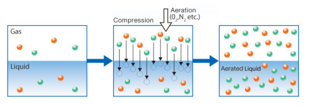
Multiphase Flow and Heat Transfer



Degasification

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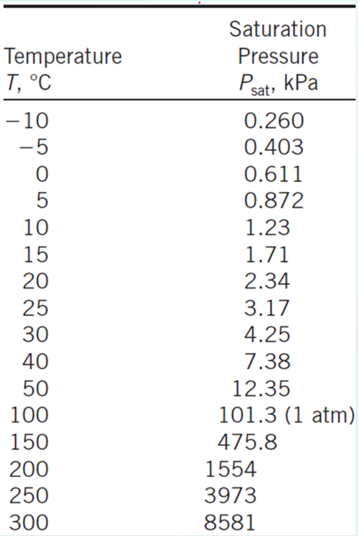
Vapor Pressure

- At a given pressure, the temperature at which a pure substance changes phase is T_{sat}.
- At a given temperature, the pressure at which a pure substance changes phase is P_{sat}.
- Vapor Pressure (P_v) of a pure substance is defined as the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature.
- For a pure substance, P_v is a Property and $P_v = P_{sat}$.



Temperature T, °C	Saturation Pressure P_{sat}, kPa
−10	0.260
−5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Saturation/vapor pressure of water

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Mole fraction of water vapor in air:

$$\begin{aligned} x_v = \frac{n_i}{n} &= \frac{n_i RT/V}{nRT/V} \\ &= \frac{P_v}{P} \\ &= \frac{1.7057}{92} \\ &= 0.0185 \end{aligned}$$

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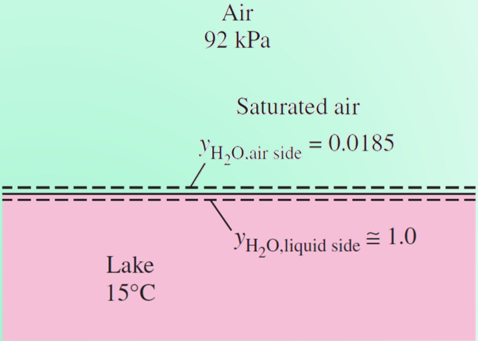

Henry’s Law

Statement

The amount of a gas that dissolves in a liquid is directly proportional to the partial pressure of that gas (Pi, g) in equilibrium with that liquid.

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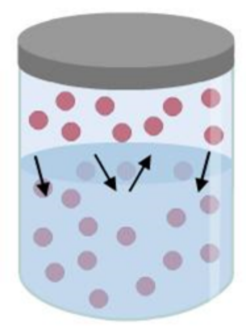
Mole fraction of species, i on liquid side,

$$x_{i,l} = \frac{P_{i,g}}{H}$$

Henry's constant in pressure units (Pa)



Henry's Law

1. The concentration of a gas dissolved is $\propto H^{-1}$
2. $H \uparrow$ with $T \uparrow$
3. $x_{i,l} \uparrow$ with $P_i \uparrow$

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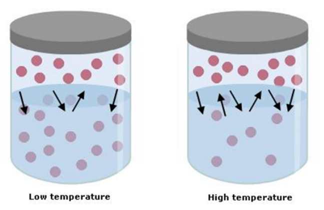

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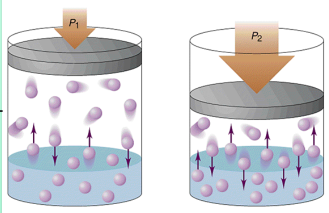

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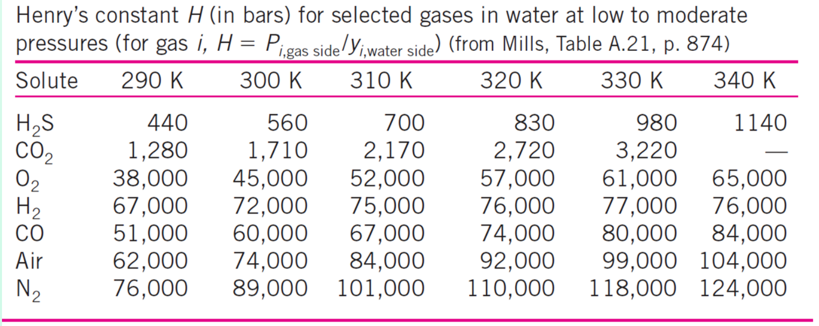

