iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 Issue: III Month of publication: March 2018

DOI: http://doi.org/10.22214/ijraset.2018.3093

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue III, March 2018- Available at www.ijraset.com

Energy and Exergy Analysis of Shower Cooling Tower with Variation in Inlet Air Dry Bulb Temperature for Industrial Application

Mohammad Zunaid [1]
[1,] Department of Mechanical Engineering, Delhi Technological University, Delhi

Abstract*: Cooling tower is very essential part of industries to cool water used for different purposes. Heat and mass transfer analysis of a downward parallel flow of air and water droplet interaction has been carried out to solve simultaneous governing differential equations to predict the exit conditions of air and water droplets. It has been observed that there is a substantial reduction of water temperature along shower cooling tower (SCT) height without fills. Based on this study the height of SCT can be reduced and thus saving in cost of the tower. Exergy analysis has also been carried out to find out variation of water and total exergy of air flowing through the SCT. It has been found that total exergy destruction maximum at beginning of air and water interaction and decrease along the tower height.

Keywords: SCT; Parallel flow; Heat and mass transfer analysis; Exergy analysis.

NOMENCLATURE			
C	specific heat (kJ/kg K)	C_d	coefficient of drag
D	droplet diameter (m)	D_c	cross-sectional diameter of SCT (m)
g	gravitational acceleration (m/s2)	h	Specific enthalpy (kJ/kg)
h_f	specific enthalpy of saturated water (kJ/kg)	h_{fg}	specific enthalpy of evaporation (kJ/kg)
$h_{fg,0}$	specific enthalpy of evaporation at 0°C (kJ/kg)	h_g	specific enthalpy of saturated vapour (kJ/kg)
h_m	mass transfer coefficient (kg/m2 s)	I	exergy destruction of system (W)
Le_f	Lewis factor	m_a	mass flow rate of air (kg/s)
m_d	mass flow rate of water from the nozzle (kg/s)	M_d	mass of a drop (kg)
N	Number of droplets	q	Heat transfer (kJ/kg)
R_a	gas constant for per unit molecular weight of dry air (J/kg K)	R_v	gas constant per unit molecular weight of water vapour (J/kg K)
S_f	specific entropy of saturated water (kJ/kg K)	S_g	specific entropy of saturated vapour (kJ/kg K)
T	Temperature (°C)	u_a	air velocity (m/s)
U	drop velocity (m/s)	W	droplet relative velocity w.r.t. air (m/s)
X	exergy (W)		
Greek letters			
ρ	density (kg/m3)	ω	specific humidity (kg_w/kg_a)
ϕ	relative humidity of air (%)	ϕ_0	ambient humidity
η_{th}	thermal efficiency (%)	η_{II}	second law efficiency (%)
Subscripts			

0	restricted dead state	a	air
av	average condition	c	convective
d	droplet	e	evaporative
in	inlet	l	evaporative loss
m	mean	out	outlet
p	constant pressure	t	total
s	saturated	v	vapor
w	water	x	horizontal coordinate
y	vertical coordinate		
Abbreviations			
DBT	dry bulb temperature	RLG	water to air mass flow ratio
SCT	shower cooling tower	SLE	second law efficiency

