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Investigating the Effects of Tilt Angle and Fill Perforation on the Performance of Forced Draft Wet Cooling Tower

Khairul Umurani[1,4], Ahmad Syuhada[2,*], Muhammad Ilham Maulana[2], Zahrul Fuadi[3]

[1] School of Engineering, Syiah Kuala University, Indonesia
[2] Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University, Indonesia
[3] Department of Mechanical and Industrial Engineering, Syiah Kuala University, Indonesia
[4] Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Sumatera Utara, Indonesia

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ABSTRACT

Cooling towers are critical components of the industrial sector, serving a crucial function in dispersing surplus heat to ensure optimal operational efficiency and protect equipment integrity. This study examines the impact of variations in the tilt angle and fill perforations on the performance of forced draft wet cooling towers. The study specifically examines two variables: the tilt angle of fill at $\theta1= 15°$, $\theta2 = 20°$, and $\theta3 =25°$, and the ratio of perforations labelled as RP1 = 2.6%, RP2 = 3%, and RP3= 3.6%. The experimental trials involved varying the airflow rates of 0.0203, 0.0263, 0.0299, 0.0377, and 0.0426 kg/s while maintaining a constant water flow rate of 0.0917 kg/s. The results indicate that a tilt angle of $\theta1°$ greatly improves the thermal and operational efficiency of the tower. In addition, greater ratio of perforations, particularly RP_3, significantly enhance the cooling tower's performance at different tilt angles compared to RP_1 and RP_2.

1. Introduction

Cooling towers are crucial in numerous industries as they efficiently dissipate surplus heat, ensuring optimal operating conditions and preventing equipment harm. Cooling towers employ evaporative and convective methods to lower hot water temperature by transferring heat to the surrounding air [1]. Wet-type cooling towers are widely utilised, attracting the attention of numerous researchers who want to analyse their thermal characteristics and evaluate their effectiveness [2]. In wet cooling towers, evaporation occurs as air combines with hot water, cooling the remaining water through either forced or natural convection. Forced draft cooling towers enhance heat exchange by increasing the contact surface area. The selection of the fill material and its arrangement greatly impacts the thermal efficiency of the tower by influencing the transfer of heat and mass. Extensive research has been conducted to investigate the impact of various fill kinds and patterns on cooling efficiency and overall system performance. The packing material needs to be lightweight, resilient, and stable to ensure stability and efficient heat transfer, which ultimately affects the level of contact

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[*] *Corresponding author.*
E-mail address: ahmadsyuhada@usk.ac.id

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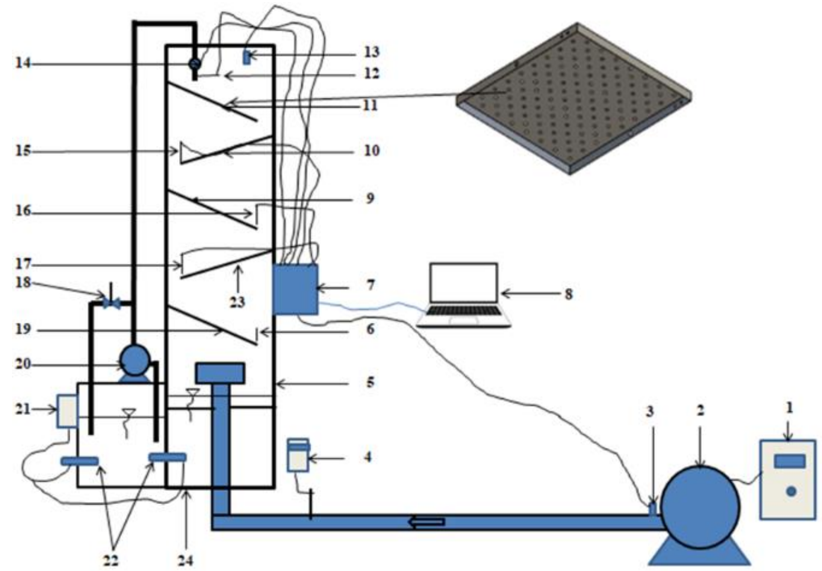
between air and water [3,4]. The cooling range is significantly affected by various packing types [5,6]. Various research has examined various coolants, including foam ceramics, to investigate their impact on efficiency and cooling properties to enhance coolant performance [7]. Progress in fill media technology enhances efficiency and lowers expenses. Ensuring proper maintenance and cleaning is crucial for achieving optimal performance [8]. Wire-mesh fill has been demonstrated to be the most effective fill, making it appropriate for use in industrial forced draft cooling towers that operate across a broad temperature range [9,10]. Nawi *et al.,* [11] used a multistage methodology to successfully prioritise the facility layout (FL) limitations, thereby solving the facility layout problem (FLP) in large spaces. We anticipate that this approach will improve building performance [11]. To examine the attributes of a wet cooling tower, it is crucial to comprehend the correlation between different variables and their influence on the system's overall efficiency. To examine the attributes of a wet cooling tower, it is crucial to comprehend the correlation between different factors and their influence on the overall efficiency of the system [12-14]. Singh and Das [15] utilized five input parameters to evaluate exergy, namely: air flow rate, water flow rate, dry bulb temperature, relative humidity, and water temperature. Subsequently, the impact of each input parameter on tower performance was analyzed about several important exergy-related variables [15]. The design of a cooling tower necessitates the utilization of many logical determinations, empirical correlations, and assumptions. Opting for an appropriate tower and implementing a suitable design will enhance its efficiency and facilitate energy conservation [16]. The ambient temperature substantially influences the cooling capability, thermal performance, and energy efficiency. Elevated ambient temperature can lead to limited or even reversed sensible heat transmission as a result of the air's ability to retain water vapour, leading to intense evaporative cooling and decreased water temperature [17-19]. The fill zone is the primary region where thermal energy is exchanged. The water is dispersed across the fill, which enhances its surface area and hence promotes more significant interaction with the air. Increasing the contact surface area makes the heat and mass transfer between the water and air more efficient, resulting in faster evaporation and enhanced cooling performance [20,21]. The type and arrangement of packing dramatically influence the performance of a cooling tower, and it is observed that the performance decreases as the (L/G) ratio increases [22,23] Splash fill is more desirable in wet cooling towers with mechanical circulation due to its lower susceptibility to clogging [24]. By optimising the water distribution in the cooling tower, it is possible to decrease entropy, enhance efficiency, and minimise energy loss. This can be achieved by ensuring uniform heat transmission throughout the system [25]. Perforated ribs enhance the heat transfer coefficient by 7.8% compared to solid ribs by increasing the surface area and creating airflow turbulence. This improves thermal performance and energy efficiency [26]. Efficient water distribution can optimize the cooling impact and enhance the economic advantages [27]. Nanofluids are utilized to enhance the thermal conductivity of a coolant, which might be employed as a cooling agent [28,29]. Enhancing the wetting rate can improve thermal efficiency, resulting in gains of up to 47.8% [30]. Choosing the most effective flow rate for water and air is crucial for increasing the effectiveness of a cooling tower [31]. Employing a non-uniform fill pattern improves the cooling efficiency of the Wet Cooling Tower with Crosswind Design (WCTWCD) under all wind situations [32]. Fill packs had their greatest cooling effectiveness at low wetting rates, as indicated by the Merkel number [33]. Non-uniform fill greatly increases the heat transfer coefficient compared to a uniform arrangement [34]. The introduction of fill pitches can significantly improve the cooling efficiency of wet cooling towers in quiet and windy conditions [35]. The popularity of packing material has a substantial impact on the performance of cooling towers, with paper fillings being the most efficient option [36]. The efficiency coefficient is directly correlated with the air mass flow rate, hot water temperature, and the number of stages [37]. Turbulent flow regime, the coefficient of friction for the solid rib arrangement is greater than that of ribs with perforated holes [38]. Moreover, the increasing pattern of temperature decrease remains essentially the same across various flow rates [39]. Utilizing multilevel models with random intercepts enables the incorporation of individual variability, hence reducing errors and enhancing the precision of the model predictions [40]. Higher crosswind velocity results in a more significant effect on thermal performance [41]. Although many studies have examined different fill kinds and patterns in wet cooling towers, there is a significant scarcity of information on the enduring impact of fill construction on the system's overall performance. Furthermore, the effects of modifying fill architecture, such as variations in the tilt angles of fill placement and the utilization of diverse types of perforated fills, have not been well examined. Further investigation is necessary to overcome these deficiencies and improve the fill design to boost cooling tower performance under changing operational conditions. The objective of this research is to examine the impact of altering the structure of the fill, such as changing the tilt angles and using perforated fill kinds on tower performance through experimental analysis by modifying the tilt angle of perforated fills. This study presents a novel strategy by adjusting the installation angle of perforated fills. This research is expected to show how altering fill structure impacts cooling tower performance, potentially improving efficiency under various conditions.

2. Materials

The experimental setup of the forced draft counterflow cooling tower is shown in Figure 1. In this study, two fill modes were used. The first mode used three variations of fill tilt angle.



