Topic 3.4. Gas-liquid contact operation

Last lecture

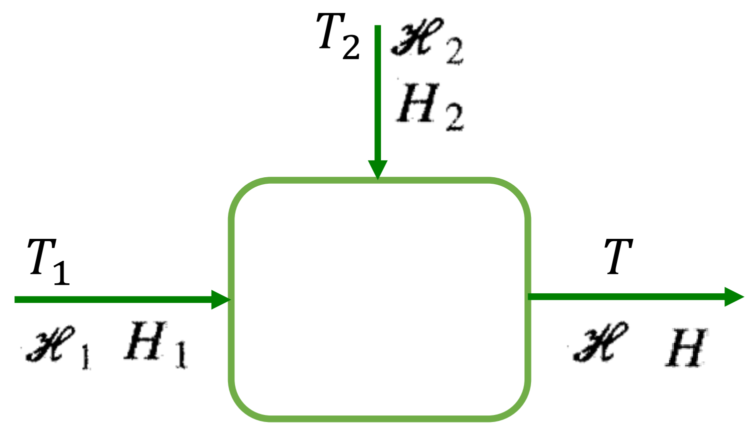
- ✓ Psychrometric (humidity) terminology
- ✓ Plot processes on a psychrometric chart and analyze processes

This lecture

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

Mixing of two streams of humid gas

Mixing of two gases of humidities $\mathscr{H}_1$ and $\mathscr{H}_2$, at temperatures T_1 and T_2, and with enthalpies H_1 and H_2 to give a mixed gas of temperature T, enthalpy H, and humidity $\mathscr{H}$, If the masses of dry gas concerned are m_1 and m_2, and m respectively



A mass balance on the dry gas, vapor, and enthalpy:

$$m_1 + m_2 = m$$

$$m_1\mathscr{H}_1 + m_2\mathscr{H}_2 = m\mathscr{H}$$

$$m_1H_1 + m_2H_2 = mH$$

$\Rightarrow$

$$m_1(\mathscr{H} - \mathscr{H}_1) = m_2(\mathscr{H}_2 - \mathscr{H})$$

$$m_1(H - H_1) = m_2(H_2 - H)$$

$$\frac{(\mathscr{H} - \mathscr{H}_1)}{(H - H_1)} = \frac{(\mathscr{H} - \mathscr{H}_2)}{(H - H_2)}$$

$$\frac{(\mathscr{H} - \mathscr{H}_1)}{(\mathscr{H}_2 - \mathscr{H})} = \frac{m_2}{m_1}$$

Example 3.4.1 Humidity of mixed streams

In an air-conditioning system, 1 kg/s air at 350 K and 10% humidity is mixed with 5 kg/s air at 300 K and 30% humidity. What is the enthalpy, humidity, and temperature of the resultant stream?

Solution

From psychrometric chart ⇨

at 350 K and 10% humidity $\mathscr{H}_1 = 0.043$ kg/kg $H_1 = 192$ kJ/kg

at 300 K and 30% humidity $\mathscr{H}_2 = 0.0065$ kg/kg $H_2 = 42$ kJ/kg

$$m_1\mathscr{H}_1 + m_2\mathscr{H}_2 = m\mathscr{H} \quad \Rightarrow \quad (1 \times 0.043) + (5 \times 0.0065) = (1+5)\mathscr{H}$$

$$\mathscr{H} = 0.0125 \text{ kg/kg}$$

$$m_1(H - H_1) = m_2(H_2 - H) \quad \Rightarrow \quad 1(H - 192) = 5(42 - H)$$

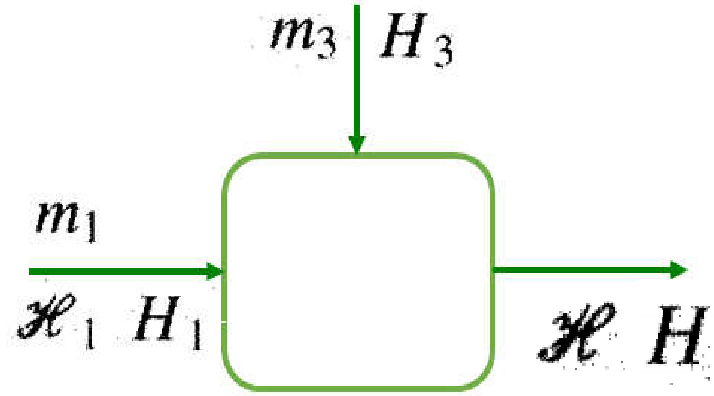
$$H = 67 \text{ kJ/kg}$$

From psychrometric chart ⇨ at $H = 67$ kJ/kg and $\mathscr{H} = 0.0125$ kg/kg

$$T = 309\ K$$

Addition of liquid or vapor to a gas

If a mass m_3 of liquid or vapour of enthalpy H_3 is added to a gas of humidity $\mathscr{H}_1$ and enthalpy H_1 and containing a mass m_1 of dry gas, then



$$m_1(\mathscr{H} - \mathscr{H}_1) = m_3$$

$$m_1(H - H_1) = m_3 H_3$$

$$\Rightarrow \quad \frac{(H - H_1)}{(\mathscr{H} - \mathscr{H}_1)} = H_3 \quad \Rightarrow \quad (\mathscr{H} - \mathscr{H}_1) = \frac{m_3}{m_1}$$

