Experimental Study on the Thermal Performance of a Counterflow Wet Cooling Tower with Bamboo Woven Packing

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Bamboo packing has been found to be a superior alternative to plastic packing for cooling towers, but traditional bamboo grid packing comprises numerous components, resulting in high production costs and low production efficiency. Therefore, a novel structured bamboo woven packing was designed in this study. The bamboo woven packing consisted solely of bamboo strips, which simplified the production process. The thermal performance of bamboo packing was systematically investigated. The results indicated that increasing the inlet air velocity and gas-liquid ratio enhanced the cooling water range and cooling efficiency, whereas a higher water drenching density had the opposite effect. The pressure drop increased upon increasing the inlet air velocity and water drenching density, while the influence of the gas-liquid ratio on pressure drop did not exhibit a discernible trend. A comparative analysis of the thermal performance of cooling towers utilizing bamboo woven packing and bamboo grid packing was also conducted under identical experimental conditions. The results showed that the cooling tower with bamboo woven packing exhibited a higher air velocity, a lower outlet water temperature, and superior cooling efficiency. Consequently, the newly designed bamboo woven packing outperformed traditional bamboo grid packing in terms of structural design, manufacturing process, and thermal performance.

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INTRODUCTION

Cooling towers are applied in various industrial sectors, including air conditioning, chemical engineering, power generation, petrochemicals, and metallurgy due to their excellent heat dissipation capabilities and considerable energy-saving benefits (Chamanthi *et al*. 2022). As the core component of cooling towers, the cooling packing plays a crucial role in heat and mass transfer because it determines the air-to-water contact. Its characteristics significantly influence the cooling efficiency and operating costs of cooling towers (Lemouari *et al*. 2007; Yang *et al*. 2024). Ideally, the cooling packing materials should be light, strong, and durable (Salins *et al*. 2023), but current materials utilized as cooling tower packing include plastics, metals, and ceramics. These different packing materials affect the heat transfer efficiency of cooling towers (Yang *et al*. 2024).

Researchers have examined how material type, specific surface area, pore size, and shape of cooling packings affect the thermal performance of cooling towers. Their findings have indicated that these factors significantly influence the performance of cooling towers, with several packing materials exhibiting good thermal performance (Kong *et al*. 2018; Kong *et al*. 2019; Raj *et al*. 2019; Boev and Boeva 2020; Ozgur and Bayrakci 2020; Merentsov *et al*. 2021; Ahmed *et al*. 2022; Kariem *et al*. 2022; Shinde and Gulhane 2023). Nonetheless, commonly used cooling packings have various shortcomings, such as plastic packings (PVC and PP) that suffer from a short service life, poor thermal stability, low mechanical strength, and environmental burdens. Ceramic packings are heavy, brittle, and expensive, while metal packings are susceptible to corrosion and are also expensive. In contrast, bamboo, as a biomass composite material composed of various natural polymers, has advantages such as environmental friendliness, a long service life, favorable mechanical properties, and cost-effectiveness (Escamilla *et al*. 2018; Ma *et al*. 2021; Feng *et al*. 2024; Young *et al*. 2024). Notably, its glass transition temperature exceeds 100 °C (Huang *et al*. 2015), ensuring resistance to softening or deformation in the hot and humid conditions of a cooling tower. Consequently, researchers have explored bamboo as a replacement for plastic packing in industrial cooling towers, with field applications demonstrating its favorable thermal performance (Chen *et al*. 2016; Saifullah and Sies 2024).

Life cycle assessment results revealed that when bamboo packing was used to replace PVC packing in cooling towers, the total cumulative energy demand decreased from 3420 to 561 MJ per functional unit. Additionally, the Building for Environmental and Economic Sustainability indices showed a desirable reduction, with the values decreasing to between 1/1.5 to 1/10.5 of the original values (Ma *et al*. 2021). After nine years of use, no blockage was observed in the bamboo packing channels, and the material's mechanical properties still met the operational standards of cooling towers (Chen *et al*. 2018). The methods for fabricating traditional bamboo packing involve drilling a hole at the center of each dried bamboo strip and then inserting a round bamboo piercing rod into these holes to connect multiple bamboo strips. The spacing between the bamboo strips is maintained within the range of 3.8 to 5.0 cm using polypropylene sleeves for separation. The ends of the bamboo packing are secured by inserting bamboo nails into the holes of the round bamboo piercing rod. The assembled bamboo packing units have a grid-like structure and are termed bamboo grid packing (BGP). These cooling packing units are then arranged in a vertically staggered manner, and once the desired packing height is attained, they are placed into the cooling tower for operation, as illustrated in Fig. 1 (Chen *et al*. 2018).

BGP, which consists of numerous components such as bamboo strips, round bamboo piercing rods, bamboo nails, and polypropylene sleeves, has several drawbacks. Notably, it requires numerous manufacturing processes to produce its components, and the assembly of BGP is predominantly manual rather than mechanized, leading to low production efficiency and weak market competitiveness. Perforating the bamboo strips significantly compromises the mechanical strength of BGP, and the humid and thermally unstable environment in cooling towers accelerates the aging of the polypropylene sleeves. These factors ultimately shorten the service life of BGP. Moreover, BGP fails to fully utilize the inherent flexibility and bending strength of bamboo or address the connectivity issues between the bamboo strips. These issues have served as barriers to the adoption of

BGP in industrial cooling towers. Optimizing the structure of cooling packings can enhance their thermal performance (Pooriya *et al*. 2016) and also simplify the manufacturing process, reduce production costs, and extend their service life. Therefore, the key challenges to developing bamboo packing are avoiding drilling holes in bamboo strips when using them as the sole component for cooling packings, thereby reducing production costs, and ensuring effective thermal performance.

In view of the above key challenges, this study innovatively designed a bamboo woven packing (BWP). Its thermal performance was systematically compared with BGP under different inlet air velocities and water drenching densities. Furthermore, the comparative analysis was extended to different gas-liquid ratios, since this parameter is a critical factor in cooling packing thermal performance testing. It influences both cooling efficiency and the number of transfer units (NTU). The thermal performance investigation followed established experimental norms and standards, encompassing measurements of the cooling water range (the difference between the inlet and outlet water temperatures), cooling efficiency, and pressure drop. Empirical equations were also used to fit the number of transfer units, volumetric dispersion coefficient, and airflow resistance. To further enhance the rigor of comparative analysis, this study also employed MATLAB software to establish identical experimental conditions and leveraged this computational framework to investigate thermal performance discrepancies between cooling towers equipped with BWP and BGP. The findings of this research have implications for promoting bamboo packing and advancing the bamboo industry.

