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IMPROVEMENT OF THE EFFICIENCY OF THE OPERATION OF COUNTERFLOW COOLING TOWERS BY MEANS OF NEW PERFORATED PLASTIC PACKING: AN EXPERIMENTAL INVESTIGATION AND MATHEMATICAL MODELING APPROACH

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ABSTRACT
A cooling tower is an important element of industry equipment which ensures dissipation of excess heat via simultaneous heat and mass transfer of water and air streams. The thermal efficiency of cooling towers depends on the packing which offers an effective surface area for evaporative cooling. Polymer packings are used in the majority of industrial cooling towers due to their low price, durability, and anti-corrosion properties; but the lack of wettability and non-uniform distribution of water in these packings can restrict efficiency, especially in critical operational conditions. Hence, optimization of geometric parameters of packing to increase heat and mass transfer efficiency becomes a key issue in modern research.
In this study, the thermal performance of a laboratory-scale counterflow cooling tower with novel perforated plastic packings made of transparent acrylic plates using CNC cutting technology is investigated experimentally. Various geometrical packing structures were analyzed using variations in the perforation ratio, shape of holes, hole diameter, and thickness of plates in different values of liquid-to-gas mass flow ratio (L/G). The thermal performance was characterized by such indices as reduction of water temperature, efficiency of the cooling tower, volumetric mass transfer coefficient Ka V/L and heat removal rate. Moreover, a theoretical mathematical model based on the principles of Merkel theory was developed for estimation of the thermal characteristics of the cooling tower and validation of experimental data.
The obtained results demonstrate that the geometry of holes has a great effect on the thermal performance: circular holes provide the best thermal efficiency of the packing due to more uniform water distribution and lesser aerodynamic resistance compared to other types of holes. The optimal packing which guarantees maximum efficiency and volumetric mass transfer coefficient consists of packing with 10% perforation ratio, 2 mm holes and 1 mm thickness of plates. The proposed Merkel model proved good correspondence with experimental data: the accuracy of predictions exceeded 95%. Novel perforated plastic packing can be considered a perspective way of improvement of efficiency of cooling towers in the conditions of low cost and simple manufacturing.

KEYWORDS: Cooling tower; Perforated plastic packing; Heat and mass transfer; Merkel theory; Cooling efficiency; Volumetric mass transfer coefficient; Counterflow cooling tower; Experimental investigation.

1.INTRODUCTION
Cooling towers are core thermal components in industrial plants that discharge waste heat generated during manufacturing and energy conversion processes. They can be used in power stations, oil refineries, petrochemical complexes, chemical plants, steel mills, refrigeration systems, and heating, ventilation, and air conditioning (HVAC) facilities. They bring circulating water into direct contact with the atmosphere to carry away excess heat, so that the water can be recycled and reused. Their efficient operation is directly tied to a plant's production capacity, energy consumption, equipment reliability, and operational safety. Unlike typical heat exchangers, wet cooling towers move both sensible and latent heat at the same time. As warm water trickles down through the packing, air rises past it in the opposite direction, and a small portion of that circulating water turns into vapor. As the remaining water evaporates, it pulls in a lot of hidden heat, cooling things down strongly without using much energy. So, the packing material's design is what matters most for how well the system handles heat, since it controls how much air touches water, how steady the water film stays, how air spreads, and how much pressure is lost. Over the past few decades, people have

come up with many packing setups to boost cooling efficiency. Film-type packings move heat well because they offer a big surface, but bad water quality can cause buildup. Splash packings resist fouling better, though they usually transfer heat less effectively. Hybrid designs try to get the best of both worlds, but keeping strong wetting while also avoiding a big pressure drop is still a tough engineering job. In the last few years, people have paid more attention to plastics like PVC, polypropylene, and acrylic because they resist corrosion, are light, are easy to make, and often cost less to produce. Even with these benefits, traditional plastic packing usually doesn't wet well, so water spreads unevenly, leaves dry patches, and limits heat and mass transfer. Researchers have tried many fixes, like changing the surface, adding nano-coatings, using tiny textures, and optimizing shapes, to beat these limits. But many of these methods make factories harder and more expensive to run, which limits their use in industry. One good option is to add holes to plastic packing sheets. Well-designed perforated structures help spread water more evenly, stir up flow, cut down dead zones, and let air move through the packing without raising pressure drop much. Still, no one has fully studied how the perforation ratio, hole shape, hole size, and plate thickness work together under lab conditions, using careful experiments and math models. Not fully evaluating this issue leaves a major gap in what we know about cooling tower research. To address this, the study introduces a new type of perforated plastic packing made with CNC machining and tests how well it cools in a lab-scale counterflow cooling tower. We carefully test how perforation ratio, hole shape, hole size, and plate thickness affect performance at various liquid-to-gas flow rates. Using a Merkel-based math model, researchers forecast cooling tower performance and check that the experimental measurements are accurate. The proposed design boosts heat and mass transfer, keeps production simple, and stays affordable, offering a practical cooling tower option for future industrial use.

2.LITERATURE REVIEW

In the past decade, considerable work has been done to improve the thermodynamic efficiency of wet cooling towers through the optimization of the packing material, geometry of the cooling tower, and operating parameters. Considering the fact that the packing is the area where heat and mass transfer take place, the design of the packing area plays an important role in the performance of the cooling tower The conventional cooling tower fill materials can be classified into three types: film, splash, and hybrid fills. The film presents an extensive heat transfer surface area; however, the risk of fouling is higher for these films. In comparison, the splash fills provide better fouling resistance but lower thermal efficiency. From 2016 to 2018, studies focused more on improving the existing polymer-based packing material. Shahabi et al. (2016), Ma et al. (2017), and Ning et al. (2018) have shown that the change in geometry and increase in wettability contributed to better cooling performance and Ka V/L. From 2019 through 2021, studies expanded to consider issues of airflow control, water delivery, and energy efficiency. The importance of packing geometry and conditions on improving thermal performance was highlighted by Bakhtiyar et al. (2019), the ASHRAE Handbook (2020); and Gao et al. (2021). Since 2022, the scientific community has begun emphasizing the use of sophisticated packing geometries and numerical simulations. In this regard, Zargar et al. (2022) developed a numerical Merkel model; on the other hand, Shinde et al. (2023), Xi et al. (2023), Hashemi et al. (2023), Salins et al. (2023), and Jourdan et al. (2023) explored studies on advanced packing, water distribution, and CFD simulation. In 2024, Zhao et al. found that microgrooves in the filling surfaces increase the wettability, while Li et al. developed packing geometries through numerical optimization. However, there still exist a few studies investigating the perforated acrylic packing produced using CNC machining while considering perforation ratio, hole geometry, hole diameter, and plate thickness at the same time. This study aims to fill these gaps through conducting experiments and employing the Merkel model for mathematical modeling.

