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Computational Fluid Dynamics of Air in Forced Draft Counter Flow Wet Cooling Tower: Using Comsol Multi-Physics

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

A cooling tower is a type of heat exchanger that uses air contact and water evaporation to chill water. The Port Harcourt refinery will be used as a case study in this paper's computational fluid dynamics CFD analysis of air flow in mechanical draft wet cooling towers. To achieve this, the CFD analysis of air under low Re-K-e flow conditions was done in Comsol Multi-Physics interface, The tower's schematic was created on AutoCAD. The results of the air's CFD analysis showed that the distribution profiles of velocity, temperature, relative humidity, and pressure inside the cooling tower are consistent with the air's postulated and calculated characteristics. AutoCAD was used to draw the schematic of the tower. The CFD analysis of air revealed that the velocity, temperature, relative humidity and pressure distribution profiles within the cooling tower are in accord with postulated and calculated characteristic of air within the Cooling Tower.

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Keywords: CFD analysis; counter flow; forced draft; wet cooling towers; comsol multi-physics; PHRC.

NOTATIONS

Cp : *Specific heat capacity at constant pressure (KJ/kgK)*
Cv : *Saturation vapour concentrstion*
G_k : *Generation of turbulent kinetic energy due to mean velocity gradients*
G_b : *Generation of turbulent kinetic energy due to buoyancy k Turbulent kinetic energy/($m^2 s^{-2}$)*
u : *fluid velocity,*
p : *fluid pressure,*
ρ : *fluid density, and*
F : *external forces applied to the fluid*
K : *Kinetic Energy*
P : *pressure*

GREEK SYMBOLS

Ρ : Density of air at inlet to the filter housing/(kgm–3)
γ : Uniform index
μ : Dynamic viscosity/(Pas)
σε : Turbulent Prandtl number
ε : Turbulent energy dissipation rate/($m^2 s^{-3}$)
μ_T : Turbulent viscosity
k : Turbulent kinetic energy
ϵ : turbulent dissipation

1. INTRODUCTION

Cooling towers also called heat rejection systems. They are used in large-scale HVAC systems to dissipate heat from the condenser water loop. They provide a means for transferring heat from the cooling water to the atmosphere through evaporation [16,33,35]. They are huge and important parts of modern power plants with a water flow rate of 20–30 thousands tons per hour or more [29]. They are heat rejection device which extracts waste heat to the atmosphere through cooling of a water stream to a lower temperature [30]. They are mechanical devices that reject heat this is made possible through the cooling tower setup's water evaporation in a stream of moving air [1-3]. “They cool the hot water flow based on the evaporative cooling phenomenon that takes place when air and hot water interacts. A fraction of water evaporates within the airstream, the required heat of vaporization at atmospheric pressure is obtained from the remaining water flow, cooling it down” [2,33]. The combination of the rising airstream and the falling water causes the exit air stream's temperature and humidity to rise. The cooled water is collected at the basin as the air is released to the surroundings via the evaporation of water in a moving air stream in the cooling Tower set-up. This interaction between the falling water and rising air streams leads to the increase in temperature and humidity of the exit air stream. While the air is discharge to the surrounding, the cooled water is collected at the basin. Wilbert and Jerold, [4] posited that “in most cooling towers serving refrigeration and air conditioning systems, one or more propeller or centrifugal fans are used to move air vertically up the Tower or horizontally via the tower”. “A large and significant surface area of water is provided by spraying the water through the sprinklers and down the tower from one baffle to another. Cooling towers were classified (Fig. 1) based on the following characteristics [16,22,33]; (1) classification based on build (2) classification based on heat transfer method (3) classification based on type of Fill (4) classification based on air draft (5) classification based on air flow pattern.

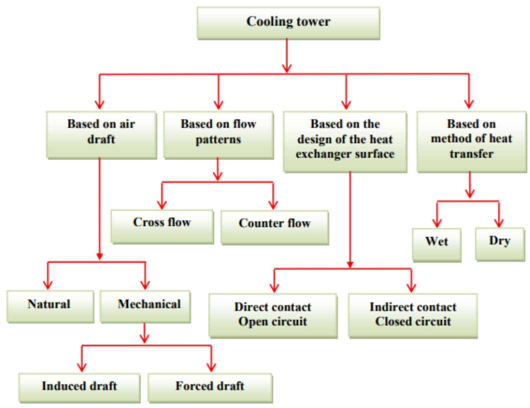


Fig. 1. Classifications of cooling tower [16,22,33]

CFD (computational fluid dynamics) models were created to simulate the functioning of cooling towers based on the mass/energy conservation laws and mass/heat transfer equations” [5,6]. However, Smrekar, et al. [7] held that “the differences between the modelling world and the actual operations keep the simulation models from being utilized in the real-time operation”. The precise goal is to simulate the airflow through a forced draft counterflow wet cooling tower using computational fluid dynamics. Comsol Multi-physics 5.4 is specifically applied in the computational fluid dynamics (CFD) of air as it flows through the Tower. COMSOL is used to simulate real-world designs, devices, and processes with multiphysics software from COMSOL; it can be used as a general-purpose simulation software based on advanced numerical methods; it is fully coupled with multiphysics and single-physics modeling capabilities; it completes modeling workflow, from geometry to results evaluation and, it is a user-friendly tools for building and deploying simulation apps [31]. To carry out a successful CFD analysis a good and simple diagram is priceless.

To predict and/or evaluate the cooling tower performance, many numerical and analytical models have been developed on the basis of heat and mass transfer theory with suitable assumptions [23]. ASHRAE [17] Discussed, in details, cooling tower types, components, operation, maintenance, and water treatment.

The thermal performance of a cooling tower and its cooling water system is critical for industrial plants, and small deviations from the design conditions may cause severe instability in the operation and economics of the process [19]. To address some of these issues, [18] carried out an investigative study of one of the tools – Fast Analysis Cooling Tower Simulator computer code - used to evaluate the performance of cooling towers, developed and validated by the Electric Power Research Institute. The investigative study includes technical software performance validation and verification; the authors also documents results of the computer code’s validation. Interestingly, they proposed a novel detailed standard operating procedures on how to evaluate proposed modifications to improve the performance of select cooling towers.

In their novel investigative study, [19] developed data-driven model-based assessment strategy to assess the performance of a cooling tower, having a non linear system. The methodology adopted was: the operations of cooling tower are first characterized using a data-driven method, multiple models, which presents a set of local models in the format of linear equations. Satisfactory fuzzy c-mean clustering algorithm is used to classify operating data into several groups to build local models. The developed models are then applied to predict the performance of the system based on design input parameters provided by the manufacturer. The tower characteristics are also investigated using the proposed models via the effects of the water/air flow ratio. Results from the predictive study, tend to agree well with the calculated tower characteristics using actual measured operating data from an industrial plant. By comparison with the design characteristic curve provided by the manufacturer, the effectiveness of cooling tower can be obtained in the end. The cooling tower used for the study is shown in figure below.

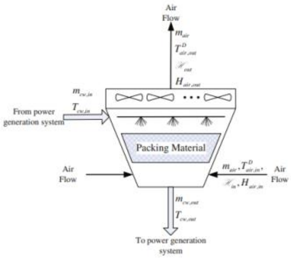


Fig. 2. schematic of the cooling tower by [19]

The cause of this non linearity associated with cooling towers studied by [19], was identified as well as addressed by [20], while [21] attributes the source of this complexities in cooling tower modeling and optimization to be: (1) the original design conditions of the cooling tower (2) the type of tower (evaporative, draft driven) (3) due to under or over sizing, controls that are not properly functioning (4) flawed strategies for operation, and (4) basic lack of maintenance that can create fouling of the exchangers. in their work, [20] identified complexities in the design and optimization of cooling towers to be:(1) External disturbances such as variation in the thermal demand of the process or oscillations in atmospheric conditions. (2) Poor coordination between the utility and process sectors. (3) The complexity of the operation increases because of the strong interaction among the process variables. To address or linearise these challenges, and to subsequently, solve them, [20] developed an integrated model for the minimization of the operating costs of a cooling water system. The system is composed of a cooling tower as well as a network of heat exchangers. After the model is verified, several cases are studied with the objective of determining the optimal operation. It is observed that the most important operational resources to mitigate disturbances in the thermal demand of the process are, in this order: the increase in recycle water flow rate, the increase in air flow rate and finally the forced removal of a portion of the water flow rate that enters the cooling tower with the corresponding make-up flow rate.

