**Mass Transfer Operations II**
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**Lecture 02 - Humidification and Air Conditioning**

Now, I will be discussing on the Humidification and Air Conditioning.

Welcome come back to Mass Transfer Operations II, we were discussing on humidification and air conditioning in the previous class. We discussed on the important terminologies namely temperature, humidity and enthalpy, adiabatic saturation temperature and then we learnt how to read the psychrometric chart and then we discussed something on classification on cooling tower. Now, will be discussing on design calculations of cooling tower.

### Design calculations of cooling tower

Primarily we need to calculate,

(i) tower cross-section required to take the given load of warm water

(ii) height of the packing required to achieve the desired cooling

Basic assumptions for the design of cooling tower are as follows:

(i) the rate of vaporization of water is much less than the rate of water input to the tower (about 1% loss of feed water)

(ii) evaporative or adiabatic cooling of water occurs in the tower

The schematic of cooling tower is shown in Figure 10.

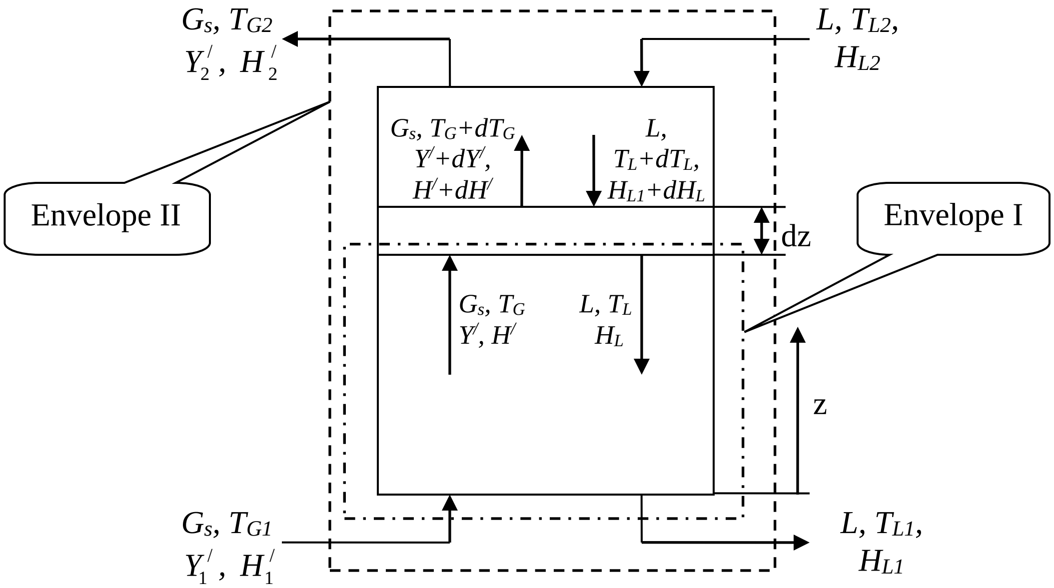


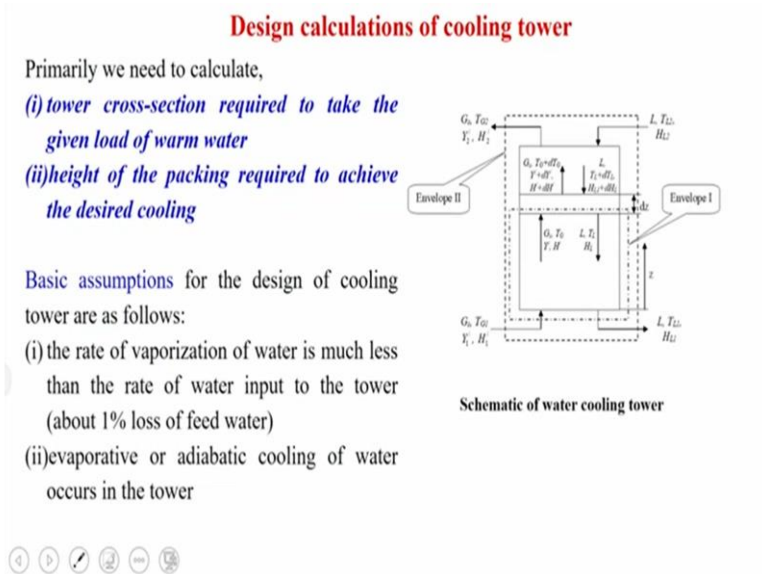

**Figure 10. Schematic of water cooling tower**

Let, $L$ is the constant water flow rate (kg/m$^2$s) and $G_s$ is the air rate (kg dry air/m$^2$s). Across a differential thickness $dz$ of the bed, temperature of water is decreased by $dT_L$ and the enthalpy of air is increased by $dH^{/}$.

Hence, change in enthalpy of water=$L.c_{WL}.dT_L$

and, change in enthalpy of air =$G_s.dH^{/}$

Differential enthalpy balance over $dz$ is $L.c_{WL}.dTL=G_s.dH^{/}$ (16)




Preliminary we need to calculate the tower cross-section required to take the given load of this warm water which will be fed from the top of this cooling tower and height of the packing material required to achieve the desired cooling. Means what will be the final temperature of the cooled water. For this we need to assume two basic assumptions like the rate of vaporization of water is much less than the rate of water input to the tower, we assume that around one percent loss of feed water takes place and for that also we will be discussing that make-up water is there and second one that evaporating or adiabatic cooling of the water occurs in the tower. Say the schematic of the water cooling tower is presented here in this figure.

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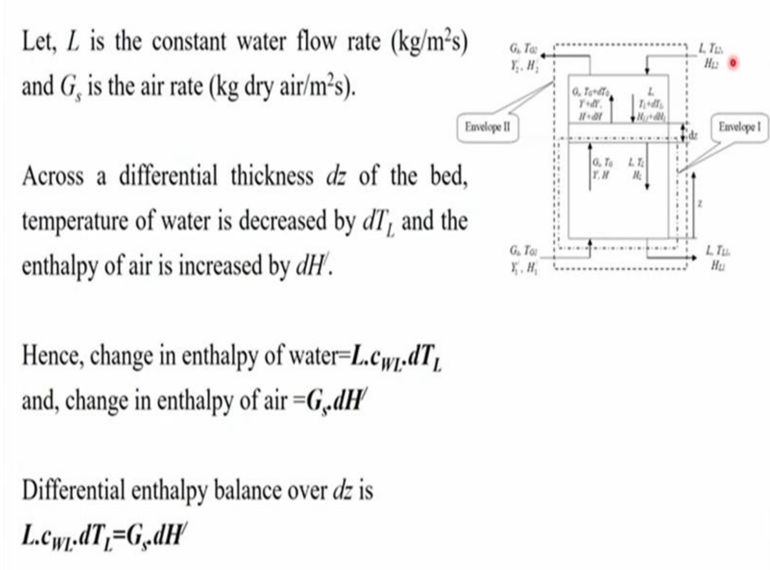


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Enthalpy balance over *envelope I*,

$$Lc_{WL}(T_L - T_{L1}) = G_s(H^/ - H_1^/) \quad (17)$$

This is the operating line for air-water contact.

Enthalpy balance over entire tower (*envelope II*)

$$Lc_{WL}(T_{L2} - T_{L1}) = G_s(H_2^/ - H_1^/) \quad (18)$$

The equilibrium curve for air-water system on $T_L$-$H^/$ plane is the plot of enthalpy of saturated air versus liquid temperature at equilibrium.

