impinged on the horizontal square steel plate. Two nozzles of 0.002 m diameter were used in the current investigation. The nozzle length to diameter ratio is kept above 20 to avoid the effect of entrance on jet exit. The centre-to-centre distance between two nozzles was 40 mm during experimentation. K-type thermocouples made by Techno Instruments (Gujarat, India) were used to measure the plate temperatures at different desired locations. The thermocouples were of insulated junction and sheathed by stainless steel of 0.0005 m outside diameter. The thermocouples were embedded at the bottom surface of the plate at desired locations as shown in Figure 6(a). The thermocouples were inserted in 0.002 m diameter and

Figure 5. Schematic of the jet impingement cooling experimental set-up.
0.001 m length holes in the plate using spot welding operation as depicted in Figure 6(b). Water jet temperature was measured using a thermocouple before jets exit from the nozzles. The thermocouples and data acquisition system were calibrated at ice and boiling points. At the ice point, the error in thermocouple readings was in the range from 0.2 to 0.1 °C. At the boiling point, the error in the thermocouple readings was in the range from 0.15 to 0.5 °C.

2.3. Experimental procedure

Tests were performed to examine the influence of types of nanofluids, nanofluid flow rates and concentrations, nozzle exit to plate distance on transient cooling of horizontal square steel plate. Experimental data were generated for nanofluids with Al$_2$O$_3$ and TiO$_2$ nanoparticle weight concentrations of 0.01%, 0.03%, 0.05% and 0.07%. Deionised (DI) water with no nanoparticle was used as reference liquid in the present study since it was the base fluid of the used nanofluids. Two nozzles were used to investigate the heat transfer characteristics of jet cooling of 4 mm thick hot steel plate. The jets from the two nozzles covered the total surface of the plate during cooling.

To examine the effect of flow rate on cooling, the control valve was used to regulate the desired flow rate through the nozzles. The test plate was heated to the required temperature with the help of an electrical heater in air. As soon as the plate reached the desired
temperature, it was then shifted to the test bed below the nozzle for cooling by impingement of the fluid. The data acquisition started collecting thermocouple readings and data were processed in the computer loaded with ZAILA application software. The experiments were conducted at a nozzle to plate distance of 120 mm. The tests were carried out first for pure water only, further for two types of nanofluids (water–Al$_2$O$_3$ and water–TiO$_2$) with different weight concentrations (0.01%, 0.03%, 0.05% and 0.07%).

3. Data computations

Cooling result was obtained from the time the hot plate was placed on the test bed and the jet impingement on the plate started. The data acquisition system had a sampling time of 0.01 sec during temperature measurement. The jet cooling 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. From the obtained temperature distribution curves at each thermocouple location, the corresponding maximum value of cooling rates were computed by taking the peak values of temperature and time, and by using Equation (2).

$$CR = \frac{T_1 - T_2}{t_2 - t_1}, \ {^\circ}C/sec$$  \hspace{1cm} (2)

where CR is the maximum value of cooling rate in $^\circ$C/sec, $T_1$ and $T_2$ are the temperatures (in $^\circ$C) at the start and end of jet impingement, $t_1$ and $t_2$ are the initial and final cooling times (in sec) during the cooling process.

The heat transfer coefficient based on the temperature difference between the plate average temperature $T_s$ and the water jet temperature $T_c$ (before hitting the hot surface) was calculated based on Equation (3).

$$h = \frac{\rho \times C \times \tau \times CR}{T_s - T_c}, \ W/m^2.{^\circ}C$$  \hspace{1cm} (3)

4. Results and discussion

4.1. Experimental uncertainty analysis

In the current investigation, the main sources of errors in the experimental results are measured parameters. The effort was made to minimise these errors for better accuracy in the investigated outcomes. According to uncertainty methodology by American Society of Mechanical Engineers (ASME) test code PTC 19.8-1983, the errors are expressed in terms of two components: (1) systematic or bias error ($B$), due to faults in the measuring instruments involved in the investigations, and (2) random or precision error ($S$), due to the imperfection/inadequacy in explaining the parameters being measured, due to noise in the system.[29] The additive uncertainty calculation approach was used to determine the
total measurement errors in the experimental data as per Equation (4). [30]

$$U_{\text{Add}} = \pm \left[ (B) + t_{95} (S) \right]$$

(4)

where $t_{95}$ is ‘Student’s t’ at 95% for the appropriate degrees of freedom.