Fig. 3 shows the cooling system water made up of thermal and hydraulic models for the cooling tower, pipelines and heat exchangers. The authors [20] set out to develop and validate an optimization approach for the operation of a cooling water system that incorporates economical aspects into the operation of the cooling water system. The thermal model used for this study comprises of an enthalpy balance model is given by [20].

$$W_j(T_{hi,j} - T_{h0,j})C_{pj} = w_j c_{pj}(T_{i,j} - T_{w0}) \;\; j = 1, \dots, n$$

While, the load model of the heat exchanger is given as [20].

$$w_j c_{pj}(T_{i,j} - T_{w0}) = U_j A_j F_{rj} \Delta T_{lm,j} \quad j = 1, .., n$$

And, the hydraulic model, represented by mass balances for water at the nodes at the intake side of the heat exchangers, are given as

$$w = \sum_{j=1}^{n} w_j \tag{1}$$

$$w_{2/1} = w_1 \tag{2}$$

$$w_{j-1/j-2} = w_{j/j-1} - w_{j-1} \qquad j = 3, \dots n \tag{3}$$

$$w_{n/n-1} = w - w_o \tag{4}$$

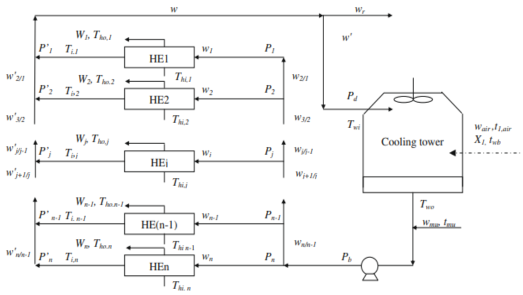


Fig. 3. Cooling water system for [20]

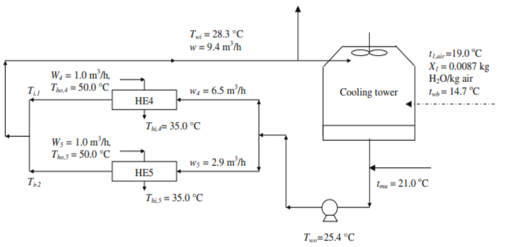


Fig. 4. Process variables for the base case of [20]

The optimization model – minimization of the operating cost - developed by [20], which minimizes the operating cost among the process variables, has as objective function of the model:

$$C_T = C_e + C_{cw} \tag{5}$$

The operating cost used for the optimization, is compoased of electricity cost C_e and cooling water cost C_{cw}. The electricity cost is in turn composed of pumping cost C_{pump} used to circulate the cooling water and the fan operation cost C_{fan}

$$C_T = C_{pump} + C_{fan} + C_{cw} \tag{6}$$

Donald et al. [21] developed a methodology to measure and estimate the efficiency relationship between the cooling tower and chiller. The work also identified the appropriate design conditions for the tower, its temporal performance, as well as tips from major tower manufacturers on design, performance and maintenance.

Hayder et al. [22] would apply the tools of first and second law of thermodynamics (energy and exergy analyses) to design, manufacture and testing of prototype of a modified counter flow forced draft for cooling capacity of 9 kW; the study involves experimental and computational analysis to evaluate the thermal performance of the modified closed wet cooling tower. The energy analysis carried out on the thermal performance of the tower are: cooling range, tower approach, cooling capacity, thermal efficiency, heat and mass transfer coefficients and evaporation losses; while the thermal performance parameters in view of exergy analysis were: exergy destruction, exergy efficiency, exergy change of air and exergy change of water. The theoretical study included simulation of six models by an Adaptive NeuroFuzzy Inference System (ANFIS) to predicting various performance parameters of the tower including the cooling range, tower approach, thermal efficiency, cooling capacity, evaporation losses and exergy destruction. MATLAB program version 7.12.0(R2011a) was used as a tool of simulation for ANFIS. Fig. 5 shows the schematic diagram for experimental apparatus used in the study.

Heidarinejada et al. [23] carried out performance analyses of counter-flow closed wet cooling towers based on a simplified calculation. simplified calculation method for conveniently and accurately analyzing the thermal performance of the two types of counter-flow CWCTs, viz. the parallel counter-flow CWCT

(PCFCWCT) and the cross counter-flow CWCT (CCFCWCT). A simplified cooling capacity model that just includes two characteristic parameters is developed. The Levenberg–Marquardt method is employed to determine the model parameters by curve fitting of experimental data. Based on the proposed model, the predicted outlet temperatures of the process water are compared with the measurements of a PCFCWCT and a CCFCWCT, respectively, reported in the literature. The results indicate that the predicted values agree well with the experimental data in previous studies. The maximum absolute errors in predicting the process water outlet temperatures are 0.20 and 0.24°C for the PCFCWCT and CCFCWCT, respectively. These results indicate that the simplified method is reliable for performance prediction of counter-flow CWCTs. Although the flow patterns of the two towers are different, the variation trends of thermal performance are similar to each other under various operating conditions. The inlet air wet-bulb temperature, inlet cooling water temperature, air flow rate, and cooling water flow rate are crucial for determining the cooling capacity of a counter-flow CWCT, while the cooling tower effectiveness is mainly determined by the flow rates of air and cooling water. Results from the study show, that compared with the CCFCWCT, the PCFCWCT is much more applicable in a large-scale cooling water system, and the superiority would be amplified when the scale of water distribution system increases. Without multiple iterative calculations and extensive experimental data, the simplified method could be used to effectively analyze the thermal performance of counter-flow CWCTs in operation. It is useful for optimization operation of counter-flow CWCTs such that to improve the energy efficiency of the overall cooling water system.

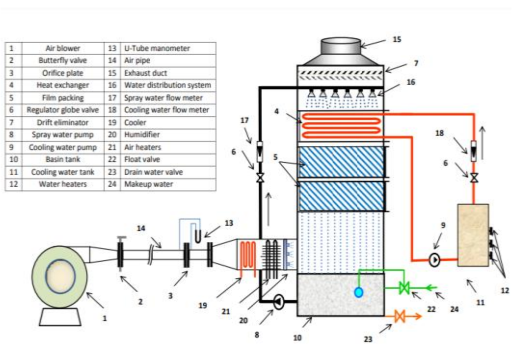


Fig. 5. Schematic diagram for experimental apparatus [22]

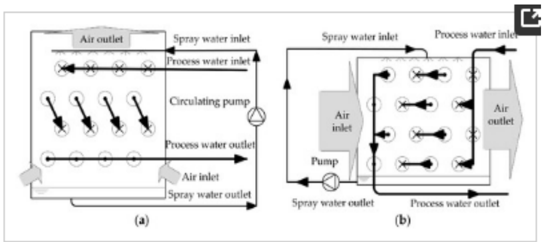


Fig. 6. Schematic diagrams of the two typical counter-flow CWCTs with different constructions: (a) parallel counter-flow (PCFCWCT) and (b) cross counter-flow (CCFCWCT) [23]

Him et a. [24] developed a visible plume abatement; developed a sophisticated mathematical model – a web-based calculator - using the Poppe Approach; also, a real size mechanical cooling tower in China was constructed to carry out a validation test and showed to be very accurate and more accurate than the industrial approach, the Merkel Approach. Based on this validated Poppe Approach, an artificial environmental chamber was designed and constructed in China, and tests were conducted to identify the visible plume formation. CFD simulations were conducted to compare with the experimental results to validate the results of the CFD simulation. To reduced the hour of visible plume occurrence and also to reduce the severity of visible plume, the water shedding approach. CFD simulation was carried out in an urban city environment. It was found that CFD simulation results showed that there was a maximum reduction in temperature of 0.33 ^{o}C and maximum moisture content of 0.0003 kgDA/kgM. So that results from [25] was verified and validated since the Poppe Approach has better results than the Merkel Approach: (1) considered the effect of lewis factor (2) water evaporation [26] the determination of the outlet state corresponds to a differential equation and (4) since the Poppe approach was developed to account for the weakness of the Merkel approach, the discharged air is not assumed to be at saturation with water vapor. Liu et al. [26] proposed a comprehensive approach for RCWS accurate synthesis problems; and used the Poppe Approach to determine the optimum cooler configurations, while simultaneously evaluating the water and air parameters. Then different types of matching, comparison of different tower inlet limit temperatures, and makeup temperatures are proposed to explain the discrepancy of tower calculation methods and stage numbers. The validation and discussion show that the TAC calculations for the four cases are reduced by about 4% and the outlet air temperature of the Poppe method is about 2°C lower than the Merkel method, with a supersaturated state. Fig. 7 shows the schematic diagrams of the experimental setup for mechanical crossflow cooling tower as used in the study by [24].

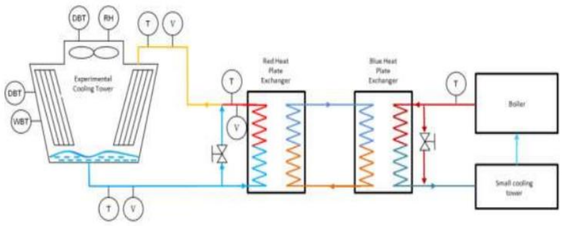


Fig. 7. Schematic diagrams of the experimental setup for mechanical crossflow cooling tower [24]

Figure shows diagram of the integrated configuration of re-circulating cooling water system, (RCWS) synthesis used in the of [26].

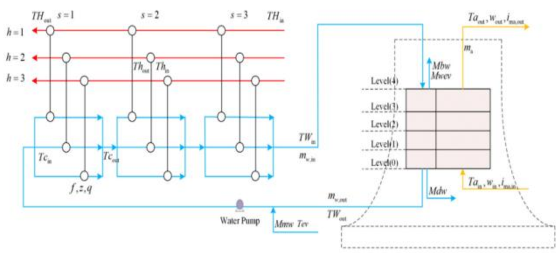


Fig. 8. Integrated configuration of re-circulating cooling water system, (RCWS) synthesis [26]

Kariem et al. [27] investigated experimentally and theoretically heat and mass transfer characteristics of the cooling tower. The investigation carried out at a mechanical forced direct cooling tower. A column-packing unit is made of a new type of packing named honeycomb (plastic). Air and water are used as fluids and the runs are done at the air and water mass flow rates ranging between 0.05 and 0.15 kg/s, and between 0.1 and 0.25 kg/s, respectively. The inlet water temperatures range between 35 and 50°C. A mathematical model based on the equations of mass transfer and energy is used and solved to determine the characteristics of cooling tower, pressure drop, temperature ratio, and tower effectiveness. There was reasonable agreement from the comparison between the calculated and measured data.

