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Enhancing Thermal Efficiency in Fluidized Bed Cooling Towers: An Experimental Approach to Bed Design

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ABSTRACT

The study aimed to investigate the thermal performance of a fluidized bed cooling tower (FBCT) by examining the effects of varying bed heights and circular tempestuous spheres on cooling efficiency. An experimental setup was designed to evaluate the FBCT's performance under different conditions, including variable water flow rates, bed heights ranging from 200 to 300 mm, and spherical balls with diameters of 25 mm and 50 mm. Critical parameters such as the range and approach of temperature and the liquid-to-gas (L/G) ratio were analyzed to understand their influence on the cooling tower's efficiency. The findings indicated that more petite turbulence balls significantly enhanced air mixing efficiency, improving thermal performance. It was observed that an increase in the ratio of water mass flux to air mass flux resulted in decreased cooling tower effectiveness. The static bed height was also identified as a critical factor affecting performance, with the entry water temperature impacting the static bed height. The study concluded that optimizing bed height and utilizing more petite (25mm) spherical balls can enhance the thermal efficiency (92.83%) of fluidized bed cooling towers. The relationship between water and air mass flow rates is crucial for achieving effective cooling performance, highlighting the importance of these parameters in the design and operation of FBCTs in industrial applications.

Akışkan Yataklı Soğutma Kulelerinde Isıl Verimliliğin Artırılması: Yatak Tasarımına Deneysel Bir Yaklaşım

MAKALE BİLGİSİ

Anahtar Kelimeler:
akışkan yataklı soğutma kulesi
yatak yüksekliği
ısı transferi
hız
verim
soğutma

ÖZET

Bu çalışma, değişen yatak yüksekliklerinin ve dairesel fırtınalı kürelerin soğutma verimliliği üzerindeki etkilerini inceleyerek akışkan yataklı bir soğutma kulesinin (FBCT) termal performansını araştırmayı amaçlamıştır. FBCT'nin performansını, değişken su akış hızları, 200 ila 300 mm arasında değişen yatak yükseklikleri ve 25 mm ve 50 mm çapında küresel toplar dahil olmak üzere farklı koşullar altında değerlendirmek için bir deney düzeneği tasarlandı. Sıcaklığın aralığı ve yaklaşımı ile sıvı-gaz (L/G) oranı gibi kritik parametreler, soğutma kulesinin verimliliği üzerindeki etkilerini anlamak için analiz edildi. Bulgular, daha küçük türbülans toplarının hava karıştırma verimliliğini önemli ölçüde arttırdığını ve termal performansı iyileştirdiğini gösterdi. Su kütle akısının hava kütle akısına oranındaki artışın soğutma kulesi etkinliğinin azalmasına neden olduğu gözlendi. Statik yatak yüksekliğinin de performansı etkileyen kritik bir faktör olduğu ve giriş suyu sıcaklığının statik yatak yüksekliğini etkilediği belirlendi. Çalışma, yatak yüksekliğini optimize etmenin ve daha küçük (25 mm) küresel bilyalar kullanmanın, akışkan yataklı soğutma kulelerinin termal verimliliğini (%92,83) artırabileceği sonucuna varmıştır. Su ve hava kütle akış hızları arasındaki ilişki, etkili soğutma performansı elde etmek için çok önemlidir ve bu parametrelerin endüstriyel uygulamalarda FBCT'lerin tasarımı ve çalıştırılmasındaki önemini vurgulamaktadır.

INTRODUCTION

Since the beginning of the twenty-first century, there has been a significant rise in the number of people around the world who are experiencing water scarcity. There are a number of causes that are posing an increasing threat to the availability of freshwater resources. These include drought, contamination of water reserves, and changes in the patterns of rainfall. All of these concerns have been made worse by human activities and the consequences of climate change (Distefano and Kelly, 2017). Businesses that deal in oil and gas in the Middle Eastern region, which has a limited supply of water, are always looking for alternative sources of groundwater. An industry may face risks associated with water that can be classified as physical, regulation, or reputational (Moglia et al., 2024). At the ideal concentration, municipally recovered water exhibited reduced inorganic scale formation and did not deposit any scale on the surfaces of the cooling system. Based on the findings of the biohazard assessment that was carried out on the operations of cooling towers, it was determined that the deployment of a comprehensive water treatment system that included disinfection, in conjunction with stringent operating procedures, successfully reduced the potential for adverse health effects (Badruzzaman et al., 2022). Desalination is an innovative method employed to address worldwide water limitations. Desalination is the process of converting seawater and saltwater into freshwater (Ayaz et al., 2022). The feasibility of zero-liquid discharge cooling tower technique was evaluated in several parts of the Mediterranean basin, considering environmental concerns. Based on the findings of this investigation, the induced draft cooling tower has the capacity to evaporate 177 litres per hour of brine liquid fraction at a temperature of 23 °C (deNicolas et al., 2023).