In order to achieve a high degree of accuracy in the experiments, the systematic errors must be very small. Therefore, initial calibration of the measuring instruments is required in order to minimise the systematic errors. In the present research work, the measured parameters are air flow rate, water flow rate and temperature. The maximum monitored errors for these parameters have been proclaimed in Table 1. Based on veracity/correctness of rotameter and weighing machines, bias errors were found out for flow rates. For measurement of temperatures, the thermocouples were calibrated at the boiling point of water and by pyrometer and standard thermocouple at high temperatures. The emblematic bias in the thermocouple reading is $\pm 2.2^\circ$C having zero precision/correctness error.

In order to achieve minimum error in the temperature measurement, specially calibrated thermocouple extensions wire was used in every investigation. Thermocouple installation through the holes of the test specimen plays an important role to determine the correctness of the measured temperature data during cooling process. Therefore, much attention should be taken for proper contact of the thermocouple, test plate and measured point by stuffing the thermocouple hole with an extremely conductive material to reduce the secluded air gap. Another important aspect for temperature error is DAS involved in the investigation. As proclaimed by the manufacturer, the offset in the temperature measurement is $+0.7^\circ$C and sensitivity is $<0.07^\circ$C.

Each set of cooling experiment was repeated 3—4 times, and the cooling rate as well as the heat transfer coefficient has been computed at the same operating circumstances condition. From the imitated experimental results, the average value and the standard deviation have been computed and the variation from the average value was $\pm 1.38\%$. This illustrates the correctness of the experiments administered in the present investigation.

4.2. Cooling curves

Figure 7 presents the typical boiling phenomena during the impingement cooling of a hot steel plate under base fluid (DI water) jet with initial temperature ranging from 650 to
750 °C at each thermocouple location (i.e. TC1, TC2, TC3 and TC4) and different jet pressures. The cooling curves plotted at each thermocouple location were used as reference to compare the effects of different governing factors. For Figure 7, the cooling rate in the stable film boiling regime increases with the increase in working fluid pressure. As the surface temperature decreases from Leidenfrost in the transition boiling regime, the cooling rate increases as more surface wetting and boiling occur. Though, TC1, TC2 and TC4 were located in the symmetry positions, there might be wetting delay time of the jets from the central thermocouple TC3 lead to a large difference in their corresponding heat transfer performances. The expression ‘wetting delay time’ in connection with jet quenching first appeared in the work of Piggot et al. [31]. The wetting delay time should not be thought of as purely a film boiling time since the present observations clearly indicate that surface wetting in the central region can occur a considerable time before movement of the wetting front.

The several transitions in the boiling mode change the heat flux on the plate surface, resulting in the centre temperature (TC3-time) history. The film boiling started immediately after the jet impinged on the plate. Temperature decreased gradually in the film boiling regime, as the heat transfer coefficient is small. In case of the central thermocouple (TC3), approximately at 660 °C, temperature started to rapidly decrease with a significant change in the slope of the curve. This change was caused by collapse of the stable vapour film over the plate. Finally, this temperature converged asymptotically to the temperature of the surrounding liquid at 30 °C.

4.3. Effect of nanoparticle concentration

Figures 8 and 9 depict a comparison of the transient cooling curves for a fresh steel plate cooled in water and in nano fluids with Al2O3 and TiO2 nanoparticle concentrations of 0.01, 0.03, 0.05 and 0.07 % wt. and different jet pressures. The cooling performance of nano fluids is closely identical to that of pure water under the test range of the present investigation. At lower nanoparticle concentrations, this result has good agreement with
that of the previous work. Therefore, at low concentrations, there is no significant influence of addition of nanoparticles in the fluid on the heat transfer behaviour of plate. However, with gradually increased concentrations (0.03 and 0.05 % wt.), the heat transfer rate increased drastically in case of Al₂O₃ nanofluid as compared to that of pure water and TiO₂ nanofluid. Interestingly, with higher particle concentrations (0.07 % wt.), the heat transfer rate decreased for both the nanofluids as compared to pure water.

