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Research article

Experimental investigation on cooling tower performance with Al_2O_3, ZnO and Ti_2O_3 based nanofluids

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Abstract: This study deals with an experimental investigation of the thermal performance of a prototype mechanical wet cooling tower with a counter flow arrangement. Different volume concentrations ranging from 0.18 to 0.50 vol.% of stable Al oxide (Al_2O_3), Zn oxide (ZnO), and Ti oxide (Ti_2O_3) nanoparticles of 80, 35, and 70 nm diameter were considered. Water was taken as a base fluid, and the experiment was carried out at 60, 70, and 80 °C, respectively, in laboratory conditions. The study revealed that an increase in the volume concentration of the nanofluids increased the cooling range, cooling efficiency, convective heat transfer coefficient, tower characteristic called number of transfer unit (NTU), and effectiveness of the cooling tower compared with water at the same mass flow rate and inlet temperature. However, increasing the volume concentration increased the viscosity of the nanofluids, leading to an increase in friction factor. For instance, for 0.18% volume concentration of ZnO, at an inlet water temperature of 66.4 °C and water/air (L/G) flow ratio of 1.93, the cooling range increased by 3.62%, cooling efficiency increased by 33.3%, and NTU increased by 50.5% compared with fresh water (FW).

Keywords: cooling tower; volume concentration; nanofluids; cooling efficiency; NTU

Abbreviations: Δh: Enthalpy change (kJ); L: Water mass flow rate (kg/s); G: Air mass flow rate (kg/s); CR: Cooling range or cooling effect (°C); T_{wi}: Water inlet temperature (°C); T_{wo}: Water outlet temperature (°C); $T_{a,wet,i}$: Wet bulb temperature of the entering air (°C); CA: Cooling approach (°C); CE: Cooling tower efficiency (%); NTU: Cooling tower characteristics or number of transfer unit (-); K: Mass transfer coefficient (kg_{water}/m^2s); a: Contact area of heat transfer per unit tower volume (m^2/m^3); V: Active cooling volume per unit ground area (m^3/m^2); h': Enthalpy of saturated air at bulk water temperature (kJ/kg); h: Enthalpy of air stream (kJ/kg); Q_1: Heat load (i.e., heat transfer rate from water side) (J/s); Q_2: Heat load (i.e., heat transfer rate from air side) (J/s); C_{pw}: Specific heat of water (J/kg·K): h_1: Enthalpy of air at inlet (kJ/kg); h_2: Enthalpy of air at outlet (kJ/kg); α_{avg}: Latent heat of evaporation for water (kJ/kg); $\dot{m}_{water\ loss}$: Water lost to evaporation (kg/s); V: Volume of solution (m^3); m: Mass of substance (kg); ρ: Density of substance (kg/m^3); R: correlation coefficient (-); ε: Relative error (%); y_i: Measured value of cooling efficiency (%); $\hat{y}_i$: Predicted value of cooling efficiency (%); $\bar{y}$: Mean of measured value of cooling efficiency (%); n: Number of interpretations (-); η: Goodness of fit (-)

1. Introduction

The enhancement of heating or cooling in an industrial process may create energy savings, reduce process time, raise thermal rating, and lengthen the working life of equipment. To achieve this, high-performance thermal systems for heat transfer enhancement have become popular [1]. Various works have been conducted on heat transfer performance for practical application to heat transfer enhancement using cooling towers, resulting in the generating cooling tower in the 19th century [2–4].

In a cooling tower, water is cooled by exchanging heat with the air passing along it and is reused in a thermodynamic cycle, absorbing heat from machine components to constantly cool them. The inherently poor thermal conductivity of conventional fluids is a fundamental limitation of heat transfer. Enhancing the thermal conductivity of fluids is a way to increase heat transfer performance [5–7]. However, a major problem of using such large particles is their rapid settling in fluids. To overcome this problem, solids known as nanoparticles that have high thermal conductivity can be added to a fluid, increasing its thermal conductivity [8–11].