1	Motor speed control	13	Outlet air humidity sensor (DHT11)
2	Centrifugal blower	14	Water flow rate sensor
3	inlet air humidity sensor (DHT11)	15	Thermocouple sensor stage 2nd
4	Hot wire Anemometer	16	Thermocouple sensor stage 3rd
5	Tower	17	Thermocouple sensor stage 4th
6	Thermocouple sensor stage 5th	18	Bypass valve
7	Arduino Mega Board	19	Perforated Fill plate stage 5th
8	Personal computer	20	Pump
9	Perforated Fill plate stage 3rd	21	Digital temperature controller
10	Perforated Fill plate stage 2nd	22	Heater
11	Perforated Fill plate stage 1st	23	Perforated Fill plate stage 4th
12	Thermocouple sensor stage 1th	24	Water tank

Fig. 1. Research test rig

The tilt angle of fill is the angle of inclination of the perforate fill relative to the horizontal line in the cooling tower. This angle affects the flow of water and air through the fill indicated by a symbol depicting how the fill is positioned to optimize the contact between the air flowing from the bottom up and the water flowing from the top down as shown in Figure 2. Three variations of fill tilt angles $\theta_1 = 15^o$, $\theta_2 = 20^o$, and $\theta_3 = 25^o$ and the second mode three variations of ratio of perforation fill RP_1, RP_2, RP_3 as shown in Figure 3 and description of ratio of perforations as shown in Table 1. The fill is constructed using a galvalume plate that has a thickness of 0.3 mm and measures 500 mm by 470 mm the plate exhibits staggered configurations of 72, 90, and 110 perforated holes, each having a diameter of 10 mm. The tower has a height of 3000 mm, and each level has a height of 500 mm. They are contemplating Figure 1. The water in the tank (24) was initially heated to a temperature of 60 ± 1.5°C using a 5000-watt heater (22). During the experiment, a digital temperature controller (21) was employed to maintain a consistent temperature. The centrifugal blower (2) and water circulation pump (20) activate once the water reaches the target temperature. The cooling tower is supplied with hot water from the top, and the temperature of the hot water is measured using a thermocouple (12). This temperature data is used to monitor the hot water entering the tower and its distribution across different levels of the tower, namely fill level 1 (11), fill level 2 (10), fill level 3 (9), fill level 4 (23), and fill level 5 (19). Thermocouples are used to measure the water temperature at the first, second, third, fourth, and fifth level exits. These thermocouples are labelled 15, 16, 17, and 6. The recorded temperatures represent the water temperature as it leaves each fill level. The water mass flow rate was monitored with a YF-S201 water flow sensor (14) with an accuracy of 10%. The flow rate was maintained at ± 5.5 litres/minute by adjusting the bypass valve (18). The cooling tower's base is equipped with a centrifugal blower that has a 120 mm eye impeller diameter, which forcefully introduces air into the water. The maximum rotational velocity of a 1 HP 3 Phase motor is 1440 revolutions per minute (rpm), and it is regulated by (1) to control any variations in rotation.

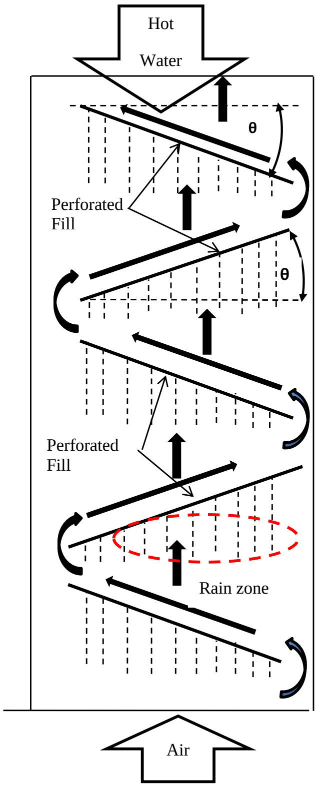


Fig. 2. Description of tilt angles

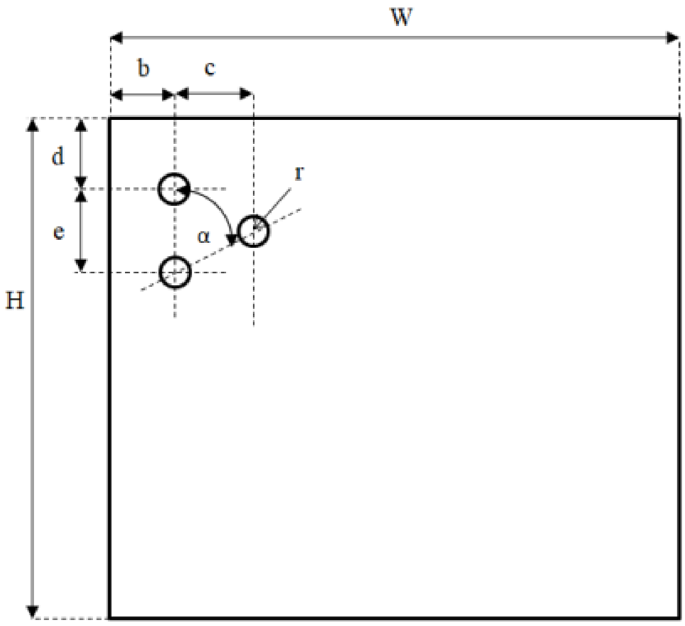


Fig. 3. Perforation fill configuration

Table 1
Details of three fill perforation patterns

Item	RP_1	RP_2	RP_3
n = number of holes	72	90	110
r = hole radius (mm)	5	5	5
α = degree	60	60	60
W (mm)	470	470	470
H = (mm)	500	500	500
b = (mm)	15,57	22,11	19
c = (mm)	62,62	53,62	48,62
d = (mm)	44,19	26	24.46
E = (mm)	54,23	46,44	42,11
A = area of plate = WxH (mm^2)	235.000	235.000	235.000
a = total area of your = $n\pi r^2$ (mm^2)	5652	7065	8635
RP = (Ratio of Perforation) = (a/A) %	2,41	3	3,67

The relative humidity sensor (DHT 11) records the air conditions at the point of tower arrival. The air data for the tower entrance is obtained by collecting relative humidity and dry bulb temperature. As the air ascends, it will traverse each fill level, undergoing an increase in temperature and humidity. The DHT 11(13) is used to measure the temperature and relative humidity at the top of the tower once the warm, wet air has reached that point. The temperature and relative humidity of the dry bulb are measured to simulate the air exiting the tower and spreading into the surrounding area. Upon the departure of the cooling tower, the recorded data indicates a significant decrease in water temperature, reaching the fifth level. The water accumulates in the storage tank (24) and is reheated when it has cooled down before being pushed back into the tower. The temperature, water flow rate, humidity, and air temperature at intake and outflow conditions were measured using an Arduino Mega board (7) and a data collection tool called PLX-DAQ. Subsequently, a personal computer (8) was employed to document the data. Using a Benetech Hot wire Anemometer type GM8903 (4), the air mass flow rate, ma, may be measured with an accuracy of ±3% ±0.1. The air mass flow numbers are 0.0203, 0.0263, 0.0299, 0.0377, and 0.0426 kg/s. The DHT11 (3,13) humidity sensor provides a temperature measurement accuracy of ±2°C within the range of 0 to 50°C and a relative humidity (RH) measurement precision of ±5% within the range of 20% to 90%. Hot and humid air is expelled from the cooling tower's upper section, while cold water accumulates in a reservoir located at the tower's bottom. The table displays the precise measurements of the absolute humidity, enthalpy, and wet bulb temperature of the air as it enters and exits the system. The cooling tower being tested is of the counterflow variety. Consequently, the hot water enters the cooling tower from the top, while the cold air enters from the bottom. Figure 4 provides a visual representation of the test cooling tower.

Fig. 4. The image capturing the test cooling tower

3. Results and Discussion

This section calculates critical parameters that determine the functioning of a cooling tower. These characteristics include cooling range, effectiveness, Merkel Number, and evaporation rate. The cooling range is the temperature difference between the inlet hot fluid (Tw, i) and the exit cold fluid (Tw,o). It can be calculated using the equation provided by Rahmati *et al.,* [37].

$$R = T_{w,i} - T_{w,o} \tag{1}$$

Additionally, the value of (ε) was chosen to refer to the coefficient of effectiveness, which represents the maximum cooling capacity of WCT [37].

$$\varepsilon = \frac{R}{T_{w,i} - T_{wb}} \tag{2}$$

Merkel’s number, KaV/L, is commonly used to quantify tower of characteristics of wet cooling towers. It is widely accepted and defined by Eq. (3) [3].

$$Me = \frac{KaV}{L} = \int_{Tw,o}^{Tw,i} \frac{C_{pw} dT}{H_w - H} \tag{3}$$

The numerical solution of Eq. (3) is used to determine the tower characteristics under various experimental operating situations is solved using the Chebyshev four point method [16].

The mass of water evaporated with the air can be determined by calculating the water evaporation rate (m_{eV}) using Eq. (4). In this equation, ma represents the air mass flow rate, ω_o represents the absolute humidity of the air leaving the tower, and ω_i represents the absolute humidity of the air entering the tower [31].

$$m_{eV} = m_a(\varpi_o - \varpi_i) \tag{4}$$

Heat rejection (Q) by Merkel was the omission of the water mass flow rate reduction in the energy equation approach. The heat transfer is described by Eq. (5) [32].

$$Q = \dot{m}_w C_{Pw}(T_{w,i} - T_{w,o}) \tag{5}$$

3.1 Effect of the Tilt Angle of Fill on Cooling Tower Performance Range

Figure 5 shows the data collected by data acquisition. The recorded data is for a tilt angle of θ_1, ratio of perforation RP_1, L/G = 4.51. The tower inlet water temperature fluctuates slightly, around 60±2.25 C, due to the control of the heater. The water temperature leaving the tower is relatively stable, but there is a decrease in temperature along with the decrease in water temperature entering the tower. The air temperature and relative humidity of the environment were stable. The average incoming water temperature is 60.75 C, the average outgoing water temperature is 52.69 C, the average ambient air temperature is 33.46 C, and the relative humidity of the ambient air is 53.64%.

