Spring Semester course

CH31010: Mass Transfer II

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L3: Gas Liquid Contact Operations

Types of Gas-Liquid contact operations

Adiabatic operations

Cooling a liquid: Cooling occurs by sensible heat transfer and evaporation, in contact with atmospheric air.

Cooling a hot gas: Direct contact leads to a non-fouling heat exchanger, which is very effective.

Humidifying gas: For controlling the moisture content of air for drying.

Dehumidifying gas: Contact of a warm vapour-gas mix with cold liquid results in condensation of the vapour (e.g. applications in air conditioning, recovery of solvent vapours from gas)

Non-adiabatic operations

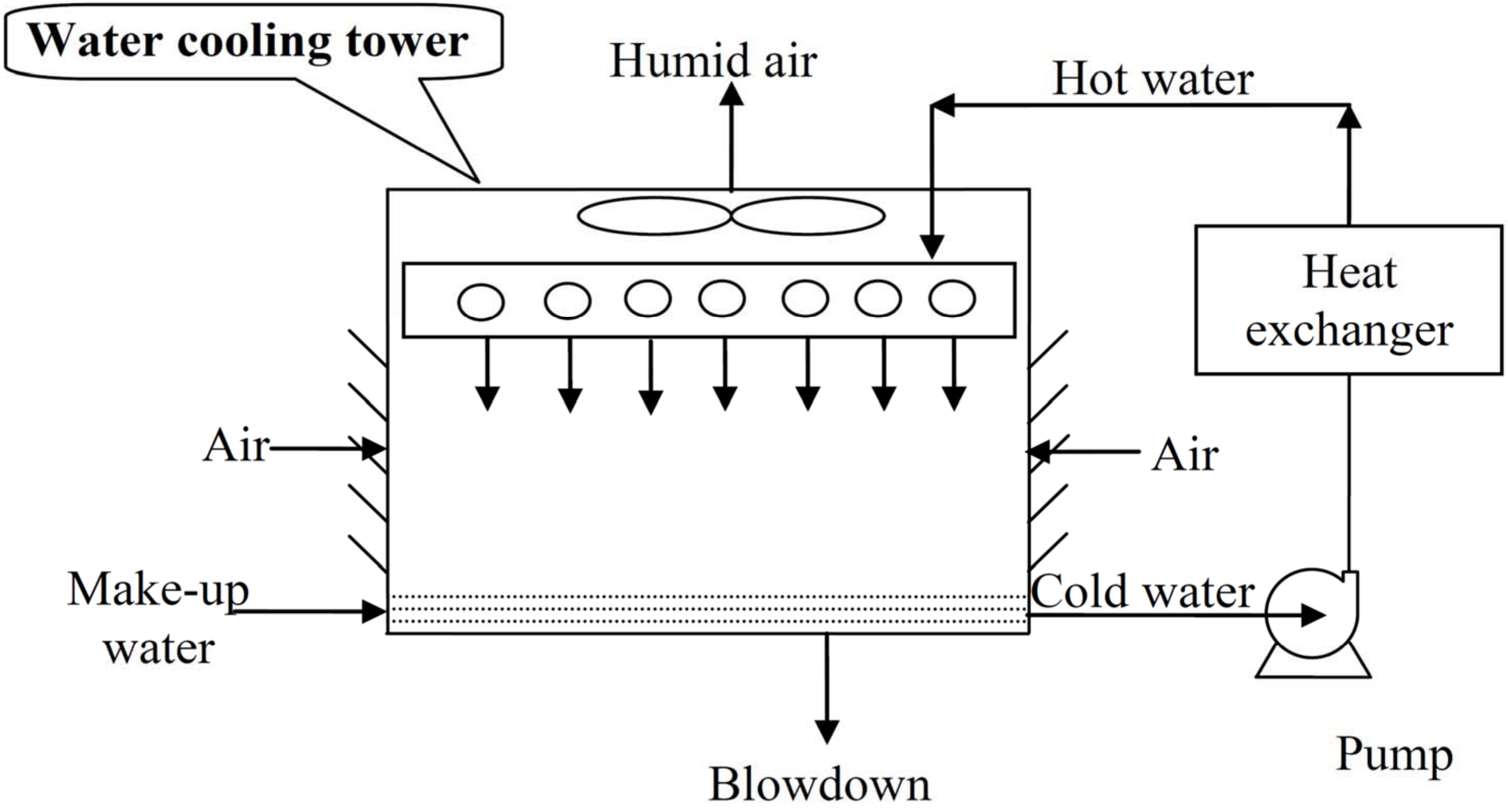
Evaporative cooling: A liquid / gas inside a pipe is cooled by a flowing water film outside, the latter is cooled by contact with air.