In general, cooling towers, popularly known as heat exchangers, transfer heat from the hot water by flowing air via perforated tubes. Consecutively, the water in the cooling tower cools as it transfers heat via conduction to the materials continuously [12–13]. By suspending nanophase particles in heating or cooling fluids, the heat transfer performance of the fluid can be significantly improved [14–16]. Studies have shown that solid materials have the highest thermal conductivity, followed by liquid and gaseous materials [17–19]. A literature review study also revealed that carbon nanotubes, such as MWCNTs-COOH and MWCNTs-OH water-based nanofluids, significantly impact the thermal performance of a heater, reducing energy consumption and increasing the heat transfer rate by approximately 19% compared with pure water [20]. The thermal performance and efficiency of a cooling tower can also be enhanced by using nanofluids such as MWCNTs/H_2O, MWCNTs-COOH/H_2O, MWCNTs-OH/H_2O, and TiO_2 [21–23]. At a concentration of 0.1 wt.%, the nanofluids mentioned above can increase the efficiency by 43%–46% and thus increase the performance characteristics by approximately 6%–16% compared with pure water. However, all investigations have been laboratory- or software-based; hence, the full effects of nanofluids considering thermal conductivity, viscosity, and stability require further examination [24–26].

Surprisingly, adding toner, which is a microfluid, to water increases the effective area for heat transfer by incorporating suspended toner materials. In addition, this increased area exhibits solid-like properties within the water, which helps to enhance thermal conductivity since solids have higher thermal conductivity. To evaluate the impact of using toners at different percentages in water, experiments were conducted to assess total heat transfer in terms of cooling tower efficiency [27]. It was observed, however, that toner tends to adhere to the surface of the cooling tower, damaging the overall system. Therefore, in this research, nanofluids containing Al_2O_3, ZnO, and Ti_2O_3 with water as base fluid were used to enhance heat transfer performance in terms of the number of transfer units (NTU) and cooling efficiency (CE) for a small-scale cooling tower developed in the laboratory. Furthermore, this study emphasizes a counterflow experimental investigation with and without nanofluids in different volume concentrations.

2. Materials and methods

2.1. Theoretical modeling

A cooling tower usually reduces temperature by heat balance based on the mathematical formulation by Eq 1 as [28],

$$\Delta h = \left(\frac{L}{G}\right) \times CR \tag{1}$$

where Δh is the enthalpy change of air (kJ), L is water mass flow rate (kg/s), G is the air mass flow rate (kg/s), and CR is the cooling range or cooling effect (°C).

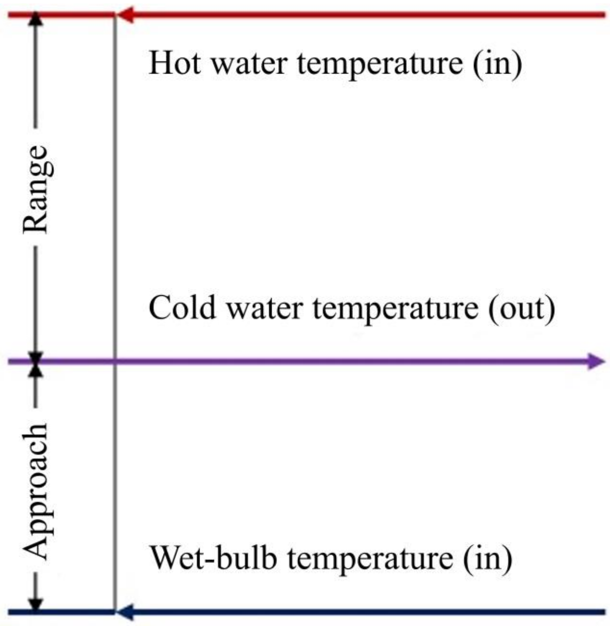

Figure 1. Range and approach in a cooling tower.

The cooling range and the approach are two important characteristics used in cooling towers, as shown in Figure 1. The difference between the water inlet and the outlet temperature is known as the cooling range (*CR*) or as temperature drop and is shown by Eq 2 [15,21]:

$$CR = T_{w_i} - T_{w_o} \tag{2}$$

where T_{w_i} is the water inlet temperature (°C), and T_{w_o} is the water outlet temperature (°C). The difference between water outlet temperature (T_{w_o}) and wet bulb temperature of the entering air ($T_{a,wet,i}$) (the lowest temperature to which the water can be cooled) is known as the cooling approach (*CA*) and is shown by Eq 3 [15,21]:

$$CA = T_{w_o} - T_{a,wet,i} \tag{3}$$

In addition, the cooling tower efficiency (*CE*) is the most important characteristic [15,21,28] defined by Eq 4 as:

$$CE = \frac{Range}{Range+Approach} \times 100\% \tag{4}$$

where range and approach were defined earlier in Eqs 3 and 4. However, various parameters of cooling tower characteristics are primarily represented by the Merkel equation shown by Eq 5 [29,30]:

