Topic 3.5. Design of cooling tower

Last lecture

- ✓ Psychrometric (humidity) terminology
- ✓ Plot processes on a psychrometric chart and analyze processes

This lecture

- ✓ humidity of mixed streams
- ✓ Gas-liquid contact operation

The content of this topic was obtained from notes of Professor Zayed Hammouri, ChE-UoJ

Fundamental relations for adiabatic operations

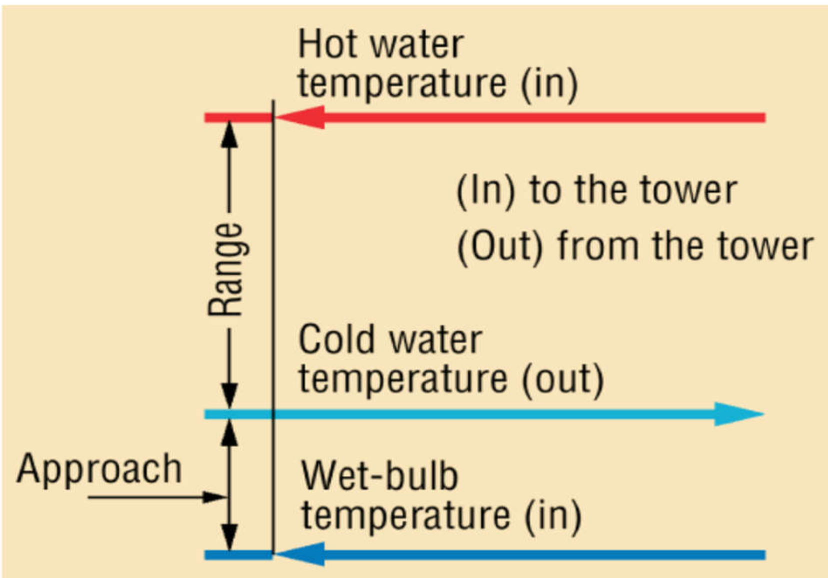
$$N_A M_A a_M \, dZ = -G'_S \, dY' = M_A F_G \left(\ln \frac{1 - \bar{p}_{A,i}/p_t}{1 - p_{A,G}/p_t} \right) a_M \, dZ$$

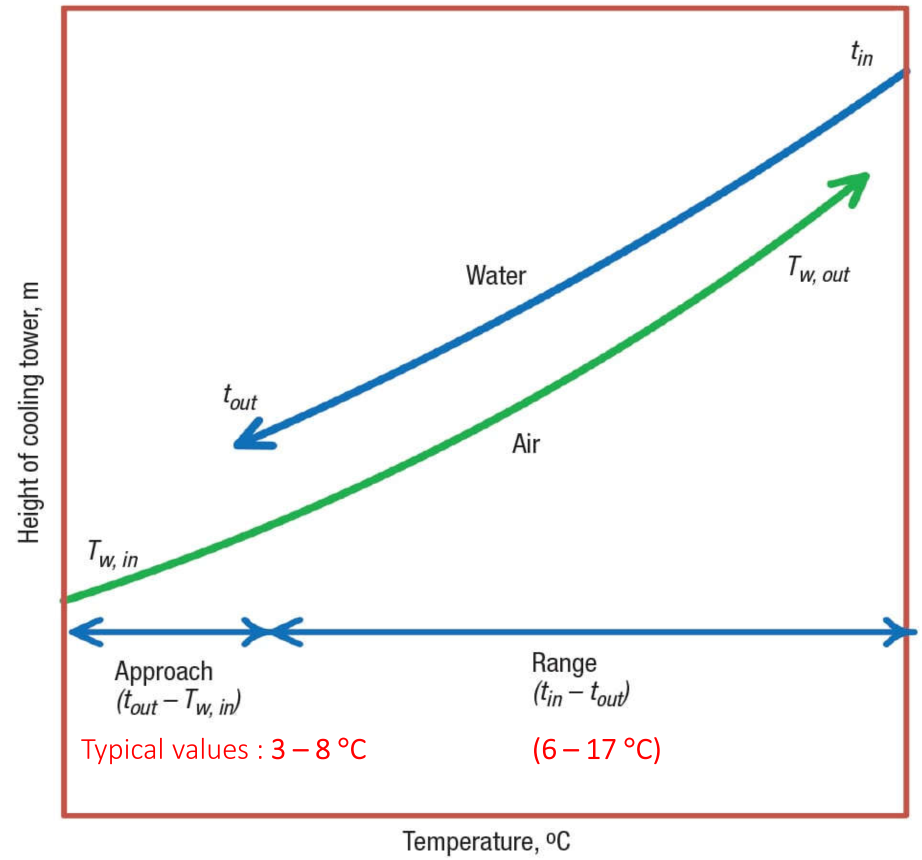
$$-G'_S C_S \, dt_G = h'_G a_H (t_G - t_i) \, dZ$$

$$L' C_{A,L} \, dt_L = (G'_S C_{A,L} \, dY' - h_L a_H \, dZ)(t_i - t_L)$$

$$L' C_{A,L} \, dt_L = G'_S \{ C_S \, dt_G + [C_A (t_G - t_0) - C_{A,L}(t_L - t_0) + \lambda_0] \, dY' \}$$

Performance parameters in cooling towers





$$Effectivness = \frac{Range}{Range + Approach} \times 100$$

- There is no driving force for mass transfer in the liquid phase, since water is a pure liquid.
- The humidity driving force in the gas phase is

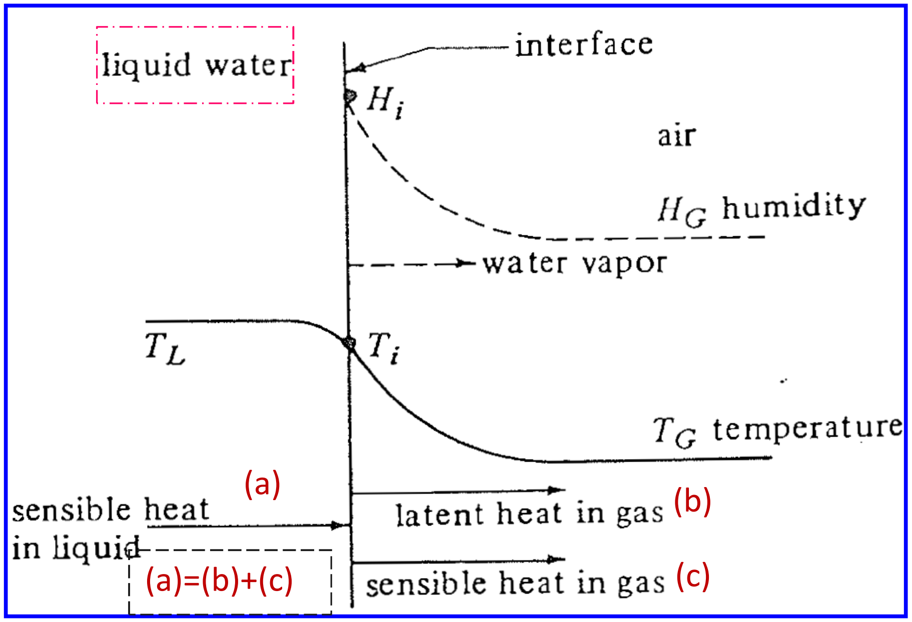
$$\Delta H = (H_i - H_G) \quad kg\ H_2O/kg\ dry\ air$$

- The temperature driving force is

$$\Delta T_L = T_L - T_i \quad \text{in the liquid phase}$$

and

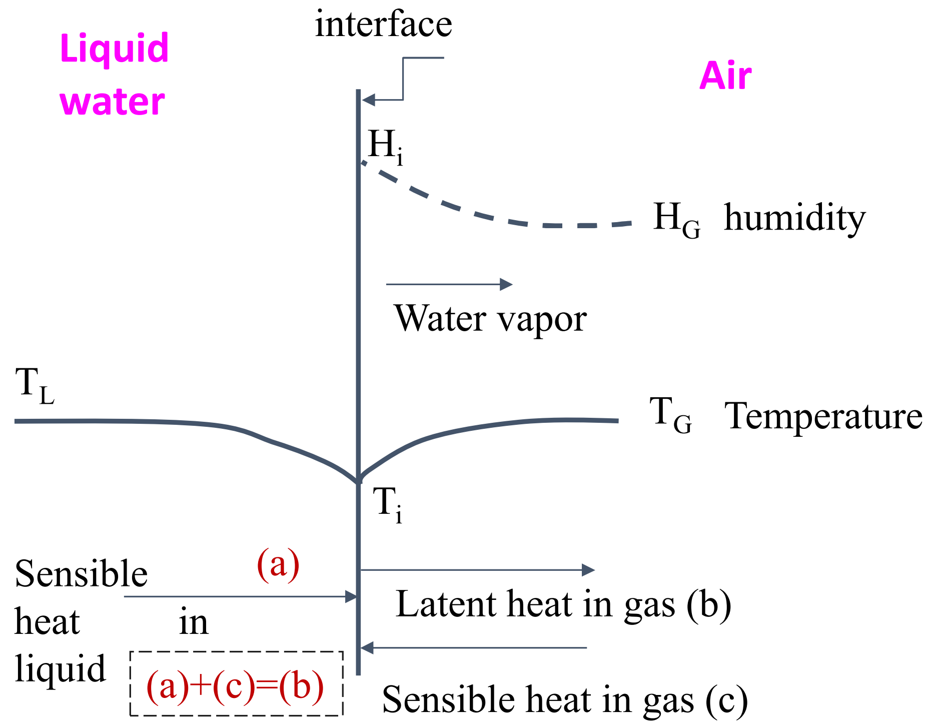
$$\Delta T_G = T_i - T_G \quad \text{in the gas phase.}$$