Rate of transfer of water vapor to air in the differential volume is

$$G_s dY^/ = k_Y^/ \bar{a}(Y_i^/ - Y^/) \quad (19)$$

The decrease in temperature of air for sensible heat transfer to water is

$$-G_s c_H dT_G = h_G \bar{a}\, dz(T_G - T_i) \quad (19)$$

Differentiation of Eq. (6) and multiplication with $G_s$ gives

$$G_s dH^{/} = G_s c_H dT_G + G_s dY^{/} \lambda_0 \tag{20}$$

$$= -h_G \overline{a}\, dz(T_G - T_i) + k_Y^{/} \overline{a}\, dz(Y_i^{/} - Y^{/})\lambda_0$$

$$= k_Y^{/} \overline{a}\, dz \left\{ \frac{h_G}{k_Y^{/}} (T_i - T_G) + (Y_i^{/} - Y^{/})\lambda_0 \right\} \tag{21}$$

$$= k_Y^{/} \overline{a}\, dz \left\{ c_H (T_i - T_G) + (Y_i^{/} - Y^{/})\lambda_0 \right\} \tag{22}$$

$$= k_Y^{/} \overline{a}\, dz \left\{ c_H (T_i - T_0) + c_H (T_0 - T_G) + Y_i^{/}\lambda_0 - Y^{/}\lambda_0 \right\} \tag{23}$$

$$= k_Y^{/} \overline{a}\, dz \left\{ c_H (T_i - T_0) + Y_i^{/}\lambda_0 - [c_H (T_G - T_0) + Y^{/}\lambda_0] \right\} \tag{24}$$

$$= k_Y^{/} \overline{a}\, dz (H_i^{/} - H^{/}) \tag{25}$$

The height ($z$) of the packing in the cooling tower is obtained by

$$\int_{H_1^{/}}^{H_2^{/}} \frac{dH^{/}}{(H_i^{/} - H^{/})} = \frac{k_Y^{/} \overline{a}}{G_s} \int_0^z dz = \frac{k_Y^{/} \overline{a}}{G_s} z \tag{26}$$

Number of gas-enthalpy transfer units

$$N_{tG} = \int_{H_1^{/}}^{H_2^{/}} \frac{dH^{/}}{(H_i^{/} - H^{/})} \tag{27}$$

Height of gas-enthalpy transfer units

$$H_{tG} = \frac{G_s}{k_Y^{/} \overline{a}} \tag{28}$$

Hence, height of cooling tower (packing section), $z$

$$z = H_{tG} . N_{tG} \tag{29}$$

***Volumetric mass or enthalpy transfer coefficient ($k_Y^{/} \overline{a}$) should be known. Then $H_{tG}$ can be estimated from given mass flow rate.***

There is no direct relation available between enthalpy of bulk gas $H^{/}$ and that of $H_i^{/}$. So, integral can not be evaluated analytically. For numerical or graphical evaluation of the integral, we have to know the values $H_i^{/}$ (interfacial enthalpy) for a set of values of $H^{/}$.

Let, $h_L \bar{a}$ is volumetric heat transfer coefficient on the water side,

$$G_s dH^{/} = L c_{WL} dT_L = h_L \overline{a} (T_L - T_{Li}) \tag{30}$$

$$k_Y^{/}\,\overline{a}\,dz(H_i^{/} - H^{/}) = -h_L\,\overline{a}\,dz(T_{Li} - T_L) \quad (31)$$

$$\frac{(H_i^{/} - H^{/})}{(T_{Li} - T_L)} = -\frac{h_L}{k_Y^{/}} \quad (32)$$

A point ($T_L$, $H^{/}$) on the operating line meets the equilibrium line at the point ($T_{Li}, H_i^{/}$ ).

Substituting $G_s dH^{/} = Lc_{WL} dT_L$ in Eq. (25) we have,

$$Lc_{WL} dT_L = k_Y^{/}\,\overline{a}\,dz\left(H_i^{/} - H^{/}\right)$$

and

$$\int_{T_{Li}}^{T_{L0}} \frac{dT_L}{(H_i^{/} - H^{/})} = \frac{k_Y^{/}\,\overline{a}}{Lc_{WL}} \int_0^z dz = \frac{k_Y^{/}\,\overline{a}}{Lc_{WL}} z \quad (33)$$

Eq. (33) is called ‘***Merkel Equation***’.

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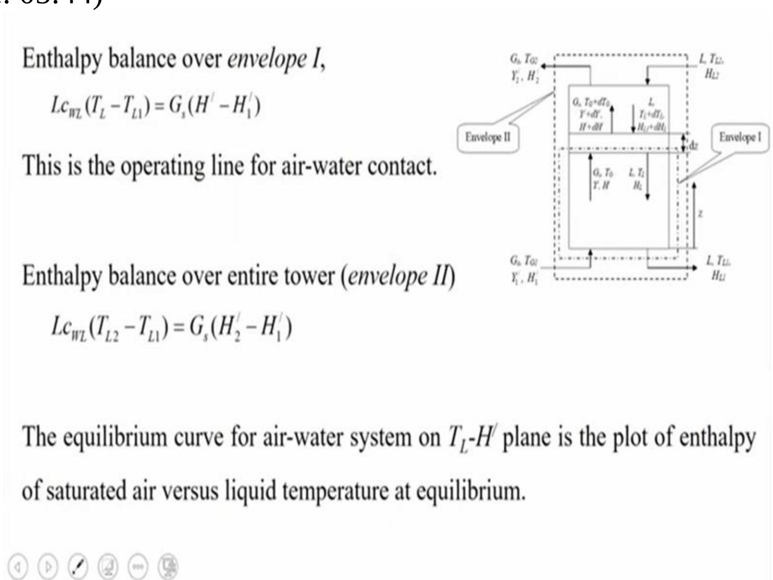


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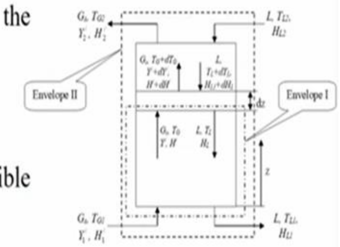
Rate of transfer of water vapor to air in the differential volume is

$$G_s dY' = k_Y' \bar{a}(Y_i' - Y')$$

The decrease in temperature of air for sensible heat transfer to water is

$$-G_s c_H dT_G = h_G \bar{a}\, dz (T_G - T_i)$$




Differentiation of Eq. $H' = c_H(T_G - T_0) + Y'\lambda_0 = (1.005 + 1.88Y')(T_G - T_0) + 2500Y'$ and multiplication with $G_s$ gives

$$G_s dH' = G_s c_H dT_G + G_s dY' \lambda_0$$

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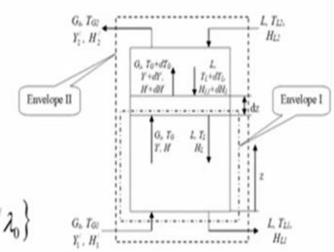
$$\begin{aligned}
G_s dH' &= G_s c_H dT_G + G_s dY'\lambda_0 \\
&= -h_G \bar{a}\, dz (T_G - T_i) + k_Y' \bar{a}\, dz (Y_i' - Y')\lambda_0 \\
&= k_Y' \bar{a}\, dz \left\{ \frac{h_G}{k_Y'}(T_i - T_G) + (Y_i' - Y')\lambda_0 \right\} \\
&= k_Y' \bar{a}\, dz \left\{ c_H (T_i - T_G) + (Y_i' - Y')\lambda_0 \right\} \\
&= k_Y' \bar{a}\, dz \left\{ c_H (T_i - T_0) + c_H (T_0 - T_G) + Y_i'\lambda_0 - Y'\lambda_0 \right\} \\
&= k_Y' \bar{a}\, dz \left\{ c_H (T_i - T_0) + Y_i'\lambda_0 - [c_H (T_G - T_0) + Y'\lambda_0] \right\} \\
&= k_Y' \bar{a}\, dz (H_i' - H')
\end{aligned}$$




