

PARAMETRIC EFFECTS ON THE PERFORMANCE OF AN INDUSTRIAL COOLING TOWER

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ABSTRACT

Sensible and latent heat rejection from heat engines is of high necessity for system efficiency and continuous production. The cooling tower is one of the major heat-exchanging systems used for cooling industrial heat systems by intimately mixing hot water with cooling air. Optimal operating conditions and parameters of the system are highly essential for its effectiveness and efficiency. This study used the Poppe model to evaluate selected thermodynamic relations of a rectangular counter-flow industrial cooling tower of a steel rolling mill using the system's inlet and outlet data as initial conditions. The effect of increasing the water temperature on the air moisture content, Merkel number, and specific enthalpy was studied across the fills of the cooling tower. Air moisture content, Merkel number and specific enthalpy of the system increase with increasing water temperature. However, while other variables reach a stationary point at half the nodal segments, the specific enthalpy increases across the fills in the system. It was concluded that the use of nano particles with high heat removal rate could increase the efficiency of the system. Also, an increase in the quantity of the makeup water of a force draft system is recommended towards increasing the system efficiency.

Keywords: *Cooling Tower, Natural Draft, Parametric Modelling, Poppe Model*

INTRODUCTION

Many manufacturing systems are associated with a heat removal process. The waste heat is removed most often by circulating cooling water across the system [1–3]. An efficient removal of the waste heat from these systems significantly affects the performance and lifecycle of these systems [4]. Cooling towers are mostly used in these systems as heat-extracting systems and have found relevance in petrochemical industries, refrigeration and air conditioning systems, power plants, steel rolling mills and so on [5,6]. A typical cooling tower chamber is divided into fills and each fill receives the cooling fluid carrying sensible heat. The fills increase the surface area available for heat rejection from the thermodynamic system. The direction of movement of air in the cooling tower system is used to characterize it as either counter-flow or cross-flow. In cross-flow cooling towers, ambient air entering the system travels horizontally through the fills as the hot water moves downwards while for the counter flow, ambient air travels in opposite direction to the hot water movement [7,8]. Figure 1 shows a classification of cooling towers based on draft, airflow, construction, shape, and heat transfer. In this study, a rectangular mechanical draft cross flow industrial cooling tower of a typical steel rolling mill was considered.

Several mathematical models have been developed for analysis of the thermal behaviour of wet cooling tower. For example, heat and mass transfer process in wet cooling towers was first practically modelled by Merkel [9]. The Merkel model presents a simplified heat and mass equations of enthalpy difference. The model takes the Lewis factor as unity (1), which neglects the reduction in the mass flow rate of water consequential to evaporation [10]. Similar to Merkel model are the Poppe and ϵ - number of transfer units (ϵ -NTU) models. Kloppers and Kroger [11] investigated the differences between the Merkel, Poppe, and the ϵ -NTU models. Their findings concluded that the less accurate Merkel and ϵ -NTU approach fits best when outlet water temperature constitutes the only significant parameter to the cooling tower designer. However, these two models give lower values than the Poppe model when heat transfer rate is

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of interest. The effect of the Lewis number and heat transfer resistance in the air-water interface was also investigated by Khan and Zubair [12] where a detailed model was developed for a counterflow wet cooling tower. On the contrary, Prasad [13] developed a numerical model for cross-flow wet cooling towers. The model was applied to the packing of a multi-cell cross-flow cooling tower to estimate the variance of fill characteristics from their functional design values.

Also, for cross-flow cooling towers, Hajidavalloo et al. [14] applied the Merkel's model to predict the thermal performance of an existing cross-flow tower at varying wet bulb temperature. The authors compared the numerical results with the experimental results under varying operating conditions.

