HUMIDIFICATION AND WATER COOLING

ChEn 5402 Fall 1990 A.A. Servida

DEFINITION :

- Operations in which mass and energy are transferred between a liquid stream and a gas stream
- The gas is insoluble in the liquid; the liquid contains only one component
  - ⇒ no resistance to mass transfer in the liquid phase

PURPOSES :

- Humidification and/or Dehumidification
- Cooling of gases
- Cooling of liquids

DRIVING FORCE :

(Partial pressure of the vapor) - (Equilibrium vapor pressure at the prevailing temperature)

► ***Mass and Heat transfer are important aspects of the process and cannot be treated separately***

BASIC DEFINITIONS

(SI Units)

Vapor : (Component A) — gaseous form of the component also present as liquid, e.g. water;

Gas : (Component B) — component which is present only in the gaseous form, e.g. air;

Humidity, H : (Kg of vapor/Kg of dry gas) — mass of vapor per unit mass of vapor-free gas:

$$H = \frac{M_A\, p_A}{M_B\,(P - p_A)} \qquad (1)$$

Saturated Gas : gas in which the vapor is in equilibrium with its liquid at the given temperature:

$$p_A = p_{AS}(T) \quad \text{and} \quad H = H_S \qquad (2)$$

Percentage Relative Humidity, H_R :

$$H_R = 100\, p_A / p_{AS}$$

Percentage Humidity, H_P :

$$H_P = 100\, H / H_S$$

Dry Bulb Temperature, T : (^oC) — temperature measured by the ordinary thermometer;

Dew Point : temperature at which the vapor-gas mixture becomes saturated when cooled at constant pressure;

BASIC DEFINITIONS (cont.)

(SI Units)

Humid Volume, V_H : total volume of a unit mass of dry gas plus its accompaining vapor at 1.0 atm:
(m^3/Kg of dry gas)

$$V_H = \left(\frac{1}{M_B} + \frac{H}{M_A} \right) 22.41 \frac{T + 273}{273} \qquad (3)$$

M_i : molecular weight of the species i-th (Kg / Kg mol)
T : temperature in ^0C

Humid Heat, c_s : heat required to raise the temperature of a unit mass of dry gas plus its vapor contenent by 1^0K or 1^0C at constant pressure:
(J/Kg of dry gas ^oC)

$$c_s = c_{pB} + H\, c_{pA} \qquad (4)$$

c_{pi} : specific heat at constant pressure of the component i-th (J/Kg ^0K)

Enthalpy, H_y : total enthalpy of a unit mass of dry gas and its vapor contenent:
(J/Kg of dry gas)

$$Hy = c_{pB}\,(T - T_o) + H\,[\, c_{pA}\,(T - T_o) + \lambda_o \,] \qquad (5)$$

or

$$Hy = c_s\,(T - T_o) + \lambda_o H \qquad (6)$$

T_o : *reference* (or *base*) temperature (^0C)
λ_o : latent heat at the temperature T_o (J/Kg)

PSYCHROMETRIC RELATIONS FOR THE SYSTEM AIR - WATER

(A : water; B : dry air)
(Reference : Treybal, 1980)

	SI units (Kg, J, m, Pa*, °C)	English engineering units (lb_m, Btu, ft, lb_f/in^2, °F)
M_A	18.02 Kg/Kgmol	18.02 lb_m/lb mol
M_B	28.97 Kg/Kg mol	28.97 lb_m/lbmol
H	$H = \frac{18.02\, p_A}{28.97\,(P - p_A)}$ Kg H_2O/Kg air	$H = \frac{18.02\, p_A}{28.97\,(P - p_A)}$ $lb_m H_2O$/Kg air
V_H	(0.00283 + 0.00456 H) (T + 273) m^3 /Kg dry air (T in °C)	(0.0252 + 0.0405 H) (T + 460) ft^3 /lb_m dry air (T in °F)
c_s	(1005 + 1884 H) J/(Kg dry air) °C	(0.24 + 0.45 H) Btu/(lb_m dry air) °F
T_o	0 °C	32 °F
λ_o	2.5014×10^6 J/Kg	1075.8 Btu/lb_m
H_y	(1005 + 1884 H) T + 2.5014×10^6 H J/(Kg dry air) referred to gaseous air and saturated liquid water at 0 °C (T in °C)	(0.24 + 0.45 H) (T - 32) + 1075.8 H Btu/(lb_m dry air) referred to gaseous air and saturated liquid water at 32 °F (T in °F)