The height ($z$) of the packing in the cooling tower is obtained by

$$\int_{H_1'}^{H_2'} \frac{dH'}{(H_i' - H')} = \frac{k_Y' \bar{a}}{G_s} \int_0^z dz = \frac{k_Y' \bar{a}}{G_s} z$$

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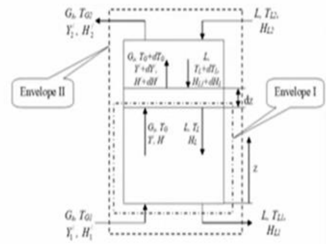
Number of gas-enthalpy transfer units

$$N_{tG} = \int_{H_1^{/}}^{H_2^{/}} \frac{dH^{/}}{(H_i^{/} - H^{/})}$$




Height of gas-enthalpy transfer units

$$H_{tG} = \frac{G_s}{k_Y^{/} \bar{a}}$$

Hence,

height of cooling tower (packing section), $z$

$z = H_{tG} . N_{tG}$

***Volumetric mass or enthalpy transfer coefficient ($k_Y^{/}\bar{a}$) should be known.***

***Then $H_{tG}$ can be estimated from given mass flow rate.***

There is no direct relation available between enthalpy of bulk gas $H^{/}$ and that of $H_i^{/}$

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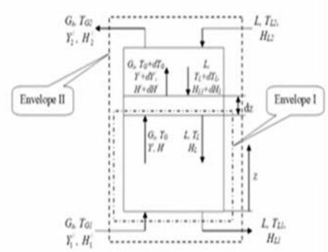
So, integral can not be evaluated analytically.

For numerical or graphical evaluation of the integral, we have to know the values of $H_i^{/}$ (interfacial enthalpy) for a set of values of $H^{/}$.




Let, $h_L\bar{a}$ is volumetric heat transfer coefficient on the water side,

$$G_s dH^{/} = L c_{WL} dT_L = h_L \bar{a}(T_L - T_{Li})$$

$$k_Y^{/} \bar{a}\, dz (H_i^{/} - H^{/}) = -h_L \bar{a}\, dz (T_{Li} - T_L)$$

$$\frac{(H_i^{/} - H^{/})}{(T_{Li} - T_L)} = -\frac{h_L}{k_Y^{/}}$$

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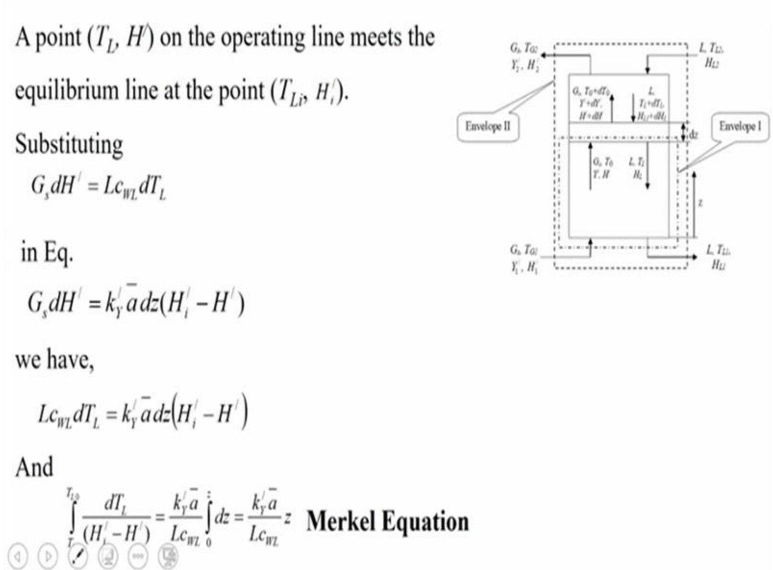


*A simplified design equation based on overall enthalpy transfer coefficient:*

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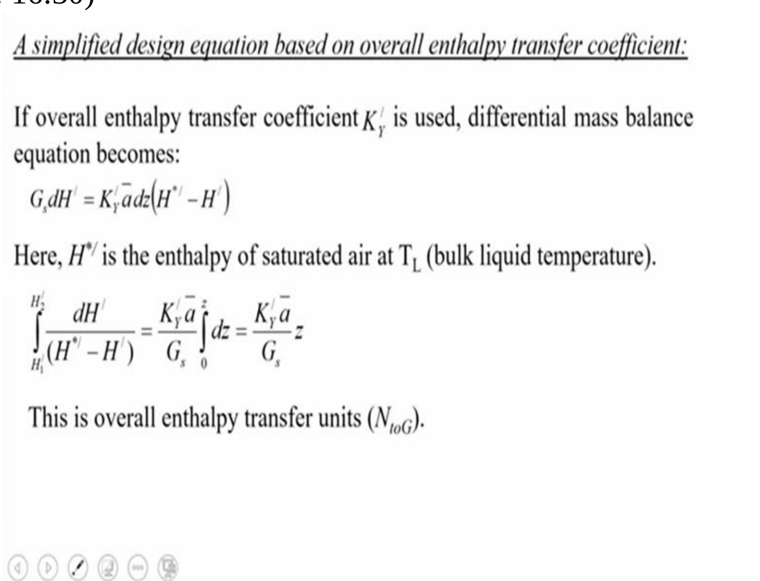


If overall enthalpy transfer coefficient $K_Y'$ is used, differential mass balance equation becomes

$$G_s dH' = K_Y' \bar{a}\, dz\left(H^{*'} - H'\right) \qquad (34)$$

Here, $H^{*'}$ is the enthalpy of saturated air at TL (bulk liquid temperature).

$$\int_{H_1'}^{H_2'} \frac{dH'}{(H^{*'} - H')} = \frac{K_Y' \bar{a}}{G_s} \int_0^z dz = \frac{K_Y' \bar{a}}{G_s} z \qquad (35)$$

This is overall enthalpy transfer units ($N_{toG}$).

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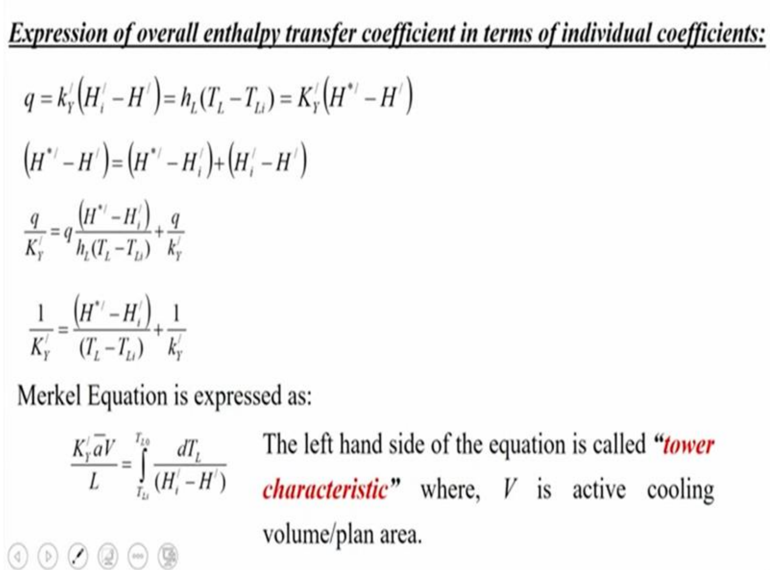


$$q = k_Y^/\left(H_i^/ - H^/\right) = h_L(T_L - T_{Li}) = K_Y^/\left(H^{*/} - H^/\right) \tag{36}$$

$$\left(H^{*/} - H^/\right) = \left(H^{*/} - H_i^/\right) + \left(H_i^/ - H^/\right)$$

$$\frac{q}{K_Y^/} = q\frac{\left(H^{*/} - H_i^/\right)}{h_L(T_L - T_{Li})} + \frac{q}{k_Y^/}$$

$$\frac{1}{K_Y^/} = \frac{\left(H^{*/} - H_i^/\right)}{(T_L - T_{Li})} + \frac{1}{k_Y^/} \tag{37}$$

Equation 33 (Merkel Equation) is also expressed as:

$$\frac{K_Y^/ \bar{a} V}{L} = \int_{T_{Li}}^{T_{L0}} \frac{dT_L}{(H_i^/ - H^/)} \tag{38}$$

The left hand side of the equation is called ***"tower characteristic"*** where, *V* is active cooling volume/plan area.