Dehumidifying gas: A gas-vapour mix is contacted with refrigerated tubes, and the vapour condenses over the pipes.

Cooling tower

A cooling tower is a special type of heat exchanger in which the warm water and the air are brought in direct contact for '***evaporative cooling***'. It provides a very good contact of air and water in terms of the contact area and mass transfer co-efficient of water vapor while keeping air pressure drop low. Sensible heat and latent heat transfer takes place from water drop to surrounding air.

Thus, cooling is accomplished by sensible heat transfer from water to air and evaporation of a small portion of water. The hot water which is coming from heat exchanger is sprayed at the top of the cooling tower. Air enters through the louvers at the two opposite walls of the cooling tower. During the cooling process of water, around 2% water is evaporated. Make-up water is used to compensate the water loss due to evaporation. Blow-down is there to drain a part of water containing solid deposit. The exit cold water from the cooling tower is used in the heat exchanger or other unit operation.



Water cooling tower
Humid air
Hot water
Heat exchanger
Air
Air
Make-up water
Cold water
Blowdown
Pump

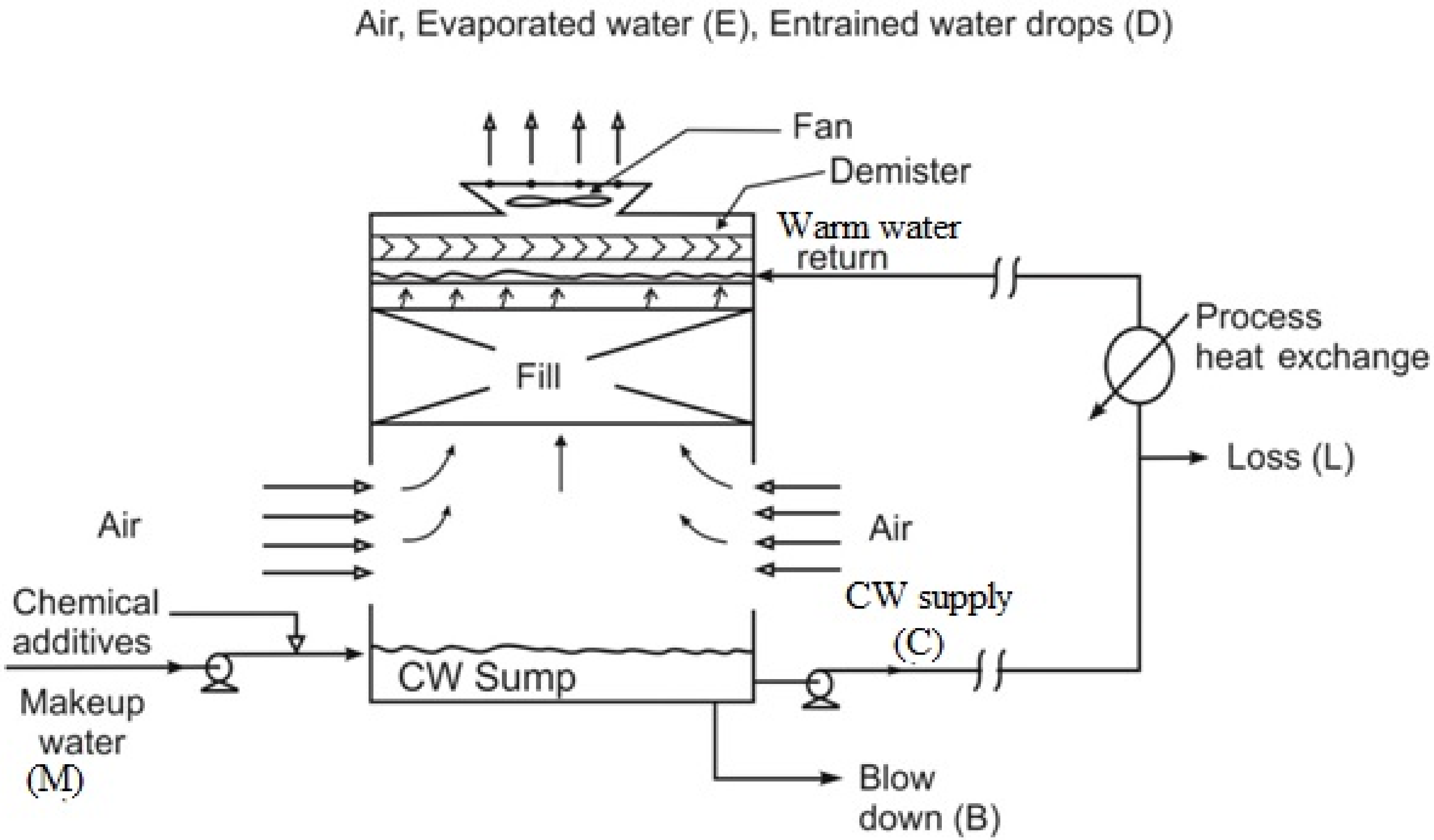
Factors that affect the performance of cooling water:

Temperature of air
Temperature of incoming water
Contact efficiency between air and water in terms of the mass transfer coefficient

Contact time between air and water
Uniformity of the distribution of the phases within the tower
Air pressure
Contact time between air and water

Types of cooling tower:

Refer to the document “CT-classification.pdf”



Schematic showing a circulating cooling water system

Few important parameters

Cooling range R (K)

Capacity C (kcal/h)

Approach A (K)

Liquid/Gas ratio

Effectiveness

Heat Load

Typical cooling capacity requirement for different equipment

Equipment	Cooling Load Requirement
Air Compressor	
- Single-stage	129 kcal /kW/hr
- Single-stage with after cooler	862 kcal/kW/hr
- Two-stage with intercooler	518 kcal/kW/hr
-Two-stage with intercooler and after cooler	862 kcal/kW/hr
Refrigeration, Compression	63 kcal/min/Ton Refrigeration load
Refrigeration, Absorption	127 kcal/min/Ton Refrigeration load
Steam Turbine Condenser	555 kcal/kg of steam
Diesel Engine, Four stroke	880 kcal/kW/hr
Natural Gas Engine, Four stroke	1523 kcal/kW/hr (for 18 kg/cm^2 compression)

Evaporation loss

It varies with temperature and humidity, a general rule is that for every 6^{o}C drop in water temperature across tower, approximately 0.85% of recirculation rate (C) will be evaporated.

An empirical formula from Perry handbook: $E\left({m^3}/{hr}\right) = 0.0085 \times \left({R}/{6}\right) \times C\left({m^3}/{hr}\right)$

The evaporation loss can also be estimated from the heat balance across the cooling tower, i.e., the amount of heat to be removed from circulating water and the amount of heat removed by evaporative cooling.

$$Q = C\left(\frac{m^3}{h}\right) \times C_p \times R = E \times \lambda$$

A more rigorous way of calculating evaporation loss is based on humidity difference of inlet and exit air and its flow rate

Drift loss

is usually estimated based on a percentage of recirculation. Estimates vary from 0.002 to 0.01% of recirculation.

It may be considered to be –

(i) 0.3 to 1.0 % C for a natural draft cooling tower

(ii) 0.1 to 0.3 % C for an induced draft cooling tower

(iii) about 0.01 % C or less, if the cooling tower has windage drift eliminators

Makeup water

is the sum of the water lost in evaporation, drift loss and bleeding / blow-down.

Design/Sizing of a cooling tower

Design specifications:

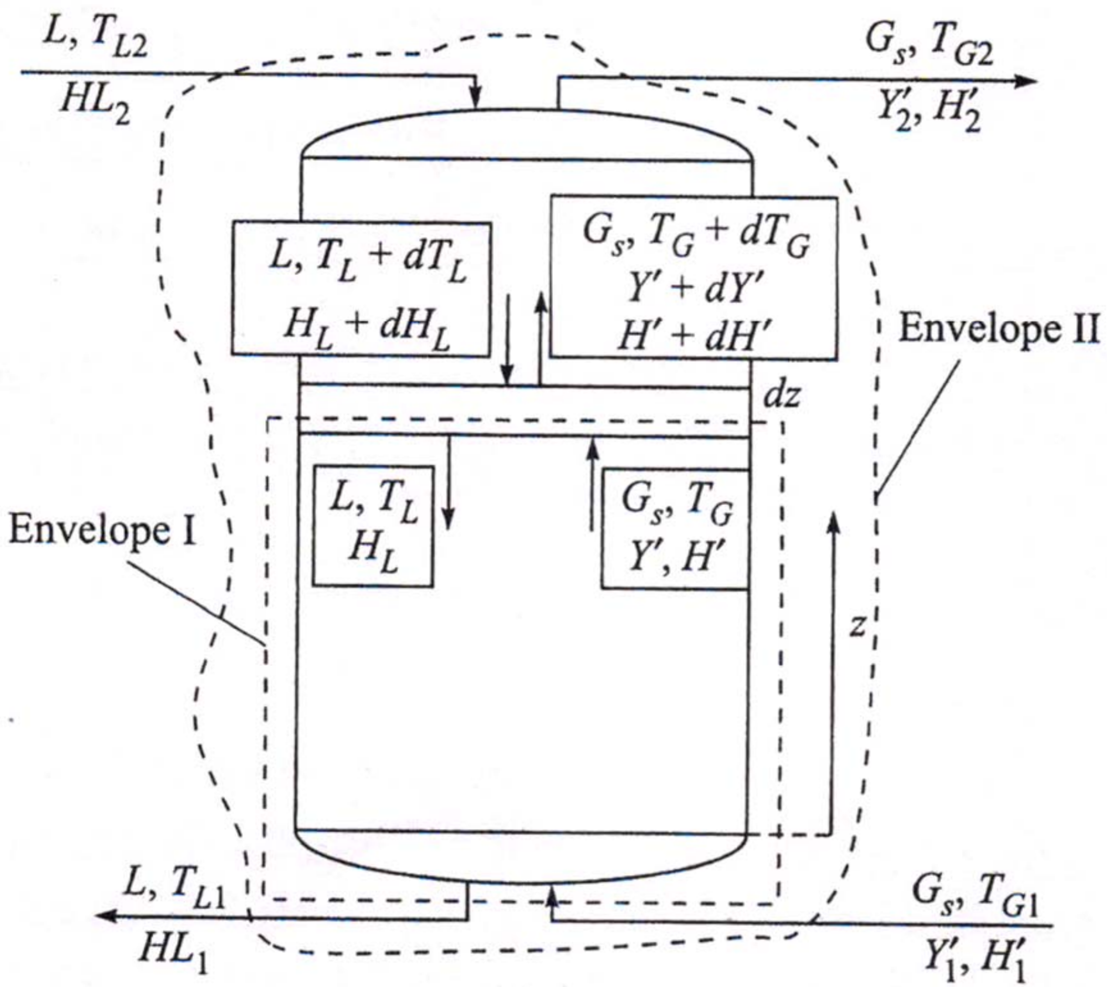
1. Tower cross-section / diameter
2. Tower height

Assumptions:

(i) Rate of vaporization is small and loss of feed water is insignificant

(ii) Adiabatic cooling (no heat exchange through the tower walls)