Temperature and humidity (concentration) profiles at the top of the cooling tower

- Latent heat 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

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



Temperature and humidity (concentration) profiles at the bottom of the cooling tower

Continuous countercurrent adiabatic water cooling

L= water flow, kg water/s·m^2

T_L = water temperature, °C or K

G = dry air flow rate, kg/s·m^2

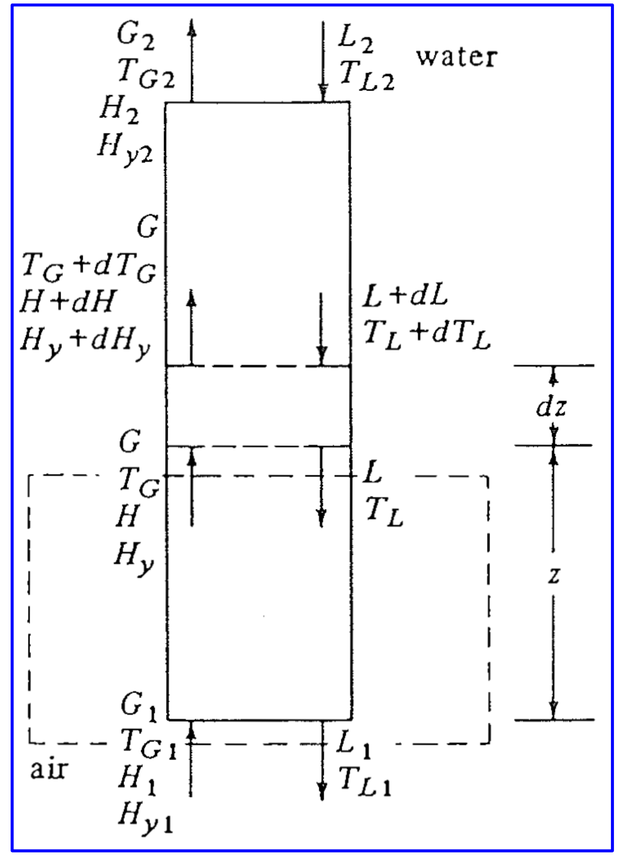
T_G = air temperature, °C or K

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:

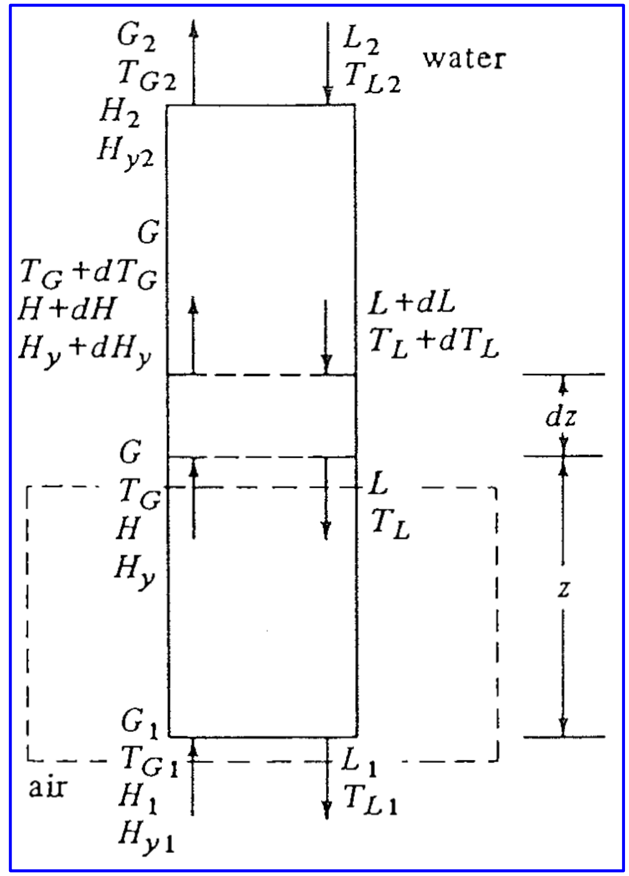
$$H_y = c_s(T - T_o) + H\lambda_o$$
$$= (1.005 + 1.88H)10^3(T - 0) + 2.501 \times 10^6 H$$

*Humidity, H can be retrieved from the humidity chart

➢ 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 $c_L = 4.187 \times 10^3$ 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 :

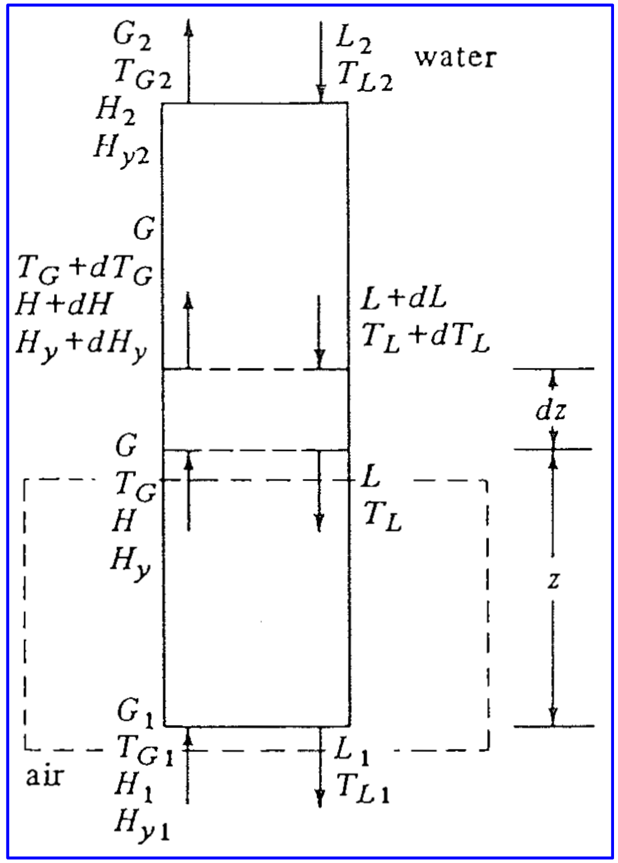
→ Total sensible heat transferred from bulk fluid to interface;

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

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

Liquid phase volumetric heat transfer coefficient

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



Considering the two terms to left, Integration

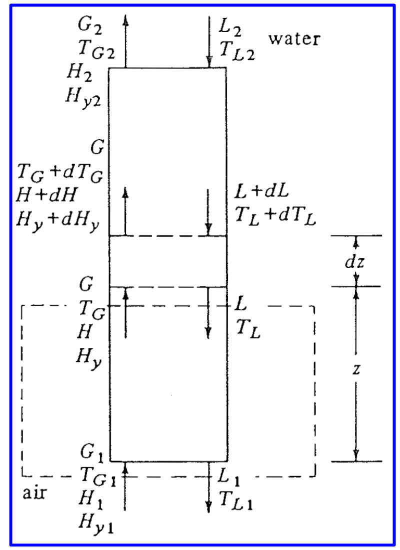
$$G\,(H_y - H_{y1}) = Lc_L\,(T_L - T_{L1})$$

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

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

When plotted on a chart of H_y versus T_L, 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).