$$NTU = \frac{KaV}{L} = \int_{T_{wo}}^{T_{wi}} \frac{dT}{h\prime - h} \tag{5}$$

where *K* is the mass transfer coefficient in $kg_{water}/m^2 s$; $\frac{dry\ air\ (kg)}{water\ (kg)}$, *a* is the contact area of heat transfer per unit of tower volume (m^2/m^3), *V* is the active cooling volume per unit of ground area (m^3/m^2), *L* is the water flow rate (kg/s), *h'* is the enthalpy of saturated air at bulk water temperature (kJ/kg), *h* is the enthalpy of air stream (kJ/kg), T_{wi} and T_{wo} are water inlet and outlet temperature (°C), and *G* is the air flow rate (kg/s). The right side of Eq 5 relates to air and water properties and is independent of tower dimensions. Furthermore, $\frac{KaV}{L}$, known as cooling tower characteristics or NTU, can be determined by the integration of Eq 5. $\frac{KaV}{L}$ varies with L/G ratio.

The heat load is defined as the heat content that needs to be removed from the cooling water to the atmosphere per unit of time. The heat load, equal to the heat lost to the atmosphere, can be found based on (i) the water temperature difference at inlet and outlet, and (ii) the fluid's heat lost to and gained by air, using Eqs 6 and 7 [29]. Hence, heat load (i.e., heat transfer rate from water side):

$$Q_1 = \mathrm{L}C_{p_w} = (T_{w_i} - T_{w_o}) \tag{6}$$

Heat load (i.e., heat transfer rate from air side):

$$Q_2 = \mathrm{G}(h_1 - h_2) + \dot{m}_{water\ loss}\alpha_{avg} \tag{7}$$

In Eqs 6 and 7, C_{pw} is the specific heat of water equal to 4180 J/kg·K; h_1 and h_2 are the enthalpy of air at inlet and outlet, respectively; α_{avg} is the latent heat of evaporation for water, equal to 2257 kJ/kg; and $\dot{m}_{water\ loss}$ is water lost to evaporation in kg/s, which is equal to make-up water. Note that evaporation loss is usually very small (i.e., negligible).

The following parameters were used in this study for thermo-physical properties:

1. Dry-bulb temperature (DBT): the temperature indicated by a thermometer exposed to the air in a place sheltered from direct solar radiation.

2. Wet-bulb temperature (WBT): the temperature that 1% of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel.

3. Relative humidity: the ratio of the vapor pressure of moisture in the sample to the saturation pressure at the dry bulb temperature of the sample.

4. Dew point temperature: the saturation temperature of the moisture presents in the air; it can also be defined as the temperature at which the vapor changes into liquid (condensation).

5. Specific humidity: the proportion of the mass of water vapor per unit mass of the moist air sample (dry air plus the water vapor); it is closely related to humidity ratio and always low in value.

6. Absolute humidity: the mass of water vapor per unit of volume of air containing the water vapor. This quantity is also known as the water vapor density.

7. Specific enthalpy: specific enthalpy, h (J/kg), of moist air is defined as the total enthalpy (J) of the dry air and the water vapor mixture per unit of mass (kg) of dry air.

8. Specific volume: the space occupied by air. It is the increase of density and is expressed as a volume per unit of weight.

2.2. Nanofluid preparation

The concentration of nanofluids used in this study refers to the amount of nanoparticles present in the base fluid. This can be expressed as mass percentage, mass fraction, volume percentage, or volume fraction [31,32]. However, for this research work, two concentrations—mass percentage or mass fraction and volume percentage or volume fraction—were considered for preparing nanofluids. In general, mass percentage refers to the amount of solute mass present in the mass of the solution, i.e., grams of solute per 100 grams of solution, which typically includes both solute and solvent. Mass concentration is a useful metric to compare the individual mass of the solute to that of the solvent and helps in predicting the characteristics of the solution. Mass fraction is generally expressed by Eq 8 as:

$$Mass\ Fraction = \frac{Mass\ of\ Solute}{Mass\ of\ Solute + Mass\ of\ Solvent} \times 100\% \tag{8}$$

