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Energy and Second Law of Thermodynamics Analysis of Shower Cooling Tower with Variation in Inlet Air Temperature

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ABSTRACT

A shower cooling tower (SCT) operates without fill because of salt decomposition on the fill that leads to deterioration of conventional cooling tower performance. This study presents a two-dimensional mathematical model for energy and exergy analysis of multi-diameter droplets and air interaction along with the height of the forced draft SCT, to predict the exit condition of water droplet for industrial application. Different inlet air dry bulb temperatures (DBT) were used for the study and the model was validated with experimental results. At the inlet of the tower, ten different diameters of water droplets simultaneously were used at a given time for analysis and the droplet diameter model based on Rosin Rammler distribution. The result showed that thermal efficiency and second law efficiency relatively increased along the height of SCT with increase of the inlet air temperature. It was confirmed that maximum reduction in water droplet temperature along the height of SCT was achieved by minimum inlet air DBT. It was also noticed that exergy supplied by water was more than exergy absorbed by air and maximum destruction of total exergy took place at the beginning of air-water interaction.

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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/s^2)	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/m^2 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 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)		

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Greek letters

ρ	Density (kg/m^3)	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		

1. INTRODUCTION

The traditional cooling tower has one main disadvantage that salt deposited from water on the fills and causes fouling smell and reduces the cooling tower performance [1]. To enhance the cooling tower performance fills must be replaced or cleaned which is very challenging and costly. Therefore, to overcome these disadvantages shower cooling tower (SCT) has developed where the fills have replaced with water nozzles; they produce small diameter water droplets and interact with air causing simultaneous heat and mass transfer. Farnham et al. [2] carried out experiments by spraying water from varying heights in a large entrance hall and found that 41 microns Sauter mean diameter of the water droplet from spraying single nozzle drops the temperature by 0.7 K. Bejan [3] expressed total exergy of air as the sum of convective and evaporative exergy. Cui et al. [4] concluded that the water droplet temperature distribution and thermal efficiency of the cooling tower are directly proportional to the diameter of the water droplet. Givoni [5] considered three types of climatic conditions and showed that cooling performance of developed SCT is efficient even in an extreme desert climate. Qi et al. [6] developed a numerical model of heat transfer and exergy analysis for a counter flow SCT and observed that at the bottom of SCT destruction of the exergy of water was high, gradually decreasing up to the top. Kachhwaha et al. [7] established a 2-D mathematical model and found that during the summer season in India, the evaporative cooling system with 4.8 mm diameter nozzle decreases up to 9 °C in DBT. Muangnoi et al. [8] numerically and experimentally studied water-jet cooling tower; they found that cooling capacity of spray cooling tower was influenced by the evaporative energy and exergy transfer. Pearlmutter et al. [9] developed and monitored a small-scale down draft evaporative cooling tower. The result showed that during summer substantial temperature reduction of about 10 °C occurred. Qureshi and Zubair [1] carried out a numerical study to find the changes in exergy efficiency with variation in RLG, relative humidity and temperature using engineering equation solver (EES). It showed that second-law of efficiency increases with an increase in the relative humidity of the inlet air stream. Sureshkumar et al. [10] developed a one-dimensional parallel flow heat and mass transfer model to solve air and droplets interaction for different combinations of drop diameter, air velocities, DBT and specific humidity. Sureshkumar et al. [11] studied evaporative cooling of air by water sprays for hot-dry and hot-humid ambient conditions at different dry bulb temperatures (DBTs) and relative humidities. Sirok et al. [12] found that as RLG increases the thermal efficiency of cooling tower decreases. Zunaid et al. [13, 14] said total exergy of air controlled by its convective and evaporative exergy, and evaporative exergy of air is the major component present in total exergy of air. Ardekani et. al. [15] said inlet and outlet water temperature difference for the wind facing sector was about twice that of the peripheral sectors. Kumar and Pant [16] found that as Reynolds number increases flow pattern changes. Heidarnejad and Delfani [17] showed that Reynolds number changes with variation in the geometrical and physical perimeters of flow. Murtaza et al. [18] said air enhances the break-up of the liquid sheet from an atomizer, air also disperses droplets and prevents its collision. Nandan and Singh [19] showed that improvement in dimensionless exergy loss represented more amount of energy being utilized from the system. Kasaeian et al. [20] said available energy is always destroyed when a process involves a temperature change; this destruction is proportional to increase in the entropy of the system. Ardekani et al. [21] found that 2 ºC reduction in the temperature of the radiators resulted in 7% enhancement in the overall performance of the cooling tower compared to the still air condition. Keshtkar [22] said the exergy of water is the major component in the total exergy of system.