Table 1 Cooling Tower Models and Experimental Research Overview

Author(s)	Year	Research Focus	Main Contribution
Shahabi et al.	2016	Ribbed PVC packing	Improved water distribution and cooling efficiency.
Ma et al.	2017	Bamboo-grid packing	Enhanced simultaneous heat and mass transfer.
Ning et al.	2018	Corrugated PVC fill	Higher Ka V/L than conventional packing.
Bakhtiyar et al.	2019	Splash packing	Evaluated cooling performance under different operating conditions.
ASHRAE	2020	Cooling tower design	Updated design and performance evaluation methods.

Gao et al.	2021	Fill arrangement	Optimized airflow distribution numerically.
Zargar et al.	2022	Merkel model	Accurate numerical prediction of tower performance.
Shinde et al.	2023	Commercial packing	Improved water distribution enhanced efficiency.
Xi et al.	2023	Straight-wave packing	Enhanced heat and mass transfer.
Hashemi et al.	2023	Fill media review	Reviewed advanced fill materials and technologies.
Salins et al.	2023	Structured packing	Compared packing configurations experimentally.
Jourdan et al.	2023	CFD analysis	Improved understanding of airflow and liquid distribution.
Zhao et al.	2024	Micro-grooved fill	Improved wettability and evaporation.
Li et al.	2024	Structured packing	Optimized geometry using numerical simulation.
Fang et al.	2025	Packing-free cooling tower	Validated new cooling concept experimentally.

3. MATERIALS AND METHODS

3.1 Experimental and setup

The study was carried out in a lab-scale P. A. Hilton H893 counterflow forced-draft cooling tower, commonly used in teaching and research, to examine how heat and mass are transferred in cooling tower systems. The test setup includes a connected water loop, an air circulation unit, swap-in packing pieces, measuring tools, and electric heaters. The packing section measures about 150 by 150 by 600 mm, giving enough space for heat and mass to move at the same time between the liquid and gas. The system moves water using a storage tank, a centrifugal pump, an electric heater, a control valve, a distributor, and a collection basin. Before it reaches the packing, water is warmed to the set inlet temperature, then spread evenly across it using a perforated tray. As the water runs down through the packing, it cools, then collects in the cold-water basin and is sent back to the heater, so the system can keep running steadily. A centrifugal blower sits near the bottom of the cooling tower and pushes air through the system. Air moves into the unit through the air inlet and rises upward, flowing opposite to the water as it drops. A movable damper controls the airflow, helping set different liquid-to-gas mass flow ratios (L/G). A drift eliminator is put by the tower outlet to cut down water carryover and keep the measurements accurate. Temperature was checked with calibrated thermocouples placed in key spots around the cooling tower. They also recorded the water flow, air flow, how much power the heater used, and the surrounding conditions. We kept a close watch on these settings to make sure everything stayed stable for each test run.

Table 2 ***Main specifications of the experimental cooling tower.***

Parameter	Description	Value / Range
Cooling tower type	Laboratory-scale forced-draft counterflow unit	P.A. Hilton H893
Packing section	Test column dimensions	150 x 150 x 600 mm
Water circuit	Tank, pump, heater, distributor, collection basin	Closed recirculating loop
Air circuit	Centrifugal blower with adjustable damper	Counterflow direction
Measurements	Water/air temperature, flow rates, ambient conditions	Calibrated instruments

3.2 Packing Design

The main objective of the present study is to investigate the effect of the geometry of the perforated plastic packings on the cooling tower operation. In comparison with commercial packing materials, the new design of packings was fabricated out of transparent acrylic plates by a computer-controlled milling technique. All the packing plates were made based on the predetermined geometrical design and installed inside custom-made plastic frame structures. The factors that were tested include the perforation percentage, hole geometry, hole size, and the thickness of the plate. In order to test the impact of open area, varying levels of perforation percentage were considered, from solid plates (0%)

to very perforated plates. Holes with circular, square, and rectangular geometries were made with equal perforation percentages. The diameter of the holes, ranging in different sizes, was considered in order to analyze their effect on water re-distribution, air flow penetration, and hydraulic resistance. The same goes for the thickness of the plates, which was varied to study its effect on the stiffness and thermal properties. The modules of the packings have been produced by means of CNC machining in order to achieve the same dimensions for all samples.

Table 3 Investigated packing design parameters.

Design variable	Investigated values	Purpose
Perforation ratio	0%, 2%, 4%, 6%, 8%, 10%	Evaluate open-area influence on air-water interaction
Hole geometry	Circular, square, rectangular	Compare flow distribution and wetting behavior
Hole diameter	2 mm and larger diameters	Assess water redistribution and airflow communication
Plate thickness	1 mm and thicker plates	Evaluate flow resistance and structural effects
Material	Transparent acrylic sheet	Low-cost plastic packing material