To address the problems of heat and mass transfer in the over-shower zone of a Cooling Tower, the influence of crosswind and ambient factors on the aerodynamics and heat and mass transfer in the over-shower zone, [28,29] investigated the influence of flow rotation in the over-shower zone of a natural draft wet cooling tower (NDCT) on heat and mass transfer in this zone is investigated numerically. The 3D geometry of an actual NDCT and three models of the induced rotation velocity fields are utilized for calculations. Two phases (liquid and gaseous) and three components are taken into consideration. The interphase heat exchange, heat transfer to the walls, condensation–evaporation intensity field, and other parameters are investigated as functions of the induced rotation intensity (the inclination of the velocity vector at the periphery). It is shown that the induced flow rotation intensifies the heat and mass transfer in the over-shower zone of an NDCT. Flow rotation leads to specific redistribution of evaporation–condensation areas in an NDCT and stimulates water condensation near its walls. Fig. 9 is a Schematic of the natural draft wet cooling tower used in this study. It has the following parts: 1) over-shower zone; 2) drift eliminators; 3) spray nozzles; 4) fi ll; 5) rain zone.

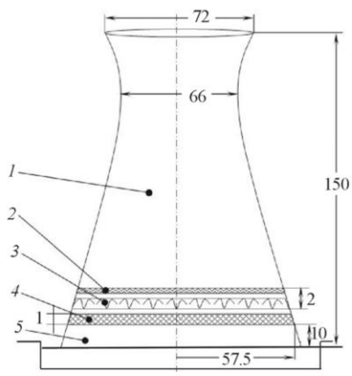


Fig. 9. Schematic of a natural draft wet cooling tower: 1) over-shower zone; 2) drift eliminators; 3) spray nozzles; 4) fi ll; 5) rain zone. Dimensions are all in meters [29]

Satish et al. [30] studied factors affecting the performance like environmental conditions, cooling water quality have been studied on Induced draft cooling tower of 32 Mw thermal power plant. The performance parameters like range, approach, cooling capacity, evaporation loss liquid to gas ratio have been evaluated when the plant is operated at full load and part load under the same water flow rates. The problem this work has is with its approach it used to study the performance of the cooling tower. In this present section, the limitations of the Merkel approach was stated, quoting peered reviewed journals. Fig. [10] shows a cross flow induced draft towers, the water enters at the top and passes over the fill.

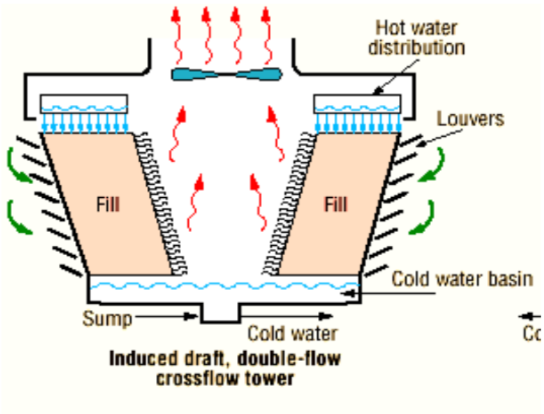


Fig. 10. Cross flow induced draft of cooling towers [30]

Pan et al. [32] presented a data-driven model-based assessment strategy to investigate the performance of a cooling tower. In order to achieve this objective, the operations of the cooling tower were first characterized using a data-driven method, multiple models, which present a set of local models in the format of linear equations. The limitation of this study is the neglect of evaporation rate of water. The authors employed the Merkel approach for their study, which has this limitation; the Poppe Approach should have been used instead. This study ignored a major part of cooling tower modeling and design. Pranav et al. [33] puts it succinctly, thus: Cooling tower operation is based on evaporative cooling as well as exchange of sensible heat. During evaporative cooling in a cooling tower, a small quantity of the water that is being cooled is evaporated in a moving stream of air to cool the rest of the water. The energy balance around the cooling tower, after some rearranging, was modeled as [32].

$$T_{CW,out} = T_{CW,in} - \frac{m_{air}^{D}\left[C_s\left(T_{air,in}^{D} - T_{air,out}^{D}\right) + \lambda_0(\kappa_{in} - \kappa_{out})\right]}{m_{cw}C_{p,w}} \quad (7)$$

Where $T_{CW,out}$ is outlet temperature of the tower, $T_{CW,in}$ is temperature of the water stream at the inlet, Both the dry temperature $T_{air,in}^{D}$; $T_{air,out}^{D}$ and relative humidity κ_{in} , κ_{out} of the air stream entering and leaving the cooling tower

The configuration and schematic of the cooling tower on which they carried out their investigative study is shown in Fig. [11].

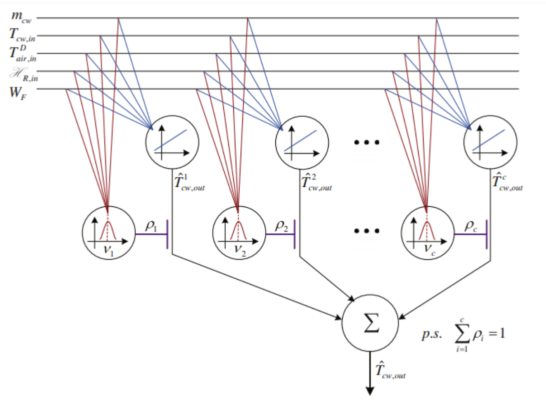


Fig. 11. Multi-model structure for modeling the cooling tower [32]

Pranav et al. [33] developed a new model to predict cooling tower performance to give a more accurate picture of the various energy conservation measures that are available for cooling towers. The weaknesses of the current model are demonstrated and prediction capabilities of the new model analyzed and validated. Figure shows schematic of a typical mechanical draft cooling tower.

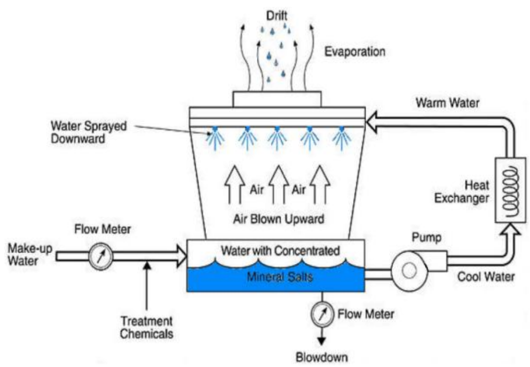


Fig. 12. Schematic of a Typical Mechanical Draft Cooling tower [33]

Qureshi et al. [34] presented thermodynamic analysis of counter flow wet cooling towers and evaporative heat exchangers using both the first and second laws of thermodynamics. A parametric study is carried out to determine the variation of second-law efficiency as well as exergy destruction as a function of various input parameters such as inlet wet bulb temperature. Irreversible losses are determined by applying an exergy balance on each of the systems investigated. In this regard, an engineering equation solver (EES) program, with built-in functions for most thermodynamic and transport properties, is used. The concept of total exergy as the sum of thermomechanical and chemical parts is employed in calculating the flow exergies for air and water vapor mixtures. For the different input variables investigated, efficiencies were, almost always, seen to increase or decrease monotonically. We notice that an increase in the inlet wet bulb temperature invariably increases the second-law efficiency of all the heat exchangers. Also, it is shown that Bejan's definition of second-law efficiency is not limited in evaluating performance. Furthermore, it is understood that the variation in the dead state does not significantly affect the overall efficiency of the system.

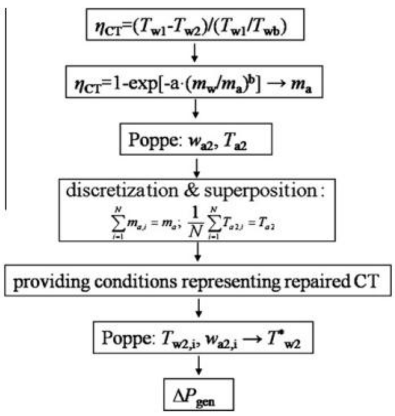


Fig. 13. Flow chart for the evaluation of CT performance [36]

Smrekar et al. [36] Applied Poppe equations for the performance evaluation of cooling tower. . The study establishes the connection between CT performance and power output. It can estimate a change in a CT's efficiency as well as an increase in power output as a function of cooling water temperature and load to the plant. The methodology consists of three subparts, i.e. Cooling Tower Profiler (CTP) method, CT model and a model of the power plant. The work also focuses on application of the methodology in a way that minimizes error of the CT model. One week of data from the power plant were acquired for the analysis. In the CT a small area with irregularities was examined, and increased efficiency and power output are estimated by the methodology. Furthermore, another aspect of solving Poppe equations is examined resulting in reduced computational effort by approximately a half without losing any computational accuracy. The methodology applied is as shown in figure [13]:

Fig. 14 shows the evaporative cooler used in the study of [34,37].