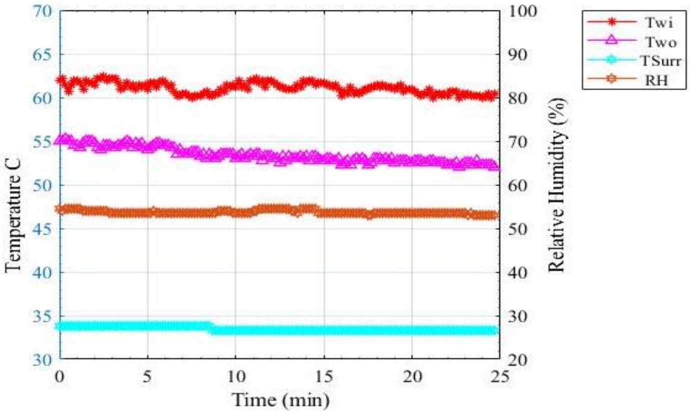
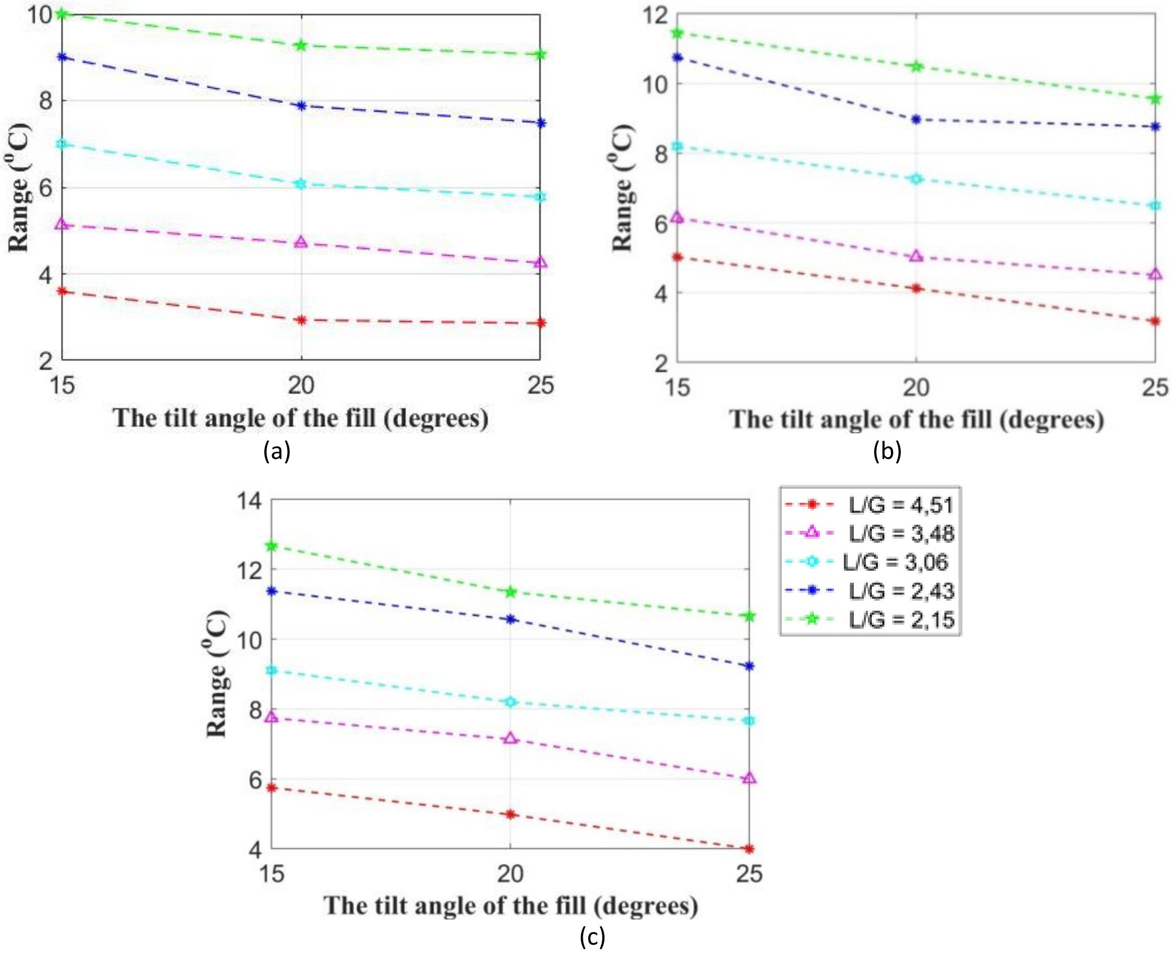


Fig. 5. Air and water data measurement

Figure 6(a) to Figure 6(c) shows the range distribution of a wet draft cooling tower at different fill tilt angles (θ_1, θ_2, θ_3) and perforation degrees (RP_1, RP_2, RP_3). The experiments were conducted at various air-water mass ratios (L/G) of 4.51, 3.48, 3.06, 2.43, and 2.15. The L/G ratio of 4.51 corresponds to the smallest value range, while an L/G ratio of 2.51 corresponds to the maximum value. Figure 5(a) illustrates the impact of fill tilt angles (θ_1, θ_2, θ_3) on the range at RP_1. It is evident that at θ_1, the maximum range is 8.41% more than the maximum range at θ_2 and 16.5% greater than the range at θ_3 tilt angle.

Figure 6(b) displays the distribution effect of fill tilt angles (θ_1, θ_2, θ_3) on the range at RP_2 specifically at a tilt angle of θ_1. the maximum range is 7.3% more than the maximum range at θ_2 and 9.3% greater than the maximum range at θ_3. Figure 6(c) displays the effect of fill tilt angles (θ_1, θ_2, θ_3)

on the range distribution for RP_3. The maximum range at θ_1 is 10.4% greater than the maximum range at a tilt angle of θ_2 and 15.86% greater than the maximum range at θ_3. The graph shows that when the tilt angle increases from θ_1 to θ_3, the temperature range reduces for all L/G values. This demonstrates an inverse relationship between the angle of tilt and range. The ideal angle for efficient and effective energy distribution is θ_1, outperforming bigger angles. The expansion in range resulting from the reduction in water temperature as it exits the tower signifies the act of dissipating heat. At lower tilt angles of fill, such as θ_1, water enters the fill from the top of the tower and moves downwards at a slower rate. This leads to a longer contact time between the water and the air, resulting in increased heat transfer. It is imperative to guarantee that the tower efficiently reduces the water temperature. In contrast, when the tilt angle is increased, the duration of air-water contact is decreased, resulting in a decrease in energy exchange [25].

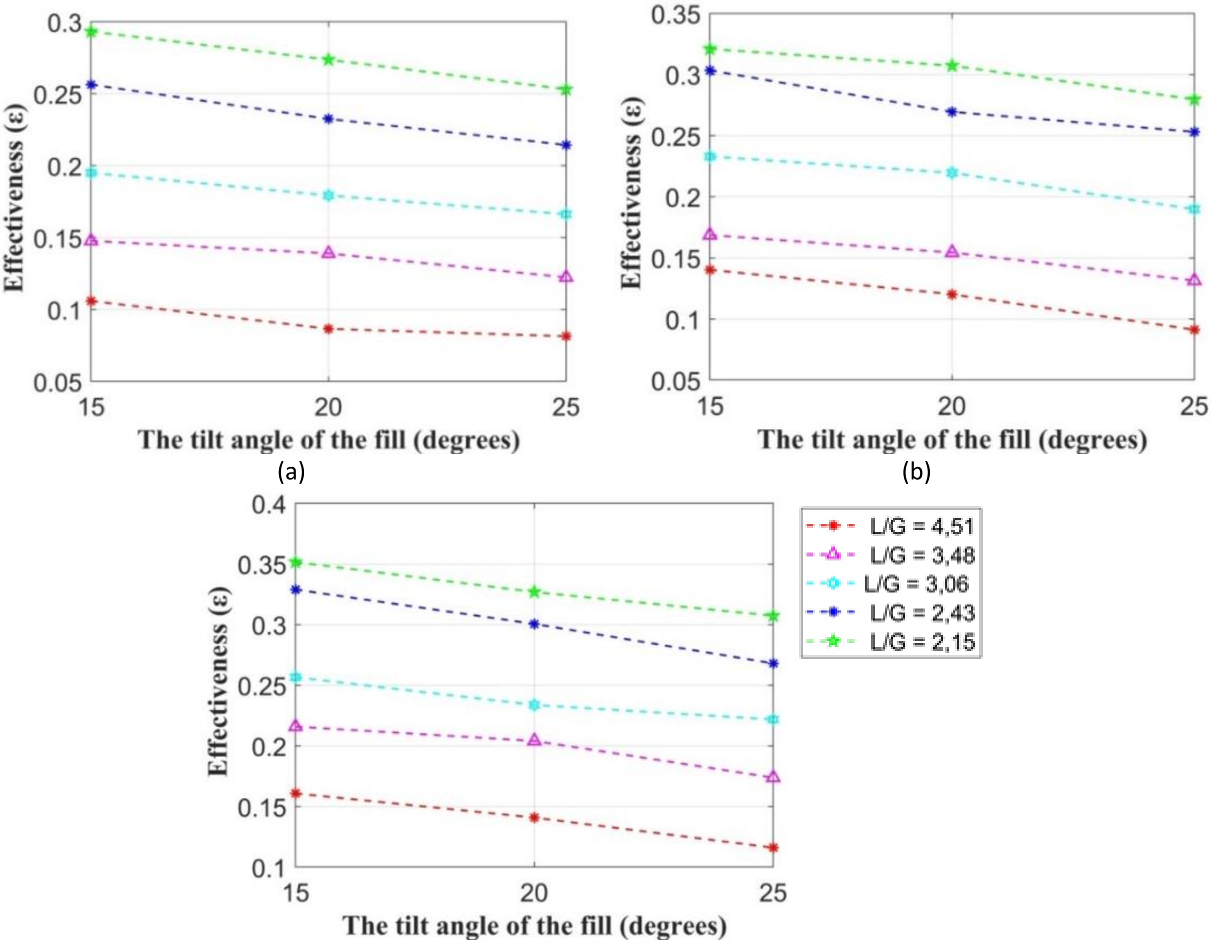


(a) (b) (c)

Fig. 6. Effect of fill tilt angle on range (a) RP_1; (b) RP_2; (c) RP_3

3.2 Effect of Fill Tilt Angle on Tower Effectiveness

The effectiveness of a wet cooling tower depends largely on the tower's ability to transfer heat from water to air. The fill tilt angle plays an important role in determining this effectiveness, with optimization of the angle improving tower performance. Based on Figure 7(a) displays the effect of fill tilt angle of (θ_1, θ_2, θ_3) on the effectiveness of RP_1, a significant increase in effectiveness compared to higher angles. Effectiveness at θ_1 is 4.3% higher than at θ_2 and 12.86% higher than at θ_3. Further analysis of effectiveness Figure 7(b) showed that at an angle of θ_1, the effectiveness was higher by 6.6% compared to θ_2 and 13.68% compared to θ_3. θ_3. at RP_2.