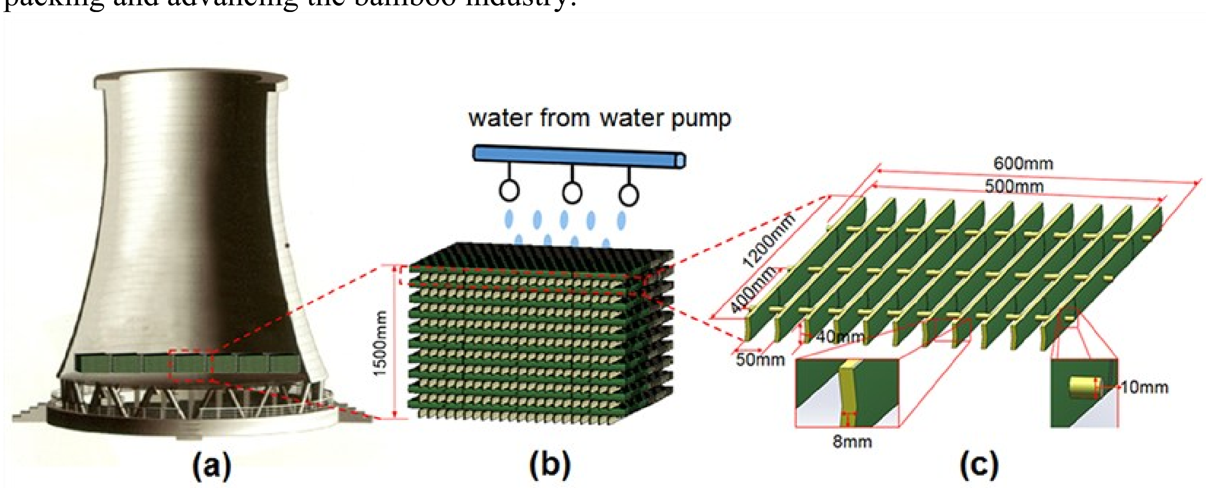

Fig. 1. (a) Application of BGP in hyperbolic cooling towers; (b) BGP units stacked to a height of 1.5 m; (c) BGP unit assembled with bamboo strips (from Fig. 1 in Reference (Chen *et al*. 2018))

EXPERIMENTAL

Materials

Raw materials were sourced from Moso bamboo (*Phyllostachys edulis* (Carr.) J.Houz) cultivated in Zhangping, Fujian Province, China. Healthy, four-year-old bamboo was selected and classified based on stem diameter, with a preference for culms having a diameter of approximately 12 cm and a wall thickness of about 1 cm. A 3-meter-long bamboo segment was extracted starting at a height of 1.5 meters above the ground, and the bamboo segments were air-dried before use. To investigate whether the thermal performance of the BWP was better than that of traditional bamboo grid packing, this study employed BGP as a control sample. The dimensions of the individual BGP units were 100 cm × 100 cm × 4 cm (length × width × height; same dimensions apply hereinafter). A large BGP block with dimensions of 100 cm × 100 cm × 152 cm was assembled using thirty-eight BGP units arranged in a vertically staggered manner. This large BGP block was then installed in a cooling tower for thermal performance tests.

The Structural Design and Manufacturing Process of BWP

The BWP was fabricated from bamboo through a process of sorting, cutting, and drying to produce uniform, curved bamboo strips. These strips were then woven in both the longitudinal and transverse directions, leveraging the inherent flexibility of bamboo. This production method is notably simple. Finally, the BWP units were arranged in a staggered front-and-back configuration to form a new type of BWP block. The step-by-step preparation process for the BWP is described below.

Sorting and sawing of bamboo

The bamboo was split into four equal segments along its growth direction using a bamboo cutting machine. These segments were then sawed into bamboo strips with two different lengths: (a) 150 cm × 4 cm × 1 cm (length × width × thickness, same dimensions apply hereinafter), which were used as vertical bamboo strips; (b) 300 cm × 4 cm × 1 cm, which were used as horizontal bamboo strips, as illustrated in Fig. 2.

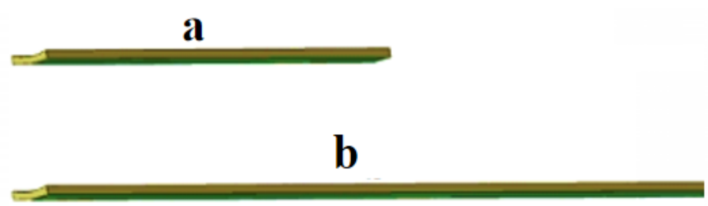

Fig. 2. Two different lengths of bamboo strips

Weaving bamboo strips

Five vertical bamboo strips and several horizontal bamboo strips were fed into the bamboo weaving machine and then woven in both the longitudinal and transverse directions. The center-to-center spacing between the vertical strips was set to 60 cm, with horizontal strips interwoven among them.

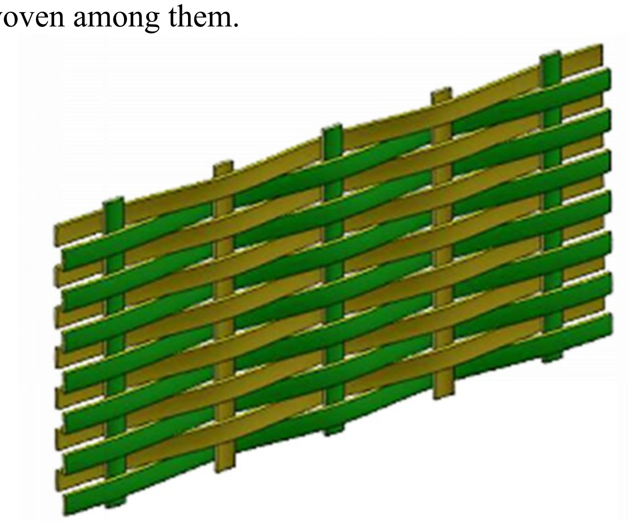

Fig. 3. Bamboo woven packing unit

The adjacent bamboo strips were oriented in opposite directions, and a gap of approximately 30 cm was left at both ends of the vertical strips (Fig. 3). The number of horizontal bamboo strips determined the height of the BWP unit, which could be adjusted according to actual requirements. This weaving method facilitates airflow within the BWP units, which can enhance the cooling efficiency.

Arrangement of BWP units

Due to bending stress, the ends of the horizontal bamboo strips had a tendency to splay outwards. To prevent the vertical bamboo strips from falling out when this occurs, the packing can be secured by binding it with bamboo slivers at the left and right ends. Additionally, the BWP units can be arranged in a staggered front-and-back configuration to form larger BWP blocks. The compression between adjacent BWP units exerts reverse loads on the opened bamboo strips, which helps mitigate warping at the ends of the bamboo units. This arrangement constrained the splay angle of the horizontal bamboo strips, thereby preventing the vertical bamboo strips from slipping, as illustrated in Fig. 4.