* 1 Pa (Pascal) = 1 N/m^2; 1 atm = 101.325 KPa

PSYCHROMETRIC CHART FOR AIR-WATER SYSTEM

(Reference: Geankoplis,1983)

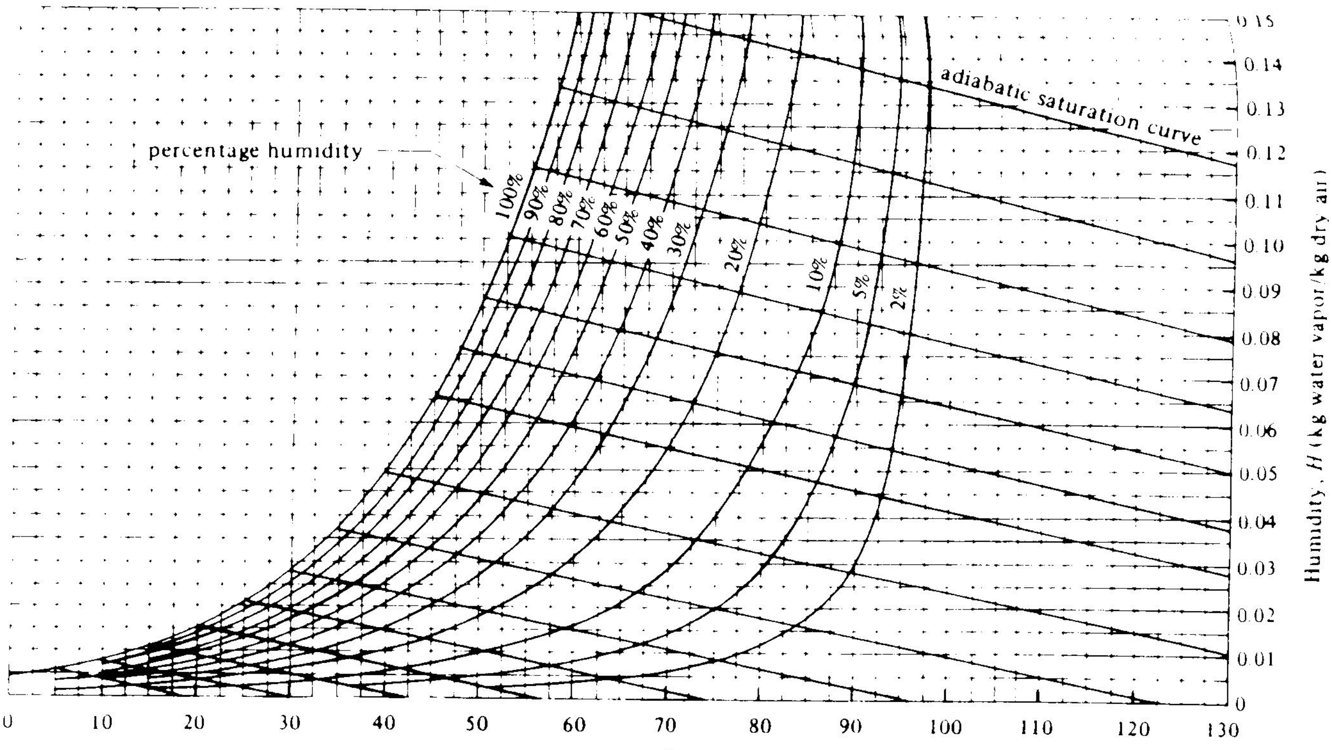
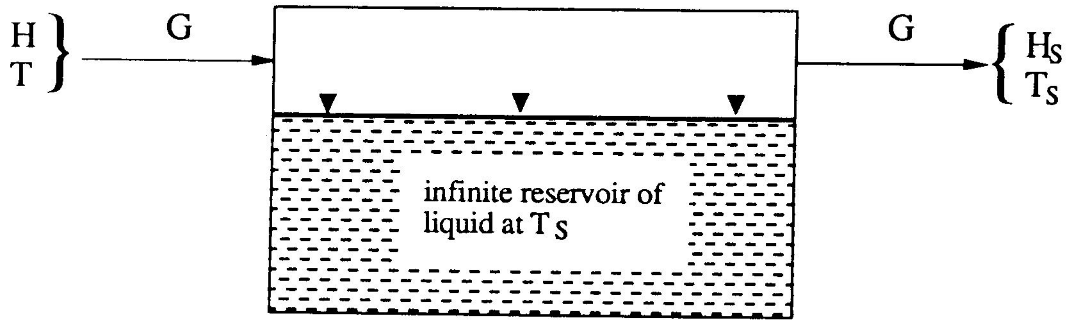