The volume fraction or volume percentage is generally expressed as concentration of a solution. It is defined as the ratio of volume of solute to the volume of the solution. Water is the solvent in this case. Furthermore, the volume of the solute is insignificant compared to the volume of the base fluid; hence, the volume of solution ≈ the volume of solvent. The volume is equal to the mass of substance divided by density, i.e., $V = \frac{m}{\rho}$; hence, the volume fraction can be expressed by Eqs 9 and 10 as:

$$Volume\ Fraction = \frac{Volume\ of\ solute}{Volume\ of\ solute + Volume\ of\ Solvent} \times 100\% \tag{9}$$

$$Volume\ Fraction = \frac{\frac{Mass\ of\ solute}{Density\ of\ Solute}}{\frac{Mass\ of\ solute}{Density\ of\ solute} + \frac{Mass\ of\ solvent}{Density\ of\ solvent}} \times 100\% \tag{10}$$

In this study, nanofluids are used to enhance the thermal conductivity and increase the cooling capacity of cooling towers. Nanofluids were prepared from nanoparticles of Al_2O_3, ZnO, and Ti_2O_3 in powder form. During preparation, base fluids and volume concentration were considered. Furthermore, the stabilization of the nanofluids was also considered, and the thermal conductivity of nanofluids needs to be estimated. Hence, parameters and characteristics of Al_2O_3, ZnO, and Ti_2O_3 nanofluids were closely observed and the thermal conductivity of nanofluids was estimated accordingly. Thermal conductivity depends on the volume concentration of nanofluids; however, there are limitations in predicting thermal conductivity theoretically. Hence, an empirical formula was used to calculate the conductivity of the two-phase mixture. Note that one-step and two-step methods were used for preparing nanofluids. Consecutively, for powder particles, the two-step method is more convenient and easier to use based on instrumentation limitation. Dispersion was chosen as the method for preparing the nanofluids. Nanofluids were prepared by suspending nanoparticles with average sizes below 100 nm into base fluids, such as water. Several experiments were conducted by changing the ratio of water flow rate to air mass flow to observe the behavior of different characteristics, which are represented graphically. The performance prediction of the cooling tower, related to the performance curves, was made using a few design parameters, including water flow rate, range, cold water temperature, wet bulb temperature, and others.

In this work, five samples of Al_2O_3, ZnO, and Ti_2O_3 nanofluids with different volume percentages were prepared. The data from the experimental investigation is shown in Table 1, considering sample as microfluids (MF) and nanofluids (NF). A total of 28 g of nanoparticles were produced, which underwent a two-step process to become nanoparticles. The procedure involved using a magnetic stirring machine and ultrasound vibrator. Aluminum and zinc salts are generally not dissolvable in water but are 95% dissolvable in ethanol, propanol, and ethylene glycol, so these solvents were used to aid in the preparation of the oxide–water mixture.

Table 1. Volume fractions for microfluids and nanofluids.

Sample name	Volume of solute (L)	Volume of solution (L)	Volume of solution (vol.%)
ES1 MF-1	0.100	165	0.06
ES1 MF-2	0.300	165	0.18
ES1 MF-3	0.500	165	0.30
ES2 NF-1	$\frac{3\ gm}{3.95\ gm/cm^3}$ = 0.000759 L	3.0	0.025
ES2 NF-2	$\frac{20\ gm}{3.95\ gm/cm^3}$ = 0.00506 L	8.0	0.063

The mixture, prepared by a two-step process, is transferred to a magnetic stirring machine and is mixed for 75 min. Once the solution looks homogenous, 800 mL of water is added to the solution. The mixed solution is stirred for another 30 min in order to get 1 L of nanofluids sample solution. The samples are then placed in an ultrasonic vibrator for 30, 60, and 90 min. At this stage, precipitation is not present and the nanoparticles have finer grains suspended in water. Agglomeration of particles is expected to have been reduced due to sonication. The first sample is used primarily as a test drive to check the microscopic structure of the nanofluid.

2.3. Schematic diagram of cooling tower

A schematic diagram of the cooling tower is shown in Figure 2. Air enters through the lower passage of the cooling tower through a dry bulb sensor, which provides the value of air humidity. Continuous air goes through the cooling tower and is cooled down by the induced fan that dissipates the heat from the air. Heated air then goes out through the upper portion of the cooling tower and into the atmosphere. With the help of another dry bulb sensor, the value of humidity of the air going out in the atmosphere is obtained. Water enters through the inlet of the cooling tower from a reservoir via a pump of 0.5 hp capacity. A waterproof temperature sensor gives the temperature.