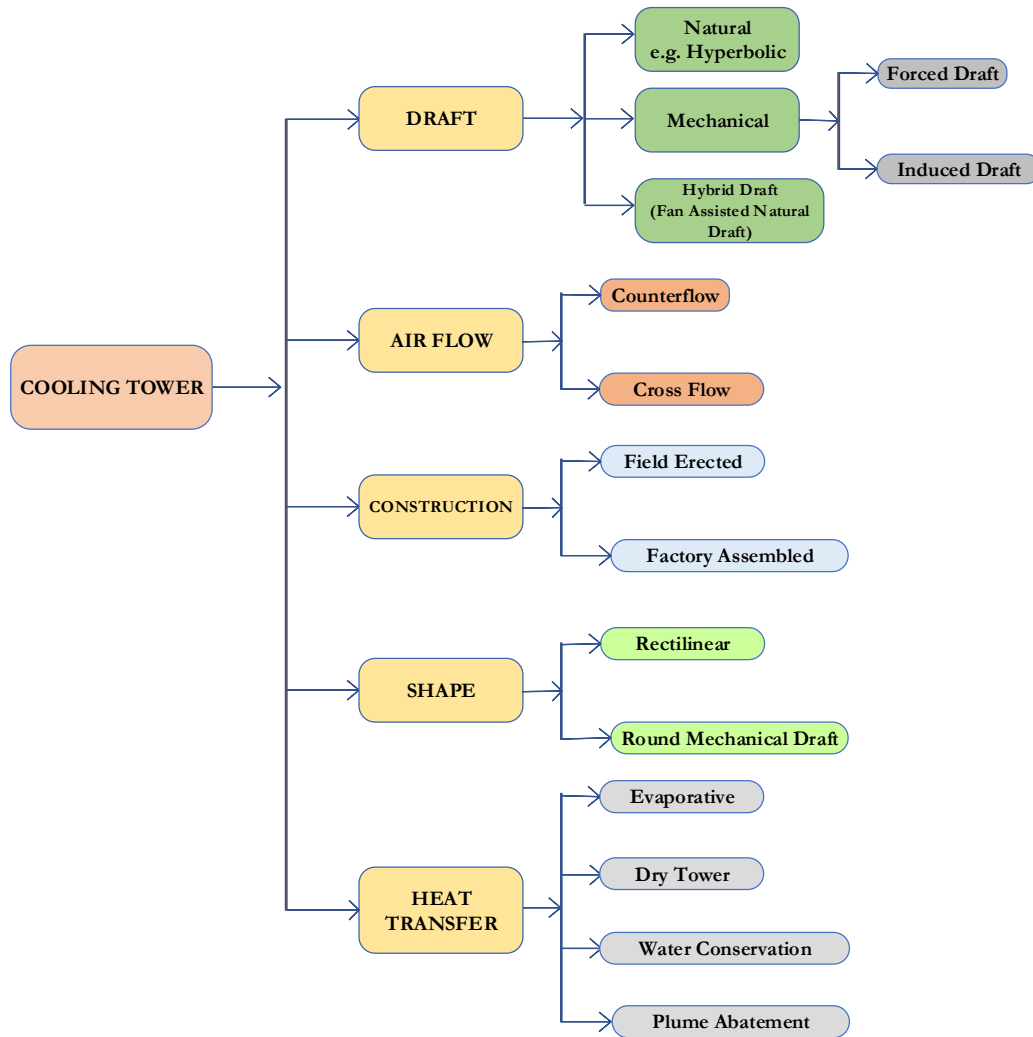


Figure 1. Categories of cooling tower

Several thermodynamic parameters affect both the physical structure and the efficiency of the cooling tower. Some of these include the water inlet and outlet temperatures, specific enthalpy, Merkel Number, variation of mass transfer across the system and so on. The wet bulb temperature also affects the tower efficiency and this varies inversely with the tower size [15]. Obtaining optimal design parameters predicates an efficient cooling tower. The range of the tower (difference between hot water temperature entering and the cold water exiting the tower) exhibits inverse variation with the size of the tower [16]. The variation in these parameters with temperature change across the system and the significance of this variation in sustaining efficiency and effectiveness of the system is of paramount importance.

Asides from white-box models, black-box models have also demonstrated relevance in predictive and analytical models in energy systems [17–19] and cooling systems [20,21]. These models map inputs to output(s) without necessarily having a prior understanding of the system being modelled. They are data-driven models which operates intelligently by fitting data into a model but do not explicitly give details of their mode of operations. This influences their nomenclature as being a black-box [22]. Recent developments in cooling systems have demonstrated the efficiency of black-box models and their hybrids with evolutionary algorithms in predictive analysis and parameter optimization[23,24]. Significant among these studies is the work of Rashidi et al. [24]. The study developed a multi-objective optimization model, which optimizes the exergy efficiency, thermal efficiency, and specific work for regenerative Clausius and organic Rankine cycles with two integrated feedwater heaters. The study uses three multi-layer artificial neural network (MLP-ANN) model and artificial bee colony technique for function optimization. Also, another study by the author[25] proceeds using ANN and particle swarm optimization (PSO) to minimize entropy generation of a stretchable rotating disc relevant in thermal system design. Many other studies have used both evolutionary algorithm and black box models in cooling tower analysis [20,21,26–28]. These studies, however, do not undermine the significance of numerical modelling of the cooling tower system as most data for the black box models were obtained either from historical records, experimental procedures, or numerical simulations.