(a) (b)

(c)

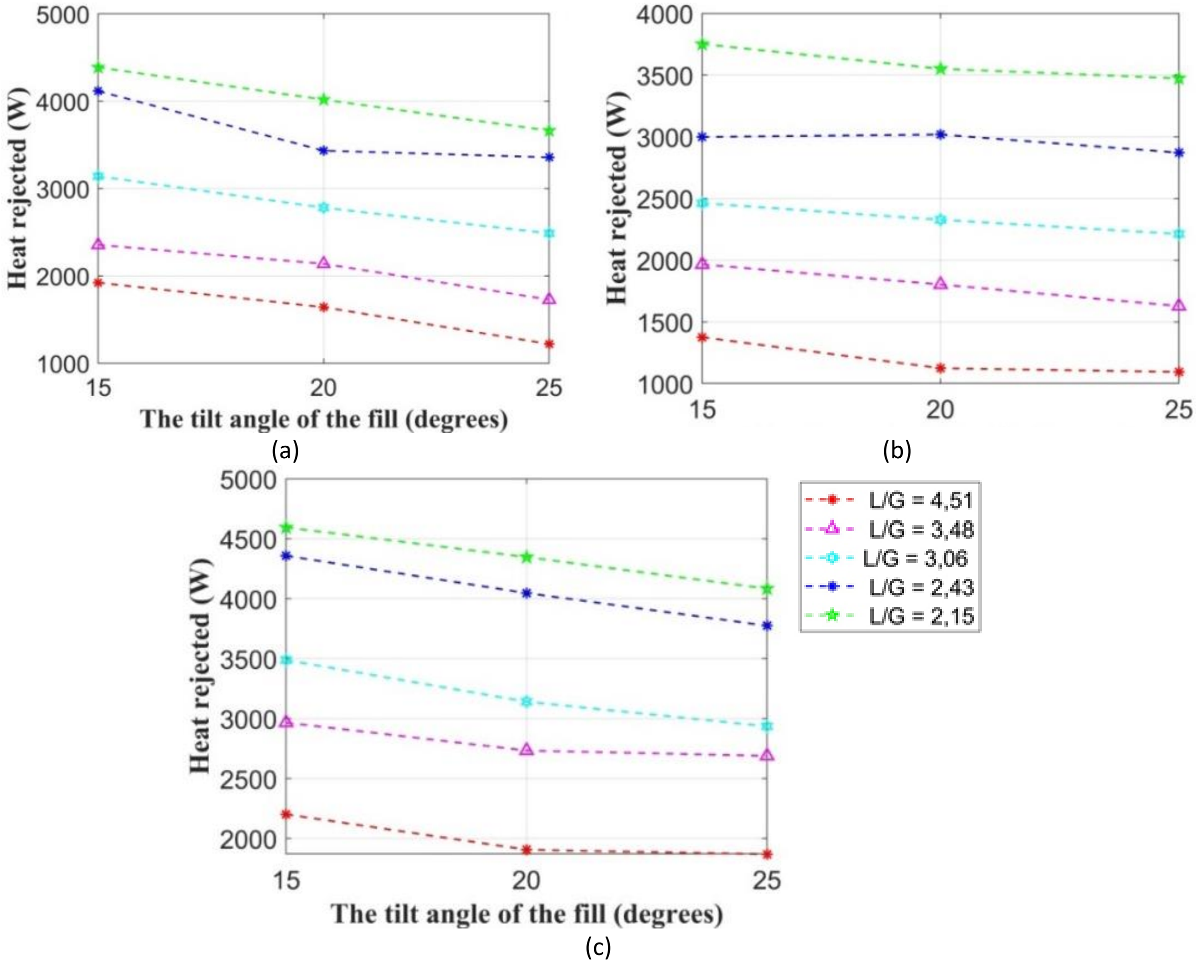
Fig. 7. Effect of fill tilt angle on effectiveness (a) RP_1; (b) RP_2; (c) RP_3

The relatively small tilt of the fill tilt angle will lead to a longer interaction time of water and air, thereby increasing the consistent distribution of the interacting phases across the cross-sectional area, thereby increasing the heat transfer rate [32,33]. A more gentle tilt angle can result in the resistance to airflow in the rain zone increasing, resulting in a more uniform distribution of water and an increase in the area where water and air come into contact with the tower [32].

3.3 Effect of Fill Tilt Angle on Heat Rejection

When air moves over a damp surface, it transfers both sensible heat and latent heat. The disparity in partial pressure of water vapour between the air drives mass transfer. When water evaporates from the water layer, the latent heat is transferred to the air, causing heat energy transfer. This study examines the impact of plate tilt angle on the process of air-water heat rejection in an air-water cooling system. A series of experiments were conducted to monitor and analyze this effect.

The results are shown in Figure 8(a), which shows the effect of fill tilt angle tilt angles θ_1 on heat rejection at RP_1. Maximum heat rejection at a fill inclination angle of fill tilt angles θ_1 is 8.41% greater than the θ_2 angle and 16.5% higher than the θ_3, Figure 8(b) shows at an inclination angle θ_1 the heat rejection is 5.3% higher than the θ_2 and 7.4% times higher than the θ_3. In Figure 8(c) the data shows that the maximum heat rejection occurs at an θ$_1$, which is 5.38% higher than the fill inclination angle of θ$_2$ and 11.11% higher than the angle of θ$_3$. Figure 8 (a) to Figure 8(c) explores the effect of fill tilt angle on water heat rejection in a cooling tower, highlighting how tilt angles of θ$_1$, θ$_2$, and θ$_3$, as well as variations in ratio of perforation (RP$_1$, RP$_2$, RP$_3$), affect this process. A consistent trend is seen in all graphs, where heat absorption increases with a decrease in fill tilt angle from θ$_3$ to θ$_1$. The thermal loss of circulation in cooling towers can be divided into two parts, i.e., vaporisation heat and contact heat rejection, which are given by Yaqub and Zubair [21]. At smaller fill tilt angles, the velocity of water sliding off the plate is lower, which decreases the wetting rate, giving longer interaction time between water and air and more opportunity for water to escape from the perforation holes [2,33]. This allows the formation of more water droplets, increases the contact area of the water-air flow, and, as a result, improves heat transfer, as indicated by the increase in the range value. This optimisation is important to ensure effective cooling water temperature reduction by the tower. This approach not only maximises the cooling effect but also increases the economic benefits of the system [27].



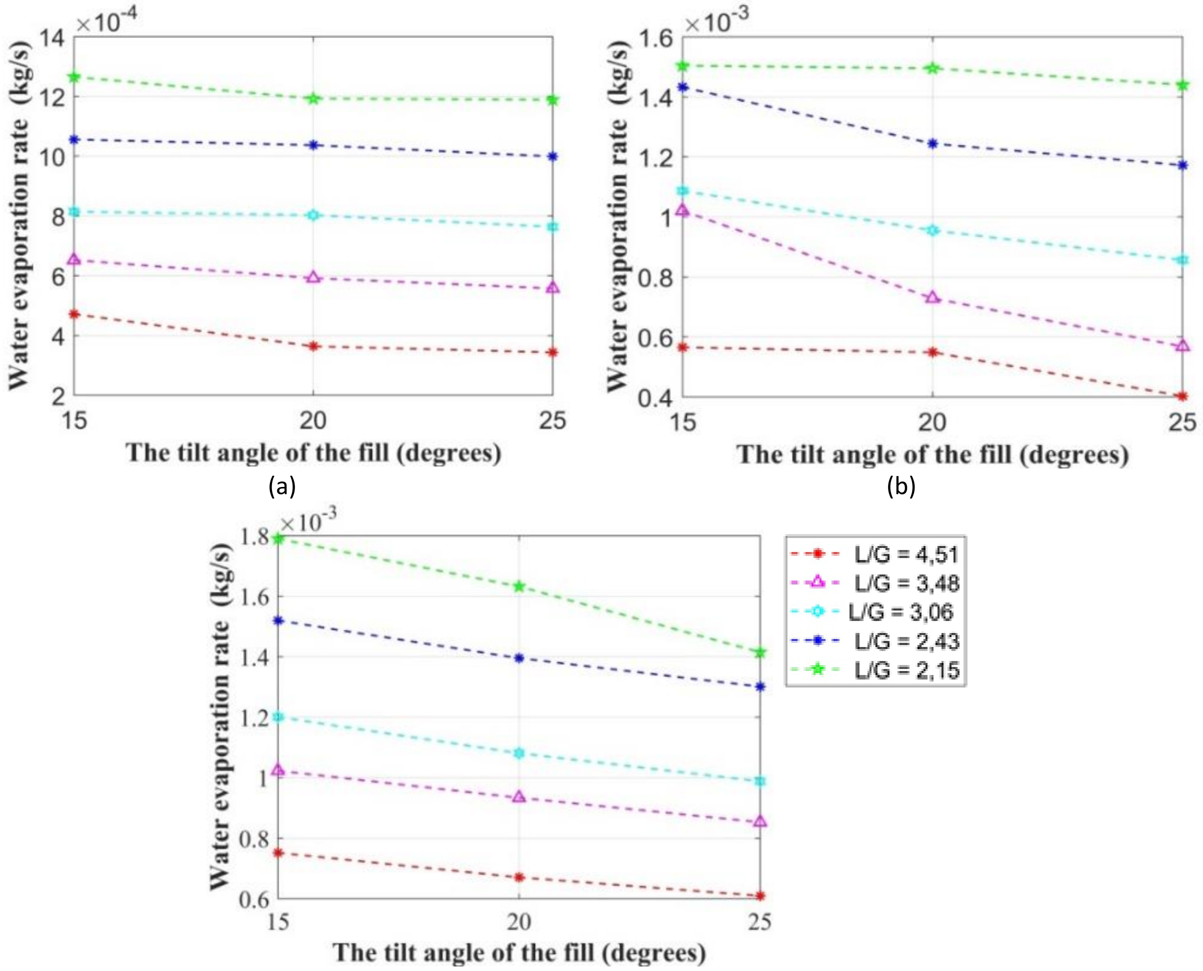
(a) (b)