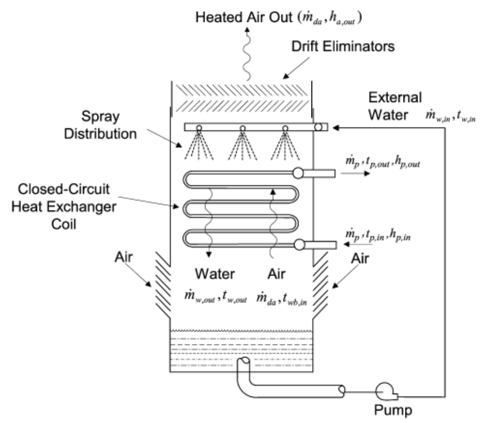


Fig. 14. An evaporative cooler [34]

Smrekar et al. [38] extended its study in [36] to develop a methodology for evaluation of natural draft cooling tower (CT) performance and its application is presented. The study establishes the connection between CT performance and power output. It can estimate a change in a CT's efficiency as well as an increase in power output as a function of cooling water temperature and load to the plant. The methodology consists of three subparts, i.e. Cooling Tower Profiler (CTP) method, CT model and a model of the power plant that are described in the first part of the paper. The second part focuses on application of the methodology in a way that minimizes error of the CT model. One week of data from the power plant were acquired for the analysis. In the CT a small area with irregularities was examined, and increased efficiency and power output are estimated by the methodology. Furthermore, another aspect of solving Poppe equations is examined resulting in reduced computational effort by approximately a half without losing any computational accuracy.

Söylemez et al. [39] carried out a thermo-hydraulic performance optimization analysis, yielding simple algebraic formula for estimating the optimum performance point of counter current mechanical draft wet cooling towers. The effectiveness-NTU method is used in the present study, together with the derivation of psychrometric properties of moist air based on a numerical approximation method, for thermal performance analysis of wet cooling towers of the counter flow type.

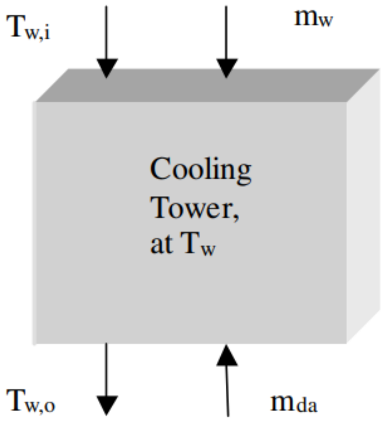


Fig. 15. Schematic figure of counter current wet cooling tower [39]

Störm et al. [40] modeled and investigated flow in and around anatural draft cooling tower [41]. Designed and fabricated an Efficient Cooling Tower for Alaoji Power Plant, Aba, Abia State, Nigeria. Wang et al. [42] developed an analytical model on thermal performance evaluation of counter flow wet cooling tower [43]. Exergy based performance analysis of a shower cooling tower. Yao et al. [44] carried out optimal operation of a large cooling system based on an empirical model.

Chan, [8], in his attempt to identify the formation of visible plume develop a concise mathematical model, Poppe Approach: it was used to carry out a validation test to identify the visible plume formation a cooling Tower in China. The validated CFD simulation in combination with the water shedding approach, aided the conduct of CFD Simulation in an urban city environment. The CFD simulation results showed that there was a maximum reduction in temperature of 0.3 [^{o}C] and maximum moisture content of 0.0003 [-].

In this study, Heinrich (2010) used CFD to simulate the input losses of cooling towers, the effective flow diameter in the absence of a crosswind, and the pressure distribution around a cylinder subjected to a crosswind. Data from an experimental cooling tower configuration was utilized to evaluate the model. In order to enhance cooling tower inlet designs, the impact of various inlet geometries on the inlet loss coefficient and the effective diameter is examined. From result of the investigation it is found that using the k-ε realizable model, tetrahedral elements with an inlet diameter to cell size ratio of 700 [-] and a turbulence intensity of between 2 [%] and 10 [%] delivers the most accurate prediction of the inlet loss and effectiveness.

With the help of computational fluid dynamics, Rameshkumar et al. [9] examined the distribution of temperature and air flow under various human loads inside the passenger compartment in steady-state settings. In the current inquiry, CFD analysis was used to simulate the temperature distribution and air flow in the passenger car cabin. It was found from the comparison's results that the predicted and experimental values are practically identical. It shown that the CFD model's forecast of the temperature and air flow distribution in a passenger car's cabin is accurate.

Vijayaragavan, et al. [10] in this work used here ANSYS workbench for the CFD analysis of cooling tower. The boundary condition were set at; the inlet water temperature 380[^{o}c], inlet air temperature 200[^{o}c], volume of circulating water circulated in cooling tower 30[m^3/hr]. CFD is used for performance and analysis of cooling tower because it helps in ascertaining terms of cooling efficiencies/effectiveness. When the water intake angle is reduced, so does the air inlet angle. As a result, cooling tower efficacy and efficiency rise. For the selected cooling Tower, the angle of 150[^{o}] results in maximum efficiency and efficacy. Also, the air inlet angle increases with the increase in water outlet temperature, cooling efficiency and the reduction in effectiveness of the Cooling Tower.

The goal of Matilda's [11] project was to use COMSOL Multi-physics to model a cooling tower system. As an experiment was being run on the setup, data was gathered. The model was fitted to the data in order to estimate the parameter; the parameter estimation was done using Matlab Live link, and Comsol Multi-Physics was used for the simulation. In order to calculate the heat transport coefficient, Onda's approach is utilized to estimate the value of the parameter, h. The heat transmission coefficient varies between 14.5 and 15.7 [kW/m2°C] because the term h is expected to be 30.6 [kW/m2°C].

Leo et al. [12] carried out "an investigative study on a thermally activated building system based on a cooling tower, which acts as an indirect evaporative cooling system, using a computational fluid dynamics tool for the hot semi-arid climate of New Delhi. Three design parameters, namely spacing, vertical position, and the arrangement of embedded pipes in the ceiling and floor, were analyzed to determine their influence on the cooling performance of the system. The results indicate that reducing the pipe spacing by 0.3 to 0.1 [m] and moving the pipes closer to the inner surface by 0.135 to 0.015 [m] could reduce operating temperatures by 1.6 and 2.7 [℃], respectively. For the same total water flow, a change in piping arrangement from serpentine to parallel showed negligible influence on indoor comfort indices. The best combination of these three parameters can achieve an average operating temperature of 29 [℃], which is comfortable for the hot semi-arid climate of New Delhi, where the adaptive neutral temperature was found to be 29.4 [℃]". Fig. 16a and 16b shows schematics of thermally activated building system (TABS) supported with cooling tower and schematic of thermally activated building system (TABS), respectively.

The studies and or the research of cooling systems would be furthered by Cui et al. [13]. In this study, hybrid air conditioning system was proposed integrating an indirect evaporative system precooling unit. In the proposed system, the exhaust air from the room is used for indirect evaporation cooler (IEC) to precondition ambient intake air. The validation of the numerical model was performed by comparing the simulated results with the experimental data in terms of the output temperature and heat flux along the surface of the heat exchanger. The pre-cooling performance of the IEC is theoretically investigated for climate in representative cities selected from five different climate zones. Psychrometric illustration of air conditioning

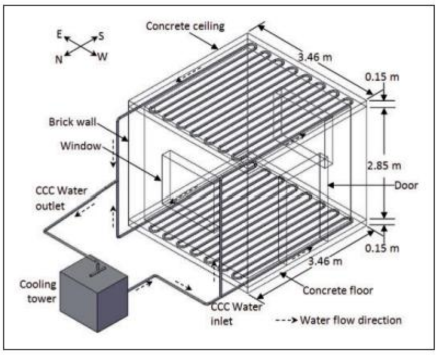


Fig. 16a. Schematic of a TABS supported with a cooling tower

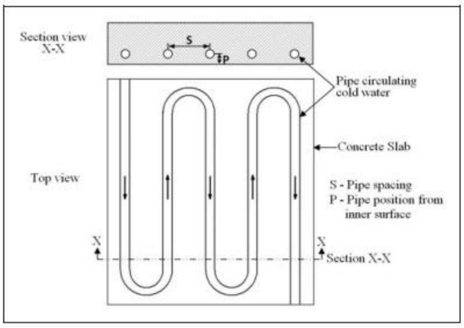


Fig. 16b, Schematic diagram of a TABS [12]

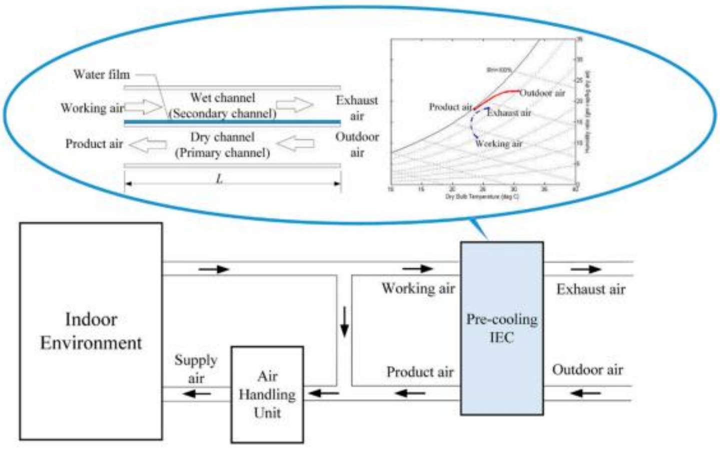


Fig. 17. Schematic of the hybrid system with the integration of a pre-cooling IEC [13]

variation has indicated that ambient air can be pre-cooled and pre-dehumidified via the IEC. Results from simulations show that the possibility of water vapor condensation depends on the humidity ratio of the ambient intake air. The simulation result demonstrates the ability of IEC pre-cooling to meet part of the ambient cooling load intake air resulting in marked energy saving potential. Fig. 17 shows a Schematic of the hybrid system with the integration of a pre-cooling IEC.