FIGURE 9.3-2 *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

ADIABATIC SATURATION TEMPERATURE, T_s

(Contact of a small volume of gas with a large volume of liquid)



(G : Mass flowrate of the vapor-free gas, Kg/hr)

$$\Delta H = \left(\frac{\text{amount of evaporated liquid}}{\text{unit mass of vapor–free gas}} \right) \qquad (7)$$

The system is *adiabatic* :

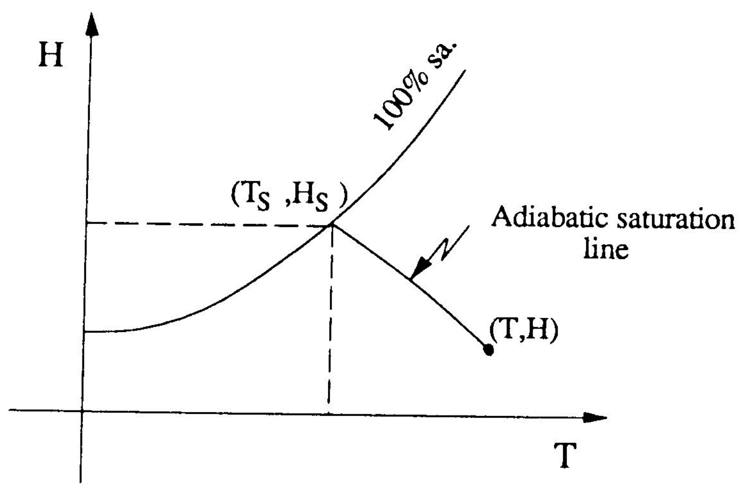
(Enthalpy in) = (Enthalpy out)

or:

$$G \{c_s (T - T_S) + H \lambda_s\} = G H_S \lambda_s$$

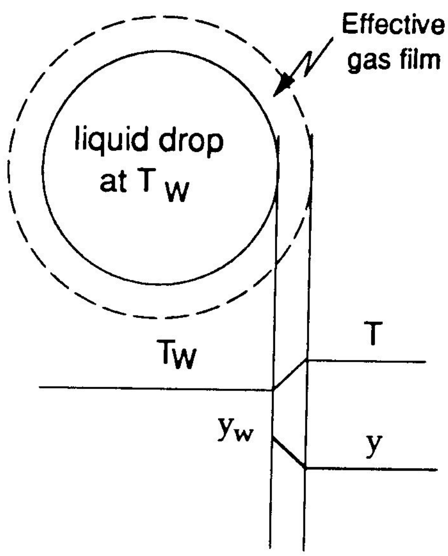
or by solving w.r.t. $H_S - H$:

$$H_S - H = \frac{c_s}{\lambda_s} (T - T_S) \qquad (8)$$



WET BULB TEMPERATURE, T_W

(Contact of a small volume of liquid with a large volume of gas)



At steady state:

$$\left(\text{Rate of heat transfer from the gas to the liquid} \right) = \left(\text{Rate of heat required for the evaporation} \right)$$

or:

$$h\,A\,(T - T_W) = \lambda_w\,A\,M_A\,k_y\,(y_W - y) \qquad (9)$$

h : heat-transfer coefficient in watt/m²; k_y : mass-transfer coefficient in mole/(sec m^2 mol frac.); A : surface area in m^2 ; y : molar fraction of the water vapor; y_w : molar fraction of the water vapor at the liquid-gas interface; M_A : molecular weight of water in kg/kg mol.

