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Effect of Design of Uniform Packing Characteristic to Improve Cooling Tower Performance

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Abstract

An experimental study of the effect of uniform packing design on cooling tower performance is presented in this thesis, with a focus on contrasting a newly developed Uniform Packing New Design (UPND) with a Previous Packing Design (UPPD) and a Non-Uniform Packing (NUP) configuration. Thermal performance is assessed under a range of operating conditions, including inlet water temperatures of 35°C, 43°C, and 50°C, and water flow rates ranging from 25 to 200 kg/h, using a laboratory-scale cooling tower apparatus (Model HE 152). The primary factors that were looked at were the tower characteristic (KaV/L) and the cooling efficiency. The results show that the UPND does much better than the UPPD in all tested conditions. The tower characteristic values were 0.35, 0.39, and 0.37, which is an improvement of 52%, 86%, and 76%, respectively. UPND also showed better cooling efficiency across the tested temperature range, with values of 64.59%, 57.05%, and 54.89%, which was up to 54.3% better than UPPD. The better performance is due to better contact between water and air, a more even flow distribution, and the removal of thermal dead zones in the packing structure. NUP worked best at certain liquid-to-gas (L/G) ratios, but UPND worked well and consistently over a wider range of L/G ratios (0.20 to 1.70), showing that it can handle changing load conditions. The study finds that the uniform packing design not only improves heat rejection and thermal stability, but it also fits with sustainable energy goals by lowering entropy generation and fan energy use. These results show that UPND is a practical and high-performance option for industrial cooling systems. They also help make cooling tower technologies that are more efficient, reliable, and good for the environment.

1. Introduction

Cooling towers are important cooling equipment used in petroleum, chemical, electric power, metallurgical, pharmaceutical and other industries. They are utilized in the recycling of hot water and preserving water same. This is probably why the counter current wet cooling tower is the most common due to the advantages it has such as high efficiency, excellent heat transfers among other qualities. Since cooling towers are large, efficient and capable of transferring heat at low temperatures they are widely used in circulating water systems. Efficient utilization of industrial water usage becomes the one and only solution to the problem of industrial water use

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[1][2]. In fact, packing material is one of the core items that must be incorporated in a cooling tower since it has an influence on the cooling tower efficiency. Cooling tower packing, also known as a heat transfer pack or fill pack, is a main part of cooling towers, which offers a sizable surface area for evaporative cooling [3]. The effectiveness of cooling towers' heat rejection has a direct impact on power plants' performance [4]. It has structure that it is thin wall where both water and air have the biggest surface that makes it possible for heat transfer. An excellent packing material enables water to be spread all over the cooling tower structures. This avoids water accumulation and makes sure that all parts of the packing are exploited fully as far as heat transfer is concerned. The packing material which must be used can afford corrosion, chemical attack as well as high temperature. This arrangement also guarantees long-span durability and puts less demand on the time invariant maintenance.

Suboptimal performance due to non-uniform packing in cooling tower increases entropy. That's primarily because non uniform packing can lead to uneven water distribution and compromised airflow. Additional resistance to airflow due to non-uniform packing may increase the pressure drop across a tower. As a result, with increased pressure drops, more energy is required to drive the fans thereby increasing the procedure of energy consumption and the entropy generation. Acrylic packing's flat surface and high heat conductivity are known to reduce entropy production compared to other materials. This reduced development of entropy is due to the effective heat transmission capabilities of this technique. Acrylic packing is smooth, so there is lower airflow resistance with pressure drop and energy use. Its high thermal conductivity also makes it easy for rapid transmission of heat between the water and surrounding air, resulting in reduced irreversibility and temperature differentials.

The primary objective of this research is to examine and compare the tower characteristics of cooling towers with uniform packing design (new design and previous) with non-uniform packing design under varied operating circumstances. Examining the effects of each design on the cooling tower's overall efficiency and thermal performance at various temperature and flow rate settings is part of this. The study also intends to examine the effects of various packing features on the cooling tower's water and air flow behavior. To find a more efficient and energy-efficient packing configuration for real-world industrial applications, special attention is paid to comprehending how these variations impact cooling efficiency, pressure drop, and the consistency of heat transfer.