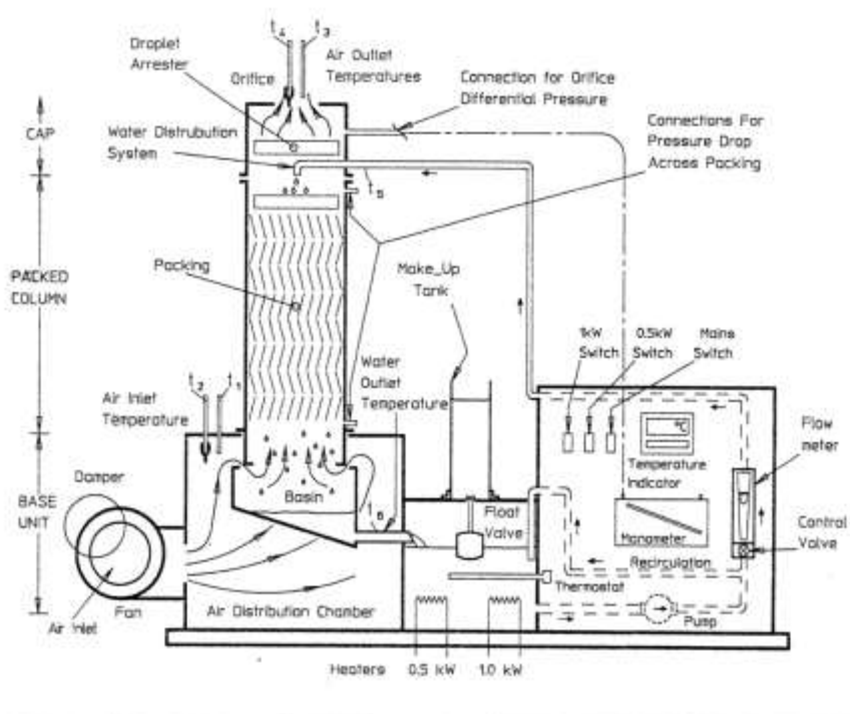

Figure 1. Schematic diagram of bench scale cooling tower.

Figure 2. **Geometry of the proposed perforated plastic packing plate and support frame.**

3.3 Experimental Procedure

Before conducting each experiment, there was an examination of the whole cooling tower system for the proper functioning of all the parts. Measurement devices such as thermocouples, flow meters, and pressure gauges were all checked in order to reduce any errors in measurements. The procedure included the following steps:

1. The selected packing module was installed inside the cooling tower test section.
2. The water circulation system was started, and the electric heater was adjusted to obtain the required inlet water temperature.
3. The centrifugal blower was operated to establish the desired airflow rate.
4. Water and air flow rates were adjusted until the required liquid-to-gas ratio (L/G) was achieved.
5. The system was allowed to operate until steady-state conditions were established.
6. Once thermal equilibrium had been reached, all operating parameters were recorded.
7. Each experiment was repeated to verify measurement repeatability and improve data reliability.

Following the execution of one test run, the packing was replaced by a new arrangement, and the same experiment was conducted again under similar operational parameters for a balanced comparison between all types of packings considered.

3.4 Performance Parameters

Cooling tower performance was evaluated using several thermodynamic and heat-transfer indicators commonly adopted in cooling tower analysis. The water temperature drop was calculated as:

$$\Delta T_w = T_{w,in} - T_{w,out} \quad (1)$$

where $T_{w,in}$ and $T_{w,out}$ represent inlet and outlet water temperatures, respectively.

The cooling efficiency was determined from:

$$\eta = [(T_{w,in} - T_{w,out}) / (T_{w,in} - T_{wb})] \times 100 \quad (2)$$

where T_{wb} denotes the inlet air wet-bulb temperature.

The total heat rejected by the cooling tower was calculated from:

$$Q = \dot{m}_w C_p (T_{w,in} - T_{w,out}) \quad (3)$$

Volumetric mass transfer coefficient has been calculated using the Merkel equation theory, and is one of the most important factors that determine cooling tower efficiency. Larger Ka V/L values signify better heat and mass transfer from the packing region.

3.5 mathematical model

A mathematical model for simulating the thermal performance of the counterflow cooling tower was formulated using Merkel's theory of heat and mass transfer. The model takes into account conservation of energy, psychometrics, and mass transfer correlations for the prediction of exit temperature of water, exit condition of air, efficiency, and mass transfer coefficient.

This model assumes that there is a steady state, a uniform distribution of water, counter flow in one dimension, no heat exchange with the surroundings, constant thermophysical properties, and saturation at the air-water interface. Such assumptions have been used in many first-order cooling tower models and are thus an appropriate basis for verifying the experimental trends.

The methodology of solving begins with the formulation of operating conditions, which include inlet water temperature, inlet air temperature, water mass flow rate, air mass flow rate, and relative humidity. Psychrometric characteristics of humid air are then evaluated to find the values of humidity ratio and enthalpy variation along the length of the packing. The solutions are then found iteratively for the outlet water temperature, outlet air temperature, cooling effectiveness, heat rejection rate, evaporation rate, and the Merkel number (Ka V/L). Comparison is made between theoretical and experimental results to evaluate the mathematical model.

4. RESULTS AND DISCUSSION

4.1 Effect of Perforation Ratio on Cooling Tower Performance

The perforation ratio becomes an important geometrical factor influencing the thermal behavior of the cooling tower packing because it determines how the falling water film will interact with the rising airflow. Perforation of the packing creates new hydrodynamic properties of the packing due to better airflow penetration into the packing and better distribution of water across the packing. The change in water temperature reduction(ΔTw) with respect to the L/G ratio for different perforation ratios shows that there is a gradual decrease in (ΔTw) with an increase in L/G ratio. This is expected since an increase in water flow rate means that water stays in the packing region for a shorter period of time and hence limits the time for both heat and mass transfer processes to take place. Of all the geometries analyzed, the perforated packing with a 10% ratio of perforation always showed the largest decrease in water temperature for all the tested conditions. In comparison with the solid surface, the addition of perforations improved the cooling characteristics due to better distribution of air flow and water streams on the surface of the packing. The excellent results obtained with the 10% ratio of perforation could be explained by the formation of local turbulence, breaking of continuous water stream, generation of smaller liquid streams and decreasing the dry zones. However, too many perforations will finally decrease the area of wetted surfaces that contribute to the heat transfer process.