Mass & Enthalpy balance



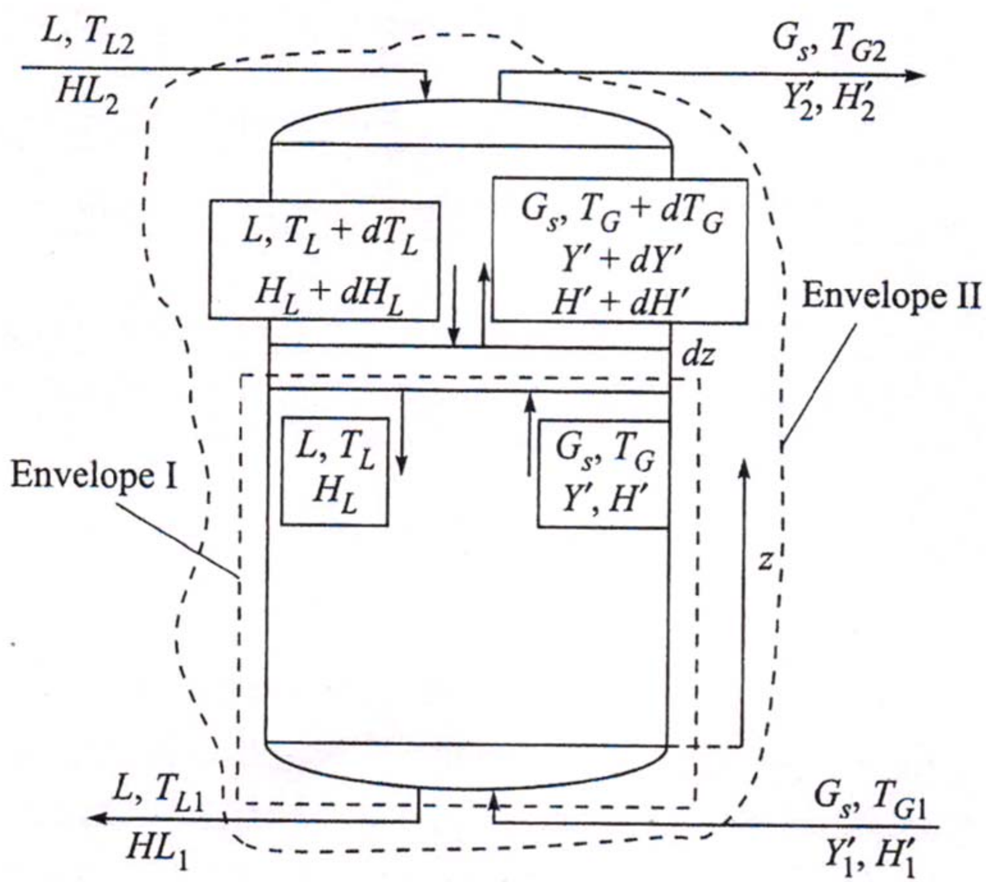
Differential enthalpy balance over Δz, $\quad L\, c_{wL}\, \mathrm{d}T_L = G_s\, \mathrm{d}H'$

The enthalpy balance over the envelope I gives

$$Lc_{wL}(T_L - T_{L1}) = G_s(H' - H'_1)$$

Operating line for the air-water contact

Slope of the *Operating line*: $\frac{c_{wL}L}{G_s}$



Making an enthalpy balance across the entire tower (Envelope II):

$$L\, c_{wL}\, (T_{L2} - T_{L1}) = G_s\, (H'_2 - H'_1)$$

The rate of transfer of water vapour to air in the differential volume is

$$G_s \, \mathrm{d}Y' = k_{Y'} \, \bar{a} \, \mathrm{d}z \, (Y_i' - Y')$$

where

$k_{Y'}$ = mass transfer coefficient of water vapour
$\bar{a}$ = specific interfacial area of the air–water contact
Y_i' = humidity of air at the air–liquid interface.

The decrease in the air temperature is because of the sensible heat transfer

$$-G_s \, c_H \, \mathrm{d}T_G = h_G \, \bar{a} \, \mathrm{d}z \, (T_G - T_i)$$

Definition of the enthalpy of the gas: $H' = Y'\lambda_0 + c_H(T - T_0)$

The differential form multiplied by G_s results into

$$
\begin{aligned}
G_s dH' &= G_s \lambda_0 dY' + G_s c_H dT_G \\
&= G_s \lambda_0 dY' - h_G \bar{a}\, dz(T_G - T_i) \\
&= -h_G \bar{a}\, dz(T_G - T_i) + \lambda_0 k_{Y'} \bar{a}\, dz(Y_i' - Y') \\
&= k_{Y'} \bar{a}\, dz[(h_G/k_{Y'})(T_i - T_G) + \lambda_0(Y_i' - Y')]
\end{aligned}
$$

Using the result $(h_G/k_{Y'}) = c_H$ in the above equation,

$$
\begin{aligned}
G_s dH' &= k_{Y'} \bar{a}\, dz[c_H(T_i - T_G) + \lambda_0(Y_i' - Y')] \\
&= k_{Y'} \bar{a}\, dz[\{Y_i'\lambda_0 + c_H(T_i - T_0)\} - \{\lambda_0 Y' + c_H(T_G - T_0)\}]
\end{aligned}
$$

Using the definition of enthalpy of the gas

$$G_s dH' = k_{Y'} \bar{a}\, dz(H_i' - H')$$

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

Invoking the concept of transfer units, we can define

$$N_{tG} = \int_{H_1'}^{H_2'} \frac{dH'}{H_i' - H'} \quad \text{and} \quad H_{tG} = \frac{G_s}{k_{Y'}\bar{a}}$$

where

N_{tG} = number of gas-enthalpy transfer units
H_{tG} = height of a gas-enthalpy transfer unit.