Rakhmanov and Zakhidov, [14] carried out simulation of new filling tape for thermal power plant cooling towers with COMSOL Multifísica. A comparison of the results of the laboratory studies with those of full scale was also carried out. A mathematical model of the movement of water and gas as an incompressible fluid is given. The incompressible fluid model includes: the Navies-Stokes equations (the law of conservation of momentum), the continuity equation (the law of conservation of mass of a liquid); law of conservation of energy; the equation for diffusion transfer of a scalar quantity (the law of conservation of mass) and the k – e equation for the turbulence model. The area in which the solution of differential equations was sought was divided into a finite number of subregions (elements) in the amount of 68555 (Fig. 17), in each of which the type of approximation function was chosen arbitrarily. Free triangles are used as finite elements. The program determined their sizes and locations automatically**.**

Salins et al. [2] carried out “design and construction of a counterflow forced draft cooling tower unit using Celdek 7090, Celdek 5090, corrugated and honeycomb as packing materials. Experiments are carried out for the different air and water flow rates at an inlet hot water temperature of 60 °C. The performance parameters of the cooling tower range, evaporation rate, cooling tower efficiency, characteristic cooling coefficient, and heat transfer are determined. The results showed that the type of packing has a significant impact on the performance of the cooling tower. Celdek 7090 packing provided maximum cooling tower efficiency, range, evaporation rate, and characteristic coefficient of cooling equal to 73%, 24 °C, 3 g/s, and 3, respectively. All performance parameters increase with increasing airborne Reynolds number over the tested range. The water plane effect has a positive effect on performance up to 3 LPM, but for larger water flow rates, performance deteriorates. Among the four packaging types studied, Celdek 7090 provided the best performance and is also energy efficient”.

2. MATERIALS AND METHODS

2.1 Description of Study Area

According to the Department of Petroleum Resources report (2014), the Port Harcourt Refining Company, (PHRC), is an indigenous oil and gas company domicile in Nigeria whose core mandate is primarily the refining of crude oil into petroleum products. The company is situated in Eleme Elesa area of Rivers State, South-South Nigeria. The company is a subsidiary of the Nigerian National Petroleum Corporation (NNPC). Nwachukwu, (2010), It is regarded as the biggest oil refining company in Nigeria with the company operates two oil refineries with a combine capacity of capacity of 210,000 barrels per day. The cell is made up of the component listed as follows: a draft fan, baffles, drift eliminators, collecting basin, open air inlets windows, water sprinklers, pumps etc. It is a forced draft wet Cooling Tower.

Fans: it functions to forced significant amount of air across the tower in an effective manner These fans are driven by An electric motor assembly; Drift Eliminators: These help in capturing water droplets entrapped in the air stream at the exit point to the surrounding; Fills/Baffles: They act to convert the water into droplets by breaking its momentum; also, it helps improve efficiency by expanding the surface area of water and in the process improve the interaction time between air and the water; Water Basin: It serves as a reservoir water for that flows down through the tower and fills

2.2 Model Description

2.2.1 Model building in comsol multi-physics

The model was built in a CFD software, Comsol multi-physics which allows the combination of different physics in simulation. The physics used in the present study includes, fluid flow, heat transfer and moisture transport. The airflow is modeled under the Turbulent Flow, Low Re k-ε interface conditions because the Reynolds number is about 1500. With the Low Re k- ε turbulence model, the turbulence variables are solved in the whole domain down to the walls and thus provide accurate input values for the transport equations. Note that because the mass contribution due to the evaporation is small at the water surface, a wall (no slip) condition is used on this boundary for the airflow computation. The Eulerian-Eulerian model enables the building of local mass and momentum equations for each phase as well as the corresponding interfacial contact conditions. Equation conservation of energy, momentum, and mass corresponds to the main and overriding equations; thus, the Low Re k-ε Equations equations for the momentum balance of the water phase and air phase it is represented by the following expression,

$$\rho(u.\nabla)u = \nabla.[-pl + K] + F \quad (8)$$

$$\rho\nabla.(\nabla) = 0 \quad (9)$$

$$K = ((\mu + \mu_T)(\nabla u + (\nabla u)^T) \quad (10)$$

$$\rho(u.\nabla)k = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla_k\right] + P_k - \rho\epsilon \quad (11)$$

$$\rho(u.\nabla)\epsilon = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla_\epsilon\right] + C_{\epsilon1}\frac{\epsilon}{k}P_k - C_{\epsilon2}\rho\frac{\epsilon^2}{k}f_\epsilon(\rho\mu k\epsilon J_w), \quad \epsilon = ep \quad (12)$$

$$\nabla G.\nabla G + \sigma_w G(\nabla.\nabla G) = (1 + \sigma_w)G^4, \; l = \frac{1}{G} - \frac{l_{ref}}{2} \quad (13)$$

$$\mu_T = \rho C_\mu \frac{k^2}{\epsilon} f\,\mu(\rho\mu k\epsilon l_w \quad (14)$$

$$P_K = \mu_T[\nabla u{:}(\nabla u + (\nabla u)^T] \quad (15)$$

Also, the Heat Transfer in Moist Air and the Moisture Transport in Air equations are represented by equation (16 to 17 9 to 10) and equations (18 to 20 11 to 13) respectively.

$$\rho c_p u.\nabla_T + \nabla.\mathrm{q} = \mathrm{Q} \quad (16)$$

$$q = -\mathrm{k}\nabla_T \quad (17)$$

$$M_v u.\nabla_{C_v} + \nabla.\mathrm{g} \quad (18)$$

$$\boldsymbol{g} = M_v D.\nabla_{C_v} \quad (19)$$

$$c_v = \phi c_{sat} \quad (20)$$

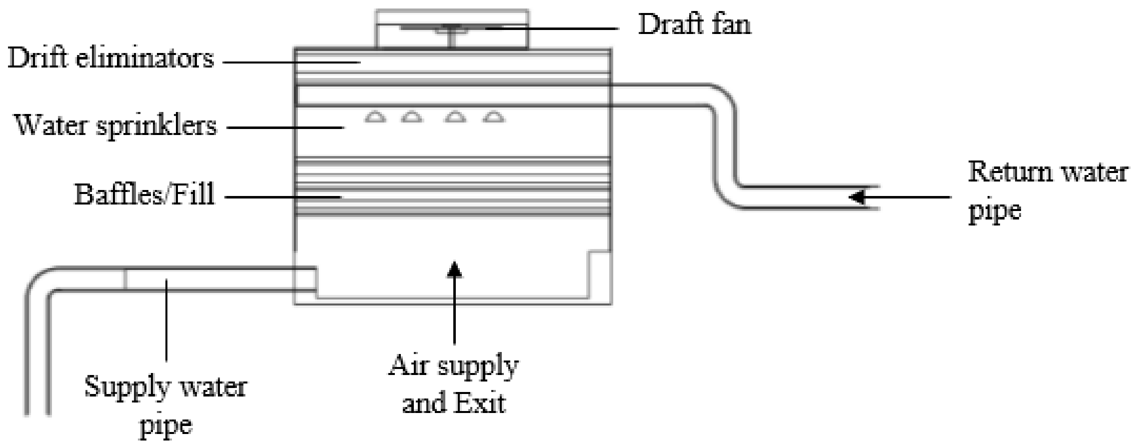


Fig. 18. Cell unit of PHRC cooling tower

3. CFD SIMULATION PROCEDURE

3.1 Modeled Cooling Tower Description

In Comsol multi-physics 5.4, the geometrical characteristics of the modeled cooling tower in Fig. 17 is described as consisting of a space dimension of 3 with 29 domains, 294 boundaries, 624 edges and 372 vertices).

3.1.1 Boundary condition

The initial values applied at the beginning of the simulation are stated in Table 1.

3.2 Material Selection

The following Tables – 1, 2, 3 and 4 - show the material selection of the different component of the cooling Tower during simulation in Comsol multi-physics. The properties of the different materials used in the simulation as shown in tables in Table 2, Table 3 and Table 4 were in-built.

Fig. 18 highlights the materials used for the different segments and domain of the cooling tower. The highlighted domain of Fig. 20(a) depicts the concrete component of the cooling tower, Fig. 20(b) highlighted parts represent the baffles and drift eliminator whose material constituent is Polyvinyl chloride, also the highlighted section of Fig. 20(c) which are fan blade and water supply pipe are both made up of steel.