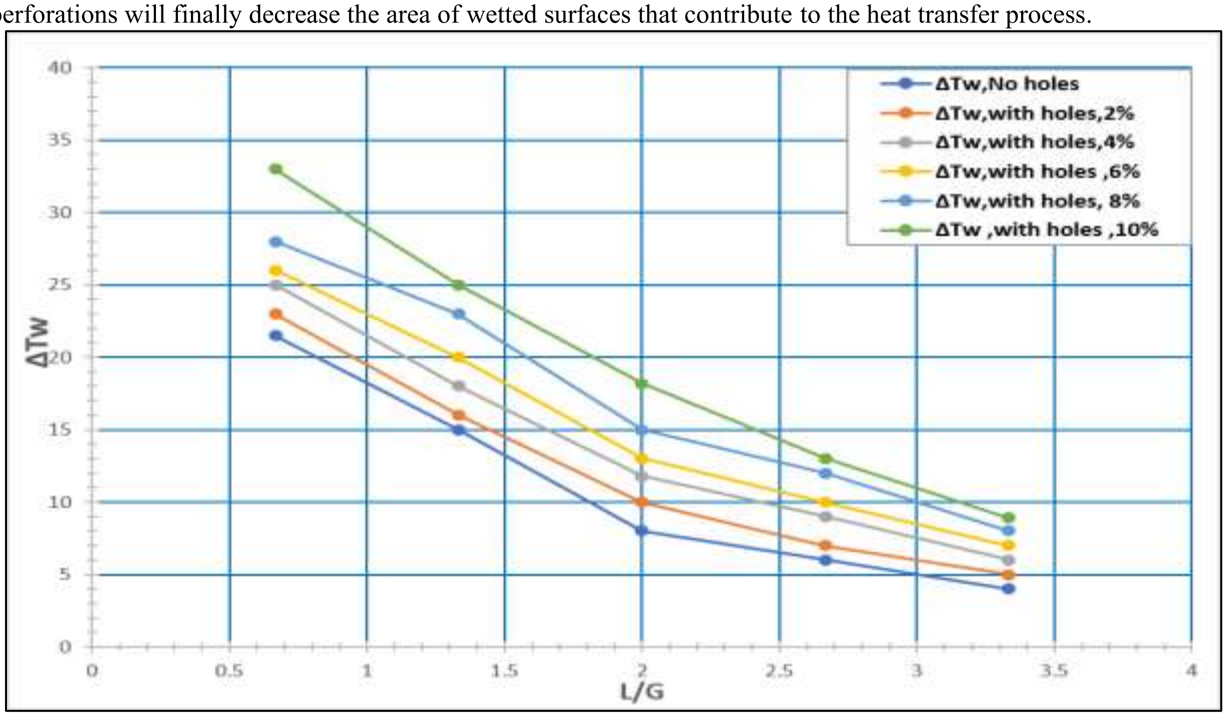

Figure 3 Effect of Perforation Ratio on Water temperature.

4.2 Effect of Hole Geometry

Perforation Shape Effect on the Cooling Tower Performance was tested by comparing circular, square, and rectangular holes while keeping the ratio of perforation constant. While having the same area, the results from the experiment showed that the shape of the holes plays an important role in cooling performance.

Circular perforations always produced maximum reduction in temperature, while square shapes were second-best, and the lowest cooling effect was provided by rectangular shapes among all the considered operating conditions. The better efficiency of the circular shapes can be mainly attributed to their aerodynamic characteristics. In other words, the circular-shaped openings provide smooth airflow with less flow separation as compared to sharp edges.

Circular holes provide for better stability in the process of redistribution of liquid on the surface of packings. Flow of water through circular holes creates uniform thin layers without dead spots in comparison with square and rectangular holes. Square and rectangular holes lead to a separation of flows of water around the edges of holes; therefore, it creates non-uniform distribution of water, which increases chances of dead spots. It can be concluded that the shape of holes is traditionally as significant as the perforation ratio.