Height of the packed section, $z = H_{tG} N_{tG}$

Tie lines:

If $h_L\bar{a}$ is the volumetric individual heat transfer coefficient on the water-side of the interface, a differential heat balance equation over a small section of the packing gives

$$Lc_{wL}dT_L = h_L\bar{a}\,dz(T_L - T_{Li})$$

Using the relations: $Lc_{wL}dT_L = G_s dH' = k_{Y'}\bar{a}\,dz(H_i' - H')$

You can write: $k_{Y'}\bar{a}\,dz(H_i' - H') = -h_L\bar{a}\,dz(T_{Li} - T_L)$

$$\Rightarrow \frac{H_i' - H'}{T_{Li} - T_L} = -\frac{h_L}{k_{Y'}}$$

Conditions of the cooling tower at the top (left) and bottom (right) of the tower.

Alternative form of N_{tG}:

An alternative form of N_{tG} can be obtained by substituting $G_s \mathrm{d}H' = L\, c_{wL} \mathrm{d}T_L$

$$Lc_{wL}dT_L = k_{Y'}\bar{a}\,dz(H_i' - H') \quad \Rightarrow \quad \int_{T_{Li}}^{T_{Lo}} \frac{dT_L}{H_i' - H'} = \frac{k_{Y'}\bar{a}}{Lc_{wL}} \int_0^z dz = \frac{k_{Y'}\,\bar{a}}{Lc_{wL}}\, z$$

Steps of the design calculations:

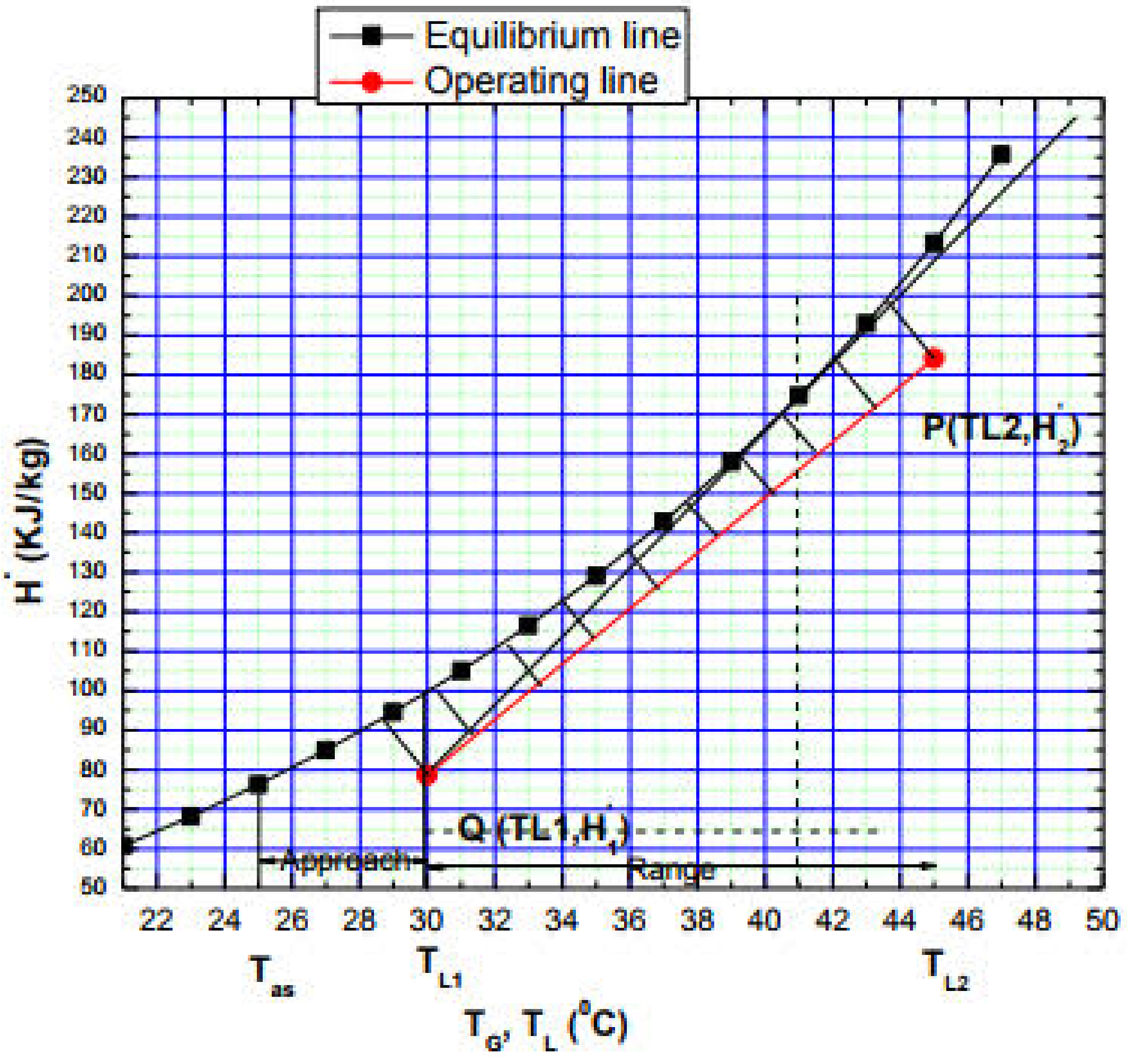
(a) Specify the inlet and outlet temperatures and the flow rate of warm water. These quantities are governed by the requirement of cooling water in the heat exchangers and other cooling devices in a plant.

