Journal of Chemical Engineering and Materials Science Vol. 2(2), pp. 21-27, February 2011
Available online at http://www.academicjournals.org/jcems
ISSN-2141-6605 ©2011 Academic Journals

Full Length Research Paper

The estimation of the cooling tower height by modeling the water and air contact situation in cooling tower falling film

Mortaza Gholizadeh* and Mosen Momayyeza

Department of Chemical Engineering, Islamic Azad University-Ahar Branch, Ahar, I.R Iran.

Accepted 1 December 2010

Deterioration of the filling material in traditional cooling towers is of serious concern. In this study, cooling towers of Arvand and Boualisia Petrochemical plants in the South of Iran are used as the filling material. The size of the cooling towers and outlet conditions are measured in a real situation and compared with heat and mass transfer correlations by modeling the towers and then calculating the tower heights. An experimental study to model the heat and mass balance equations and their relationship by tower height is conducted. The previous correlations found in the literature did not predict the relationship between these equations and tower height for the tested towers. A new formula by supplying the numerical methods was developed, and new variables defined. This correlation can predict the height of tower within an error of ±10%. The developed correlation is used along with theoretical modeling to predict the cooling tower outlet conditions within an error of ±5%.

Key words: Cooling tower, modeling, mass transfer coefficient, tower height.

INTRODUCTION

Cooling towers are one of the most widely equipment units used in cooling systems, which also consist of a network of heat exchangers in closed circuit that consume water only to make up for the inherent losses in the process. The thermal performance of cooling towers has vital importance in the operation of a process. Because of their relevance in the processing industry, there are many works in the literature that address cooling water systems, Moreover, specific aspects are studied, namely design of cooling towers, control and operation of towers; modeling and simulation of the thermal performance and mass transfer on the height of the tower. The highly integrated features of cooling water systems (a single tower usually supplies multiple users) produce strong interactions among the hydraulic and thermal and mass process variables. For instance, the overall point of the pump, which results from its characteristics and on the entire cooling system. In addition, the recycle water flow rate depends on the operating distribution of rates in the parallel branches is also a function of their resistance to flow that is determined from pipe diameters, equivalent lengths and adjustment of the valves in each of the pipeline segments (Soylemez, 2004; Kloppers and Kroger, 2005).

The operation of the system is even more complex at the thermal and mass levels. In each heat exchanger, a given heat load must be removed from process requirements. Furthermore, the inlet and outlet temperatures of the cooling water in the process heat exchangers must be within ranges that are compatible with the capacity of the cooling tower, as the total thermal load that is removed from the process units (through the heat exchangers) must be removed from the system in the cooling tower (Thomas and Houston, 1959a; Lowe and Christie, 1962; Thomas and Houston, 1959b).

On the other hand, the transferred mass of the water in the cooling tower to air changes the outlet temperatures and flow rates of air. The outlet water temperature at the cooling tower is determined by its performance including air velocity, rate, and temperature and transferred water mass from hot water to the air affecting the height of the cooling tower (Lebrun and Silva, 2002; Pannkoke, 1996; Badran, 2003).

*Corresponding author. E-mail: morteza_gh2000@yahoo.com. Tel: +98 426 2225551. Fax: +98 426 2225551.

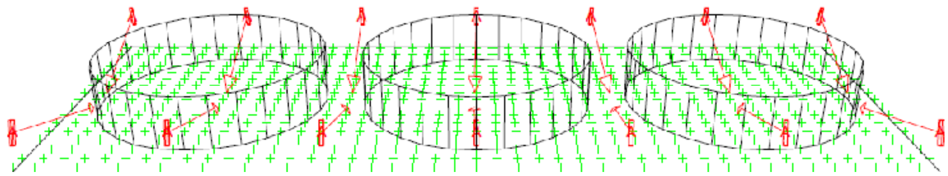

Figure 1. Arvand petrochemical plant cooling tower schematic.

Table 1. Inlet water condition for the supplied cooling towers.