To understand the heat and mass transfer phenomenon in pact cooling tower, sufficient literature on experimental and simulation studies is available. However, very limited reports are available on SCT. Simplicity and low maintenance cost of SCT motivated us to study and correlate heat and mass transfer in-depth and determine the factors which govern the performance of SCT. In this work, a mathematical model for ten different diameters of water droplet and air interaction in downward vertical parallel flow configuration is developed and evaporation loss of water droplets along the height of SCT which has not been studied till now is considered. At inlet ten different diameters of water droplets (31.8184, 63.6368, 95.4552, 127.2736, 159.092, 190.9104, 222.7288, 254.5472, 286.3656 and 318.184 µm) come in contact with air simultaneously. The spray air model represented by the differential equation of mass, momentum, energy, exergy and trajectories of multi droplets with considering water evaporation is developed in MATLAB. These equations are developed with the help of mathematical equations of the single droplet and air interaction model [6, 23]. A parametric study has been performed to determine the variation in energy and exergy of air and water droplets with different inlet air temperatures i.e. 24, 30, 36, 42 and 48 ˚C along the SCT height. The results from the experimental study are used for validation of numerical results.

2. EXPERIMENTAL FACILITY

Downdraft parallel flow SCT is shown in Figure 1. Water from the storage tank is supplied to the nozzle by the help of the reciprocating pump. Nozzle disintegrates the water into the small droplets for maximizing the surface area so as to increase the energy transfer between the water and air. Atmospheric air and water spray droplets enter at the top of the tower. Air come in contact with the water spray droplets at the upper part of SCT and due to convective and evaporative heat transfer between air and water droplets temperature decreases. Thus exit water at the lower temperature can be used for industrial application.

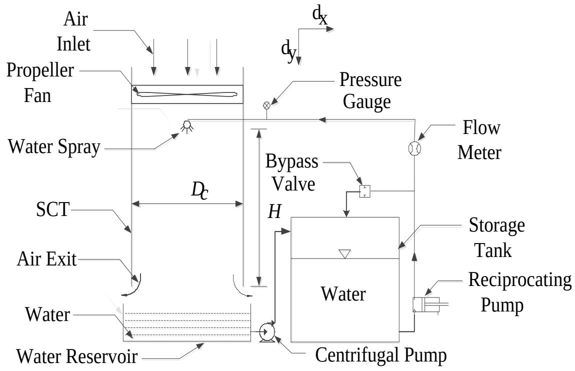

Figure 1. Parallel flow downdraft evaporative SCT

3. MATHEMATICAL MODEL

To pronounce the air and water interaction, some critical assumptions have been made. The water was expected to be sprayed in the form of ten droplets of different diameters. It has been assumed that the water droplet shape is spherical and droplet temperatures are uniform. The chances of smash and breaking of the water droplet within SCT is ignored. The mass, momentum and energy conservation equations for varying diameter of multi droplets and air are derived by technique suggested by Kloppers et al. [23] and Qi et al. [6] for mono droplet and air interaction. The SCT height is divided into 'n' sections of finite thickness $'dy'$.

Conservation of mass for $'i^{th}'$ category of water droplet can be written as:

$$\frac{d(D_i)}{dy} = -\frac{2h_{m,i}}{U_{y,i}\rho_w}(\omega_{s,i} - \omega_a) \tag{1}$$

For the drop of the category $'i'$, variation in the momentum of the droplet in horizontal and vertical direction with tower height is expressed as:

$$\frac{dU_{x,i}}{dy} = -\left[\frac{3(C_{d,i}\rho_a W_i U_{x,i})}{4D_i\rho_w U_{y,i}}\right] - \frac{3U_{x,i}}{D_i}\frac{dD_i}{dy} \tag{2}$$

$$\frac{dU_{y,i}}{dy} = \left[g(\rho_w - \rho_a) - \frac{3(C_{d,i}\rho_a W_i(U_{y,i} - u_a))}{4D_i}\right] \frac{1}{\rho_w U_{y,i}} - \frac{3U_{y,i}}{D_i}\frac{dD_i}{dy} \tag{3}$$