Both the economic and social growth of a region are significantly impacted when there is a shortage of water. Having access to clean water is critical for several different industries as well as for human well-being; nevertheless, a lack of this resource can have a detrimental effect on agricultural and livestock production, which can result in higher food prices and insecurity (Dolan et al., 2021). Desalination plants have been developed in the region in recent years to treat water that contains substantial levels of salt and nitrate. This is done to ensure that people continue to have access to water that is free of contamination from this contaminated aquifer. This strategy, on the other hand, does have a few significant limitations, such as the significant expenditures that are associated with the treatment method and the discharge of brine that has been rejected into the ecosystem that is located nearby (Shalaby et al., 2022). Sedimentation and corrosion not only hinder the functioning of cooling tower pipes and equipment, but also impede heat transfer and result in higher energy consumption (Safari et al., 2013; Turetgen, 2014; Wang et al., 2019). Ultraviolet C/ Vacuum Ultraviolet (UVC/VUV) treatment performance is improved in acidic conditions due to increased light absorbance. On the other hand, alkaline environments enhance the performance of Photochemical Degradation (PCD) treatment. The influence of pH on other therapies is minimal (Saha et al., 2021).

Usually, freshwater sources are utilised to provide the water, and additional substances like acids, anticalins, corrosion inhibitors, and microbiological inhibition are included. Water concentration increases by evaporation, a process in which heat is transformed into latent heat. When the cooling tower discharges water (CTBD), the water gets released in order to keep the water's quality consistent throughout the entire processing system. As a consequence of this, the discharge from the cooling tower, which is known as cooling tower blow down (CTBD), is anticipated to have high levels of salt and to contain varying quantities of humic substances (HS) in addition to other organic compounds (OCs) (Yu et al., 2013). The thermal and diffusion properties of a wet cooling tower that employs a counter flow configuration and packs foam made from ceramics were investigated in a study that was carried out. According to the findings of the study, applying of foam-type ceramic material for packing led to a superior cooling performance for the tower in contrast to the deployment of alternative packing materials Huang et al (Chaibi et al., 2013). The temperature ratio improved the efficiency of the tower by increasing the rate of airflow and decreasing the temperature of the water at the output. This was done in order to evaluate the efficacy of employing plastic balls as packaging in FBCT (Ren, 2008). A higher temperature ratio has led to greater NTU values with various L/G ratios. Increased airflow resulted in a greater reduction in pressure. The findings indicated that this approach exhibited a 50% quicker cooling rate compared to alternative methods. Lower liquid-to-gas (L/G) ratios resulted in higher cooling rates (El-Dessouky, 1993).

The primary parameters that have a considerable impact on the tower's performance are the spray characteristics and the precise location of the manifold. The results that were acquired indicate that the configuration with the taller manifold is the most advantageous solution for all of the mass flow ratios that occurs when the tower operates. It obtains a performance that is 25% higher than that of the intermediate manifold and a performance that is 37% higher than that of the lower manifold respectively (Muscio et al., 2023). The design and operation of a wet cooling tower's fill, water supply system, and drift eliminator are the factors that affect the thermal efficiency of the tower. For the purpose of determining the impact that the filling have on the thermal performance of the cooling tower, a comprehensive analysis has been carried out (Navarro et al., 2023; Mohiuddin and Kant, 1996). For the purpose of determining the thermodynamic effectiveness of a mechanical system, an investigation was carried out. The cooling tower makes use of a number of different drift eliminators and distribution of water strategies during operation. With reference to the drift eliminators, the researchers arrived at a conclusion. As a result of the fact that the existence of an eliminator is unlikely to inevitably decrease the effectiveness of a cooling tower, this is an essential aspect to take into consideration. It is logical to infer that there is an effect, as there is a further reduction in air pressure throughout the airflow (MirabdolahLavasani et al., 2014). The presence of biohazards in high-temperature conditions poses challenges to the utilisation of municipal reclaimed water. Microbiological growth can occur in cooling towers within the temperature range of 20 to 50 °C (68 to 122 °F).