I. INTRODUCTION

The main function of wet cooling towers is to reject heat carried by water via direct contact with atmospheric air. Water temperature is reduced by evaporative and convective cooling in the tower. In conventional cooling tower fills are used to break up the water into droplets to maximize contact with the cooling air. The general disadvantage of the conventional cooling tower is fouling due to salt deposition on the fills and is a major source of cooling tower performance deterioration. Therefore, to overcome these disadvantages, SCT are developed. In SCT water is sprayed at top and heat and mass transfer takes place between water droplets and air (Fig. 1). Because of heat and mass transfer between the air and the water, the water temperature is reduced while the air enthalpy is increased. In down draft SCT water is sprayed through pressurized nozzles and flows downward. The air also enters from top and flows downward. The cold water is collected at the bottom from where it is pumped to the desired location. The warm and humid air is expelled from the tower. Muangnoi et al. (2014) analyzed water-jet cooling tower using experiments and numerical simulations. They found that evaporation share of the total energy transfer and total exergy supplied influence the performance. Nuyttens et al. (2007) developed a test rig and protocol for the characterization of spray nozzles using a phase doppler particle analyser (PDPA). This test rig was able to measure droplet sizes and velocities based on light-scattering principles. It has been observed that nozzle type as well as nozzle size have an important effect on droplet size as well as on velocity spectra. Kloppers and Kroger (2005) gave a detailed procedure to solve the governing equations with its unique requirements for heat and mass transfer equations of evaporative cooling in wet-cooling towers. Xiaoni et al. (2007) conducted study on cooling tower without fill packing and found that small sauter mean droplet diameter is desirable for high performance of SCT. Qi et al. (2008) design towers with no tower packing and observed that equivalent diameter of inlet water droplets and the initial air velocity affect the outlet water temperature. In a study of SCT, Yajima and Givoni (1997) observed about 7 ˚C drop in DBT at the maximum ambient temperature. Pearlmutter et al. (1996) develop and monitor small-scale down draft evaporative cool tower in arid Negev Highlands of southern Israel. The result shows a scope for substantial temperature reduction in the order of 10 °C under summer daytime conditions. Farnham et al. (2011) carried out experiments by spraying water from varying heights in a large atrium and found that a single spray nozzle with sauter mean droplet diameter of 41 microns can provide cooling of 0.7 ˚K. Kachhwaha et al. (1998) develop two dimensional simple and efficient numerical model and observed that DBT decrease of up to 9°C by employing evaporative cooling during dry summer months. Sureshkumar et al. (2008) Study evaporative cooling of air by water sprays for two ambient conditions, viz., hot-dry and hot-humid, covering DBT from 35 to 47 ˚C, and relative humidity 10 – 60%. Sureshkumar et. al. (2007) develop 1-D parallel flow heat and mass transfer model to solve air and water spray interaction for different combinations of drop diameter, air velocities, DBT and specific humidity. By using an optimum number of categories and velocity sub-classes, reasonably accurate predictions are obtainable with savings in computation time. Qureshi and Zubair (2006) investigated complete cooling tower which consists of three zones; namely, spray zone, packing and rain zones. In cooling towers, a significant portion of the total heat rejected may occur in the spray and rain zones and fouling is a major source of cooling tower performance deterioration. Cui et al. (2016) concluded that the droplet diameter had large impact on the droplet temperature distribution and thermal performance of cooling tower. Bejan (1997) expressed total exergy air is the sum of convective and evaporative exergy of air. Muangnoi et al. (2007) developed a mathematical model based on heat and mass transfer principle to find the properties of water and air. The results show that water exergy decreases continuously from top to bottom. Qureshi and Zubair (2003) carried out numerical study using engineering equation solver (EES) to determine the variation of second-law efficiency as a function of mass flow rate, relative humidity and temperature. It has been observed that an increase in the relative humidity of the incoming air stream increases second-law efficiency. Qi et al. (2013) developed mathematical model of energy and exergy for a counter flow SCT. The destruction of the exergy of water is high at the bottom and gradually decreases moving up to the top of the tower. The experimental and simulation studies to understand the heat and mass transfer phenomenon in pact cooling tower are sufficiently available in the literature. However, a very limited published literature is available on SCT. Simplicity and low maintenance of SCT motivate to undergo in-depth study to correlate heat and mass transfer analysis and to determine the factors which govern the performance of SCT. This could be helpful for maximizing the effects of advantages posed by SCTs as a replacement for conventional cooling towers. In the present work a simple and numerically efficient heat and mass transfer model for water-air interaction in downward vertical parallel flow configuration in which diameter of water droplets are varying along height of SCT has been developed in MATLAB. A parametric study has been performed to determine the effect of variation in inlet air DBT along SCT height. The spray air model is represented by differential equation of mass, momentum and energy of droplets. Experimental study has also been carried out for spray characterization and to study performance of SCT under variable conditions. The results from experimental study have been used for validation of numerical results.