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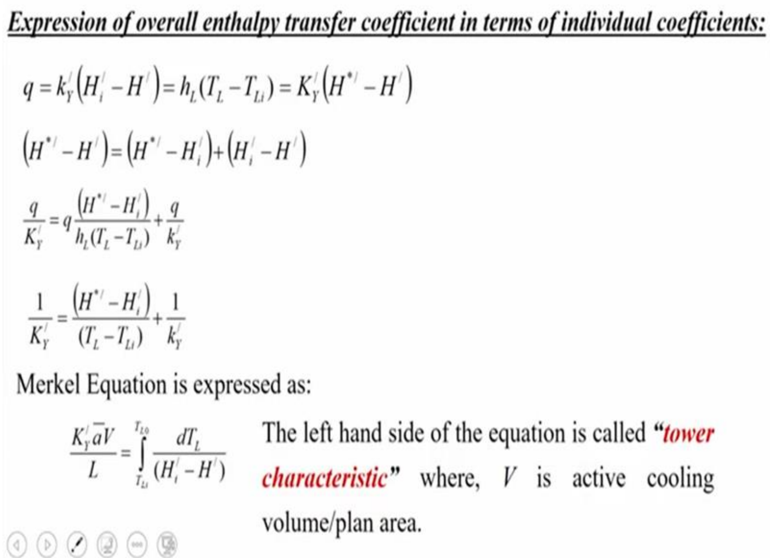


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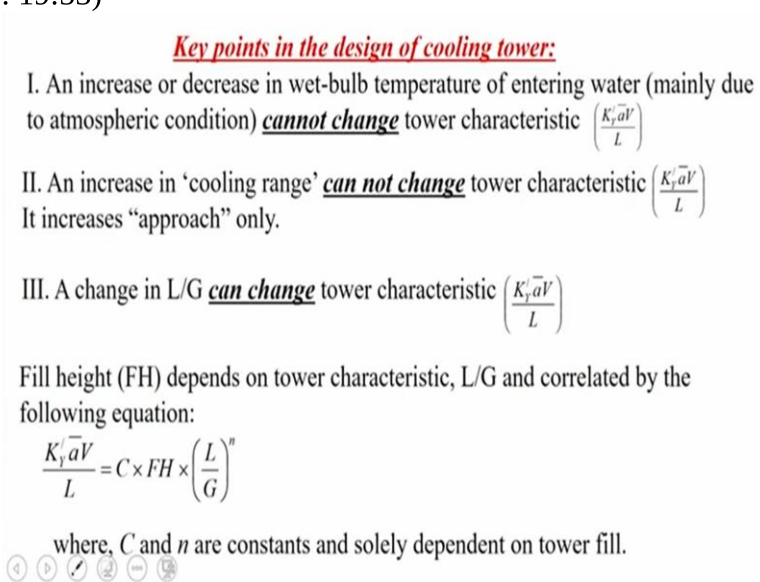


***Key points in the design of cooling tower:***

(I) An increase or decrease in wet-bulb temperature of entering water (mainly due to atmospheric condition) ***cannot change*** tower characteristic $\left(\frac{K_Y^{/}\bar{a}V}{L}\right)$.

(II) An increase in 'cooling range' ***can not change*** tower characteristic $\left(\frac{K_Y^{/}\bar{a}V}{L}\right)$. It increases 'approach' only.

(III) A change in L/G ***can change*** tower characteristic $\left(\frac{K_Y^/ \overline{a} V}{L}\right)$.

Fill height (FH) depends on tower characteristic, L/G and correlated by the following equation:

$$\frac{K_Y^/ \overline{a} V}{L} = C \times FH \times \left(\frac{L}{G}\right)^n$$

where, $C$ and $n$ are constants and solely dependent on tower fill.

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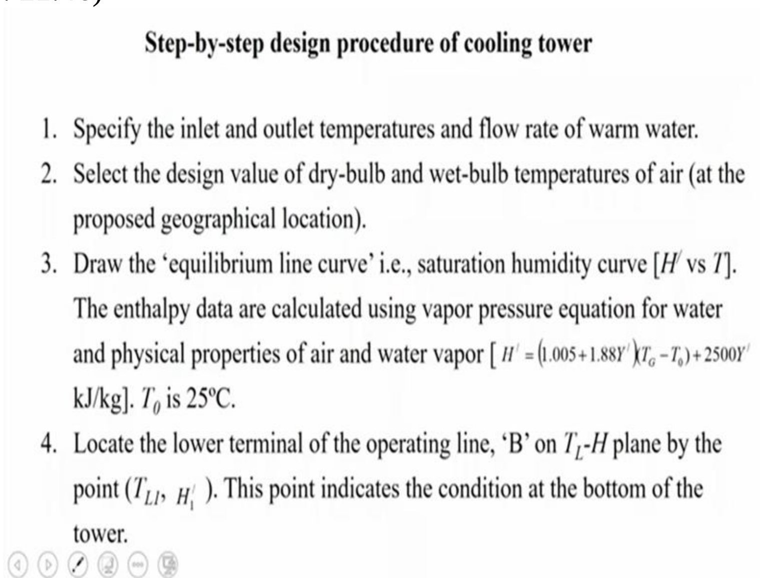


1. Specify the inlet and outlet temperatures and flow rate of warm water.
2. Select the design value of dry-bulb and wet-bulb temperatures of air (at the proposed geographical location).
3. Draw the 'equilibrium line curve' i.e., saturation humidity curve [$H^/$ vs $T$]. The enthalpy data are calculated using vapor pressure equation for water and physical properties of air and water vapor [ $H^/ = (1.005 + 1.88Y^/)(T_G - T_0) + 2500\,Y^/$ kJ/kg]. $T_0$ is 25ºC.
4. Locate the lower terminal of the operating line, 'B' on $T_L$-$H$ plane by the point ($T_{L1}$, $H_1^/$). This point indicates the condition at the bottom of the tower.
5. Draw a tangent to the equilibrium line through the point '$B$'. The slope of the tangent gives the ratio of the liquid and minimum gas flow rate. Hence, minimum air rate is calculated. Actual air rate taken is usually 1.25 to 1.5 times the minimum [not required if air rate is given].

6. The upper terminal of the operating line is located by the point '*A*' ($T_{L2}$, $H_2^{/}$). It is the point where the operating line of the slope determined in step 5 meets the vertical line through $T_{L2}$. It can also be located by calculating the top end enthalpy $H_2^{/}$ from Eq. (18) as $Lc_{WL}(T_{L2} - T_{L1}) = G_s(H_2^{/} - H_1^{/})$.

7. Evaluate the integral in Eq. (27) $N_{tG} = \int_{H_1^{/}}^{H_2^{/}} \frac{dH^{/}}{(H_i^{/} - H^{/})}$, number of gas-phase enthalpy transfer units and calculate height gas-phase enthalpy transfer units, $H_{tG}$ as $H_{tG} = \frac{G_s}{k_Y^{/}\bar{a}}$.