The cooling tower efficiency during operation and within its useful life is affected by several thermodynamic variants [29]. These variants not only culminate to affect the efficiency of the cooling tower but also has impact on the useful life of the system. The Poppe's model is popular in its use in the assessment of large-scale power plants [30]. Its use for cooling tower efficiency studies has demonstrated its high efficiency in estimating the heat transfer rate compared to the ϵ -NTU and Merkel methods. However, its use for industrial cooling tower parametric studies is sparse in the literature. The quest to improve the present technology in the plant also forms the rationale behind this study, thus providing motivation for an improvement in the transfer fluid used in the system. With the peculiarities associated with steel rolling plants in terms of their heat load, this study therefore seeks to fill this gap, thus performing a parametric study on the cooling tower of a steel rolling mill using numerical simulation approach. In this study, the effects of varying cooling tower parameters were investigated using Poppe's method. This study also (i) computes a nodal analysis of significant thermodynamic properties in the system (ii) establishes the significance of the results obtained relative to the case study and makes further conclusion and prospects for further research in the domain.

MATHEMATICAL MODELLING

Brief Description of The Steel Plant

Ajaokuta steel plant is one of the first-generation steel rolling mills in Nigeria aimed at producing long steel products expected to be used in civil engineering and construction industries. The plant, located in Kogi State, the central region of Nigeria, is built on 24,000 hectares of land. The plant operates on Blast Furnace (BF) and Basic Oxygen Furnace (BOF) technologies designed to function at high pressure. By design, the plant was built to integrate iron and steel complex based on the traditional blast furnace for iron production and basic oxygen furnace for steel making [31]. Its expected yearly output of molten iron is estimated to about 1.3 million tons with a provision for increased capacity further to 5.2 million tonnes per annum [32].

Model description

Structural variations based on functional performance exist in cooling towers. These structural variations affect the analysis and performance of a cooling tower. The rectangular forced convection cooling tower of the steel rolling mill was chosen for this analysis. The cooling tower is divided into four fills. Thermodynamic conditions of first and last fills were known with certainty and taken as initial conditions of the system. The Runge-Kutta fourth order iterative numerical method was used to solve the set of ordinary differential equations. The numerical simulation codes were written and compiled using the SCILAB programming language. Certain parametric performance measures were calculated and their variations with temperature across the fill analysed.

Several approaches to cooling tower parametric study exist in the literature. These include the Merkel, e -NTU and the Poppe's method [6,33–36]. However, the Poppe's method was adopted which rigorously addressed the transport phenomena in the tower packing [11,37]. One of the advantages of the Poppe's method is its efficiency in

predicting heat transfer rate [26,38] as it is a more rigorous approach of the Merkel and e-NTU method [39]. Even though the Poppe's method does not have most of the simplifying assumptions associated with the Merkel method, it does not consider the liquid film heat transfer resistance [40]. The Poppe's approach permits a supersaturation of the moist air during the heat and mass transfer process. Evaporation rate was evaluated, the heat and mass transfer resistances were taken into account through the estimation of the Lewis factor, the outlet air conditions were calculated, and the NTU was obtained by solving the relevant set of differential equations. Important optimization variables for this model include: water to air mass ratio, water mass flow rate, water inlet and outlet temperatures, operational temperature approach, height and area of the tower packing, total pressure drop of airflow, water consumption, outlet air conditions, and NTU.

Model assumptions

In this study, certain assumptions were made regarding the system, fluid, and the model. These assumptions are as follows;

- i. Steady operating conditions exist and thus mass flow rate of dry air remains constant during the entire process.
- ii. Counter flow exists between air and water.
- iii. A constant water flow rate is assumed.
- iv. Enthalpy of unsaturated air (dry air + water (gas)) = enthalpy of saturated air at normal wet bulb temperature.
- v. The laminar air film is assumed not saturated but having the same temperature as the body of water.
- vi. Dry air and water vapor are ideal gases.
- vii. Water surface resistance to heat and mass transfer is negligible. (The air film is the governing mechanism).
- viii. The kinetic and potential energy changes are negligible.

Model equations

The schematic diagram in Figure 2 is the material flow in the cross flow mechanical draft wet cooling tower. Figure 3 shows the pictorial view of the cooling tower arrangement in the steel rolling mill. Warm water sprayed at the top of the tower mixes with ambient air flowing in a cross-flow direction. Evaporation of water occurs due to partial pressure difference between the water and air. During this process, the air acquires moisture by the virtue of the latent heat of water released into it. The water is cooled in the process and the air is cooled or heated based on the inlet water temperature. The resulting cold water enters the heat system, where it is heated up again and the cycle continues. From the law of energy and mass balance, the heat loss by the hot water from the heat engine is gained by the cold water and cold air. The amount of water circulating the heat engine decreases over time due to evaporation. As a result of this, the make-up water compensates for this loss as shown in Figure 2.