	Data for Arvand tower	Data for Boualisina tower
Cooling water flow rate(m^3/h)	12,000	16,000
Density water@45℃(kg/m^3)	991	991
Hot water temperature (T1)(˚C)	45	45
Site atmospheric pressure (bar)	1	1
Site elevation(m)	3.2	3.2
Dry bulb temperature of inlet air(˚C)	50	50
Wet bulb temperature of inlet air (˚C)	31	31
Relative humidity of inlet air(at 48˚C)	30%	30%
Evaporation losses	1.9% of circulation water	1.9% of circulation water
Drift (wind age) losses	1.9% of circulation water	1.9% of circulation water
Drift (Wind age) losses	0.005% of circulation water	0.005% of circulation water
No. of cells	3	4

In a cooling tower, the water surface is extended by filling, which presents a film surface or creates droplets. The air flow may be cross flow or counter flow and caused by mechanical means, convection currents or by natural wind. In mechanical draft towers, air is moved by one or more mechanically driven fans to provide a constant air flow. The function of the fill is to increase the available surface in the tower, either by spreading the liquid over a greater surface or by retarding the rate of fall of the droplet surface through the apparatus. The fill should be strong, light and deterioration resistant. In this study, real cooling towers from Arvand and Boualisina petrochemical plants in the South of Iran were used as the filling material (Sirok et al., 2003; Kairouani et al., 2004; Kloppers and Kroger, 2005).

EXPERIMENTAL

The tested cooling tower is an induced draft counter flow type from Arvand and Boualisina petrochemical plants. The schematic diagram of the Arvandan tower is shown in Figure 1. Some of the applied cooling tower data are written as follows:

Inlet water conditions

All information is shown in Table 1.

Outlet water conditions

For both cooling towers, the outlet temperature was 35˚C.

Main dimension of one cell of cooling tower

All dimensions are given in Table 2.

Condition of outlet air

With assuming that the air outlet temperature is the same as the temperature of hot water (113 ºF) and the condition of the air outlet is saturated, all other parameters were calculated and presented in Table 3. Furthermore, the calculation procedure for Arvand petrochemical plant cooling tower is written as:

Pv1 = Vapor pressure = 9.6 Kpa (at T1 = 45ºC) =1.4 psi (at T1 = 113ºF)

$$W1 = \text{Absolute humidity} = 18/29\ 29\ \frac{Pv^1}{P\text{-}Pv1}$$

$$W1 = 0.622 \times 1.4/(14.5-1.4)$$

$$W1 = \text{Absolute humidity}=0.07\ \frac{lb\ H_2O}{lb\ dry\ air}$$

hg1 = Saturated vapor enthalpy (at T1 = 45℃= 113℉) = 2582.43 kj/kg = 1110. 25 (BtU/lb of water)

$$h1 = 0.24\ (T1 - T0) + W1 \quad h1=0.24\ (113 - 32) + 0.07\ (1110.25) = 97.16\ \frac{Btu}{lb\ dry\ air}$$

Condition of inlet air

The data are written in Table 4 and also the calculation for this part

Table 2. Main dimension of one cell of cooling tower.

	Data for Arvand tower	Data for Boualisina tower
Wetted area per cell(m^2)	242	242
Inner cell size(1×w) [m×m]	14.4×16.8	14.4×16.8
Cooling tower size (1×w) [m×m]	44.2×18	60×18
Top of basin curb	0.0	0.0
Depth of basin slab	3 m	3 m
Height of air inlet	5 m	5 m
Water distribution height	8.35 m	8.35 m

Table 3. Condition of outlet air

	Data for Arvand tower	Data for Boualisina tower
Pv_1 (at T_1 = 45℃)(kpa)	9.6	9.6
$W_1\left(\frac{\text{lb } H_2O}{\text{lb dry air}}\right)$	0.07	0.07
hg_1(at T_1 = 45℃)(BTU for lbm of water)	1110.25	1110.25
h_1(BTU for lbm of dry air)	97.16	97.16

of Arvand tower is written in below:

T2 = 31℃ = 87.8℉

Pv_2 = 4.5 Kpa(at T=31℃) = 0.652 psi (at Tw=87.8℉)

$$W_2 = \frac{0.622\ 0.652}{14.5-0.652} = 0.03$$

$$hg_2 = 2557.35 \text{ kj/kg} = 1099.\ 5\ \frac{\text{Btu}}{\text{lb of water}}$$

$$h_2 = 0.24\ (T1 - T0) + Whg_2 = 0.24(87.8-32) + 0.03(1099.5) = 46.4\ 4\ \frac{\text{Btu}}{\text{lb dry air}}$$