   $k_Y^{/}\bar{a}$ and $h_L\bar{a}$ are required. A set of parallel lines (tie lines) of slope $-\frac{h_L\bar{a}}{k_Y^{/}\bar{a}}$ is drawn between the operating line and equilibrium line. $H^{/}$ and $H_i^{/}$ are taken from terminals. Integral is calculated numerically or graphically. [ $N_{tG} = \int_{T_{Li}}^{T_{L0}} \frac{dT_L}{(H_i^{/} - H^{/})}$ and $H_{tG} = \frac{Lc_{WL}}{k_Y^{/}\bar{a}}$ ].

8. If the overall enthalpy transfer coefficient $K_Y^{/}$ is known and used, 'tie lines' are ***vertical***. For a given value of $H^{/}$, value of $H^{*/}$ is given by the point on the equilibrium line vertically above it. The integral of Eq. $\int_{H_1^{/}}^{H_2^{/}} \frac{dH^{/}}{(H^{*/} - H^{/})} = N_{toG}$ gives the number of overall transfer units.

9. The height of a transfer unit $H_{t0G} = \frac{G_s}{K_Y^{/}\bar{a}}$ or $H_{t0G} = \frac{Lc_{WL}}{K_Y^{/}\bar{a}}$ is calculated.

The packed height is the product of height of transfer unit and number of transfer units.

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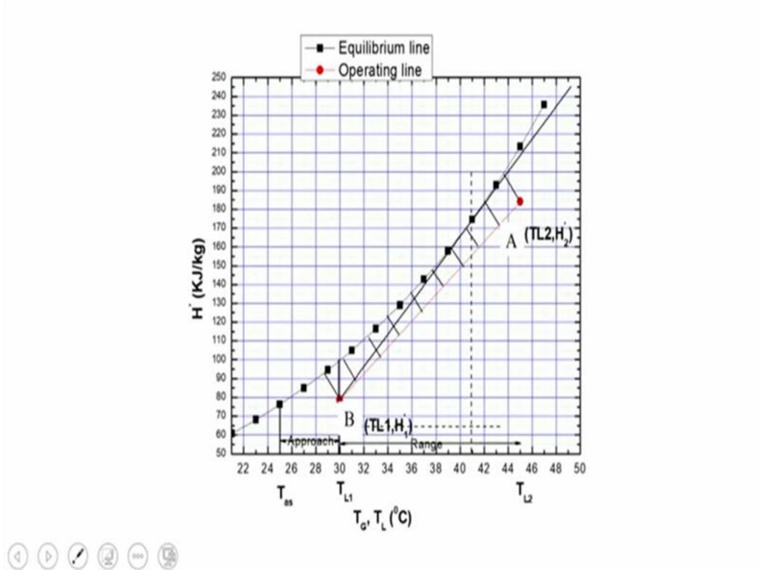


Say this one we can say this is the, we can say this one lower point of this operating line, this one this. We know this T L 1 and we know this how much amount of enthalpy is there, H 1 prime, so we need to locate this point B, ok?

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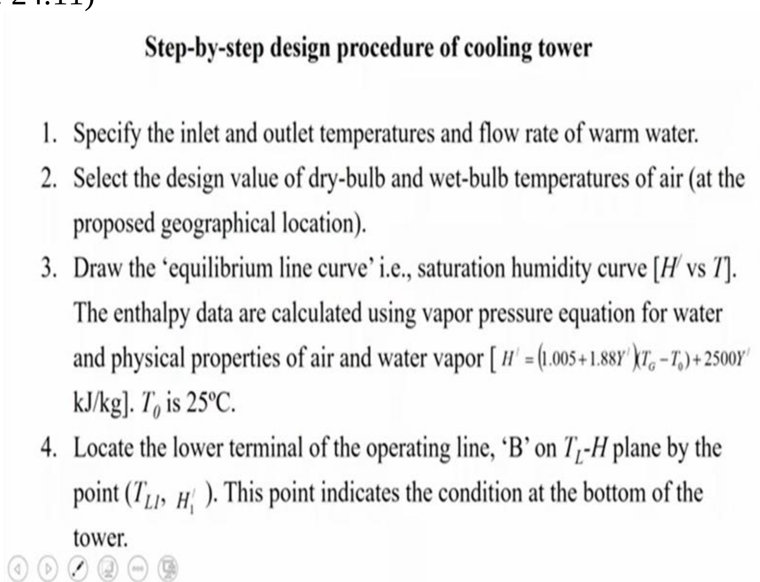


And say this point indicates the condition at the bottom of the tower means from where this liquid actually cold water will be exiting from the cooling tower. So we need to get this point, if we know the enthalpy value if we know the temperature that with temperature it will be exiting then will be able to get what is called point B.

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**Step-by-step design procedure of cooling tower**

5. Draw a tangent to the equilibrium line through the point '*B*'. The slope of the tangent gives the ratio of the liquid and minimum gas flow rate. Hence, minimum air rate is calculated. Actual air rate taken is usually 1.25 to 1.5 times the minimum [not required if air rate is given].
6. The upper terminal of the operating line is located by the point '*A*' $(T_{L2}, H_2^{/})$. It is the point where the operating line of the slope determined in step 5 meets the vertical line through $T_{L2}$. It can also be located by calculating the top end enthalpy $H_2^{/}$ from Eq. $Lc_{WL}(T_{L2}-T_{L1}) = G_s(H_2^{/}-H_1^{/})$ as $Lc_{WL}(T_{L2}-T_{L1}) = G_s(H_2^{/}-H_1^{/})$

Now, you see this we need to draw tangent actually to the equilibrium line through point B.

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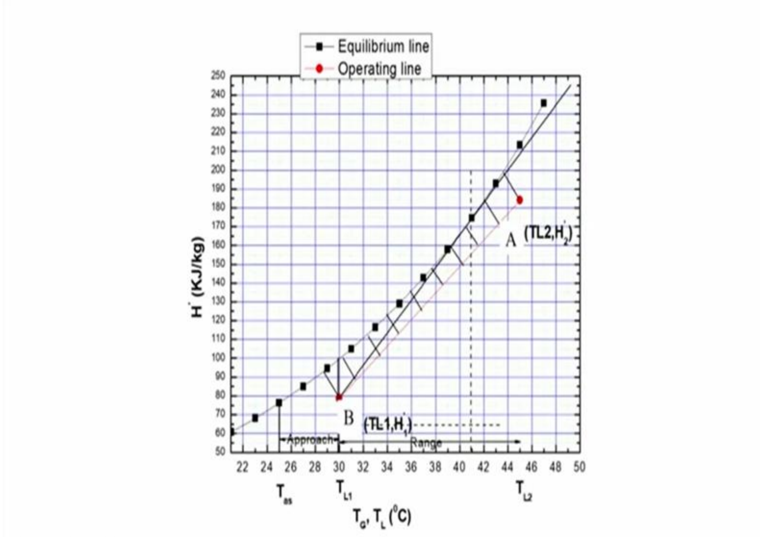


Like this from point B we need to draw this tangent say this one say equilibrium line we have this one and we will be drawing this tangent, ok? So, from B from point B actually we will be drawing this tangent we need to draw. See this, the slope of the tangent gives the ratio of the liquid and the minimum gas flow rate.

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**Step-by-step design procedure of cooling tower**

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So hence minimum gas air rate is actually calculated but actual air rate is taken usually 1.25 to 1.5 times of the minimum. So if it is supplied by this manufacturer then we can say or we can say this one from the vendor then I think it is not required and then upper terminal of the operating line is located by the point A. That is we can say this one from where this liquid water, hot water actually is fed from the top of this cooling tower.