II. EXPERIMENTAL FACILITY FOR SPRAY CHARACTERIZATION

Schematic diagram of downdraft parallel flow SCT used for experimental work is shown in Fig. 1. The atmospheric air enters at the top of SCT with the help of a fan. Water from the storage tank supplied to the impaction pin nozzle with the help of reciprocating pump. Nozzle disintegrates the water into the small droplets for maximizing the surface area so as to increase the heat transfer between the droplets and the air. The different sizes of droplets are produced by applying different pressure on the jet. Increasing the water pressure results in an increase in velocity of jet and flow rate of a nozzle, decrease in droplets sizes. Malvern spraytec laser diffraction system is used for measure droplets sizes at the different pressure. The spray water droplets cool down by convection and evaporation heat transfer with air and leave the tower from the bottom. The exit air goes to the atmosphere, and exit water used for industrial application.

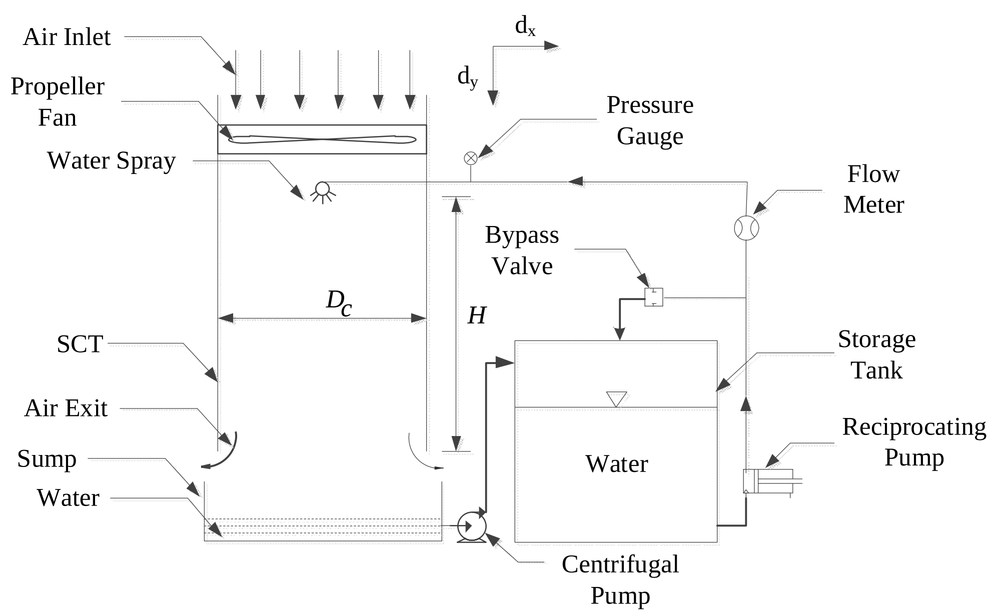


Fig.1 Parallel flow downdraft evaporative SCT

III. MATHEMATICAL MODEL

To describe the motion characteristics of the water droplets in a mathematical model, some critical simplifying assumptions concerning the water droplet are made. The water droplet is spherical in shape and droplet temperatures are uniform. The possibility of collision or scattering of the water droplet during the motion process is ignored. Equilibrium is reached when the drop is cooled by circumgyration. Liberation, non-uniformity of internal flow and temperature distribution are ignored. The SCT height is divided into n sections of finite thickness $'dy'$ and finite volume $'dV'$. The water is assumed to be distributed evenly in the form of water droplets with average diameter. The positive direction is taken from top to bottom of the tower.

A. Conservation of Mass for Water Droplet

Variation in diameter of water droplet with tower height can be written as:

$$\frac{d(D)}{dy} = -\frac{2h_m}{U_y \rho_w}(\omega_s - \omega_a) \tag{1}$$

B. Conservation of Momentum for Water Droplet

Variation in momentum of droplet in horizontal and vertical direction with tower height is expressed as:

$$\frac{dU_x}{dy} = -\left[\frac{3(C_d \rho_a W U_x)}{4D\rho_w U_y}\right] - \frac{3U_x}{D}\frac{dD}{dy} \tag{2}$$

$$\frac{dU_y}{dy} = \left[g(\rho_w - \rho_a) - \frac{3(C_d \rho_a W (U_y - u_a))}{4D}\right]\frac{1}{\rho_w U_y} - \frac{3U_y}{D}\frac{dD}{dy} \tag{3}$$

