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# Experimental and Computational Study of the Most Influential Parameters of a Lab-Scale Forced Draft Cooling Tower by Considering Different Number of Packing Ribs

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***Abstract-*** This research work incorporates experimental investigation and simulation to inspect the impact of influential parameters on the efficiency of a forced draft cooling tower. The number of packing ribs, the flow rate of water, the flow rate of air, the surface area, and the area of contact are the parameters investigated in this study. All of these parameters are altered and their effect on efficiency is explored. Two types of packing with varying rib numbers of packing and areas are utilized to observe their influence on the efficiency of the cooling tower. Modeling and CFD analysis of the aforementioned cooling tower is done on SOLIDWORKS and ANSYS Fluent respectively. Finally, the results from experimental data and CFD analysis are compared to inspect the effectiveness of the simulation. The results depicted that the efficiency of a forced draft cooling tower varies directly with the flow rate of air and inversely with the flow rate of water. Moreover, the performance of the cooling tower has a direct relationship with the area of contact, time of contact between air and water, and the number of ribs. The results obtained from CFD analysis are compared and validated with experimental results. Finally, percentage error analysis is also presented between simulation model efficiency and experimentation efficiency of the benchtop cooling tower and it exhibits good agreement with the experimental data.

***Keywords-*** Forced draft cooling tower, efficiency, simulation, air flow rate, performance parameters, water flow rate.

## I. INTRODUCTION

The world is facing huge energy demands and power plants are a major source to meet these demands [1]. Cooling tower is an integral part of power plants. Cooling towers are extensively used heat-exchanging devices to exchange the heat from condenser water through air flow in power plants and to reject the extracted heat to the atmosphere [2]. Process industries use cooling towers on a large scale to extract the heat from process water and cool down specific parts [3]. Power stations, manufacturing industries, and air conditioning units are some of the common applications of cooling towers [4]. Cooling towers work on evaporative and convective cooling when both water stream and air stream encounter, and air gains heat [5-6]. Water droplets are sprayed from the distribution system at the top through nozzles on a surface i.e., cooling tower fills or packing which provides a larger area for water droplets and facilitates proper air and water contact [7]. At the top of the cooling tower, drift eliminators are incorporated to decrease the emissions of water droplets due to evaporation in the outer environment. Cooling towers are generally categorized into natural and mechanical draft based on the mode of air flow. Based on the position of the fan, the latter category is further divided into two types i.e., induced draft and forced draft [8]. A forced draft cooling tower uses a power-driven fan at the bottom to throw cool air upward for heat exchange [9].

Improving the cooling performance and the cooling efficiency of cooling towers because of their wider use has been an area of interest for researchers. In a study, it was revealed that increasing the water/air flow rate ratio can result in decreased performance of mechanical cooling towers [10]. Another study backed the result that heat transfer is in inverse relation to water flow rate [11]. Hosoz utilized Artificial Neural Network (ANN) to predict the cooling tower performance. It was revealed that the performance can be accurately predicted through ANN [12]. In another study, researchers incorporated the VGA (Vertical Grid Apparatus) packing in the forced draft tower to inspect the thermal performance. They explored the performance by considering air and water flow rate. They reported an enhancement in the cooling water range with an increased flow rate of air and decreased flow rate of water [13]. Ramakrishnan and Arumugam studied a forced draft cooling tower to assess its performance with ANN and RSM (Response Surface Methodology). The considered parameters were water temperature, water and air flow, and fill height. Based on the response variable i.e., cold water temperature, they predicted that the ANN model showed better accuracy. The most influential parameters in that study were packing height, air flow, and water flow [14]. Another work also reported an increase in efficiency with an increased flow rate of air and packing stage numbers [15]. Ali also reflected on the direct relation between air flow rate and efficiency [16].