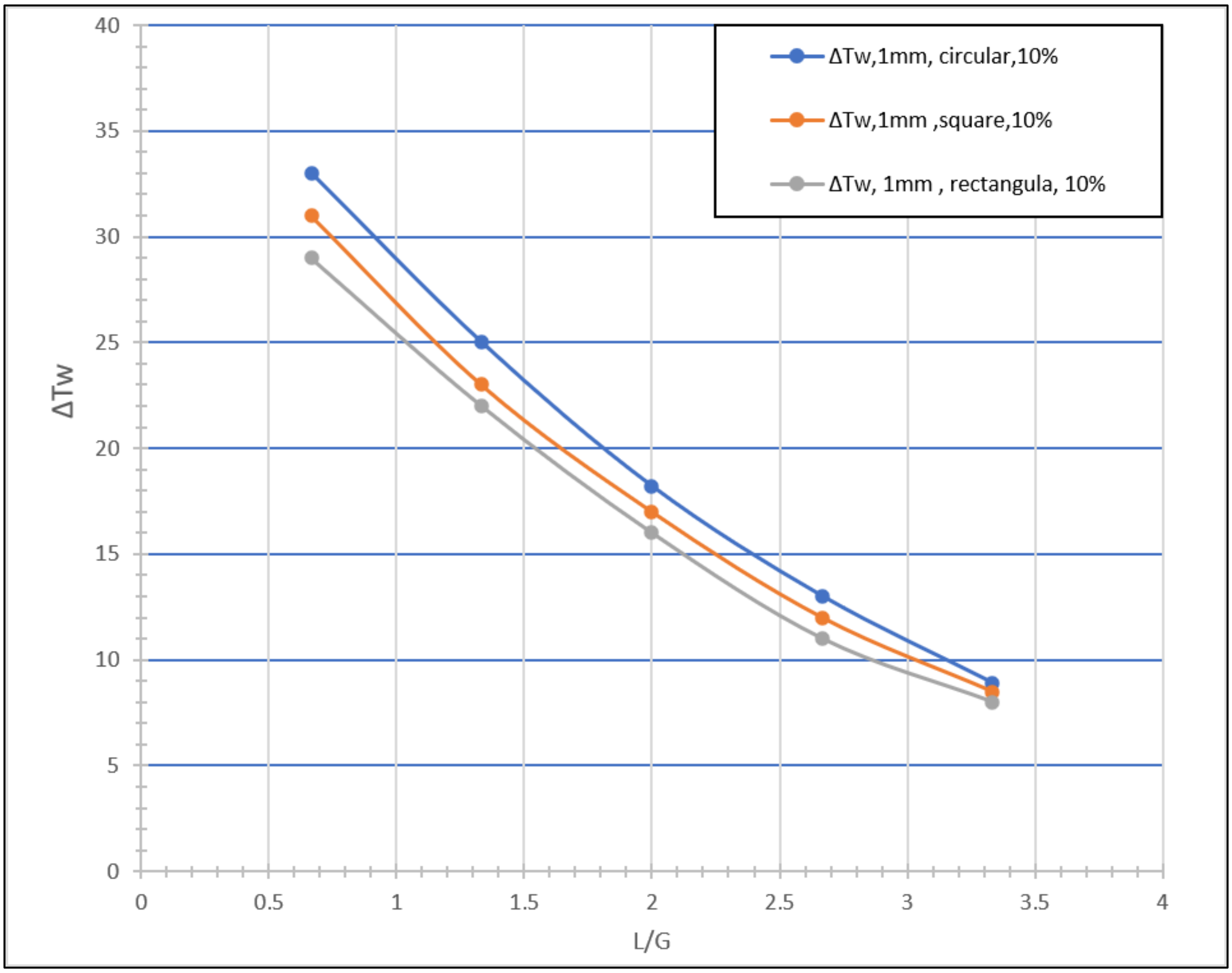

Figure 4 Effect of hole geometry on water temperature drop.

4.3 Heat and Mass Transfer mechanisms

The noted improvement in relation to perforated packing results from increased heat and mass transfer that is experienced in the cooling tower. In the cooling process, hot circulating water flows down through the packing surface while the air flows up. Heat is transferred from the water to the air through sensible cooling and evaporation. Perforation contributes to an increase in the level of turbulence in the packing, better penetration of air into the packing, better water distribution, lower areas of stagnant liquid, increases the effective surface area, and better wetting of polymer surfaces. All these processes contribute to an increase in the heat and mass transfer coefficient, which means that better cooling is provided. In the suggested packing structure, we attempt to overcome the main disadvantage of traditional polymers, namely, low wettability. Through using appropriate perforations, water will be redistributed while flowing through the packing down, so that there will be no dry spots.

4.4 Effect of Hole Diameter on cooling Tower Performance

Hole size is one factor that determines airflow, redistribution of water, hydraulic resistance, and heat transfer surface area. Therefore, it is very important to choose a proper diameter to optimize the operation of the cooling towers. Based on the experiment results, it has been found that in all packing geometries, there is a gradual reduction of ΔT with an increase of L/G ratio. In all the possible combinations studied, the one with a diameter of holes of 2 mm provided the maximum decrease in the water temperature for the entire range of operation studied. This implies that small-sized holes have an advantageous combination of water retention on the surface of the packing and air flow through the packing. The improved performance achieved in relation to the diameter of 2 mm can be explained by the creation of many thin streams of liquid that are evenly spread on the packing surface. The small sizes of holes create a situation whereby water is broken down into thin films and small drops, thus increasing the contact interface between the water and air. As the diameter of holes becomes larger, poor cooling performance is recorded because of the reduced area of solid surfaces for sustaining water films.

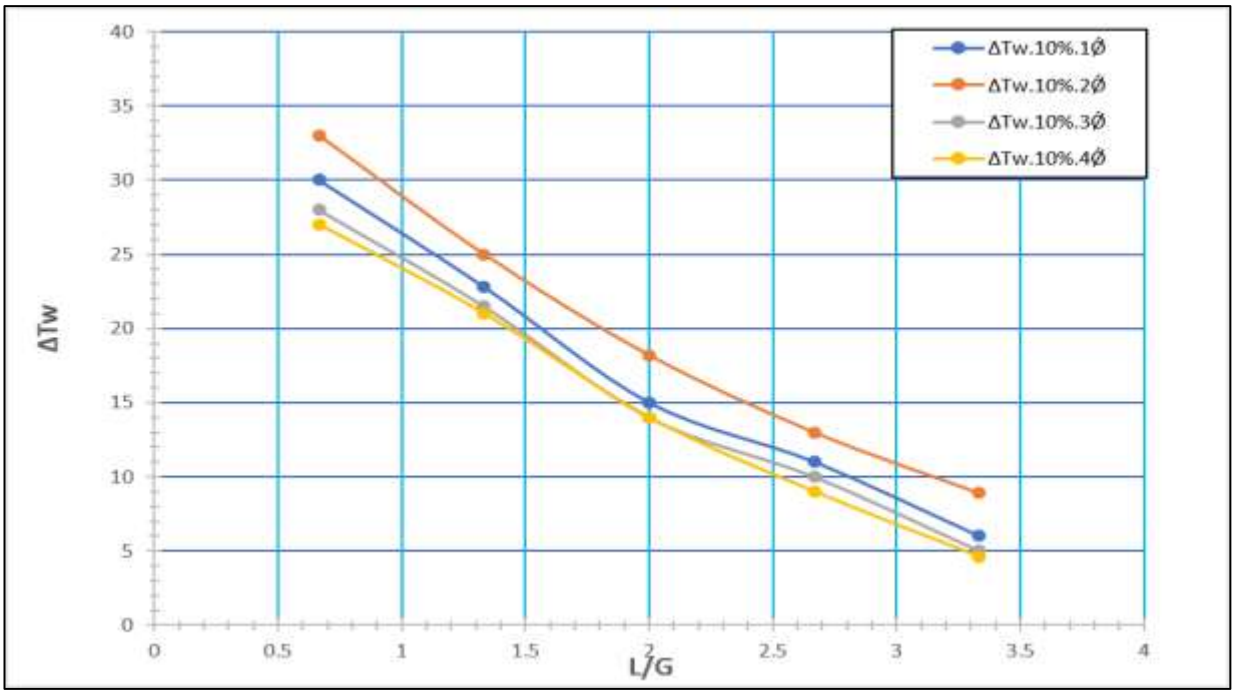

Figure 5 Effect of hole Diameter on water temperature drop.

4.5 Effect of Plate Thickness on cooling Tower Performance

The plate thickness influences both the mechanical properties and the hydraulic properties of the perforated packing media. Although the plate of higher thickness tends to have better strength, it also increases the airflow path length inside the hole and changes water distribution properties. The 1 mm packing plate showed the best thermal behavior at all the examined thicknesses. The smaller thickness of the plate reduces the distance traveled by air between the edges of the holes, reduces friction loss, and improves the evenness of the air distribution within the packing. Also, the smaller thickness allows easy spread of water around the holes and formation of thin and wide-surface liquid layers. On the other hand, an increase in plate thickness reduces heat dissipation ability. Large-thickness plates tend to act similar to small cylindrical tubes and increase hydraulic resistance. Also, thicker plates limit the entry of air inside the packing. In terms of fabrication, 1 mm thick acrylic plates reduce material and processing time requirements, while still having sufficient strength.