(c)

Fig. 8. Effect of fill tilt angle on water heat rejection (a) RP$_1$; (b) RP$_2$; (c) RP$_3$

3.4 Effect of Fill Tilt Angle on Water Evaporation Rate

Wet cooling towers use water evaporation to lower the temperature of the cooling water. Hot water flowing from the top of the tower is allowed to drip into the chamber against the flow of air. Heat transfer in cooling towers is carried out through evaporation, so it is unavoidable to analyze the evaporation rate in cooling towers. As shown in Figure 9(a) to Figure 9(c), it shows the effect of the fill inclination angle on the rate of water evaporation at RP_1, RP_2 and RP_3.



(a)

(b)

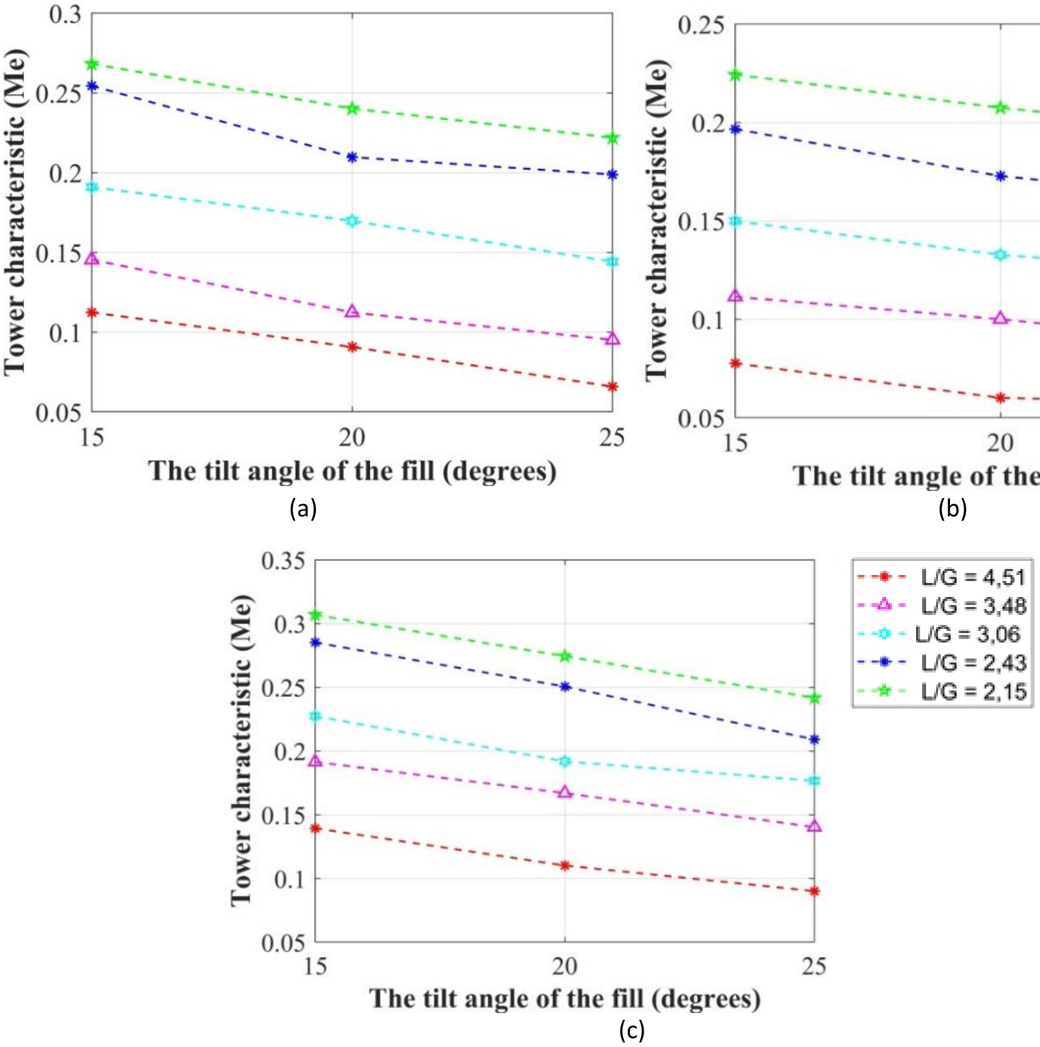
(c)

Fig. 9. Effect of fill slope on water evaporation rate (a) RP_1; (b) RP_2; (c) RP_3

Figure 9(a) shows the effect of fill tilt angles (θ_1, θ_2, θ_3) on the water evaporation rate at RP_1. There was no significant difference in the maximum water evaporation rate between the tilt angles of θ_1 and θ_2, only 0.566% greater than the θ_2 and 4.25% greater than the θ_3. Figure 9(b) shows the effect of fill tilt angles (θ_1, θ_2, θ_3) on the water evaporation rate at RP_2.: water evaporation at θ_1 is 5.75% higher than at θ_2 and 6.6% higher than at θ_3. Figure 9(c) shows the effect of fill tilt angles (θ_1, θ_2, θ_3) on the water evaporation rate at RP_3. Maximum water evaporation at θ_1 is 8.8% higher than that at θ_2 and 20.95% higher than that at θ_3. From the above data, a fill tilt angle of θ_1 shows higher evaporation effectiveness than higher angles. This confirms that a low angle is favourable in increasing the evaporation rate in the cooling tower. The relationship between the fill tilt angle and the evaporation rate is negative. The evaporation rate of water increases with decreasing fill tilt angle. The lower the fill tilt angle, the more water sliding on the fill plate will stay longer, creating more water droplets and enlarging the contact surface area between water and air [4], which allows more water vapour to form and increases evaporation per unit mass of air inflow. A more even distribution of water at a gentle angle facilitates faster evaporation. Conversely, a larger tilt angle increases the water flow rate, which can block the airflow through the fill, reduce the contact between water and air, and decrease the evaporation rate [24].

3.5 Effect of Fill Tilt Angle on Tower Characteristics

Figure 10(a) to Figure 10(c) illustrates the impact of the fill tilt angle (θ_1, θ_2, θ_3) on the cooling tower characteristics, considering (RP_1, RP_2, RP_3) and L/G values. When the tower is tilted at angles of θ_1, θ_2, and θ_3 with a ratio of perforation of RP_1, its performance reaches greater maximum values at lower tilt angles. Specifically, there is an increase of 10.4% and 17.27% compared to the performance at higher angles Figure 10(a). Similarly, at RP_2, the peak performance at θ_1 was 7.5% and 13.6% greater than that at θ_2 and θ_3 Figure 10(b), respectively.



(a) (b)

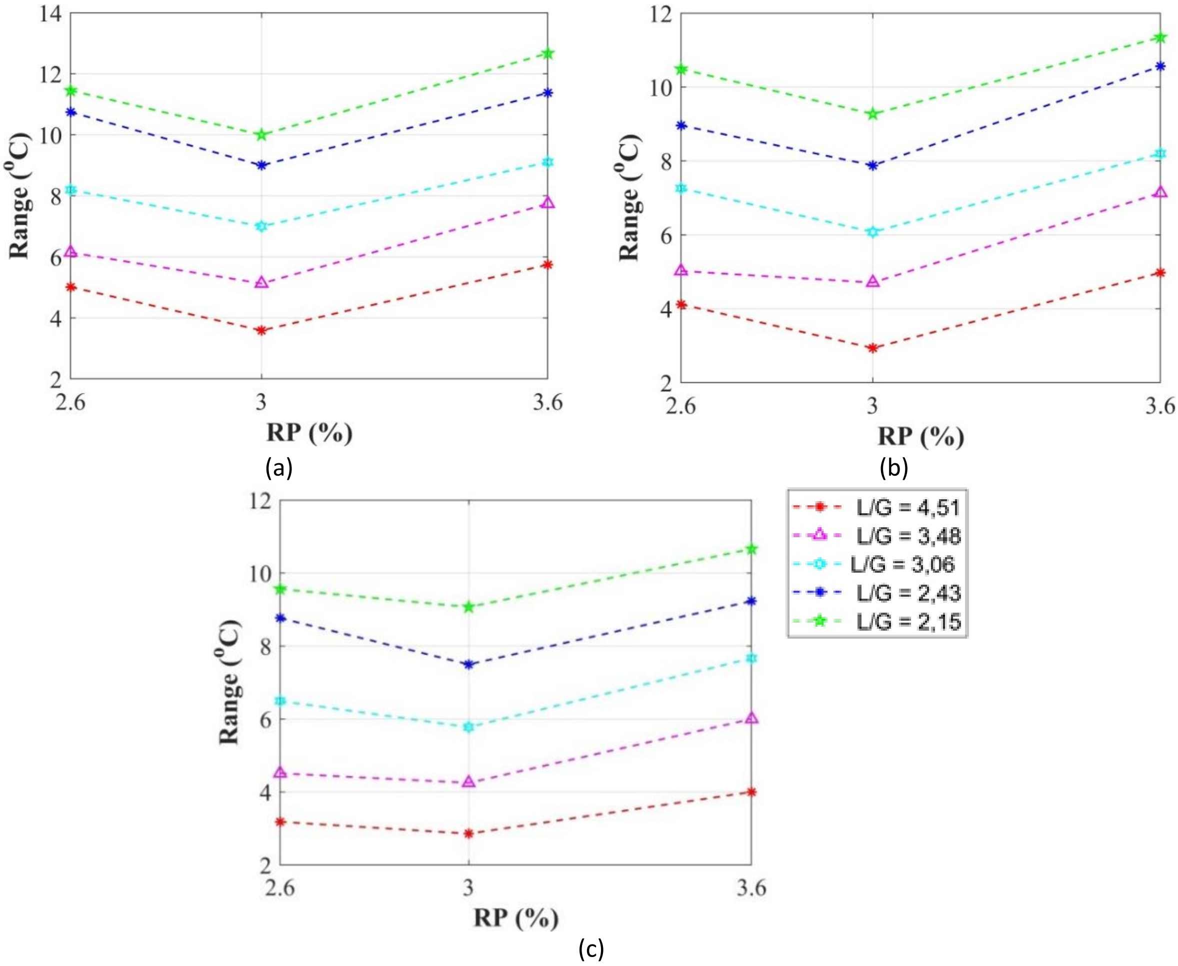
(c)