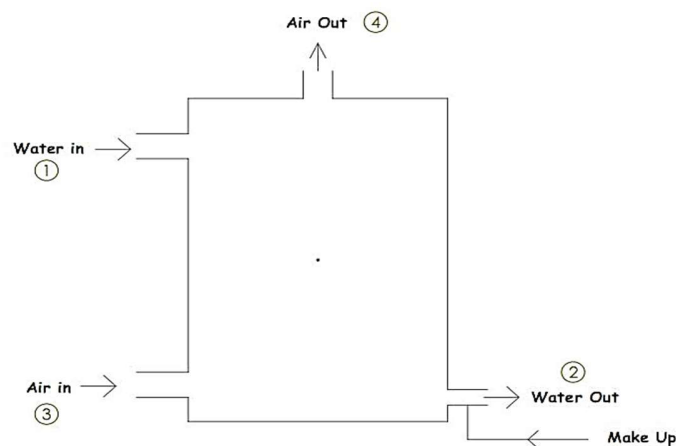


Figure 2. A schematic representation of the cross-flow mechanical draft wet cooling tower



Figure 3. A pictorial view of the arrangement of cooling towers in Ajaokuta Steel Rolling Mill

For unsaturated air, the ordinary differential equation for determining the moisture content ω , enthalpy of the air-vapour mixture i_{ma} , and Merkel number M_{ef} , for any value of the cooling water temperature T_w , in the cooling tower are given by [41] as:

$$\frac{dw}{dT_w} = \frac{C_{pw}(w_{sw}-w)(m_w/m_a)}{X} \quad (1)$$

$$\frac{di_{ma}}{dT_w} = C_{pa}(m_v/m_a)[1 + (w_{sw} - w)C_{pw}T_w/X] \quad (2)$$

$$\frac{dM_{ef}}{dT_w} = C_{pw} \quad (3)$$

Parameter X can be calculated using equation (4)

$$X = i_{masw} - i_{ma} + (L_{ef} - 1)[i_{masw} - i_{ma} - (w_{sw} - w) i_v] - (w_{sw} - w)C_{pw}T_w \quad (4)$$

where

$$i_{masw} = c_{pa}T_w + \omega_{sw}(i_{fgwo} + c_{pv}T_w) \quad (5)$$

$$i_{ma} = c_{pa}T_a + \omega(i_{fgwo} + c_{pv}T_a) \quad (6)$$

were calculated. By definition, Merkel and Lewis numbers are given as (7) and (8);

$$M_{ef} = \frac{h_d a_{ft} A_{ft} L_{ft}}{m_w} \quad (7)$$

$$L_{ef} = \frac{h}{h_d c_{pa}} \quad (8)$$

The mass flow rate of the water in the fill is given by equation (9)

$$r_{wa} = \frac{m_w}{m_a} = \frac{m_{wi}}{m_a} \left[1 - \frac{m_a}{m_{wi}} (w_o - w) \right] \quad (9)$$

which can be written as

$$y_4 = m_{win} \times \left(1 - (m_a/m_{win}) \times (w_{out} - y_1) \right) \quad (10)$$

Where w_{out} is air specific humidity at tower top outlet, while w_{in} is the vapour flow rate at the air inlet located at the bottom of the tower.

Initial conditions

For counter flow cooling tower (CFCT), it is traditional to choose the bottom of the tower as the initial point. Thus, the value of w , i_{ma} and M_{ef} or (NTU) are known at the bottom of the tower. At the start of the simulation, $\omega = \omega_1$, and $i_{ma} = (C_{pa1} + w_1 C_{pv1}) T_{a1}$. The specific enthalpy of the inlet air water vapour mixture. $M_{ef} = 0$ at the bottom of the tower.