In order for the implementation to be successful, it is vital to have effective regulation of the replication of both bacteria and viruses. The levels of bacteria and viruses that are present in wastewater that has not been treated might vary substantially. Both the primary and secondary treatment techniques have the potential to lower viral concentrations, despite the fact that they were not specifically developed for this objective specifically. As a consequence of this, tertiary treatments, which incorporate filtration, are commonly incorporated in order to construct numerous barriers. It has been determined that cooling towers are the source of every single outbreak of Legionnaire's disease that has ever occurred (Lucas et al., 2013; Tsao et al., 2019). It is possible for the efficiency of a cooling tower to be affected by a number of factors, including the temperature of the air around them, the humidity, and the temperature of the wet bulb. This study proposes a new cooling tower structure that contains an innovative control system that is capable of making optimal use of energy based on the weather conditions that are currently in effect. By implementing this concept, the overall efficiency of the cooling system is going to be improved (Crook et al., 2020). A comparison of the novel packing to the conventional straight-wave packing revealed that the novel packing exhibited a 14.4% gain in cooling efficiency. This phenomenon has a significant impact and presents a novel approach to improving heat transport in cooling towers, that can be employed in engineering procedures thanks to its unique nature. After examining the present operational characteristics of the tower, it has been concluded that raising the height of the packaging enhances the cooling process. Furthermore, by decreasing the ratio of gas to liquid and air volume needs, substantial air volume reductions of up to 30% can be achieved (Salins et al., 2023).

Novelty and objective of the research

The novelty of this study on fluidized bed cooling towers (FBCT) lies in its comprehensive examination of the combined effects of varying bed heights (200 mm and 300 mm) and different sizes of spherical turbulence balls (25 mm and 50 mm) on thermal performance have not been extensively explored in prior research. By analyzing air-water interactions and providing detailed metrics on air-side pressure drops and fluidization velocities, the study aims to evaluate how these parameters influence cooling efficiency, explicitly focusing on enhancing air mixing efficiency through more petite spherical balls. Additionally, the research seeks to understand the relationship between water flow rates, air flow rates, and inlet temperatures on the thermal performance of FBCTs, ultimately contributing to improved design and operational strategies for enhanced energy efficiency and reduced costs in industrial cooling applications.

HEAT TRANSFER BEHAVIOUR IN FLUIDIZED BED COOLING SYSTEMS

This highly specialist type of heat exchanger, known as fluidized bed cooling towers, has been utilised in a wide variety of industrial applications for the purpose of chilling hot water. In order to determine the thermal parameters of a fluidized bed cooling tower, it is necessary to conduct comprehensive investigation of heat transfer, fluid flow, and thermodynamics throughout the entire system. Heat transfer mechanisms, fluidization, and temperature gradients are some of the important aspects that can be used to characterise the thermal characteristics of fluidized bed cooling towers. Shape factors to be considered include the height of the bed, the size of the particles, and the shape of the heat exchange surface.

EXPERIMENTAL ARRANGEMENT AND METHODOLOGY

Figure 1 depicts a comprehensive experimental setup as well as the components that were utilised to ascertain the heat and mass transport properties of a fluidized bed cooling tower. The dimensions of the duct's cross-sectional area are 20 cm x 20 cm, as shown in Table 1. The height of the duct is 100 cm. There is a thickness of 0.15 cm in the conduit. One of the components that supplied the cooling water was a rotameter, which had a discharge capacity of 2-18 lpm. The water was consistently dispersed throughout the cooling tower in a uniform manner. After careful consideration, it was decided to deliberately set up a water reservoir in close proximity to the lowest of the tower in order to collect the cold water that was expelled from the tower. An aquatic pump was employed in order to transport water from the storage tank to the highest point of the tower column. To determine the pressure difference that existed between the airflow channels, a manometer with a U-tube was utilised. For the goal of measuring a wide range of temperatures, the RTD sensors were use. An inductive water heater with a power output of three thousand watts was utilised to supply thermal energy. For supplying fluidized air, the tower was fitted with a centrifugal air blower that had a capacity of 650 watts. When it came to adjusting the rate of airflow to the column, a valve that had controls was utilised. In addition, a bypass connection was installed prior to the throttle valve in order to safeguard the air blower against any potential damage. This action was taken in order to avoid any potential destruction. An electric air heater was employed in order to achieve the desired effect of adjusting the temperature of the air that was being circulated. The experimental setup is depicted in a schematic form in Figure 1, which features an illustration. Experiments were conducted for the following parameters.