Fig. 10. Effect of fill tilt angles on tower characteristics (a) RP_1; (b) RP_2; (c) RP_3

Figure 10(c) shows the performance reached its peak at an angle of θ_1, with an increase of 10.6% and 21.2% compared to angles of θ_2 and θ_3 at RP3, respectively. This research validates that decreasing tilt angles enhances the performance of cooling towers by improving the features of the cooling tower at lower L/G values, which suggests more effective water distribution and increased evaporation efficiency. The study reveals that as the tilt angle rises, the tower characteristics (Me) decline for all L/G ratios, demonstrating an inverse correlation between the tilt angle and the tower characteristics (Me). The tower features were found to be influenced by the fill tilt angle. Furthermore, in all of the studies, the cooling tower's performance was superior when it had a tilt angle of θ_1 compared to angles of θ_2 and θ_3. At low tilt angles, the cooling water enters the fill and descends at a reduced speed, forming uniform water droplets. This enhances the overall efficiency of the cooling tower [28,29]. The water slides off the plate at a slower velocity, resulting in a lower wetting rate [26,29]. Consequently, the water remains in contact with the air longer. The tower features are more pronounced when the tilt angle is low, resulting in an increased range that provides optimal cooling. The tilt angle elevates the Merkel number, which signifies an enhanced cooling capability and improved heat transfer efficiency [30]. This study demonstrates that the cooling tower features, represented by the parameter Me, diminish as the tilt angle increases for all L/G ratios. An inverse correlation exists between the tilt angle and the tower's performance. The fill tilt angle of θ_1 consistently demonstrates superior performance in comparison to the angles of θ_2 and θ_3. This is because, at lower tilt angles, the cooling water enters the fill and moves slower due to the low wetting rate [26,29]. This results in the formation of uniform water droplets and a longer contact time with air, ultimately leading to an increase in cooling and heat transfer efficiency [26,28]. This is characterized by an elevation in Merkel number, which indicates a greater cooling capacity [30].

3.6 Effect of Fill Perforation on Tower Range

Figure 11(a) depicts how the temperature range of the tower is influenced by the ratio of perforation (RP_1, PR_2, RP_3) while maintaining a full tilt angle of θ_1. Maximum range at RP_3 was 21.07% higher than RP_2 and 9.61% higher than RP_1. Figure 11(b) investigates the effect of the (RP_1, RP_2, RP_3) on range at θ_2. Ratio perforation (RP_3) exceeds RP_2 by 18.3% and surpasses RP_1 by 7.56%. Figure 11(c) displays the range of RP_1, RP_2, and RP_3 at θ_3.



(a)

(b)

(c)

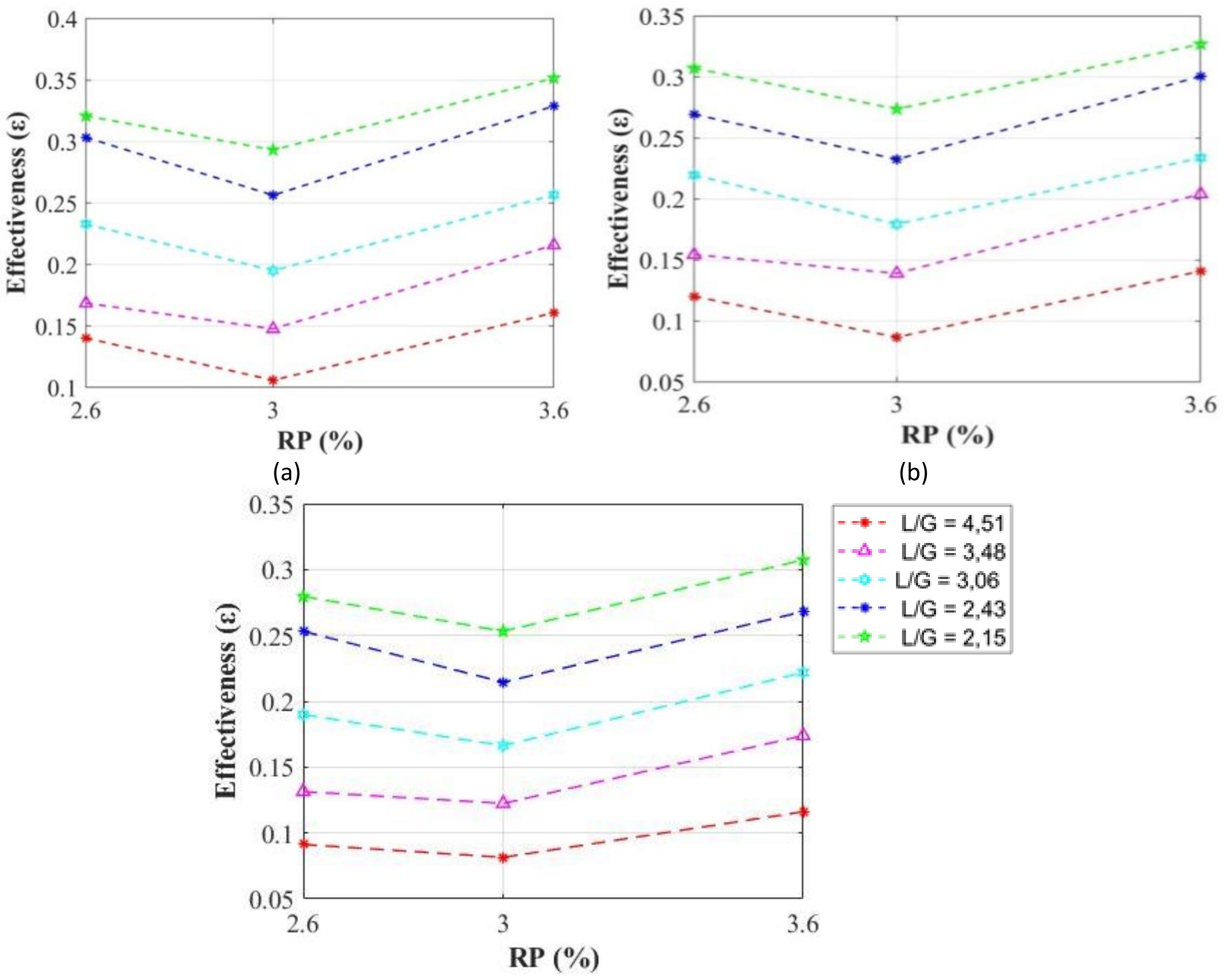
Fig. 11. Effect of fill perforation on tower range (a) θ_1; (b) θ_2; (c) θ_3

Ratio of perforation (RP_3) has a maximum value of 14.95% greater than RP_2 and 10.3% greater than RP_1. The data presented in Figure 10(a) to Figure 10(c) demonstrates that the range decreases from RP_1 to PR_2 about the ratio of perforation. However, there is an increase in the range from RP_2 to RP_3, with RP_2 being a significant turning point. Ratio perforation (RP_3) yields the highest range among the three ratios of perforations. The increased heat rejection results from the enhanced interaction between bigger quantities of water and air, leading to improved heat and mass transfer and a more effective cooling effect. The cooling tower's ventilation and heat transfer capability is enhanced by increasing the contact surface area by adding more holes or perforations in the plates, as indicated by the expanded range seen [31]. Using RP_3 in filling perforations optimises aerodynamic drag, resulting in cooling towers' most efficient heat and mass exchange [32].

3.7 Effect of Fill Perforation on Tower Effectiveness

Enhancements to the cooling range expansion are necessary to assess the effectiveness of a cooling tower accurately. Furthermore, other relevant factors should be taken into account. Effectiveness is one of these variables. The wet cooling tower's effectiveness, determined by Eq. (2), considers both the moist air wet bulb temperature and the water temperature at the inlet and outflow. Figure 12(a) to Figure 12(c) illustrates the impact of the ratio of perforations (RP_1, RP_2, RP_3) on the tower's effectiveness. Figure 12(a) displays the effectiveness of the cooling tower at (RP_1, RP_2, RP_3) at θ1. The maximum effectiveness of RP_3 is 16.6% higher than that of RP_2 and 8.73% higher than that of RP_1. Figure 12(b) shows the effect of (RP_1, RP_2, RP_3) on the tower's effectiveness at a tilt of θ_2. Ratio perforation (RP_3) shows a maximum effectiveness increase of 16.3% compared to RP_2 and a 6% increase compared to RP_1. Figure 12(c) displays the effect of the ratio of perforation (RP_1, RP_2, RP_3) on the cooling tower's effectiveness at a θ_3. Ratio perforation (RP_3) has a maximal effectiveness of 17.6% more than RP_2 and 9% greater than RP_1. Figure 12(a) to Figure 12(c) demonstrates the impact of the ratio perforation on heat rejection. The results indicate that RP_1 and RP exhibit superior cooling performance, with higher levels of heat rejection. Based on the three data provided, it is evident that RP_3 yields the most effective outcomes. This can be attributed to the significant enhancement in heat rejection resulting from increased air-water interaction in the rain zone. Higher ratio of perforations results in less ventilation resistance, which may elucidate the impact of airflow resistance on the tower's effectiveness. Enhanced cooling will be achievable as the water flowing through the fill will be subjected to increased airflow [7].