This study makes a substantial contribution to cooling tower design by providing a thorough understanding of the connection between packing properties and overall performance. These discoveries will optimize heat transfer efficiency while assisting engineers and operators in lowering airflow resistance and maintenance issues. Sustainable Development Goals 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action) are all directly supported by the optimization focus of this study.

2. Methodology

Figure 1 illustrates the schematic layout of a cooling tower system, which operates based on three primary fluid flow mechanisms: airflow, hot water circulation, and cold-water collection. These components work synergistically to achieve efficient heat removal from the process stream. The system begins with airflow, which is driven by a fan that forces air into the tower. This air travels upward through the packing material, a high-surface-area structure that enhances heat and mass transfer. As air flows upward, it interacts with hot water descending through the packing, promoting evaporative cooling. Hot water circulation originates from the heat exchanger or process unit and is pumped to the top of the tower. From there, it is evenly distributed over the packing media using spray nozzles. As the hot water trickles down through the packing, it undergoes heat exchange with the upward-moving air, causing part of the water to evaporate and remove heat in the process. The remaining cool water is collected at the bottom of the tower as part of the cold-water transformation process. This cooled water is then recirculated back into the system or the process unit. The continuous cycle allows for sustained cooling efficiency and temperature regulation.

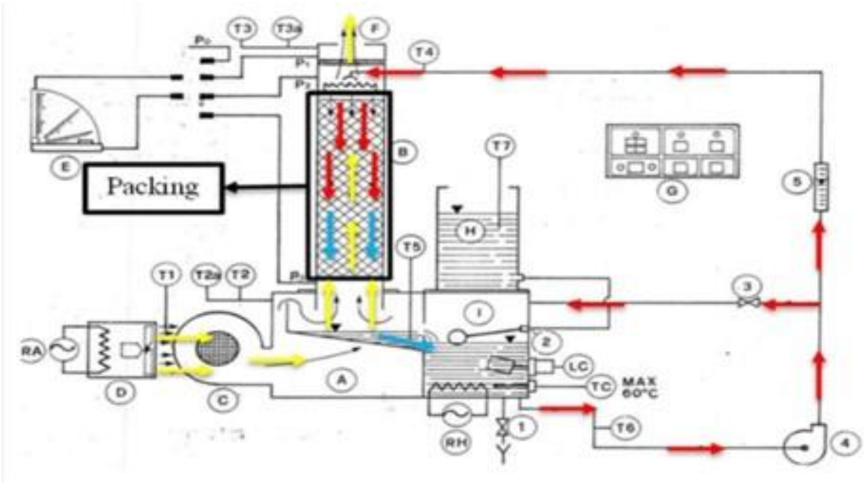


Fig. 1 *Schematic Diagram of Cooling Tower (M. Picón-Núnez et. al. 2011)*.

2.1 Materials

The primary material is polyvinyl chloride (PVC) pipes, which are 60 mm in diameter and 15 feet long. They were selected due to their extensive industrial use, ease of fabrication, and resistance to chemicals. The packing structure's support framework was built using hollow rods that were 12 feet long and 6 mm in diameter.

These rods guaranteed minimal airflow obstruction while offering sufficient mechanical strength. For packing assembly, these pipes were divided into smaller pieces. To create standardized packing units, the PVC pipes were typically cut into 140 mm lengths.

The chosen PVC material not only satisfied the experiment's structural and thermal requirements but also reflected common industrial uses, so the results can be applied to real world cooling tower design improvements. All materials were purchased and prepared in a controlled laboratory environment to ensure consistency and reproducibility throughout all experimental trials.

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

i. Non-Uniform Packing (NUP)

ii. Uniform Packing Previous Design (UPPD)

iii. Uniform Packing New Design (UPND)