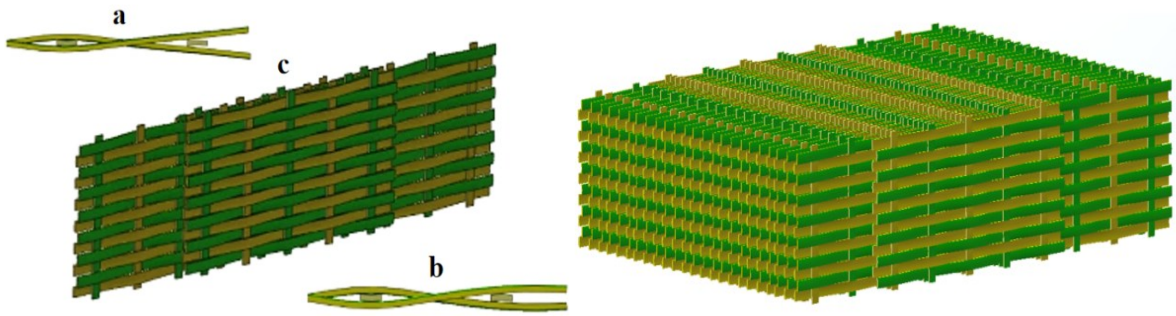

Fig. 4. The arrangement of BWP units. Note: a: The angles at both ends of the transverse bamboo strips were relatively large before assembly; b: The angles at both ends of the transverse bamboo strips were relatively small after assembly; c: The BWP block formed by the staggered front-and-back arrangement of three BWP units

The innovative BWP has a structure whose only units are curved bamboo strips. During production, the curved bamboo strips remain intact, giving BWP superior mechanical strength and durability compared to BGP. The dimensions of the BWP units can be flexibly adjusted to modify their cooling efficiency for different cooling towers. The entire production process was fully mechanized, including sorting the bamboo poles, cutting curved bamboo strips, and weaving bamboo packing. This approach decreases labor costs and significantly enhances production efficiency.

Experimental System

Fourteen BWP units were assembled into a large BWP block. The thermal performance of the cooling tower equipped with a bamboo packing block was tested according to DL/T 933-2005 (2005).

Figure 5 illustrates the overall workflow of the cooling tower, in which circulating water was pumped into the horizontal heat exchanger for heating, and heated water flowed through the upper pipe into the flow orifice plate. After its temperature was measured using a hot water thermometer, the water was then discharged into the water distribution system. The dispersed hot water was sprayed into the cooling packing and continued to flow downward, after being cooled by air in the cooling packing zone. As it flowed, its temperature was measured by a cold water thermometer before being collected in the collection basin. After temperature and humidity regulation, the air was expelled into the cooling tower by a centrifugal blower, and it passed through a vane anemometer and an air thermometer along the way.

Upon entering the cooling tower, the air flowed upward, passing through the cooling packing, water distribution system, drift eliminator, and finally the air thermometer. During its upward flow, it exchanged heat and mass with the circulating water, which decreased the water temperature.

Table 1 provides additional details on the main measurement devices utilized within the experimental system.

Table 1. Information about Measuring Devices Used during the Tests

Measurement Parameters	Measuring Instrument	Instrument Type	Manufacturer	Measuring Range	Accuracy
Temperature	Temperature probes	Pt–100	Hangzhou Liance Automation Technology Co., Ltd.(Hangzhou, China)	0 to 80 °C	±0.01 °C
Air velocity	Vane anemometer	UNI–363	Shenyang Zizun Technology Co., Ltd. (Shenyang, China)	0 to 30 m/s	±0.1 m/s
Pressure drop	Digital manometer	MP120	Shanghai Kewang Industrial Co., Ltd. (Shanghai, China)	-1000 to 1000 Pa	±0.15%
Atmospheric pressure	Multifunctional Weather Station	NK4500	Shanghai Hengdong Instrument Co., Ltd. (Shanghai, China)	75 to 110 kPa	±0.01 kPa
Water volume	Flow orifice plate	DN25	Jiangsu Jinfan Instrument Co., Ltd.(Huaian, China)	3 to 35 t/h	±0.5%