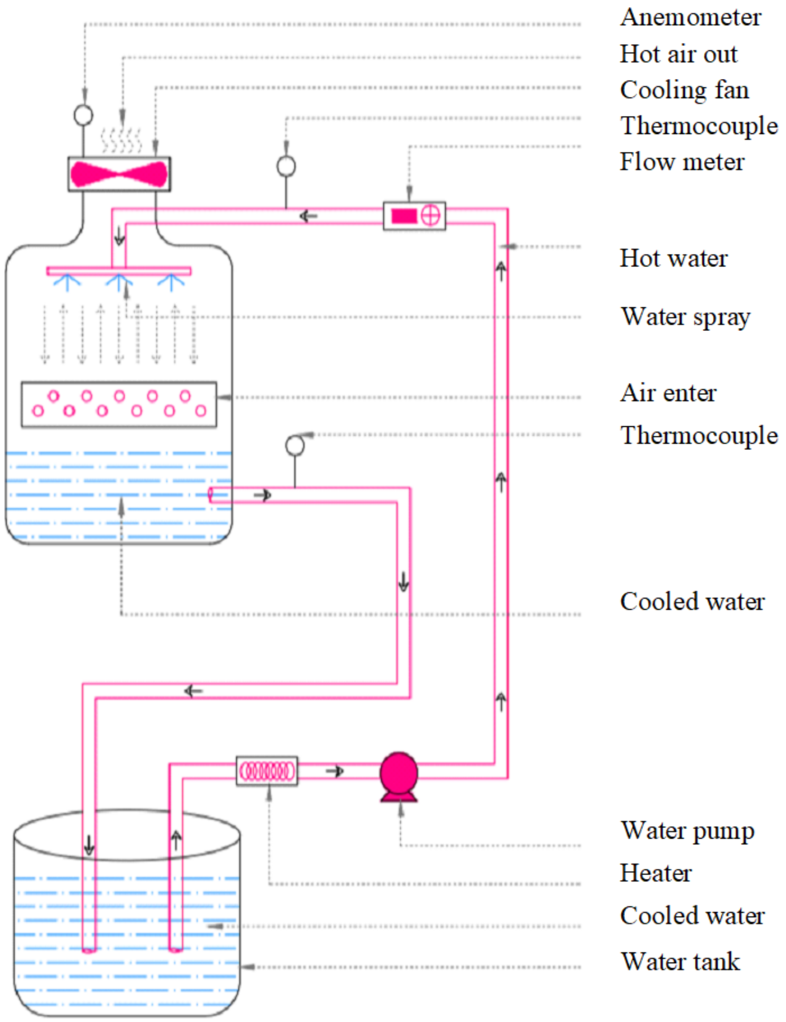

Figure 2. Schematic diagram of a cooling tower.

2.4. Experimentation

During the experimental investigation, make-up water (i.e., water added to the circulating water system to replace the water lost) is supplied to the cooling tower developed by the authors in laboratory (Figure 3) in order to compensate for water loss. Hence, the water lost to vaporization needs to be replaced to the cooling tower occasionally. Cooling tower details can be found elsewhere published by the authors [28]. In this experiment, 0.25, 0.375, and 0.5 vol.% of Al_2O_3, 0.18, 0.27, and 0.36 vol.% of ZnO, and 0.23, 0.35, and 0.46 vol.% of Ti_2O_3 were used, with 7 L of fresh water, to carry out the experiment at a nanofluid flow rate (m_w) of 0.33, 0.066, 0.083, 0.119, and 0.122 kg/s at 60, 70, and 80 °C.

Figure 3. Cooling tower test facility.

3. Results and discussion

In this study, nanoparticles based on Al_2O_3, ZnO, and Ti_2O_3 with diameters of 80, 35, and 70 nm were used at concentrations of 10, 15, and 20 g/L for the experiment conducted at 60, 70, and 80 °C in a 7 L tank. A mass of 0.07 kg (10 g/L) of solute was added to 7 L of solvent (water), resulting in 0.49 wt.%. The volume fraction for the 7 L solution was 0.12397. Therefore, the mass fraction is approximately four times higher than the volume fraction.