The equation for heat balance is given by:

$$Q = G\ (h_{hair\ outlet} – h_{hair\ inlet})$$

$$G = \text{Mass flow rate of dry air} \quad \frac{(\text{lb dry air})}{H}$$

Q = 138.1 MW = 130,893.5 Btu/Sec

$$G = \frac{130,893.5}{(97.16 – 46.4)} = 2578.7 \text{ lb dry air/sec}$$

Each cell air flow rate = 2578.7 ÷ 3 = 859.5(lb dry air/s) = 389.86 kg/s

Air specific volume @ 31℃ = 0.872 m^3/kg

⇒389.86 kg/s × 0.872 m^3/kg = 340 m^3/s

$$L = 11,892,000 \text{ kg/h} = 26,217,340\ \frac{\text{lb dry air}}{h}$$

⇒ G = 2578.7(lb dry air/s) = 9,283,320 (lb dry air/h)

$$\frac{L}{G} = \frac{26,217,340}{9,283,320} = 2.82$$ (It will be finalized by SPX company calculation)

340=V*14.4*16.8 ⇒ V=1.4m/s(air velocity)

The power of selected fan is = 165 Kw

Cooling tower design data

All information is shown in Table 5

Thermal design data of cooling tower

This data is presented in Table 6.

Mechanical design data of cooling tower

All relevant information is illustrated in Table 7.

Cooling tower dimension

Cooling tower dimentions are written in Table 8.

RESULTS AND DISCUSSION

When air flow passes a wetted surface, there is a transfer of sensible and latent heat. If there is a difference in temperature between the air and the wetted surface, heat will be transferred. If there is a difference in the partial

Table 4. Condition of inlet air.

	Data for Arvand tower	Data for Boualisina tower
T_2(°C)	31	31
Pv_2(kpa)	4.5	4.5
W_2 (lb H_2O)/lb dry air	0.03	0.03
hg_2(at T_1 = 45°C)(BTU for lbm of water)	1099.5	1099.5
h_2(BTU for lbm of dry air)	46.4	46.4
Q(BTU/S)	130,893.5	174,493.1
G(lb dry air / s)	2578.7	3,437.61
Each cell air flow rate((lb dry air)/S	859.5	859.5
Air specific volume (at 31°C)(m^3/kg)	0.872	0.872
L(lb dry air)/h	26,217,340	34,956,450
G (lb dry air)/h	9,283,320	12,375,396
The power of selected fan(kw)	165	165

Table 5. Cooling tower design data.

	Data for Arvand tower	Data for Boualisina tower
Number of cooling towers	1	1
Number of cells per cooling tower	3	4
Type of cooling tower	WIC240	WIC240
Working area per cell(m^2)	242	242
Arrangement of cooling tower	In line	In line
Number of air inlet sides/cell	2	2

pressure of water vapor in the air and that of the water, there will be a mass transfer. This transfer of mass causes a thermal energy transfer because if some water evaporates from the water layer, the latent heat of this vaporized water will be supplied to the air. The concept of enthalpy potential is a very useful one in quantifying the transfer of heat (sensible and latent) in those processes and components where there is a direct contact between the air and water (Kloppers and Kroger, 2005; Smrekar et al., 2006; Zhai and Fu, 2006; Lemouari, 2007). The expression for transfer of the total heat, dqt through a differential area, dA is expressed by Stoecker and Jones (1985):

$$dq_t = \frac{h_c dA}{C_{pm}}(h_i - h_a) \tag{1}$$

The name of enthalpy potential originates from the above equation because the potential for the transfer of the sum of the sensible and latent heats is the difference between the enthalpy of the saturated air at the wetted surface temperature hi and the enthalpy of the air stream h_a (Fredman and Saxén, 1995; Al-Nimr, 1998; Tan and Deng, 2003).

The rate of heat removed from the water is equal to the rate gained by the air, so the following expression can be written:

$$dq_t = m_a.dh_a = 4.19 m_w.dt \tag{2}$$

The heat transfer coefficient can be calculated by Equating Equations (1) and (2) and rearranging:

$$\frac{h_c A}{C_{pm} m_w} = 4.19 \int_{in}^{out} \frac{dt}{h_i - h_a} \tag{3}$$

However, A = aV and V = SZ, so Equation (3) can be written as:

Table 6. Thermal design data of cooling tower.

	Data for Arvand tower	Data for Boualisina tower
Duty(MW)	138.1	184.1
Water flow rate of cooling tower(m^3/h)	12,000	16,000
Water flow rate per cell(m^3/h)	4,000	4,000
Hot water temperature(℃)	45	45
Cold water temperature(℃)	35	35
Cooling range(K)	10	10
Inlet wet bulb temperature(℃)	31	31
Dry bulb temperature(℃)	50	50
Average ambient pressure(mbar)	1000	1000
Type of fill	Film fill, type FB20 or equal	Film fill, type FB20 or equal
Evaporation rate in % of water flow (%)	1.9	1.9
Evaporation rate(m^3/h)	228	304
Drift rate in % of water flow(%)	>0.005	>0.005

Table 7. Mechanical design data of cooling tower.

	Data for Arvand tower	Data for Boualisina tower
Fan type	Axial	Axial
No. of fans per cell	1	1
Fan diameter/no. of blades(m/pcs)	9.9/7	9.9/7
Output power at motor shaft(kw)	133	133
Motor size (750/1500 rpm) (kw)	38.165	38.165
Pumping head wet section(MWG)	9.85	9.85

Table 8. Cooling tower dimension.

	Data for Arvand tower	Data for Boualisina tower
Inner cell size (l ×W)(m×m)	14.4 ×16.8	14.4 ×16.8
Cooling tower size (l ×W)(m×m)	44.2 × 18	60 ×18
Top of basin curb(m)	0.0	0.0
Depth of basin slab(m)	3.0	3.0
Height of air inlet(m)	5.0	5.0
Water distribution height(m)	8.35	8.5
Fan deck height(m)	11.47	11.47
Height of fan stack(m)	2.67	2.67
Total higher of cooling tower(m)	14.34	14.34

Table 9. The calculated mass coefficient of the cooling tower and its height.

	a(m^2)	m'_w(kg/s)	m'_a(kg air/s)	K_x	V(m/s)	Z(m)
Data for Arvand tower	242	1111.11	389.86	1200.7	1.4	7.6
Data for Boualisina tower	242	1101	389.86	1197.8	1.5	8.25

$$\frac{h_c aZ}{C_{pm} m'_w} = 4.19 \int_{in}^{out} \frac{dt}{h_i - h_a} \qquad (4)$$

The relation between the heat and mass transfer coefficients is expressed by Reynold's analogy (Treybal, 1981):

$$\frac{h_c}{K_x C_{pm}} = Le^{\frac{2}{3}} \tag{5}$$

It is found that in most cases of air–water contact, the Lewis number Le can be considered to be unity as a good approximation (Kern, 1997):

$$\frac{h_c}{C_{pm}} = K_x \tag{6}$$

By substituting Equation (6) in Equation (4), the mass transfer coefficient can be expressed as:

$$\frac{K_x aZ}{m'_w} = 4.19 \int_{in}^{out} \frac{dt}{h_i - h_a} \tag{7}$$

The integration of Equation (7) is solved numerically by dividing the packed height into small segments starting from the bottom to the top of the tower with considering the relationship between air and water flow rates written in Equation 10 (Tan and Deng, 2003; Jin et al., 2007; Giorgia et al., 2009):

$$V = 0.3523.Z^{0.6781} \tag{8}$$

In addition, the design of a ceramic tile cooling tower requires heat and mass transfer correlations to estimate the tower height and to predict the water and air outlet conditions. Several workers have measured the heat and mass transfer coefficient in cooling towers. Thomas and Houston developed heat and mass transfer correlations using a tower of 2 m height and 0.3 m^2 cross section. They gave the following relations for the heat and mass transfer coefficients (Thomas and Houston, 1959):

$$h_c a = 3.0 m'^{0.26}_w m'^{0.72}_a \tag{9}$$

$$K_x a = 2.95 m'^{0.26}_w m'^{0.72}_a \tag{10}$$

In our calculations, firstly we calculated K_X from Equation 10 and then through Equation 7 and 8 we calculated Z and compare it with the real height. The result is written in Table 9. This correlation can predict the height of tower within an error of ±10%.

As we can see from the real data, the height of water-air contact for Arvand petrochemical plant cooling tower is 8.35 m that is comparable with our calculation result (7.6 m) by 10% error.

Conclusion

A mathematical model is used to simulate the effect of any change in operating conditions of cooling tower, especially the mass transferring coefficient, on the thermal performance of a cross flow tower. Available data was obtained using a numerical–experimental method which provides an insight on the current performance of the Arvand and Boualisina petrochemical plant towers. It is found that increasing the mass transferring coefficient between water and air, at constant dry bulb, the height of the tower will decrease considerably. The evaporation rate is increased as the dry bulb temperature increases and the rate of increase is almost constant at different wet bulb temperatures. The suggested model can predict the tower height with relating the contact situation between water and air.