For easy computing, variables were indexed at each fill i ($i = 0, 1, 2, 3$). Following the procedure of Kloppers and Kroger [41], the temperature of the air-vapour mixture is determined once the specific enthalpy is known. It is given by equation (11).

$$T = \frac{i_{ma} - w i_{fgwo}}{C_{pa} + w C_{pv}} + 273.15 \quad (11)$$

where the latent heat of evaporation of water i_{fgwo} is evaluated from equation (12)

$$i_{fgwo} = 3.4831814 \times 10^6 - 5.8627703 \times 10^3 T + 12.1395687 T^2 - 1.40290431 \times 10^2 T^3 \quad (12)$$

The specific heat for dry air, C_{pa} is a function of temperature. It is given by equation (13)

$$C_{pa} = 1045.356 - 0.3161783 T + 7.083814 \times 10^{-4} T^2 - 2.705209 \times 10^{-7} T^3 \quad (13)$$

The specific heat for liquid water is given by equation (14) [39]

$$C_{pw} = 8.15599 \times 10^3 - 2.80627 \times 10 T_w + 5.11283 \times 10^{-2} T_w^2 - 2.17582 \times 10^{-13} T_w^6 \quad (14)$$

The saturated vapour pressure for water vapour in air is given by equation (15)

$$p_{sat} = 10^z \quad (15)$$

where;

$$z = 10.79586 \times (1 - tx) + 5.02808 \times \log_{10}(T_x) + 1.5047 \times 10^{-4} \times \left(1 - 10^{(-8.29692 \times (\frac{1}{T} - 1))} \right) \quad (16)$$

$$\text{and } T_x = \frac{273.16}{T_a} \quad (17)$$

The Lewis factor L_{ef} for unsaturated air is calculated using the equation (18)

$$y_8 = L_{ef} = 0.865^{2/3} \frac{(x-1)}{(\log_{10}(xx))} \quad (18)$$

where;

$$x = \frac{(w_{sw}+0.622)}{w+0.622} \quad (19)$$

The specific humidity w for air temperature at T_a is given by equation (20)

$$w = 0.622 \times \frac{p_s}{(p - p_s)} \quad (20)$$

where p is the ambient pressure and p_s is the partial pressure of the vapour. If the air is saturated, then $p_s = p_{sat}$ and is calculated using equation (15).

Similarly, the vapour flow rate at any position, y_5 , is given by equation (21)

$$y_5 = m_{win} - y_4 \quad (21)$$

The mass transfer coefficient, $y_6 = h_d$ is given by equation (22)

$$y_6 = h_d = M_{ef} m_w a_{fl} A_{flr} L_{fl} \quad (22)$$

where the Merkel number, M_{ef} is given by the equation (7) and a_{fl} is the wetted area per unit volume of the fill (here set at unity) [42,43] and A_{flr} is the cross-sectional area of the tower. The mass transfer coefficient was determined by a SCILAB script.

$$I = (X_{w,H(j+1)} - X_{w,H(j)}) + (X_{air,H(j)} + X_{air,H(j+1)}) \quad (23)$$

A measure of the quality of energy is defined as *exergy*, which is the work potential of energy in a given environment. Assuming that air–water thermodynamics properties are known at discrete points along the tower height, the exergy destruction for each incremental tower height dH is calculated using equation (23).

Table 1. Model initial conditions

Variable	Unit	Plant data
Cooling tower height (L_{fl})	m	10.0
Cooling tower area (H)	m^2	64.0
Dry air mass flow rate (m_a)	kg/s	750000
Inlet water mass flow rate (m_{w3})	kg/s	15527.728
Atmospheric pressure (p_a)	N/m^2	101712.27
Relative humidity (rh)	%	51.0
Air inlet temperature (t_{a1})	$^{\circ}C$	36.7
Hot water inlet temperature (t_{w3})	$^{\circ}C$	40.0
Water outlet temperature (t_{w4})	$^{\circ}C$	32.0

Table 1 represent the operating conditions and the characteristics of working fluids through the system used as initial conditions. All the equations modelling the system were solved numerically using the computational flow chart shown in Figure 4. This was implemented using the SCILAB scripts described in ref [44].