[17] inspected the efficiency of a forced draft cooling tower by utilizing film, splash, and trickle fills. For each fill, the evaporation rate, cooling tower characteristic ratio, and cooling range were analyzed. They revealed that wire mesh (trickle fill) was more efficient. They also presented decision-making criteria to control the variables according to the requirement. Gao et al. inspected the impact of non-uniform filling on thermal performance. They reported a 30% increase in thermal performance with an optimized non-uniform filling layout [18]. Another research included the impact of the fill pattern on the efficiency of the cooling tower (mechanical draft type). The outcomes demonstrated that a non-uniform fill pattern can boost performance [19]. In another study, Lavasani examined the thermal efficiency of a mechanical cooling tower with the use of rotational splash packing. They found out that rotation of packing did affect the evaporation rate majorly however, heat rejection from the water was enhanced [20].

Researchers explored the cooling tower's performance (mechanical type) in the presence of non-uniform rotational splash packing by utilizing nanofluids. They reported an enhancement in thermal performance with nanofluids. Cuo/water nanofluid provided the best results whereas performance increased with increased concentration of nanofluid [21]. Imani-Mofrad reported that Graphene/water nanofluid can enhance the thermal performance of a cooling tower. The coefficient of volumetric heat transfer can be enhanced by 36.2% as compared to water [22]. In another study, researchers studied the influence of ZnO nanoparticles in water on thermal performance. It was revealed that cooling efficiency was enhanced with increased concentration of nanofluid. Increased density of packing yielded more effects of nanofluids [23]. Another study explored the efficiency of a prototype inverted wet cooling tower and stated that this tower provided 6.98% better efficiency than a film flow distribution system cooling tower [5]. Deng and Sun optimized the arrangement of the layout pattern for improved thermal performance [24].

Shahli explored the influence of rib numbers of packing and other influential parameters on the forced draft cooling tower's performance. It was verified that the number of ribs in packing was in direct relation to the performance [25]. Rahmati also backed this result [15]. Blain generated a CFD model of the natural draft cooling tower. After the calculations, the simulation results were validated through experimentation [26]. Llano-Restrepo et al. presented a simulation model for the prediction of mass transfer inside the tower body to assess the experimental thermal performance [27]. Al-Dulaimi inspected the thermal performance of both categories of cooling towers (i.e., natural as well as mechanical) numerically and experimentally. They developed a CFD simulation model to study temperature profiles and relative humidity. They reported an increase in performance when employing a fill thickness of 20 cm [28]. In another study, researchers devised a CFD model for a blade of a fan in a mechanical draft cooling tower and validated the outcomes through experimentation [29]. Researchers presented a simulation model for the industrial cooling tower for decreased power consumption. The validated model reduced energy consumption by 30% [30]. In a most recent study, a numerical model of a hybrid mechanical draft tower has been developed. The results depicted that humidity and water flow have a smaller impact on the water saving rate whereas dry bulb temperature and the water temperature have more impact [31]. Zargar studied plume abatement and the performance of a hybrid cooling tower. A model was presented to study the performance of a cooling tower [32]. In another study, researchers presented a strategy to reduce the risk of Legionnaires' disease in cooling towers [33].

Despite the importance and frequent use of cooling towers, this topic, unfortunately, has undergone very little research in Pakistan. Due to the energy crisis in Pakistan, the gap between supply and demand has elevated significantly [34]. The role of cooling towers in conjunction with power plants in these scenarios has become very important. Based on this gap, this research is carried out to evaluate the efficiency of a forced draft cooling tower experimentally and through a simulation model. Two different types of packings are used in this study with a different number of ribs (plates) or staging. For each type of packing, the effects of the flow rate of air, the flow rate of water, and the contact area on the efficiency are investigated and tower models are developed on SOLIDWORKS. Based on those models, temperature profiles through CFD analysis on ANSYS Fluent are developed. In the end, simulation results are validated and error analysis is done.