C. Conservation of Energy for Water Droplet

The water droplets lose its sensible heat and latent heat to the air. Energy balance of the water droplet is shown below:

$$\frac{dT_d}{dy} = -\frac{6h_m[Le_f(h_s - h_{av}) + (1 - Le_f)(\omega_s - \omega_a)h_{fg}]}{U_y c_{pd} D \rho_w} - \frac{3T_d}{D}\frac{dD}{dy} \tag{4}$$

D. Thermal Balance Equations in the SCT

The total enthalpy transfer at air-water interface can be expressed as:

$$\frac{dh_{av}}{dy} = \left(\frac{m_d}{m_a}\right)\frac{6h_m}{\rho_w D U_y}\left[Le_f\left(h_s - h_{av}\right) + \left(1 - Le_f\right)h_{fg}\left(\omega_s - \omega_a\right)\right] \tag{5}$$

E. Mass balance equation in the SCT

The mass transfer associated with the control volume expressed as:

$$\frac{dw_a}{dy} = \frac{m_d h_m A_s}{m_a M_d U_y}\left(\omega_s - \omega_a\right) \tag{6}$$

F. Drop Trajectory Equation

Drop trajectory expressed in terms of horizontal and vertical components of velocity.

$$\frac{dx}{dy} = \frac{U_x}{U_y} \tag{7}$$

G. Exergy Formulation

Total exergy of air and water vapour mixture is sum of exergy of water (X_d) and total exergy of air (X_a). The total air exergy is sum of convective exergy of air (X_c) and evaporative exergy of air (X_e).

$$X_d = m_d\left((h_{fd} - h_{g0}) - T_0(s_{fd} - s_{g0}) - R_v \ln\left(\phi_0\right)\right) \tag{8}$$

Exergy of air due to convective heat transfer

$$X_c = m_a\left[c_{pa}\left(T_a - T_0\right) - T_0\, c_{pa} \ln\left(\frac{T_a}{T_0}\right) + \omega_a\left\{c_{pv}\left(T_a - T_0\right) - T_0\, c_{pv} \ln\left(\frac{T_a}{T_0}\right)\right\}\right] \tag{9}$$

Exergy of air due to evaporative heat transfer

$$X_e = m_a \left[R_a T_0 \ln\left(\frac{1+1.608\omega_{a0}}{1+1.608\omega_a} \right) + \omega_a R_v T_0 \ln\left(\frac{\omega_a (1+1.608\omega_{a0})}{\omega_{a0}(1+1.608\omega_a)} \right) \right] \quad (10)$$

Total exergy of water and air is given as:

$$X_{total} = X_d + X_c + X_e \quad (11)$$

The total exergy destruction $'I'$ per unit time for discrete height of tower will be:

$$\underbrace{I}_{\substack{total\ exergy/unit\ time \\ destroyed}} = \underbrace{X_{total,y(j)}}_{\substack{total\ exergy/unit\ time \\ entering\ at\ height\ y(j)}} - \underbrace{X_{total,y(j+1)}}_{\substack{total\ exergy/unit\ time \\ leaving\ at\ height\ y(j+1)}} \quad (12)$$

IV. RESULT AND DISCUSSION

A. Model Validation

The experimental data of a parallel flow down draft SCT has been used for model validation. Comparison of outlet water droplet temperature obtained from the experiment and those obtained from the computational work are shown in Fig. 2. It can be seen that the majority of the data fall within ±10% of the model.