Now:

$$y = \frac{H/M_A}{H/M_A + 1/M_B} \qquad (10)$$

WET BULB TEMPERATURE, T_W (cont.)

since H is usually small, it follows:

$$y \approx H\,(M_B/M_A) \qquad (11)$$

and eqn. (9) can be recasted in the following form:

$$H_w - H = \frac{h/(M_B\,k_y)}{\lambda_w}\,(T - T_w) \qquad (12)$$

$h/(M_B\,k_y)$: *psychrometric ratio.* For the system air-water experimental data show that : $c_s = h/(M_B\,k_y)$ (*Lewis Relation*)

⟹ *For the system air-water the adiabatic saturation line coincides with the psychrometric line and* $T_S = T_W$

PSHYCHROMETRIC CHART FOR THE SYSTEM AIR-BENZENE

(From : McCabe, Smith and Harriott, 4-th ed.)

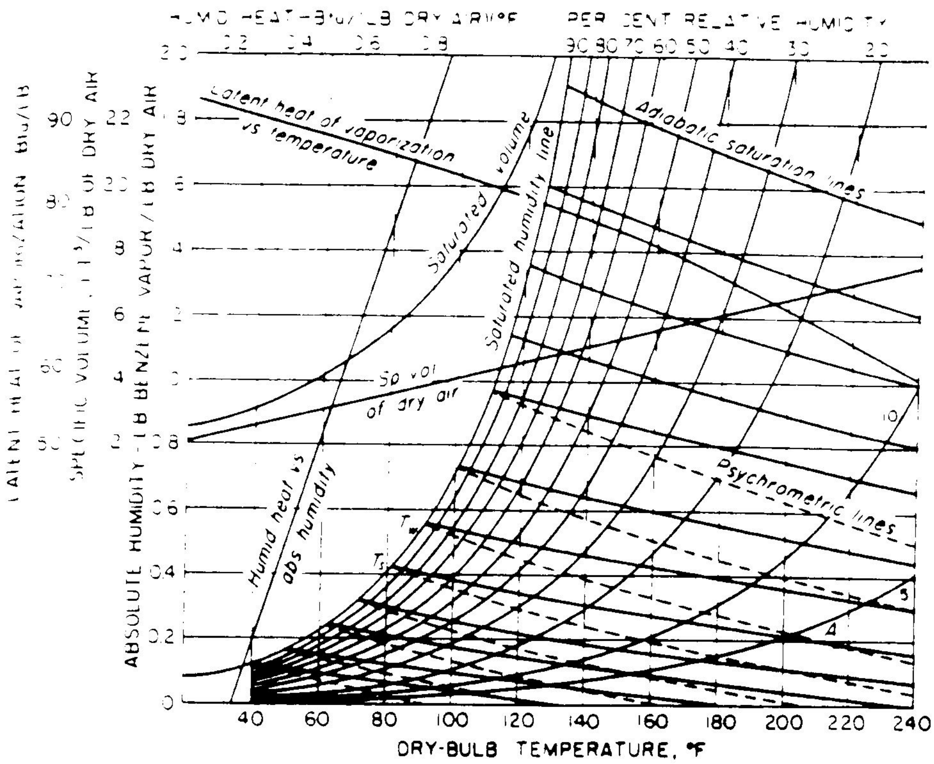


Figure 23-6 Humidity chart for air-benzene vapor mixtures. [*By permission, from J. H. Perry (ed.), "Chemical Engineers' Handbook," 3d ed. Copyright, 1950, McGraw-Hill Book Company.*]

GAS-LIQUID CONTACT

The gas-liquid contact can be achieved
Adiabatically or *Non-Adiabatically*

Adiabatic Operations

a) Cooling a Gas :
- no fouling heat exchanger;
- some of the liquid is lost;

b) Humidifying a Gas :
- way to control the moisture contenent;

c) Dehumidifying a Gas :
- air conditioning;
- solvent recovery;

d) Cooling a Liquid :
- water cooling.

Non-adiabatic Operations

a) Evaporating Cooling :
- liquid or gas flowing inside a pipe is cooled by an external film which is cooled by direct contact with a flowing air stream;

b) Dehumidifying a Gas :
- gas-vapor mixture brought into contact with refrigerated pipe.

GAS-LIQUID CONTACT (cont.)

Equipment

- **Packed Towers** :
  - conventional equipment;

- **Tray Towers** :
  - conventional equipment;

- **Water Cooling Towers** :
  - packing : wood grid (redwood), or plastic grid;
  - high void space $\Longrightarrow$ handling of large volumetric flowrates with small $\Delta P/L$;

- **Spray Chambers** :
  - horizontal spray towers;
  - for adiabatic humidification with recirculating liquid;

- **Spray Ponds** :
  - they are fountains;
  - high liquid losses by windage.