Example of the variation of heat transfer coefficient in liquid jet impingement for water, Al₂O₃ and TiO₂ nanofluid concentrations 0.01 % wt. at different nozzle to plate
Figures 8—10 present a comparison on heat transfer effectiveness of the used nanofluids with that of DI water. The heat transfer enhancement is clearly noted at the same jet pressure, which means that the nanofluids with different concentrations under study were superior to that of DI water. Effect of nanofluids at jet pressures of 0.1863 and 0.2452 bar can be seen in Figures 8—10 for alumina and titania nanofluids with different concentrations of 0.01—0.07 % wt. and nozzle tip to plate distance of 120 mm. The cooling profile for both surface temperature and heat transfer coefficient was recorded. Generally, they have an increase in heat transfer coefficient as the
nanoparticle concentration increases for both Al₂O₃ and TiO₂ nanofluids, except concentration 0.01% for TiO₂ nanofluids. Such an inconsistency might be due to transient instability or experimental uncertainty. Surprisingly, it was found that Al₂O₃ and TiO₂ nanofluids significantly increased the heat transfer performance during jet cooling in comparison with DI water, as shown in Figure 10. The characteristics of a nanofluid
depend on a number of parameters, including: the properties of base fluid and the dispersed phase, nanoparticle size (Al₂O₃/TiO₂, present study), concentration and morphology. Upon careful investigation, although it was found that Al₂O₃ nanofluids have a little higher thermal conductivity increase than TiO₂ nanofluids, which can be found later, TiO₂ nanofluids have a superior cooling performance to that of Al₂O₃ nanofluids. Although the effect of the nanoparticle concentration is limited, differences among them can be clearly noted again. The effect of nanofluids on cooling curves is quite significant as well, especially when the cooling time is more than 15 sec. Furthermore, the higher nanoparticle concentration would cause a higher cooling performance for both nanofluids due to the effective thermal conductivity increase with particle concentration.

4.4. Effect of impinging pressure

Figures 11 shows the effect of jet pressure on the calculated local heat transfer coefficient at various concentrations of alumina and titania nanofluids, and different nozzle to plate distances, i.e. 120, 180 and 240 mm. The data were compared with that of pure water. It was observed that the heat transfer coefficient increased for the addition of alumina nanoparticles with water compared to titania nanoparticles. This might be due to the higher thermal conductivity of the alumina powders. Increase in jet pressure decreased the heat transfer coefficient. For each nozzle to plate distance, this reduction in HTC value might be due to the fact that with increase in jet pressure, the fluid got blown-off from the plate surface.

4.5. Effect of nozzle exit to plate distance

Three distinct jet to plate distances, such as 120, 180 and 240 mm, were taken in the present investigation. The effect of nozzle height on the surface heat transfer coefficient was compared for the two nanofluids and distilled water. Figures 12 and 13 show the effect of variation of nozzle height on cooling rate. Experimental results revealed that for the enhanced heat transfer, there was combined effect of nozzle to heated plate distance, impingement pressure and particle weight fraction. The maximum heat transfer coefficient can be obtained with the combination of intermediate nozzle to plate distance 180 mm and particle weight fraction of 0.01% in the case of water—Al₂O₃ nanofluid, while nozzle to plate distance 120 mm and particle weight fraction of 0.03% in the case of water—TiO₂ nanofluid. However, the impingement pressure also had significant role in the heat transfer enhancement mechanism.

5. Conclusions

An experimental set-up was designed and fabricated to investigate the heat transfer performance of nanofluids for a 4 mm thick steel plate with an initial temperature of 700 °C. Multiple jet cooling characteristics of nanofluids with 0.01, 0.03, 0.05 and 0.07% weight concentrations of alumina (Al₂O₃) and titania (TiO₂) nanoparticles were extensively examined for DI water with three different nozzle tip to plate distances of 120, 180 and 240 mm, respectively. The transient experiments were carried out and required data for the jet impingement heat transfer coefficient and cooling profiles were reported.
Figure 11. Variation of surface heat transfer coefficient at central thermocouple with respect to nano-fluid concentrations for jet pressures of 0.1863 and 0.2452 bar and nozzle to plate distances (H) of (a) 120, (b) 180 and (c) 240 mm.
The effect of nano fluids on these governing factors was described. The major conclusions are as follows:

- The heat transfer performance in both the nanofluids was found to be almost identical to that in DI water at the lower nanoparticle concentration, i.e. 0.01% wt. The major heat transfer enhancement mechanism can be attributed to the increased mixing rather than to the conventional higher thermal conductivity of the nanofluid, as expected.