By efficiently lowering the water temperature, the range can be expanded. The perforations of the fill plate also impact the airflow within the tower. The presence of excessive plate perforation density leads to an increase in flow resistance resulting in a decrease in cooling effectiveness [29].



(a) (b)

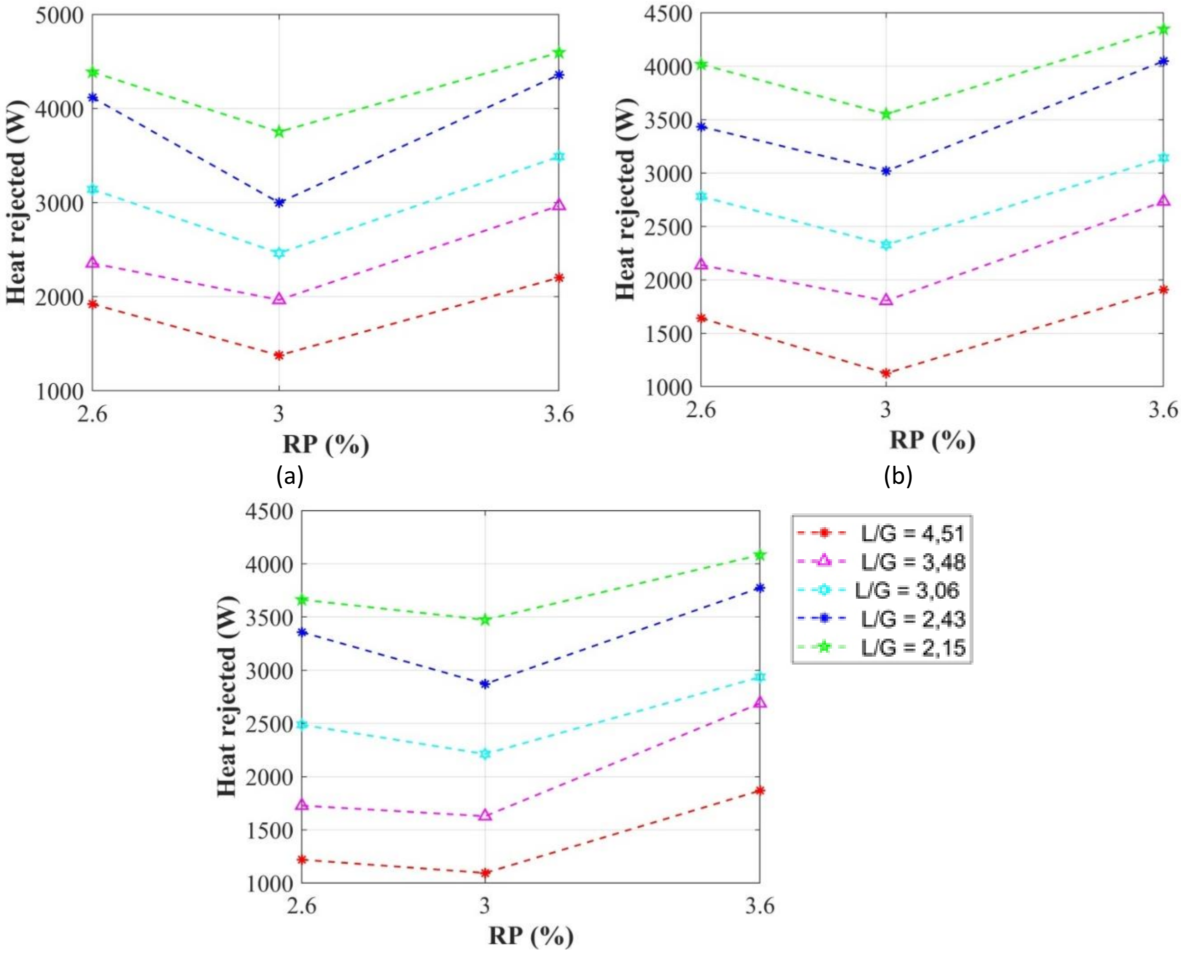
(c)

Fig. 12. Effect of fill performance on tower effectiveness (a) θ_1; (b) θ_2; (c) θ_3

3.8 The Impact of Fill Perforation on Heat Rejected

Figure 13(a) to Figure 13(c) demonstrates that increasing the Ratio of perforation (RP) from RP$_1$ to RP$_2$ leads to a reduction in the heat absorbed for all water mass to air mass ratios (L/G). However, the quantity of heat absorbed grows again when the RP is further raised from RP$_2$ to RP$_3$. The maximum absorbed heat for L/G 2.15 was measured at approximately 4500 W at a concentration of RP$_1$, decreased to around 3500 W at 3%, and then increased back to about 4500 W at RP$_3$. Meanwhile, the L/G 4.51 exhibits a decrease in absorbed heat, starting at approximately 2000 W at RP$_1$ and reaching a minimum of around 1500 W at RP$_2$ before increasing back to about 2000 W at RP$_3$. The observed trend is constant in all plots, with the absorbed heat declining until the RP$_2$ and subsequently increasing beyond this threshold. For instance, in the case of L/G 2.15, the amount of heat absorbed reduced from around 4000 W at a concentration of RP$_1$ to 3000 W at a concentration of RP$_2$ and subsequently increased again to 4000 W at a concentration of RP$_3$.

This phenomenon suggests an optimal point at RP$_3$ exists where the system attains the highest heat transfer efficiency. The decline in absorbed heat to its minimum point, followed by an increase, suggests that the system runs optimally at this specific reference point (RP). However, it is essential to note that the system's capacity is constrained; hence, raising the RP beyond this point may decrease efficiency. Enhancing the fluid's wetting rate can significantly improve its thermal performance [23]. This process helps to cool the circulating water in the tower. The three data above show that RP3 gives the highest heat rejection results, as more water granules interact with the air—the impact of fill perforations on heat rejection in cooling towers [33]. Sloped and perforated plates play an important role in determining the heat rejection efficiency of a cooling tower [26].



(a) (b)

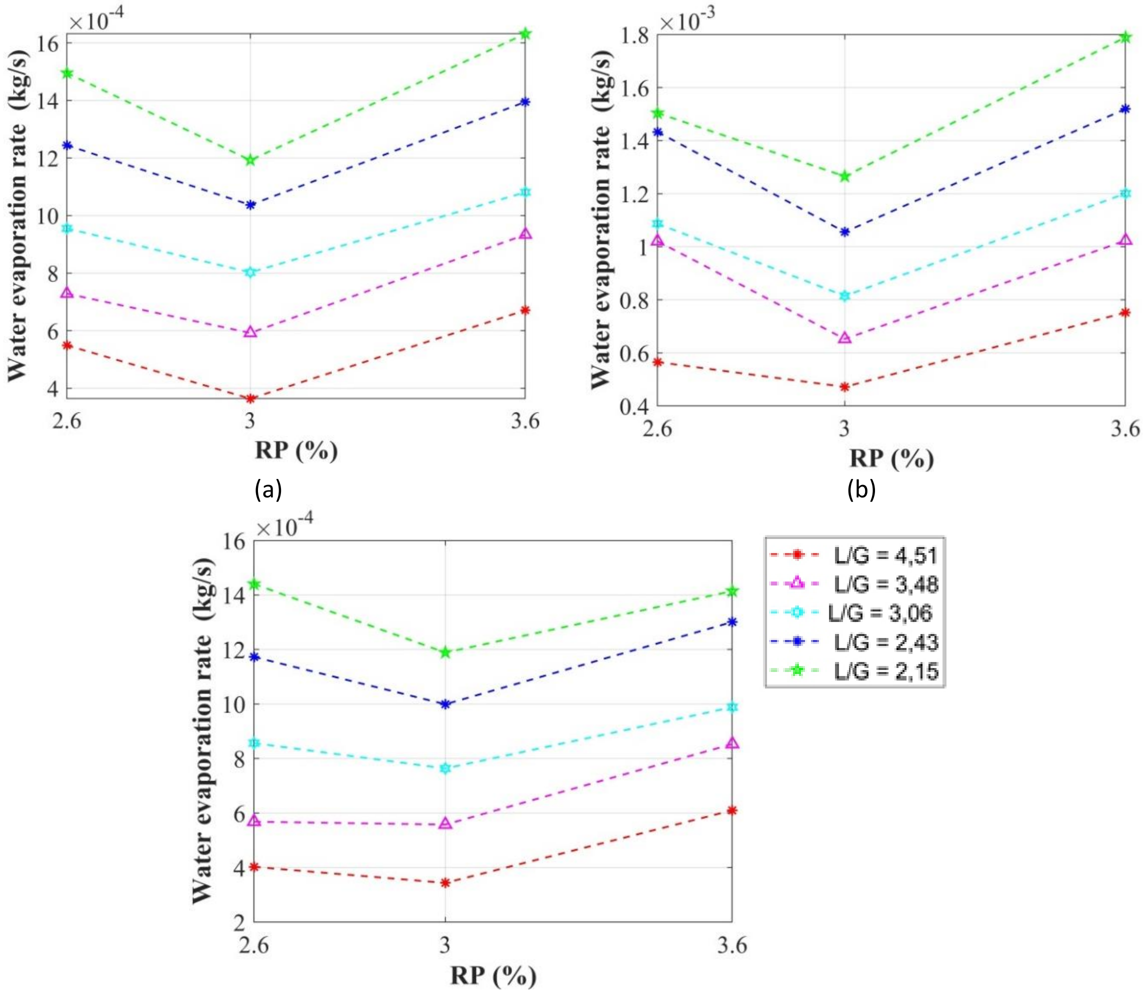
(c)

Fig. 13. Effect of fill perforation on heat rejection (a) θ_1; (b) θ_2; (c) θ_3

3.9 Effect of Fill Perforations on Water Evaporation Rate

The presence of perforations in the cooling tower facilitates a more vigorous interaction between the air and water, resulting in an enhanced rate of water evaporation from the plate fill.