The water droplets lose their sensible heat and latent heat to the air. Energy balance for the $'i$ th' category of droplet is shown below:

$$\frac{dT_{d,i}}{dy} = -\frac{6h_{m,i}[Le_{f,i}(h_{s,i} - h_{av}) + (1 - Le_{f,i})(\omega_{s,i} - \omega_a)h_{fg,i}]}{U_{y,i}c_{pd,i}D_i\rho_w} - \frac{3T_{d,i}}{D_i}\frac{dD_i}{dy} \tag{4}$$

$$T_{d,m} = \frac{\sum_i (m_{d,i}) T_{d,i}}{\sum_i m_{d,i}} \tag{5}$$

Variation in air temperature due to mass and heat transfer interaction for the 'i^{th}' drop can be given as:

$$\frac{dT_a}{dy} = \sum_i \left(\frac{m_{d,i}}{m_a}\right) \frac{6h_{m,i}}{\rho_w D_i U_{y,i} C_{pav,i}} \left[\begin{array}{l} Le_{f,i}\left(h_{s,i} - h_{av,i}\right) \\ +\left(1 - Le_{f,i}\right) h_{fg,i}\left(\omega_{s,i} - \omega_a\right) \end{array}\right] - \frac{h_{fg,0}}{C_{pav,i}} \frac{dw_a}{dy} \tag{6}$$

The mass transfer associated with the control volume is expressed as:

$$\frac{dw_a}{dy} = \sum_i \frac{m_{d,i} h_{m,i} A_{s,i}}{m_a M_{d,i} U_{y,i}} \left(\omega_{s,i} - \omega_a\right) \tag{7}$$

Droplet trajectory is expressed in terms of horizontal and vertical components of velocity:

$$\frac{dx}{dy} = \frac{U_{x,i}}{U_{y,i}} \tag{8}$$

Thermal efficiency of SCT is given as:

$$\eta_{th} = \frac{\left(T_{d,i} - T_{d,m}\right)100}{T_{d,i} - T_{wb,i}} \tag{9}$$

Exergy of water is given as:

$$X_{d,i} = m_{d,i} \left(\begin{array}{l} (h_{fd,i} - h_{g0}) - T_0 (s_{fd,i} - s_{g0}) \\ -R_v \ln\left(\phi_0\right) \end{array}\right) \tag{10}$$

Convective exergy of air is expressed as:

$$X_c = \sum_i m_a \left[\begin{array}{l} c_{pa}\left(T_a - T_0\right) - T_0 c_{pa} \ln\left(\frac{T_a}{T_0}\right) + \\ \omega_a \left\{ c_{pv}\left(T_a - T_0\right) - T_0 c_{pv} \ln\left(\frac{T_a}{T_0}\right) \right\} \end{array}\right] \tag{11}$$

Evaporative exergy of air is given as:

$$X_e = \sum_i m_a \left[\begin{array}{l} R_a T_0 \ln\left(\frac{1 + 1.608\omega_{a0}}{1 + 1.608\omega_a}\right) + \\ \omega_a R_v T_0 \ln\left(\frac{\omega_a (1 + 1.608\omega_{a0})}{\omega_{a0} (1 + 1.608\omega_a)}\right) \end{array}\right] \tag{12}$$

Total exergy of water and air is calculated as:

$$X_t = \sum_i (X_{d,i} + X_c + X_e) \tag{13}$$

The total exergy obliteration 'I' for distinct height of tower is given as:

$$I = X_{t,y(j)} - X_{t,y(j+1)} \tag{14}$$

Second law efficiency of SCT is given as:

$$\eta_{II} = \frac{X_{t,out} \times 100}{X_{t,in}} \tag{15}$$

4. RESULTS AND DISCUSSION

4. 1. Model Validation The experimental data of a parallel flow downdraft SCT has been used for model validation. The experimental and model predicted results at different test conditions are shown in Table 1. It can be seen that the errors between experiment and model predicted results are less than 10%.