COUNTERCURRENT ADIABATIC OPERATION: WATER COOLING

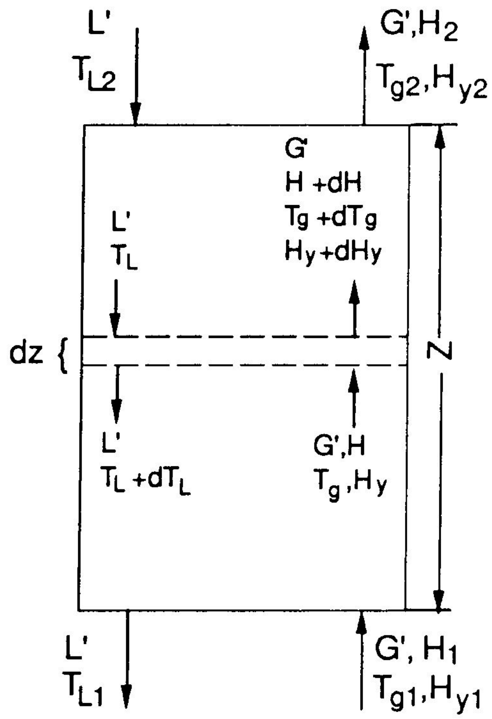
- **Semplifications** :

  i) Lewis relation holds;

  ii) Small amount of liquid evaporates $\Rightarrow$ $L' \approx$ const.;

  iii) Temperature level is fairly low $\Rightarrow$ the transfer of sensible heat is negligible.

- **Differential Mass and Enthalpy Balances** :



Mass Balance

$$dL' = G'\,dH \qquad (13)$$

Enthalpy Balance

$$L'\,c_{pL}\,dT_L = G'\,dH_y \qquad (14)$$

or

$$L'\,c_{pL}\,dT = G'\,(c_s dT_g + \lambda_0 dH)$$

L′ and G′ are superficial mass velocity: Kg/(hr m²); G′ represents the superficial mass velocity of the dry air stream.

COUNTERCURRENT ADIABATIC OPERATION: WATER COOLING

L′ and G′ are constant, therefore eqn. (14) can be directly integrated between the sections 1 and 2 leading to:

$$L' c_{pL} (T_{L2} - T_{L1}) = G' (H_{y2} - H_{y1}) \qquad (15)$$

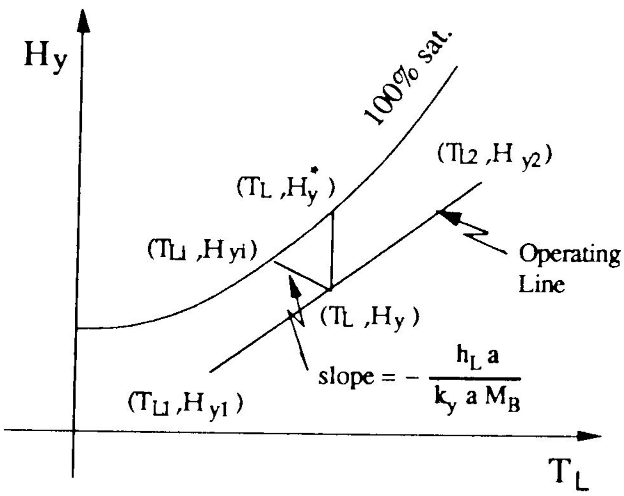
If in eqn. (15) we replace the values (T_{L2},H_{y2}) with the current values (T_L,Hy) we obtain:

$$L' c_{pL} (T_L - T_{L1}) = G' (H_y - H_{y1}) \qquad (16)$$

The equation (16) defines the *operating line* in the plane (T_L,H_y). From eqn. (16) it follows:

$$\text{(slope operating line)} = - L' c_{pL}/G'$$

- **Evaluation of the Column Height**



In order to calculate the height of the column we need to use the rate equations for heat and mass transfer.

COUNTERCURRENT ADIABATIC OPERATION: WATER COOLING (cont.)

From the enthalpy balance at the water-gas interface:

$$\left(\begin{array}{l}\text{Sensible heat lost across}\\ \text{the interface by the liquid}\\ \text{phase}\end{array}\right) = \left(\begin{array}{l}\text{Sensible heat entering the gas phase}\\ \text{plus the latent heat associated with}\\ \text{the evaporating flux}\end{array}\right)$$

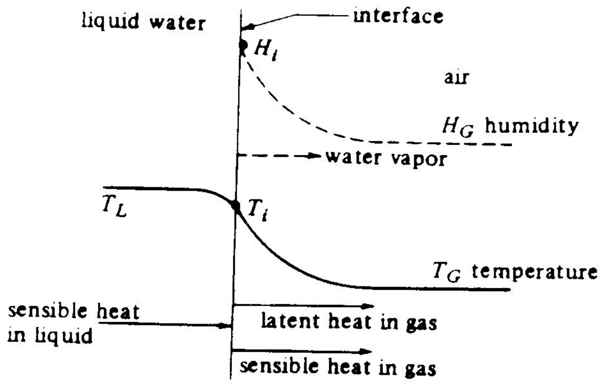


FIGURE 10.5-1. *Temperature and concentration profiles in upper part of cooling tower.*

it follows (for details cf. Geankoplis,1983):

$$G'\,dH_y = k_y\,aM_B\,(H_i - H)\,dz \qquad (17)$$

or:

$$G'\,dH_y = K_y\,a\,M_B\,(H^* - H)\,dz \qquad (18)$$

Equation (18) is equivalent to eqn. (17). K_y is the overall mass-transfer coefficient. K_ya and k_ya represent volumetric mass-transfer coefficients. a is the specific interfacial surface area (m^2/m^3)

COUNTERCURRENT ADIABATIC OPERATION: WATER COOLING (cont.)

Assuming that the volumetric mass-transfer coefficients K_ya and k_ya are constant along the column the integration of eqns.(16) and (17) leads to:

$$Z = \underbrace{\frac{G'}{k_y\, a\, M_B}}_{H_G} \underbrace{\int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_{yi} - H_y}}_{N_G} \qquad (19)$$

and

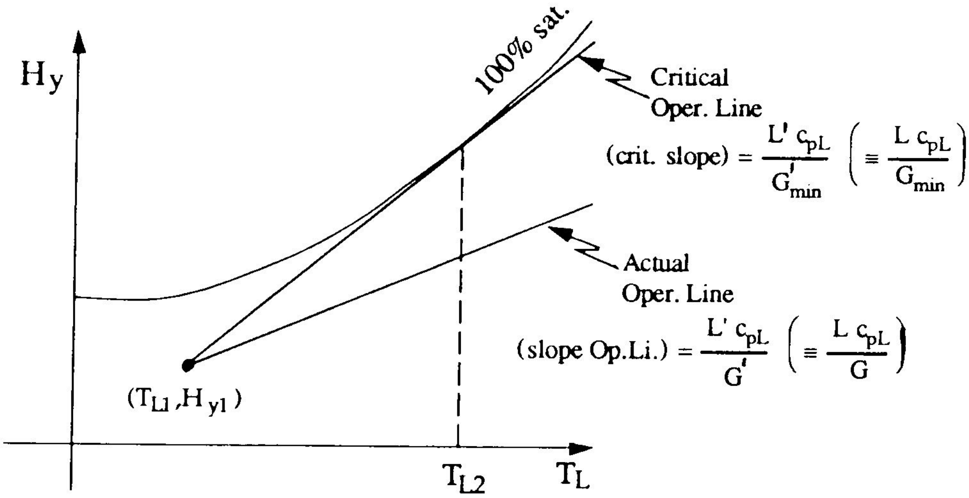
$$Z = \underbrace{\frac{G'}{K_y\, a\, M_B}}_{H_{OG}} \underbrace{\int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_y^{*} - H_y}}_{N_{OG}} \qquad (20)$$

Z : height of the column;
H_G : height of a gas enthalpy unit (m);
N_G : number of gas enthalpy units (non-dimensional number);
H_{OG} : height of an overall gas enthalpy unit (m);
N_{OG} : number of the overall gas enthalpy units (non-dimensional number).