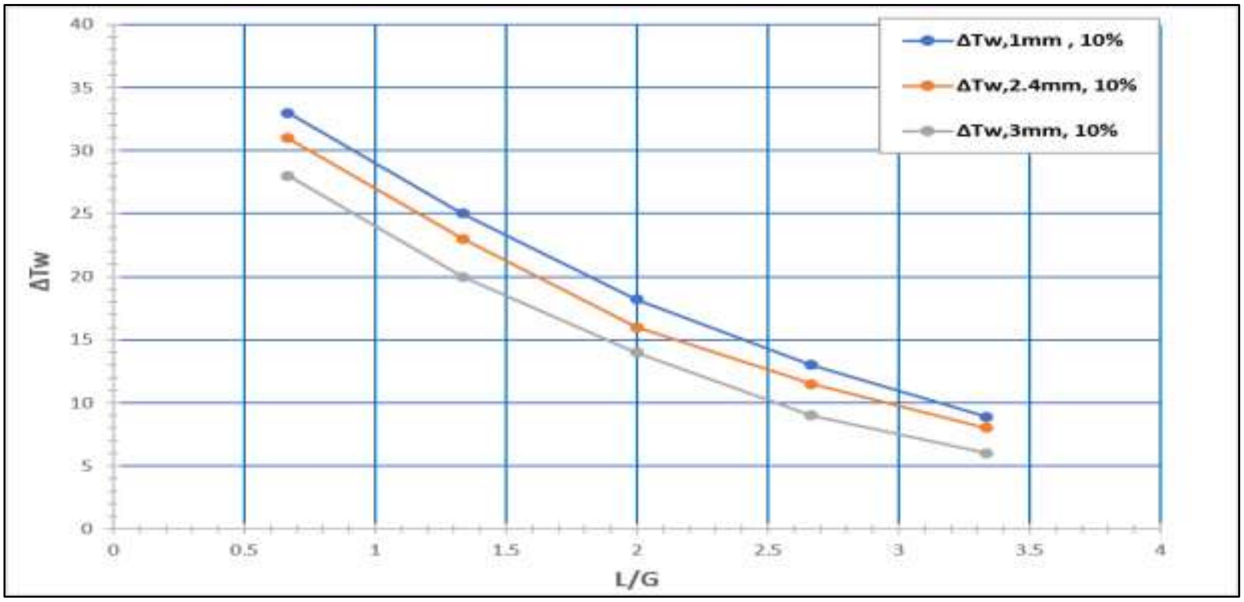

Figure 6 Effect of Plate Thickness on water temperature drop.

4.6 Cooling Tower Efficiency

The efficiency of the cooling tower is the measure of how effectively the tower is able to cool the circulating water down to the wet-bulb temperature of the environment. No matter what arrangement of the packing was used, the efficiency of cooling decreased with an increase in the liquid/gas mass flow rate ratio. This trend agrees well with the conventional theory of cooling towers, according to which increasing the water flow rate reduces its time in the heat exchanger. Nonetheless, certain variations were observed in the different packing structures being investigated. Among all the cases that were analyzed, the packing structure consisting of a perforation percentage of 10%, circular holes, a hole diameter of 2 mm, and a plate thickness of 1 mm was able to provide the best cooling performance at all conditions. These improvements could be credited to better water spread and enhanced airflow distribution. The improvement in performance was better at low L/G ratios because of sufficient airflow available to take advantage of the increased packing surface area. With high L/G ratios, although there was a decrease in cooling efficiency in all cases, the new perforated packing still had a definite performance edge over the traditional packing.

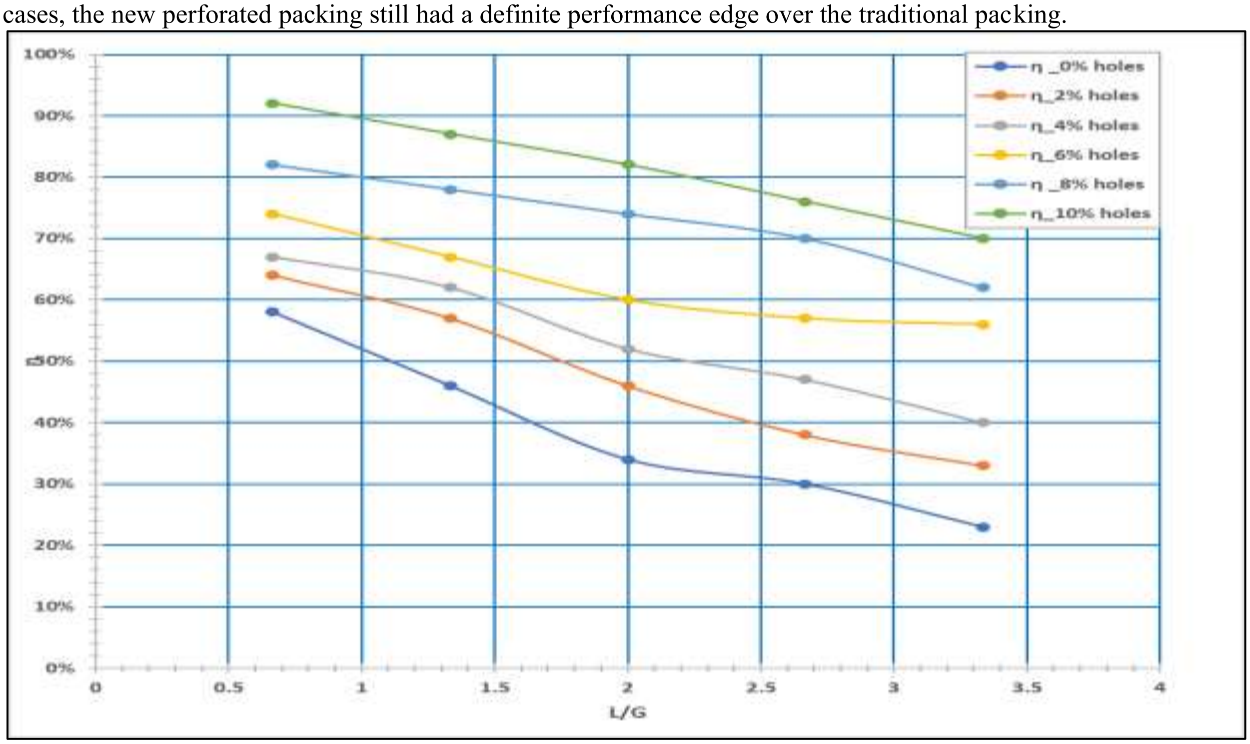

Figure 7 Variation of Cooling Tower Efficiency (η) with Water-to-Air Flow Ratio (L/G) for Different Packing Perforation Ratios.