Figure 12. Variation of surface heat transfer coefficient due to alumina nanofluid at different nozzle tip to plate distances for (a) $P = 0.1863$ bar and (b) $P = 0.2452$ bar.
A very little amount of nanoparticle deposition was visible on the plate surface during the cooling process.

The effect of nanofluids on enhancement of heat transfer coefficient values is quite significant. Nanofluid prepared with Al₂O₃ nanoparticles provided better heat transfer characteristics as compared to that of TiO₂ and DI water; possibly, it is because the Al₂O₃ nanofluid solution has an evenly dispersed phase without any agglomeration, compared to that of TiO₂ nanofluids.

Figure 13. Variation of surface heat transfer coefficient due to titania nanofluid at different nozzle tip to plate distances for (a) $P = 0.1863$ bar and (b) $P = 0.2452$ bar.
The effect of nanofluids was found significant for the lower nozzle to plate distance, i.e. 120 mm and jet pressure of 0.1863 bar. Increase in the nozzle to plate distance, decreased the cooling rate and heat transfer coefficient. This result might be due to the fact that at the increased distance and pressure, the nanoparticles spread out of the plate surface.

**Nomenclature**

A  Cross-sectional area of plate, m²
B  Total bias error, %
C  Specific heat, J/kg.K
CR  Cooling rate, °C/sec
h  Heat transfer coefficient, W/m² °C
H  Nozzle to plate distance, m
m  Mass of the plate, kg
S  Total random error, %
T  Surface temperature, °C
t  Cooling time, sec
TC  Thermocouple
V  Volume of the plate, m³
U  Total measurement error, %
W  Mass concentration, g

**Greek symbols**

τ  Thickness of the plate, m
ρ  Density of plate material, kg/m³

**Subscripts**

1  Initial condition
2  Final condition
s  Surface
c  Fluid
n  Nanoparticle
f  Standard nanofluid
Add  Additive

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**References**

[1] Xu F, Gadala MS. Heat transfer behavior in the impingement zone under circular water jet. Int J Heat Mass Transfer. 2006;49:3785–3799.
[2] Liu X, Lienhard JH, Lombara JS. Convective heat transfer by impingement of circular liquid jets. J Heat Transfer. 1991;113:571–582.
[3] Woodfield PL, Mozumder AK, Monde M. On the size of the boiling region in jet impingement quenching. Int J Heat Mass Transfer. 2009;52:460–465.

[4] Miyasaka Y, Inada S. The effect of pure forced convection on the boiling heat transfer between a two-dimensional subcooled water jet and a heated surface. J Chem Eng Japan. 1980;13:22–28.

[5] Robidou H, Auracher H, Gardin P, et al. Controlled cooling of a hot plate with a water jet. Exp Therm Fluid Sci. 2002;26:123–129.

[6] Zhou DW, Ma CF. Local jet impingement boiling heat transfer with R113. Heat Mass Transfer. 2004;40:539–549.

[7] Mozumder AK, Monde M, Woodfield PL, et al. Maximum heat flux in relation to quenching of a high temperature surface with liquid jet impingement. Int J Heat Mass Transfer. 2006;49:2877–2888.

[8] Yousefi T, Shojaeizadeh E, Mirbagheri HR, et al. An experimental investigation on the impingement of a planar jet of Al2O3–water nanofluid on a V-shaped plate. Exp Therm Fluid Sci. 2013;50:114–126.

[9] Jaberi B, Yousefi T, Farahbakhsh B, et al. Experimental investigation on heat transfer enhancement due to Al2O3–water nanofluid using impingement of round jet on circular disk. Int J Therm Sci. 2013;74:199–207.

[10] You SM, Kim JH, Kim KH. Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer. Appl Phys Lett. 2003;83:3374–3376.