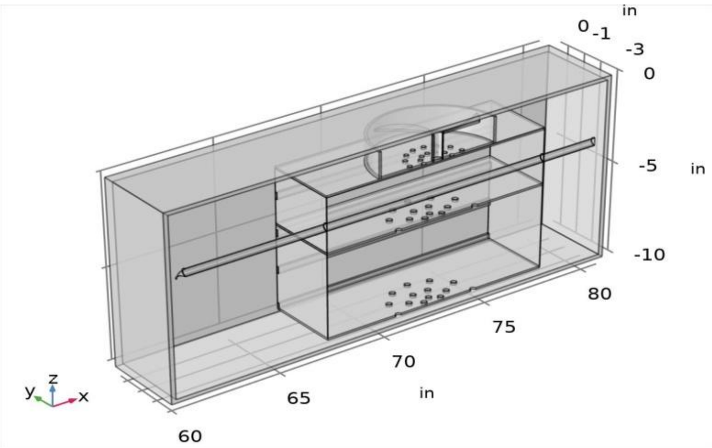


Fig. 19. Modeled Geometry of the cooling tower

Table 1. Initial values for Key simulation parameters

Parameters	Velocity [m/s]	Pressure [Pa]	Temperature [K]	Relative humidity [-]	Evapouration rate
Values	0	0.03	293.15	0.0189	1.725

Table 2. Properties of concrete selected for the cooling tower geometry

Property	Value
Coefficient of thermal expansion	{{10e-6[1/K], 0, 0}, {0, 10e-6[1/K], 0}, {0, 0, 10e-6[1/K]}}
Density	2300[kg/m^3]
Thermal conductivity	{{1.8[W/(m*K)], 0, 0}, {0, 1.8[W/(m*K)], 0}, {0, 0, 1.8[W/(m*K)]}}
Heat capacity at constant pressure	880[J/(kg*K)]
Young's modulus	25e9[Pa]
Poisson's ratio	0.20

Table 3. Properties of PVC selected for the cooling tower geometry

Description	Value
Coefficient of thermal expansion	{{100e-6[1/K], 0, 0}, {0, 100e-6[1/K], 0}, {0, 0, 100e-6[1/K]}}
Relative permittivity	{{2.9, 0, 0}, {0, 2.9, 0}, {0, 0, 2.9}}
Density	1760[kg/m^3]
Thermal conductivity	{{0.1[W/(m*K)], 0, 0}, {0, 0.1[W/(m*K)], 0}, {0, 0, 0.1[W/(m*K)]}}
Young's modulus	2.9e9[Pa]

Table 4. Properties of low carbon steel selected for the cooling tower geometry

Description	Value
Electrical conductivity	{{8.41[MS/m], 0, 0}, {0, 8.41[MS/m], 0}, {0, 0, 8.41[MS/m]}}
Relative permittivity	{{1[1], 0, 0}, {0, 1[1], 0}, {0, 0, 1[1]}}

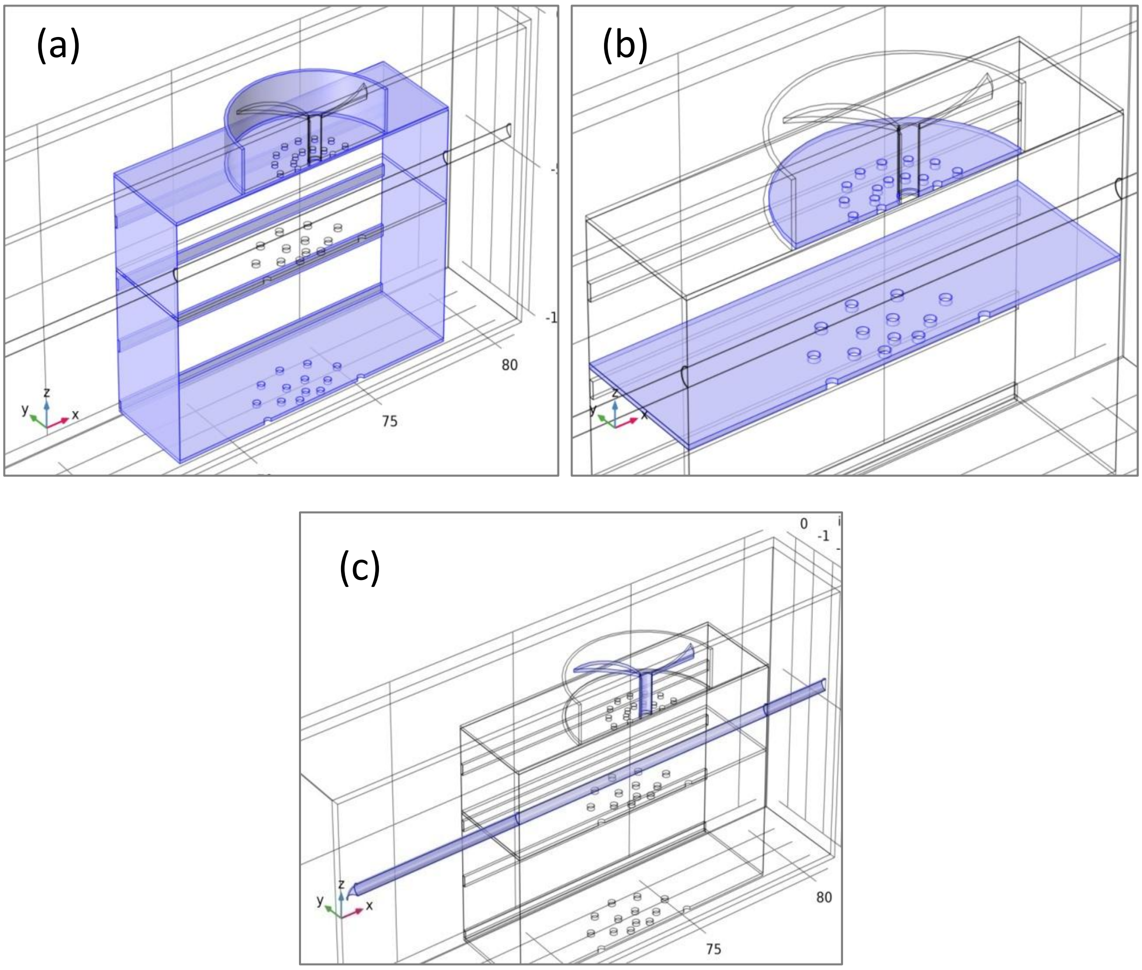


Fig. 20. Categorization and selection of Materials
(a) concrete section of the cooling tower geometry (b) Polyvinyl chloride. (Domains 3, 5, 8, 15–19 were selected as concrete following the design characteristics while domains 13, 20 for PVC)). (c) Low Carbon Steel 1002, (Boundaries 11, 13–14, 16, 72, 75, 112–113, 160–161, 163, 167, 194, 207–208, 287, 289)

3.2.1 Plots of water and air properties

The comsol plots of Fig. 21 clearly shows the interaction among the material properties of air. Sound speed and specific capacity of air increase with temperature while the coefficient of expansion decreases with air temperature.

The comsol plots of Fig. 22 clearly show the interaction among the material properties of water. The density and dynamic viscosity of water increases with the temperature, specific capacity increases with temperature, while thermal conductance produces a concave quadratic curve with temperature.

3.2.2 Domain segmentation and description

The selected edges for water flow in Fig. 23 (c) are **(***20, 28, 33, 113, 117, 155, 179–180, 192, 213–214, 219, 222–223, 232, 259, 264, 267, 269, 271, 275, 320–321, 327, 337, 346, 417–418, 425–426, 440, 442, 472, 477, 479, 482, 485, 490, 508–509, 516, 605, 609, 615)* while that of air flow boundaries in Fig. 23(d) is within these boundaries (*1, 3–8, 293–294).*