4.7 volumetric mass transfer coefficient (Ka V/L)

The volumetric mass transfer coefficient, known as the Merkel number, is an important factor in evaluating the efficiency of cooling towers, because this number represents the combined efficiency of heat and mass transfer taking place in the packing region. Experiments have shown that the value of Ka V/L decreases gradually with the increase in L/G ratio for all the tested packings. The reason behind this decreasing tendency lies in the increased water loading, which decreases the time of contact between the air and water. Out of all the investigated configurations, the perforated packing with 10% perforation ratio, circular orifices, 2 mm diameter holes, and 1 mm plate thickness always produced the largest Ka V/L ratios under all conditions. The optimized design of the perforated packing intensifies turbulence, increases airflow penetration, and ensures the continuous mixing of the water film. As observed in the results obtained, an increase in the value of Ka V/L shows that the suggested packing increases the processes of heat transfer that take place in cooling towers. This is because the value of Ka V/L shows the efficiency of the packing to transfer sensible and latent heat.

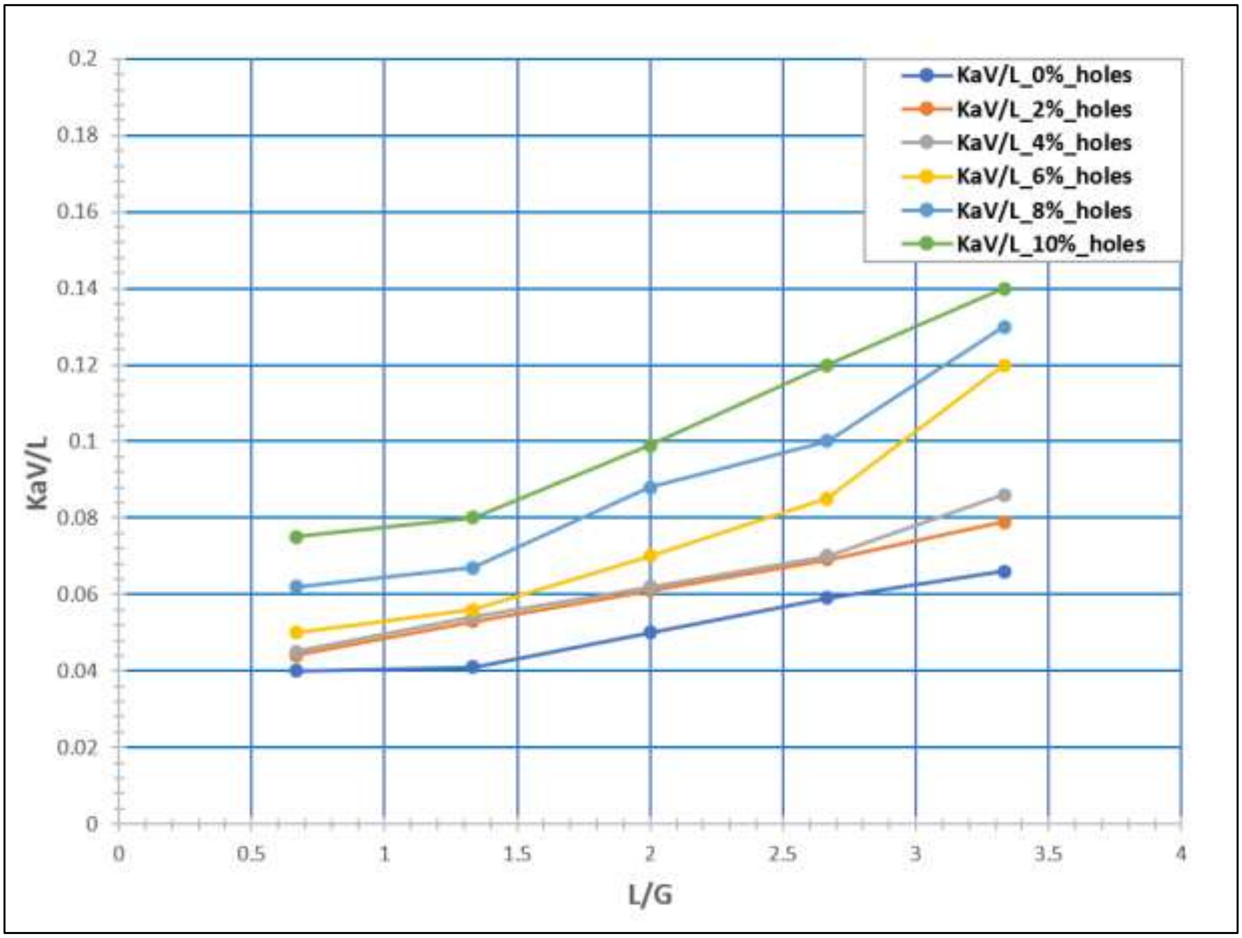

Figure 8 Variation of Cooling Tower volumetric mass transfer (Ka V/L) coefficient with Water-to-Air Flow Ratio (L/G) for Different Packing Perforation Ratios.

4.8 Heat Rejection Analysis

The term heat rejection refers to the amount of energy that is rejected by the cooling tower into the atmosphere via the circulation of the water. The amount of heat rejected depends on the volume of water circulation, the cooling range, and the physical characteristics of water. The amount of heat rejected tends to be directly proportional to the flow rate of the water since the more water flowing, the more energy conveyed. The perforated packing was able to show higher rates of heat rejection than those recorded by the solid packing at the same operating conditions. The increase is due to the more efficient evaporation process because of better water distribution and better contact between the air and water. Heat rejection takes place through sensible heat rejection, where heat energy is transferred from hot water to cooler air, and latent heat rejection, where water evaporates.