Henry’s constant H (in bars) for selected gases in water at low to moderate pressures (for gas i, $H = P_{i,\text{gas side}}/y_{i,\text{water side}}$) (from Mills, Table A.21, p. 874)

Solute	290 K	300 K	310 K	320 K	330 K	340 K
H_2S	440	560	700	830	980	1140
CO_2	1,280	1,710	2,170	2,720	3,220	—
O_2	38,000	45,000	52,000	57,000	61,000	65,000
H_2	67,000	72,000	75,000	76,000	77,000	76,000
CO	51,000	60,000	67,000	74,000	80,000	84,000
Air	62,000	74,000	84,000	92,000	99,000	104,000
N_2	76,000	89,000	101,000	110,000	118,000	124,000

Problem

Determine the concentration of dissolved air in water at ambient conditions. $H_{\mathsf{N_2}} = 9.2 \times 10^9$ Pa, $H_{\mathsf{O_2}} = 4.3 \times 10^9$ Pa

At phase equilibrium: $P_v = P_{\text{sat@30°C}} = 4.25$ kPa

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$$\begin{aligned} P_{\text{total}} &= P_v + P_{\text{dry-air}} \\ P_{\text{dry-air}} &= 101.42 + 4.25 = 97.17 \text{ kPa} \\ P_{\text{dry-air}} &= P_{\mathsf{N_2}} + P_{\mathsf{O_2}} \\ P_{\mathsf{N_2}} &= 79\% P_{\text{dry-air}} = 76.7643 \text{ kPa} \end{aligned}$$

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Mole fraction of $\mathrm{N}_{2,l}$, $x_{\mathrm{N}_{2,l}} = \frac{P_{\mathrm{N_2}}}{H} = \frac{76.7643 \times 10^3}{9.2 \times 10^9} = 8.34 \times 10^{-6}$

Mass fraction of $\mathrm{N}_{2,l}$, $y_{\mathrm{N}_{2,l}} = x_{\mathrm{N}_{2,l}} \times \frac{M_{\mathrm{N_2}}}{M_{\mathrm{H_2O}}}$

$$= 8.34 \times 10^{-6} \times \frac{28}{18} = 13 \times 10^{-6}$$

Solubility of $\mathrm{N_2}$ in water, $\mathrm{S}_{\mathrm{N_2}} = 13 \times 10^{-3}$ g/kg

i.e., 13 ppm of dissolved $\mathrm{N_2}$ in water.

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Mole fraction of $\mathrm{O}_{2,l}, x_{\mathrm{O}_{2,l}} = \frac{P_{\mathrm{O_2}}}{H} = \frac{20.4057 \times 10^3}{4.3 \times 10^9} = 4.75 \times 10^{-6}$

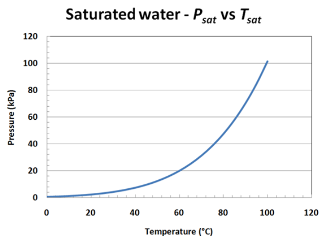
Mass fraction of $\mathrm{O}_{2,l}, y_{\mathrm{O}_{2,l}} = x_{\mathrm{O}_{2,l}} \times \frac{M_{\mathrm{O_2}}}{M_{\mathrm{H_2}O}} = 8.5 \times 10^{-6}$

Solubility of $\mathrm{O_2}$ in water, $\mathrm{S}_{\mathrm{O_2}} = 8.5 \times 10^{-3}$ g/kg

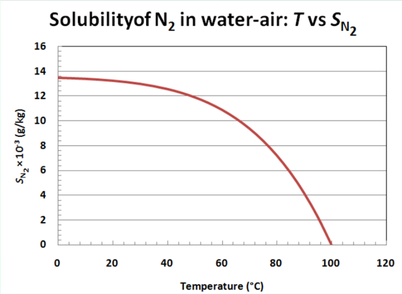
i.e., 8.5 ppm of dissolved $\mathrm{O_2}$ in water.