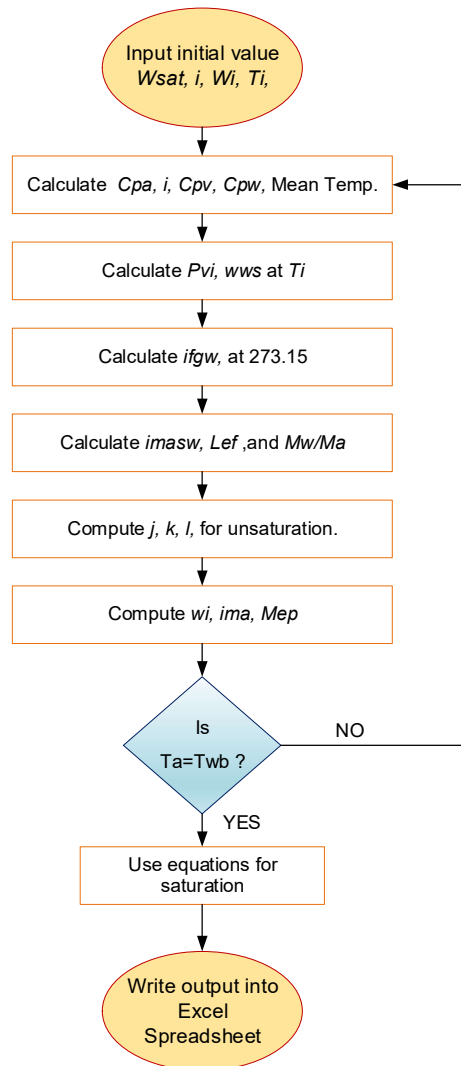


Figure 4. Flow chart of solution procedure

RESULTS AND DISCUSSIONS

The comparative results are the outlet conditions of the working fluid. Also, the effect of variation in wet bulb temperature of inlet air on various thermodynamic parameters was studied. Thus, this model can be used for predicting the conditions of water and air in cooling towers. Thermodynamic properties vary across the compartments of the tower and invariably across the fills. Many results of the program could be of interest. Since water temperature is used as the independent variable, all other parameters could be tabulated and plotted as a function of the water temperature. For the tower considered, the computed results for water temperature, air moisture content, specific enthalpy and Merkel number at each node beginning from the bottom of the tower is shown in Table 2. The air moisture content increased with the increase in the water temperature throughout the first half of the nodal result. However, a stationary value was obtained in the second half of the nodal result as presented in Table 2. Similar occurrence existed for the Merkel number. This value increases throughout the first half of the nodal result but decreased in the second half of the run. The specific enthalpy on the other hand increases down the nodal results across the cooling tower system.

Table 2. Cooling tower nodal result

Node	T_w (K)	w	i_{ma} (J/Kg)	Mel
1	305.15	0.0197013	87422.10	0
2	306.48	0.0197046	87429.42	0.4827
3	307.82	0.0197075	87436.26	0.8285
4	309.15	0.0197101	87442.84	1.0948
5	310.48	0.0197105	87446.58	1.1344
6	311.82	0.0197105	87449.78	1.1344
7	313.15	0.0197105	87452.96	1.1344
8	313.15	0.0197105	87452.96	1.1344

Important thermodynamic relationship which varies across the system as heat is rejected from the system were considered. The parametric study of the tower involved perturbations in selected input parameters and determining its effect on the tower performance.

Effect of Increasing Water Temperature on Air Moisture Content

The variation of moisture content with water temperature from the bottom of the tower is shown in Figure 5. Air moisture content increases with increasing water temperature. This accounts for the addition of make-up water for the evaporative loss in the process. Despite the efficiency of wet-cooling towers, they are known to consume a significant quantities of water, which becomes a problem if the plant is situated in areas with water scarcity [4]. This challenge has lately necessitated recent studies on dry-cooling technologies [45–47], which have recorded laudable water savings most especially in the arid regions.

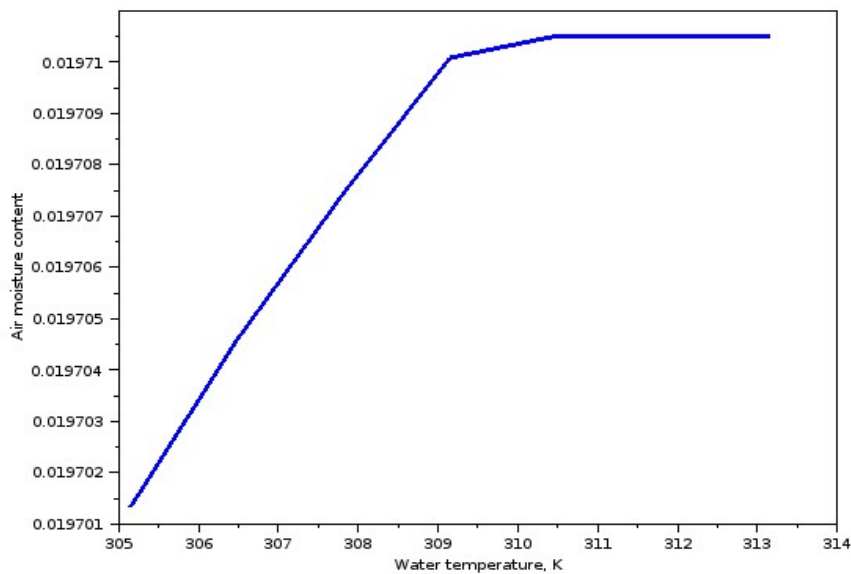


Figure 5. Air moisture content variation with water temperature

Effect of Increasing Water Temperature on the Merkel Number

The Merkel number, also known as the transfer characteristics, constitute one of the significant parameters that determines the thermal performance of a wet-cooling tower [48]. This parameter depends on the air and water mass flow rates [49]. The variation of Merkel number with water temperature from the bottom of the tower is shown in Figure 6. In this study, it was observed that the Merkel number increases with increasing water temperature. However, at 310 °C the curve tends to stationarity towards the top of the cooling tower. At this point there exists no