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 ^oC : λ_0 = 2502.3 kJ/kg water

T_0 =32 ^oF : λ_0 = 1075.8 Btu/lbm water

$$\begin{aligned} c_S &= 1.005 + 1.88 H_i \text{ ; kJ/(kg dry air.K)} \\ &= 0.24 + 0.45 H_i \text{ ; btu/(lbm dry air.}^o\text{F)} \end{aligned}$$

⇒ *Enthalpy;* $H_{yi} = (1.005 + 1.88\ H_i) \times 10^3\ (T - 0) + 2.501 \times 10^6\ H_i$ *J/kg air*

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

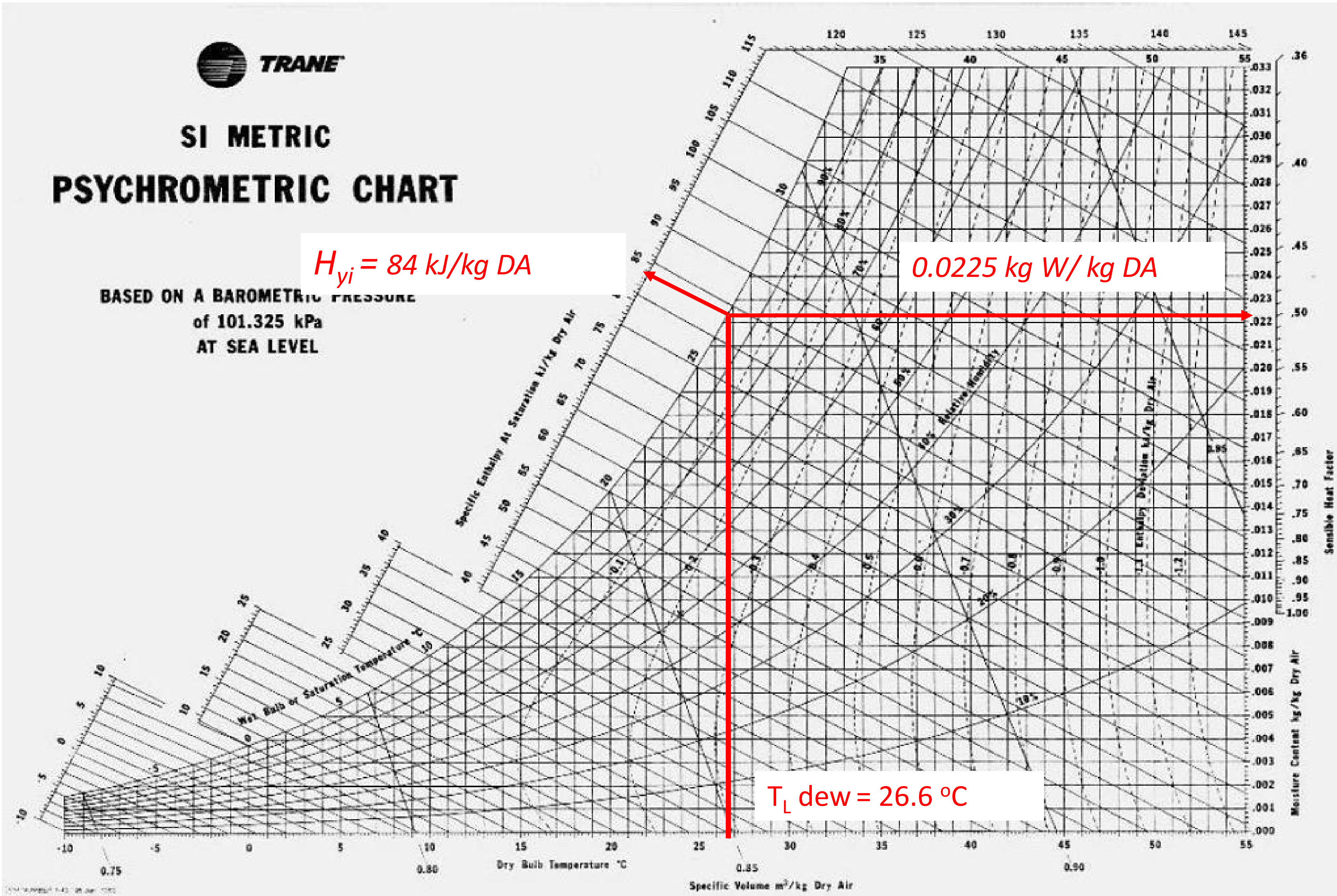
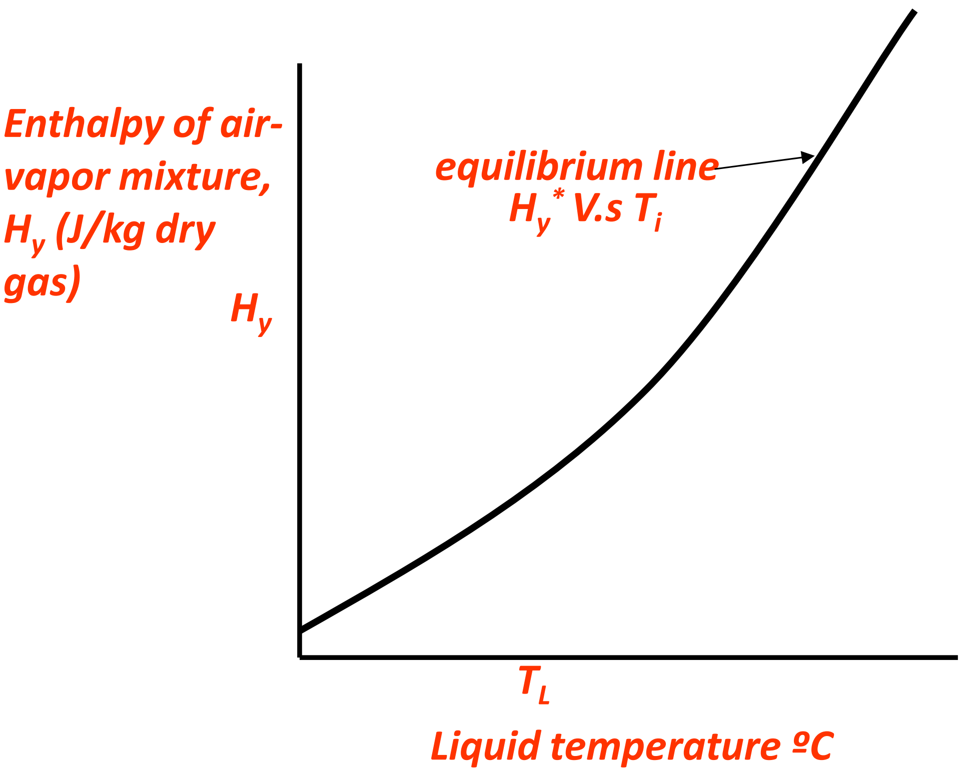
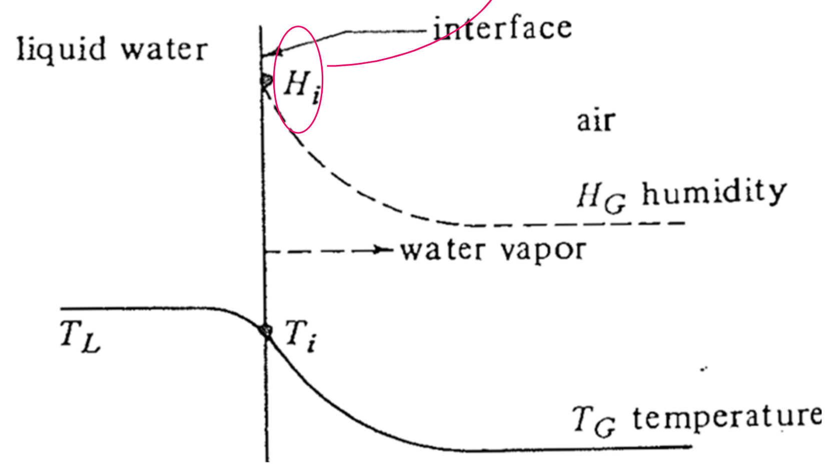

TRANE
SI METRIC
PSYCHROMETRIC CHART
BASED ON A BAROMETRIC PRESSURE
of 101.325 kPa
AT SEA LEVEL
Hyi = 84 kJ/kg DA
0.0225 kg W/ kg DA
TL dew = 26.6 °C
Specific Enthalpy At Saturation kJ/kg Dry Air
Wet Bulb or Saturation Temperature °C
Relative Humidity
Enthalpy Deviation kJ/kg Dry Air
Dry Bulb Temperature °C
Specific Volume m³/kg Dry Air
Moisture Content kg/kg Dry Air
Sensible Heat Factor

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

T_L		H_y		T_L		H_y	
		$\frac{btu}{lb_m \text{ dry air}}$	$\frac{J}{kg \text{ dry air}}$			$\frac{btu}{lb_m \text{ dry air}}$	$\frac{J}{kg \text{ dry air}}$
°F	°C			°F	°C		
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



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



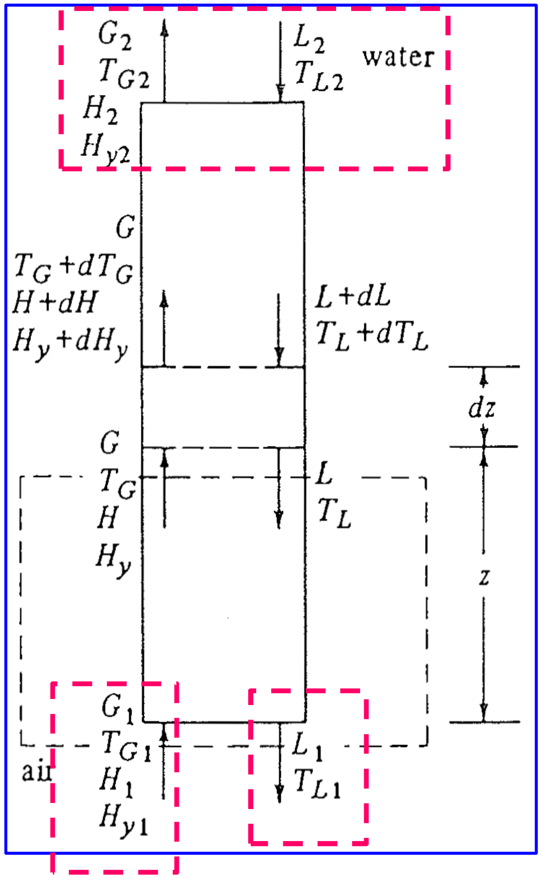
- **Draw the operating line Equation**

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

- 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})