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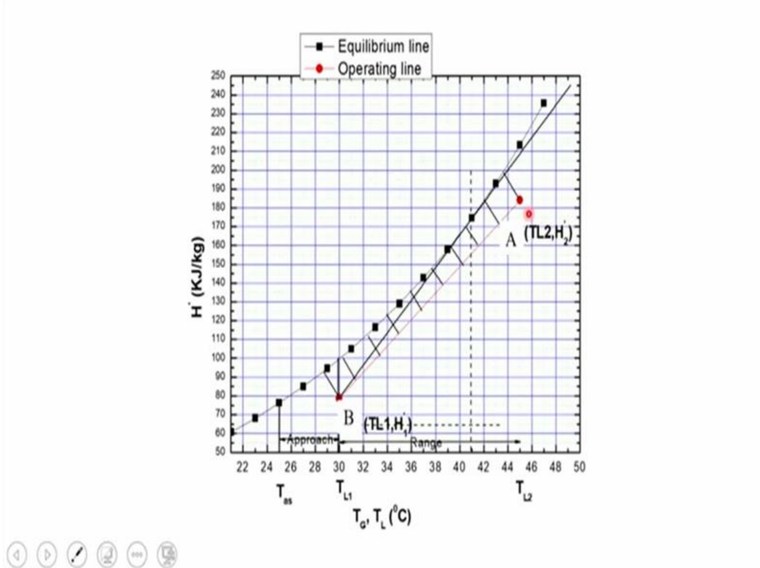


So, that is we can say this one whatever the slope actually we have determined in the here, so that A point is this one, so we can say this one that is indicating that whatever the T L 2 or we can say this one hot water temperature and whatever the enthalpy value H 2 prime. This is we can say this one the top of this cooling tower condition it is designated in point A, ok?

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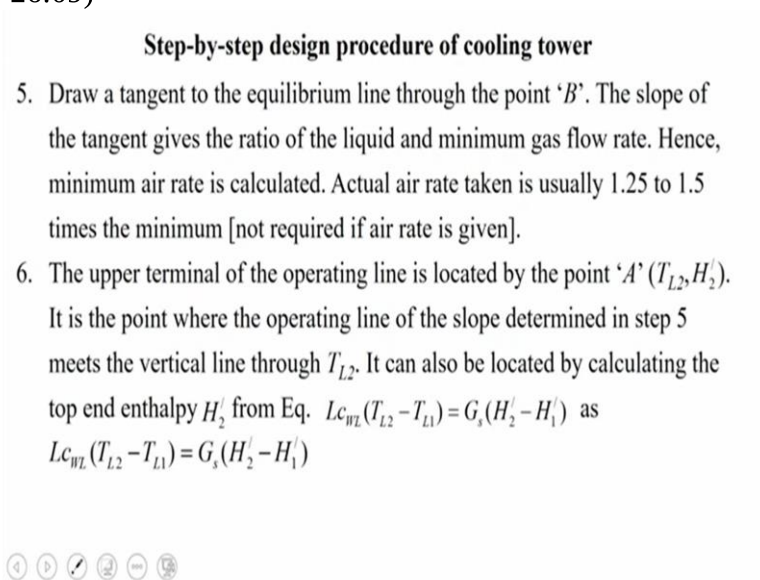


So now you see this one and so it can also be located by calculating the top end enthalpy H 2 prime from equation like L C WL into T L2 minus T L1 that is we obtained this one from the envelope 2, that is nothing but equal to G s into H 2 prime minus H 1 prime as this Lc W into T L2 minus T L1 is equal to this one G s into H 2 prime minus H 1 prime, ok?

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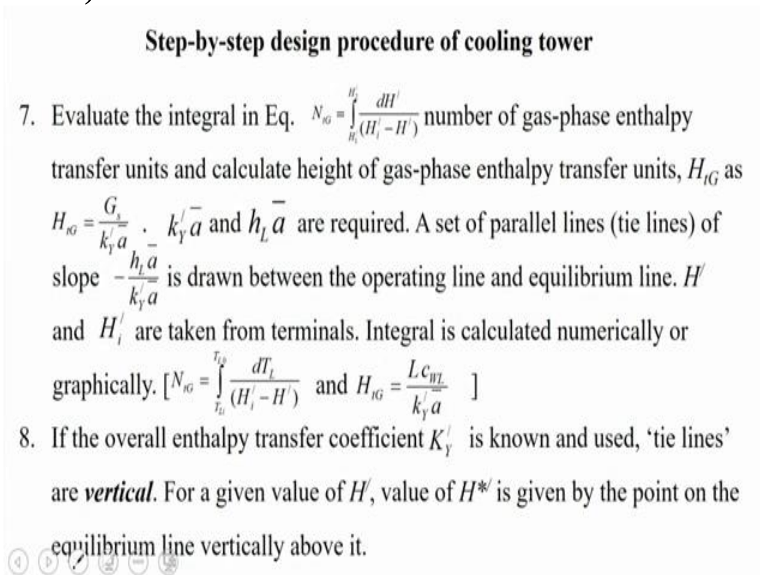


So now you see this one we need to evaluate the integral because ultimately we have to calculate this N tG that is we can say this one we will be getting this integral dH by H 1 prime minus H prime from H 1 prime to H 2 prime because that is the number of gas phase enthalpy transfer units and we need to calculate the height of this we can say gas-phase enthalpy transfer units, that H tG as we can say this H tG is equal to G s by small k Y prime into a bar and this small k Y prime a bar and H L into a bar these are required, that will be actually supplied for the calculation of the cooling tower or air-water system. A set of parallel lines we can say of the slope minus H L into a prime by k Y prime is drawn between the operating line and the equilibrium line.

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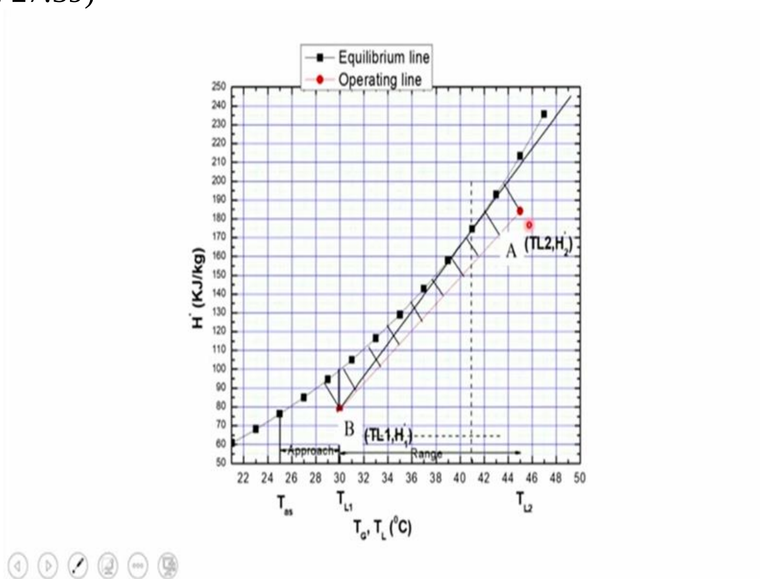

Just like we will be drawing these all the parallel lines like this we will drawing a set of all parallel lines we will drawing this one, all this we can say this all the parallel lines we will be drawing here, ok?

