Exergy Analysis of Counter Flow Wet Cooling Tower in Khuzestan Steel Co.

Navid Bozorgan[1*]

Abstract: Since the energy analysis considers the quantity of energy, it cannot show the performance of the cooling tower. Therefore, in order to optimize the performance of the tower and also the process which the cooling tower is a part of it, it is necessary to analyze the energy and exergy of the tower simultaneously. In this paper, the energy and exergy of one of the cooling towers of Khuzestan Steel Co. is analyzed in order to improve the function of this unit and its effect on the related units. Moreover, the exergy of water and air which exchange heat with each other has also been studied. The mathematical model presented in this paper has been based on the principle of heat and mass transfer between water and air. The results of this study show that water makes more exergy than air because the system generates entropy. The results also show that the exergy of water decreases constantly from the upper part of the tower to its lower part, the exergy of air, however increases from bottom to top along the tower. When the temperature decreases water loses exergy but when the temperature is increased the air gains exergy.

Keywords: Exergy, Heat and Mass Transfer, Optimization, Cooling Tower

1. Introduction

The main objective of the exergy analysis is to find and quantitatively survey the reasons for the thermody-namic defections of the stated process. Examination of air and water conditions in exergy analysis of cooling tower is of high importance. Khan and Zubair [1] examined the operation of cooling tower with counter flow and they used the thermodynamic property equations that are formu-lated by Hyland and Wexlar [2, 3] in their analysis of heat and mass transfer mechanism in cooling towers. Bahaidrah [4] examined the operation of cooling towers with consideration of water and air condition all over the tower. El-Dessouky et al. [5] proposed a model for heat analysis of counter flow wet cooling tower in a stable state. Nimr [6] presented a mathematical model to describe the thermal behavior of packed cooling towers. A closed form solution was obtained for both the transient and steady temperature distribution in a cooling tower. Jameel [7] investigated the heat and mass transfer mechanism and performance characteristics using a detailed theoretical model in counter flow cooling towers. In this model, an approximate equation was used to calculate wet air enthalpy. This equation was obtained from the thermodynamic properties of saturated air-water vapor mixture. To obtain proper results calculating accurately the properties of wet air appears to be essential.

In this paper, through presenting the mathematical model and studying the heat and mass transfer equations and numerical solutions of these equations, the properties of wet air such as humidity ratio, enthalpy and temperature are exactly compu-ted all over the tower. Due to evaporation in the cooling tower, part of water in the cooling process is evaporated when hitting the air stream.

Therefore, process includes heat and mass transfer. The Lewis factor Le_f is an indication of the relative rates of heat and mass transfer in an evaporative process. In many performance analyses of the cooling tower, Le_f is assumed to be 1 in order to simplify the heat and mass transfer equations between air and water [8]. If so, evaporative loss is negligible. But in this paper, although heat and mass transfer equations and their numerical solutions are more compli-cated, Le_f is calculated for all parts of the tower in order to achieve more accurate results in predicting air and water conditions in the cooling tower in the analysis of exergy.

2. Mathematical modeling

Cooling towers, as shown in Fig. 1. In the case of counter current towers, the air motion is due to the

1*.Corresponding Author: M.Sc., Islamic Azad University, Abadan Branch, Abadan, Iran (nariman_bozorgan@yahoo.com)

natural chimney effect of the warm moist air in the tower or may be caused by fans at the bottom (forced draft) or at the top (induced draft) of the tower.

In cooling towers, water and air exchange heat with each other. Using Pop heat and mass transfer mathematical model and numerical solution, it can analyze the internal air and water conditions in the cooling tower. Calculating wet air properties is important to obtain proper results in analyzing exergy. Therefore, humidity ratio, enthalpy and temperature of the air in different points of the cooling tower are calculated through analyzing heat and mass transfer equations in intersection surface between air and water. The assumption used in analysis of air and water conditions in the counter flow wet cooling tower is as follows:

- Heat and mass transfer from tower walls to external environment is negligible.

- Heat transfer from fan of the tower to air or water vapor is negligible.

- Water and dry air specific heat are constant.

- The water temperature at each cross section is uniform.

- Cross sectional area of the tower is uniform.

- Exiting water drops from the tower by outlet air stream is negligible.

The enthalpy of the air-water vapor mixture per unit mass of dry air, is expressed by:

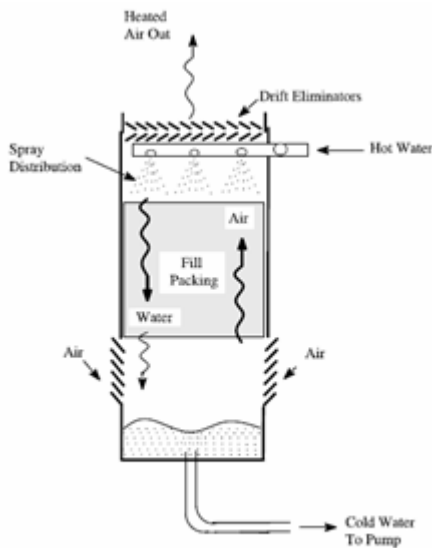$$i_{am} = c_{pa}T_a + \omega(i_{fgwo} + c_{pv}T_a) \tag{1}$$

Fig. 1. Schematic of a wet counter flow cooling tower [9]

Knowing the humidity ratio and temperature of the cooling tower, the enthalpy of the inlet air can be calculated according to Eq. (1). In this paper to identify the enthalpy, humidity ratio and air temperature in different places of the cooling tower, variations in air humidity in relation to water temperature and enthalpy differential of the air-water vapor mixture to water temperature are calculated by analyzing heat transfer rate in the interface surface between air and water.

In the outset, heat exchange between air and water in the cooling tower, according to Fig. 2 is the total value of heat transfer results from mass transfer and convective heat transfer rate due to the differential temperature between air and water. First, we will calculate heat transfer between air and water resulting from mass transfer.

Mass transfer in the interface surface between air and water is formulated as follows:

$$dm_w = h_d(\omega_{sw} - \omega)dA \tag{2}$$

Knowing the water vapor pressure at the dew point, we can calculate humidity ratio of the saturated air at water temperature.

$$\omega_{sw} = 0.622\,P_E\,/(P - P_E) \tag{3}$$

$$p_g = e^{18.6 - \frac{5206.9}{T_w}} \tag{4}$$

By considering Fig. 2, rate of heat transfer resulted from mass transfer is given by:

$$dQ_m = i_v dm_w = i_{vh}$$

$$dQ_m = i_v dm_w = i_v h_d(\omega_{sw} - \omega)dA \tag{5}$$

If the latent heat of water is i_{fgwo}=2500 kJ/Kg$_w$, then the enthalpy of the water vapor, is given by

$$i_v = i_{fgwo} + c_{pv}T_w \tag{6}$$

By the analysis of heat transfer rate due to mass transfer between air and water in cooling tower, now by considering temperature differential bet-
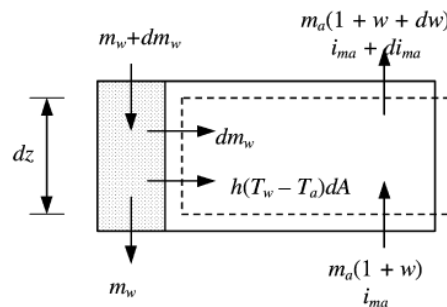

Fig. 2. Air side control volume of the fill [8]

tween air and water, convective heat transfer is expressed by:

$$dQ_c = h(T_w - T_a)\, dA \qquad (7)$$

In Eq. (7), temperature differential between air and water is the most influential parameter in the convective heat transfer. By considering the equations of enthalpy of the saturated air and enthalpy of the air-water vapor mixture, the temperature differential is calculated.

Knowing the temperature of water, we can obtain enthalpy of the saturated air.

$$i_{masw} = c_{pa}T_w + \omega_{sw}(i_{fgwo} + c_{pw}T_w) \qquad (8)$$

By considering Eqs. (1) and (8), temperature differential between air and water in the cooling tower is given by:

$$T_w - T_a = \frac{(i_{masw} - i_{ma}) - (\omega_{sw} - w)i_v}{c_{pma}} \qquad (9)$$

In the Eq. (9) specific heat of air-water vapor mixture is expressed by:

$$c_{pma} = (c_{pa} + \omega c_{pv})\, kJ\,/\,K\, kg\, dry\, air \qquad (10)$$

By substitution of Eq. (9) in Eq. (7), the following equation will be obtained:

$$dQ_c = h\frac{(i_{masw} - i_{ma}) - (\omega_{sw} - \omega)i_v}{c_{pma}}\, dA \qquad (11)$$

Therefore, total heat transfer in the cooling tower is as follows:

$$dQ = dQ_m + dQ_c = h_d[\frac{h}{c_{pma}h_d}(i_{masw} - i_{ma}) +$$
$$(1 - \frac{h}{c_{pma}h_d})i_v(\omega_{sw} - \omega)]dA \qquad (12)$$

$h_c/c_{pma}\, h_d$ in Eq. (12) is known as the Lewis factor Le_f and is an indication of the relative rates of heat and mass transfer in an evaporative process. Bosnjakovic proposed the Lewis factor Le_f for air-water vapor systems [10], therefore:

$$Le_f = 0.865^{0.667}(\frac{\omega_{sw} + 0.622}{\omega + 0.622} - 1)\,/\,[ln(\frac{\omega_{sw} + 0.622}{\omega + 0.622})] \quad (13)$$

By considering Le_f and heat transfer rate between air and water in the cooling tower, the enthalpy transfer to the air system is given by:

$$di_{ma} = \frac{1}{m_a}dQ = \frac{h_d dA}{m_a}[Le_f(i_{maw} - i_{ma}) +$$
$$(1 - Le_f)i_v(w_{sw} - w)] \qquad (14)$$

When the enthalpy transfer in air stream is

obtained through the examination of heat exchange between air and water in the cooling tower, we attempt to obtain the variations of humidity ratio of air and variations enthalpy of air- water vapor mixture to water temperature via which we can obtain humidity ratio and enthalpy of air in the cooling tower. A mass balance for the control volume in Fig. 3 yields

$$dm_w = m_a d\omega \qquad (15)$$

The energy balance for the control volume in Fig. 3 is as follows:

$$m_a di_{ma} - m_w di_w - i_w dm_w = 0 \qquad (16)$$

Where, di_w in Eq. (16) is :

$$di_w = c_{pw}dT_w \qquad (17)$$

Therefore, by considering Eqs. (15) and (16) and (17), the temperature differential of the water is given by:

$$dT_w = \frac{m_a}{m_w}(\frac{1}{c_{pw}}di_{ma} - T_w d\omega) \qquad (18)$$

Also, by dividing both sides of Eq. (18) by $T_w dT_w$ and simplifying, the equation, which are expressed by:

$$\frac{d\omega}{dT_w} = \frac{1}{c_{pw}T_w}\frac{di_{ma}}{dT_w} - \frac{1}{T_w}\frac{m_w}{m_a}\ or$$
$$\frac{d\omega}{dT_w} = \frac{1}{T_w di_w} - \frac{1}{T_w}\frac{m_w}{m_a} \qquad (19)$$

Substitute Eqs. (2) and (14) in Eq. (16), rearrange and find,

$$m_w di_w = h_d dA[i_{masw} - i_{ma} + (Le_f - 1)[i_{masw} - i_{ma} -$$
$$- (\omega_{sw} - \omega)i_v] - (\omega_{sw} - \omega)c_{pw}T_w] \qquad (20)$$

Variations of humidity ratio of the air in relation to temperature of the water results from substitution
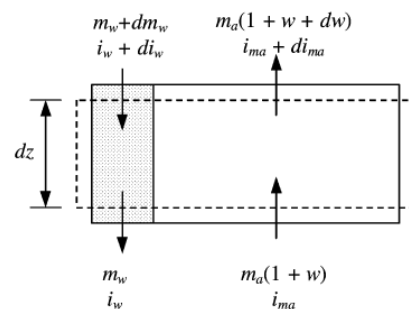

Fig. 3. Control volume of counter flow fill [8]

$$\frac{d\omega}{dT_w} = \frac{c_{pw}\dfrac{m_w}{m_a}}{i_{masw} - i_{ma} + (Le_f - 1)[i_{masw} - i_{ma} - \dfrac{(\omega_{sw} - \omega)}{(\omega_{sw} - \omega)i_v] - (\omega_{sw} - \omega)c_{pw}T_w}} \quad (21)$$

Substitution of Eq. (21) in Eq. (19) and find,

$$\frac{di_{na}}{dT_w} = \frac{m_w c_{pw}}{m_a} =$$

$$(1 + \frac{(\omega_{sw} - \omega)}{i_{maw} - i_{ma} + (Le_f - 1)[i_{maw} - i_{ma} - \dfrac{v_{pw}T_w}{(\omega_{sw} - \omega)i_v] - (\omega_{sw} - \omega)c_{pw}T_w}}) \quad (22)$$

In order to obtain the ratio of humidity and enthalpy of air in different sections of cooling tower, these variables in the above sections must be clear. Therefore, computations will start by considering the variations of humidity ratio of wet air to water temperature and variations of enthalpy of wet air to water temperature according to Eqs. (21) and (22) and by utilization of Runge-Kutta method, it is possible to compute humidity ratio, enthalpy and temperature of air in different sections of cooling tower.

3. Exergy calculation

Analysis of air and water conditions in cooling tower by using mathematical model is highly important in studying of the exergy. According to Shukuya and Hammache [11], the total exergy in the cooling tower equals sum of thermomechanical and chemical exergies, both of which play a significant function in the evaluation of the real thermodynamic value of humidity assessment process. This paper, aims to analyze the exergy relations between water and air as well as the factors affecting them. In the cooling towers, disregarding the effect of potential and kinetic energies, the special exergy in the stable state is as follows:

$$\psi = \psi_{tm} + \psi_{ch} \quad (23)$$

Substituting the current state for the inlet state and also the dead state for the outlet state, the thermomechanical exergy will be obtained as follows [12]:

$$\psi_{tm} = (i - i_0) - T_0(s - s_0) \quad (24)$$

Which for an ideal gas, the formula will be:

$$\psi_{tm} = c_p(T - T_0) - T_0(c_p ln\frac{T}{T_0} - Rln\frac{p}{p_0}) \quad (25)$$

Pressure differential in the cooling tower is negligible, and so:

$$\psi_{tm} = c_p(T - T_0 - T_0 ln\frac{T}{T_0}) \quad (26)$$

Chemical exergy, which is an exergy change based on the concentration change, is defined as follows [13]:

$$\psi_{ch} = \sum_{k=1}^{n} x_k(\mu_{k,0} - \mu_{k,00}) \quad (27)$$

In Eq. (27), x_k is the mole portion of k material in the mixture. Assuming the concentration change with a slight change of pressure, the chemical potential for the ideal gas mixture will be as follows:

$$\mu_{k,0} - \mu_{k,00} = RT_0 ln\frac{P_{k,0}}{P_{k,00}} \quad (28)$$

The total exergy is the result of both thermo mechanical exergy, which has turned from the real state into the dead state, and chemical exergy, which has turned from the dead state into the environment state. Accordingly:

$$\psi = (i - i_0) - T_0(s - s_0) + \sum_{k=1}^{n} x_k(\mu_{k,0} - \mu_{k,00}) \quad (29)$$

As mentioned earlier, water and air are the fluids that have a significant function in the cooling towers, and so in order to do the exergy analysis, it is necessary to obtain the exergy equations of both water and air.

Temperature differential of the water in the cooling tower and the chemical exergy of the environmental humidity are influential in the exergy analysis of water. Drawing on Eq. (29), since water is an incompressible fluid, its exergy can be obtained as follows [7]:

$$X_w = m_w[(i_{f,w} - i_{f,0}) - T_0(s_{f,w} - s_{f,0}) - R_v T_0 \ln\theta_0] \quad (30)$$

When we want to analyze the exergy of air in the cooling tower, the changes in the temperature and humidity are considered as effective factors.

Assuming the pressure changes in the cooling tower as negligible and drawing on the Eqs. (25) and (26) and (27), the exergy of air as follows:

$$X_{air} = m_a[(c_{pa} + \omega c_{pv})(T - T_0 - T_0 LnT/T_0) + R_a T_0 ((1 + 1.608\omega) Ln(1 + 1.608\omega_{00})/ (1 + 1.608\omega) + 1.608\omega Ln\omega/\omega_{00})] \quad (31)$$

Taking the exergy equations of water and air into account, the analysis of water and air conditions in the cooling tower are of significant importance in

the exergy analysis. In this paper, the water and air conditions in the cooling tower are analyzed using the mathematical model of heat and mass transfer.

4. Exergy analysis of counter flow wet cooling tower in Khuzestan Steel Co.

As it was mentioned earlier, exergy analysis of water and air in the cooling tower of Khuzestan Steel Company was carried out.

By considering table 1 and $T_0 = 298.15°K$, $\theta = 0.5$, and $\omega_{00} = 0.009923$ $kg_w kg_a^{-1}$ analyzed the cooling tower in the Steelmaking unit of Khuzestan Steel Co. Also, grid type cooling tower packing is made from PVC.

The results of this analysis are displayed in Figs. 4-8. As shown in Fig. 4, at first the temperature of the inlet air decreases in the tower, but it increases when it reaches the height of over 0.3 meters. This height is actually the contact point in the curves of point, the air temperature is higher than the water temperature; therefore, the heat transfer occurs from air to water. In fact water and air have the same temperature when the curves of water and air temperature meet. At this point the heat difference

Table 1. Reference operating parameters and ambient condition

Conditions	Reference
Height of column packing (m)	1.8
Total surface area of packing (m^2)	207
Atmospheric pressure (kPa)	101
Air flow rate (kg/s)	157.2
Air dry bulb temperature (C)	36.9
Air wet bulb temperature (C)	27.8
Humidity ratio of the air (kg_w/kg_a)	0.02
Water flow rate (kg/s)	693.22
Water temperature (C)	50

between water and air is zero.

The temperature increases after the contact point. After this point the heat transfer is from water to air, since the temperature of water is higher than that of air. As shown in Fig. 5, the exergy of air decreases at the point where air inlet to tower, while it constantly increases when heat transfer occurs through evapora-tion and convection. Heat transfer through evaporation and convection is an effective factor in the analysis of the air exergy. At first, the temperature of the entering air decreases from the lower part of the tower to its upper part.

Though, it later increases when through convective heat transfer, the exergy makes the flow of heat energy in the air possible. As air tempera-ture increases, so does the air exergy. As shown in Fig. 6, from the lower part of the tower to its upper part, the air exergy increases as the air humidity rises.

The temperature of water is a determining factor in the energy of water, according to Fig. 7. When hot water from the upper part of the tower is splashed on the packing, then the temperature of the water decreases constantly. The energy of water, therefore, decreases from the upper part of the cooling tower to its lower part as the temperature of water decreases. As indicated by Fig. 8, since the system generates entropy, the exergy of water is more than the exergy of air. The exergy of air, however, constantly increases from the lower part of the tower to its upper part. As the temperature decreases, so does the exergy of the water. While as the temperature, so does the exergy of air.
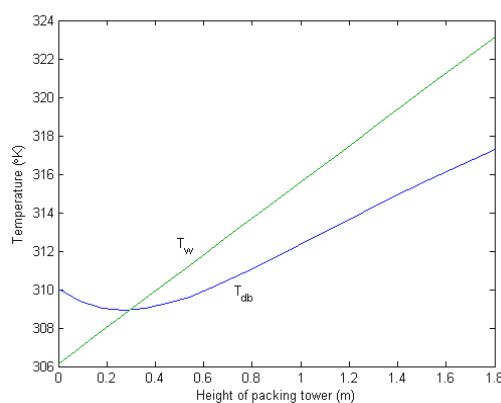