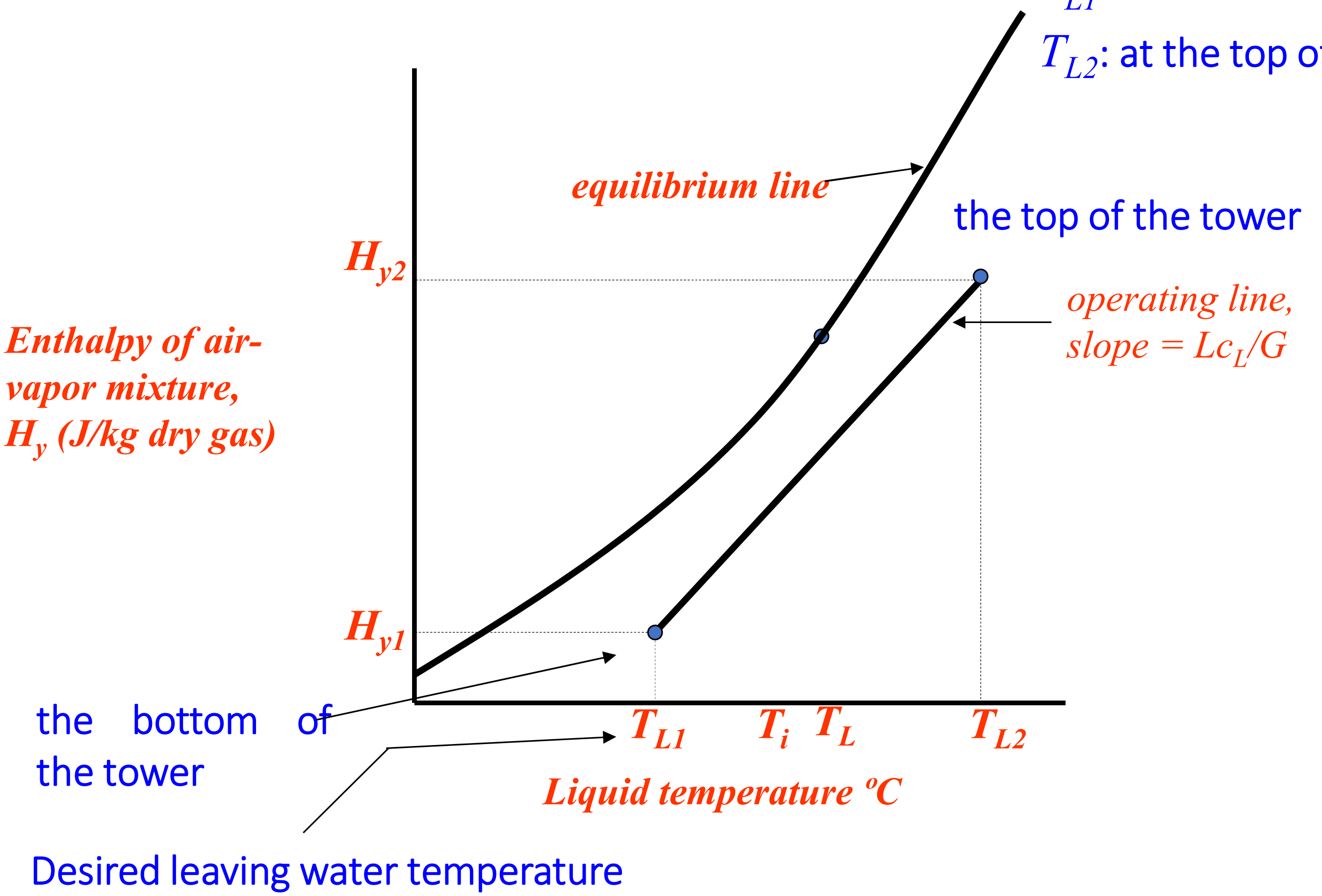
$$\text{Intercept} = H_{y1} - \mathrm{T}_{L1}\frac{Lc_L}{G} \quad ; \quad \text{Slope} = \frac{Lc_L}{G}$$

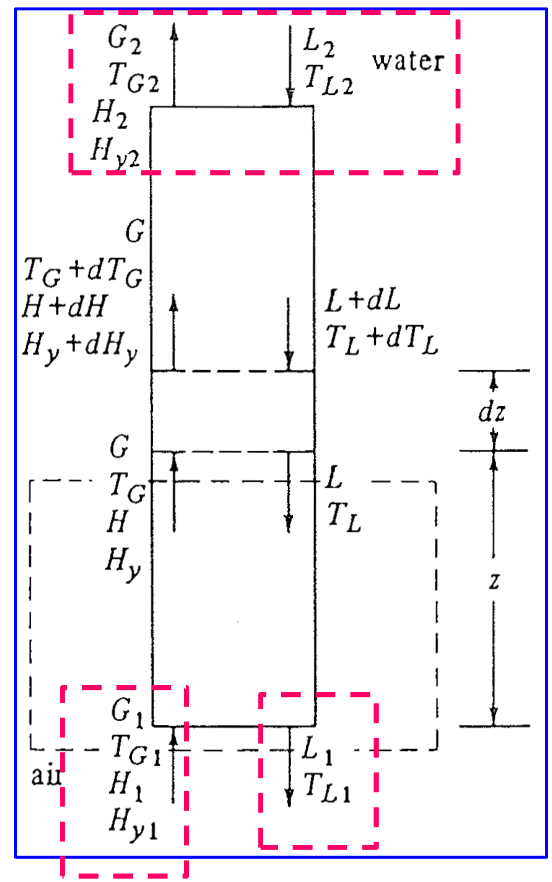
- Knowing T_{G2} and H_2, the enthalpy of this air H_{y2} can be also calculated and the point (T_{L2} and H_{y2}) is plotted as a second point on the operating line



T_{L1}: at the bottom of the tower; z=0

T_{L2}: at the top of the tower; z=Z





- We know from **mass transfer course,** that the flux, N_A, kmol water evaporating/s.m^2:

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

$$k_y = k_G P$$

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).

- 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:

$$y \cong \frac{M_B H}{M_A}$$

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

$$\rightarrow \quad N_{A,vol} = \frac{M_B}{M_A} k_y a_M (H_i - H_G)$$

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

Note that $$M_B\, k_y\, a_M = k_H\, a_M$$

$k_G\, a_M$ [=] kgmol/(s.m^3.Pa)

$k_H\, a_M$ [=] kg/(s.m^3)

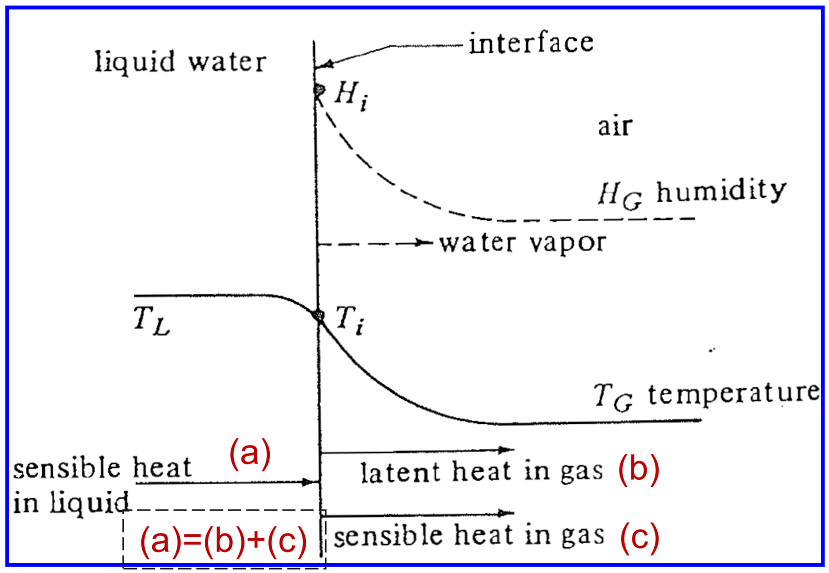
$k_y\, a_M$ [=] kgmol/(s.m^3)

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

Liquid phase volumetric heat transfer coefficient

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

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)