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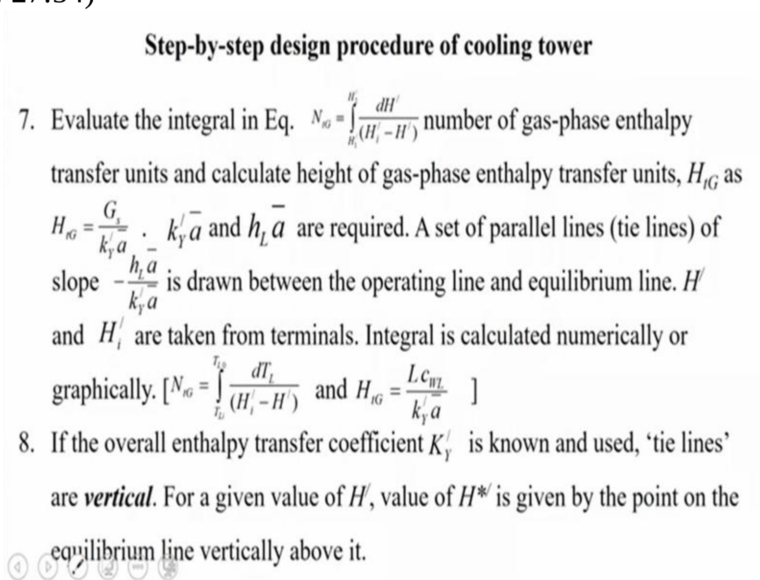


So a set of parallel lines of the slope minus H L into a bar by k Y prime into a bar is drawn between this operating line and the equilibrium line and H prime and H i prime are taken from the terminals and integral is calculated numerically or we can say from graphically where we can say this one we will be getting N tG is equal to T L 1 to T L 0 that is integrated for d TL by H i prime minus H prime and H tG is equal to L into c WL by small k Y prime into a bar. If the overall enthalpy transfer coefficient capital K Y is known and used then tie lines will be vertical like this and whatever the tie line where all these were parallel this one what is called from the operating line where will be all this will be vertically this will be placed and for a given value of this H prime value of H star prime also is given by the point on the equilibrium line vertically above it.

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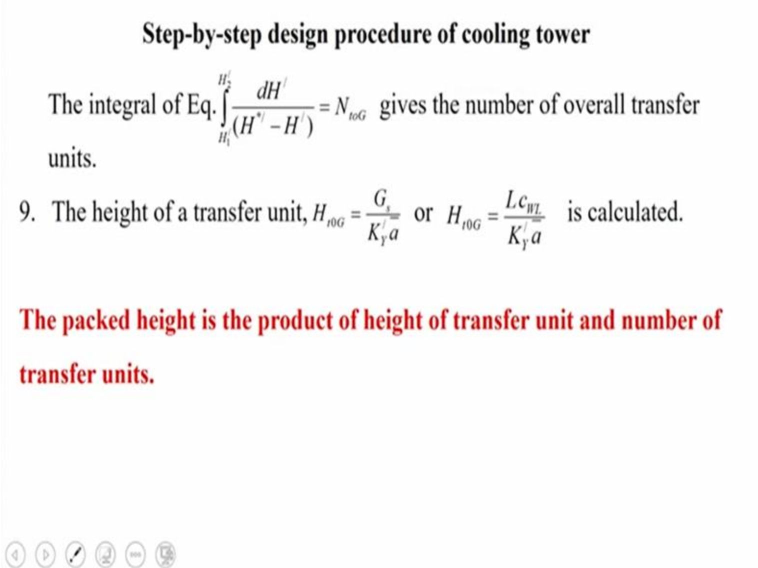

**Step-by-step design procedure of cooling tower**

The integral of Eq. $\int_{H_1'}^{H_2'} \frac{dH'}{(H^{*'}-H')} = N_{toG}$ gives the number of overall transfer units.

9. The height of a transfer unit, $H_{toG} = \frac{G_s}{K_Y' \bar{a}}$ or $H_{toG} = \frac{Lc_{WL}}{K_Y' \bar{a}}$ is calculated.

**The packed height is the product of height of transfer unit and number of transfer units.**

And then the integral of the equation this dH prime by H star prime minus H prime from this H 1 prime to H 2 prime that will be nothing but N toG that gives the number of overall transfer this one what is called units and the height of the transfer unit H toG will be G s by capital K Y prime into a bar or we can say this one H toG will be in terms of liquid flowrate that is L into c WL by capital K Y prime by into a bar. So from this we will be getting so the packed height is the product of height of the transfer unit and number of the transfer units.

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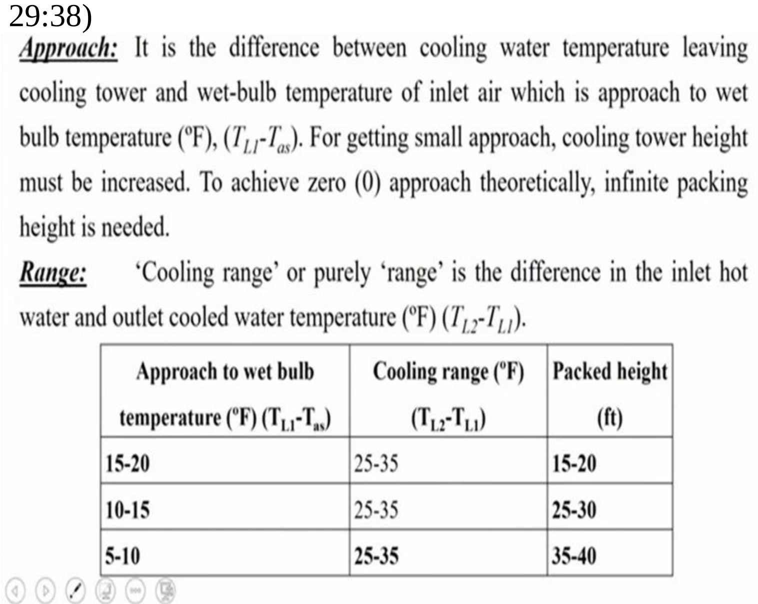

***Approach:*** It is the difference between cooling water temperature leaving cooling tower and wet-bulb temperature of inlet air which is approach to wet bulb temperature (°F), ($T_{L1}$-$T_{as}$). For getting small approach, cooling tower height must be increased. To achieve zero (0) approach theoretically, infinite packing height is needed.

***Range:*** 'Cooling range' or purely 'range' is the difference in the inlet hot water and outlet cooled water temperature (°F) ($T_{L2}$-$T_{L1}$).

| Approach to wet bulb temperature (°F) ($T_{L1}$-$T_{as}$) | Cooling range (°F) ($T_{L2}$-$T_{L1}$) | Packed height (ft) |
|---|---|---|
| 15-20 | 25-35 | 15-20 |
| 10-15 | 25-35 | 25-30 |
| 5-10 | 25-35 | 35-40 |

So we will be doing this one and we need to know these two important terms like this approach and range, so this approach is nothing but we can say this it is the difference between this cooling water temperature leaving cooling tower and wet-bulb temperature of inlet air which approaches to wet bulb temperature in degree Fahrenheit, that is nothing but we can say this T L1 minus T a s. So, for getting small approach, cooling tower height must be increased. So, to achieve this zero approach theoretically, infinite number of packing height is needed.

If we talk about this range or simply we can say this cooling range or purely range that is difference in the inlet hot water and outlet cold water temperature that is nothing but T L 2 minus T L 1. Now, this approach to wet bulb temperature or we can say this approach that is in terms of degree Fahrenheit that is if it 15 to 20 degree Fahrenheit then this cooling range will be around 25 to 35 degree Fahrenheit and the typical packed height requirement will be 15 to 20 feet. If we say this approach to wet-bulb temperature will be in the range of 10 to 15 degree Fahrenheit then cooling range will be around 25 to 35 degree Fahrenheit and packed height will be around 25 to 30 feet. And we say approach to a wet-bulb temperature will be 5 to 10 degree Fahrenheit then cooling range will be 25 to say 35 degree Fahrenheit and this packed height will be in the range of 35 to 40 feet.