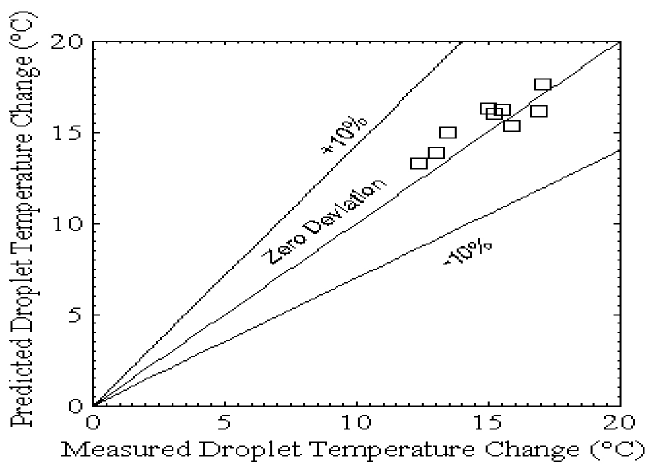


Fig. 2 Comparison of predicted and measured droplet temperature

B. Parametric Study

After validation, a parametric study has been performed computationally to determine the effect of variation in air DBT. Initial conditions used for computer simulation are, inlet DBT of air 24 - 48 ^{0}C; relative humidity 65%, inlet air volume flow rate 400 m^3/h, inlet water temperature 56 ˚C, ratio of mass flow rate of water to air 0.5, The distance between spray water inlet to bottom of tower (tower height) 1.25 m (along the direction of y-coordinate) and tower diameter 0.61 m. Droplet diameter was 250 µm, droplet velocity from 20 m/s and droplet angle of projection at inlet is 45^0. The reference temperature and relative humidity are same as inlet condition and acceleration due to gravity is 9.81 m/s^2.

C. Effect of Variation in Inlet Air DBT

DBT of air has been varied from 24 - 48 ^{0}C. Fig. 3 and Table 1 shows exit droplet temperatures increases relatively along SCT as inlet air DBT increases, it also shows 24 ˚C DBT air produce maximum cooling and it cool down water droplet up to 22.50 ˚C. As air temperature increases (keeping the water temperature constant) the sensible and evaporative cooling decreases. Table 1 also show that increase in inlet air DBT, the specific humidity of air increases because as inlet air DBT increases more water vapour added into air from upper layer of water droplet. The thermal efficiency of the cooling tower increases by increasing the inlet air DBT (Table 1) because as the air DBT increases its wet bulb temperature also increase. The convective and evaporative exergy of air, exergy of water, total exergy of system decreases with increase the inlet air DBT (Table 1). SLE at the exit of SCT increases with increase the inlet air DBT (Table 1) because exergy destruction of system relatively decreases with increasing the initial air DBT. The maximum reduction in outlet water temperature achieved up to 0.5 m height of tower (Fig. 3), so optimal performance of the SCT can be achieved at 0.5 m height. So by reducing tower height up to 0.5 m initial investment and operational cost of SCT can be reduced.

Table 1 Effect of variation in inlet air DBT

$T_{a,in}$ (˚C)	$T_{a,out}$ (˚C)	$\omega_{a,out}$ (kg_w/kg_a)	$T_{d,out}$ (˚C)	$m_{d,l}$ (kg/s)	η_{th} (%)	$X_{c,out}$ (W)	$X_{e,out}$ (W)	$X_{a,out}$ (W)	$X_{d,out}$ (W)	$X_{t,out}$ (W)	I_t (W)	η_{II} (%)
24	34.22	0.0321	34.21	0.0028	59.39	20.55	214.54	235.09	3985.4	4220.49	1151.47	78.57
30	36.40	0.0373	36.39	0.0026	62.95	7.72	154.45	162.17	3880.8	4042.97	1005.99	80.08
36	38.90	0.044	38.89	0.0023	68.19	1.52	103.72	105.24	3757.68	3862.92	871.33	81.60
42	41.76	0.0528	41.75	0.0021	77.83	1.49	63.27	64.76	3660.09	3724.85	701.56	84.15
48	46.83	0.0641	46.84	0.0018	86.82	1.42	33.4	34.82	3605.65	3640.47	583.75	86.18