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

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

$$dV = dzA$$

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

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

or $$dQ_\lambda = k_H a_M (H_i\text{-}H_G)\lambda_o A dz$$

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

$$dq_s = Gc_s dT_G$$
$$= h_G \cdot a_{H,G} \cdot (T_i\text{-}T_G) \cdot dz$$

dQ= dQ_λ+dq_s

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

✓ *Keep in mind that* $$dq = h_L a_{H,L}(T_L - T_i)dz$$

➢ 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)**

• 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.:**

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

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

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 $dq = G dH_y$

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

Design Eq. of the cooling tower

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

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

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

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

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

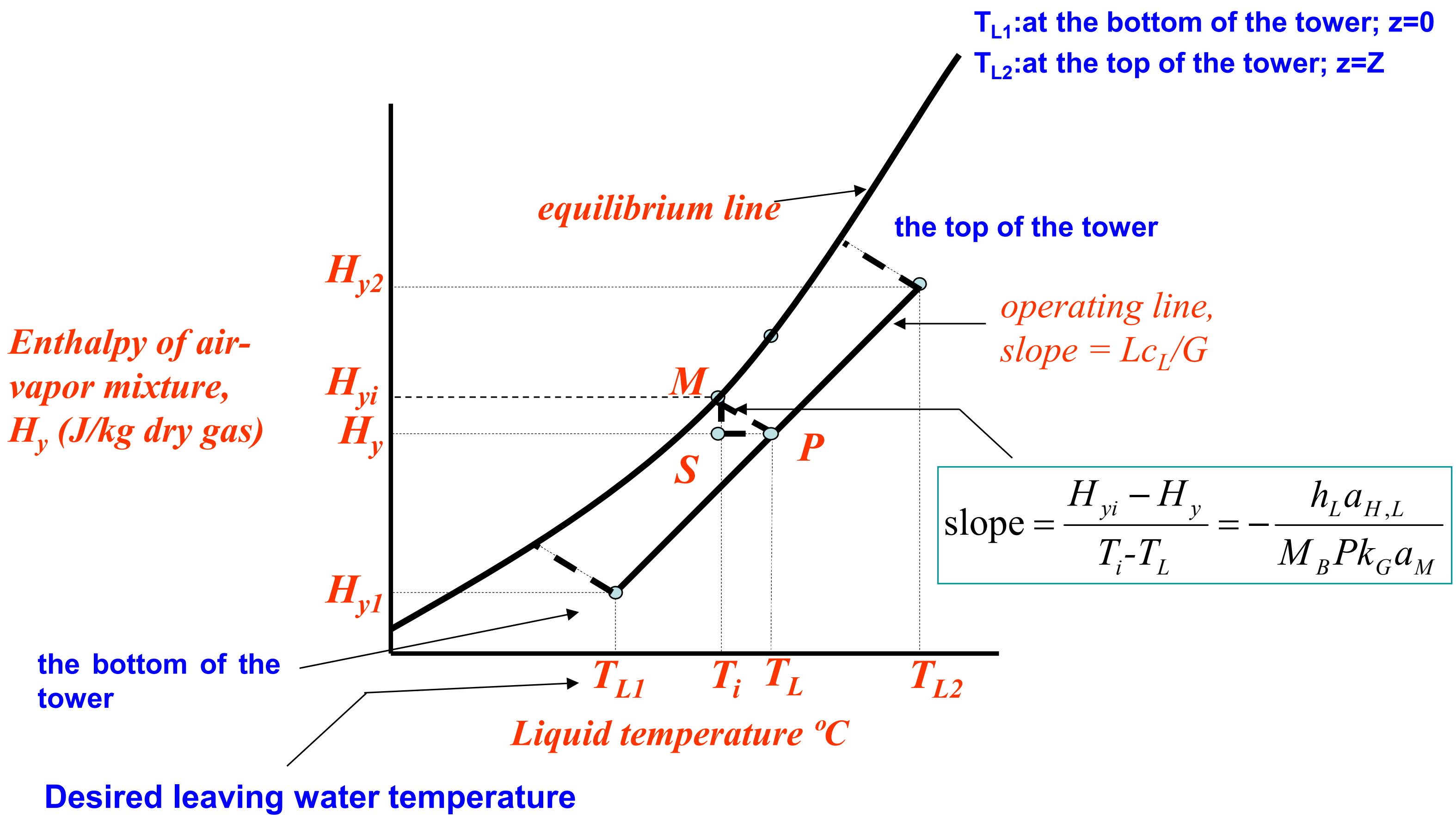
$$\frac{H_{yi} - H_y}{T_i \text{-} T_L} = -\frac{h_L a_{H,L}}{M_B P k_G a_M}$$

Note that $Lc_L dT_L = G dH_y$, $dq = G dH_y$

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

Hence, $Lc_L dT_L = M_B P k_G a_M \left[H_{yi} - H_y) \right] dz$

$$\Rightarrow \quad \boxed{z = \underbrace{\frac{Lc_L}{M_B P k_G a_m}}_{\text{HTU}} \underbrace{\int_{T_{L1}}^{T_{L2}} \frac{dT_L}{H_{yi} - H_y}}_{\text{NTU}}}$$



T_{L1}:at the bottom of the tower; z=0
T_{L2}:at the top of the tower; z=Z
equilibrium line
the top of the tower
H_{y2}
operating line, slope = Lc_L/G
Enthalpy of air-vapor mixture, H_y (J/kg dry gas)
H_{yi}
M
H_y
P
S
$\text{slope} = \frac{H_{yi} - H_y}{T_i - T_L} = -\frac{h_L a_{H,L}}{M_B P k_G a_M}$
H_{y1}
the bottom of the tower
T_{L1}
T_i
T_L
T_{L2}
Liquid temperature °C
Desired leaving water temperature

Design procedure of water cooling tower using film mass transfer coefficients

1. Draw the equilibrium curve:

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

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

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

2. Draw the operating line:

- Use the operating line equation (enthalpy vs Temp)

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

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

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

H_{y1} and H_{y2} is the gas mixture enthalpy at T_{G1} and T_{G2} , respectively.
$\rightarrow$ To draw the operating line we need either two points or one point and slope (Lc_L/G).

3. Draw lines with slope: (Lewis relation)

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

- 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.

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: $\text{Z} = (\text{HTU})(\text{NTU})$

Example 3.5.1 Effectiveness of a cooling tower

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). The term $h_L a_{HL}/M_B P k_G a_M$ 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

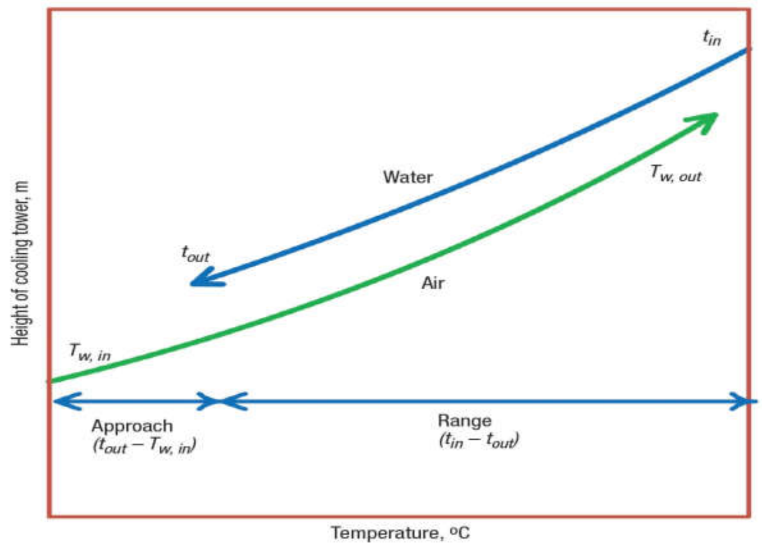
$$G = L = 1.356 \text{ kg/(s.m}^2)$$

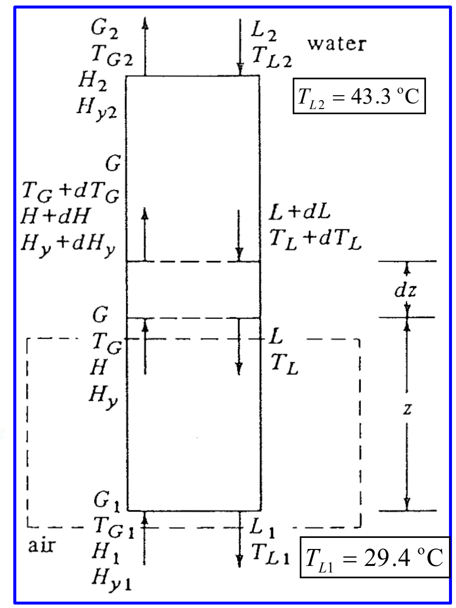
$$T_{G1} = 29.4\ ^{\circ}\text{C}; \text{T}_{\text{WB1}} = 23.9\ ^{\circ}\text{C}$$