Since latent heat transfer was the principal means of cooling, at the same time the optimization of packing geometry enhanced the sensible heat transfer through turbulence of air flow and reduction of thermal boundary layer thickness.

The observed improvement in heat transfer shows that the packing configuration improves heat and mass transfer without additional energy consumption.

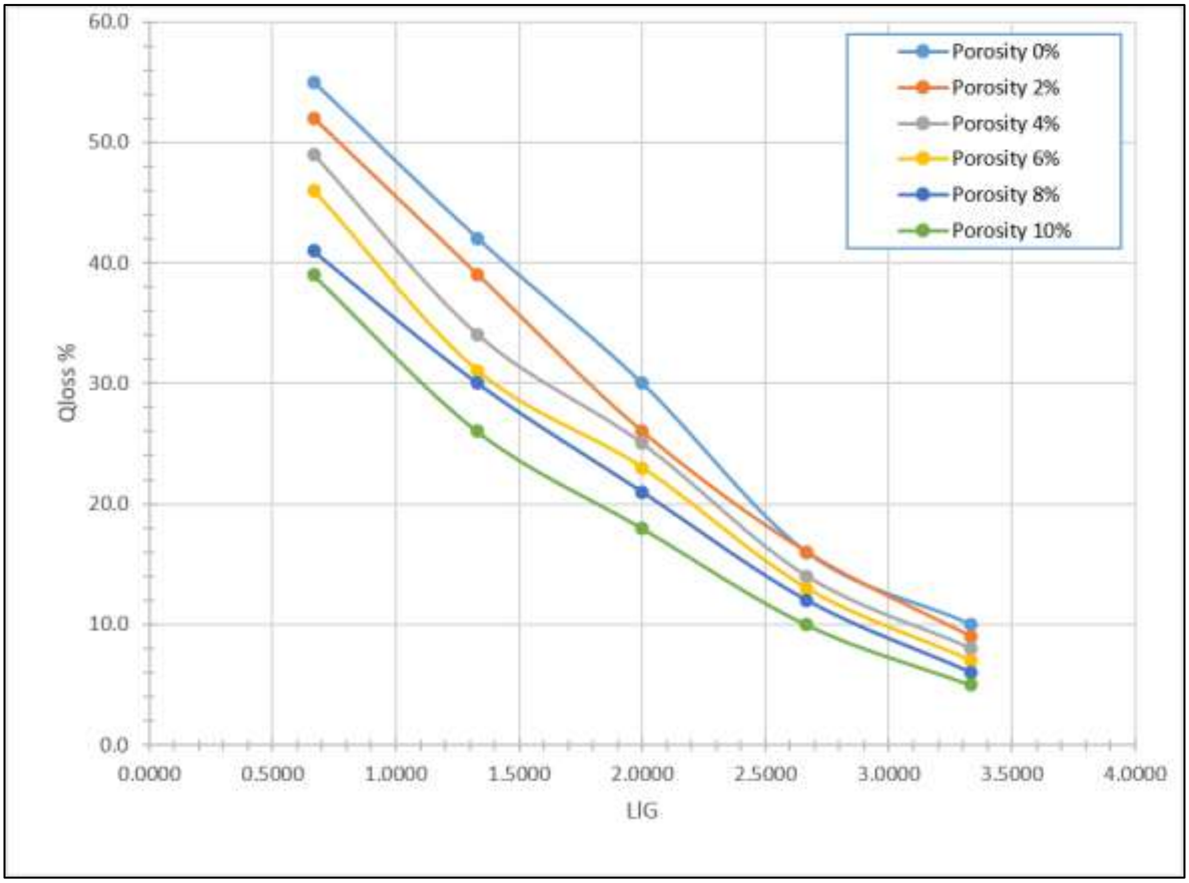

Figure 9 Relationship Between Liquid-to-Gas Ratio and Heat Loss Percentage.

4.9 Conclusions

1.It can be observed that the cooling tower's thermal performance was greatly influenced by the geometry of the packing. This shows that optimization of packing is one of the best methods to improve cooling tower efficiency.

2.Introducing perforations into conventional plastic packing significantly enhanced water redistribution, promoted airflow penetration, and increased the effective air-water contact area, resulting in improved simultaneous heat and mass transfer.

3. Among the various packing designs studied, the design having a perforation percentage of 10% performed better thermally because it had the best compromise between airflow communication and heat transfer surface area. Circular perforations consistently outperformed square and rectangular holes because of their superior hydraulic characteristics, smoother airflow distribution, and more uniform water spreading over the packing surfaces.

4.The 2 mm hole diameter provided the highest cooling effectiveness by producing stable thin water films and increasing the interfacial contact area without excessively reducing the wetted packing surface.

5.A packing plate thickness of 1 mm exhibited the best overall performance due to reduced airflow resistance, improved wettability, and lower hydraulic losses.

6.The optimized perforated packing produced the highest cooling tower efficiency, water temperature reduction, heat rejection rate, and volumetric mass transfer coefficient under all investigated operating conditions.

7.Increasing the liquid-to-gas mass flow ratio generally reduced cooling efficiency and Ka V/L because of the shorter water residence time within the packing section.

8.The Merkel-based mathematical model accurately predicted the thermal behavior of the cooling tower, with prediction accuracy exceeding 95%, demonstrating its suitability for engineering analysis and cooling tower design.

9.The proposed perforated plastic packing can be considered as a cheaper and easier-to-manufacture alternative to other commercially available packings and holds great promise for the enhancement of cooling tower efficiency under hot weather conditions.

5.Recommendations

- Investigation of additional perforation patterns generated using topology optimization.
- Evaluation of hydrophilic surface coatings to further improve wettability.
- Experimental investigation under industrial operating conditions.
- Long-term fouling and scaling studies.
- CFD simulation of airflow and water distribution inside the packing.
- Multi-objective optimization considering thermal performance and pressure drop simultaneously.
- Investigation of advanced polymeric materials manufactured by additive manufacturing.
- Techno-economic analysis of industrial-scale implementation.

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