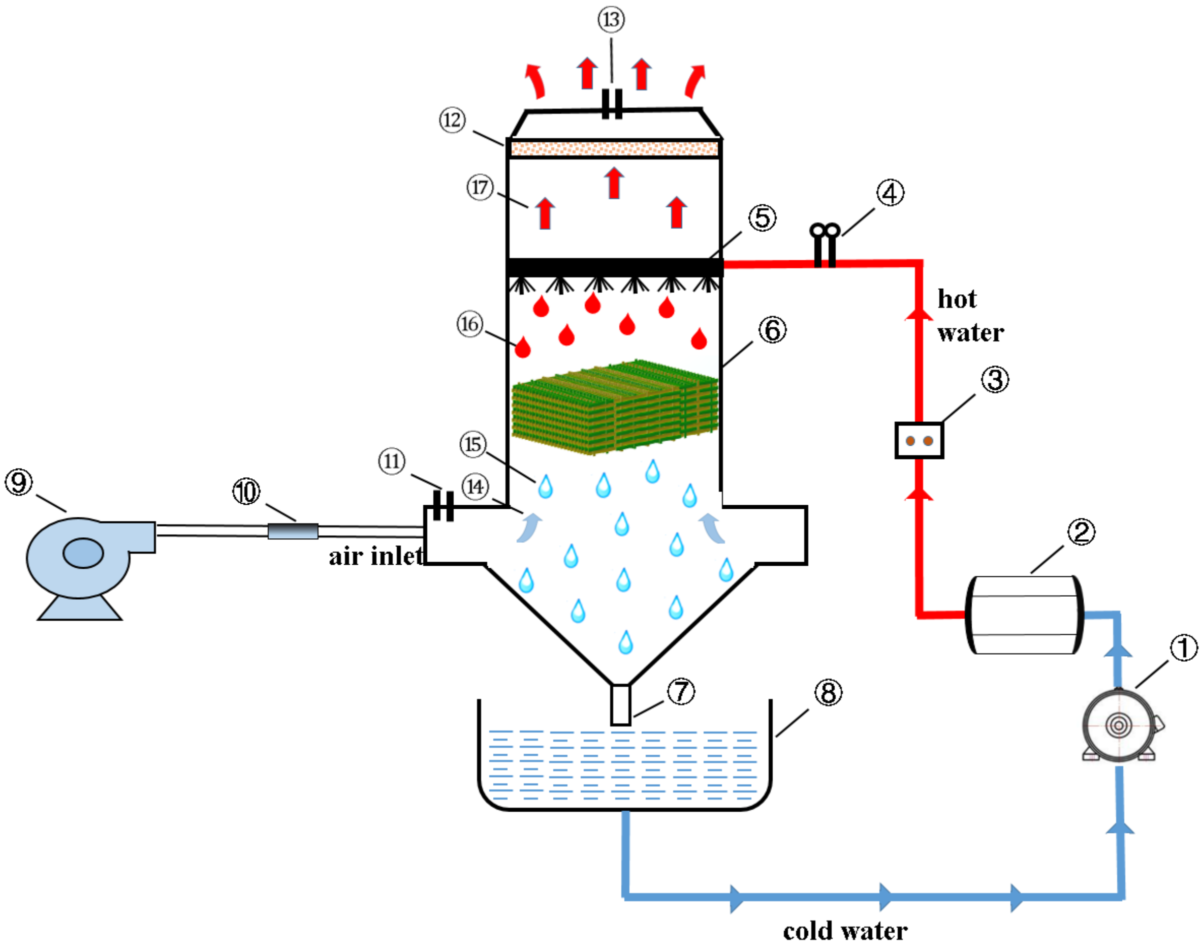

Fig. 5. Cooling tower components. 1: Water pump; 2: horizontal heat exchanger; 3: flow orifice plate; 4: hot water thermometer; 5: water distribution system; 6: cooling packing; 7: cold water thermometer; 8: collecting basin; 9: centrifugal blower; 10: vane anemometer; 11: air thermometer (measuring the inlet air temperature); 12: drift eliminator; 13: air thermometer (measuring the outlet air temperature); 14: inlet air; 15: cold water; 16: hot water; 17: steam and outlet air after absorbing heat

Data Processing and Thermal Performance Evaluation

The circulating cooling water transferred heat through direct contact with air and dissipated it through evaporation. Consequently, the cooling process involved both heat transfer and mass transfer. The thermal performance of the cooling tower was evaluated based on the cooling water range, cooling efficiency, NTU, volumetric dispersion coefficient, and air resistance.

Cooling water range

The cooling water range is defined as the difference between the inlet water temperature and the outlet water temperature and is calculated as follows,

$$R = T_1 - T_2 \quad (1)$$

where R refers to the cooling water range (°C), T_1 is the inlet water temperature, and T_2 is the outlet water temperature.

Cooling efficiency

The cooling efficiency refers to the degree to which the cooling tower reduces the temperature of the circulating water and is related to two key factors: the wet bulb temperature of the inlet air and the cooling water range (Kumar *et al*. 2023). The cooling efficiency was calculated using the following equation,

$$e = \frac{R}{T_1 - T_{iw}} \times 100\% \tag{2}$$

where e refers to the cooling efficiency, and T_{iw} is the wet bulb temperature of the inlet air. For example, when T_1 is 40 °C, T_2 is 35 °C, and T_{iw} is 26 °C, then R equals 5 °C. By substituting R = 5 °C into Eq. 2, one can calculate that e equals 35.71%.

NTU and volumetric dispersion coefficient

The NTU reflects the cooling capacity of the cooling packing, which depends on the size and structure of the cooling packing, water drenching density, external air conditions, and air volume (Huang 2014). The most widely accepted theory of the cooling tower process was developed by Merkel (Lavasani *et al*. 2014). By transposing and integrating Merkel's equation, NTU can be expressed as Eq. 3. Based on the measured data, Eq. 3 can be simplified to Eq. 4 using Simpson's rule and the ordinary least-squares method (Zhao 1996; Kong *et al*. 2018), as follows,

$$N = \frac{K_a V_p}{L} = \int_{T_2}^{T_1} \frac{C_w}{h' - h} dt \tag{3}$$

$$N = \frac{K_a V_p}{L} = B\left(\frac{G}{L}\right)^b = B\lambda^b \tag{4}$$

where V_p is the volume of the cooling packing (m^3), L is the water flow rate (kg/h), G is the inlet air flow rate, λ is the gas-liquid ratio, *i.e.*, G/L, C_w is the specific heat capacity of water (kJ/(kg·°C)), h is the enthalpy of air (kJ/kg), h' is the saturated enthalpy of air at the water temperature, and B and b are experimental constants. According to Eq. 3, the calculated values of N and λ under different operating conditions are plotted on a logarithmic graph, and these constants are subsequently determined using the least squares method. K_a is the volumetric dispersion coefficient, which represents the mass of water evaporated from the unit volume of the cooling packing to the air per unit time, reflecting the heat dissipation capability of the cooling packing. K_a is primarily influenced by the air velocity, water drenching density, and the structure and material of the cooling packing (Huang 2014). Its value can be calculated using Eq. 5 (Singla *et al*. 2016).

$$K_a = \frac{L}{V_p} \int_{T_2}^{T_1} \frac{C_w}{h' - h} dt \tag{5}$$

Using the least-squares method, K_a can be empirically correlated with the mass flux of air and water as shown in Eq. 6,

$$K_a = D \times g^c \times q^n \tag{6}$$

where g is the mass flux of air (kg/(m^2·h)), q is the mass flux of water, and D, c, and n are experimental constants that can be fitted based on the experimental data by means of the least squares method (Huang 2014).

Resistance characteristics

The resistance characteristics of the cooling packing reflect the magnitude of resistance encountered by air as it flows through the cooling packing, which is a critical factor affecting the cooling efficiency of cooling towers. The resistance characteristics are influenced by the air velocity, water drenching density, and the cooling packing structure. Their magnitude is typically measured using pressure drop. Based on test data, the pressure drop can be fitted by Eq. 7 (Wang *et al*. 2018),

$$\frac{\Delta P}{\gamma} = A \times V^{s} \tag{7}$$

where ΔP is the pressure drop (Pa), γ refers to the specific gravity of air (N/m^3), V is the windward velocity of the packing section (m/s), and A and s are parameters related to the water drenching density, which can be expressed using the following equations,

$$A = a_1 \times q^2 + a_2 \times q + a_3 \tag{8}$$

$$S = a_4 \times q^2 + a_5 \times q + a_6 \tag{9}$$

where a_1, a_2, a_3, a_4, a_5, and a_6 are experimental constants. By selecting multiple sets of different q and V values, and subsequently substituting them along with the measured ΔP into Eqs. 7 to 9, these constants can be determined (Huang 2014).

RESULTS AND DISCUSSION

Effect of Inlet Air Velocity and Water Drenching Density on Thermal Performance

To enhance measurement accuracy, the thermal performance tests of the bamboo packing were conducted in a large-scale cooling tower located at a scientific research institution rather than in a small, modified cooling tower, resulting in prolonged testing time for each sample. Consequently, the air parameters (including dry bulb temperature, wet bulb temperature, and barometric pressure) varied across the individual thermal performance tests of BWP and BGP. However, these variations did not compromise the validity of the thermal performance comparisons between them. In this study, the arithmetic average of three measurements under the same working condition was taken as a representative working condition. The main test parameters of a cooling tower with BWP were as follows:

V = 1.0–2.5 m/s, q = 7000–13000 kg/(m^2·h), P = 101.6 kPa.