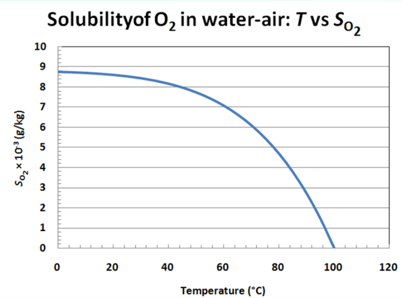
Solubility with Temperature

T (°C)	P_{sat} (kPa)	S_{N_2} (g/kg)	S_{O_2} (g/kg)
30	4.247	13×10^{-3}	8.4×10^{-3}
50	12.325	12×10^{-3}	7.7×10^{-3}
70	31.202	9.4×10^{-3}	6.1×10^{-3}
80	47.416	7.2×10^{-3}	4.7×10^{-3}
90	70.183	4.2×10^{-3}	2.7×10^{-3}
100	101.42	0	0



Solubility of air at Water-Air Interface


Solubilityof N_2 in water-air: T vs S_{N_2}


Solubilityof O_2 in water-air: T vs S_{O_2}

Henry's constant is considered not to vary with temperature

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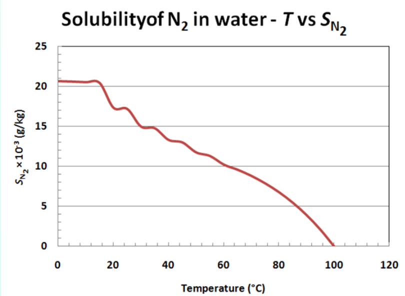
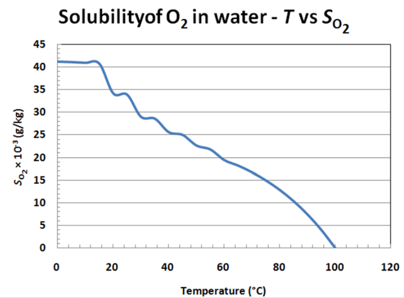

Solubilityof N_2 in water - T vs S_{N_2}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Degassing Techniques

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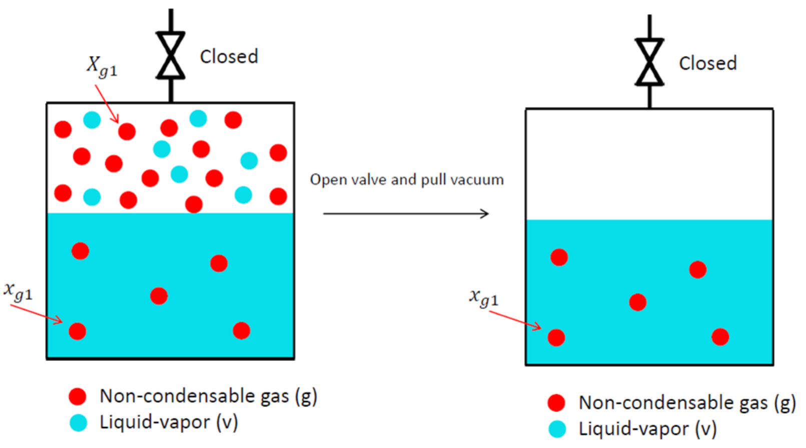
4. Membrane degasification

Degassing Techniques

1. **By boiling or superheating**
    - Low purity limits
    - Significant fluid is lost while pulling vacuum