## II. MATERIALS AND METHODS

In this study, PA Hilton's H893 Bench Top

Cooling tower is utilized for experimentation. This is a lab-scale forced draft cooling tower that represents all the processes of an industrial cooling tower. The dimensions of the equipment are 450 mm x 750 mm x 1200 mm (LxWxH). The dimensions of the column are 150 mm x 150 mm x 600 mm (LxWxH). The water tank is connected to two heaters of power 0.5 and 1 kW respectively that heat the water inside the tank. Thermocouples and humidity sensors are installed at different instances to take measurements of temperature and humidity respectively. The equipment is demonstrated in fig. 1 which consists of tower body (1), packing (2), air temperature (inlet) (3), distribution chamber (4), radial fan (5), water temperature (outlet) (6), floating valve (7), water temperature (hot) (8), heater (9), feed water pump (10), manometer (11), flow meter and valve (12), display (13), switching buttons (14), make-up water tank (15), hot water distribution pipe, (16), water tank (17), air temperature (outlet) (18) and nozzle (water distribution) (19).

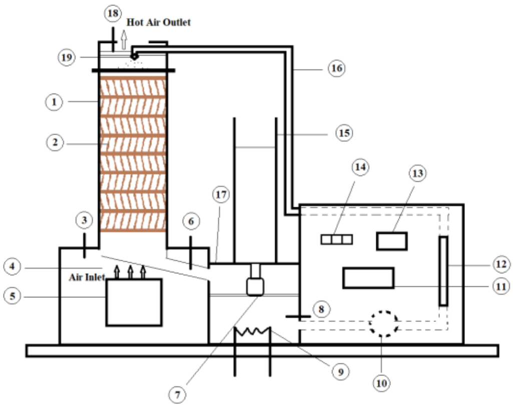


Figure 1: Bench Top Cooling Tower (H893)

Two packing types are used in this research based on the number of ribs. The first packing (Packing A) has 7 ribs of packing whereas the second packing (Packing B) contains 10 ribs. The specifications of both packings are presented in table I. The water inside the tank was heated with the aid of a heater. The heated water was pumped through the pump to the distribution system at the top where it was sprayed and water passed through the packing material. At the same time, cool air started to travel from a centrifugal fan in the upward direction. The water stream made a thin film on packing ribs while passing through the packing material. The heat was exchanged when the air came in contact with water film through evaporation and some part through convection. Air and water temperatures were studied at different instances and flow rates were altered. The recorded data was used to calculate the experimental efficiency of the cooling tower.

This study consists of four sets of experiments. In the first set, for packing A, the air flow rate was kept constant at 60 g/s and the water flow rate was altered. Readings were taken at 10 g/s, 20 g/s, 30 g/s, 40 g/s and 50 g/s. In the second set, for packing A, the flow rate of water was kept at 20 g/s (constant), and the effect of the air flow rate was studied. The effect of water flow rates at 52 g/s, 54 g/s, 54 g/s, and 58 g/s were observed. Similarly, in sets 3 and 4, the same parameters were repeated for packing B. The design of the experiments is also presented in table II. Experiments were performed at 26 $^{o}$C room temperature and 52% humidity.

TABLE I: Specifications of Packing Used

| **Specification** | **Packing A** | **Packing B** |
|---|---|---|
| Number of decks | 8 | 8 |
| Number of ribs (plates) | 7 | 10 |
| Density | 77 $m^2 / m^3$ | 110 $m^2 / m^3$ |
| Material | Plastic | Plastic |

TABLE II: Design of Experiment

| **Set Number** | **Packing** | **Air Flow Rate (g/s)** | **Water Flow Rate (g/s)** |
|---|---|---|---|
| 1 | A | 60 | 10, 20, 30, 40, 50 |
| 2 | A | 52, 54, 56, 58 | 20 |
| 3 | B | 60 | 10, 20, 30, 40, 50 |
| 4 | B | 52, 54, 56, 58 | 20 |

## III. MODELING AND SIMULATION

For simulation and CFD analysis, the model of the same cooling tower was constructed with SOLIDWORKS 2019. During modeling, data from real equipment was incorporated for accurate simulation results later on. Geometry models of both packings (A and B) were modeled which are shown in fig. 2. Both models contained 8 decks each and the number of packing ribs was 7 and 10 as already mentioned. The model was validated by comparing the computational results from the model with experimental results.