Figure 14 shows the effect of ratio perforation (RP_1, RP_2, RP_3) on the water evaporation rate at fill tilt angle. Figure 14(a) shows a 29.3% increase from RP_2 and a 16% increase from RP_1. Figure 13(b), demonstrates that RP_3 has a higher maximum water evaporation rate of 26.92% compared to RP_2 and 8.4% to RP_1. Figure 14(c) show RP_3 is 15.96% higher than RP_2 and 1.8% higher than RP_1. The results suggest that RP_3 exhibits the highest evaporation efficiency due to the strong interaction between air and water, leading to an increased evaporation rate and improved heat absorption efficiency. This is accomplished by creating a greater surface area of contact between water and air, facilitated by the openings in the fill plate, which enhances ventilation. In general, a rise in RP leads to a corresponding increase in the evaporation rate. This is because more water is cycled through the system, creating more evaporation chances. Nevertheless, the optimal evaporation efficiency is attained when the L/G ratios are lower. The airflow passing through the cooling tower fill plates influences the rate at which water evaporates. This is because the air velocity and flow rate are affected, enhancing the heat transfer between the water and air. This is due to the reduced airflow resistance at RP_3 as the level of ventilation increases, the rate of evaporation also increases, resulting in a more significant influx of chilly air into the tower resulting in increased efficiency [31-33,36].



(a)

(b)

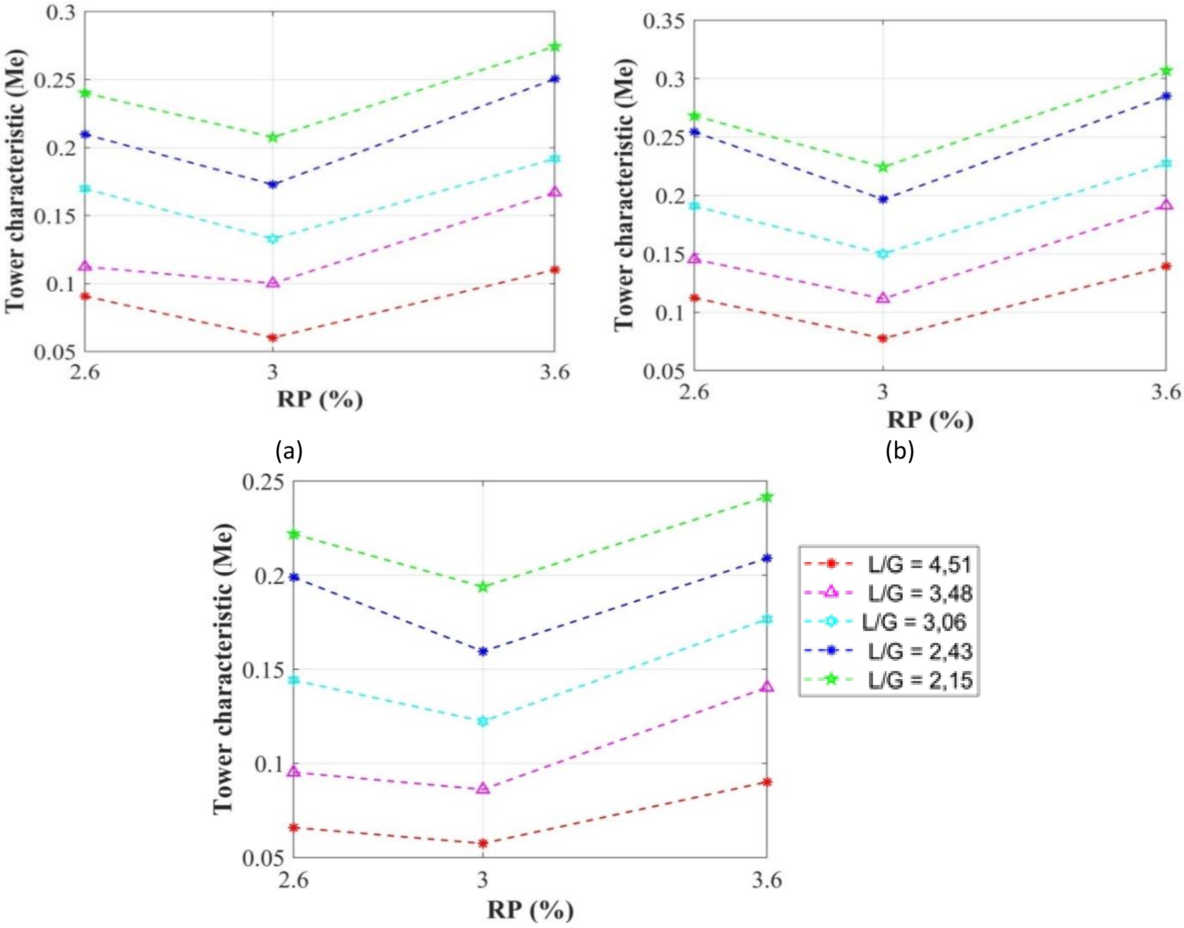
(c)

Fig. 14. Effect of perforate fill on water evaporation rate (a) θ_1; (b) θ_2; (c) θ_3

3.10 Effect of Fill Perforation on Tower Characteristics

Figure 15(a) displays the tower characteristics for perforation fill RP_1, ranging from a minimum value of 0.11 to a maximum value of 0.27. RP_2 exhibits tower features ranging from a minimum of 0.078 to a maximum of 0.224, whereas RP_3 displays characteristics ranging from a minimum of 0.14 to a maximum of 0.31. RP_3 demonstrates a maximum increase of 26.89% compared to RP_2 and a 12.59% increase compared to RP_1.

Figure 15(b) illustrates the tower's attributes when tilted angle of fill at θ_2. Ratio of perforation one (RP_1) ranges from a minimum of 0.091 to a maximum of 0.24, RP_2 ranges from a minimum of 0.060 to a maximum of 0.21, and RP_3 ranges from a minimum of 0.11 to a maximum of 0.274. This demonstrates a maximum increase of 24.37% over RP_2 and 12.40% over RP_1 Figure 15(c) reflects the impact of a θ_3-degree tilt angle on perforation: RP_1 ranges from a minimum of 0.066 to a maximum of 0.22, RP_2 ranges from a minimum of 0.057 to a maximum of 19.38, and RP_3 ranges from a minimum of 0.09 to a maximum of 0.242. The most significant increase is 19.8% for RP_3 and 8.2% for RP_2. The tower's features dropped when the Ratio of perforation at RP_2, but it rose once it RP_2, suggesting a rebound in efficiency. The investigation indicates that RP impacts tower characteristics, with the maximum efficiency for heat and mass transfer occurring at approximately at RP_3. This occurrence demonstrates that RP_3 positively impacts tower features by enhancing the uniformity of air temperature distribution as the airflow velocity increases [37]. The presence of fill perforations can significantly affect the characteristics of the tower. Increased Merkel numbers increase heat and mass transfer coefficients [26].



(a) (b)

(c)

Fig. 15. The impact of fill perforation on tower characteristic (a) θ_1; (b) θ_2; (c) θ_3

4. Conclusion

This study demonstrates that the angle at which the fill is tilted in a wet cooling tower has a substantial impact on the efficiency of heat transfer. Based on the observations, it was consistently found that a $\theta_1 = 15^o$ angle of tilt resulted in more efficient performance compared to angles of $\theta_2 = 20^o$ and $\theta_3 = 25^o$. This was assessed using different perforations (RP_1, RP_2, RP_3) and the air-water mass ratio (L/G). An angle of θ_1(15°) results in a greater temperature range and improved heat transfer efficiency due to the prolonged contact time between water and air. Furthermore, a decreased tilt angle promotes the creation of water droplets and increases the surface area of contact with water and air, leading to a substantial enhancement in heat transmission. More precisely, the heat transmission efficacy increases by 16.5% when the angle is changed from θ_3 to θ_1. This enhancement is further bolstered by the greater evaporation rate of water at reduced tilt angles, which leads to a rise in the total effectiveness of the system. Hence, a tilt angle of θ_1 was found to be the most advantageous in enhancing heat transfer efficiency and cooling effectiveness in a wet cooling tower.

The impact of different ratio of perforations (RP_1 =2,6%, RP_2 = 3%, RP_3 =3,6%) on cooling towers' temperature range and efficiency with fixed tilts of θ_1, θ_2, and θ_3. RP_3, which had a ratio of perforation of 3,6%, demonstrated notable enhancements in temperature range and efficiency when compared to RP_1 and RP_2. Increasing the size of the holes on the plate enhances the area of contact between water and air, leading to improved transfer of heat and mass and optimal reduction of aerodynamic drag. This enhances the efficiency of heat dissipation and imperforation over ventilation effectiveness. The study demonstrates that as the ratio of perforation increases, the airflow resistance decreases, and the heat absorption is maximized. The highest efficiency is attained at approximately 3,6% ratio of perforation. Overall, RP_3 regularly provides the highest level of performance when it comes to enhancing cooling tower efficiency and heat rejection.

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