Degassing Techniques

2. Vacuum degasification (Assuming only v & g are evacuated)



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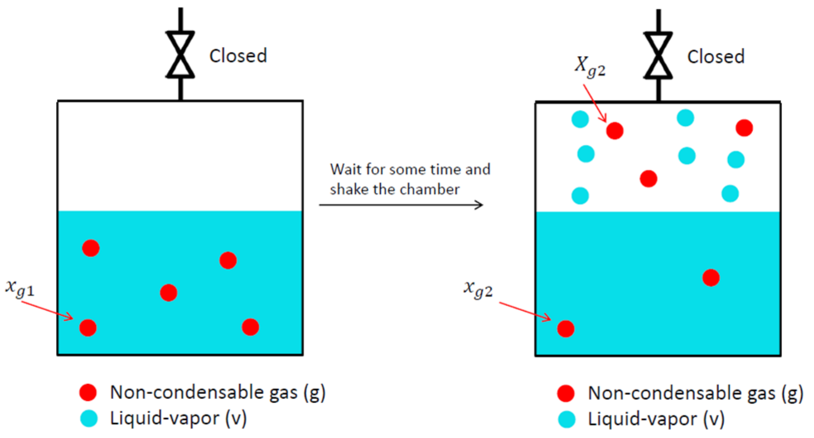

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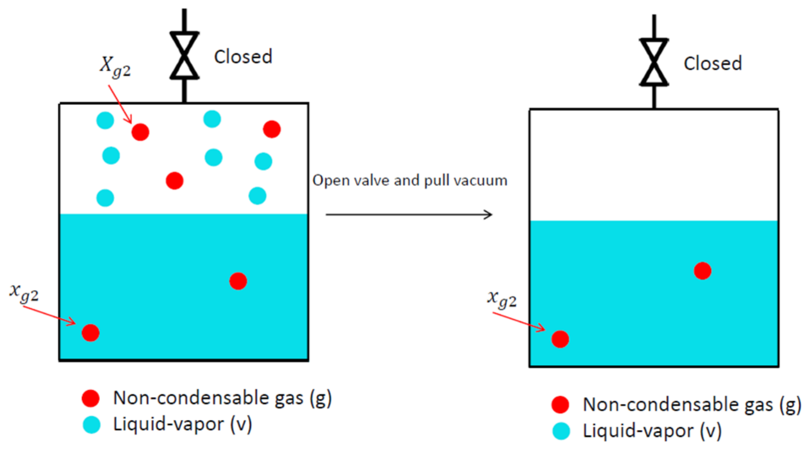

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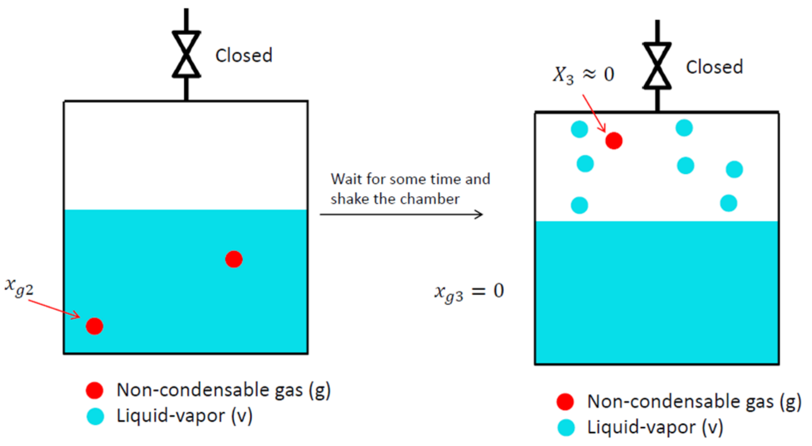

Problem

Imagine an insulated chamber with negligible thermal mass where the volume of the vapor and nitrogen space is equal to the volume of the liquid space (1 liter). Start with 70°C, and 101.325 kPa total pressure. Compute the number of moles of N_2 dissolved in the chamber after 3 cycles of vacuum degasification.

$H_{\mathrm{N_2}} = 9.2 \times 10^9$ Pa, $P_{\mathrm{sat@70^\circ C}} = 31.176$ kPa.

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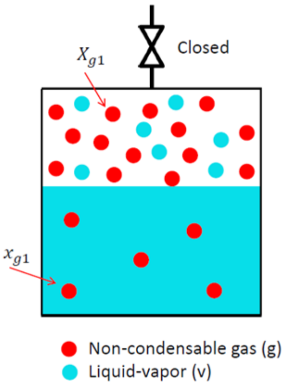
Hint: Calculate the number of moles of N_2 and water on gas side and also on liquid side for each cycle. Assume that no other gas exists other than N_2 and H_2O.