3.1. Cooling tower characteristics: NTU

In this study, tower characteristics or NTU, known as demand curve or tower demand, were totally independent of tower size and fills configuration. Figure 4a–c shows the relation between cooling characteristics or NTU and water flow rate for an induced draft cooling tower with fresh water (FW) and with Al oxide (Al_2O_3), Zn oxide (ZnO), and Ti oxide (Ti_2O_3) nanofluids at different volume concentrations (VC) (i.e., VC: 10, VC: 15, and VC: 20 g/L) at three different temperatures (case 1: 60 °C; case 2: 70 °C; case 3: 80 °C). The results show that the NTU decreases with the increase of water flow rate.

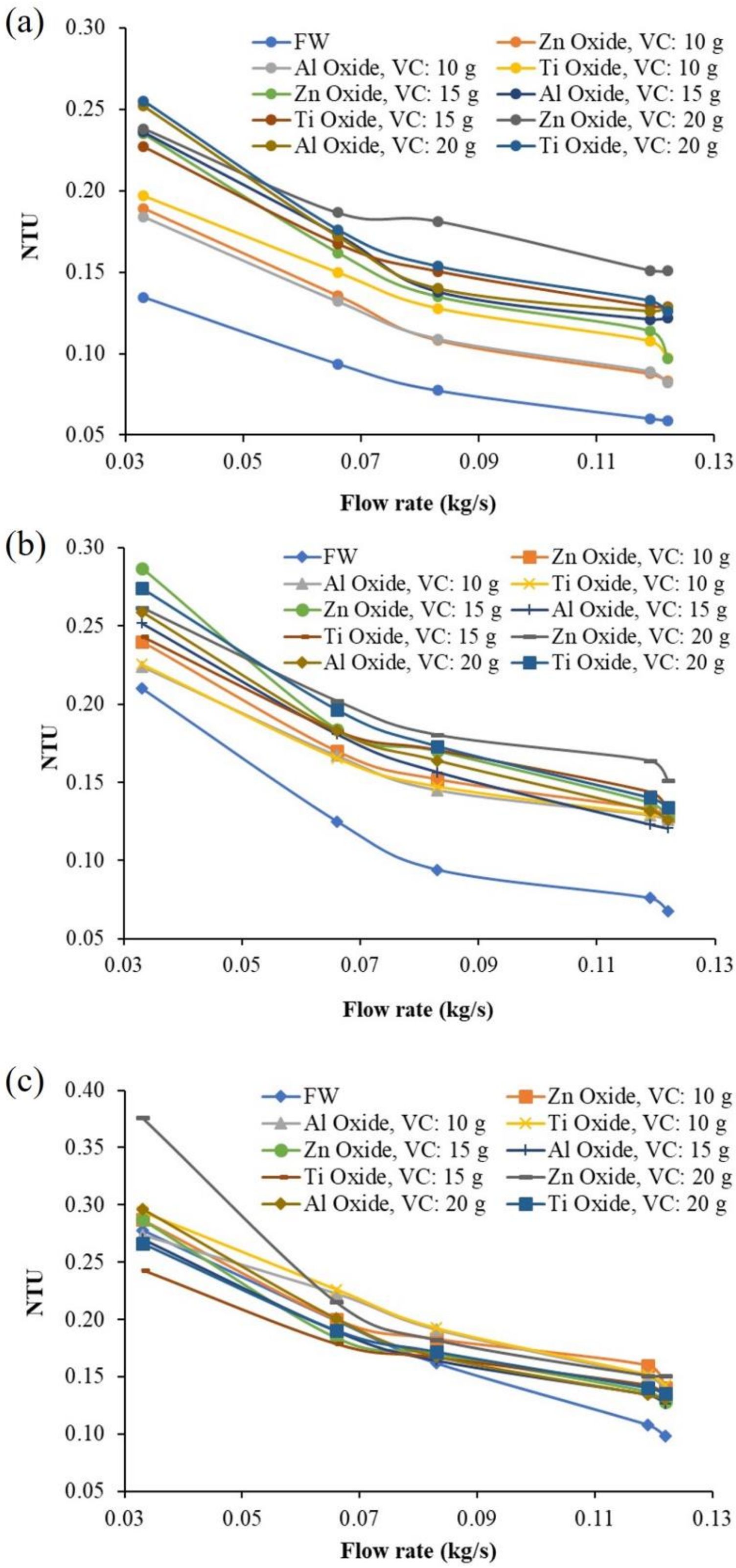

Figure 4. Variation of NTU with water flow rate at different volume concentrations and at different temperatures: (a) 60; (b) 70; and (c) 80 °C.