$$k_G a_M = 1.207 \times 10^{-7} \text{ kmol/(s.m}^3)$$

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

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





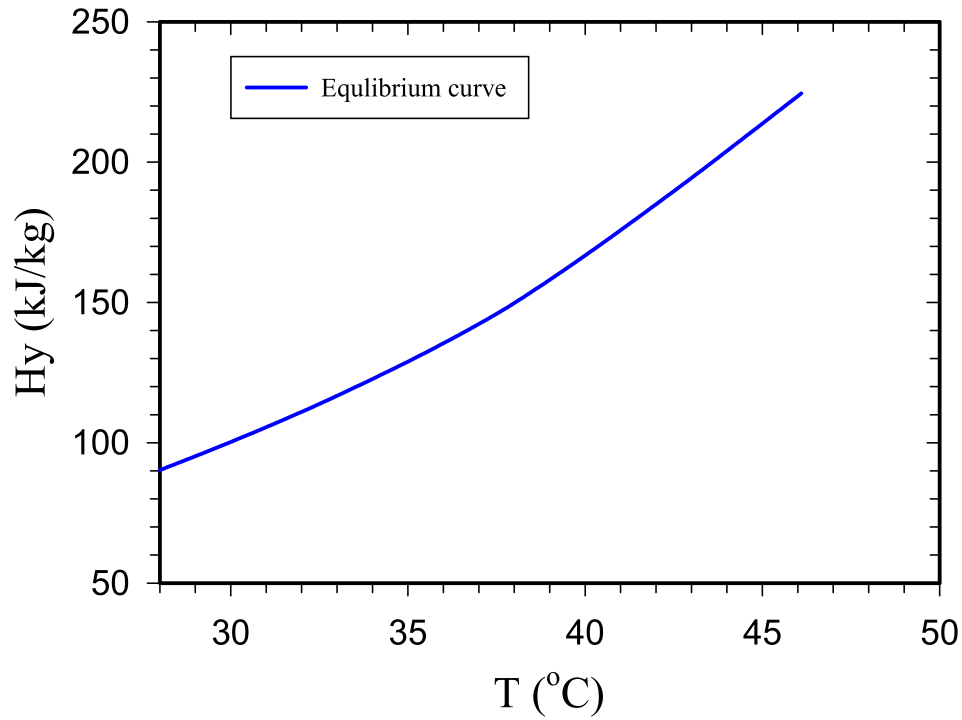
$$\text{Effectivness} = 100 \times \text{Range}/0(\text{Range} + \text{Approach}) = 71.6\%$$

Height of the packed tower.

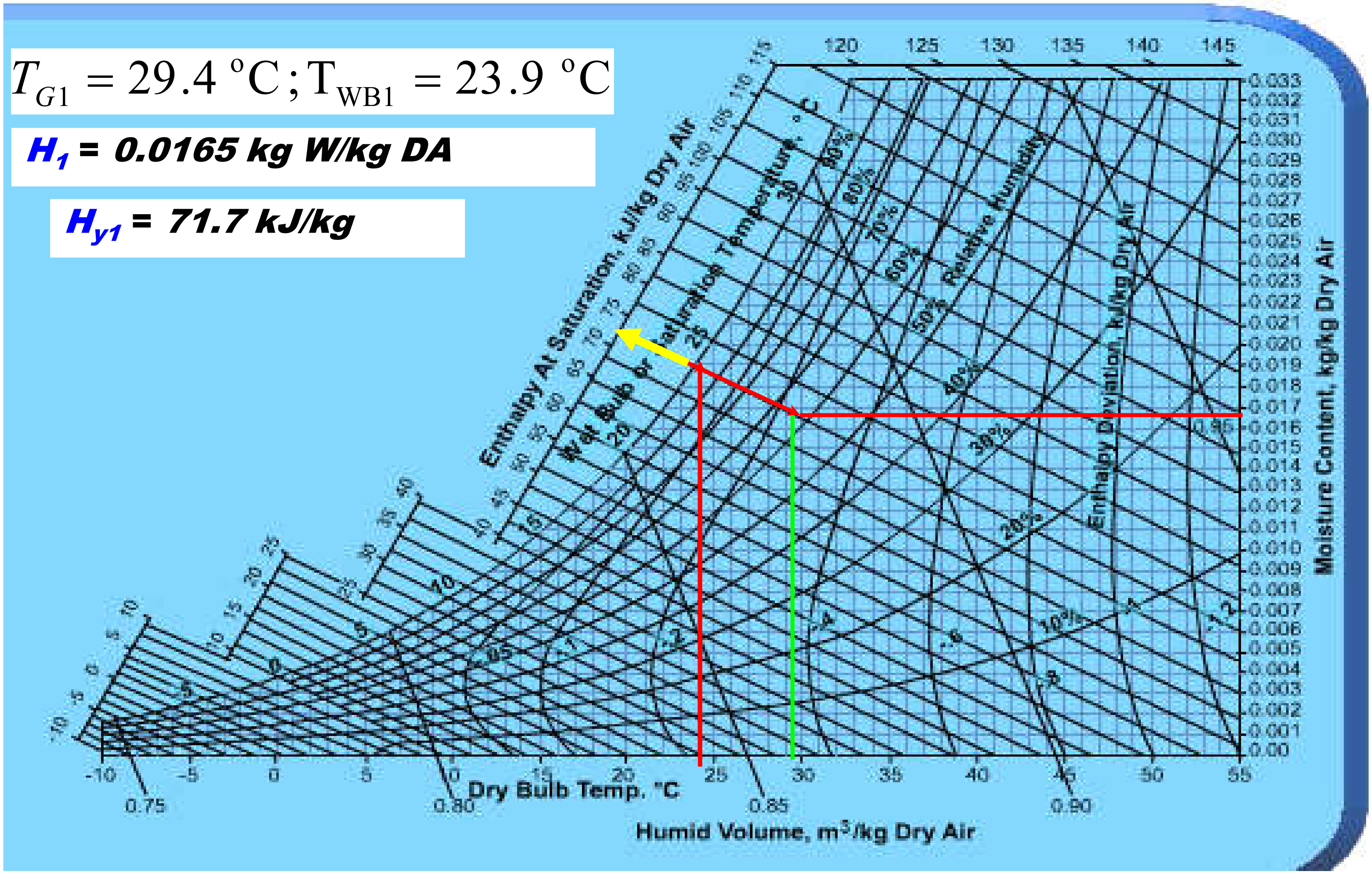
1. **Draw the equilibrium curve:** use saturated humidity curve in the psychrometric chart and enthalpy Eq. to get:

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

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



2. Draw the operating line:



$$T_{G1} = 29.4\ ^{o}\mathrm{C}\,;\, \mathrm{T_{WB1}} = 23.9\ ^{o}\mathrm{C}$$

H_1 = 0.0165 kg W/kg DA

H_{y1} = 71.7 kJ/kg

Draw the operating line:

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

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

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

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

$$G = L = 1.356 \text{ kg/(s.m}^2)$$

$$c_L = 4.187 \text{kJ/(kg.K)}$$

$$T_{L1} = 29.4\ ^\circ\text{C}$$

$$T_{L2} = 43.3\ ^\circ\text{C}$$

$$H_{y1} = 71.7 \text{ kJ/kg}$$

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

We have two points enough to draw the operating line:

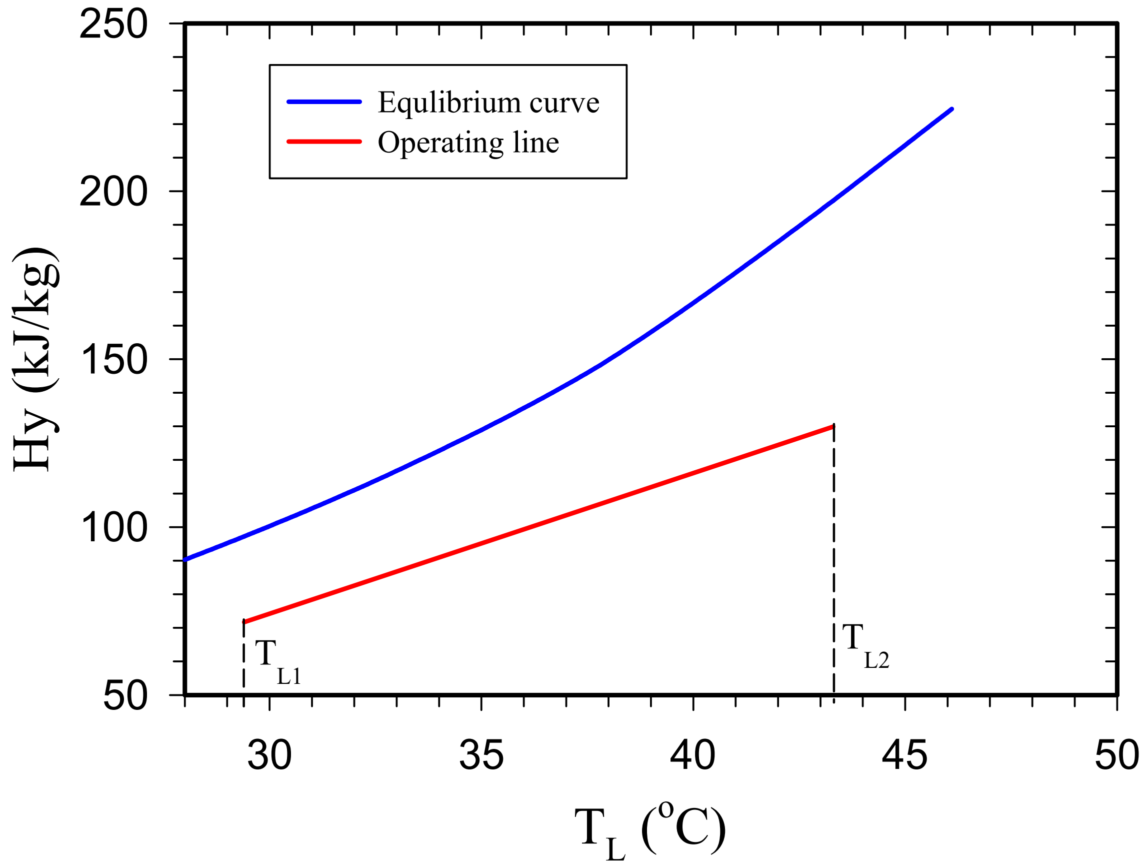
$$(T_{L1}, H_{y1}) = (29.4\ ^\circ\text{C}, 71.7 \text{ kJ/kg})$$