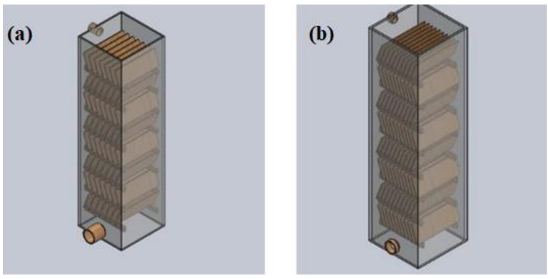


Figure 2: SOLIDWORKS models of (a) Packing A with 7 ribs and (b) Packing B with 10 ribs

For simulation, these geometry models were imported into ANSYS Fluent R15.0. In this model, fluid regions were created that depicted the domain from inlet to outlet in the direction of fluid flow. After that, input and output regions for air and water were created. After creating surfaces on the inlet and out, those regions were filled. The same boundary conditions were applied in ANSYS that were used in an experimental model. In the next step, models of both packings were meshed which divided the models into finite elements. Tetrahedron meshing with corner sizing of 0.001 mm was utilized in the analysis and mesh independence was not studied.

The meshed models of Packing A and Packing B are displayed in fig. 3(a) and fig. 3(b) respectively. Then, five inflation layers were made around the meshed packing models. In the final step, models were solved. After solving the models, temperature contours of general model, water outlet view, and packing view are displayed in fig. 4, fig. 5, and fig. 6 respectively.

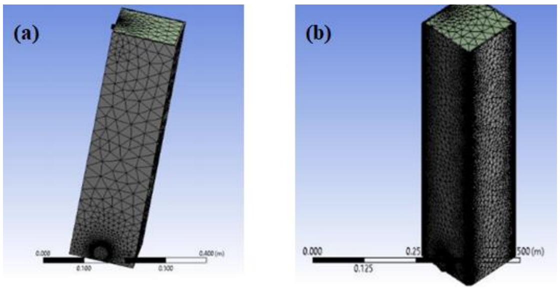


Figure 2: Meshed models of (a) Packing A and (b) Packing B

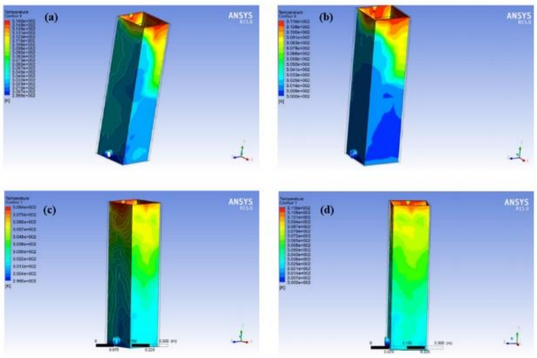


Figure 3: Temperature contours of (a) Packing A at constant air flow, (b) Packing A at constant water flow rate, (C) Packing B at constant air flow rate, and (d) Packing B at constant water flow rate

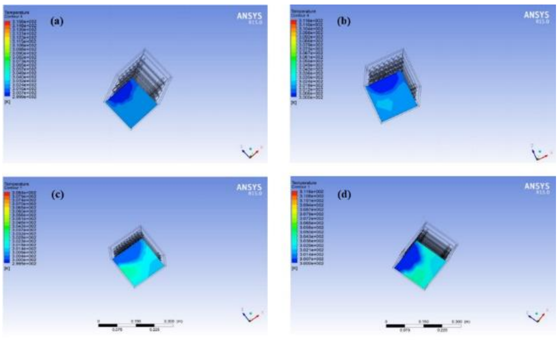


Figure 4: Outlet water view showing temperature contours of (a) Packing A at constant air flow, (b) Packing A at constant water flow rate, (C) Packing B at constant air flow rate, and (d) Packing B at constant water flow rate

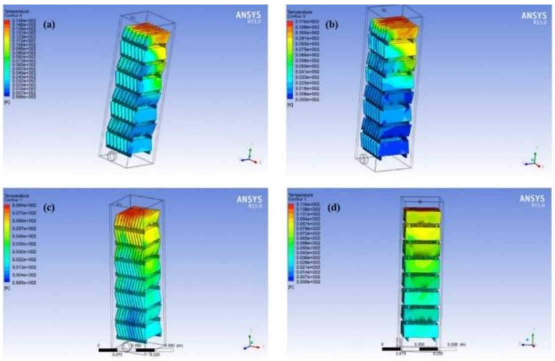


Figure 5: Packing view showing temperature contours of (a) Packing A at constant air flow, (b) Packing A at constant water flow rate, (C) Packing B at constant air flow rate, and (d) Packing B at constant water flow rate