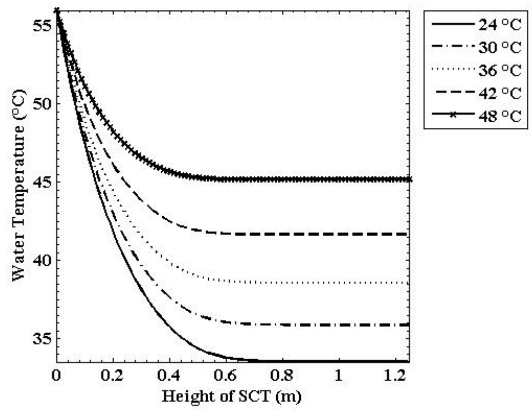


Fig. 3 Variation of water temperature along the tower height

V. CONCLUSION

Simple and efficient mathematical model for predicting the exit condition of water droplet along the downdraft parallel flow SCT have been developed. Tower operates in different inlet air DBT. Air of 24 ˚C DBT produce maximum cooling and it cool down water droplet up to 22.50 ˚C. The energy concept alone is not sufficient to describe some important view points on energy utilization. The present model predicts the exergy of air and water along SCT height through the fundamental balance law. An exergy analysis also used to indicate exergy destruction of air and water flowing through the cooling tower to explain the performance of cooling tower. Exergy destruction of system is high at the top and low at the bottom of tower because water droplets reduce its exergy faster when it comes in contact of air at the top of tower.

REFERENCES

[1] Bejan, A. (1997) ‘Advanced Engineering Thermodynamics’, 3 ed. Wiley.
[2] Cui, H., Li, N., Peng, J., Cheng, J., & Li, S. (2016) ‘Study on the dynamic and thermal performances of a reversibly used cooling tower with upward spraying’, Energy, Vol. 96, pp.268-277.
[3] Farnham, C., Nakao, M., Nishioka, M., Nabeshima, M., & Mizuno, T. (2011) ‘Study of mist-cooling for semi-enclosed spaces in Osaka, Japan’, Procedia Environmental Sciences, Vol. 4, pp.228-238.
[4] Kachhwaha, S. S., Dhar, P. L., and Kale, S. R. (1998) ‘Experimental studies and numerical simulation of evaporative cooling of air with a water spray—I. Horizontal parallel flow’, International Journal of Heat and Mass Transfer, Vol. 41, No. 2, pp.447-464.
[5] Kloppers, J. C., & Kröger, D. G. (2005) ‘A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers’, International Journal of Heat and Mass Transfer, Vol. 48, No. 3, pp.765-777.
[6] Qi, X., Liu, Y., & Liu, Z. (2013) ‘Exergy based performance analysis of a shower cooling tower’, Strojniški vestnik-Journal of Mechanical Engineering, Vol. 59, No. 4, pp.251-259.
[7] Muangnoi, T., Asvapoositkul, W., & Hungspreugs, P. (2014) ‘Performance characteristics of a downward spray water-jet cooling tower’, Applied Thermal Engineering, Vol. 69, No.1, pp.165-176.
[8] Muangnoi, T., Asvapoositkul, W., & Wongwises, S. (2007) ‘An exergy analysis on the performance of a counterflow

wet cooling tower', Applied thermal engineering, Vol. 27, No. 5, pp.910-917.

[9] Yajima, S., & Givoni, B. (1997) 'Experimental performance of the shower cooling tower in Japan', Renewable Energy, Vol. 10, No. 2, pp.179-183.

[10] Nuyttens, D., Baetens, K., De Schampheleire, M., & Sonck, B. (2007) 'Effect of nozzle type, size and pressure on spray droplet characteristics', Biosystems Engineering, Vol. 97, No. 3, pp.333-345.

[11] Pearlmutter, D., Erell, E., Etzion, Y., Meir, I. A., and Di, H. (1996) 'Refining the use of evaporation in an experimental down-draft cool tower', Energy and Buildings, Vol. 23, No. 3, pp.191-197.