$$(T_{L2}, H_{y2}) = (43.3\ ^\circ\text{C}, 129.9 \text{ kJ/kg})$$

Draw the operating line:

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

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



3. Draw lines with constant slope:

For example,

at T_i =35 ^oC, from the equilibrium curve H_{yi} =128.9 kJ/kg .

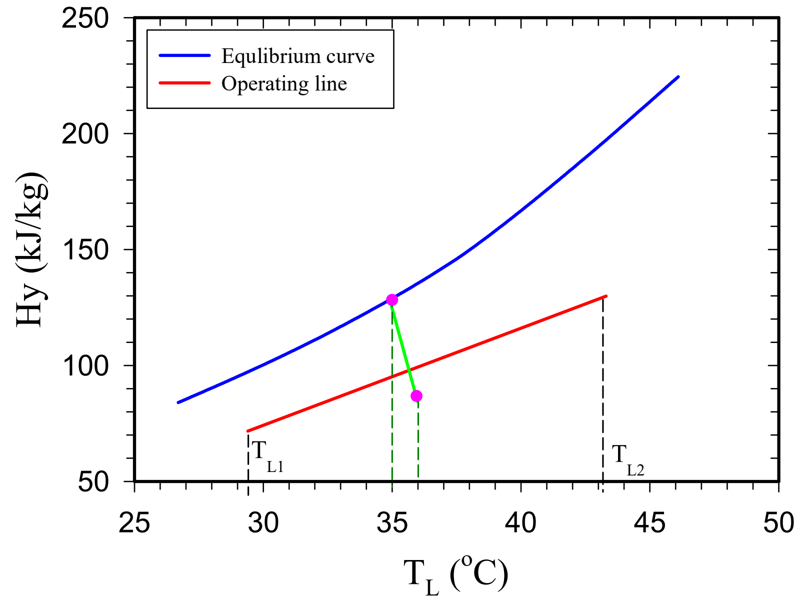
- at T_L= 36 ^oC, calculate H_y from:

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

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

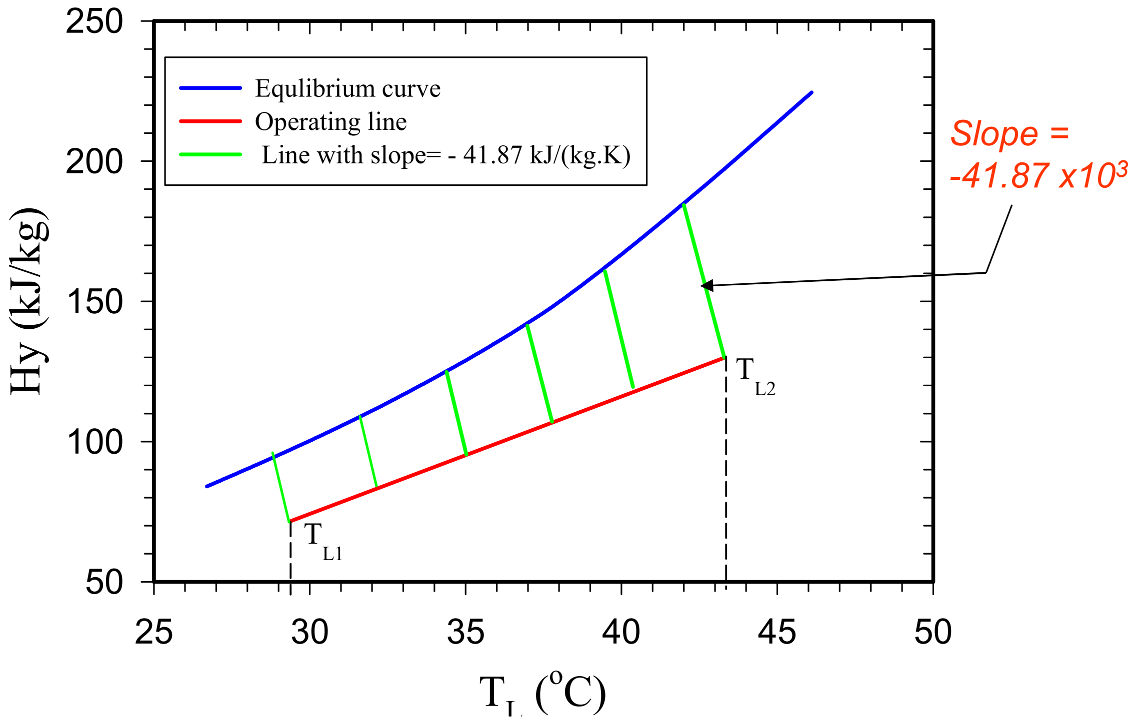
- Draw a line passes through the points (35 ^oC, 128.9 kJ/kg) and (36 ^oC, 87.03 kJ).