Nomenclature: a, area of heat and mass transfer (m^2/m^3); **Cp,** specific heat (kJ/kg K); **h,** enthalpy (kJ/kg); **hc,** heat transfer coefficient (kW/m^2 K); **Kx,** mass transfer coefficient (kW/m^2 K); **Le,** Lewis number; M, flow rate (kg/s); **Q,** heat flux (kJ/kg); **Z,** tower height (m)x humidity ratio (kg water/kg dry air); **Pv,** vapor pressure; **W,** absolute humidity; **hg,** saturated vapor enthalpy; **G,** mass flow rate of dry air; **m,** superficial flow rate (mass velocity) (kg/m^2 s); **m,** flow rate (kg/s); **t,** contact time(s); **V,** air velocity.

Subscripts: a, air; **I,** inlet or interface; **o,** outlet; **v,** vapor**; w,** water.

REFERENCES

Al-Nimr MA (1998). Dynamic thermal behaviour of cooling towers. Energy Convers. Manage., 39: 631 – 6.
Badran AA (2003). Performance of cool towers under various climates in Jordan. Energy Build., 35: 1031 – 5.
Fredman T, Saxén H (1995). Modeling and simulation of a cooling tower. In European simulation multiconference, Prague, p. 66 – 70.
Giorgia F, Cortinovis, José L, Paiva, Tah W, Song, José MP (2009). A systemic approach for optimal cooling tower operation. Energy Conv. Manage., 29(14-15): 3124-3131.
Jin GY, Cai WJ, Lu L, Lee EL, Chiang AA. (2007). Simplified modeling of mechanical cooling tower for control and optimization of HVAC systems. Energy Convers. Manage., 48: 355 – 65.
Kairouani L, Hassairi M, Tarek Z (2004). Performance of cooling tower in south of Tunisia. Build. Environ., 39: 351–5.
Kern DQ (1997). Process heat transfer. (New York, McGraw-Hill), (36):2: 149-159.
Kloppers JC, Kroger DG (2005). The Lewis factor and its influence on the performance prediction of wet-cooling towers. Int. J. Therm. Sci., 44: 879 – 84.
Lebrun J, Silva CA (2002). Cooling tower—model and experimental validation. ASHRAE Trans., pp. 751–9.
Lemouari M, Boumaza M, Mujtaba IM (2007). Thermal performances investigation of a wet cooling tower. Appl. Therm. Eng., 27: 902 – 9.
Lowe HJ, Christie DG, (1962). Heat transfer and pressure drop data on cooling tower packings, and model studies of the resistance of natural draft towers to air flow. Inst. Mech. Eng. (Steam Group) Symposium Heat Trans., 113: 933.
Pannkoke T (1996). Cooling tower basics. Heat, Piping, Air Cond., 68: 137–55.
Sirok B, Blagojevic B, Novak M, Hocevar M, Jere F (2003). Energy and mass transfer phenomena in natural draft cooling towers. Heat. Transf. Eng., 24: 66 – 75.

Smrekar J, Oman J, Sirok B (2006). Improving the efficiency of natural draft cooling towers. Energy Convers. Manage., 47: 1086 – 100.
Soylemez MS (2004). On the optimum performance of forced draft counter flow cooling towers. Energ. Convers. Manage., 45: 2335 – 41.
Stoecker WF, Jones JW (1985). Refrigeration and air conditioning. (Singapore) .1: 74-81.
Tan K, Deng SA (2003). Numerical analysis of heat and mass transfer inside a reversibly used water cooling tower. Build Environ., 38: 91 – 7.
Thomas WJ, Houston P (1959a). Simultaneous heat and mass transfer in cooling towers. Brit. Chem. Eng., 160: 217.
Thomas WJ, Houston P (1959b). Simultaneous heat and mass transfer in cooling towers. Brit. Chem. Eng., 160: 217.
Treybal RE (1981). Mass transfer operations. (New York, McGraw-Hill).
Zhai Z, Fu S (2006). Improving cooling efficiency of dry-cooling towers under cross-wind conditions by using wind-break methods. Appl. Therm. Eng., 26: 1008 – 17.