## IV. RESULTS AND DISCUSSIONS

### *4.1 Influence of Flow Rate of Air on Efficiency:*

To adjust the flow rate of air, the speed radial fan can be altered. By keeping the flow rate of water constant at 20 g/s and increasing the flow rate of air, it was detected that the efficiency started to elevate. The major contributing factor to this trend is that more air passes through the fixed space of the cooling tower.

The given volume of water coming down from the nozzle comes in contact with more air and hence, loses more heat as compared to that of a low air flow rate. Air flow rate shows a direct relation with a cooling performance at a constant water flow rate as plotted in fig. 7. Both packings with packing densities of 77 $m^2/m^3$ and 110 $m^2/m^3$ hold this result valid. On an industrial level, the power consumption of fans may be another constraint for higher air flow rate but it is out of this study’s scope.

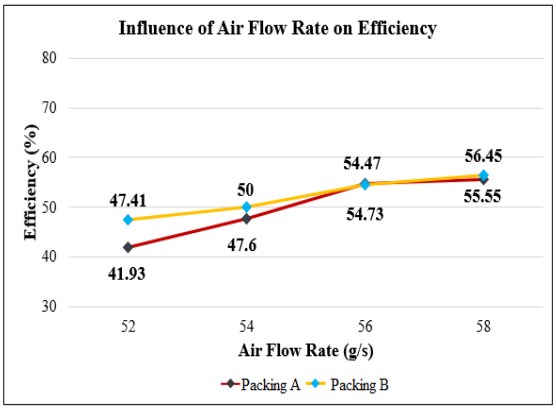


Figure 6: Influence of flow rate of air on efficiency (at 20 g/s water flow rate)

### *4.2. Influence of Flow Rate of Water on Efficiency:*

The flow rate of water can easily be adjusted using a flow valve. To study the influence of water flow rate on efficiency, the flow rate of air was kept constant at 60 g/s for both packings and the water flow was varied. The results of efficiency against the water flow rate for both packings are plotted in fig. 8. It is evident that at a lower water flow rate, the efficiency is much higher. At higher flow rates of water, in the fixed space of the cooling tower and air flow, there is more water from which heat is to be extracted. Consequently, there will be less surface area for water to exchange the heat and it results in less heat exchange which decreases the efficiency. Moreover, at higher water flow rates, there is less time available for water for evaporation and convection as compared to lower water flow rates. For both packings, the aforementioned statements are agreed upon. There can be a combined effect of air flow rate and water flow rate on the efficiency if both the quantities are changing at a time. This effect can be studied with the help of experiments.

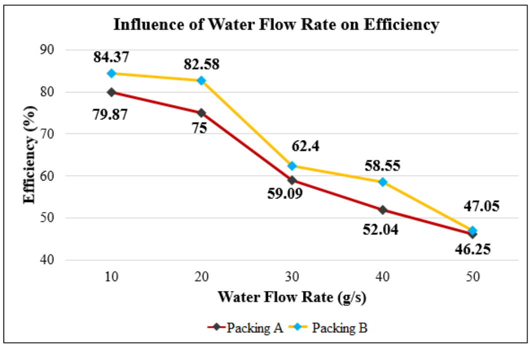


Figure 7: Influence of flow rate of water on efficiency (at 60 g/s air flow rate)