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

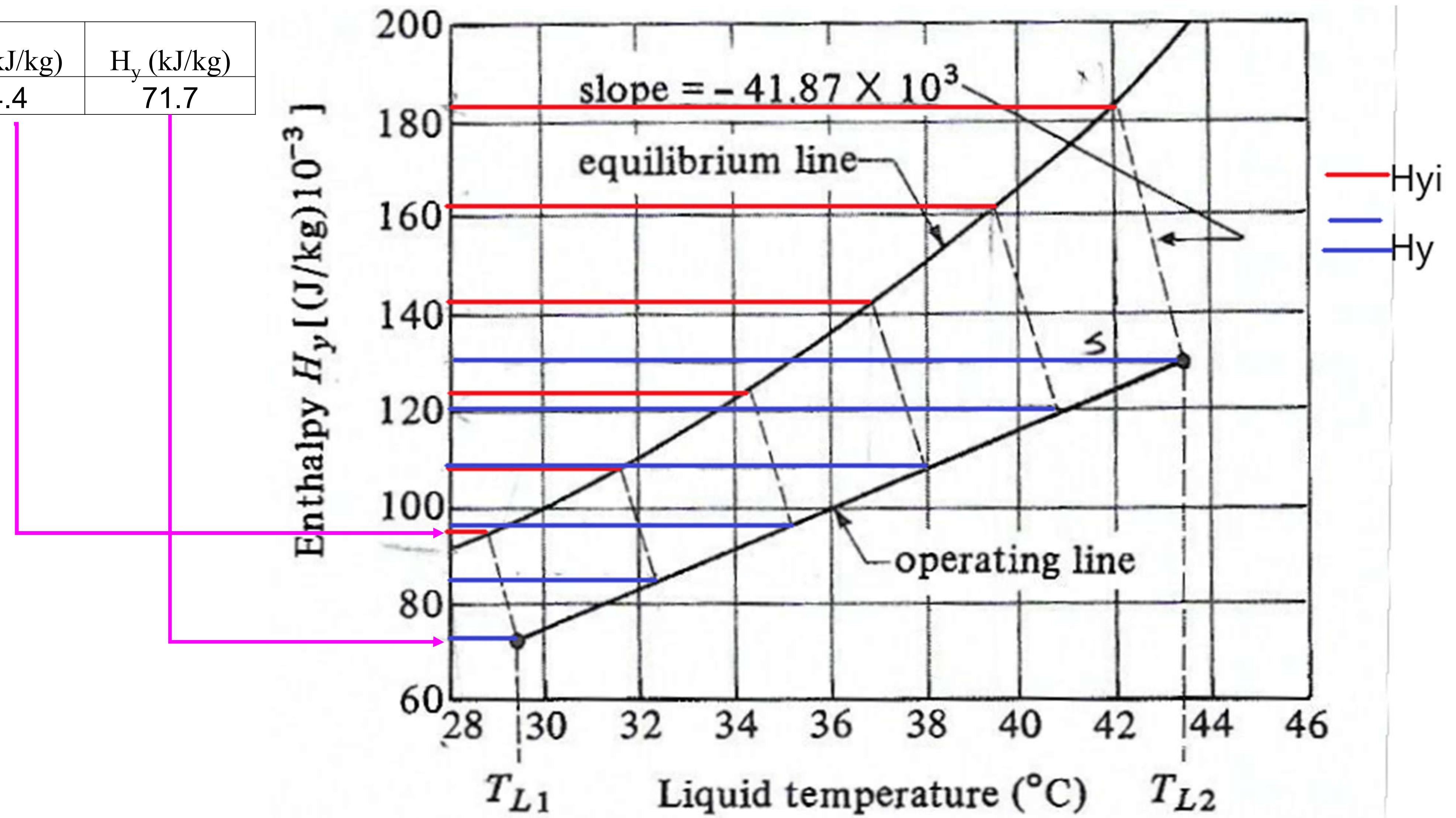


4. Calculate the number of transfer units (NTU):

- 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

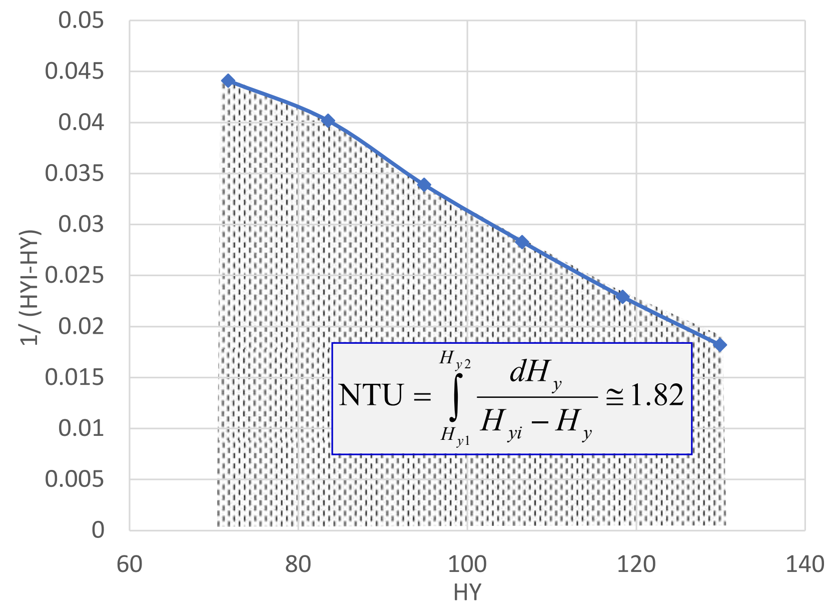


H_{yi} (kJ/kg)	H_y (kJ/kg)
94.4	71.7



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



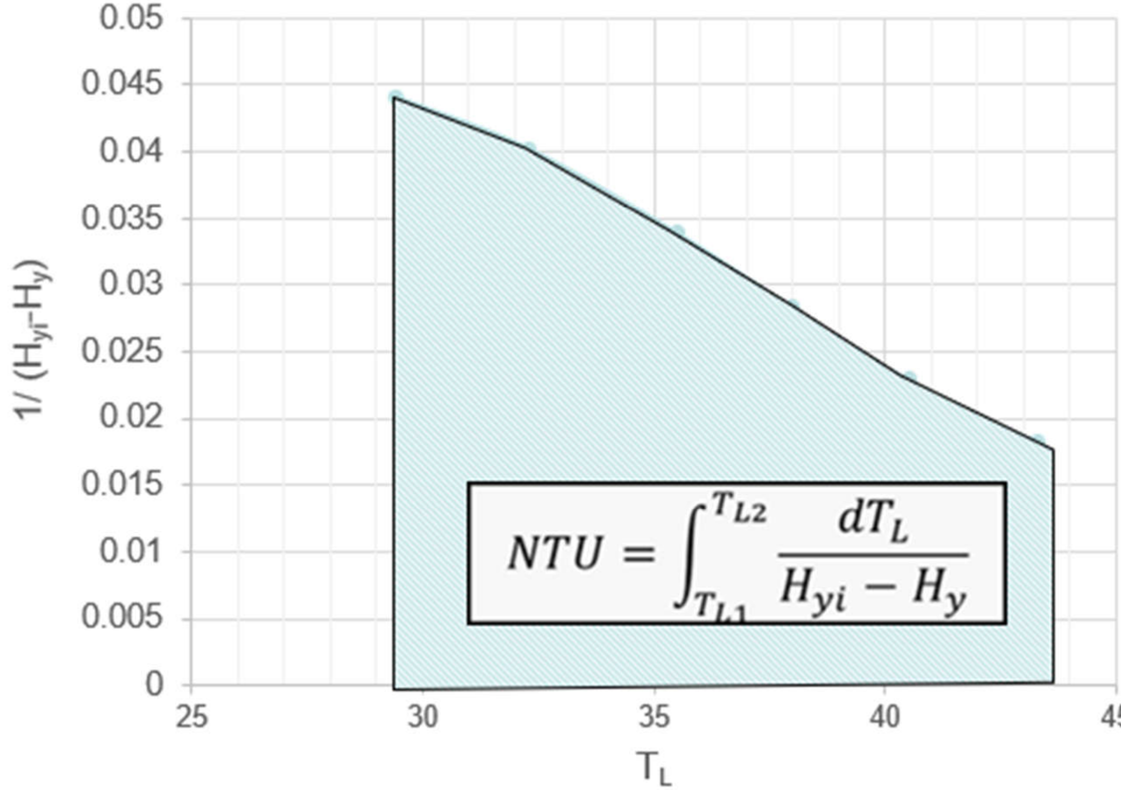
- Using Trapezoidal rule of numerical integration:

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

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

$$z = \frac{Lc_L}{M_B P k_G a_m} \int_{T_{L1}}^{T_{L2}} \frac{dT_L}{H_{yi} - H_y}$$

$$HTU = \frac{Lc_L}{M_B P k_G a_m}$$



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

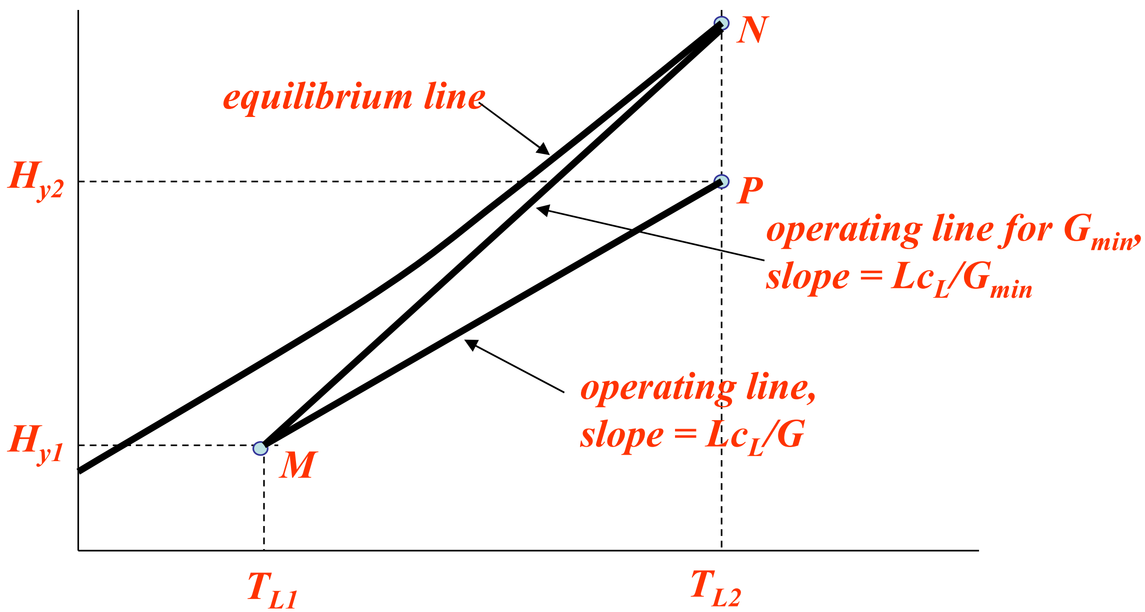
$$\text{HTU} = \frac{G}{M_B P k_G a_M} = \frac{1.356}{(29)(101325)(1.207\times10^{-7})} = 3.82\,\text{m}$$

6. Calculate the height of the cooling tower:

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

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

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



▪ 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

$$\text{Slope}_{\max} = \frac{H_{y2} - H_{y1}}{T_{L2} - T_{L1}}$$

$$= \frac{194 - 71.7}{43.3 - 29.4}$$

$$= 8.8\,\text{kJ/(kg.K)}$$

$$\text{Slope}_{\max} = \frac{Lc_L}{G_{\min}}$$

$$G_{\min} = \frac{Lc_L}{\text{Slope}_{\max}}$$

$$= 0.64\,kg/(s.m^2)$$