4. 2. Parametric Study Initial conditions used for the computer simulation are water inlet temperature 56 ^{0}C; relative humidity 65%, air volume flow rate 11.11×10^{-2} m^3/s, droplet velocity from 20 m/s, droplet angle of projection at inlet 45^0. Five different inlet air DBTs are 24, 30, 36, 42 and 48 ^{0}C. The droplets of ten different diameters i.e. 31.8184, 63.6368, 95.4552, 127.2736, 159.092, 190.9104, 222.7288, 254.5472, 286.3656 and 318.184 µm are used for analysis. Droplets distribution is based on Rosin Rammler distribution function. The distance between the spray water inlets to the bottom of the tower (tower height) was 1.25 m (along with the direction of y-coordinate) and tower diameter was 0.61 m. Effect of variation in inlet air DBT on various energetic and exergetic performance parameters was studied and exit conditions are shown in Table 2 and 3.

TABLE 1. Comparison between experimental and model predicted results

Test No.	Inlet water temperature (˚C)	Experimentally observed exit water temperature (˚C)	Model predicted exit water temperature (˚C)	Error in exit water temperature (%)
1	48.10	33.16	34.62	9.77
2	48.10	34.27	35.11	6.10
3	48.10	34.85	35.74	6.75
4	48.10	32.14	32.91	4.80
5	48.10	31.92	32.62	4.35
6	48.10	31.80	33.11	8.03
7	48.10	32.75	32.20	3.56
8	48.10	30.50	31.06	3.20
9	48.10	31.95	31.16	4.88

TABLE 2. Effects of inlet air DBT on the energetic parameters

$T_{a,i}$ (°C)	$T_{a,out}$ (°C)	ω_{out} (kg_w/kg_a)	$T_{d,m,out}$ (°C)	$m_{d,l}$ (kg/s) $\times(10^{-3})$	η_{th} (%)
24	33.01	0.0327	34.62	2.64	58.28
30	35.51	0.0379	36.76	2.53	61.77
36	38.35	0.0446	39.23	2.35	66.83
42	41.91	0.0534	42.06	2.07	76.12
48	47.91	0.0563	43.92	43.92	91.06

TABLE 3. Effects of inlet air DBT on the exergetic parameters

$T_{a,i}$ (°C)	$X_{c,out}$ (W)	$X_{e,out}$ (W)	$X_{air,out}$ (W)	$X_{d,out}$ (W)	$X_{t,out}$ (W)	I_t (W)	η_{II} (%)
24	18.54	198.80	217.34	4024.44	4241.78	1130.18	78.96
30	11.72	144.91	156.63	3907.58	4064.21	989.77	80.40
36	6.71	98.54	105.25	3794.40	3899.65	840.13	82.25
42	1.18	59.76	60.94	3686.27	3747.21	680.37	84.63
48	0.002	20.47	20.47	3641.22	3661.69	554.30	86.87

4. 3. Effect of Variation of Inlet Air Temperature

Water at 56 ^{0}C is sprayed from the top of SCT and air is also admitted from the top. The temperature of air varies from 24-48 ^{0}C with the interval of 6 ^{0}C. When water is sprayed from the top, it breaks into ten different diameters. Trajectories of these particles are shown in Figure 2; it is clear that the distance traveled by smaller diameter droplet is larger and thus the retention of these droplets is greater than larger size droplets. Due to the interaction of air and water, the air temperature increases due to sensible heat transfer as the water temperature is higher than air (Figure 3). At the same time water temperature drops (Figure 4) due to evaporation of outer layer of water droplet; outer layer takes the heat of evaporation from the inner part of the droplet. At about 0.3 m height of SCT, the temperature of the water droplet is equal to air temperature at that location, therefore no sensible heat transfers from water to air. Since the air is still unsaturated, the evaporative heat transfer continues which further reduces the water temperature and reverses the heat transfer (air to water) and there is no further drop in air temperature. It is evident from Table 2 that as inlet air DBT increases its specific humidity increases because air can sustain more water as its DBT increases along the height of SCT. Table 2 also shows that the evaporative water loss decreases with increase of the inlet air temperature because at low inlet air temperature, the temperature gradient between the continuous and discrete phase is high, leading to higher convective heat transfer and lower evaporative heat transfer leading to less water evaporation.

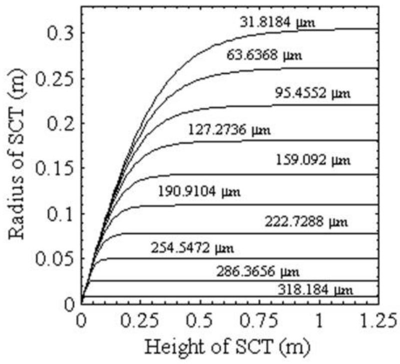

Figure 2. Trajectories of ten different diameters water droplets along tower height

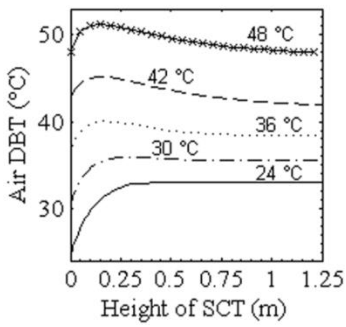

Figure 3. Air DBT along the tower height

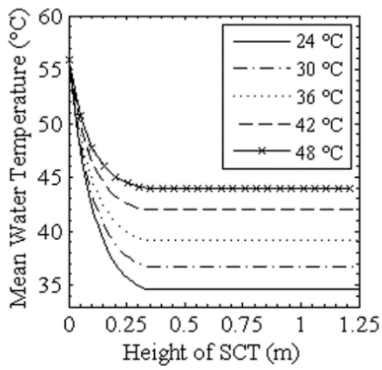

Figure 4. Mean water droplet temperature along the tower height

As air temperature increases total change in convective and evaporative exergy of air decreases because as air temperature increases heat transfer between air and water decreases (Table 3). The value of exergy loss due to convective heat transfer is less than 1% of exergy loss due to evaporation, due to extremely high value of the latent heat of evaporation. Figure 5 displays variation in temperature of ten different diameter water droplets (31.8184-318.184 µm) along tower height for 48 ^{0}C inlet air DBT. Smaller size droplet covers longer paths along the tower height, so retention time of smaller size droplet in SCT is greater as compared to larger size droplet. Water temperature drops due to evaporation of the outer layer of the droplet; outer layer takes the heat of evaporation from the inner part of the droplet. For the smaller size of water droplets direction of heat transfer is reverse (air to water) along the SCT height, thus the temperature of smaller size water droplets starts increasing after a certain distance along the height of SCT. Figure 4 denoted as inlet air DBT increases, exit mean water droplet temperature relatively increases; it also shows that the highest mean water droplet temperature reduction is achieved by 24 ^{0}C inlet air DBT, and it cools down up to 21.38 ^{0}C. Total system exergy is the sum of total air and water exergy (Table 3), the same decreased along the height due to irreversibility and due to water droplets and air interaction. Rate of total system exergy destruction is very high initially but it gradually reduces and becomes asymptotic after about 0.3 m of height (Figure 6). Exergy of water is lost to air due to heat transfer by convection and evaporation. Figure 7 shows the thermal efficiency of the cooling tower increases by increasing the inlet air DBT because as the air DBT increases its wet bulb temperature also increases. Maximum and minimum thermal efficiency of the cooling tower is 91.06 and 58.28%. Second law efficiency at the exit of SCT increases with increase of the inlet air DBT (Figure 8) because exit total exergy of the system relatively increases with increase of the air DBT.