1. Variable air velocity
2. Variable water flow rate
3. Bed height (200-300 mm)
4. Fluidized Ball diameter (25mm and 50mm spherical balls).

Table 1. Cooling Tower Specifications

Parameter	*Measurement*
Tower magnitudes	100 cm height and 20x20 cm cross-section (square)
Width	0.15cm
Air Blower	650 Watts
Rotameter	2-18 lpm
Induction Heating System	3000 Watts

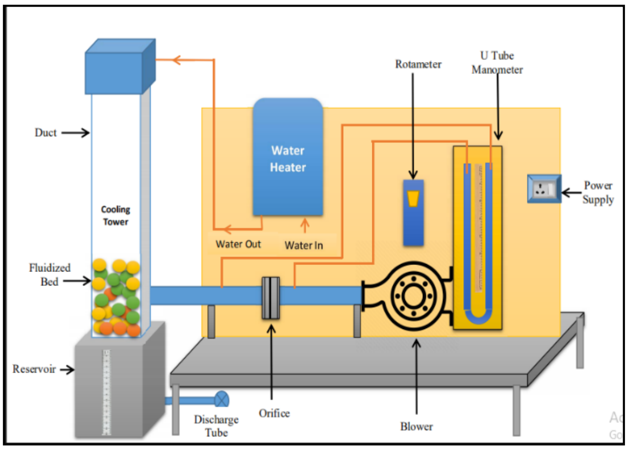

Figure 1. Schematic diagram of experimental setup

RESULTS AND DISCUSSION

Both the range, which corresponds to the difference in temperature between the cold water that enters and leaves the tower, and the approach, that is the difference in temperature among the cold water and the temperature of the wet bulb, are the key parameters that govern the features of a cooling tower. The range is the difference in temperature between the cold water and the wet bulb. The range and the approach are the terms that are used to refer to both of these distinctions, respectively. Additionally, the ratio of the flow rate of liquid to the flow rate of gas, usually commonly referred to as the L/G ratio, is also an important factor in the process. This ratio plays a significant role in the process. It was established that the two significant zones in the cooling tower were identified as a result of the interaction between the air and the water in the cooling tower. In situations where the water flow rates are quite low, the first zone that takes place is referred to as the pellicular regime (PR), and it is the zone that takes place. The bubble and dispersion phase, sometimes abbreviated as Bubble and dispersion phase (BDR), is a distinct regime that occurs at greater flow rates. It is commonly referred to as the bubble and dispersion phase.

Air velocity vs. Cooling tower efficiency

The variation in cooling tower effectiveness that occurs at various air velocities is seen in Figure 2. In compared to the other cases, the cooling tower efficiency of the BH300 mm with BD50 mm configuration was found to be significantly greater. The Wet Bulb Temperature (WBT) of the surrounding air is the point at which the water that has been cooled reaches its lowest temperature. The efficiency of the cooling tower was calculated for a BH (height of the cooling tower) of 300 mm and a BD (diameter of the cooling tower) of 25 mm, with a water flow rate of 2 litres per minute. The efficiency values achieved were 78.94%, 86.36%, 91.85%, 90.14%, and 92.83% when the air flow rates were 4.1 m/s, 6.3 m/s, 7.0 m/s, 8.2 m/s, and 8.5 m/s, correspondingly. Conventional cooling towers are unable to reach water cooling temperatures that are like the Wet Bulb Temperature (WBT). This is due to the minimal interaction between water and fresh air as the water flows over the fill surface [23].