The air and water temperatures were measured as follows:

T_{id} = 14.8–15.6 °C, T_{iw} = 13.2–13.7 °C, T_1 = 40.8–41.4°C, T_2 = 23.0–32.7 °C.

where T_{id} is the dry bulb temperature of inlet air, P is barometric pressure. The main test parameters of a cooling tower with BGP were as follows:

V = 0.85–2.25 m/s, q = 6250–13990 kg/(m^2·h), P = 96.9 kPa.

The air and water temperatures were measured as follows:

T_{id} = 29.7–32.8 °C, T_{iw} = 24.3–26.1 °C, T_1 = 40.8–42.8 °C, T_2 = 27.4–36.2 °C.

Three water drenching densities and four air velocities were combined to form twelve sets of operating conditions, and then the thermal performance of a cooling tower with a 1.5-meter-high BWP block was measured under these twelve operating conditions. For the control samples, a combination of five water drenching densities and three air velocities resulted in fifteen operating conditions. The thermal performance of the cooling tower with a 1.52-meter-high BGP block was measured under these fifteen operating conditions. Figures 6 and 7 depict the effect of inlet air velocity and water drenching density on the cooling water range and cooling efficiency.

With all other conditions kept constant, both the cooling water range and cooling efficiency increased upon increasing the inlet air velocity, which is consistent with findings reported in the literature (Kumar *et al*. 2023; Zhao *et al*. 2023). This was attributed to the intensified heat exchange between the air and water film located on the cooling packing surface, as facilitated by the increased inlet air velocity. This enhanced heat transfer promoted the faster evaporation of water molecules and enhanced heat removal, increasing both the cooling water range and cooling efficiency. Under specific conditions, particularly at a moderate crosswind velocity, increasing the ventilation volume of the cooling tower enhances its heat dissipation efficiency. However, the degree of enhancement in both the cooling water range and cooling efficiency was not positively correlated with an increase in the inlet air velocity. Instead, as the inlet air velocity increased, the magnitude of improvement diminished. For example, when the water drenching density of the cooling tower with a BWP block was maintained at 13,000 kg/(m^2·h), increasing the inlet air velocity from 1 m/s to 1.5 m/s increased the cooling water range and cooling efficiency by 2 °C and 7.76%, respectively. Conversely, when the inlet air velocity increased from 1.5 m/s to 2 m/s, the increases dropped to 1.8 °C and 6.91%, respectively. Further increases from 2.0 m/s to 2.5 m/s provided smaller improvements of 1.3 °C and 4.78%, respectively. Similar trends were observed for enhancements in the cooling water range and cooling efficiency at other water drenching densities.

Both the cooling water range and cooling efficiency decreased significantly as the water drenching density increased while other conditions were held constant, in agreement with previous findings in the literature (Shinde *et al*. 2023; Zhao *et al*. 2023). Increasing the water drenching density implies that a greater volume of water was sprayed onto the packing material per unit time, which may have caused some water droplets to fall before fully exchanging heat with the air, thereby reducing the cooling time of the water. Additionally, increasing the water drenching density formed a thicker water film on the surface of the bamboo packing, which hindered adequate contact between the air and the intermediate water layer, thereby decreasing the effective heat exchange area. As the water drenching density increased, excessive water droplets accumulated on the surface of the bamboo packing, increasing the volume of the bamboo packing. Meanwhile, it narrowed the air flow channels, impeding the airflow within the cooling packing. The reduction in airflow lowered the heat exchange efficiency, thereby affecting the cooling effect of the cooling tower. Finally, there were notable structural differences between the outer surface and inner surface of the curved bamboo strips. The outer surface protruded outward while the inner surface converged inward, resulting in distinctly different water flow patterns being formed on the inner and outer surfaces of each curved bamboo strip. Air tended to flow more readily into the surface with less resistance, leading to uneven heat exchange and a higher outlet water temperature, which decreased both the cooling water range and cooling efficiency.

Even though both the inlet air velocity and water drenching density had similar influences on both the BWP and BGP, Fig. 6 shows that the cooling water range of BWP was larger than that of BGP. Specifically, when the inlet air velocity was 2 m/s and the water drenching density was 13,000 kg/(m^2·h), the cooling water range of BWP reached 12.5. This value surpasses the 11 achieved by BGP at an inlet air velocity of 2.25 m/s and a water drenching density of 12,150 kg/(m²·h). This discrepancy occurred because the two types of bamboo packings had structural differences and were exposed to different inlet air wet-bulb temperatures during the tests, which exerted a crucial influence on the cooling water range. When the inlet water temperature of the cooling tower remained constant, a higher inlet air wet-bulb temperature increased the outlet water temperature, thereby reducing the cooling water range (Sarker *et al*. 2008). However, as illustrated in Fig. 7, BGP exhibited a higher cooling efficiency than BWP. Specifically, when the inlet air velocity was 2.25 m/s and the water drenching density was 13,940 kg/(m²·h), BGP achieved a cooling efficiency of 57.38%, which surpassed the 50.74% obtained by BWP at an inlet air velocity of 2.5 m/s and a water drenching density of 13,000 kg/(m²·h). This was because the cooling efficiency is influenced by the packing structure, cooling water range, and inlet air wet-bulb temperature. A higher inlet air wet-bulb temperature resulted in a higher cooling efficiency (Khan *et al*. 2004). According to Eq. 2, the cooling efficiency was calculated as the ratio of the cooling water range to the difference between the inlet water temperature and the inlet air wet-bulb temperature. Therefore, the higher cooling efficiency of BGP compared with BWP was due to the relatively smaller impact of the cooling water range on BGP compared with the influence of the difference between the inlet water temperature and the inlet air wet-bulb temperature.

The effects of inlet air velocity and water drenching density on the thermal performance of cooling towers with bamboo packing were not simply linear and were instead influenced by multiple factors. Therefore, to achieve optimal thermal performance, it is essential to consider these factors, including the material and structural design of the cooling packing, water drenching density, air velocity, and load variations.