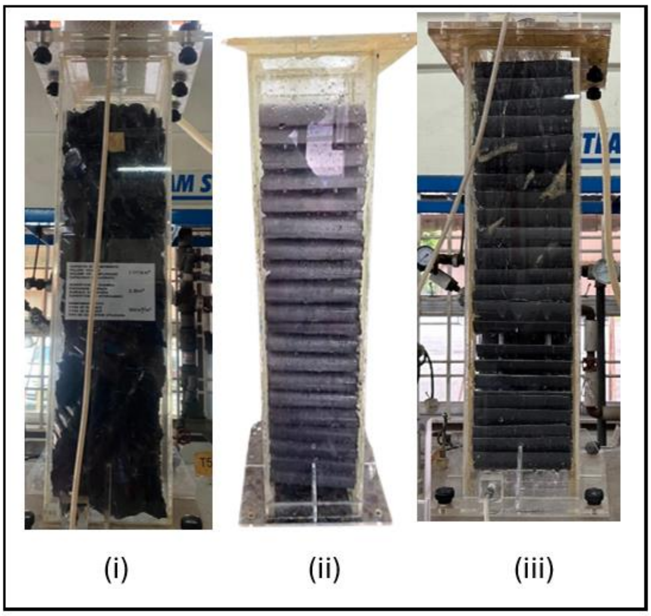


Fig. 2 *Three different packing configurations (i) NUP (ii) UPPD (ii) UPND.*

2.2 Methods

Filling the collector tank with water until it reaches the ¾ level mark is necessary to start the experiment. The next step is to turn on the fan and cooling structure. After that, the centrifugal fan needs to be fully opened on both sides. After that, the control board is turned on, and the separation chamber is opened [5]. Once this is finished, the bypass valve should be closed and the pump turned on. To bring the heater's temperature down to 35°C, a temperature control is used. Following a three-minute pause, the bypass valve is opened, and the water flow rates are adjusted to 25, 50, 75, 100, 125, 150, 175 and 200 kg/h. After that, the experiment is carried out, and T1, T2, T2a, T3, T3a, T4, T5, T6, and T7 readings are taken. After completing this process three times for every flow rate, the data is recorded to create an average.

Repeat the process at temperatures of 43°C and 50°C after finishing the experiment at 35°C. Next, repeat the experiment with uniform packing previous design and uniform packing new design, maintaining the same water flow rate and temperature.

2.3 Equations

An experimental cooling tower structure will create a controlled environment for the purpose of conducting the necessary experiments and measurements to achieve these objectives. The cooling tower employed in this investigation is the HE152 model [6]. Its objective is to enhance the efficiency of heat and mass transfer by increasing the contact area between the air and water. To achieve the first objective, it is important to determine the efficiency of these systems. To clarify this, it can be referred to equation (1), which is a fundamental result obtained through previous research. Where T_{in} is the inlet water temperature (hot temperature), T_{out} is the outlet water temperature (cold temperature) and the T_{wb} is the wet bulb temperature [7].

$$n = \frac{T_{in} - T_{out}}{T_{in} - T_{wb}} \tag{1}$$

To study the packing characteristics, the energy balances of the water and air streams in the tower are related to the mass transfer by the following equation (2) [8]. In this equation, we assume that the boundary layer temperature is equal to the water temperature T and the small change in the mass of water is neglected. From the equation (2), this formula expanded to equation (3).

$$C_{p_w}\dot{m}_w dT = K\ a\ dV\ (\Delta h) \tag{2}$$

$$\frac{K_D aV}{\dot{m}_w} = \int_{Tw,in}^{Tw,out} \frac{C_{p_w}\ dT_w}{h_s - h_a} \tag{3}$$