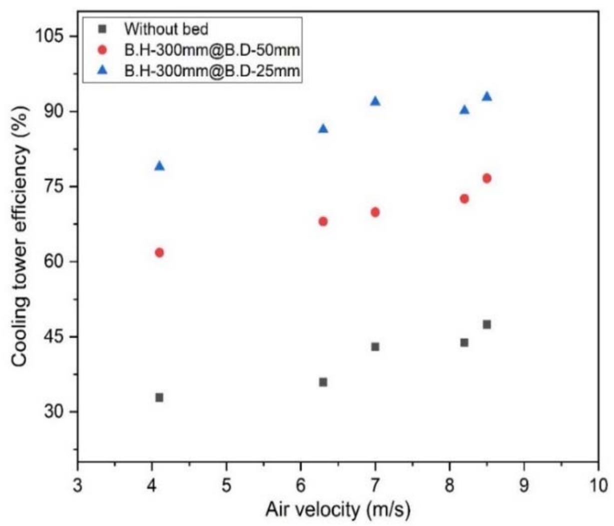

Figure 2. Air velocity vs. cooling tower efficiency

Air velocity vs. Evaporative loss

Figure 3 depicts the relationship between air velocities and the variance of evaporative loss. The evaporation rate is more significant for a BH of 300 mm and BD of 50 mm compared to other scenarios. While natural convection drives the airflow in cooling tower packing, gravitational forces primarily influence the water flow. It is feasible for water to evaporate into the air in a cooling tower, which results in the loss of heat. This phenomenon is known as evaporative loss.

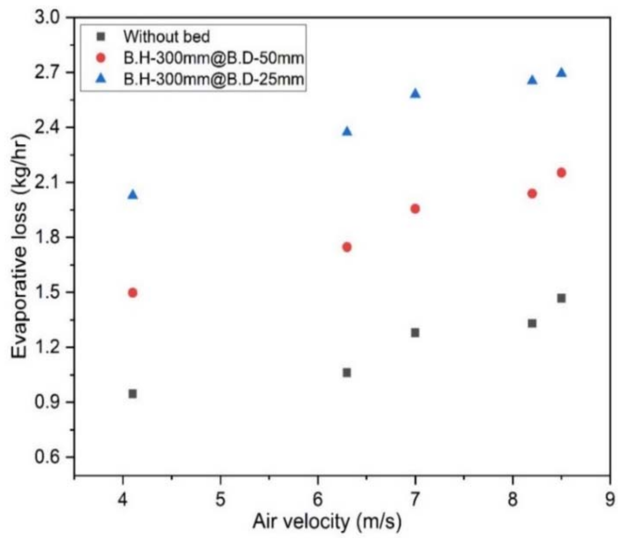

Figure 3. Air velocity vs Evaporative loss

It is good because this result has the effect of increasing the cooling impact, which is why it is desirable. In order to determine the amount of water that is lost through evaporation, there are a number of factors that play a role. These factors include the temperature difference between the water and the air, the relative humidity of the air, and the surface area that is accessible for evaporation. When the velocity of the air that is being transported rises, the potential for evaporative loss also increases. This is because improved water-to-air contact and higher evaporation both contribute to this potential increased loss (Agarwal et al., 2022). The results demonstrate that although elevated air velocity augments evaporative loss through enhanced water-to-air interaction, this increase is not limitless. The findings indicate a notable increase in evaporative loss with elevated air velocities; nevertheless, practical factors, like environmental humidity and system limitations, may restrict the maximum attainable benefit (Amir et al., 2023). The augmentation of air velocity is substantial in improving evaporative loss, especially for the configuration including a bed height (BH) of 300 mm and a ball diameter (BD) of 50 mm. However, at a certain threshold, efficiency improvements may stabilize or decline due to possible air over-saturation or constraints in water distribution efficacy (Agarwal et al., 2022). Mass loss (evaporation) directly influences the effectiveness of the cooling tower by enhancing heat removal via latent heat. Augmented evaporative loss amplifies the cooling effect, hence enhancing thermal performance. Excessive mass loss without corresponding cooling advantages may result in water wastage and operational inefficiencies (Salins et al., 2023).

Air velocity vs. L/G

Figure 4 shows the graphical representation of the fluctuation in the liquid-to-gas (L/G) ratio across different air velocities. The maximum length-to-girth ratio was observed for the tree with a B.D of 50 mm and BH of 300 mm. Based on the graphical representation, the L/G ratio exhibited a rapid increase followed by a subsequent decrease. Eventually, the curve reached a point of stability where it maintained a constant value. The primary factors that exert influence are temperature and enthalpy. At elevated temperatures, the liquid-to-gas ratio exhibits a near-constant behaviour. However, if the L/G ratio is excessively high, which indicates that there is an abundance of water in comparison to the air, this might lead to an increase in the amount of water that is carried over.