[11] Bang IC, Chang SH. Boiling heat transfer performance and phenomena of Al2O3–water nanofluids from a plain surface in a pool. Int J Heat Mass Transfer. 2005;48:2407–2419.

[12] Khedkar RS, Sonawane SS, Wasewar KL. Heat transfer study on concentric tube heat exchanger using TiO2–water based nanofluid. Int Commun Heat Mass Transfer. 2014;57:163–169.

[13] Sohel MR, Khaleduzzaman SS, Saidur R, et al. An experimental investigation of heat transfer enhancement of a minichannel heat sink using Al2O3–H2O nanofluid. Int J Heat Mass Transfer. 2014;74:164–172.

[14] Tseng AA, Bellerová H, Pohanka M, et al. Effects of titania nanoparticles on heat transfer performance of spray cooling with full cone nozzle. Appl Therm Eng. 2014;62:20–27.

[15] Arani AA, Amani J. Experimental investigation of diameter effect on heat transfer performance and pressure drop of TiO2–water nanofluid. Exp Therm Fluid Sci. 2013;44:520–533.

[16] Teng TP, Hung YH, Teng TC, et al. The effect of alumina/water nanofluid particle size on thermal conductivity. Appl Therm Eng. 2010;30:2213–2218.

[17] Li Q, Xuan Y, Yu F. Experimental investigation of submerged single jet impingement using Cu–water nanofluid. Appl Therm Eng. 2012;36:426–433.

[18] Golubovic MN, Hettiarchchi HM, Worek WM, et al. Nanofluids and critical heat flux, experimental and analytical study. Appl Therm Eng. 2009;29:1281–1288.

[19] Rimbaut B, Nguyen CT, Galanis N. Experimental investigation of CuO–water nanofluid flow and heat transfer inside a microchannel heat sink. Int J Therm Sci. 2014;84:275–292.

[20] Anoop KB, Sundararajana T, Das SK. Effect of particle size on the convective heat transfer in nanofluid in the developing region. Int J Heat Mass Transfer. 2009;52:2189–2195.

[21] Nguyen CT, Galanis N, Polidori G, et al. An experimental study of a confined and submerged impinging jet heat transfer using Al2O3–water nanofluid. Int J Therm Sci. 2009;48:401–411.

[22] Vajjha RS, Das DK, Ray DR. Development of new correlations for the Nusselt number and the friction factor under turbulent flow of nanofluids in flat tubes. Int J Heat Mass Transfer. 2015;80:353–367.

[23] Tie P, Li Q, Xuan Y. Heat transfer performance of Cu–water nanofluids in the jet arrays impingement cooling system. Int J Therm Sci. 2014;77:199–205.

[24] Lelea D, Laza I. The water based Al2O3 nanofluid flow and heat transfer in tangential microtube heat sink with multiple inlets. Int J Heat Mass Transfer. 2014;69:264–275.

[25] Mitra S, Saha SK, Chakraborty S, et al. Study on boiling heat transfer of water–TiO2 and water–MWCNT nanofluids based laminar jet impingement on heated steel surface. Appl Therm Eng. 2012;37:353–359.
[26] Chang TB. Formation of nano-adsorption layer and its effects on nanofluid spray heat transfer performance. J Heat Transfer. 2015;137:HT-14-1336.
[27] Chang TB, Yang YK. Heat transfer performance of jet impingement flow boiling using Al₂O₃-water nanofluid. J Mech Sci Tech. 2014;28:1559–166.
[28] Kamalvand M, Karami MA. Linear regularity between thermal conductivity enhancement and fluid adsorption in nanofluids. Int J Therm Sci. 2013;65:189–195.
[29] Abernethy RB, Benedict RP, Dowdell RB. ASME measurement uncertainty. J Fluids Eng. 1985;107:161–164.
[30] Dieck RH, Measurement uncertainty models. ISA Trans. 1997;36:29–35.
[31] Piggott BDG, White EP, Duffy RB. Wetting delay due to film and transition boiling on hot surfaces. Nucl Eng Des. 1976;36:169–181.
[32] Kim SJ, Bang IC, Buongiorno J, et al. Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux. Int J Heat Mass Transfer. 2007;50:4105–4116.