Combined Heat and Mass Transfer

Lec 7: Humidification-Part 3

Content

Theory and calculation of water cooling towers, Continuous countercurrent adiabatic water cooling, Design of water cooling tower using film mass transfer coefficients,

Prof. Zayed Al-Hamamre

Content

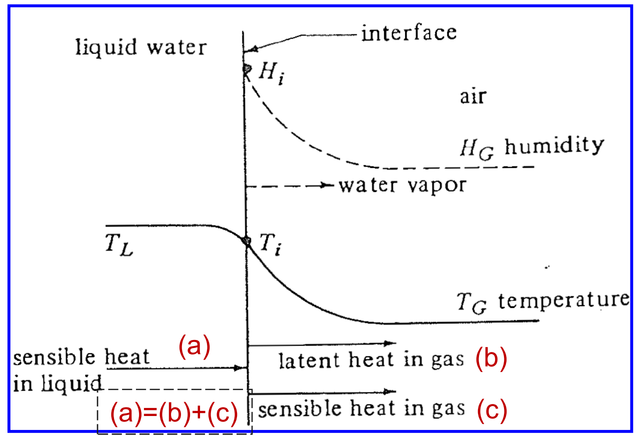
- Theory and calculation of water cooling towers
- Continuous countercurrent adiabatic water cooling
- Design of water cooling tower using film mass transfer coefficients
- Energy Efficiency Opportunities

Principal references: Chapter 9 (Drying) and Chapter 10 (Gas-liquid separation Processes) in C.J. Geankoplis book;
Chapter 19 (Humidification operations) in McCabe et al. book; Chapter 7 (Humidification operations) in Treybal book ;
Chapter 18 Seader & Roper book.

Theory and calculation of water cooling towers

In the figure:

Temperature and concentration profiles:



- There is no driving force for mass transfer in the liquid phase, since water is a pure liquid.
- The bulk gas phase with a driving force in the gas phase of $\Delta H = (H_i - H_G)$ kg H_2O/kg dry air
- The temperature driving force is $\Delta T_L = T_L - T_i$; in the liquid phase and $\Delta T_G = T_i - T_G$ **K** or °C in the gas phase.
- Latent heat also leaves the interface in the water vapor, diffusing to the gas phase.

➢ The sensible heat flow from the liquid to the interface equals the sensible heat flow in the gas plus the latent heat flow in the gas

Theory and calculation of water cooling towers

➢ These profiles occur in the upper part of the cooling tower.

➢ In the lower part, the bulk water temperature (T_L) my be below the dry bulb temperature (T_G). Then, the direction of sensible heat flow is reversed.

Continuous countercurrent adiabatic water cooling:

- Define the following:

L= water flow, kg water/s·m²

T_L = water temperature, °C or K

G = dry air flow rate, kg/s·m²

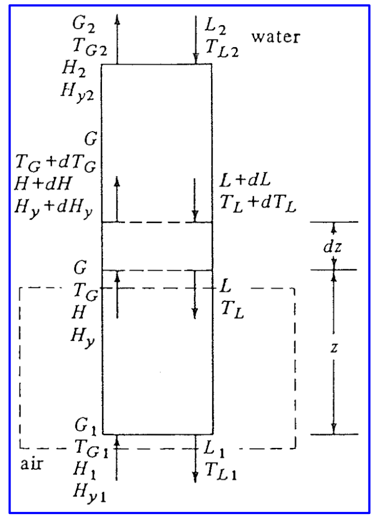
T_G = air temperature, °C or K

H = Humidity of air, kg water/kg dry air*

H_y = enthalpy of air-water vapor mixture, J/kg dry air

λ_o=latent heat of water, J/kg

c_S= humid heat = $c_L + c_G$*H



The enthalpy, H_y given by:

$$H_y = c_s(T - T_o) + H\lambda_o$$
$$= (1.005 + 1.88H)10^3(T - 0) + 2.501\times 10^6 H$$

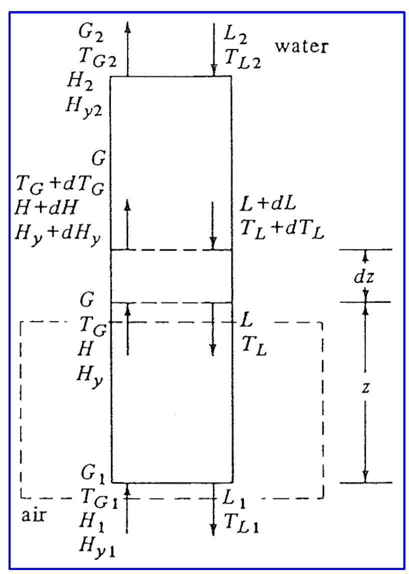
*Humidity, H can be retrieved from the humidity chart

Continuous countercurrent adiabatic water cooling:

- Assumptions

i. Flow rate of gas and liquid water is assumed constant since only a small water evaporated (1-5%).

ii. c_L is assumed constant at 4.187×10³ J/kg·K



- Perform the energy/heat balance:

Heat emitted=Heat absorbed

1) Heat balance for dashed line box making a heat balance for the dz column height :

→ Total sensible heat transferred from bulk fluid to interface;

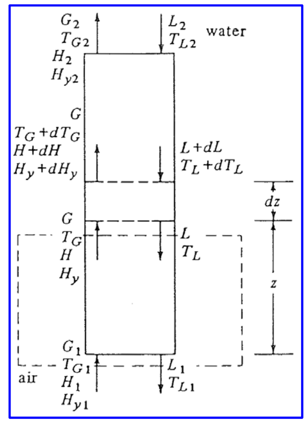
$$\mathbf{Lc_L dT_L = G dH_y = h_L \cdot a \cdot dz (T_L - T_i)}$$

Continuous countercurrent adiabatic water cooling:

$$Lc_L dT_L = G dH_y = h_L \cdot a \cdot dz (T_L - T_i)$$

Liquid phase volumetric heat transfer coefficient

$a = A/V$ (m^2/m^3)



Considering the two terms to left, Integration

$$G(H_y - H_{y1}) = Lc_L (T_L - T_{L1})$$

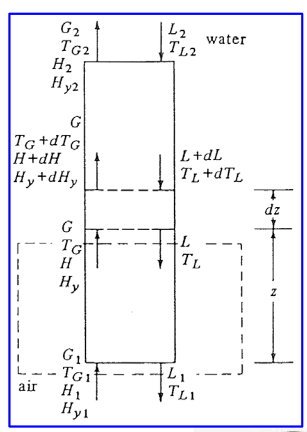
- Rearrange the above Eq. to have the following **operating line Eq.**:

$$H_y = (H_{y1} - T_{L1} \frac{Lc_L}{G}) + \frac{Lc_L}{G} T_L$$

Continuous countercurrent adiabatic water cooling:

When plotted on a chart of H_y versus T_i, this Equation is a straight line

$$\text{Intercept} = H_{y1} - T_{L1} \frac{Lc_L}{G} \quad ; \quad \text{Slope} = \frac{Lc_L}{G}$$



- Also, making an overall heat balance over both ends of the tower,

$$G(H_{y2} - H_{y1}) = Lc_L (T_{L2} - T_{L1})$$

→ To draw the operating line we need either two points or one point and slope (Lc_L/G).

Continuous countercurrent adiabatic water cooling:

1. Draw the equilibrium curve: the enthalpy of saturated air versus the dew point temperature T_L using:

$$H_{yi} = c_S (T_L - T_0) + H_i \lambda_0$$

where the T_0 is the base temperature:

T_0 =0 °C : λ_0=2502.3 kJ/kg water

T_0 =32 °F : λ_0=1075.8 Btu/lbm water

$$c_S = 1.005 + 1.88 H_i \text{ ; kJ/(kg dry air.K)}$$
$$= 0.24 + 0.45 H_i \text{ ; btu/(lbm dry air.°F)}$$

→ H_{yi} = $(1.005 + 1.88\ H_i)10^3\ (T-0) + 2.501\times10^6\ H_i$, J/kg air

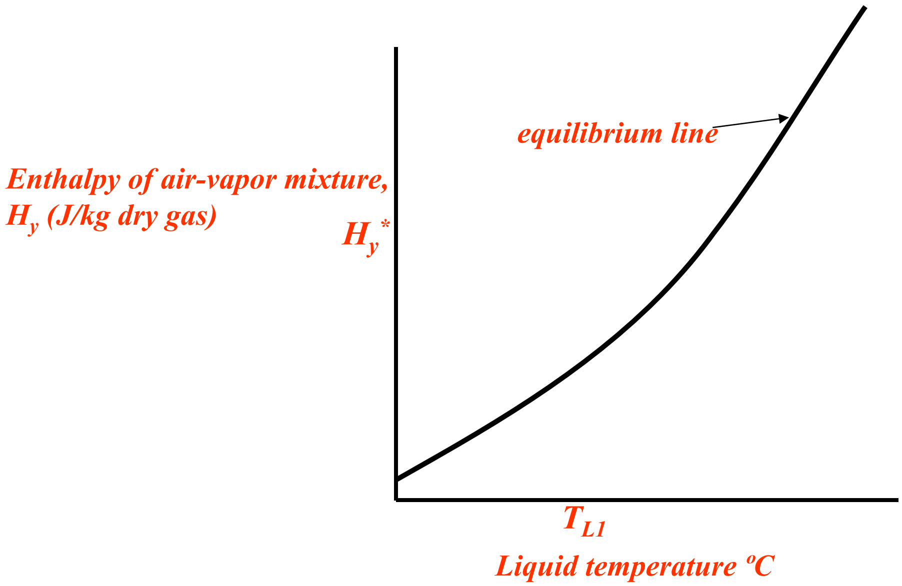
H_i is the saturated humidity picked up from the psychrometric chart at T_L.

Continuous countercurrent adiabatic water cooling:

TABLE 10.5-1. *Enthalpies of Saturated Air–Water Vapor Mixtures (0°C Base Temperature)*

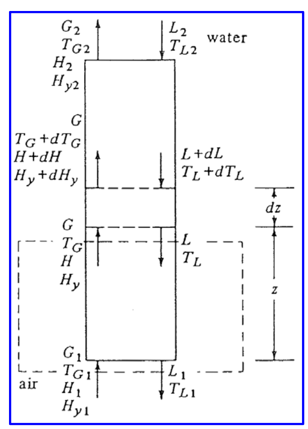
T_L		H_y		T_L		H_y	
		btu	J			btu	J
°F	°C	lb_m dry air	kg dry air	°F	°C	lb_m dry air	kg dry air
60	15.6	18.78	43.68×10^3	100	37.8	63.7	148.2×10^3
80	26.7	36.1	84.0×10^3	105	40.6	74.0	172.1×10^3
85	29.4	41.8	97.2×10^3	110	43.3	84.8	197.2×10^3
90	32.2	48.2	112.1×10^3	115	46.1	96.5	224.5×10^3
95	35.0	55.4	128.9×10^3	140	60.0	198.4	461.5×10^3

Continuous countercurrent adiabatic water cooling:



- **Draw the operating line Eq.**:

$$H_y = (H_{y1} - T_{L1}\frac{Lc_L}{G}) + \frac{Lc_L}{G}T_L$$

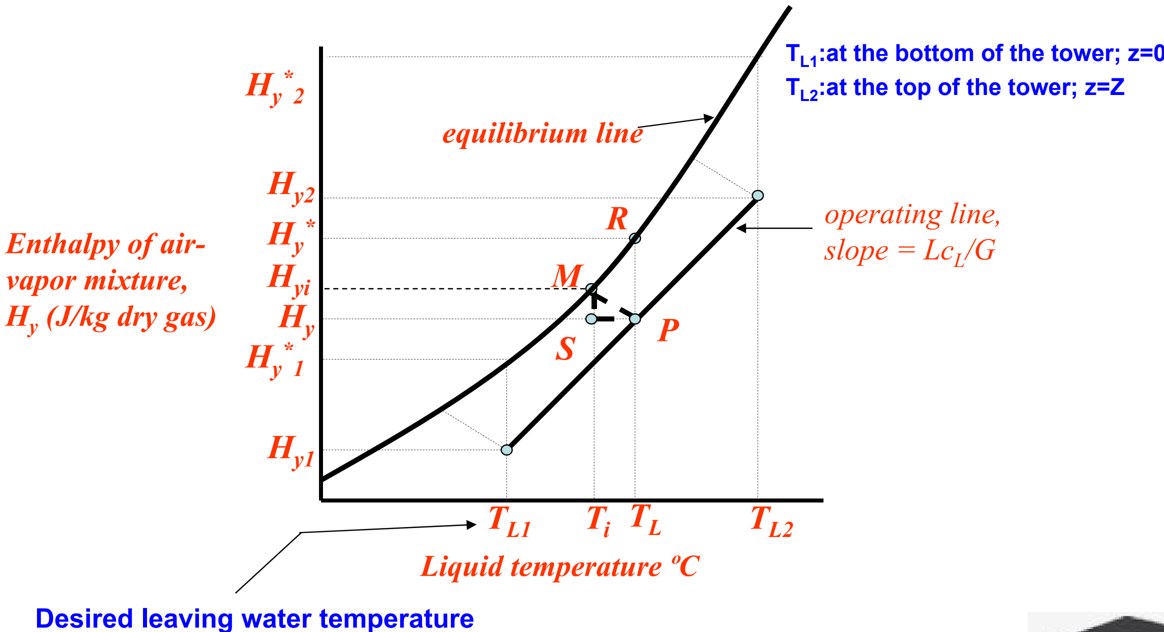


- Knowing the entering air conditions T_{G1} and H_1, the enthalpy of this air H_{y1} is calculated
- The point H_{y1} and T_{L1} (desired leaving water temperature) is plotted as one point on the operating line (T_{L1} and H_{y1})

$$\text{Intercept} = H_{y1} - T_{L1}\frac{Lc_L}{G} \quad ; \quad \text{Slope} = \frac{Lc_L}{G}$$

- Knowing T_{G2} and H_2, the enthalpy of this air H_{y2} can be also calculated and the point (T_{L2} and H_{y2}) is plotted as a second point on the operating line

Continuous countercurrent adiabatic water cooling:



Continuous countercurrent adiabatic water cooling:

- We know from **mass transfer course,** that the flux, N_A, for species A (water vapor) diffusing through stagnant gas (air) is:

$$N_A = k_y(y_{A,i} - y_{A,G}) = k_G(P_{A,i} - P_{A,G})$$

$$k_y = k_G P$$

where k_G is gas-phase film mass transfer coefficient in kgmol/(s.m^2.Pa), $P_{A,i}$ and $P_{A,G}$ is the water vapor partial pressure at the interface and in the bulk gas-phase, respectively. While y is water vapor mole fraction.

- The **mass-transfer interfacial area** between air and water droplets **is not known.**
- This film mass-transfer interfacial area is different from the surface area of packing. Here, **a quantity (a_M)**, defined as interfacial area per volume of packing section, is combined with the gas-phase mass transfer coefficient, k_G , to give a **volumetric film mass transfer coefficients** defined as (**k_G a_M**) in kgmol/(s.m^3.Pa).

Continuous countercurrent adiabatic water cooling:

- Now the volumetric diffusion rate of water vapor, $N_{A,vol}$ is:

$$N_{A,vol} = k_y a_M (y_{A,i} - y_{A,G}) = k_G a_M (P_{A,i} - P_{A,G})$$

- **The relationship between humidity and mole fraction is:**

$$y = \frac{H/M_A}{1/M_B + H/M_A}$$

- where M_A and M_B is the molecular weight of water vapor and air, respectively.
- Since *H* is small, an approximation of the relationship is:

$$y \cong \frac{M_B H}{M_A} \qquad N_{A,vol} = k_y a_M (y_{A,i} - y_{A,G}) \longrightarrow N_{A,vol} = \frac{M_B}{M_A} k_y a_M (H_i - H_G)$$

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Continuous countercurrent adiabatic water cooling:

Where;

H_i is the humidity of the gas at the interface in kg water/kg dry air, and

H_G is the humidity of the gas in the bulk gas phase in kg water/kg dry air

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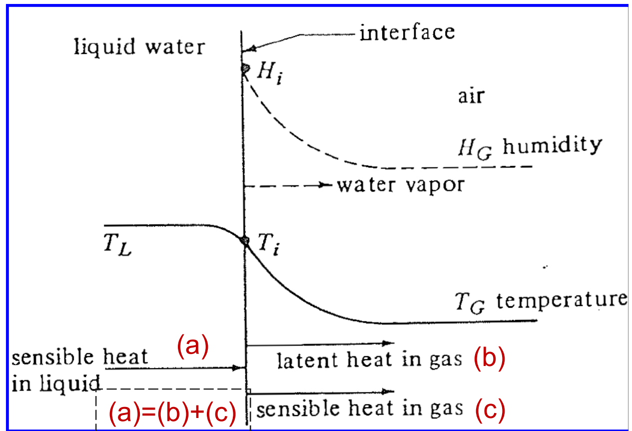
Continuous countercurrent adiabatic water cooling:

$$Lc_L dT_L = G dH_y = h_L \cdot a \cdot dz (T_L - T_i)$$

- h_L: Liquid phase volumetric heat transfer coefficient
- $a = A/V$ (m^2/m^3)

Temperature and concentration profiles



- The sensible heat flow from the liquid to the interface = the sensible heat flow in the gas + the latent heat flow in the gas

(a) = (b) + (c)

Continuous countercurrent adiabatic water cooling:

- The latent heat in the water vapor being transferred over volume dv=Adz height column is:

$$dQ_\lambda = N_{A,vol} \lambda_0 M_A dV$$

$$dV = dzA$$

$$N_{A,vol} = M_B k_y a_M (H_i - H_G) / M_A$$

$$dQ_\lambda = M_B k_y a_M (H_i - H_G) \lambda_0 A dz$$

- Further, the rate of sensible heat transfer (**convective heat transfer rate in gas phase)** over volume dv =Adz is:

$$dQ_{Conv} = h_G \cdot a_{H,G} \cdot dz \cdot A\ (T_i - T_G)$$

Continuous countercurrent adiabatic water cooling:

$dQ = dQ_{\lambda} + dQ_{Conv}$

$$dq = \frac{dQ}{A} = \left[M_B k_y a_M (H_i - H_G)\lambda_0 + h_G a_{H,G} (T_i - T_G) \right] dz$$

- It is found that for water vapor-air mixture the experimental value of which is called the **psychrometric ratio** is closed to **humid heat** c_S:

$$(h_G a_{H,G} / M_B k_y a_M)$$

$$c_S \cong \frac{h_G a_{H,G}}{M_B k_y a_M} \xrightarrow{k_y = k_G P} c_S \cong \frac{h_G a_{H,G}}{M_B P k_G a_M}$$

(Lewis relation)

Continuous countercurrent adiabatic water cooling:

- Using the above Lewis relation:

$$dq = \left[M_B k_y a_M (H_i - H_G)\lambda_0 + h_G a_{H,G} (T_i - T_G) \right] dz$$

$$c_S \cong \frac{h_G a_{H,G}}{M_B P k_G a_M}$$

$$dq = M_B P k_G a_M \left[H_i \lambda_0 + c_S T_i - (c_S T_G + \lambda_0 \mathrm{H}_G) \right] dz$$

- **adding and subtracting $c_S T_0$ inside the bracket of the above Eq.:**

$$dq = M_B P k_G a_M \left[c_S (T_i - T_0) + H_i \lambda_0 - (c_S (T_G - T_0) + \lambda_0 H_G) \right] dz$$

Continuous countercurrent adiabatic water cooling:

$$H_y = c_S(T_G - T_0) + \lambda_0 H_G$$

Enthalpy of water vapor-air mixture at T_G

$$H_{yi} = c_S(T_i - T_0) + H_i \lambda_0$$

Enthalpy of water vapor-air mixture at T_i

$$\rightarrow \quad dq = M_B P k_G a_M \left[H_{yi} - H_y \right) dz$$

But $dq = G dH_y$

$$\rightarrow \quad Z = \frac{G}{M_B P k_G a_M} \int_{H_{y1}}^{H_{y2}} \frac{dHy}{H_{yi} - H_y}$$

Design Eq. of the cooling tower

Continuous countercurrent adiabatic water cooling:

$$Z = \underbrace{\frac{G}{M_B P k_G a_M}}_{\text{HTU}} \underbrace{\int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_{yi} - H_y}}_{\text{NTU}} \equiv (\text{HTU})(\text{NTU})$$

HTU ≡ Height of a transfer unit
NTU ≡ Number of transfer units

- **The enthalpy, H_{yi}, at the interface temperature T_i is determined from:**

$$dq = M_B P k_G a_M \left[H_{yi} - H_y \right) dz$$

$$dq = h_L a_{H,L} (T_L - T_i) dz$$

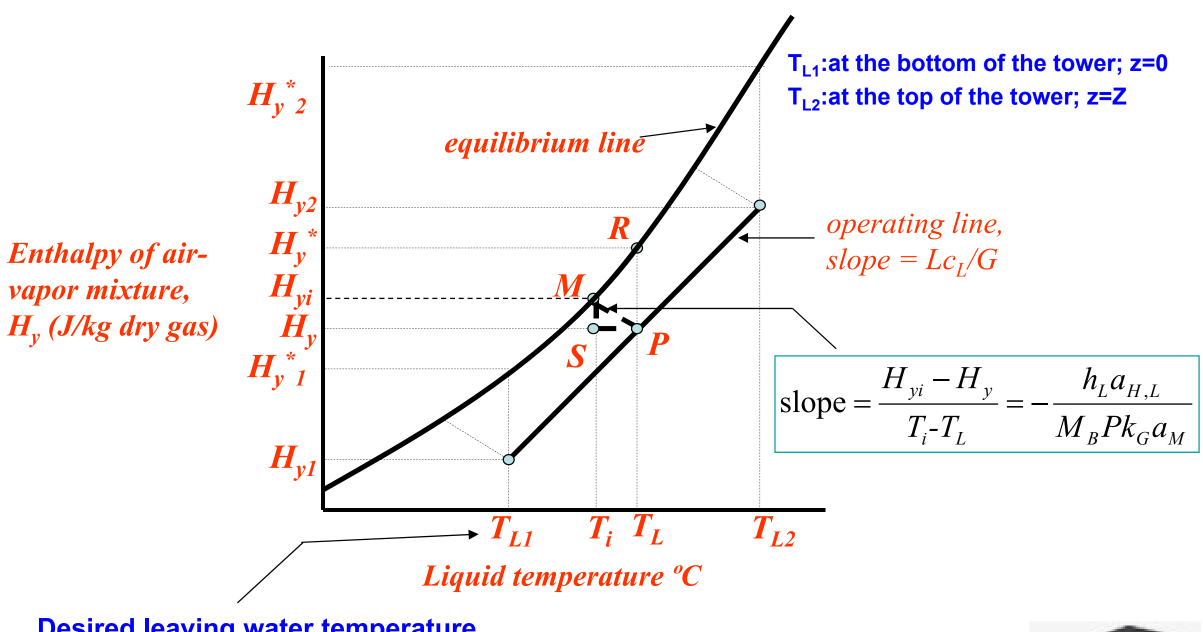
$$\downarrow$$

$$\frac{H_{yi} - H_y}{T_i - T_L} = -\frac{h_L a_{H,L}}{M_B P k_G a_M}$$

Continuous countercurrent adiabatic water cooling:

- For getting small approach, cooling tower height must be increased.
- To achieve zero (0) approach theoretically, infinite packing height is needed.

Continuous countercurrent adiabatic water cooling:



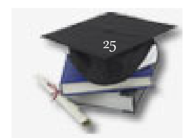
Design of water cooling tower using film mass transfer coefficients: Procedure

1. Draw the equilibrium curve:

- The enthalpy of saturated air H_{yi} is plotted versus T_i on an $\boldsymbol{H}$ versus T plot. This enthalpy is calculated using the equation

$$H_{yi} = (1.005 + 1.88\, H_i)10^3\,(T\text{-}0) + 2.501\text{x}10^6\, H_i \quad \text{, J/kg air}$$

H_i is the saturated humidity picked up from the psychrometric chart for a given temperature.



Design of water cooling tower using film mass transfer coefficients: Procedure

2. Draw the operating line:

- Use the operating line equation

$$H_y = (H_{y1} - \mathrm{T}_{L1}\frac{Lc_L}{G}) + \frac{Lc_L}{G}T_L$$

and/or the overall steady-state heat balance over the entire cooling tower:

$$G(H_{y2} - H_{y1}) = Lc_L(T_{L2} - \mathrm{T}_{L1})$$

H_{y1} and H_{y2} is the gas mixture enthalpy at T_{G1} and T_{G2} , respectively.

→ To draw the operating line we need either two points or one point and slope (Lc_L/G).

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Design of water cooling tower using film mass transfer coefficients

3. Draw lines with slope:

$$\frac{H_{yi}-H_y}{T_i\text{-}T_L}=-\frac{h_L a_{H,L}}{M_B P k_G a_M}=\text{Slope}=\frac{H_{yi1}-H_{y1}}{T_{i1}\text{-}T_{L1}}=\frac{H_{yi2}-H_{y2}}{T_{i2}\text{-}T_{L2}}$$

- Select some value of T_i and read H_{yi} from the equilibrium curve.
- Select some value of T_L and calculate H_y from the above equation.
- Draw a line pass through the points (T_i, H_{yi}) and (T_L, H_y) this line must have slope of $h_L a_{H,L}/(M_B P k_G a_M)$.
- At 6 to 8 locations, draw parallel lines (slope= - $h_L a_{H,L}/(M_B P k_G a_M$) from T_{L1} to T_{L2} to read enthalpies H_{yi} from equilibrium curve.

Design of water cooling tower using film mass transfer coefficients

4. Calculate the number of transfer units (NTU):

- Use Enthalpy vs. T_L graph to find the driving force H_{yi}-H_y for various T_L value from T_{L1} to T_{L2}.
- Calculate $1/(H_{yi}$-$H_y)$ for various T_L value from T_{L1} to T_{L2}.
- Perform graphical or numerical integration to calculate NTU:

$$\text{NTU}=\int_{H_{y1}}^{H_{y2}}\frac{dH_y}{H_{yi}-H_y}$$

5. Calculate the height of a transfer unit umber of transfer units (HTU):

$$\text{HTU}=\frac{G}{M_B P k_G a_M}$$

6. Calculate the height of the cooling tower: $Z=(\text{HTU})(\text{NTU})$

Example

A packed countercurrent water-cooling tower using gas flow rate of 1.356 kg dry air/(s.m^2) and water flow rate of 1.356 kg (s.m^2). The water is cooled from 43.3 to 29.4 ^{o}C. The entering air at 29.4 ^{o}C has a wet bulb temperature of 23.9 ^{o}C. The gas film mass-transfer coefficient is estimated as 1.207×10^{-7} kgmol/(s.m^3.Pa). $h_L a_{H,L}/(M_B P k_G a_M)$ has a value of 41.87 kJ/(kg.K). The tower operates at 1 atm. **Calculate the Range, The approach, the tower effectiveness, and the height of the packed tower.**

Solution: $G = L = 1.356 \text{ kg/(s.m}^2)$ $T_{L1} = 29.4\ ^oC$ $T_{L2} = 43.3\ ^oC$

$T_{G1} = 29.4\ ^oC;\ T_{WB1} = 23.9\ ^oC$ $k_G a_M = 1.207\times10^{-7} \text{ kmol/(s.m}^3)$

$$\text{Range} = T_{L2} - T_{L1} = 43.3 - 29.4 = 13.9\ ^oC$$

$$\text{Approach} = T_{L1} - T_{WB,1} = 29.4 - 23.9 = 5.5\ ^oC$$

$$\text{Effectivness} = 100 \times \text{Range}/0(\text{Range} + \text{Approach}) = 71.6\%$$

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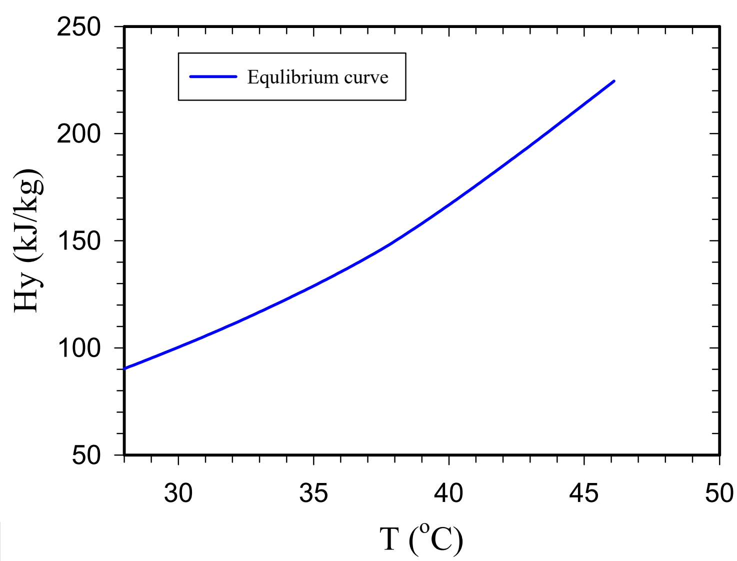
Solution

Height of the packed tower.

1. **Draw the equilibrium curve:** use saturated humidity curve in the psychrometric chart and enthalpy Eq. to get:

T_L	H_{yi}, kJ/kg
15.6	43.7
26.7	84.0
29.4	97.2
32.2	112.1
35.0	128.9
37.8	148.2
40.6	172.1
43.3	197.2
46.1	224.5



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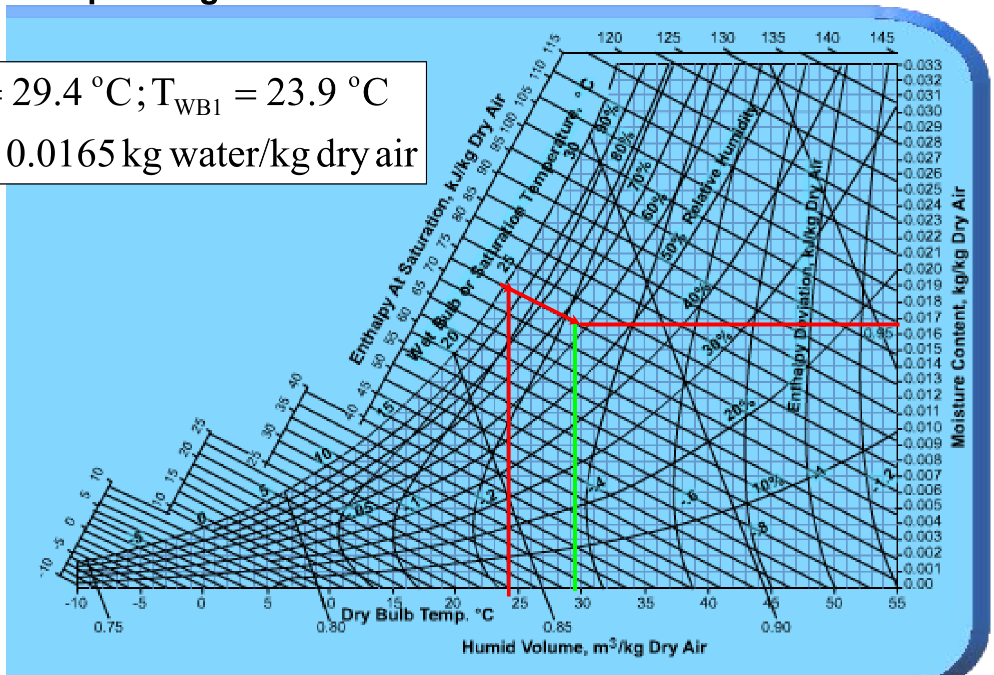
Solution Cont.d

2. Draw the operating line:

$$T_{G1} = 29.4\ ^{o}\mathrm{C};\ \mathrm{T_{WB1}} = 23.9\ ^{o}\mathrm{C}$$
$$\mathrm{H_1} = 0.0165\ \mathrm{kg\ water/kg\ dry\ air}$$



Solution Cont.d

2. Draw the operating line:

$$c_S = 1.005 + 1.88H_1 = 1.005 + 1.88(0.0165) = 1.036\ \mathrm{kJ/(kg\ dry\ air.K)}$$

$$H_{y1} = c_S(T_{G1} - T_0) + H_i\lambda_0 = 1.036(29.4 - 0) + (0.0165)(2502.3) = 71.7\ \mathrm{kJ/kg}$$

Apply overall steady-state heat balance over the entire cooling to get H_{y2}:

$$G(H_{y2} - H_{y1}) = Lc_L(T_{L2} - \mathrm{T}_{L1})$$

$$G = L = 1.356\ \mathrm{kg/(s.m^2)}$$ $$c_L = 4.187\mathrm{kJ/(kg.K)}$$

$$T_{L1} = 29.4\ ^{o}\mathrm{C}$$ $$T_{L2} = 43.3\ ^{o}\mathrm{C}$$ $$H_{y1} = 71.7\ \mathrm{kJ/kg}$$

$$H_{y2} = 129.9\ \mathrm{kJ/kg}$$

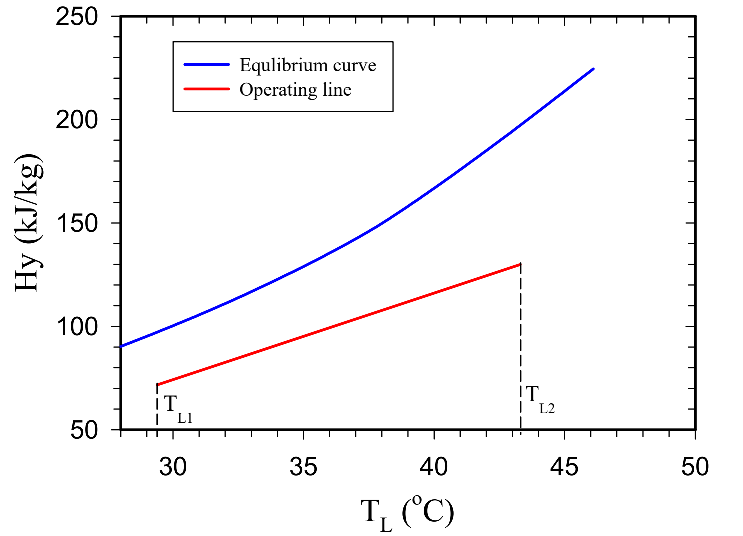
We have two points enough to draw the operating line:

$$(T_{L1}, H_{y1}) = (29.4\ ^{o}\mathrm{C}, 71.7\ \mathrm{kJ/kg})$$ $$(T_{L2}, H_{y2}) = (43.3\ ^{o}\mathrm{C}, 129.9\ \mathrm{kJ/kg})$$

Solution Cont.d

2. Draw the operating line:

$$(T_{L1}, H_{y1}) = (29.4\,^{o}\text{C}, 71.7\,\text{kJ/kg}) \qquad (T_{L2}, H_{y2}) = (43.3\,^{o}\text{C}, 129.9\,\text{kJ/kg})$$



Solution Cont.d

3. Draw lines with constant slope:

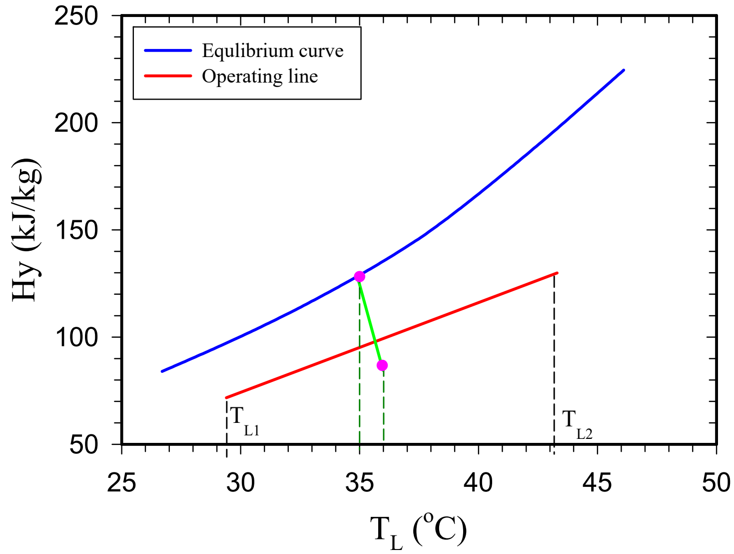
- For example, at T_i =35 ^{o}C, from the equilibrium curve H_{yi} =128.9 kJ/kg .
- at T_L= 36 ^{o}C, calculate H_y from:

$$\frac{H_{yi} - H_y}{T_i\text{-}T_L} = \frac{128.9 - H_y}{35\text{-}36} = -\frac{h_L a_{H,L}}{M_B P k_G a_M} = -41.87\,\text{kJ/(kg.K)}$$

$$H_y = 87.03\,\text{kJ/kg}$$

- Draw a line passes through the points (35 ^{o}C, 128.9 kJ/kg) and (36 ^{o}C, 87.03 kJ).

3. Draw lines with constant slope:



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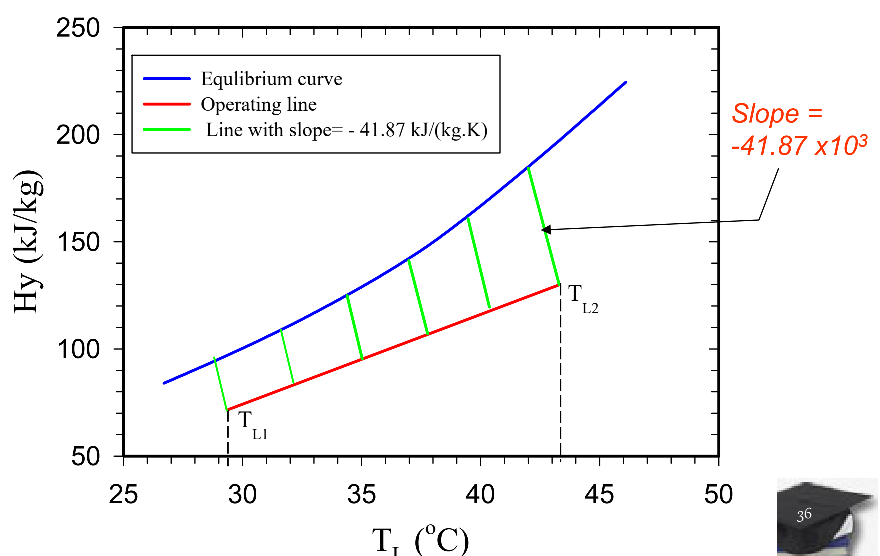
4. Calculate the number of transfer units (NTU):

- At 6 to 8 locations, draw parallel lines as shown below from T_{L1} to T_{L2} to read enthalpies H_{yi} from equilibrium curve



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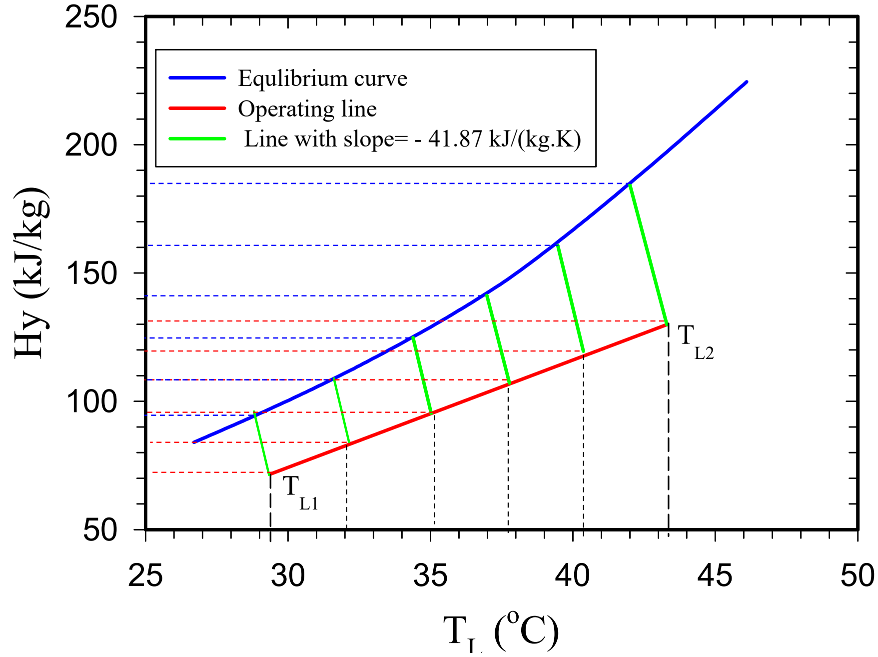


Solution Cont.d

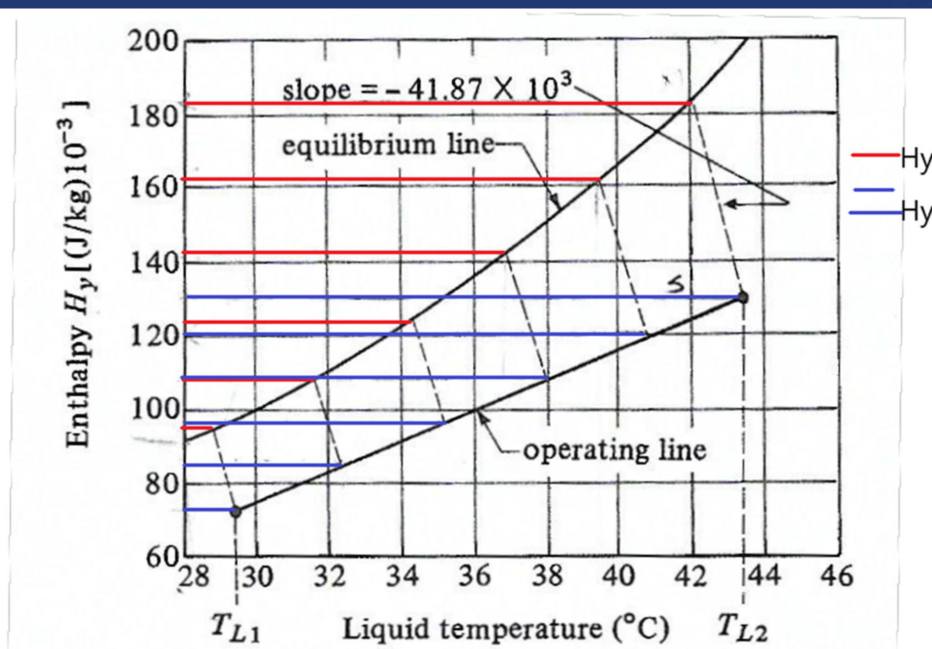


FIGURE 10.5-4. *Graphical solution of Example 10.5-1.*

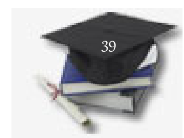
Solution Cont.d

4. Calculate the number of transfer units (NTU):

H_{yi} (kJ/kg)	H_y (kJ/kg)	H_{yi}-H_y (kJ/kg)	1/(H_{yi} - H_y); (kg/kJ)
94.4	71.7	22.7	0.0441
108.4	83.5	24.9	0.0402
124.4	94.9	29.5	0.0339
141.8	106.5	35.3	0.0283
162.1	118.4	43.7	0.0229
184.7	129.9	54.8	0.0182

- Using Trapezoidal rule of numerical integration:

$$\text{NTU} = \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_{yi} - H_y} \cong 1.82$$



Solution Cont.d

5. Calculate the height of a transfer unit (HTU):

$$\text{HTU} = \frac{G}{M_B P k_G a_M} = \frac{1.356}{(29)(101325)(1.207 \times 10^{-7})} = 3.82\,\text{m}$$

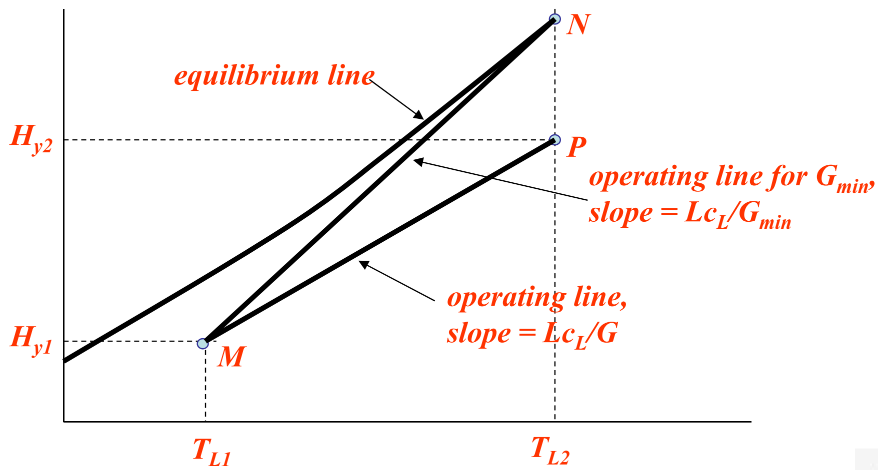
6. Calculate the height of the cooling tower:

$$\text{Z} = (\text{HTU})(\text{NTU}) = (3.82)(1.82) = 6.96\,\text{m}$$

Minimum value of air flow G_{min}:

- Minimum air flow gives maximum slope of the operating line Eq.

$$H_y = (H_{y1} - T_{L1}\frac{Lc_L}{G}) + \frac{Lc_L}{G}T_L \longrightarrow Slope_{max} = \frac{Lc_L}{G\,min}$$



Minimum value of air flow G_{min}

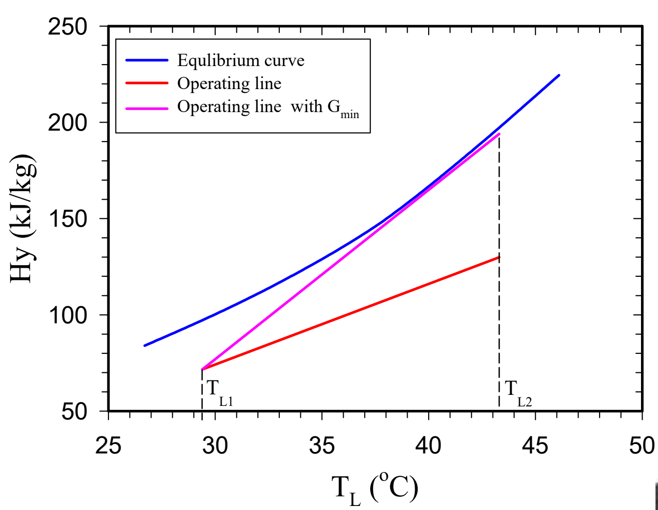
- **Minimum value of air flow G_{min}:**
- For actual cooling towers, a value of air flow rate greater than G_{min} must be used. **A reasonable value** of G is (1.3-1.5)×G_{min}.

Example. Find the minimum air flow for previous example

$$Slope_{max} = \frac{H_{y2} - H_{y1}}{T_{L2} - T_{L1}} = \frac{194 - 71.7}{43.3 - 29.4} = 8.8\,\text{kJ/(kg.K)}$$

$$Slope_{max} = \frac{Lc_L}{G_{min}}$$

$$G_{min} = \frac{Lc_L}{Slope_{max}} = 0.64\,kg/(s.m^2)$$



Design of water cooling tower using overall mass-transfer coefficients

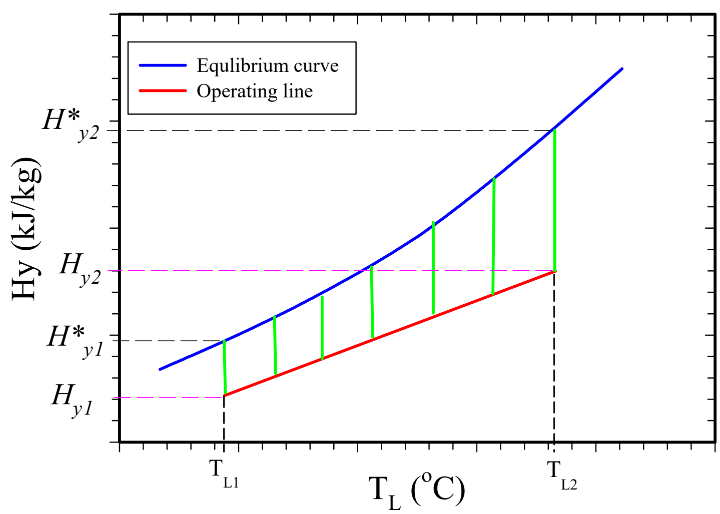
- Usually, the **overall volumetric mass-transfer coefficient** $K_G a_M$ is available and the design equation becomes:

$$Z = \underbrace{\frac{G}{M_B P K_G a_M}}_{\text{HTU}} \underbrace{\int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_y^* - H_y}}_{\text{NTU}} \equiv (\text{HTU})(\text{NTU})$$

HTU ≡ Height of a transfer unit
NTU ≡ Number of transfer units

- Use the same procedure as in film mass-transfer coefficient except that the values of H^*_y is determined by going vertically from the point H_y on the operating line up to equilibrium curve.

Design of water cooling tower using overall mass-transfer coefficients



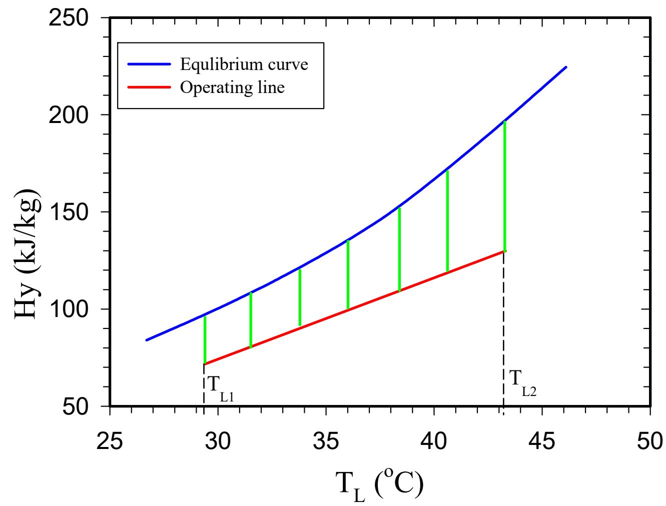
- If the experimental cooling tower data with known height (Z) are available, then design equation can be used to determine the experimental value of the overall volumetric mass-transfer coefficient.

Design of water cooling tower using overall mass-transfer coefficients

Example. Use the data and result of previous cooling tower example to estimate the overall mass-transfer coefficient $K_G a_M$.

Solution:

H_y (kJ/kg)	H^*_y (kJ/kg)
71.7	96.8
80.7	108.3
91.5	120.9
100.4	135.4
110.1	152.4
119.2	172.1
129.9	196.8



H_y (kJ/kg)	H^*_y (kJ/kg)	H^*_y-H_y (kJ/kg)	$1/(H^*_y-H_y)$ (kg/kJ)
71.7	96.8	25.1	0.0398
80.7	108.3	27.6	0.0362
91.5	120.9	29.4	0.0340
100.4	135.4	35.0	0.0286
110.1	152.4	42.3	0.0236
119.2	172.1	52.9	0.0189
129.9	196.8	66.9	0.0149

Using Trapezoidal rule:

$$\text{NTU} = \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H^*_y - H_y} \cong 1.63$$

$$\text{HTU} = \frac{Z}{\text{NTU}} = \frac{6.96}{1.63} = 4.27\ \text{m} = \frac{G}{M_B P (K_G a_M)}$$

$$K_G a_M = \frac{G}{(M_B)(P)(\text{HTU})} = \frac{1.356}{(29)(101325)(4.27)} = 1.08 \times 10^{-7}\ \text{kmol/(s.m}^3\text{.Pa)}$$

Dehumidification towers

- To reduce the humidity and temperature of air that enters.
- **For dehumidifier, the operating line must be above the equilibrium line.**
- Similar calculation methods are used.