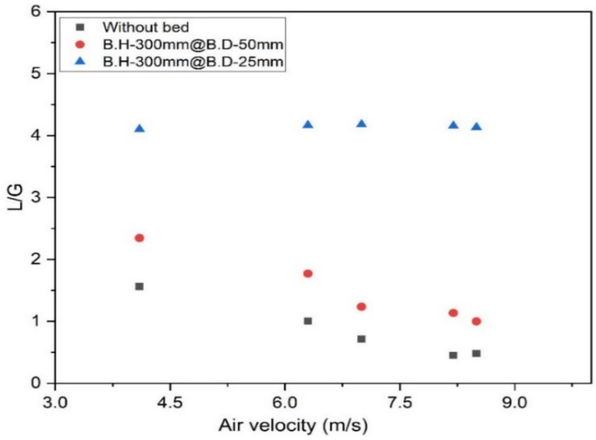

Figure 4. Air velocity vs L/G ratio

Extremely high L/G ratios have the potential to cause water droplets to be carried out of the tower along with the exhaust air, which can have adverse effects on both the environment and the operations of the tower. When it comes to maximizing the performance of cooling towers, it is essential to strike the appropriate balance between the L/G ratio and the air velocity. The use of suitable fill media, effective water distribution systems, and suitable tower designs can maintain the required L/G ratio and increase heat transfer efficiency (Xi et al., 2023).

Air velocity vs. NTU

Figure 5 depicts the correlation between NTU (Number of Transfer Units) and different air velocities. The BH 300 mm with BD 25 mm demonstrates the most minimal NTU in comparison to other variations. The relationship between air velocity and NTU in a cooling tower is complex and dependent on various factors, including the design, water flow rate, and ambient conditions. Increasing the speed of the airflow can result in a decrease in the NTU value. As the velocity of the air increases, the amount of time that the air and water are in touch with one another reduces. This leads to a reduction in the amount of heat that is transferred. This can be counteracted by modifying alternative design characteristics or tweaking operational circumstances to maintain or improve the overall efficiency of the cooling tower. The relationship between air velocity and NTU is a vital component of the thorough optimisation process for cooling tower design. Scientists consider several factors, including water distribution, material for packing, air distribution, and operating circumstances in order to achieve the necessary heat transfer efficiency (Salins et al., 2023).

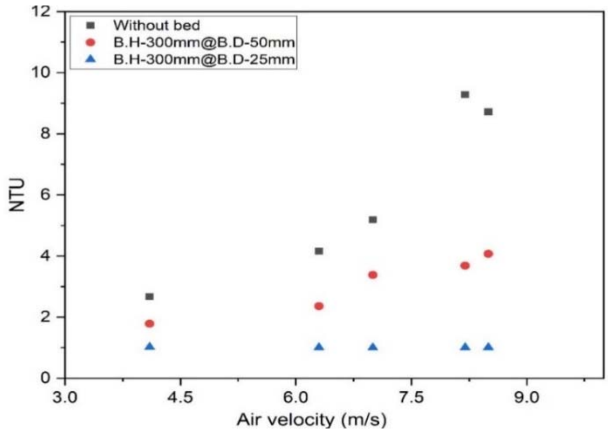

Figure 5. Air velocity vs. NTU

Water flow rate vs. cooling tower efficiency

It is common practice to measure the efficiency of a cooling tower based on its heat transfer performance. This performance is what defines the quantity of evaporative cooling that may be achieved. Figure 6 provides a visual representation of the connection that exists between the effectiveness of a cooling tower and the rate at which water enters and exits the tower. The ratio of the actual decrease in water temperature to the highest decrease that was conceivable was determined in order to evaluate the effectiveness of the heat transfer system. This ratio represented the ratio between the real decline and the maximum decrease. The capacity of the cooling tower was increased as a result of increasing the total quantity of water that was running through it simultaneously. A bed height of 300 mm and a ball diameter of 50mm allowed the cooling tower to achieve its maximum effectiveness. Utilising the height of the bed allowed for this to be accomplished. A number of different air flow rates were tested, and it was found that the cooling tower had an efficiency of 31.4%, 36.5%, 43%, 43.4%, and 47.4% when the bed material was not there. When determining the effectiveness of the cooling tower, a fluidized bed with a height of 300 millimetres, a water flow rate of two litres per minute, and a ball diameter of fifty millimetres was utilised in the calculation. According to the findings, the tower exhibited an efficiency of 61.81%, 68.01%, 69.88%, 72.59%, and 76.99% for the various air rates that were tested during the experiment. There is a potential for a substantial disparity in enthalpy to occur between the hot water which is being introduced into the tower and the water which is being cooled at the point of intake (Shublaq and Sleiti, 2020). A possible explanation for the tower's superior efficiency is that this differential is accountable for it.