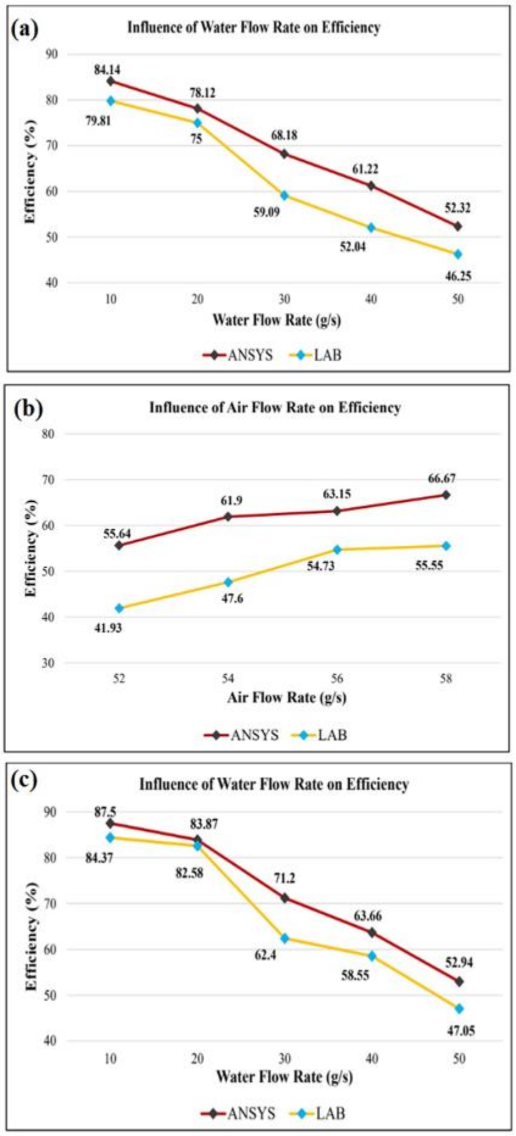
### *4.3 Influence of Number of Packing Ribs and Surface Area of Packing on Efficiency:*

Simulation and experimentation, both indicate that packing B is more efficient as compared to packing A. The reason for it can be explained by considering the rib numbers of packing. In packing B, there are more packing ribs (i.e., 10). Having more plates in packing increases the surface area as well as the density of packing. The area of contact of both fluid streams increases (where the film of water is formed on plates) with an increase in the surface area of packing. This increased contact area facilitates the heat-exchanging process between air and water. Fig. 7 and fig. 8 represent that packing B holds more efficiency percentage as compared to packing A in all the scenarios. For better cooling performance, packing with higher density or a greater number of plates must be utilized.

### *4.4 Comparison of Experimental and Simulation Results:*

Results from ANSYS Fluent agree with the experimental results with some deviation due to some losses. Simulation results (at the same combination of parameters that were used in the experimental investigation) were very close to experimental results. Fig. 9a and 9b represent the comparison of experimental efficiency and simulation efficiency of packing A at a constant air flow rate and constant water flow rate respectively. Whereas, fig. 9c and fig. 9d represents the same for packing B.

ORIGIN PRO was utilized for the percentage error analysis between both efficiencies. Fig. 10 depicts the percentage error between experimental and ANSYS efficiencies. The percentage deviation between both is shown in table III. Fig 11 shows deviation at a constant water flow rate whereas fig. 12 shows deviation at a constant air flow rate. The deviation can be contributed to some known and some unknown factors. First of all, experimental efficiency is generally lower than that of simulation due to some losses. Accuracy of equipment and testing conditions are two more factors that can contribute to this deviation.



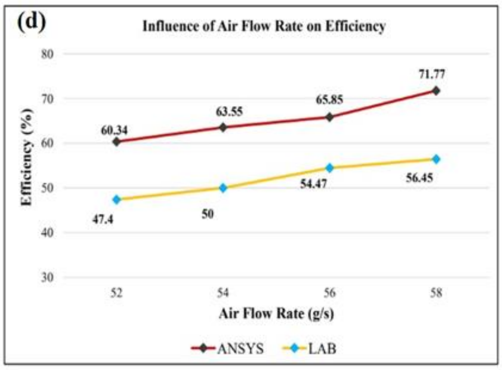


Figure 9: Comparison of experimental and ANSYS efficiencies of (a) Packing A at constant air flow rate, (b) Packing A at constant water flow rate, (c) Packing B at constant air flow rate, and (d) Packing B at constant water flow rate