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Gas-liquid contact operations

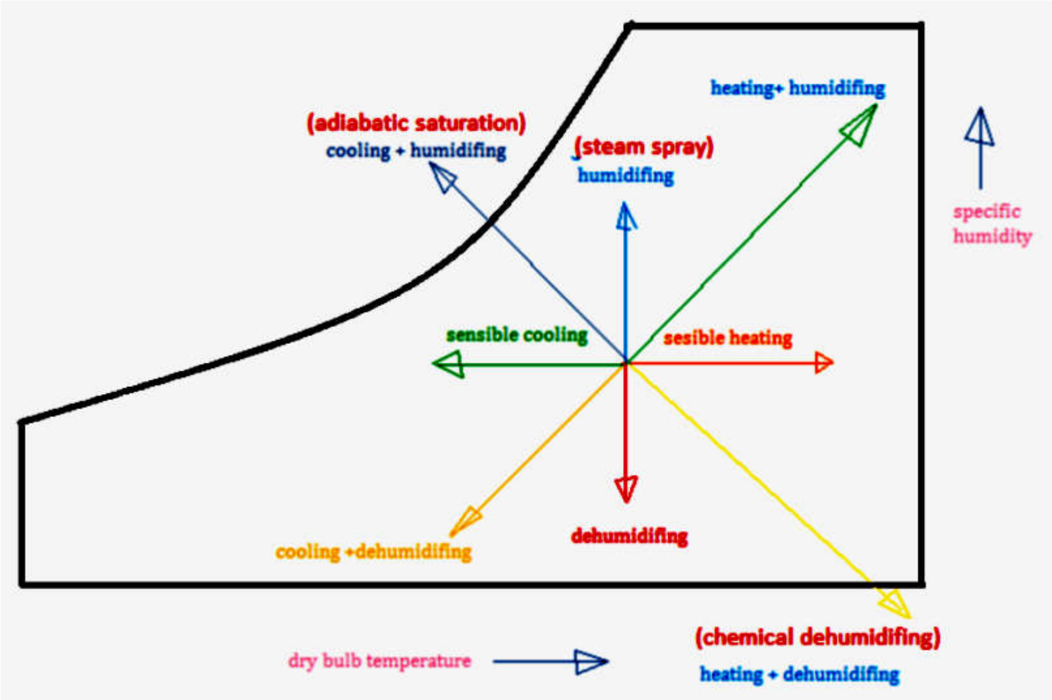
Direct contact of gas with pure liquid may have any of several purposes:

1. **Adiabatic operations**

   a. Cooling a hot gas
   b. Cooling a liquid
   c. Humidifying a gas
   d. Dehumidifying a gas

2. **Nonadiabatic operations**

   a. Evaporative cooling
   b. Dehumidifying a gas



1. Adiabatic operation

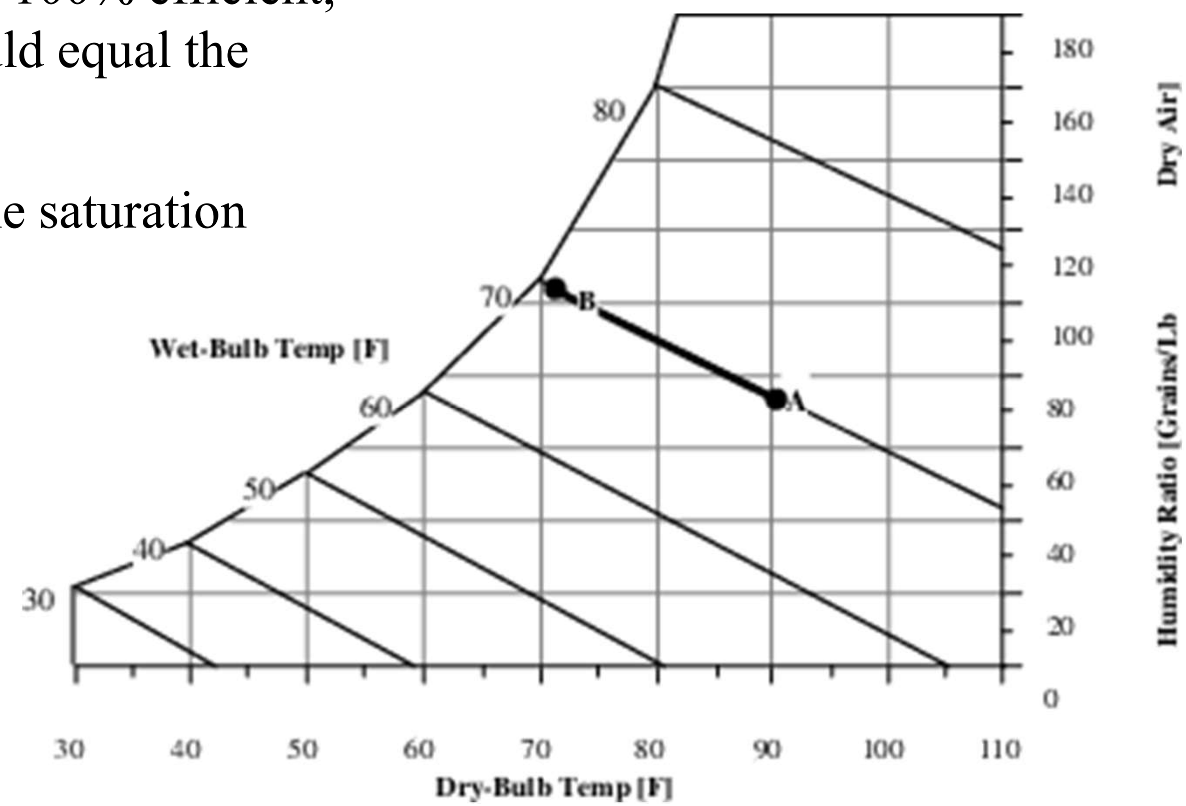
Adiabatic operation follows a constant enthalpy line on the psychrometric chart.