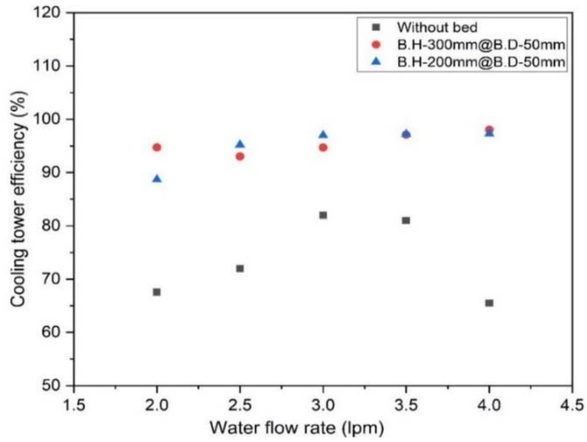

Figure 6. Water flow rate vs. cooling tower efficiency

Water flow rate vs. evaporative loss

Figure 7 depicts the fluctuation in evaporative loss that occurs as a result of switching between different water flow rates. It is possible to draw the conclusion from the figure that the rate of evaporation was lower for BH 200 mm in comparison to BD 50 mm on the other hand. The measures of BH 300 mm and BD 50 mm were the ones that experienced the highest level of evaporation.

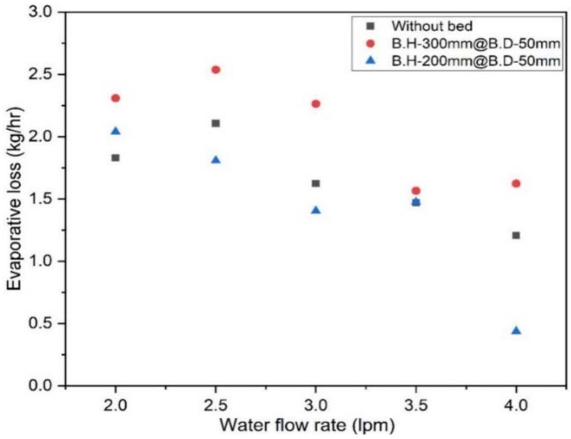

Figure 7. Water flow rate vs. evaporative loss

Water flow rate vs L/G

The variation in the L/G ratio that occurs in respect to the various water flow rates is seen in Figure 8. When compared to the situation in which a bed was present, the L/G ratio displayed a greater magnitude when there was no bed present. It is possible to establish a connection between the increased cooling capacity of the tower and a decrease in the water flow rate, which ultimately leads to a diminished cooling potential at higher water flow rates. With an air flow velocity of 8.47 metres per second, the L/G ratio was measured to be 0.5, 0.75, 1, 1.25, and 1.5 for water flow rates of 2 lpm, 2.5 lpm, 3 lpm, 3.5 lpm, and 4 lpm, respectively. This was done without the presence of the fluidized bed. It has been noted that the rate at which water flows has a crucial impact on the ratio of liquid to gas (L/G), which in turn has a substantial influence on the performance and features of a system. Enhancing the liquid flow rate in comparison to the gas flow rate facilitates the transfer of mass between the liquid and gas regimes. Increasing the flow velocity of the liquid can lead to higher reductions in pressure inside the system. This can have a significant impact on the overall efficiency and sustainability of a process, especially in instances where restrictions on pressure are crucial. The practical execution of perpetual cooling is not achievable (Xi et al., 2023).