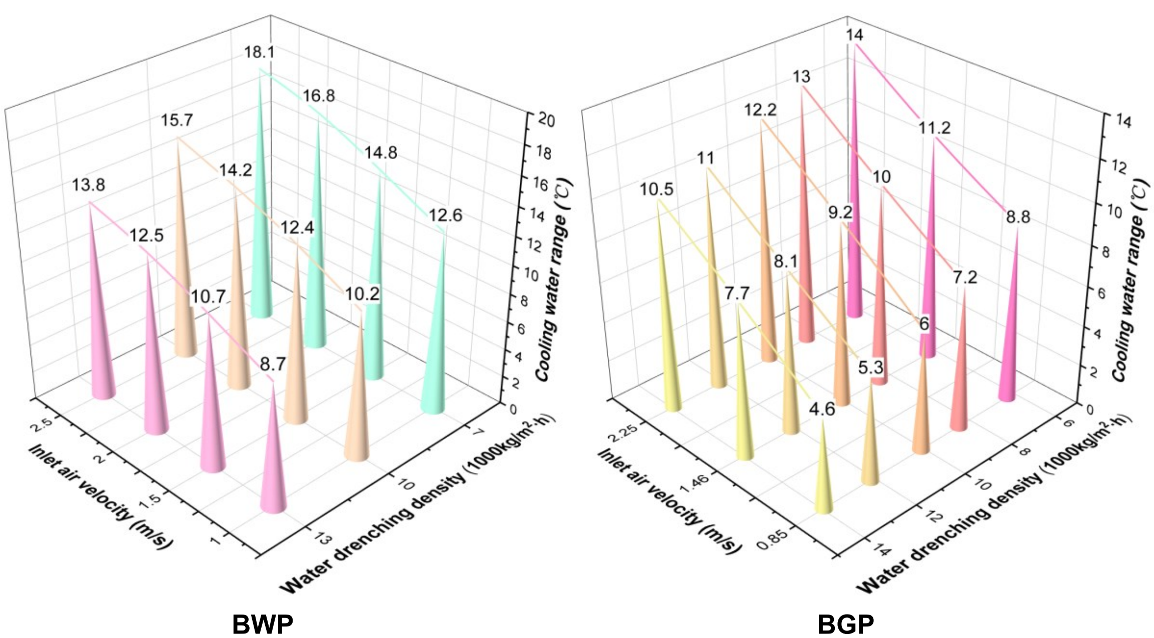

Fig. 6. Effect of inlet air velocity and water drenching density on the cooling water range

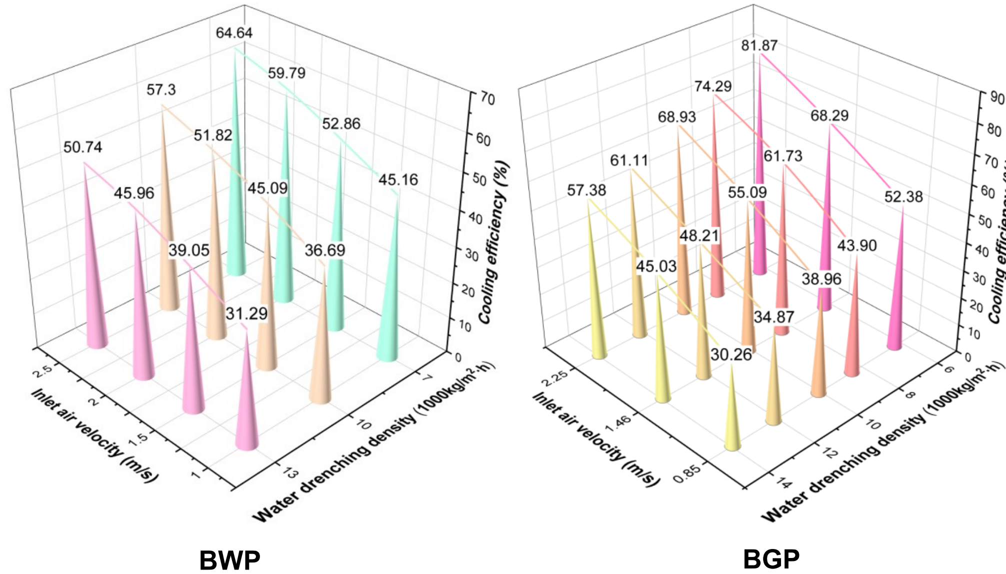

Fig. 7. Effect of inlet air velocity and water drenching density on the cooling efficiency

Effect of Gas-to-Water Mass Ratio on Thermal Performance

Increasing the water drenching density decreased the cooling efficiency of the cooling tower equipped with bamboo packings, whereas increasing the inlet air velocity had the opposite effect. To better understand how these two factors jointly influenced the cooling efficiency of the cooling tower, it was necessary to consider how the gas-to-water mass ratio (gas-liquid ratio) affected the thermal performance of the cooling tower with bamboo packings. The gas-liquid ratio refers to the ratio of the inlet air flow rate to the cooling water flow rate. Figure 8 illustrates the influence of the gas-liquid ratio on the cooling water range and cooling efficiency, in which both the cooling water range and cooling efficiency increased with the gas-liquid ratio, consistent with previous literature (Shinde *et al*. 2023). This is because a higher gas-liquid ratio means a greater mass of air is available per unit mass of water to carry away heat. This enhances the turbulence and the rate of heat and mass transfer between water and air within the bamboo packings.

The heat dissipation mechanisms included contact heat dissipation, evaporative heat dissipation, and radiative heat dissipation, with evaporative heat dissipation being one of the primary modes in cooling towers. A higher gas-liquid ratio also facilitated the evaporation of water molecules into the air, thus removing more heat from the water, lowering the water temperature, and increasing both the cooling water range and cooling efficiency. However, a higher gas-liquid ratio is not always advantageous. The marginal improvement in both the cooling water range and cooling efficiency diminished as the gas-liquid ratio increased further. This occurred because, beyond a certain point, the gains in heat and mass transfer become less significant. Furthermore, an excessively high gas-liquid ratio increased the fan energy consumption and could lead to an uneven water flow distribution within the cooling packing, adversely affecting the tower's cooling efficiency. Therefore, although increasing the gas-liquid ratio within a certain range improves cooling efficiency, an optimum value exists in practice. Selection must be based on specific cooling tower requirements to balance thermal performance against energy consumption. As inferred from Fig. 8, under the same gas-liquid ratio, the cooling water range of BWP was greater than that of BGP, yet its cooling efficiency was lower. This difference was attributed to the lower air wet-bulb temperature surrounding the BWP.

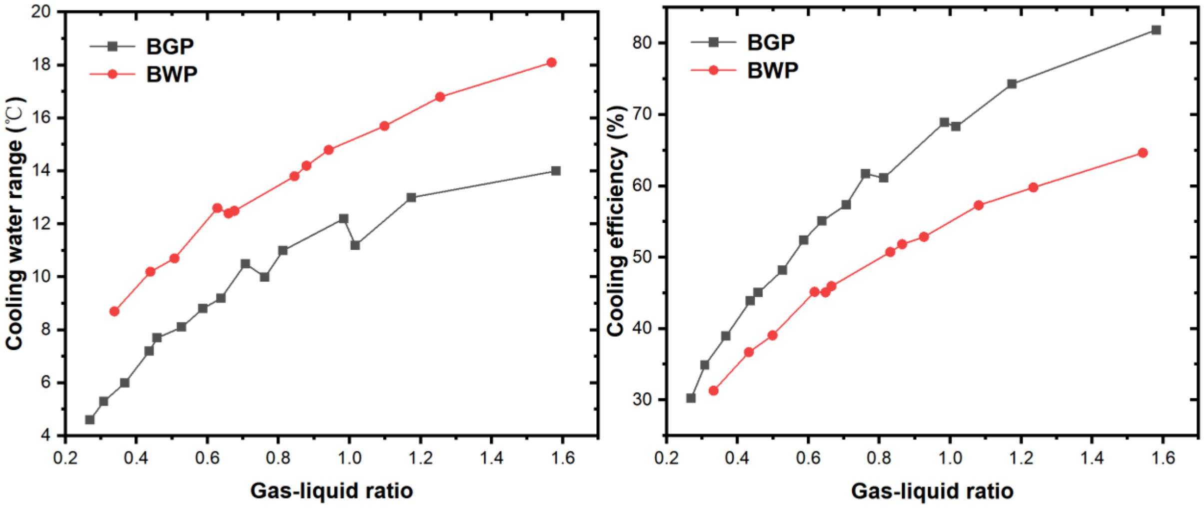

Fig. 8. Effect of gas-liquid ratio on the cooling water range and cooling efficiency

Effect of Inlet Air Velocity and Water Drenching Density on Resistance Characteristics

The resistance characteristics are typically measured using pressure drop. Figure 9 illustrates the effect of the inlet air velocity and water drenching density on the pressure drop. The pressure drop increased with the water drenching density under constant inlet air velocity. This was because a higher water drenching density introduces more water into the cooling packing, resulting in a thicker water film on the bamboo surfaces. Consequently, the air must overcome greater resistance, and the effective cross-sectional area for airflow is reduced as water occupies more of the void space. Additionally, uneven water distribution at higher densities can create localized flow constrictions, further increasing resistance.

When the water drenching density remained constant, the pressure drop increased with the inlet air velocity, due to stronger turbulence, resulting in more frequent and intense collisions and friction between the air, cooling packing, and water droplets, thereby increasing the resistance to airflow. The higher inlet air velocity was accompanied by a corresponding rise in kinetic energy, which made airflow within the cooling packing more unstable, potentially generating vortices and increasing pressure loss per unit length. When cooling water dripped onto the cooling packing, a thin boundary layer formed on the surface of both the cooling packing and water droplets. As the inlet air velocity increased, the velocity gradient within the boundary layer became steeper, leading to a reduction in the boundary layer thickness and an increase in airflow resistance. The higher airflow resistance directly contributed to the rise in pressure drop.

In summary, as the inlet air velocity and water drenching density increased, the pressure drop in the cooling tower also rose. This was attributed to the combined effects of various factors, such as changes in airflow resistance, kinetic energy, flow state, and interactions between two-phase flows. Although raising the inlet air velocity increased the cooling efficiency, it also increased the air resistance through the bamboo packings. Therefore, in practical applications, merely increasing the inlet air velocity to decrease the outlet water temperature is not advisable because it would increase the energy consumption by the fans and thus increase the operating costs. As inferred from Fig. 9, the pressure drop of the BWP was lower than that of the BGP, indicating that air flowed more easily and quickly through the BWP, which aided in heat dissipation. This was attributed to the more reasonable structural design of the BWP, which allowed air to flow both between and within units, thus reducing the pressure drop. Conversely, air flowing through the BGP encountered more obstructions from round bamboo piercing rods, resulting in a higher pressure drop.

Under a constant water drenching density, the pressure drop increased with the inlet air velocity (*i.e.*, with the gas-liquid ratio), as shown in Fig. 9, a trend that was consistent with the findings of reference (Yang *et al*. 2024). However, when the water drenching density was varied, the gas-liquid ratio failed to exhibit a clear monotonic trend in its effect on pressure drop. This behavior deviates markedly from its definitive impact on the cooling water range and cooling efficiency, suggesting a more complex interdependence. The pressure drop is not governed by a single parameter but is co-determined by both inlet air velocity and water drenching density. This relationship is profoundly complicated by non-linear two-phase flow interactions, including flooding, interfacial drag, and flow regime transitions. Due to this inherent complexity, a direct graphical representation of the relationship between the gas-liquid ratio and pressure drop was not provided.

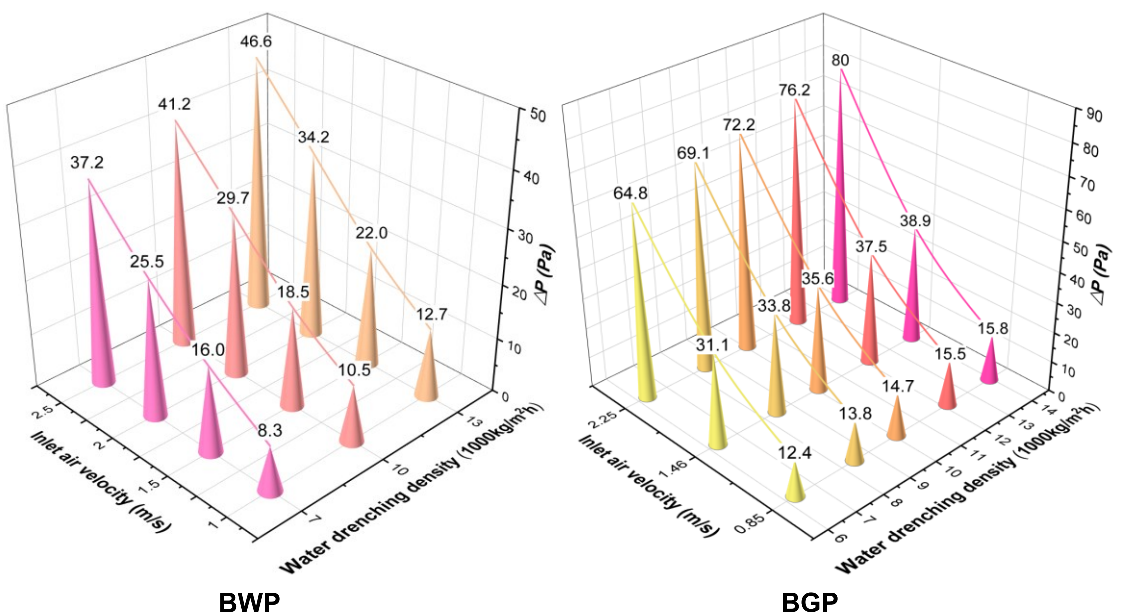

Fig. 9. Effect of inlet air velocity and water drenching density on pressure drop

Empirical Equation Fitting

Equation 4 was used to fit the experimental data to determine the specific constants for the empirical equation. The volumetric dispersion coefficient is a numerical value that indicates the performance of a cooling packing in terms of heat dissipation. It reflects the mass of water transferred to the air per unit volume of packing and per unit time *via* evaporative heat transfer (Xi *et al*. 2023). The empirical equation for the volumetric dispersion coefficient of the bamboo packing was derived using the experimental data for the 1.5-meter-high cooling packing. The resistance empirical equation was calculated by substituting various air velocities and water drenching densities into Eqs. 7 to 9. A comparison of the results of the fitted equations for NTU, volumetric dispersion coefficient, and resistance characteristics between BGP and BWP is presented in Table 2 (Ma *et al*. 2021).