If the direct evaporative process were 100% efficient, the leaving dry-bulb temperature would equal the entering wet-bulb temperature

If the process is not 100% efficient the saturation efficiency is defined by

$$\varepsilon_{se} = \frac{T_{db\ sup\ in} - T_{db\ sup\ out}}{T_{odb} - T_{owb}}$$

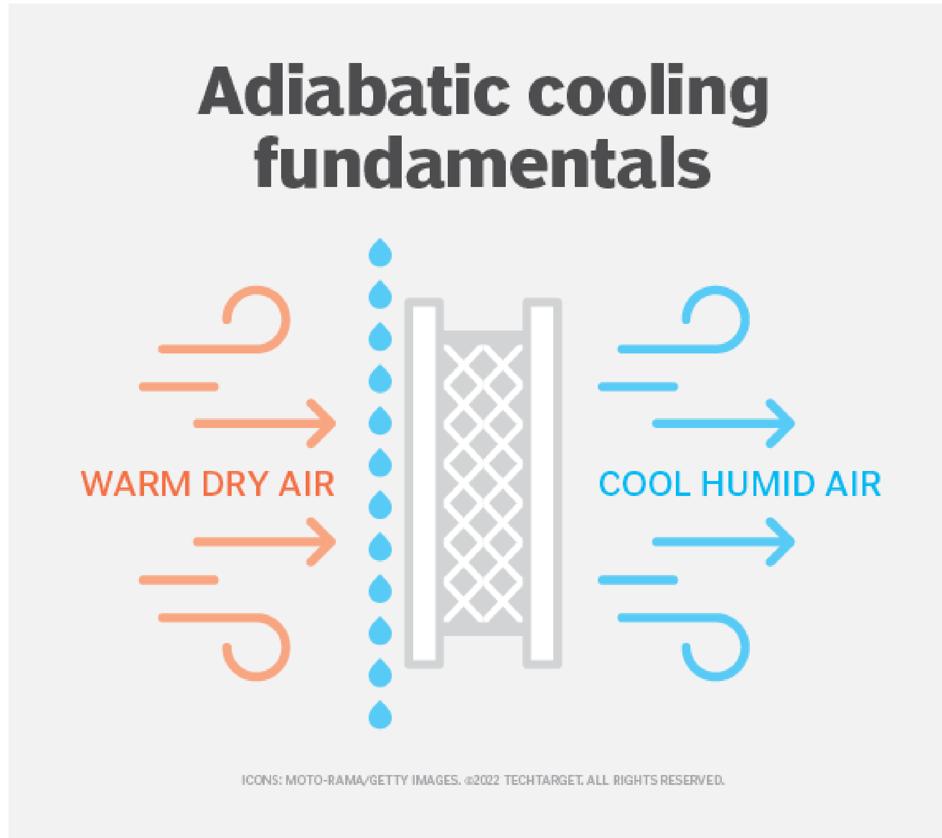
$T_{db\ \mathrm{sup}\ in}$: Temp. or dry bulb supply IN
$T_{db\ \mathrm{sup}\ out}$: Temp. or dry bulb supply OUT
T_{odb}: Temp. OUT dry bulb
T_{owb}: Temp. OUT wet bulb



1.a. Adiabatic cooling a hot gas

Adiabatic cooling systems **remove heat** by evaporating water in a **stream of warm, dry (low humidity) air**.