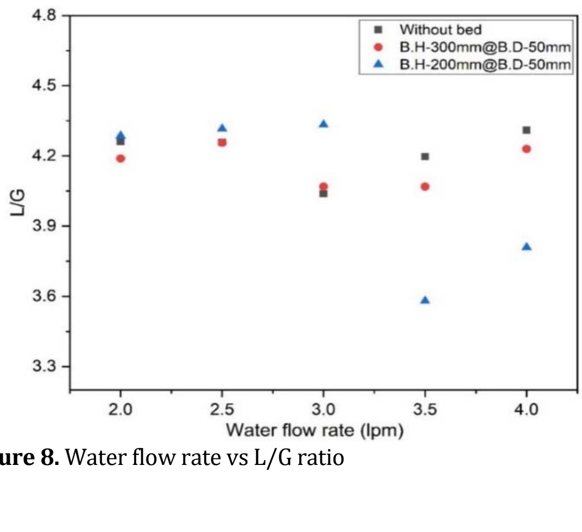

Figure 8. Water flow rate vs L/G ratio

Water flow rate vs NTU

Figure 9 illustrates the variation in the number of transfer units (NTU) that occurs when the water flow rate is changed. This variation can be observed in the figure. It was discovered that the NTU value was at its highest when the bed height was precisely 200 millimetres and the ball diameter was precisely fifty millimetres. As the ratio of L to G is raised, there is a corresponding reduction in the mass flux that takes place. The decrease in the rate of heat and mass transfer that occurred as a result of the interfacial activity level led to an increase in the temperature of the cold water. This was the result of the interfacial activity happening. When the velocity of the water with the lowest fluidization hits a critical point, the fluidized bed begins to exhibit instability. A decrease in the water flow rate is implemented in order to establish a fluidized bed that is stable. This leads to a decrease in the temperatures at the exit. In a cooling tower, the link between the mean thermal unit (NTU) and the water flow rate in the cooling tower is influenced by both the design of the cooling tower and the operational parameters of the cooling tower. Several aspects are taken into consideration while calculating the NTU. These aspects include the surface area of the heat exchanger, the heat transfer coefficient, and the rate of flow of both the hot and cold fluids flowing through the heat exchanger. It is of the utmost importance to take into consideration the fact that the influence of flow velocity on NTU and the efficiency of the cooling tower may be dramatically different depending on the architecture and characteristics of the cooling tower (Ren, 2008).

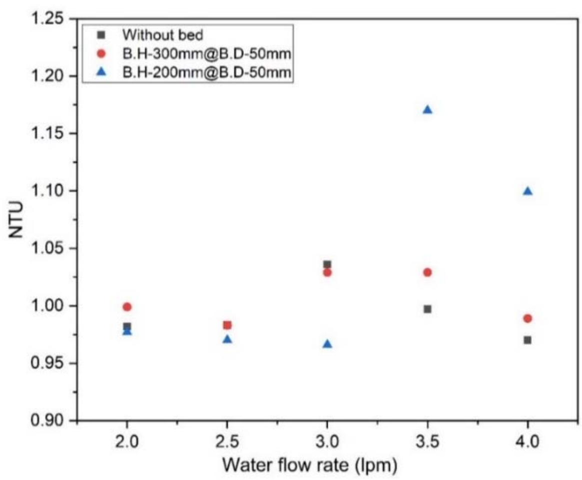

Figure 9. Water flow rate vs NTU

CONCLUSION

In conclusion, this study demonstrates that varying bed heights and the use of different sizes of spherical turbulence balls significantly impact the thermal performance of FBCT.

- Increasing the bed height from 200 mm to 300 mm significantly enhances the cooling tower's thermal efficiency.
- Compared to larger balls (50 mm), smaller spherical turbulence balls (25 mm) improve air mixing efficiency, leading to better thermal performance.
- The study reports cooling tower efficiency values reaching up to 92.83% under optimal conditions, highlighting the effectiveness of the FBCT design.
- The FBCT research achieved a maximum efficiency of 92.83%, which is competitive with, and in certain instances surpasses,

the efficiencies of traditional cooling tower designs. This indicates that fluidized bed cooling towers may provide substantial benefits in thermal performance, especially in scenarios where optimizing cooling efficiency is essential.

- The cooling tower's interaction between air and water is critical in determining heat transfer capabilities. The study identifies two distinct regimes (pellicular and bubble dispersion) crucial in this interaction.
- The research emphasizes the importance of water flow rates and air flow rates in determining the cooling tower's overall thermal performance.
- The findings provide insights for improving the design and operation of FBCTs, contributing to enhanced energy efficiency and reduced operational costs in industrial settings.

AUTHORS STATEMENTS

Sathiyamoorthi Ramalingam: Investigation, supervision, Project administration, Resource Mukilarasan Nedunchezhiyan, Ravikumar Jayabal: Methodology, Interpretation, Conducted the experiments, Writing manuscript.

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