(b) Select the design values of the dry-bulb and the wet-bulb temperature of air at the proposed geographical location of the cooling tower. The relevant data are available at the weather office in the region.

(c) Draw the 'equilibrium curve', i.e. the saturation–humidity curve. The enthalpy data can be calculated using the vapour pressure equation for water and the physical properties of air and water vapour

(d) Locate the lower terminal of the operating line Q on the T_L–H' plane by the point (T_{L1}, H'_1). This point indicates the condition at the bottom of the tower in the case of water cooling.

(e) Draw a tangent to the equilibrium line through the point Q. The slope of this tangent gives the ratio of the liquid and the minimum gas flow rates



Equilibrium line
Operating line
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
H' (KJ/kg)
P(TL2,H'2)
Q (TL1,H'1)
Approach
Range
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
T_as
T_L1
T_L2
T_G, T_L (°C)

(f) The upper terminal of the operating line is located by the point $P(T_{L2}, H_2')$. It is the point where the operating line of the slope determined in step (e) meets the vertical line through T_{L2}. It can also be located by calculating the top end enthalpy H_2' from

$$L\, c_{wL}\, (T_{L2} - T_{L1}) = G_s\, (H_2' - H_1')$$

(g) Evaluate the integral $\displaystyle\int_{H_1'}^{H_2'} \frac{dH'}{H_i' - H'}$ or $\displaystyle\int_{T_{Li}}^{T_{Lo}} \frac{dT_L}{H_i' - H'}$

This is the number of gas-phase enthalpy transfer units. The volumetric transfer coefficients $k_{Y'}\bar{a}$ and $h_L\bar{a}$ are required for this purpose. As described above, a set of parallel lines (sometimes called *tie lines*) of slope $-h_L\bar{a}/k_{Y'}\bar{a}$ is drawn between the operating line and the equilibrium line. The values of H' and H_i' are taken from the terminals of these lines. The integral is evaluated numerically or graphically.

(h) The height of the transfer unit is $G_s/k_Y\bar{a}$. The tower height is the product of the number of transfer units (N_{tG}) and the height of each of the units (H_{tG}).

Example problem:

Warm water at 45°C is to be cooled to 30°C by countercurrent contact with air in a tower packed with wood slats. The inlet air has a dry-bulb temperature of 31°C and a wet-bulb temperature of 22°C. The mass flow rate of water is 6000 kg/m^2·h and that of air is 1.4 times the minimum. The individual gas-phase mass transfer coefficient is $k_{Y'}\bar{a} = 6000$ kg/(m^3)(h)($\Delta Y'$). The volumetric water-side heat transfer coefficient is given by $h_L\bar{a} = 0.059L^{0.51}G_s$, in kcal/m^3·h·K, where L and G_s are mass flow rates of water and air (dry basis).

Determine: (a) the air flow rate to be used

(b) the height of the packing

(c) approach of the tower

Antoine equation for water is $\ln P_V\ (\text{bar}) = 11.965 - \dfrac{3984.923}{\text{T (K)} - 39.724}$