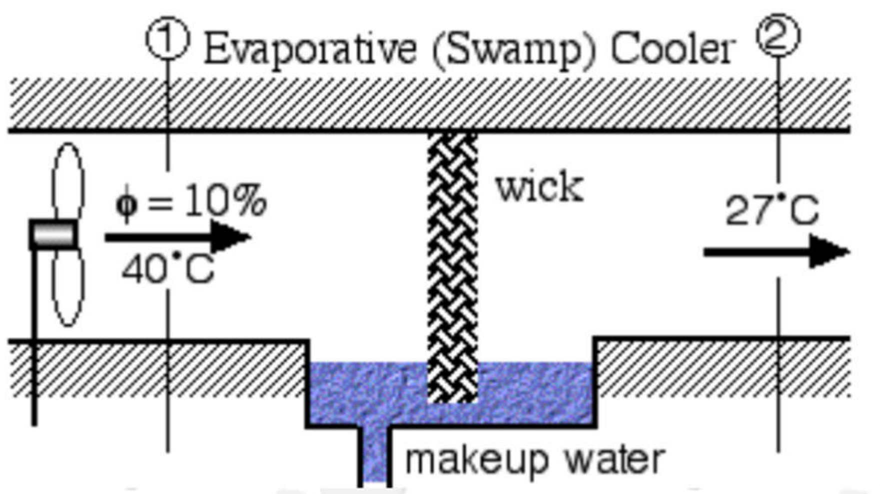
In the process of going from a liquid to a gas, **the evaporated water simultaneously humidifies and cools the air stream** to within a few degrees of the wet bulb temperature.



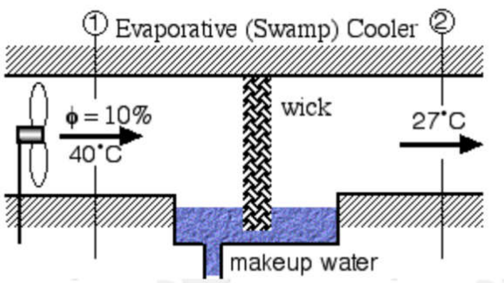
Example 3.4.2 Adiabatic cooling a hot gas

Hot dry air at 40°C and 10% relative humidity passes through an evaporative cooler. Water is added as the air passes through a series of wicks and the mixture exits at 27°C. Using the psychrometric chart determine

(a) the outlet relative humidity
(b) the amount of water added
(c) the lowest temperature that could be realized