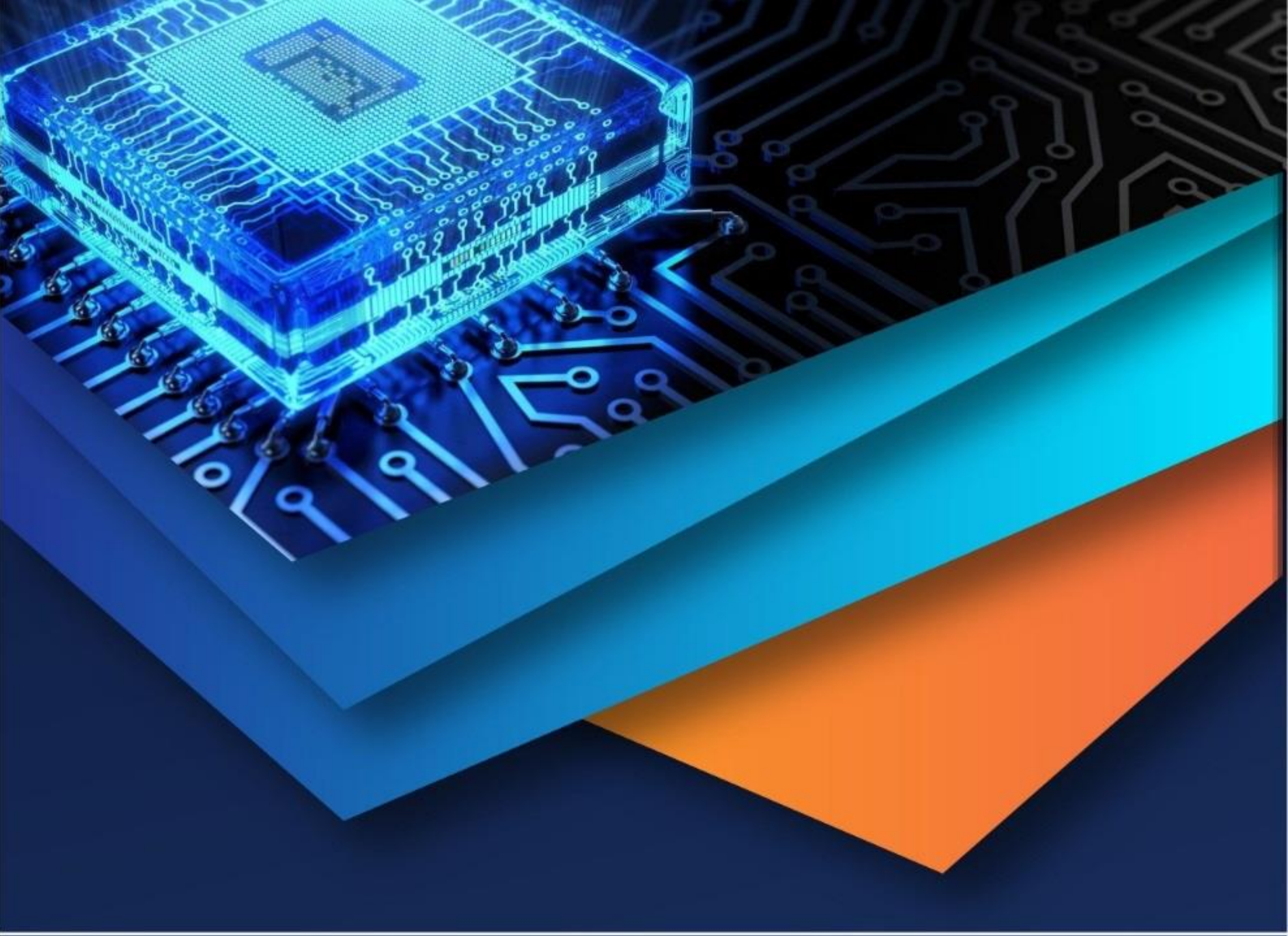
[12] Qureshi, B. A., & Zubair, S. M. (2003) 'Application of exergy analysis to various psychrometric processes', International Journal of Energy Research, Vol. 27, No. 12, pp.1079-1094.

[13] Qureshi, B. A., and Zubair, S. M. (2006) 'A complete model of wet cooling towers with fouling in fills', Applied Thermal Engineering, Vol. 26, No. 16, pp.1982-1989.

[14] Sureshkumar, R., Dhar, P. L., & Kale, S. R. (2007) 'Effects of spray modeling on heat and mass transfer in air–water spray systems in parallel flow', International communications in heat and mass transfer, Vol. 34, No. 7, pp. 878-886.

[15] Sureshkumar, R., Kale, S. R., & Dhar, P. L. (2008) 'Heat and mass transfer processes between a water spray and ambient air–I, Experimental data', Applied Thermal Engineering, Vol. 28, No. 5, pp.349-360.

[16] Xiaoni Qi., Zhenyan Liu., Dandan Li. (2007) 'Performance characteristics of a cooling tower', Energy conversion and management, Vol. 48, No. 1, pp.193-203.



10.22214/IJRASET

INDEX COPERNICUS 45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY