Chemical Engineering Principles 2
(0905212)

Gas liquid system: One condensable component

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Content

- ✓ Gas-liquid systems
- ✓ Saturation and Humidity

Gas liquid system: One condensable component

- Systems containing several components, of which only one is capable of existing as a liquid at the process conditions.
- Separation processes that involve such systems include
  - Evaporation, drying, and humidification-all of which involve transfer of liquid into the gas phase-and
  - Condensation and dehumidification, which involve transfer of the condensable species from the gas to the liquid phase.
- For liquid water – air system at T =75°C and P = 760 mm Hg,
  - Initially the gas phase contains no water $(p_{H_2O} = 0)$,
  - Water molecules begin to evaporate. y_{H_2O}, in the gas phase increases

$$p_{H_2O} = y_{H_2O}P.$$

  - The amount of water in the gas phase is such that the rate at which water molecules enter the gas phase approaches zero.

No change occurs in the amount or composition of either phase

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- ✓ The gas phase is then said to be **saturated** with water-it contains all the water it can hold at the system temperature and pressure-and
- ✓ The water in the gas phase is referred to as a **saturated vapor.**
- In the system with two phases and two components,

$$DF = 2 + c - \Pi = 2$$

- It follows that
  - Only two out of the three intensive variables T, P, *and* y_{H2O} *can be specified,* and
  - Some relationship must exist that uniquely determines the value of the third variable once the first two have been specified.

Raoult's Law, Single Condensable Species

$$p_i = y_i P = p_i^*(T)$$

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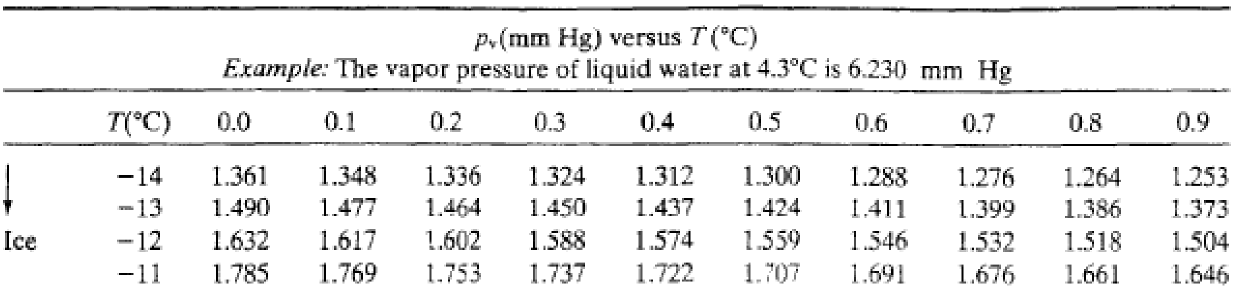
- *If a gas at temperature T and pressure P contains a saturated vapor whose mole fraction is* y_i *(mol vapor/mol total gas), and if this vapor is the only species that would condense if the temperature were slightly lowered, then the partial pressure of the vapor in the gas equals the pure-component vapor pressure* $p_i^*(T)$ *at the system temperature.*
- In a wet vapor consists of saturated vapor and saturated liquid in equilibrium, the mass **fraction of vapor** is known as the **quality.**

Table B.3 Vapor Pressure of Water[a]

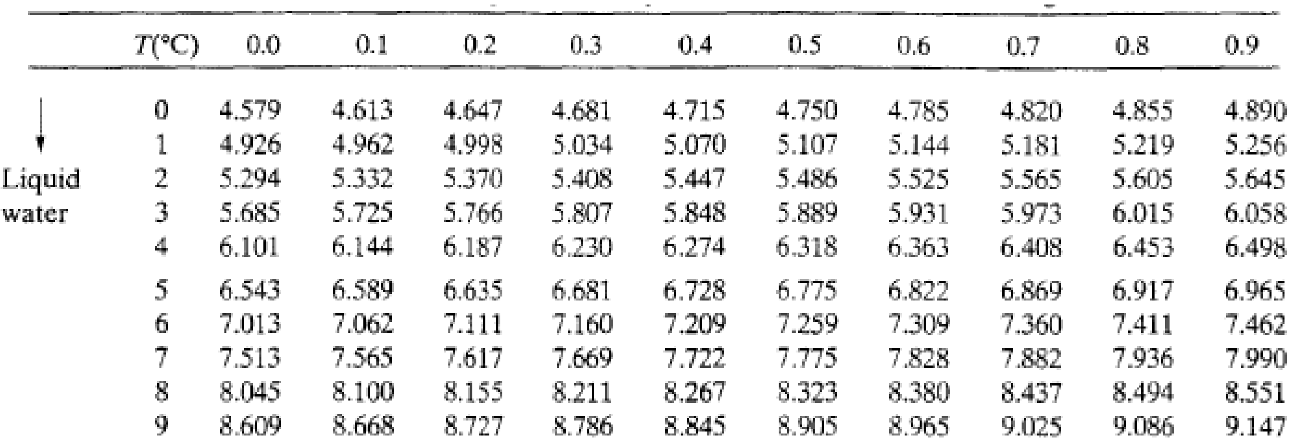


p_v(mm Hg) versus T(°C)

Example: The vapor pressure of liquid water at 4.3°C is 6.230 mm Hg

	T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
↓	−14	1.361	1.348	1.336	1.324	1.312	1.300	1.288	1.276	1.264	1.253
	−13	1.490	1.477	1.464	1.450	1.437	1.424	1.411	1.399	1.386	1.373
Ice	−12	1.632	1.617	1.602	1.588	1.574	1.559	1.546	1.532	1.518	1.504
	−11	1.785	1.769	1.753	1.737	1.722	1.707	1.691	1.676	1.661	1.646

Gas liquid system: One condensable component



	T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
↓	0	4.579	4.613	4.647	4.681	4.715	4.750	4.785	4.820	4.855	4.890
	1	4.926	4.962	4.998	5.034	5.070	5.107	5.144	5.181	5.219	5.256
Liquid	2	5.294	5.332	5.370	5.408	5.447	5.486	5.525	5.565	5.605	5.645
water	3	5.685	5.725	5.766	5.807	5.848	5.889	5.931	5.973	6.015	6.058
	4	6.101	6.144	6.187	6.230	6.274	6.318	6.363	6.408	6.453	6.498
	5	6.543	6.589	6.635	6.681	6.728	6.775	6.822	6.869	6.917	6.965
	6	7.013	7.062	7.111	7.160	7.209	7.259	7.309	7.360	7.411	7.462
	7	7.513	7.565	7.617	7.669	7.722	7.775	7.828	7.882	7.936	7.990
	8	8.045	8.100	8.155	8.211	8.267	8.323	8.380	8.437	8.494	8.551
	9	8.609	8.668	8.727	8.786	8.845	8.905	8.965	9.025	9.086	9.147

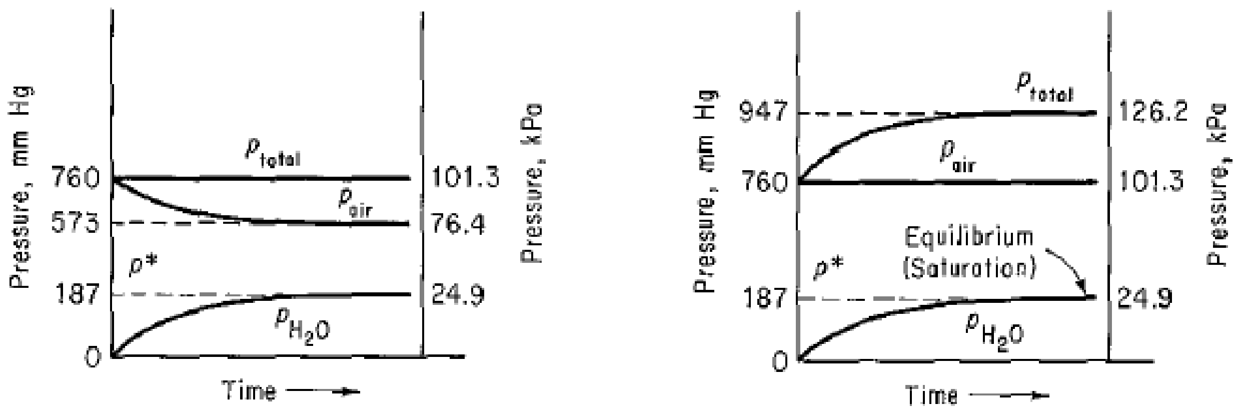
Gas liquid system: One condensable component

Summary

- When any pure gas (or a gaseous mixture) comes in contact with a liquid,
- The gas will acquire vapor from the liquid.
- If contact is maintained for a considerable length of time, vaporization continues until equilibrium is attained,
- At equilibrium, the *partial pressure of the vapor in the gas will equal the vapor pressure of the liquid* at the temperature of the system.
- Regardless of the duration of contact between the liquid and gas, after equilibrium is reached no more net liquid will vaporize into the gas phase.
- The gas is then said to be saturated with the particular vapor at the given temperature.

Gas liquid system: One condensable component

Summary



Constant Temperature
and Total Pressure
(Variable Volume)

Constant Temperature
and Volume
(Variable Pressure)

Change of partial and total pressures on vaporization of water into air at constant temperature

Example

Example: *Composition of a Saturated Gas–Vapor System*

Air and liquid water are contained at equilibrium in a closed chamber at 75°C and 760 mm Hg. Calculate the molar composition of the gas phase.

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- **For gas-liquid systems**

1. A gas in equilibrium with a liquid must be saturated with the volatile components of that liquid.

2. The partial pressure of a vapor at equilibrium in a gas mixture containing a single condensable component cannot exceed the vapor pressure of the pure component at the system temperature.

If $p_i = p_i^*$, the vapor is saturated; any attempt to increase p_i—either by adding more vapor to the gas phase or by increasing the total pressure at constant temperature—must instead lead to condensation.

3. A vapor present in a gas in less than its saturation amount is referred to as a **superheated vapor.**

$$p_i = \boxed{y_i P < p_i^*(T)}$$

Gas liquid system: One condensable component

- To achieve condensation in a system containing a superheated vapor:
    - Increasing the pressure at constant temperature or by
    - Decreasing the temperature at constant pressure.

4. If a gas containing a single superheated vapor is cooled at constant pressure, the temperature at which the vapor becomes saturated is referred to as the **dew point** of the gas.

$$p_i = \boxed{y_i P = p_i^*(T_{dp})}$$

- The difference *between the actual temperature of the superheated vapor and the* saturation temperature (dew point of a gas) for the same pressure, is called the **degrees of superheat.**
- For example, steam at 500°F and 100 psia (the saturation temperature for 100 psia is 327.8°F) (500 - 327.8) = 172.2°F is the **degrees of superheat.**

Example

Example: ***Material Balances Around a Condenser***

A stream of air at 100°C and 5260 mm Hg contains 10.0% water by volume.

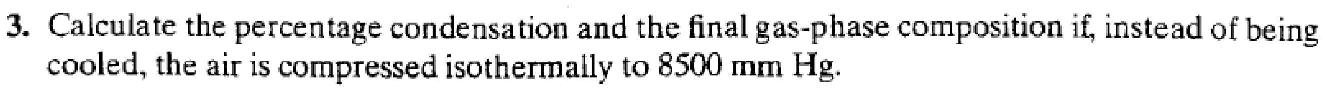
1. Calculate the dew point and degrees of superheat of the air.

Example Cont.

2. Calculate the percentage of the vapor that condenses and the final composition of the gas phase if the air is cooled to 80°C at constant pressure.

Example Cont.

Example Cont.



3. Calculate the percentage condensation and the final gas-phase composition if, instead of being cooled, the air is compressed isothermally to 8500 mm Hg.

Example Cont.

Example Cont.

Example Cont.

4. Suppose the process of part 2 is run, the product gas is analyzed, and the mole fraction of water differs considerably from the calculated value. What could be responsible for the disparity between calculated and measured values? (List several possibilities.)

(a) Experimental error

(b) The condenser was not at steady state when the measurements were made

(c) The emerging gas and liquid streams were not at equilibrium

Saturation and Humidity

- The mechanism of evaporation of a liquid depends on the relative values of the vapor pressure of the liquid and the total system pressure.
  - If evaporation takes place at a temperature such that $p^* < P$, the process involves transfer of molecules from the surface of the liquid to the gas above the surface,
  - If $p^* = P$, vapor bubbles form throughout the entire liquid, but predominantly at the heated container walls: that is, the liquid boils.
  - The temperature at which $p^* = P$ is the boiling point of the liquid at the given pressure.

- Generally, to describe the state and composition of a gas containing a single condensable vapor
  - **Saturation** refers to any gas-vapor combination, while
  - **Humidity** refers specifically to an air-water system.

Saturation and Humidity

- For a gas at temperature T and pressure P contains a vapor whose partial pressure is p_i and whose vapor pressure is $p_i^*(T)$.

Relative Saturation (Relative Humidity)

$$s_r(h_r) = \frac{p_i}{p_i^*(T)} \times 100\%$$

A relative humidity of 40%, → partial pressure of water vapor equals $\frac{4}{10}$ of the vapor pressure of water at the system temperature.

Molal Saturation (Molal Humidity)

$$s_m(h_m) = \frac{p_i}{P - p_i} = \frac{\text{moles of vapor}}{\text{moles of vapor-free (dry) gas}}$$

Saturation and Humidity

Absolute Saturation (Absolute Humidity)

$$s_a(h_a) = \frac{p_i M_i}{(P - p_i)M_{\text{dry}}} = \frac{\text{mass of vapor}}{\text{mass of dry gas}}$$

where M_i is the molecular weight of the vapor and M_{dry} is the average molecular weight of the dry (vapor-free) gas.

Percentage Saturation (Percentage Humidity)

$$s_p(h_p) = \frac{s_m}{s_m^*} \times 100\% = \frac{p_i/(P - p_i)}{p_i^*/(P - p_i^*)} \times 100\%$$

- Given any of these quantities for a gas at a given temperature and pressure, the partial pressure or mole fraction of the vapor in the gas can be calculated

Saturation and Humidity

Assuming that the ideal gas laws apply to both air and water vapor,

at saturation:

$$\frac{p_{\text{air}}V}{p_{H_2O}V} = \frac{n_{\text{air}}RT}{n_{H_2O}RT}$$

$$\Rightarrow \quad \frac{p_{\text{air}}}{p_{H_2O}} = \frac{n_{\text{air}}}{n_{H_2O}} = \frac{p_{\text{air}}}{p_{\text{total}} - p_{\text{air}}}$$

in a volume V at temperature T.

Example

Humid air at 75°C, 1.1 bar, and 30% relative humidity is fed into a process unit at a rate of 1000 m^3/h. Determine (1) the molar flow rates of water, dry air, and oxygen entering the process unit, (2) the molal humidity, absolute humidity, and percentage humidity of the air, and (3) the dew point.

Example Cont.

Example Cont.

Example Cont.