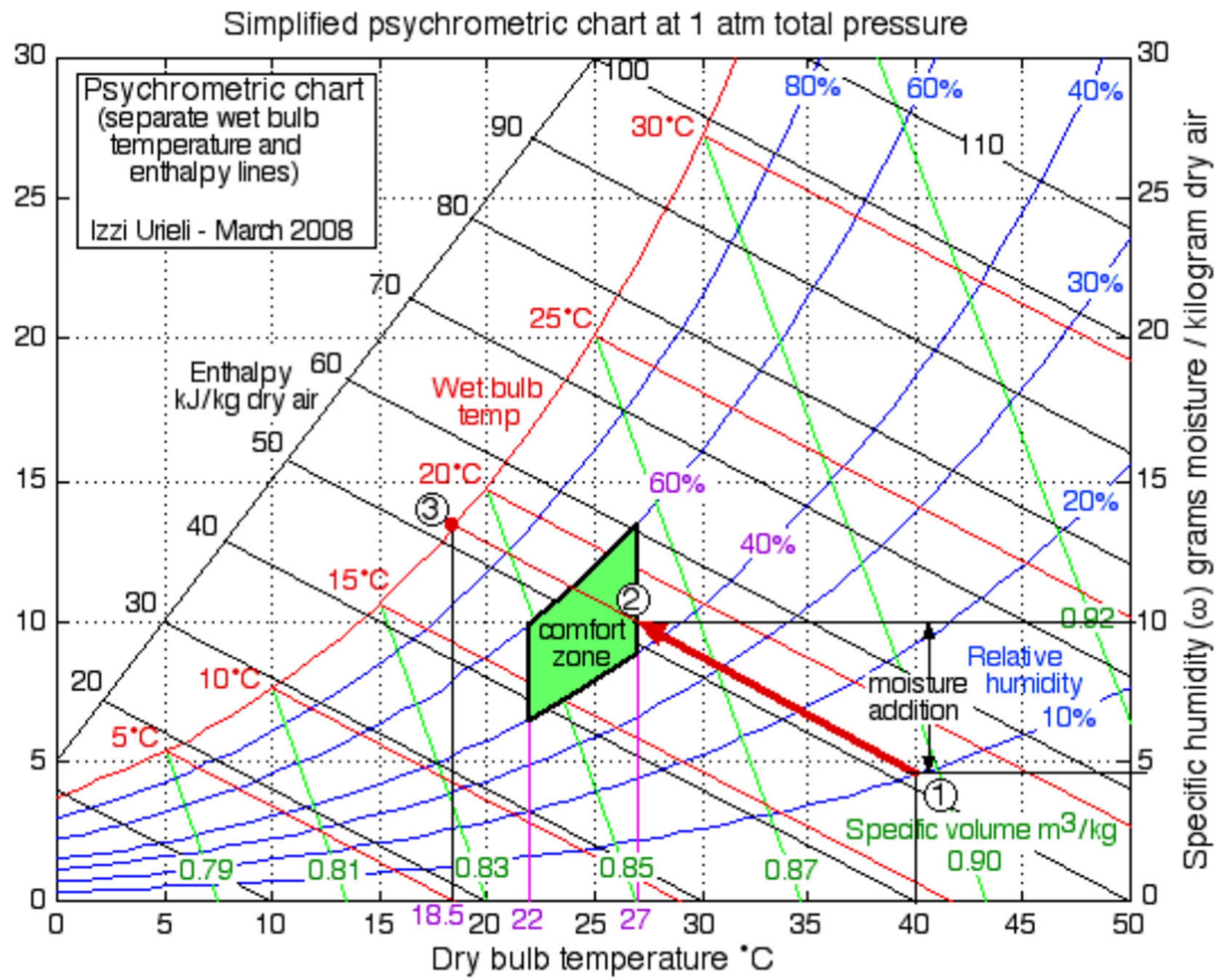
Solution



(a) the outlet relative humidity [45%]

(b) the amount of water added [5.4g-H20/kg-dry-air]

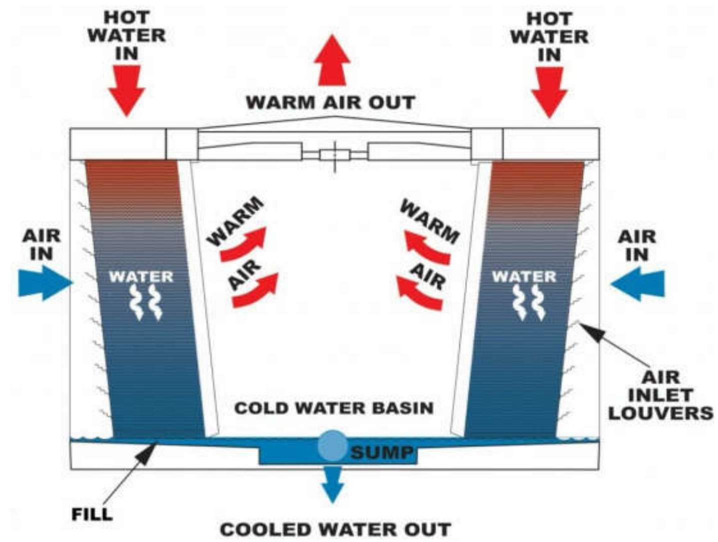
(c) the lowest temperature that could be realized [18.5°C]



1.b. Adiabatic cooling a liquid

Adiabatic cooling water occurs by transfer of sensible heat and also by evaporation.

The principal application is cooling of water by contact with atmospheric air (water cooling).



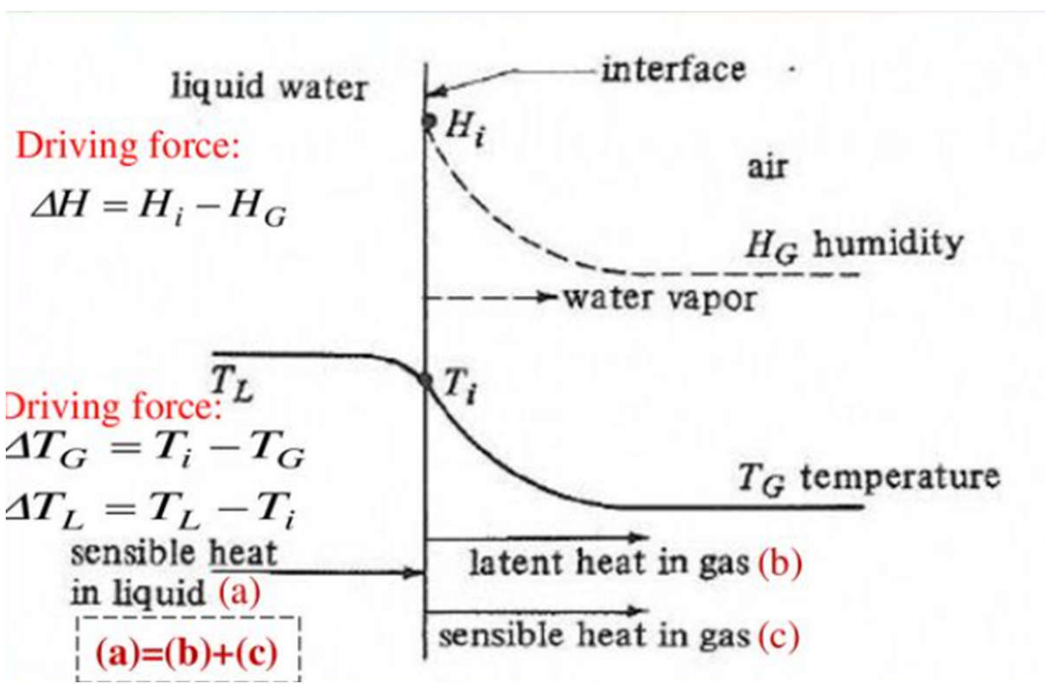
1.c. Adiabatic humidifying a gas

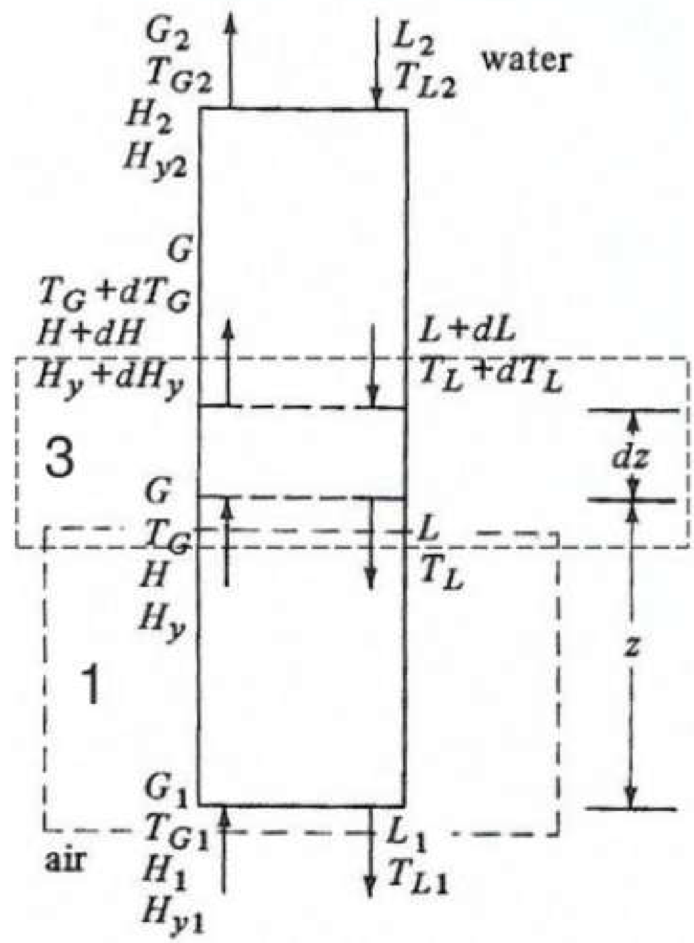
This can be used for controlling the moisture content of air for drying.

1.d. Adiabatic dehumidifying a gas

Contact of warm vapor-gas mixture with a cold liquid results in condensation of the vapor.
Application: air conditioning, and recovery of solvent vapor from gas used in drying

Fundamental relations for adiabatic operations





A mass balance over the lower part of the tower

$$L' - L'_1 = G'_S(Y' - Y'_1)$$

$$dL' = G'_S\,dY'$$

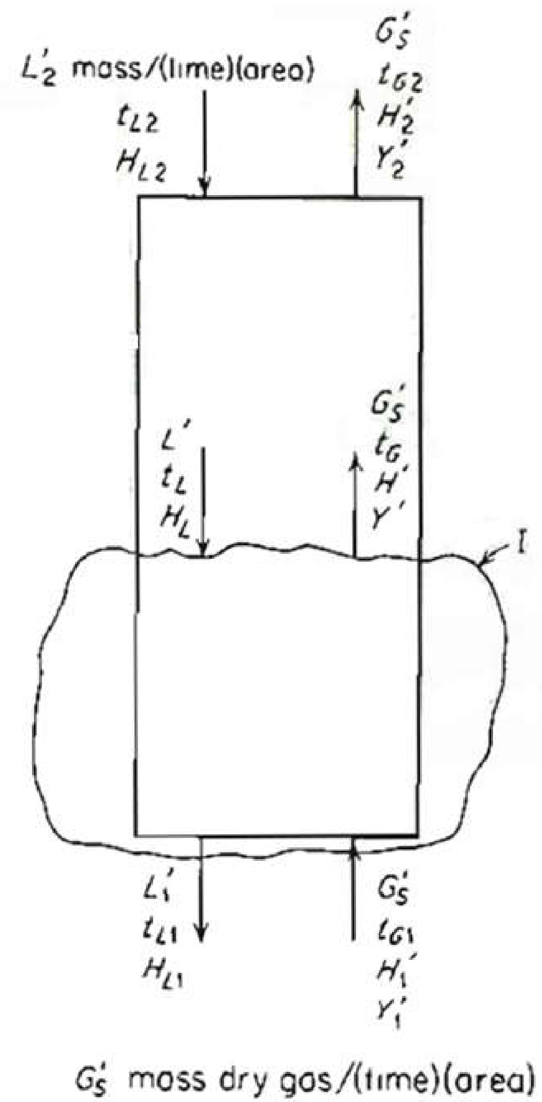
Similarly, an enthalpy balance is

$$L'H_L + G'_S H'_1 = L'_1 H_{L1} + G'_S H'$$

Mass, as mass rate per tower cross-sectional area:

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

$\bar{p}_{A,i}$ is the vapor pressure of A at the interface temperature t_i,
$\bar{p}_{A,G}$ is the partial pressure in the bulk gas