Table 2. NTU, Volumetric Dispersion Coefficient, and Resistance Characteristics of BGP and BWP

Type	$N = B\lambda^b$		$K_a = D \times g^c \times q^n$			$\Delta P/\gamma = A \times V^s$					
						$A=a_1 \times q^2+a_2 \times q + a_3$			$S = a_4 \times q^2 + a_5 \times q + a_6$		
	B	b	D	c	n	a_1	a_2	a_3	a_4	a_5	a_6
BGP	1.52	0.64	2430	0.63	0.36	-0.0038	0.1252	0.7254	0.0033	-0.0712	2.0172
BWP	1.32	0.57	841	0.52	0.48	0.0012	0.037	0.3777	0.0012	-0.059	1.9809

Further Comparison of Thermal Performance between BWP and BGP

When comparing the properties of BGP and PVC packing, researchers have found that BGP has several advantages over PVC, including resistance to clogging and fouling, strong corrosion resistance, aging resistance, and high mechanical strength (Chen *et al*. 2016; Chen *et al*. 2018). However, there is debate regarding its thermal performance, with some studies suggesting that the thermal performance of BGP is inferior to that of PVC (Chen *et al*. 2016). This is attributed to the diverse structural forms of plastic sheets in PVC packing, such as S-shapes, corrugated waves, and composite waves, as well as the smaller spacing between the PVC sheets, which better retains moisture and thus facilitates more efficient heat and mass transfer between water and air. Conversely, Saifullah and Sies (2024) argued that the BGP's thermal performance surpassed that of PVC packing. This superiority was potentially attributed to the presence of abundant vascular bundles and cell cavities within bamboo (Liu 2023), which increased the higher porosity of BGP. Consequently, BGP enhanced the heat dissipation area. Furthermore, the primary chemical compositions of bamboo, including cellulose, hemicellulose, and lignin, contain numerous hydrophilic groups (Chen *et al*. 2023) that impart BGP with superior water absorption capabilities and enable longer heat and mass transfer durations.

Compared with BWP, initial experimental data indicated that BGP exhibited higher NTU values and volumetric dispersion coefficients, but inferior resistance characteristics. However, given that the thermal performance of the two bamboo packings was evaluated under different operating parameters and ambient conditions, which can affect the cooling water range and cooling efficiency, a direct comparison was challenging. To enable a fair comparison, this study employed MATLAB to develop a thermal calculation program specifically designed to simulate a natural draft counterflow wet cooling tower with an area of 4500 m^2 and a capacity of 2200 MW. The air velocity and outlet water temperatures of the cooling tower utilizing the two different bamboo packings were calculated, and the main parameters selected for the simulation were as follows:

(1) Meteorological parameters

T_{id} = 29.3 °C, T_{iw} = 26.2 °C, Relative humidity = 76%, P = 99.58 kPa.

(2) Parameter values of circulating cooling water

R = 8.2 °C, q = 6500 kg/(m^2·h).

(3) Parameter values of the cooling tower

The water-drenching area of the cooling tower measured 4500 m^2, which was 2.5 times larger than that of the outlet area. The total height and effective height of the cooling tower were 105 and 97.2 m, respectively, and the air intake height was 7.8 m. Two kinds of bamboo packing with identical heights and volumes were individually utilized within this cooling tower, and the following results were obtained.

Under identical experimental conditions, substituting the fitted empirical equations, the air velocity measured for BWP was 1.05 m/s, which was higher than the 0.95 m/s measured for BGP. The outlet water temperature of the cooling tower employing BWP was 32.5 °C, which was lower than the 32.9 °C observed in the cooling tower using BGP. By substituting the outlet water temperature, *R*, and T_{iw} into Eqs. 1 and 2, respectively, the cooling efficiency of BWP was calculated to be 56.55%, which was higher than that of BGP (55.03%).

The higher air velocity at BWP suggests that, under similar conditions, the air encountered less resistance and experienced a lower pressure drop when flowing through BWP. This facilitates enhanced heat and mass transfer between the cooling water and air. The lower outlet water temperature of the cooling tower indicates more efficient heat and mass transfer processes between the water and air within BWP. The higher cooling efficiency of BWP indicates that it provided better cooling performance for water than BGP. Consequently, under identical experimental conditions, the cooling tower utilizing BWP demonstrated better thermal performance than the one with BGP.

CONCLUSIONS

1. The innovatively designed bamboo woven packaging (BWP) achieved significant improvements without perforating the bamboo strips. The entire production process for BWP was fully mechanized, which reduced labor costs and significantly enhanced the production efficiency.
2. A higher inlet air velocity and gas-liquid ratio enhanced the cooling water range and cooling efficiency, whereas a higher water drenching density had the opposite effect. The pressure drop exhibited an increasing trend upon increasing the inlet air velocity and water drenching density, but the gas-liquid ratio had an insignificant effect on the pressure drop.
3. By substituting relevant experimental data, the empirical equations for the number of transfer units (NTU), volumetric dispersion coefficient, and resistance characteristics of BWP were determined to be $N = 1.32\lambda^{0.57}$, $K_a = 841 \times g^{0.52} \times q^{0.48}$, and $\frac{\Delta p}{\gamma} = \left(1.2\times10^{-3}q^2 + 3.7\times10^{-2}q + 0.3777\right)\times V^{1.2\times10^{-3}q^2 - 5.9\times10^{-2}q + 1.9809}$, respectively.
4. Despite exhibiting lower NTU values and volumetric dispersion coefficient than BGP, BWP achieved a greater cooling water range and exhibited superior resistance characteristics, contributing to its overall better thermal performance.
5. Under identical experimental conditions, a comparison of the thermal performance between bamboo grid packing (BGP) and BWP showed that the air velocity measured at BWP was 1.05 m/s, which was higher than that measured at BGP (0.95 m/s). The outlet water temperature of the cooling tower using BWP was 32.5 °C, which was lower than the 32.9 °C observed in the cooling tower using BGP. Furthermore, the calculated cooling efficiency of BWP was 56.55%, which surpassed that of BGP (55.03%). These results indicated that using BWP in the cooling towers provided better thermal performance than BGP.

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