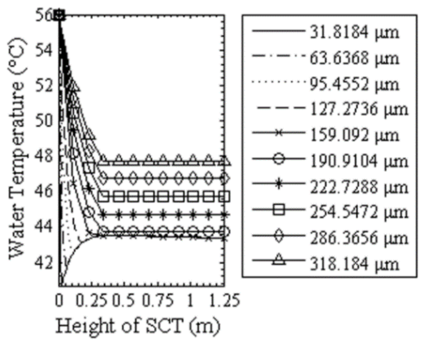

Figure 5. Ten different water droplets temperature along tower height

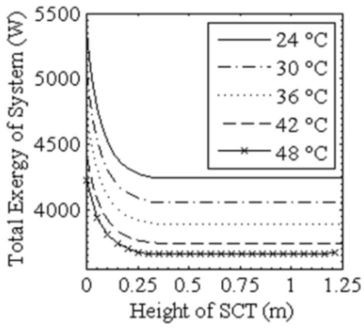

Figure 6. Total exergy of system along the tower height

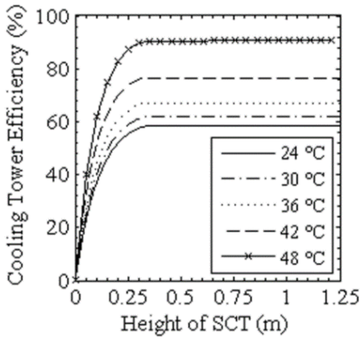

Figure 7. Thermal efficiency of SCT along the tower height

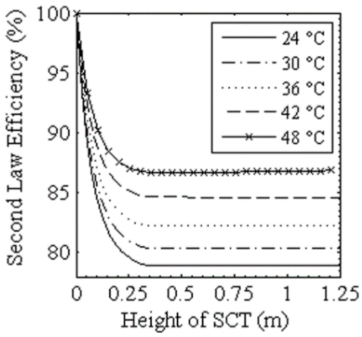

Figure 8. Second law efficiency of SCT along the tower height

Reversibility is the outcome of a process driven by the infinitesimal temperature difference. Hence, availability declines with an increase in the driving temperature gradient. Therefore the rise in inlet air DBT leads to higher exergy. Most importantly it is clear in all the results that become asymptotic after tower height of 0.5 m. Therefore, this analysis is very important for deciding the optimum height of the tower to reduce the cost.

5. CONCLUSIONS

A 2-D mathematical model to find out the exit condition of droplets and air has been developed in MATLAB. The thermal efficiency and second law efficiency of SCT increase with increase of the inlet air DBT. Maximum drop in water droplet temperature achieved for the minimum inlet air DBT, and it cooled down up to 21.38 ˚C, thus multi-droplet SCT can be used in place of the conventional cooling tower in industry for reducing the temperature of hot water. Air and water exergy variation has also been studied to explain the functioning of forced draft SCT. Air exergy is mostly governed by its evaporative exergy. Exergy obliteration is high at the top of SCT. Parameters of air and water in Figures 2-8 become asymptotic up to 0.5 m height of the tower, so the optimum height of tower should be 0.5 m for same operating conditions. Thus by reducing tower height investment cost can also be reduced.

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Energy and Second Law of Thermodynamics Analysis of Shower Cooling Tower with Variation in Inlet Air Temperature

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چکیده

برج خنک کننده دوش (SCT) به علت تجزیه نمک بدون پر شدن کار می کند که منجر به کاهش عملکرد برج خنک کننده متعارف می شود. این مطالعه یک مدل ریاضی دو بعدی برای تجزیه و تحلیل انرژی و اگزرژی قطرات با قطرهای متفاوت در تعامل هوا متناسب با ارتفاع لوله SCT برای پیش بینی شرایط خروج قطرات آب برای کاربرد صنعتی ارائه می دهد. برای آزمایش، دمای حباب خشک (DBT) مختلف هوای ورودی مورد استفاده قرار گرفت و مدل با نتایج آزمایشگاهی تأیید شد. در ورودی برج، ده قطر قطرات آب به طور همزمان برای تجزیه و تحلیل مورد استفاده قرار گرفت و از مدل قطر قطره بر اساس توزیع Rosin Rammler استفاده شد. نتایج نشان داد که بهره وری حرارتی و کارایی قانون دوم در طول ارتفاع SCT نسبت به افزایش دمای هوا ورودی افزایش می یابد. نتایج همچنین نشان داد که حداکثر کاهش دما در قطرات آب در طول ارتفاع SCT با حداقل DBT هوای ورودی به دست می آید. همچنین متوجه شدیم که اگزرژی آب بیشتر از اگزرژی جذب شده توسط هوا است و حداکثر تخریب اگزرژی کل در آغاز تعامل آب و هوا صورت گرفت.

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