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Comparative Study of Different Packing Designs in Counterflow Wet Cooling Towers

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Abstract

This study presents a comprehensive comparative analysis of three polyvinyl chloride (PVC)-based packing designs non-uniform film fill (NNU), double S-wave fill (DSW), and expanded wire mesh (EWM) in a counterflow wet cooling tower. The research addresses gaps in existing literature, which often evaluate single packing types under idealized conditions, leading to suboptimal selections in industrial applications and increased energy and water consumption. NNU features irregular film paths promoting adaptive flow and turbulence for enhanced heat and mass transfer; DSW incorporates dual S-waves to optimize surface area, improve water distribution, and minimize pressure drop; while EWM provides intermediate turbulence via its expandable mesh structure for flexible airflow. Experiments were conducted using the SOLTEQ HE152 bench-top cooling tower at inlet water temperatures of 35°C, 43°C, and 50°C, with water flow rates varied from 25 to 200 kg/h under constant airflow. Key performance indicators, including tower characteristics (KaV/L or NTU), cooling efficiency, and energy consumption, were evaluated as a function of liquid-to-gas (L/G) ratios. Results demonstrate that NNU achieves the highest average tower characteristic values (0.4036 at 35°C, 0.4873 at 43°C, and 0.5322 at 50°C) due to its adaptive flow paths. DSW exhibits superior cooling efficiency at lower temperatures (average 74.00% at 35°C) and the lowest energy consumption across all regimes (322.13 W at 35°C, 663.85 W at 43°C, and 774.74 W at 50°C), attributed to optimized surface area and reduced pressure drop. EWM performs well at intermediate temperatures but shows greater variability. Efficiency decreases while energy consumption increases with rising L/G ratios and temperatures. This research provides empirical guidelines for packing selection to optimize thermal performance, reduce operational costs, and align with Sustainable Development Goals (SDGs) related to energy efficiency (SDG 7) and water conservation (SDG 6).

1. Introduction

Cooling towers are essential heat rejection devices in industries such as power generation, petrochemicals, manufacturing, and HVAC systems. Counterflow wet cooling towers are favored for their compact design, high thermal efficiency, and adequate heat and mass transfer across a wide operating range. The packing (or filling media) is the core component, offering extended surface area for water-air interaction to maximize evaporative cooling. Packing geometry and material significantly influence water distribution, airflow resistance, heat transfer rates, and overall performance.

Despite the prevalence of PVC-based packings, systematic comparative studies under variable conditions are limited. Most research examines single packing types or idealized steady-state scenarios, resulting in suboptimal industrial choices, increased energy use, excessive water loss, and higher costs that contradict sustainability goals. This study compares three PVC-based designs: non-uniform film fill (NNU), double S-wave fill (DSW), and expanded wire mesh (EWM). Objectives include evaluating thermal and hydraulic performance at inlet water temperatures (35°C, 43°C, 50°C) and flow rates (25–200 kg/h), and analyzing the geometry's impact on efficiency and energy consumption. Findings support optimized designs, reduced resource use, and the achievement of SDGs 6, 7, 9, and 13.

2. Methodology

The schematic representation of a cooling tower, as illustrated in **Fig. 1**, represents the location of each component. The cooling tower system comprises three types of fluid flow: airflow, hot-water circulation, and cold-water transformation. Airflow, generated by a fan, is circulated within and around the tower, allowing efficient cooling as it travels through the packing material. The packing material is uniformly distributed by hot water that circulates within the tower and is pumped from the bottom. The heated water exchanges heat with the ascending airflow as it moves through the packing. The cold-water flow represents the conversion of hot water to frigid water within the tower. Temperature reduction results from the interaction between heated water and airflow during cooling. The system ensures a continuous cooling flow by collecting and recycling the chilled water produced.

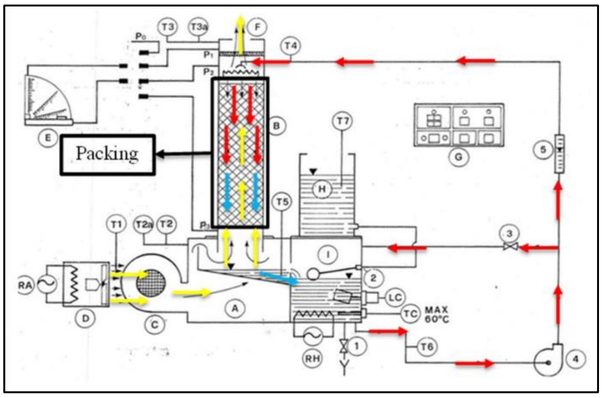


Fig. 1 *Schematic Diagram of Cooling Tower*

Experiments and measurements will be conducted using an experimental cooling tower setup to evaluate the thermal performance and efficiency of various cooling tower packing materials. Specifically, the assessment will compare the performance of each PVC packing design.

2.1 Materials

Three different PVC-based packing designs were investigated, namely non-uniform PVC film fill, double S-wave PVC structured packing, and PVC expanded wire mesh packing. These packing configurations were selected based on their distinct geometric characteristics and their reported influence on thermal and hydraulic performance in previous studies [1], [2], [3]. Each packing was installed individually in the cooling tower while maintaining identical packing height and boundary conditions to ensure a fair and unbiased comparison [4], [5].

Hence, the experiment involves three different types of materials packing **Fig. 2**:

i. Ununiform PVC

ii. Double S-Wave PVC

iii. Expandable Wire Mesh PVC

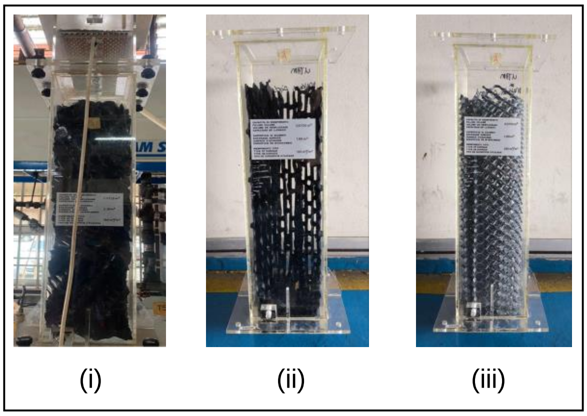


Fig. 2 *Three different packing configurations*

2.2 Methods

Experiments were conducted using the SOLTEQ Model HE152 bench-top cooling tower [6]. The system was initialised by filling the collector tank, activating the induced-draft fan, and stabilising the setup. Inlet water temperature was controlled at 35°C, 43°C, and 50°C using an integrated heater. Water mass flow rates were varied systematically from 25 to 200 kg/h (increments of 25 kg/h) while maintaining a constant air flow rate. Temperature sensors (T1–T7) recorded inlet/outlet water temperatures, wet bulb temperature, and airflow conditions. Readings were taken after steady-state was achieved and repeated three times for averaging. The procedure was replicated for each packing design.

2.3 Equations

The key performance parameters were calculated using the following equations derived from heat and mass transfer principles in evaporative cooling towers. Cooling efficiency (η), which represents the ratio of actual cooling achieved to the maximum possible cooling limited by the inlet air wet bulb temperature, is calculated as:

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_{wb}} \times 100\% \tag{1}$$

where T_{in} is the hot water inlet temperature (°C), T_{out} is the cooled water outlet temperature (°C), and T_{wb} is the wet bulb temperature of the entering air (°C) [8].

The tower characteristic (KaV/L), also referred to as the Merkel number or Number of Transfer Units (NTU), quantifies the overall mass transfer performance of the packing. It is obtained from the enthalpy driving force integral:

$$\frac{K_D aV}{\dot{m}_w} = \int_{T_{w,in}}^{T_{w,out}} \frac{C_{pw}\, dT_w}{h_s - h_a} \tag{2}$$

where C_p is the specific heat capacity of water (typically 4.18 kJ/kg·K), h_s is the enthalpy of saturated air at the local water temperature (kJ/kg dry air), and h_a is the enthalpy of the bulk air (kJ/kg dry air). The integral is evaluated numerically using psychrometric data and measured temperatures. Alternatively, it can be expressed in terms of air enthalpy change:

$$C_{pw}\dot{m}_w dT = K\, a\, dV\, (\Delta h) \tag{3}$$

where L/G is the liquid-to-gas mass flow ratio [7], [9].
Energy consumption (Q) of the cooling tower system is determined from the overall energy balance, accounting for heat rejection, fan power input, and make-up water enthalpy:

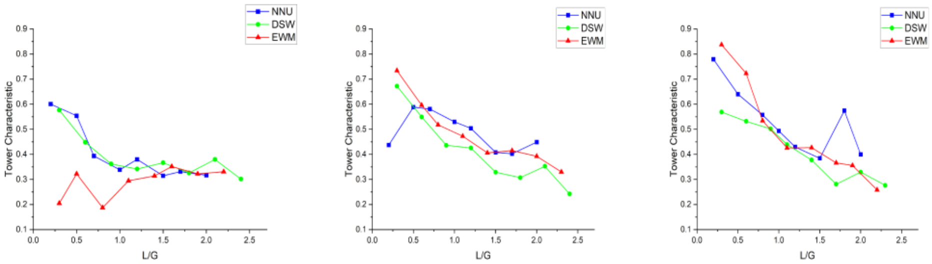
$$\dot{Q} - P = \dot{m}_a(h_B + h_A) + \dot{m}_E h_E \tag{4}$$

This equation reflects that the net heat removed from the water stream equals the increase in air enthalpy plus the energy carried by evaporated water, minus the electrical power supplied to the fan [6]. The value of Q is solved directly from measured enthalpies, flow rates, and the known fan power of 65 W. This metric is crucial for evaluating hydraulic performance and energy efficiency, which are influenced by packing resistance and pressure drop.

3. Results and Discussion

This chapter presents and discusses the experimental results obtained from comparing the Non-Uniform Film Fill (NNU), Double S-Wave Fill (DSW), and Expanded Wire Mesh (EWM) packings in the counterflow wet cooling tower. The analysis focuses on key performance metrics: tower characteristic (KaV/L), cooling efficiency, and energy consumption, evaluated against liquid-to-gas (L/G) ratios under inlet water temperatures of 35°C, 43°C, and 50°C. The objectives of assessing thermal and hydraulic performance and the impact of packing geometry on efficiency and energy use were achieved through these findings. Parameters were derived from average experimental data, ensuring accuracy and validation against prior studies [7], [8]. Results are presented in graphs to clearly illustrate trends and relationships.

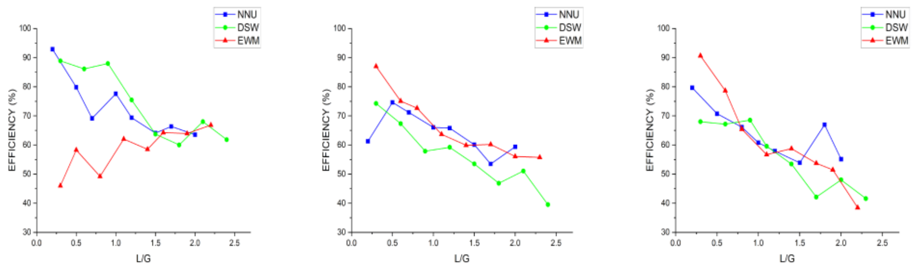
Fig. 3 illustrates the variation of tower characteristic (KaV/L) with L/G ratio for the three packing designs at inlet water temperatures of 35°C, 43°C, and 50°C. The NNU packing demonstrated the highest average tower characteristic values across all temperatures: 0.4036 at 35°C, 0.4873 at 43°C, and 0.5322 at 50°C [9]. This superior performance is attributed to its irregular geometry, which induces natural turbulence and adaptive flow paths, thereby enhancing air-water contact and mass transfer efficiency, especially at higher thermal loads when vapor pressure differentials are greater. In comparison, the DSW packing exhibited moderate values ranging from 0.35 to 0.39, representing improvements of 20-50% over EWM depending on temperature, due to its structured waves promoting uniform distribution without excessive channeling. The EWM showed greater variability, with peaks at intermediate L/G ratios but lower overall averages, likely due to inconsistent mesh interactions leading to bypass effects. Tower characteristic values generally increased with L/G ratio across all packings, indicating improved heat rejection at higher water loads. Still, NNU maintained stability across the operational range of 0.20 to 2.00, making it suitable for variable industrial conditions.



(a) (b) (c)

Fig. 3 *Comparison of Tower Characteristic vs L/G at (a) 35°C, (b) 43°C, and (c) 50°C*

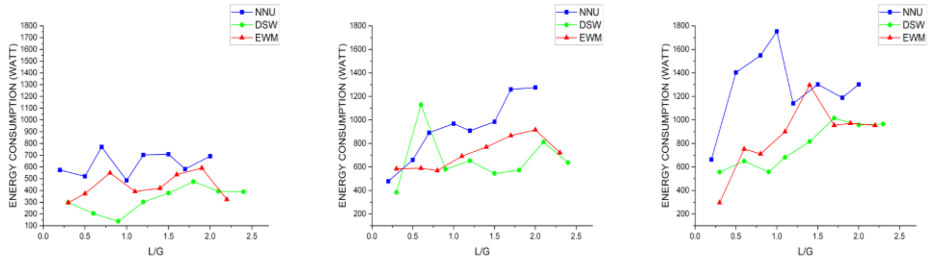
Fig. 4 shows the cooling efficiency as a function of the L/G ratio for the three packings at the tested temperatures. Cooling efficiency trends revealed a consistent decline with increasing L/G ratios and inlet temperatures across all configurations, as higher water loads reduce contact time and accelerate air saturation, diminishing evaporative potential [8]. DSW packing achieved the highest average efficiency of 74.00% at 35°C, outperforming NNU (72.85%) and EWM (58.64%), owing to its optimized S-wave structure, which ensures even water-film formation, minimal dead zones, and enhanced wetting properties under moderate conditions. At 43°C, EWM led with an average efficiency of 66.29%, benefiting from turbulence-generated mixing that improves heat transfer at intermediate thermal stresses. However, it exhibited fluctuations at higher L/G due to potential clogging risks. NNU dominated at 50°C with 63.90% efficiency, demonstrating thermal adaptability and resistance to saturation under demanding loads, with values remaining above 50% across most L/G ranges. These results underscore the temperature-dependent nature of packing performance, where DSW provides consistency for energy-efficient operations, while NNU offers robustness in high-heat scenarios.



(a) (b) (c)

Fig. 4 *Comparison of Efficiency vs L/G at (a) 35°C, (b) 43°C, and (c) 50°C*

Fig. 5 presents the energy consumption (Q) as a function of the L/G ratio at the three inlet temperatures. Energy consumption increased proportionally with L/G ratios and temperatures for all packings, driven by elevated flow resistance and fan power requirements under heavier loads. The DSW packing consistently recorded the lowest averages: 322.13 W at 35°C, 663.85 W at 43°C, and 774.74 W at 50°C, attributable to its streamlined design, which minimizes pressure drops and drag, thus optimizing hydraulic efficiency [5]. In contrast, NNU demanded the highest energy, up to 1287.60 W at 50°C, due to its non-uniform paths, which caused inconsistent frictional losses, though it balanced this with superior thermal output. EWM showed intermediate consumption with notable variability, rising sharply at higher L/G from turbulent flow effects. Overall, DSW's lower energy profile highlights its suitability for sustainable applications, reducing operational costs and entropy generation aligned with environmental goals.



(a) (b) (c)

Fig. 5 *Comparison of Energy Consumption vs L/G at (a) 35°C, (b) 43°C, and (c) 50°C*

The collective findings indicate that no packing is universally superior; selection should consider specific operating regimes. DSW balances efficiency and energy use effectively, while NNU excels in high-temperature stability, advancing cooling tower technology [9].

4. Conclusion

This experimental study compared three PVC-based packing designs—non-uniform film fill (NNU), double S-wave fill (DSW), and expanded wire mesh (EWM)—in a counterflow wet cooling tower at inlet water temperatures of 35°C, 43°C, and 50°C with water flow rates of 25–200 kg/h. Results showed that NNU achieved the highest tower characteristic (KaV/L) values (average 0.4036 at 35°C, 0.4873 at 43°C, and 0.5322 at 50°C) due to superior heat and mass transfer from turbulence, DSW delivered the highest cooling efficiency at 35°C (average 74.00%) and the lowest energy consumption across all conditions (322 W at 35°C, 664 W at 43°C, and 775 W at 50°C) owing to low pressure drop, while EWM performed best in efficiency at 43°C (66.29%) but with greater variability; overall, cooling efficiency decreased and energy consumption increased with higher L/G ratios and temperatures, making the double S-wave fill (DSW) the best packing for most practical industrial applications as it offers the optimal balance of high efficiency and minimal energy use, leading to lower operational costs and improved sustainability.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *M. Farid Sies;* ***Experimental setup and data collection:*** *Onn Lee Daniel Lee;* ***Data analysis and interpretation of results:*** *Onn Lee Daniel Lee and M. Farid Sies;* ***Manuscript drafting:*** *Onn Lee Daniel Lee;* ***Review and editing of manuscript:*** *M. Farid Sies*.

All authors reviewed the results and approved the final version of the manuscript.

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