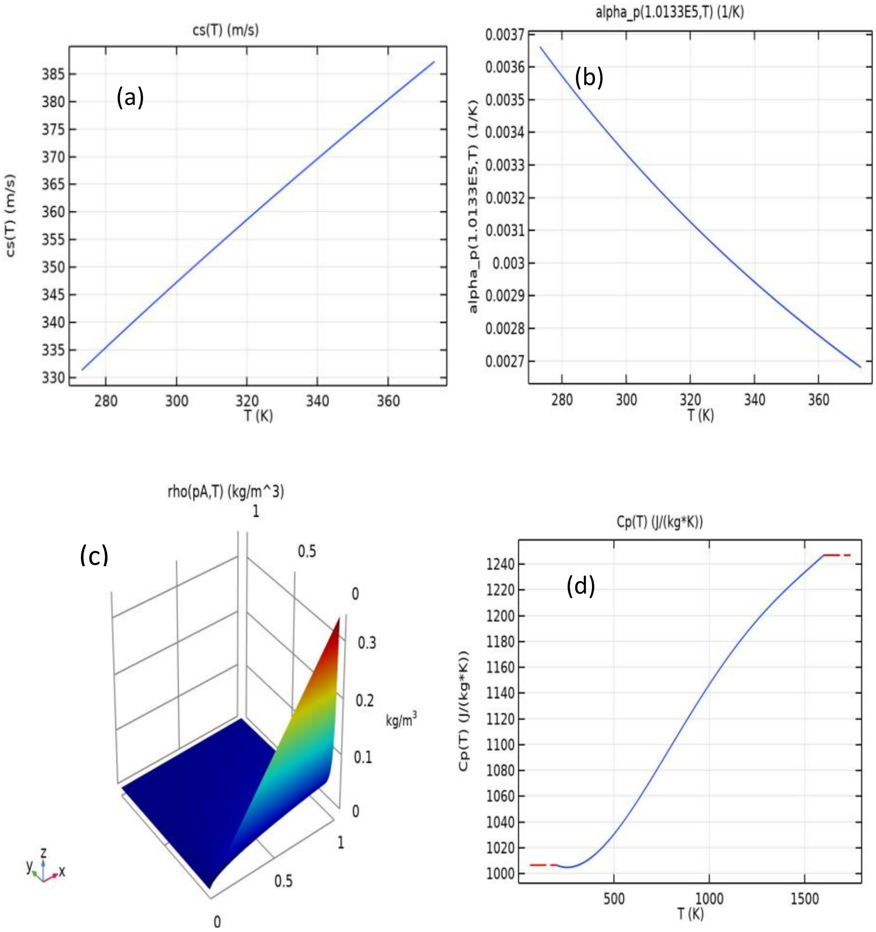
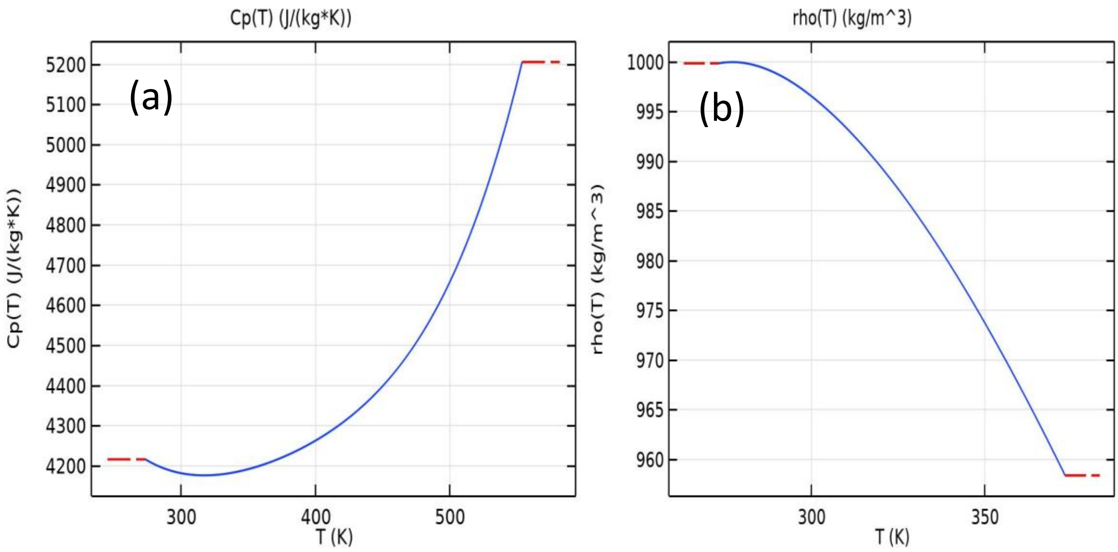


Fig. 21. Air properties plots against temperature
(a)Speed of Sound(cs) Vs Temperature; (b) Coefficient of Expansion vs Temperature; (c) Density Vs Temperature; (d) Specific Heat Capacity Vs Temperature



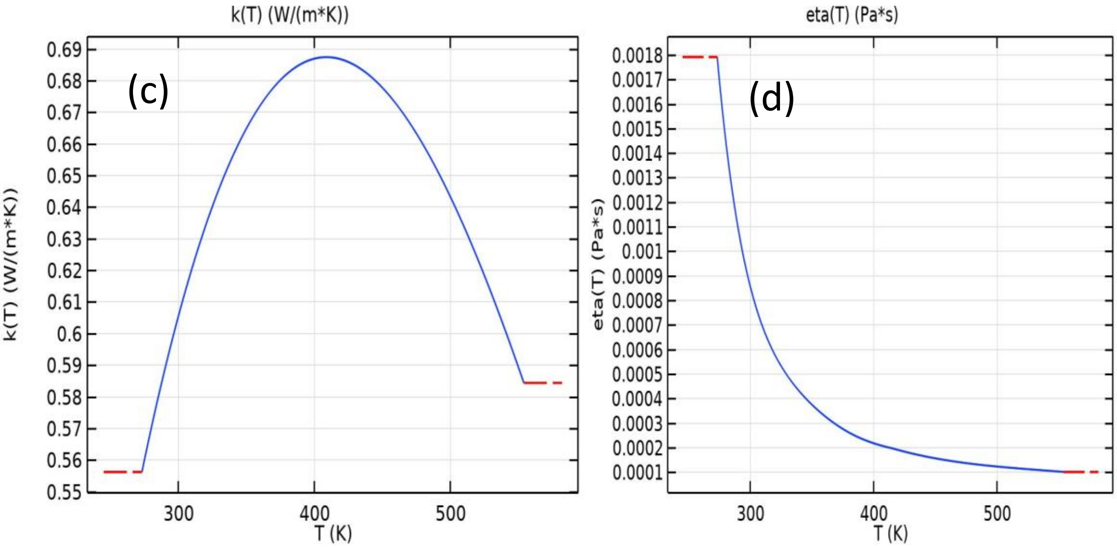


Fig. 22. Water properties plots against temperature
(a) Specific Heat Capacity Vs Temperature; (b) Coefficient of Expansion vs Temperature; (c) Thermal conductivity Vs Temperature; (d) Dynamic viscosity Vs Temperature

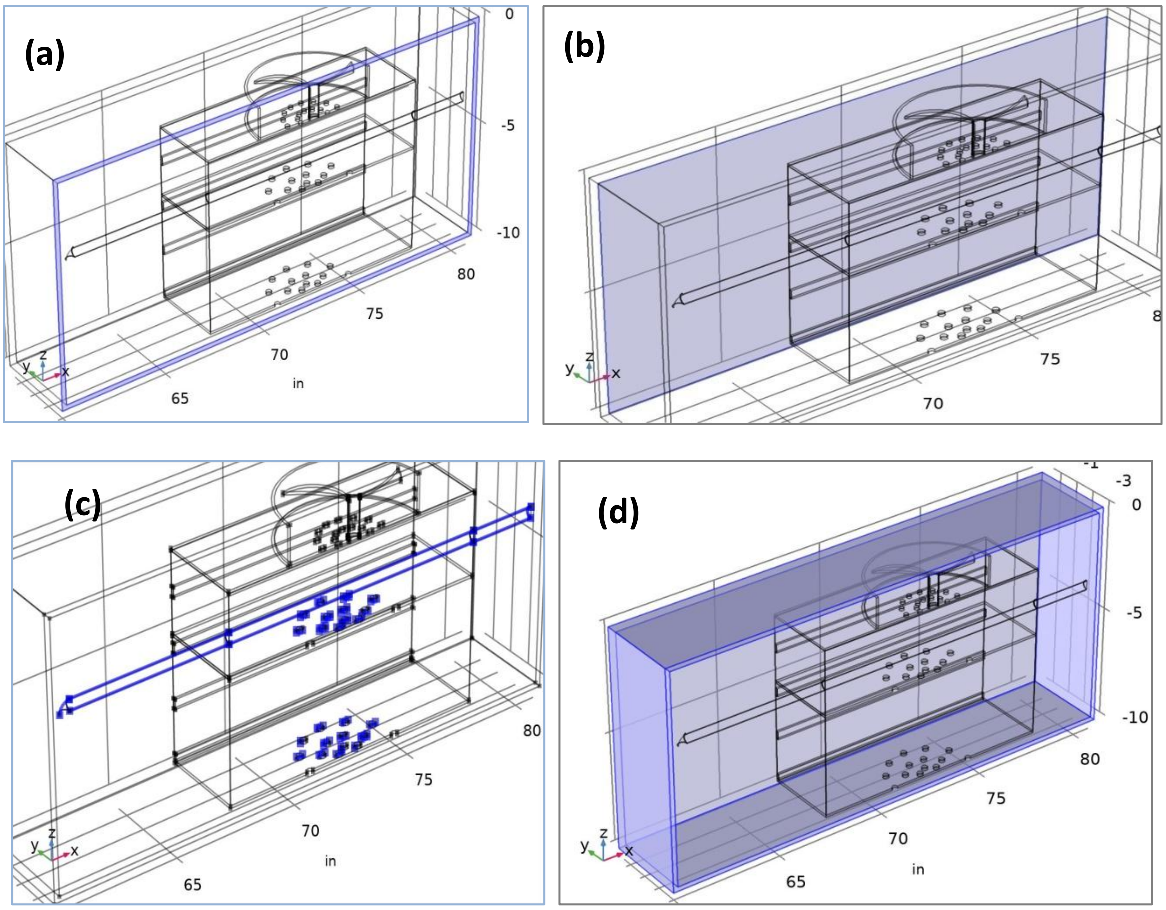


Fig. 23. Boundary/Domain Views
(a) The wall (b) Air inlet of the cooling tower (selection, 9 boundaries) (c) Water Flow Path(in Blue) (d) Air Domain Symmetry (Boundaries 1, 3–8, 293–294)