NTU is maximum at the lowest water flow rate (0.033 kg/s) in all conditions, both for FW as well as nanofluids. Also, NTU is highest in case 3, i.e., at the highest temperature, 80 °C. The NTU increase shows a good correlation with the decrease of driving force and, thereby, reducing evaporation loss [33]. In general, NTU significantly increases with higher volume concentrations, being approximately 34% higher than that of distilled water.

3.2. Cooling tower characteristics: efficiency

Figure 5 shows the relation between cooling efficiency and flow rate for an induced draft cooling tower with FW and Al_2O_3, ZnO, and Ti_2O_3 nanofluids at different volume concentrations at the highest temperature (i.e., case 3, 80 °C). It can be observed that efficiency and flow rate are inversely related. At a low flow rate, there is less water to cool, and the air is sufficient to cool the water at a lower temperature, hence providing higher cooling efficiency. On the other hand, the addition of nanofluids increases efficiency for all flow rate values; the higher the volume concentration of nanofluids, the higher the increase in efficiency for the same flow rate value. In particular, results also show that the sample with the highest concentration exhibited the highest efficiency (50%), using Al_2O_3 nanofluid at the highest temperature (case 3); the lowest concentration resulted in the lowest efficiency, 44.06 %. This concurs with the results presented in Figure 5, where the efficiency increases by 13% with increased nanofluid concentrations but approximately 27% in case of water. At higher flow rates, efficiency tends to flatten out; hence, the nanofluid volume concentration plays a negligible role. Therefore, fabricating and maintaining nanofluids at a higher flow rate would make it very expensive to increase the efficiency.

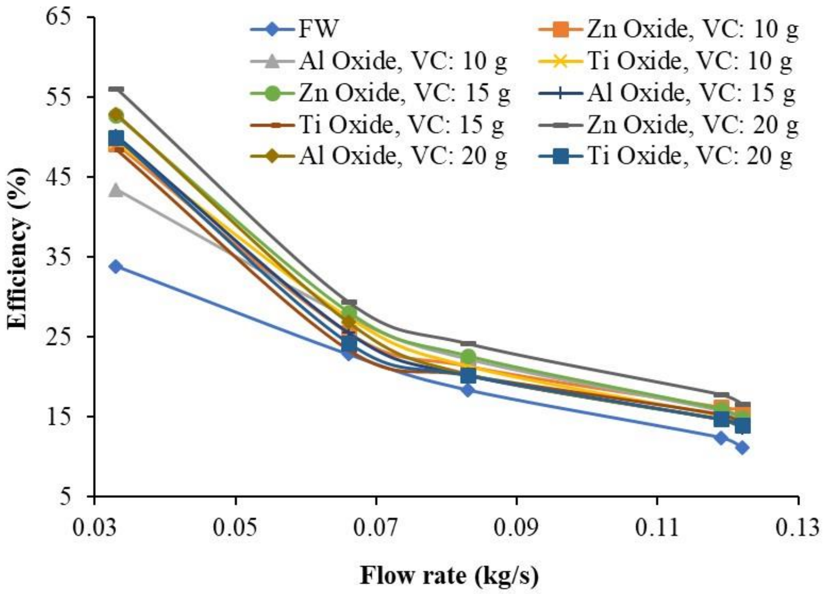

Figure 5. Variation of cooling efficiency with water flow rate at different volume concentrations and at temperature of 80 °C.

From the plots above (Figures 4 and 5), a few physical explanations can be provided regarding the relationship between efficiency and NTU with the flow rate of fresh water. First, adding Al_2O_3, ZnO, and Ti_2O_3 nanofluids with water as base fluid theoretically increases heat transfer. A similar pattern was found when cooling the temperature of the base liquid in the cooling tower. However, Figures 4 and 5 show a small amount of error—basically, the inherent error. This is because of the anemometer performing air speed reading and human errors taking dry bulb and wet bulb temperature from the psychrometer. Overall, a higher cooling efficiency occurs at higher volume concentrations. With the increase of tower characteristics, the latent heat and sensible heat transfer also increases, thereby decreasing efficiency. As efficiency increases, NTU also increases proportionately. This study shows that volume concentration is the key influential player on heat transfer performance, with significant physical effects. The base liquid can be cooled at more efficient conditions; in other words, a lower amount of air would be required to cool the liquid to the desired temperature with the addition of nanofluids. A water temperature control system can be developed in future studies, and heat losses can be calculated for a better result.