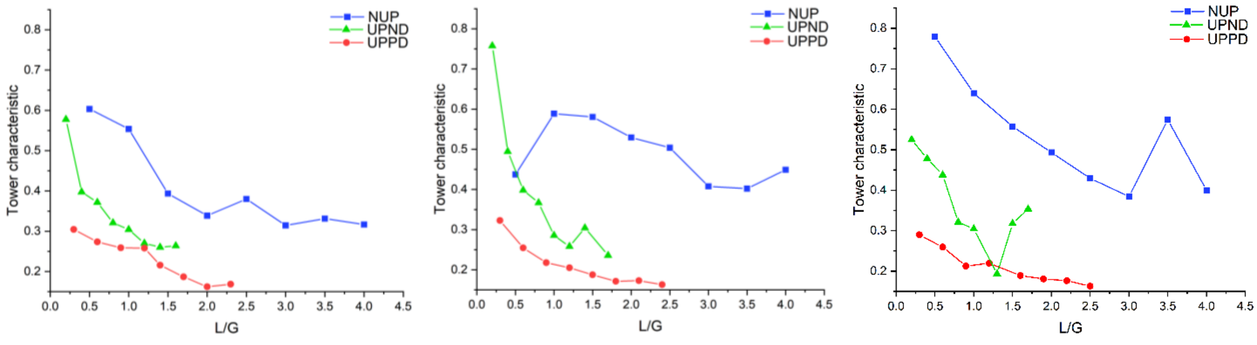
3. Result and Discussion

This section focuses on the presentation of results and discusses the use of Non-Uniform Packing (NUP), Uniform Packing New Design (UPND) and UniformPacking Previous Design (UPPD) methods in cooling tower applications. The key findings of the investigation were also examined and described in depth. The main aim was to evaluate the characteristics of a cooling tower, focusing on the relationship with packaging types impact on cooling tower performance and to investigate the relationship between the type of packaging impact to efficiency under various input conditions. This study relies on parameters obtained from previous research, ensuring the accuracy and validation of the methods used to obtain results. The results were presented in graphs to display the research data and show trends or relationships between the results.

The result in Fig.3 shown T6-50°C with NUP, which has the highest average tower characteristic of 0.53. This is outstanding performance which indicates the optimum combination of thermal driving forces and efficiency of packing design in which high operating temperatures generate stronger vapor pressure differentials to promote more efficient heat and mass transfer processes. The T6-50°C tower has been designed that will always exhibit steep tower characteristics values regardless of the values of the liquid-to-gas (L/G) ratio, and the minimum and maximum measurements have been 0.7794 at L/G=0.50 and 0.3843 at L/G=3.00 respectively which shows a good performance in various situations of operation. The irregular packing profile is a complement to the high temperature operation because it is found to permit natural flow profiles and turbulence that promote efficiency of air-water contact. The advantage of this type of configuration lies in the synergistic action of enhanced thermodynamic driving forces at high temperature and the flow optimization properties of NUP providing a maximized evaporation rates and cooling efficiency. The superiority of the performance is further supported by the fact that the configuration can hold very stable tower characteristics even when operating at the higher values of L/G ratios, thus exhibiting flexibility of operations and thermal management capabilities far better than any other of the other configurations tested.

The worst cooling tower characteristics are found in the UPPD with both of T6-43°C and T6-50°C having minimum average tower features of merely 0.21, which is the worst performance in all designed configurations. This approach towards consistently unsuccessful performance suggests some fundamental flaws inherent to the UPPD system of poor distribution of flow, high levels of channelling, and poor air-water contact surfaces. The UPPD exhibits such drastic performance loss with rising L/G ratios that T6-50°C shows tower characteristic values eroding to 0.2896 to 0.1628 as L/G ranges between 0.30 to 2.50, poor hydraulic values and low heat transfer current. The incompetency of the design to use optimally the thermos potential of operating temperatures higher indicates poor packing geometry and flow division mechanisms that do not conduct to efficient mass transfer operations. It is hard to imagine that even T6-35°C at the average of 0.23 is under this configuration significantly inferior to the overall performance of other packing designs. The very poor tower properties at all temperatures in the UPPD construction emphasize the importance of good packing engineering since although the thermal conditions were benign, the essential flaws of the design in flow and heat transfer distributions are unrelated to that condition and cannot be overcome by it.

The superiority of the UPND is evidenced by the excellent gains in performance under all temperature regimes and reaching an average tower performance of 0.35, 0.39 and 0.37 corresponding to the T6-35°C, T6-43°C and T6-50°C respectively. These numbers are approximately 52%, 86% and 76% higher than the performance of the UPPD, with T6-43°C exhibiting the greatest improvement and a higher performance TC = 0.39 than all the UPND variants. The UPND effectively overcome the drawback of its predecessor by improved flow distribution features that eliminate the dead zone and matrixing phenomena and enhance uniform air water contact over the entire tower height. The design is very thermally adaptive, continuously improving the performance in all operating temperatures, and tower properties are stable throughout the operational L/G range of 0.20 to 1.70. Although the UPND is not able to outperform the T6-50°C NUP at its peak performance, it offers a balance of performance consistency, operational reliability and maintenance simplification that is better. The technology is an important breakthrough in cooling tower design providing an industrial solution with a proven performance of large and significant performance enhancement without compromising the operational benefits of uniform packing systems, such as predictable flow characteristics, lower maintenance costs, and consistent long-term steady-state performance characteristics.