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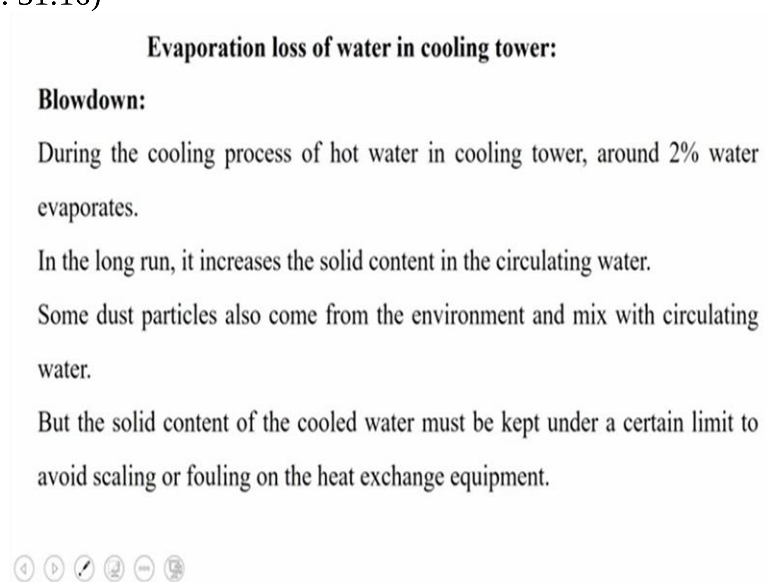


Now you see this one we need to understand these two other terms like this evaporation loss and this blowdown in the cooling tower, that is say blowdown means we can say this one whenever we want cooling tower is installed mostly it is placed on the open air and say we know that the role of the cooling tower is to cool down the hot water that is coming out of the different chemical processes or we can say this one maybe from turbine of this power plant unit.

And whenever it will be coming to this cooling tower, this we can say this one around 2 percent water actually is evaporated, maybe around 1 to 2 percent water evaporates and in the you can say this one louvers or we can say this one different sides of the cooling tower and also at the bottom huge amount of algae growth takes place as well as some amount of suspended solids are also deposited there.

So, in the long-run it increases the solid content in the circulating water. So, some dust particles also come from the environment and mix with circulating water. But the solid content of the this one cooled water must be kept under a certain limit to avoid scaling or fouling on the heat exchanger equipment or anywhere this cold water will be used.

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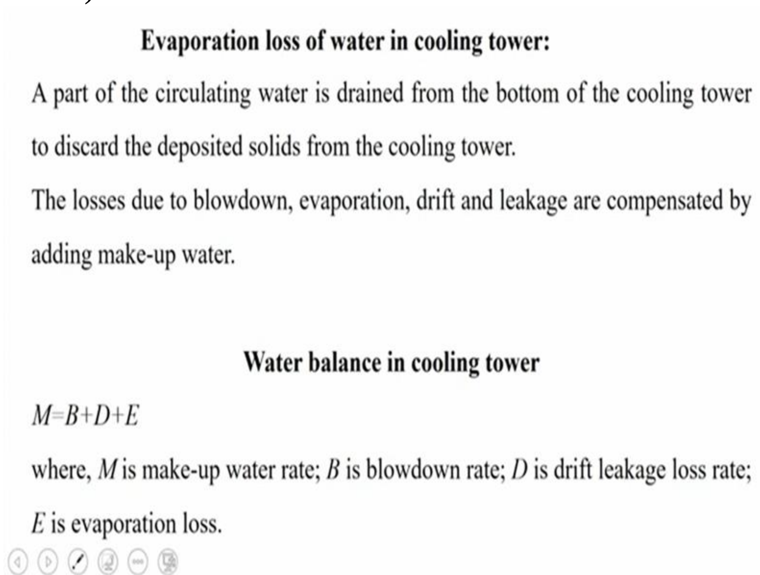


So, portion of this we can say this one water a part of the circulating water is drained from the bottom of the cooling tower periodically to discard the deposited solids form the cooling tower. And the losses due to this blowdown, evaporation, drift and leakage are compensated by this adding this make-up water. So this make-up water is added like this maybe one or two percent of total water flowrate, so we can so easily this water balance in the cooling tower like this total aim is make-up water is nothing but the summation of this B means this blowdown rate, D is drift leakage loss rate, and E is evaporation loss.

So drift leakage is also one of the we can say losses whenever it is flushed from the top of this cooling tower some amount of we can say this one water will be flushed and that will be lost form the cooling tower. It is not coming down to the cooling tower through the main stream but some amount will be this lost to the environment.

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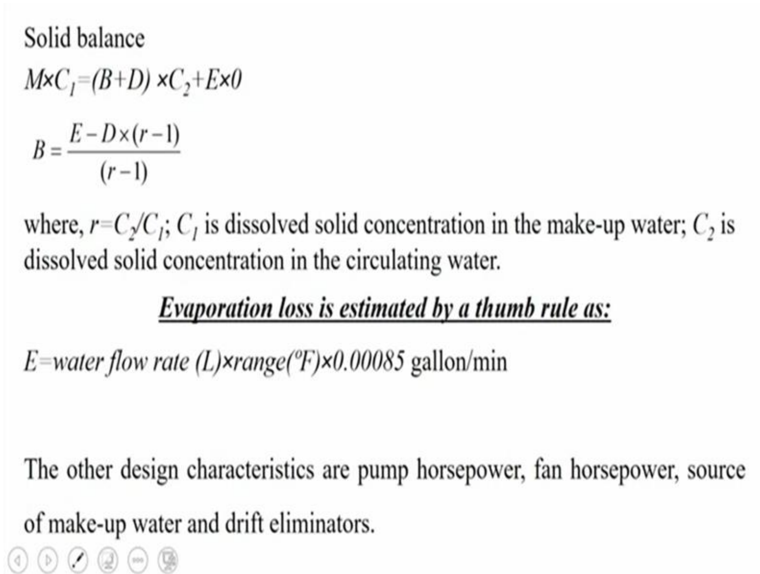


And this solid balance also we need to do solid balance like M into C 1 is equal to B plus D into C 2 plus E into zero. Because this whatever evaporated it is not containing any solid, so we can say this one B is nothing but this blowdown is equal to E minus D into r minus 1 by r minus 1 where we can say this one small r is equal to C 2 by C 1 where C 1 is the dissolved solid concentration in the make-up water and C 2 is the dissolved solid concentration in the circulating water.

And this there is one thumb rule for the calculation of the evaporation loss that is E is equal to we can say this water flow rate into to the range whatever the this cooling range is there in degree Fahrenheit into 0.00085 gallon per minute. That is the thumb rule and in most of the cooling towers this holds good. The other design characteristics are like pump horse power, then fan horsepower, then source of make-up water and drift eliminators, this also we need to consider during this we can say this one design of the cooling tower.

***Evaporation loss is estimated by a thumb rule as:***

*E=water flow rate (L)×range(ºF)×0.00085* gallon/min

The other design characteristics are pump horsepower, fan horsepower, source of make-up water and drift eliminators.

**Nomenclature**

| | | | |
|---|---|---|---|
| $\bar{a}$ | contact area/tower volume, $m^2/m^3$ | $L$ | Water flow rate, $kg/m^2s$ |
| $c_{wL}$ | Heat capacity of liquid (water), kJ/kg.K | $V$ | active cooling volume/plan area, $m^3/m^2$ |
| $G_s$ | Air rate, kg dry air/$m^2$s | $Y'$ | Humidity, kg moisture/kg dry air |
| $h_G$ | Heat transfer coefficient of air film, kJ/$m^2$.s.K | $Y'_w$ | Saturation humidity, kg moisture/kg dry air |
| $h_L$ | Heat transfer coefficient of liquid (water), kJ/$m^2$.s.K | z | Cooling tower height, m |
| $k_G$ | Mass transfer co-efficient of moisture transport, kg/$m^2$.s ($\Delta p_A$) | $\lambda_w$ | Latent heat of vaporization of water, kJ/kg |
| $K'_Y$ | Overall mass transfer co-efficient, kg/$m^3$.s | $\nu_H$ | Humid volume, $m^3$/kg dry air |

So, thank you, in the next class we will be solving one problem on the cooling tower.