3.3. Error analysis

In this study, error analysis was carried out by comparing measured and predicted cooling efficiencies (CE) in Al_2O_3-based nanofluid at the highest temperature (case 3). Prediction was performed by the fuzzy expert system (FES) approach, which has been explained elsewhere [28]. The correlation between the measured and predicted values of CE in different volume concentrations is illustrated in Figure 6. The relationship is significant for all the parameters in different volume concentrations. The correlation coefficient (R) and mean relative error (ε) between the actual and predicted values were 0.961 and 9%, respectively. The relative error gives the deviation between the predicted and experimental values (Eq 11) and is required to reach zero. In this study, the relative error was found to be less than the acceptable limit of 10% [34]. The goodness of fit of the prediction values from the FES model (Eq 12) was 0.960; as expected, close to 1.0. The goodness of fit also provides the ability of the developed system; its highest value is 1 [28].

The relative error (ε) of cooling efficiency is calculated as follows:

$$\varepsilon = \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right| \frac{100\%}{n} \tag{11}$$

The goodness of fit (η) of the predicted system is calculated as follows:

$$\eta = \sqrt{1 - \frac{\sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \tag{12}$$

where n is the number of interpretations, y_i is the measured value, $\hat{y}_i$ is the predicted value, and $\bar{y}$ is the mean of measured value.

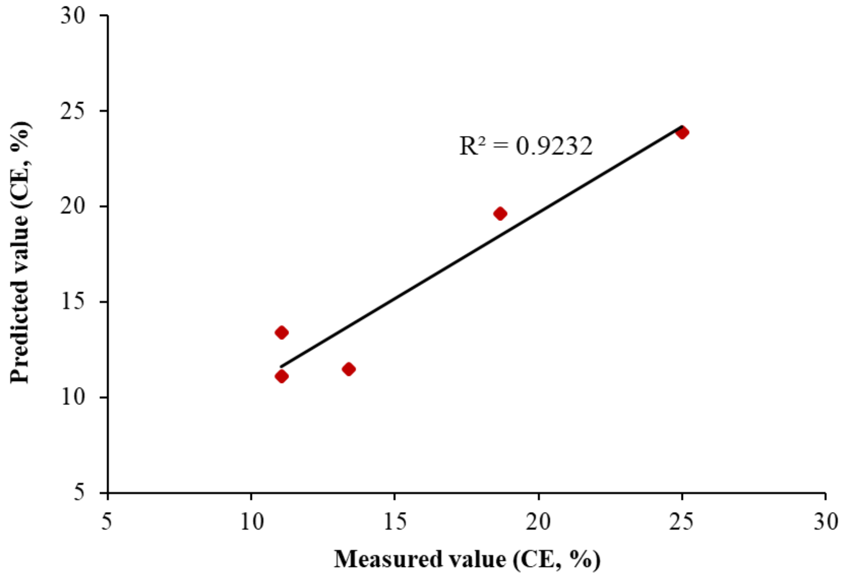

Figure 6. Correlation between measured and predicted values of cooling efficiency.

4. Conclusions

Nanoparticles are expensive, as is fabricating nanofluids from them. Even applying small volume concentrations may require large amounts of nanofluids, which is very expensive. Several experimental setups were evaluated by varying the quality of circulating fluids at different ratios. In this study, an experimental evaluation has been carried out to determine the effect of various concentrations of Al_2O_3, ZnO, and Ti_2O_3-based nanoparticles mixed in water on heat transfer characteristics of cooling towers. The results show that cooling tower characteristics and efficiency decreases with an increase in flow rate. The specific conclusions derived from this study are as follows:

(1) The addition of nanofluids increases the cooling range for all flow rate values; the higher the volume concentration of nanofluids, the greater the increase for the same flow rate value.

(2) Tower characteristics (NTU) significantly increase with higher volume concentrations, being approximately 34% higher than that of distilled water.

(3) For ZnO at 20 g/L and 80 °C, efficiency increases by 69.9% compared with distilled water.

(4) The friction factor increases with the rise in particle volume concentration. This is due to the increased viscosity of the nanofluid, resulting in a minimal pressure drop.

Use of AI tools declaration

The authors declare that Artificial Intelligence (AI) tools are not used in the creation of this article.

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Author contributions

All authors contributed to the study conception and design. Material and sample preparation, experiment and data collection and analysis were performed by Habibur Rahman, Altab Hossain and Mohammad Ali. The first draft of the manuscript was written by Habibur Rahman and all authors commented and edited of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

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