Fig. 4. Temperature profiles of water and air in the cooling tower
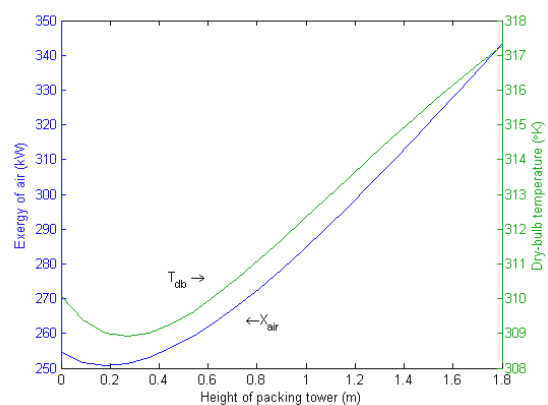

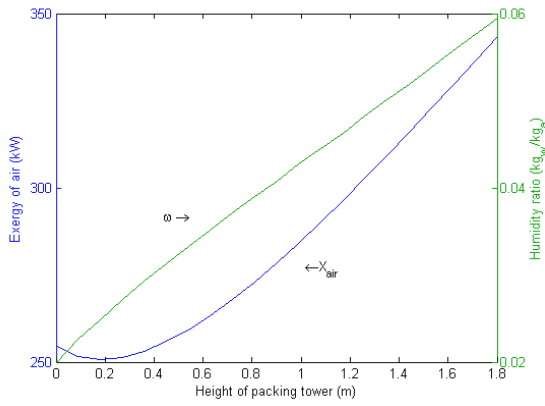**Fig. 5. Exergy of air and air temperature profiles in the cooling tower**

Fig. 6. Exergy of air and humidity ratio of air profiles in the cooling tower
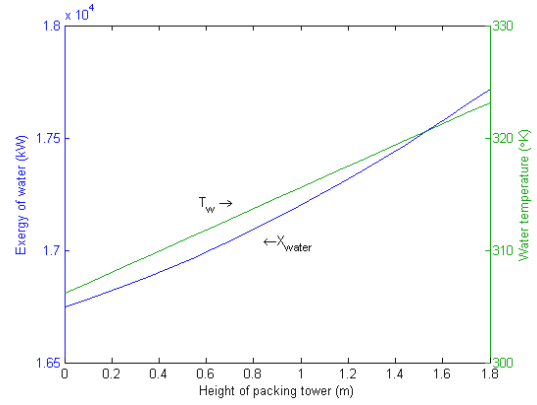

Fig. 7. Exergy of water and water temperature profiles in the cooling tower
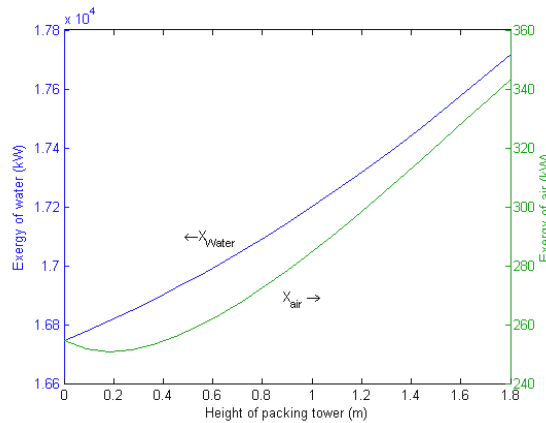

Fig. 8. Exergy profiles of water and air in the cooling tower

5. Conclusions

It is necessary to analyze energy and exergy in order to study the performance of cooling towers. In this paper, the energy and exergy of one of the cooling towers of Khuzestan Steel Co. were analyzed in order to improve its performance. It is highly important to analyze water and air conditions in exergy analysis of the cooling tower. In the present paper, the air and water conditions in the cooling towers were analyzed using the mathematical model of heat and mass transfer between water and air in the cooling towers. The results obtained from the exergy analysis of the cooling tower in the Khuzestan Steel Co. show that since the system generates entropy, water absorbs more exergy than air. The exergy of water constantly decreases from the upper part of the tower to its lower part, while the exergy of air constantly increases from the lower part of the tower to its upper part.

Nomenclature

c_{pa} specific heat of dry air at constant pressure, kJ/kgK

c_{pw} specific heat of water at constant pressure, kJ/kgK

c_{pv} specific heat of water vapor at constant pressure, kJ/kgK

h_c heat transfer coefficient of air, kW/m²K

h_d mass transfer coefficient of air, kW/m²K

$i_{fg,w}$ phase change enthalpy at T_w , KJ/Kg$_w$

$i_{f,w}$ enthalpy of saturated liquid water, kJ/kg

i_{ma} enthalpy of air in the cooling tower at T_a , kJ/kg

i_{masw} enthalpy of saturated air at T_w , kJ/kg

i_v enthalpy of water vapor at T_w ,kJ/kg

Le_f Lewis factor

m_a mass flow rate of the air, kg$_a$ /s

m_w mass flow rate of the air, kg$_a$ /s

P   pressure, kPa

R_a gas constant of dry air, kJ/kgK

R_v gas constant of water vapor, kJ/kgK

s   entropy, kJ/kgK

$s_{f,w}$ entropy of water, kJ/kgK

T_a air temperature, °K

T_w water temperature, °K

T_0 temperature in restricted dead state, °K

ω humidity ratio, kg$_w$ /kg$_a$

ω_{sw} humidity ratio of saturated air at T_w , kg$_w$ /kg$_a$

ω humidity ratio of environment, kg$_w$ /kg$_{a\ 00}$

X_{air} air exergy, kW

X_w　　　water exergy, kW
θ　　　relative humidity
Ψ_w　　specific water exergy, kJ/kg
Ψ_{tm}　　specific thermomechanical exergy, kJ/kg
Ψ_{ch}　　specific chemical exergy,kJ/kg
μ　　　chemical potential, kJ/kg

References

[1] Khan, J. R.; Zubair, S. M., "An improved design and rating analyses of counterflow wet cooling towers", ASME J Heat Transfer, 2001, 123, 770-788.

[2] Hyland, R. W., Wexler, A., "Formulations for the thermodynamic properties of the saturated phases of H_2O from 173.15 to 473.15 K.", ASHRAE Trans, 1983, 89 (2), 500-520.

[3] Hyland, R. W.; Wexler, A., "Formulations for the thermodynamic properties of dry air from 173.15 to 473.15 K, at pressure to 5 MPa.", ASHRAE Trans, 1983, 89 (2), 520-535.

[4] Bahaidrah, H. M. S., "Design and performance evalution of evaporative cooling towers", M.Sc. Thesis, Faculty of the Collage of Graduate Studies, King Fahd University of Petroleum and Minerals, Dhahran, 1999.

[5] EI-Dessouky, H. T. A.; AI-Haddad, A.; AI-Juwayhel, F., "A modified analysis of counter flow cooling towers", ASME J Heat Transf, 1997, 119 (3), 617-626.

[6] Moran, M. J., "Availability analysis: A guide to efficient energy use", Prentice-Hall, New Jersey, 1982.

[7] Bejan, A., "Advanced engineering thermodynamics", second ed., Wiley, Singapore, 1997.

[8] Kloppers, J. C.; Kroger, D. G., "A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers", 2004.

[9] Khan, J. U. R.; Yaqub, M.; Zubair, S. M., "Performance characteristics of counter flow wet cooling towers", 2002.

[10] Bosnjakovic, F., "Technische Thermodinamik", Theodor Steinkopf, Dresden, 1965.

[11] Shukuya, M.; Hammache, A., "Introduction to the concept of exergy", Paper presented in the Low exergy systems for heating and cooling of buldings, 2002, 41-44.

[12] Qureshi, B. A.; Zubair, S. M., "Application of exergy analysis to various psychrometric processes", International Journal of Energy Research, 2003, 27, 1079-1094.

[13] Wark, K., "Advanced Thermodynamics for Engineers", Mc Graw-Hill, New York, 1995.