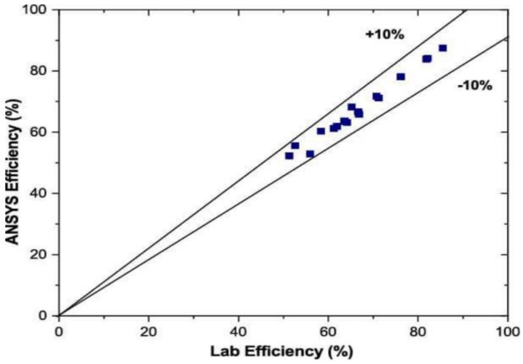


Figure 8: Percentage error analysis of experimental and simulation efficiencies

TABLE III: Percentage Deviation of Experimental Results From Computational Results

| Sr. # | Air Flow Rate (g/s) | Water Flow Rate (g/s) | Deviation for Packing A | Deviation for Packing B |
|---|---|---|---|---|
| 1 | 60 | 10 | 5.1% | 3.5% |
| 2 | 60 | 20 | 3.9% | 1.5% |
| 3 | 60 | 30 | 13.3% | 12.3% |
| 4 | 60 | 40 | 14.9% | 8% |
| 5 | 60 | 50 | 11.6% | 11.1% |
| 6 | 52 | 20 | 24.5% | 21.4% |
| 7 | 54 | 20 | 23% | 21.3% |
| 8 | 56 | 20 | 13.3% | 17.2% |
| 9 | 58 | 20 | 16.6% | 21.3% |

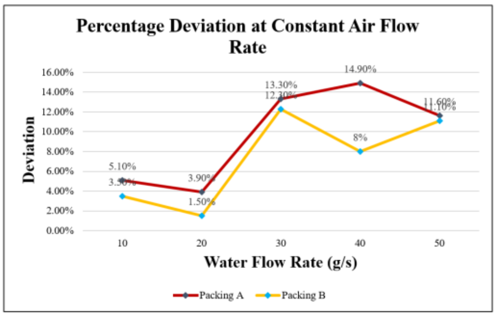


Figure 9: Percentage deviation of efficiency at constant air flow rate

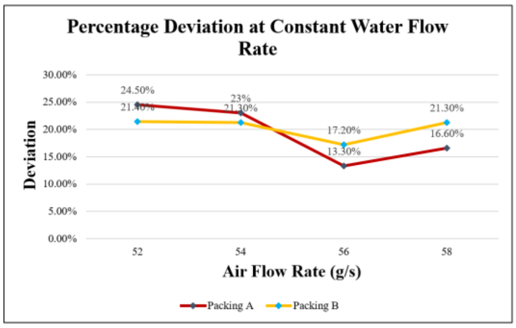


Figure 10: Percentage deviation of efficiency at constant water flow rate

## V. CONCLUSION

Experimental and computational analysis of a forced draft cooling tower has been done in this work to investigate the influence of number of packing ribs, flow rates of air and water, packing surface area, and contact area on the efficiency of the cooling tower. Two types of packings with 7 and 10 ribs were utilized. Moreover, CFD analysis was also done to get simulation results at the same set of conditions. The maximum efficiency in the computational analysis was recorded at a 10 g/s water flow rate and 60 g/s air flow rate. The recorded value of efficiency was 87.5%. the maximum efficiency for experimental results was 84.37% which was also recorded at the aforementioned set of parameters. The major conclusions of this research are:

- The cooling efficiency of the cooling tower can be enhanced with an increase in rib numbers of packing. More ribs lead to greater surface area and consequently more contact area where the process of heat exchange takes place between water and air.
- Air flow rate has a direct relationship with the cooling tower's efficiency. By increasing the air flow rate, more air can be made to extract the heat from the hot water coming from the top which in turn enhances the performance.
- Efficiency can be enhanced by reducing the flow rate of water. An increased water flow rate provides less surface area for water and less time to reject the heat.
- Greater density of packing and contact area for air and water can significantly improve the cooling tower efficiency due to the aforementioned reason.
- CFD analysis of cooling towers can hold satisfactory results and can be validated through experimental data with some deviations.

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