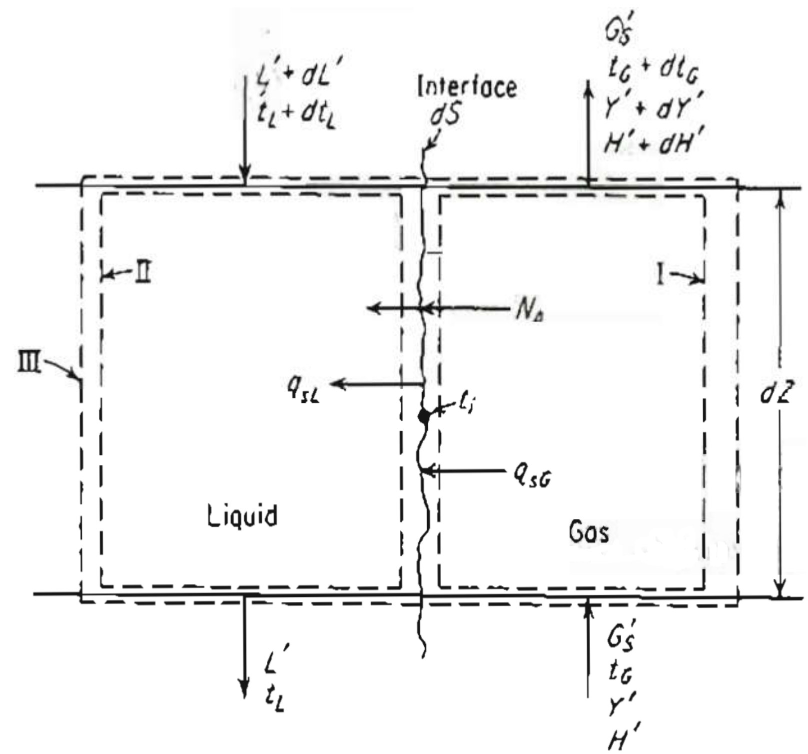


Sensible heat, as energy rate per tower cross-sectional area:

Gas: $$q_{sG}a_H\,dZ = \frac{N_A M_A C_A}{1 - e^{-N_A M_A C_A/h_G}}(t_G - t_i)a_H\,dZ = h'_G a_H(t_G - t_i)\,dZ$$

Liquid: $$q_{sL}a_H\,dZ = h_L a_H(t_i - t_L)\,dZ$$

enthalpy balances based on the envelopes



Envelope I:

Rate enthalpy in = $G'_S H'$

Rate enthalpy out =

$G'_S(H' + dH') - (G'_S\,dY')[C_A(t_G - t_0) + \lambda_0]$

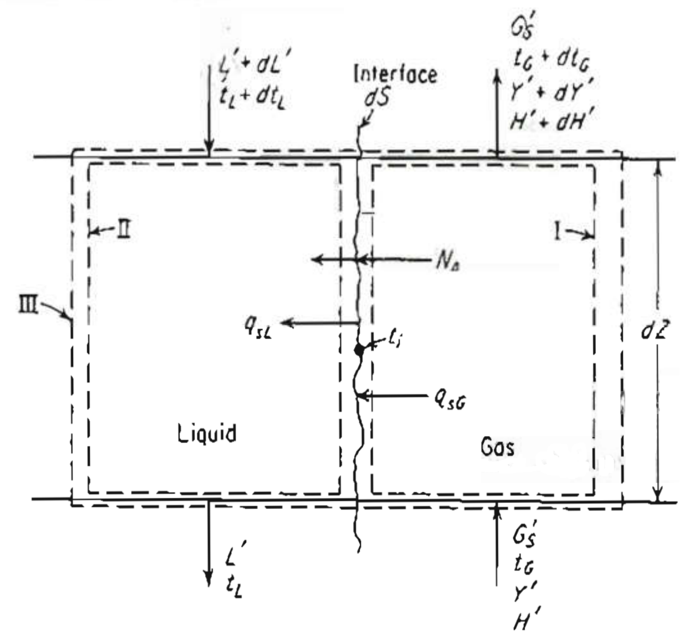
The second term is the enthalpy of the transferred vapor

Rate in − rate out = heat-transfer rate

$$G'_S H' - G'_S(H' + dH') + (G'_S\, dY')[C_A(t_G - t_0) + \lambda_0] = h'_G a_H (t_G - t_i)\, dZ$$

$$H' = C_B(t_G - t_0) + Y'[C_A(t_G - t_0) + \lambda_0] = C_S(t - t_0) + Y'\lambda_0$$