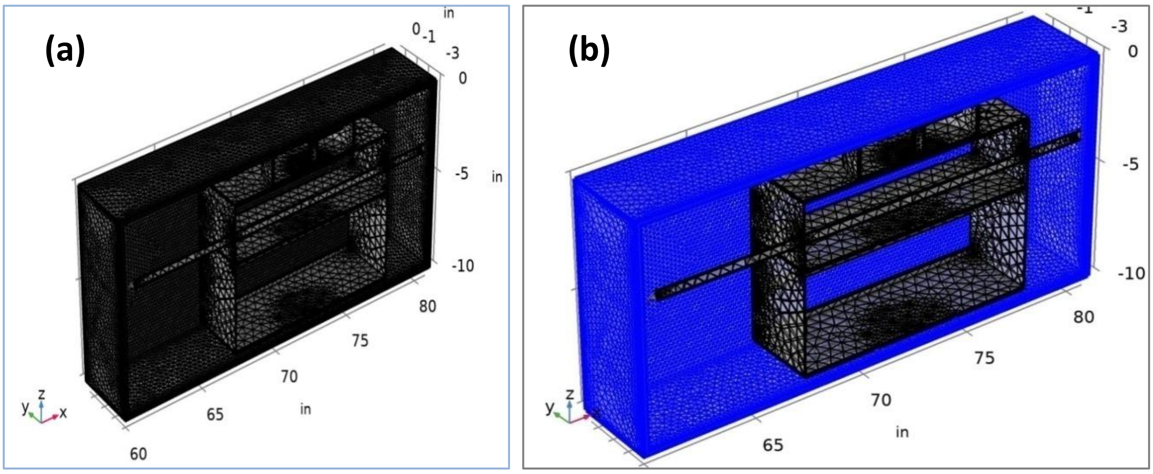


Fig. 24. Generated mesh for the cooling tower
(a) the cooling tower mesh (b) control volume mesh

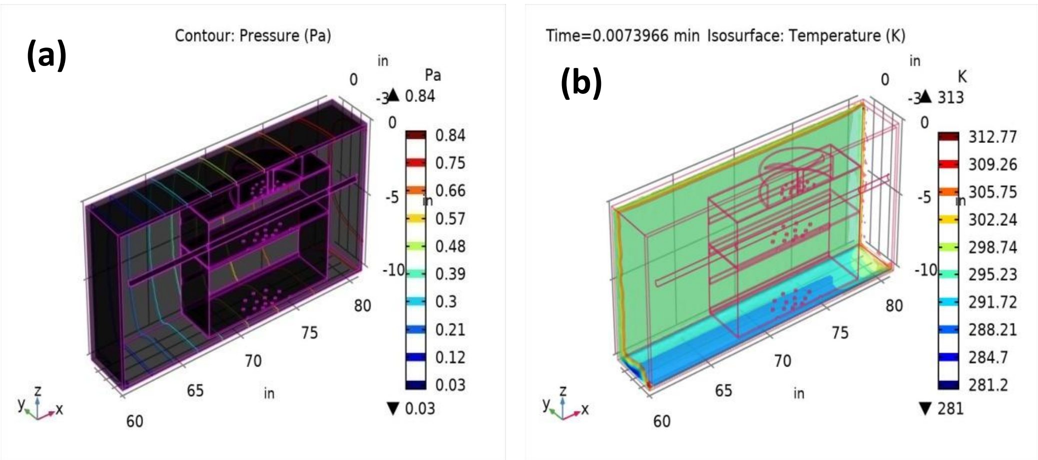
3.2.3 Generated mesh

Average element quality (0.1112), tetrahedron (102487), pyramid (6160), prism (330212), triangle (54152), edge element (4558) and vertex element (366) for the control volume mesh. While the cooling tower mesh has maximum element size (0.618), minimum element size (0.185) with curvature factor of 0.7, resolution of narrow regions (0.6), maximum element growth rate (1.2) and the predefined size is coarse. The mesh was calibrated for fluid dynamics.

4. RESULTS AND DISCUSSION

This section presents the output of the simulation results of the air fluid analysis (CFD) as modeled in Comsol Multi-Physics 5.4.

One of the biggest and most often used heat and mass transfer systems, the cooling tower, was examined using the CFD approach in this dissertation. An explicit model of cooling towers was employ to analyse air as it flows through the Cooling Tower (see Fig. 19). The process of altering the air and water temperatures as well as the driving potential for convection and evaporation heat transfer as it changes the tower's height clearly demonstrates the cooling towers' thermal performance (see Fig. 23). (a to d). Inside the cooling tower, the evaporation heat transfer rate is substantially higher than the convective heat transfer rate [15]. The total heat transfer rate in the cooling tower is greatly influenced by each kind of heat transfer rate.



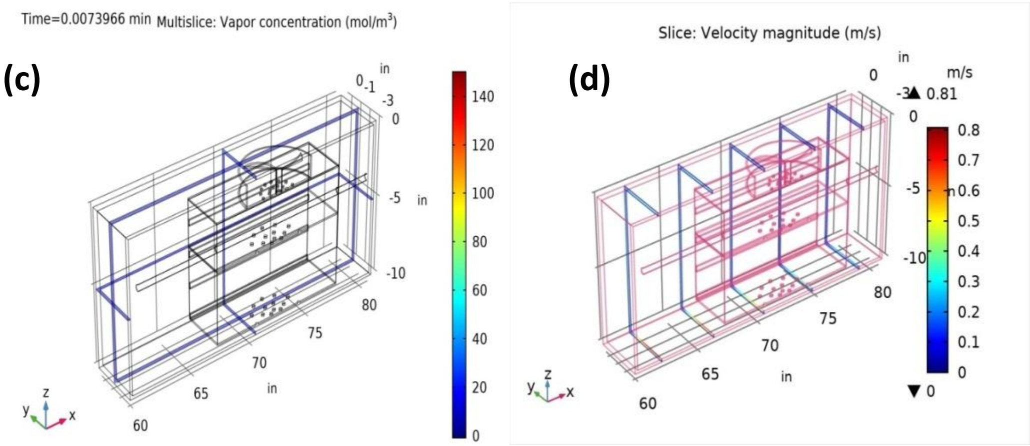


Fig. 25. Pressure, Temperature, Relative Humidity and velocity Distribution
(a) Pressure Profile; (b) temperature Profile; (c) Relative humidity Profile; (d) Velocity Profile

Convection, conduction, and evaporation all contribute to the gradual cooling of the water over time. As air flows away from the water's surface, its relative humidity value decreases from 100 to 20 [percent] accordingly. Air can absorb more water because of the high temperature. Evaporation in this model is responsible for a drop in temperature of roughly 10 [K] at the conclusion of the simulation.

The discussion will be further broken down into the following;

4.1 Velocity Distribution

Fig. 23 (d), it is clearly seen from the modelling values that the velociy of air increases as it moves from the entry point at the base of the Tower towards the exit points where the draft fan is located. The value increase from 0m/s to about 0.8m/s. This value falls within the computed range of values for the refiniries under consideration.

These profiles demonstrate how the air suffers a velocity decrease as it passes through the tower devices due to the no-slip condition over the wall of internal devices, with the maximum velocities occurring at the fan intake.At the packing area is where major loss of momentum happens, due to the close spacing between the different lamellas in zigzag from the packing. Also, the lamellas increase the air pressure drop. The drift eliminator area is short, which causes a velocity loss. From the analysis of the velocity profiles, it was initially determined using the R-e turbulence model.

4.2 Pressure Distribution

The values of air pressure from the CFD analysis as stated in Fig. 23 (a) ranges from 0.033[bar] to 0.84[bar]; the values also falls within the range of the month on month calculated vales of the case study with vales between 0.028[Bar] to 0.05[bar]. As the air passes through the cooling Tower towards the exit, it picks more and more molecules of water and subsequently the pressures of the air molecule increases just as our modelled capture it. In addition, there is a pressure gain as the air goes through the packing and drift eliminator, due to the no slip boundary condition in the internal parts of the cooling tower. This increase even though it fluctuates as it encounters the packing unit, it eventually increases as it approaches the draft fan around the exit.

4.3 Relative Humidity Distribution

Also, From Fig. 23 (c), the model show that the relative humidity of the air increases as the air flows throught the Tower, it picks up more water molecule and as a result the number the volume of water vapour in the increases considerably.The model results agrees with the calculated and measured results from the study. The relative humidity increases range as dipicted by the Tower is between 0 to 100[%]. Further more, the transport mechanism of energy in this area is given by forced convection due to the velocity differences in the boundary layer of the phases. As seen from the profile the temperature increases reasonably as the air interacts with the water. Both mass transfer and heat transfer takes.

4.4 Temperature Distribution

Tower inlet limit temperature (T_{limit}) determines the outlet temperature of the cooler network and directly affects the mass flow rate through the coolers [26]. Fig. 23 (b) illustrates the rise in air temperature as it ascends the tower, through the packing section, and through the drift eliminator portion. The highest temperatures shown were for the temperature of the air exit, which is 312.77[K].

5. CONCLUSION

i. There is a pressure gain as the air goes through the packing and drift eliminator, due to the no slip boundary condition in the internal parts of the cooling tower. This increase even though it fluctuates as it encounters the packing unit, it eventually increases as it approaches the draft fan around the exit. As the air passes through the cooling Tower towards the exit, it picks more and more molecules of water and subsequently the pressures of the air molecule increases just as our modelled capture it.
ii. The relative humidity of the air increases as the air flows throught the Tower, it picks up more water molecule and as a result the number the volume of water vapour in the increases considerably.The model results agrees with the calculated and measured results from the study.
iii. The transport mechanism of energy in this area is given by forced convection due to the velocity differences in the boundary layer of the phases.
iv. As seen from the profile the temperature increases reasonably as the air interacts with the water.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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