change in transfer characteristics/coefficient of the system. This correlated with Table 2 appears halfway of the runs. As compared to the study by Zhou et al. [50] the use of forced ventilation, rather than the natural ventilation used in the plant considered in this study, improves the Merkel number and hence the cooling efficiency of the system.

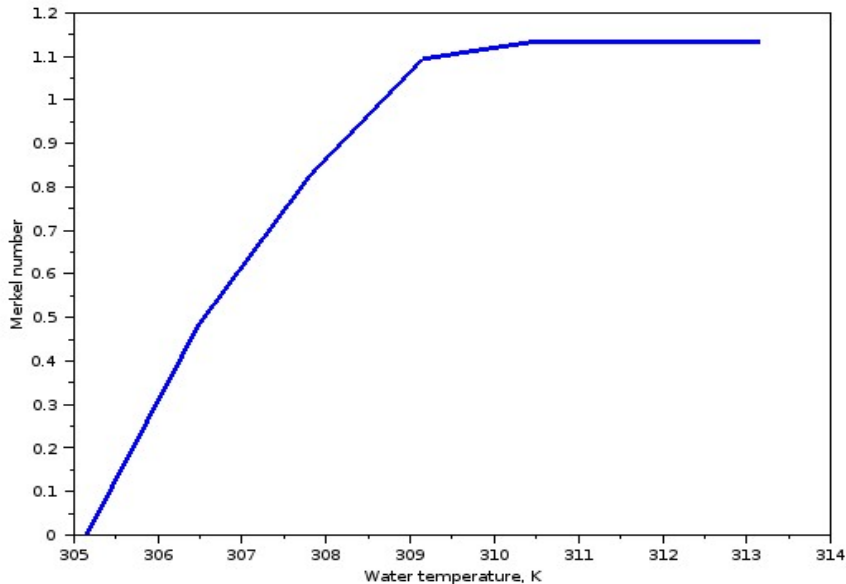


Figure 6. Variation of Merkel Number with water temperature

Effect of Increasing Water Temperature on the Specific Enthalpy

The top of the tower is associated with high temperature as hot water flows downwards. However, the specific enthalpy of the air vapour mixture increases significantly from the bottom of the tower with a near-linear relationship to the top as shown in Figure 7. This shows that sensible heat is lost as water flows from top to the bottom of the tower, which leads to considerable evaporative cooling. Hence, a makeup water is necessary to compensate for the lost water in the system.

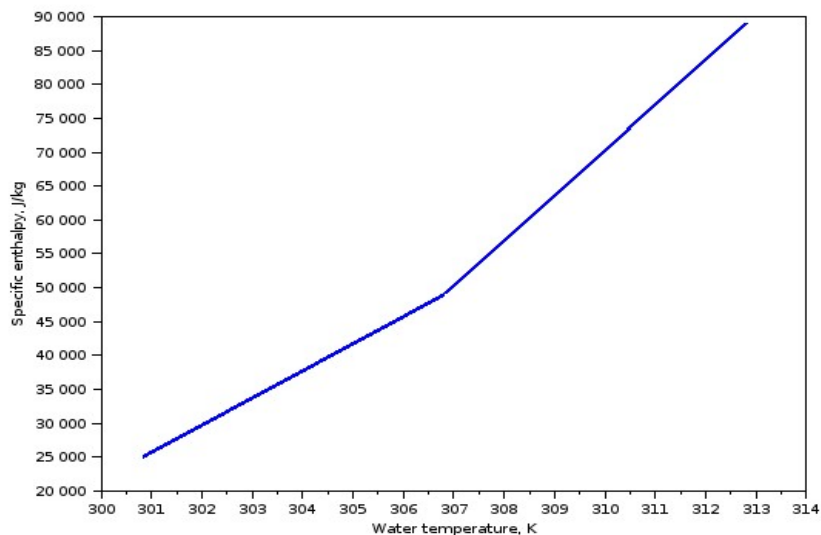


Figure 7. The variation of specific enthalpy of the air vapour mixture with water temperature from the bottom of the tower

Similar study performed by [37] on a campus vapour compression refrigeration system obtained a positive correlation between the water temperature and other thermodynamic variables like the specific gravity, though the temperature difference between the tower head is significantly different. Perturbations in the water temperature has a ripple effect on the cooling tower parameters from top to the bottom.