$$dH' = C_s dt + \lambda_0 dY'$$

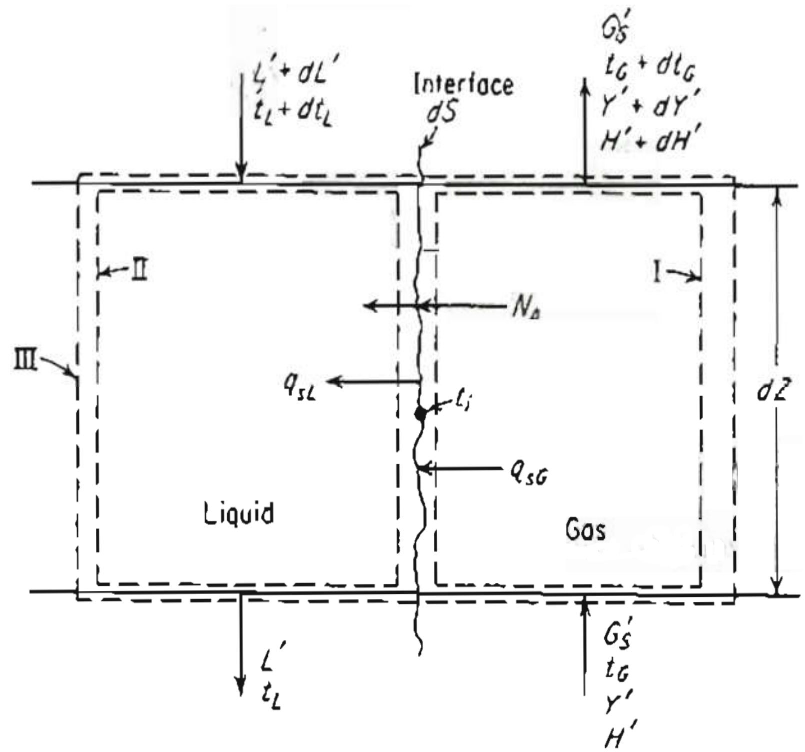


$$-\, G'_S C_S\, dt_G = h'_G a_H (t_G - t_i)\, dZ$$

Envelope II:

Rate enthalpy in $= (L' + dL')C_{A,L}(t_L + dt_L - t_0) + (-G'_S\, dY')C_{A,L}(t_i - t_0)$

Rate enthalpy out $= L'C_{A,L}(t_L - t_0)$



Rate out = rate in + heat-transfer rate

$$L'C_{A,L}(t_L - t_0) = (L' + dL')C_{A,L}(t_L + dt_L - t_0) - (G'_S\, dY')C_{A,L}(t_i - t_0) + h_L a_H(t_i - t_L)\, dZ$$

the second-order differential $dY'\, dt_L$ ignored

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

Envelope III:

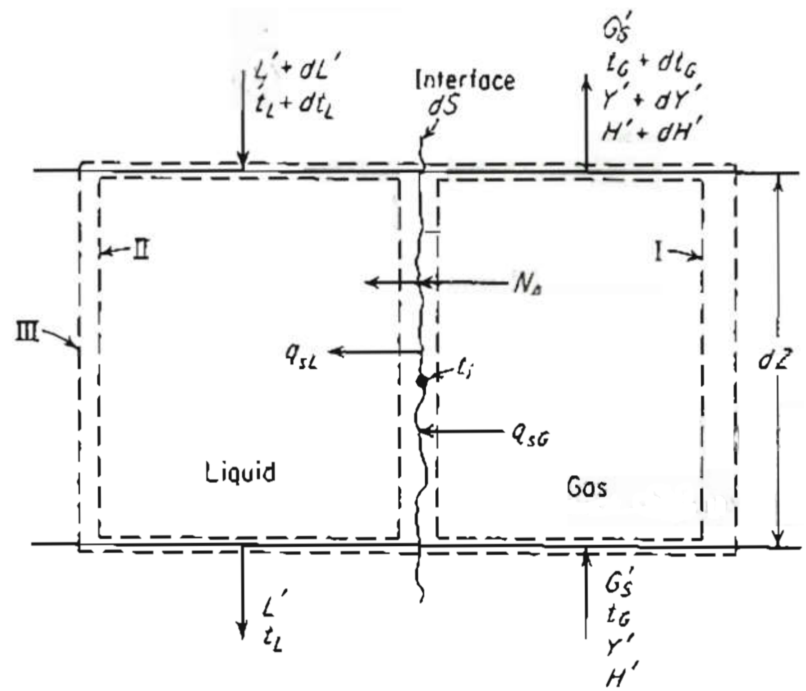
$$\text{Rate enthalpy in} = G'_S H' + (L' + dL')C_{A,L}(t_L + dt_L - t_0)$$

$$\text{Rate enthalpy out} = L'C_{A,L}(t_L - t_0) + G'_S(H' + dH')$$

$$\text{Rate in} = \text{rate out (adiabatic operation)}$$

$$G'_S H' + (L' + dL')C_{A,L}(t_L + dt_L - t_0) = L'C_{A,L}(t_L - t_0) + G'_S(H' + dH')$$

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



Water cooling with air

$$\int_{H_1'}^{H_2'} \frac{dH'}{H_i' - H'} = \frac{k_Y a}{G_S'} \int_0^Z dZ = \frac{k_Y a Z}{G_S'}$$

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

$$Z = H_{tG} N_{tG}$$