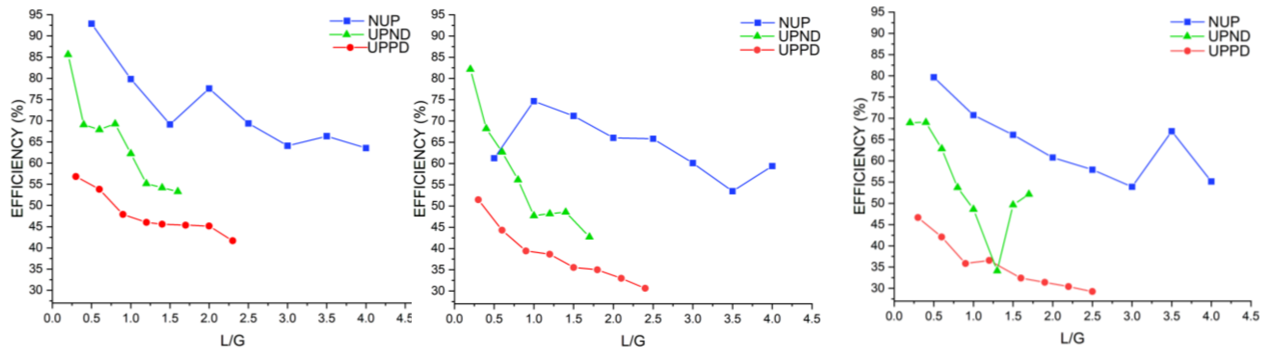
(a) T=35 °C (b) T=43 °C (b) T=50 °C

Fig. 3 *Comparison results of Tower Characteristic vs L/G at a) Temperature 35℃ b) Temperature 43℃ and c) Temperature 50℃*

Fig. 4 shown the comparison between the efficiency versus L/G. The pattern that has been observed indicates that T6-35°C with NUP has the most efficient cooling tower with all the packing and has 72.85% average efficiency. The outstanding performance is the perfect match between average thermal conditions and high efficiency of the Packing Design, with the operating temperature at T6-35°C offering the balance between thermodynamic driving forces and stability. The T6-35°C NUP also displays high efficiencies at different liquid to gas (L/G) ratios ranging between 92.89% at L/G=0.50 and 53.30% at L/G=4.00 which means that the design is very steadfast at different operating conditions. This NUP design generates excellent flow patterns and turbulence at this temperature leading to high levels of air-water contact efficiency without the problems of thermal stress that higher temperatures produce. The advantages of this geometry are that forced thermodynamic driving forces are controlled at moderate temperatures and flow optimization properties of NUP combine their synergistic effect to maximize heat transfer rates and to maximize cooling effectiveness. This performance superiority is also supported by the fact that the NUP has an operating flexibility and thermal management capability that is much better than any of the other tested packing as it achieves its best efficiency of approximately 92.89% at low L/G ratio and maintains an efficiency higher than 60% throughout most of its operating ranges.

The worst efficiency of cooling towers occurs in the UPPD, and T6-50°C recorded the lowest average efficiency of merely 35.58% showing the worst performance of the obtained result of all patterns. This performance is consistently poor enough to point to fundamental design shortcomings of the preceding packing system that provided mostly uniform packing, in insufficient flow distribution, excessive channelling, and poor air-water contact surfaces that are themselves a severely limiting factor under increased thermal loads. The UPPD can display extreme degrades in performance as temperatures rise, with efficiency dropping 47.79% at T6-35°C, 38.51% at T6-43°C, and 35.58% at T6-50°C, pointing toward a low rate of thermal stability and a tried thermal transportation capacity in the demanding temperature scale. The fact that the design does not favourably use the higher working temperatures implies poor packing geometries and flow distribution arrangements that does not facilitate an efficient process of mass transfers as thermal stress intensifies. The dramatic limitation on performance in the performance measurement of individual efficiencies at T6-50°C encompasses a meagre bank of only 46.66 percent at L/G=0.30 to a pathetic test of 29.25 % at L/G=2.50 and this beckons a poor hydraulic performance. These low values of efficiency at all combinations of temperature and L/G ratios in the UPPD where the packing was not engineered properly highlight that no amount of positive thermal gradients can accommodate other inherent deficiencies of the flow distribution and heat transfer optimization of a design that is improperly engineered.