SUMMARY: DESIGN OF A PACKED COLUMN

Design Specifications: L, T_{L2}, T_{L1}, T_{g1}, H_1 , and H_{y1}

- Pick a value for the slope of the operating line:



$$G'_{min} = \frac{L'\, c_{pL}}{\text{(crit. slope)}} \Rightarrow G' = 1.2 - 1.5\, G'_{min}$$

$$\left(G_{min} = \frac{L\, c_{pL}}{\text{(crit. slope)}} \Rightarrow G = 1.2 - 1.5\, G_{min} \right)$$

- L is usually given $\Rightarrow$ $G = L\, c_{pL} / (1.2\text{-}1.5\, G_{min})$;

- Pick Φ_t accordingly to one of the illustrated criteria (cf. pg. 12); use:

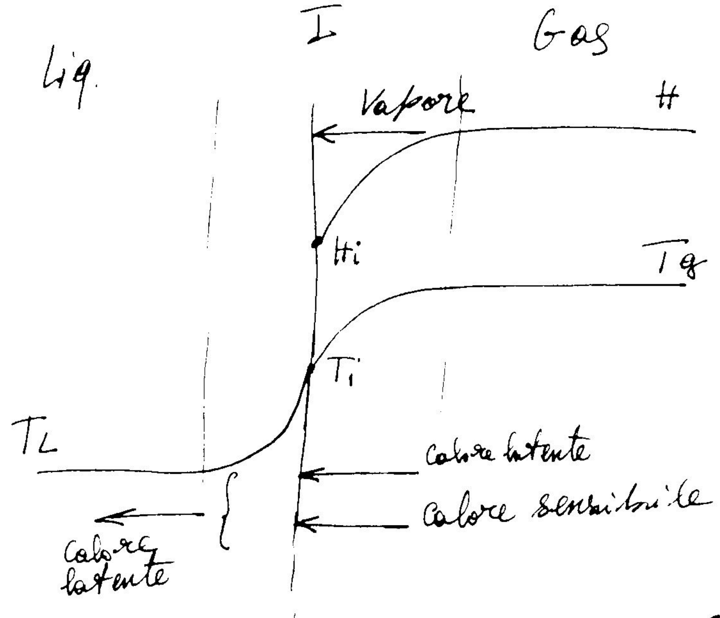
$$G' = \frac{G}{\pi\, (\Phi_t^2 / 4)}$$

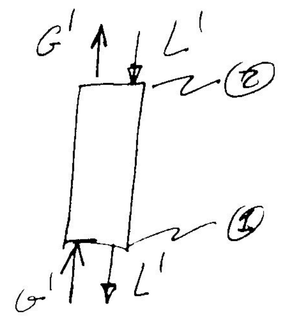
- Calculate Z from eqn.(19) or (20).

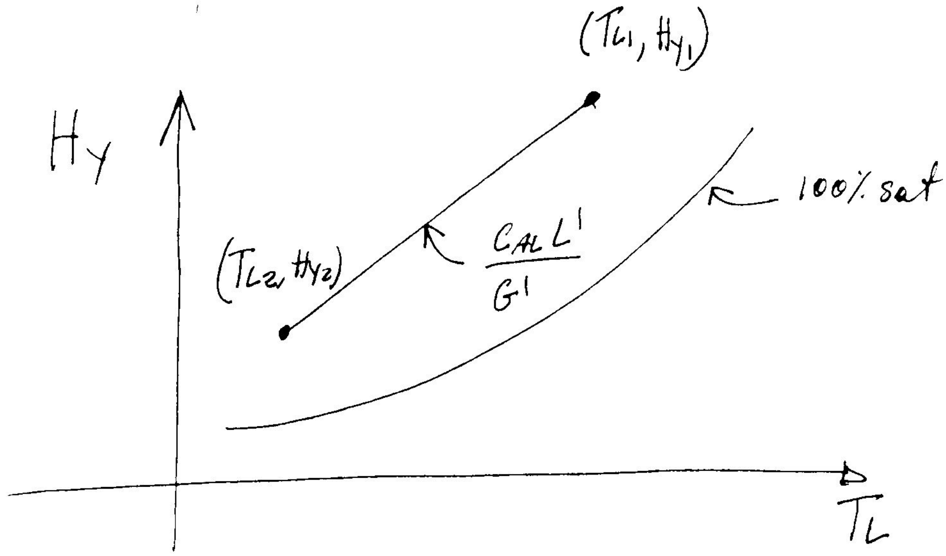
Altri Esempi di Umidificazione

Deumidificazione

- partiale condensazione del vapore $\Rightarrow$ trasferimento di materia dal gas al liquido
- raffreddamento del gas e riscaldamento del liquido







- ipotesi: $\Delta L' \simeq 0$ ovvero $\Delta L'/L' \lll 1$