Recent advances in the field of nanofluids have established remarkable improvement in the capabilities of conventional fluids for convective cooling [51]. Nanosized metallic and non-metallic materials have lately been used to enhance heat transfer in convective fluids [2,51], thus ensuring high heat transfer rate. These nanocomposites are of high functionality, however, high frictional effect and increased pump power requirement has been one of their major drawbacks. Industrial cooling towers are known for high heat removal and thus, improving the heat transfer rate in the process proffers faster cooling. There are several nanoparticles known for high heat removal rate in cooling systems. Some of these include the Al_2O_3 , TiO_2 , CuO , SiO_2 , carbon nanotubes (CNT), ZnO , and so on [52]. Their respective concentrations under varying applications have been investigated in many studies. From these studies, it is established that the nanoparticle concentration and frictional effect are directly related [53]. Enhancing the heat transfer rate of in heat systems using nanoparticles have been implemented mostly in automobiles and allied systems, however, studies on their applications in industrial cooling towers is still at sparse in the literature. Addition of nanocomposites at tested concentration in the convective cooling fluid of the cooling tower has a high prospect of increasing the heat transfer rate of the system.

CONCLUSIONS AND PROSPECTS

In this study, we investigated the downstream variation in the water temperature on some selected thermodynamic properties of a typical cooling tower used in a steel rolling mill using numerical method. For a rectangular cooling tower load, the model successfully predicts air and water outlet temperatures. For parametric analysis of a cooling tower, the model successfully predicted the behaviour of all the parameters involved in the experiment. Air moisture temperature increases as the water temperature increases. The Merkel number across the system increases with increasing water temperature. The result obtained from the study confirmed that in the literature [37]. Increase in water vapour temperature towards the tower outlet and increase in enthalpy across the fill necessitates an increase in the make-up water entering the system. Even though all other variables increased at and reached a stationary point at half the total nodal points considered in the analysis, the specific enthalpy of the system increases throughout the system. The thermal efficiency could be improved upon by the introduction of a force draft system. With the present steps in the plant towards improving the existing technology, the nanoparticles with high thermal conductivity but less frictional effect is recommended for the present or new technology in the mill. However, economic feasibility of this inclusion in large scale industrial cooling towers is highly essential. Also, in contrast with the use of numerical models, the use of artificial intelligence techniques can be explored in further studies towards monitoring the cooling tower parameters.

NOMENCLATURE

a_{fl}	The wetted area per unit volume of the fill, m^2
A_{fl}	Cross sectional area of the tower, m^2
C_{pa}	Specific heat for dry air, kJ/kgK
C_{pw}	Specific heat for liquid water, kJ/kgK
C_{pa}	The specific heat for dry air, kJ/kgK
C_{pv}	Specific enthalpy for water vapour at constant pressure, kJ/kgK
h	Enthalpy of the bulk air, kJ/kg
h_d	Mass transfer coefficient of air, kW/m^2K
i_{fgwo}	Latent heat of evaporation of water, kJ/kgK
i_{ma}	Enthalpy of the air-vapour mixture, kJ/kg
i_{masw}	Enthalpy od saturated air at T_w , kJ/kg
i_v	Enthalpy of water vapour at T_w , kJ/kg

L_{ef}	Lewis factor
L_{fl}	Height of tower, m
m_a	Dry air inlet mass flow rate, kg/s
m_{win}	Hot water inlet mass flow rate, kg/s
m_v	Mass of condensable vapour, kg
m_w	Mass of water, kg
M_{ef}	Merkel number
p_{sat}	Saturated vapour pressure for water vapour in air, kPa
r_{wa}	Mass flow rate of water in the fill, kg/s
T	Temperature of unsaturated air, K
T_a	Air temperature, K
T_w	Cooling water temperature, K
ω	Humidity ratio, kg_w/kg_a
w_{in}	Vapour flow rate at the air inlet at the lower bottom, kg/s
ω_0	Humidity ratio of the environment, kg_w/kg_a
w_{out}	Air specific humidity at tower top outlet
ω_{sw}	Humidity ratio of saturated air at T_w , kg_w/kg_a
X_{air}	Air exergy, kW
y	Coordinate

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