The importance of the UPND can only be shown by the fact that remarkable improvement shall be seen in the efficiency under all the temperature conditions and attained the average efficiencies of 64.59%, 57.05% and 54.89% in case of T6-35°C, T6-43°C, and T6-50°C respectively. These values are massive improvement of 35.2%, 48.2% and 54.3% of the UPPD with T6-50°C witnessing the most spectacular improvement and speaks volumes to the better capabilities of the design in thermal management, when subjected to gruelling operating conditions. UPND manages to overcome the limitations of the UPPD, even the distribution of mixtures flows is significantly enhanced by the elimination of dead zones and channelling effects alongside providing uniformity of air-water contact along the tower height. Its operational adaptability is outstanding with very good efficiency enhancement over a wide range of operating temperatures with consistent results throughout the operational range of L/G which ranged between 0.20 to 1.70 with a maximum efficiency of 85.61% at T6-35°C and above 68% at optimum L/G ratios at most temperature conditions. Although the UPND is not the best performer at the peak position compared to T6-35°C NUP, it offers better efficiency consistency, reliability in functionality, and stability of temperatures. The technology is a radical improvement in cooling tower engineering and one that provides industrial application with a technology that can provide the industrial user with considerable efficiency advantages and at the same time provide all the benefits of uniform packing systems such as predictable flow behavior, lower maintenance demands, and the consistent long-term behavioral characteristics that make it very well suited to variable load cooling demands with an industrial application.



(a) T=35 °C (b) T=43 °C (b) T=50 °C

Fig. 4 *Comparison results of efficiency versus L/G at a) Temperature 35℃ b) Temperature 43℃ and c) Temperature 50℃.*

Conclusion

This study was conducted to evaluate and compare the performance of different cooling tower packing configurations, with a specific focus on the Uniform Packing New Design (UPND) against the Previous Packing Design (UPPD) and a Non-Uniform Packing (NUP) arrangement. Using a laboratory scale cooling tower apparatus (Model HE 152), experiments were carried out under varying operational conditions, including inlet water temperatures of 35°C, 43°C, and 50°C, and water flow rates ranging from 25 to 200 kg/h. Key parameters such as tower characteristics (KaV/L) and cooling efficiency were analyzed to determine the effectiveness of each packing type. This conclusion summarizes how the research objectives were met and offers recommendations for future work.

The tower characteristics (KaV/L) analysis showed that the UPND continuously produced better results under all tested temperatures. The average tower characteristic values that the UPND obtained at inlet water temperatures of 35°C, 43°C, and 50°C were 0.35, 0.39, and 0.37, respectively. These values represented significant improvements of 52%, 86%, and 76% over the UPPD. Improved flow distribution, the removal of dead zones, and better air–water contact throughout the packing surface are all credited with these improvements. With L/G ratios ranging from 0.20 to 1.70, UPND proved to be more thermally stable and dependable. In contrast, the NUP configuration showed peak performance at L/G ratios. This consistency highlights how useful the UPND is for real-world applications, where a robust and flexible system design is required due to changing operating loads and environmental factors. The impact of packing characteristics on cooling efficiency was also assessed in the study. At all temperature ranges, UPND demonstrated significant efficiency gains, reaching 64.59%, 57.05%, and 54.89% at T6-35°C, T6-43°C, and T6-50°C, respectively. These figures show that UPND is more thermally adaptable under high heat loads than the UPPD, with notable efficiency gains of 35.2%, 48.2%, and 54.3%. The findings verify that the design preserves performance integrity with little sensitivity to elevated thermal stress while simultaneously facilitating better heat rejection. The UPND demonstrated the potential for deployment in high-demand industrial cooling systems by maintaining high efficiency without structural compromise, especially at T6-50°C a difficult operating condition.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****;* ***data collection; analysis and interpretation of results****;* ***draft manuscript preparation:*** *Ahmad Muhaimin Bin Che Mokhtar. M.Farid Sies reviewed the results and approved the final version of the manuscript.*

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