On Gas/vapor Side

At phase equilibrium:

$$P_v = P_{\text{sat@70}^\circ\text{C}} = 31.176 \text{ kPa}$$

$$P_{\text{total}} = P_v + P_{N_2}$$

$$P_{N_2} = 101.325 - 31.176 = 70.146 \text{ kPa}$$

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$$n_{\mathsf{N_2},v} = \frac{P_{\mathsf{N_2}} V}{RT} = \frac{70149 \times 0.001}{8.314 \times 343.14} = 0.0246 \text{ moles}$$

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Similarly for water in vapor state:

$$n_{\text{H}_2\text{O},v} = \frac{P_{\text{H}_2\text{O}}V}{RT} = \frac{31176 \times 0.001}{8.314 \times 343.14} = 0.0109 \text{ moles}$$

On Liquid Side

Number of moles of H_2O in 1 liter of volume:

$$n_{\mathsf{H_2O},l} = \frac{V_{\mathsf{H_2O},l}}{\mathsf{M}_{\mathsf{H_2O},l}} = \frac{1\ \mathsf{kg}}{18\ \frac{\mathsf{g}}{\mathsf{mol}}} = 55.55\ \mathsf{moles}$$

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From Henry's law, mole fraction of N_2 in liquid water:

$$x_{\mathsf{N_2},l} = \frac{P_{\mathsf{N_2}}}{H_{\mathsf{N_2}}} = \frac{70149}{9.2 \times 10^9} = 7.62 \times 10^{-6}$$

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By the definition of mole fraction:

$$x_{\mathsf{N_2},l} = \frac{n_{\mathsf{N_2},l}}{n_{\mathsf{H_2O},l} + n_{\mathsf{N_2},l}}$$

$$\implies n_{\mathsf{N_2},l} = n_{\mathsf{H_2O},l} \times x_{\mathsf{N_2},l} = 0.424 \times 10^{-3}\ \mathsf{moles}$$

We started with a Chamber Containing

$n_{\mathrm{H_2O},l} = 55.55$ moles

$n_{\mathrm{H_2O},v} = 0.0109$ moles

$n_{\mathrm{N_2},l} = 0.424 \times 10^{-3}$ moles

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During the first cycle of vacuum degasification, we removed all the vapor, *i.e.*, 0.0109 moles of H_2O and 0.0246 moles of N_2 from the chamber.

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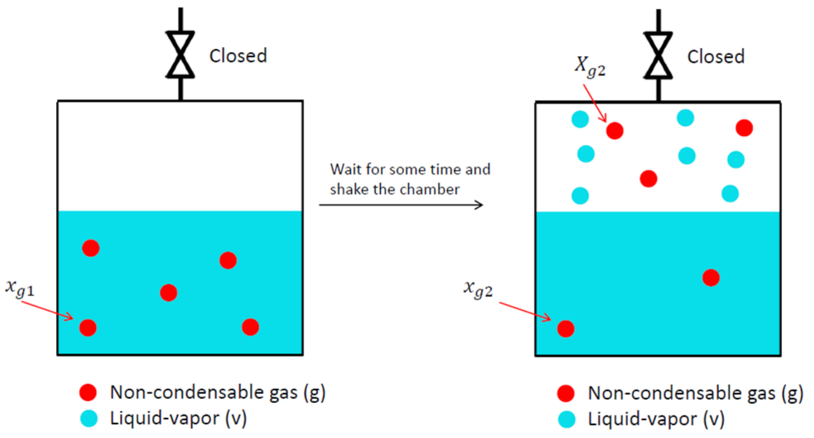
The chamber is now allowed to settle:
Phase equilibrium: Part of H_2O (l) evaporates
Dissolved N_2 in H_2O (l) comes-out following Henry's law.

After First Cycle

The molecules in the liquid have to be distributed in liquid and gas.



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$\because n_{H_2O,l} \gg n_{H_2O,v}$, change in volume of H_2O (l) is negligible,
i.e., $V_{H_2O,v} = 1$ liter $= 1$ kg $= 0.001$ m^3.

$\implies n_{H_2O,l} = 55.55$ moles

Similar to previous calculations, $n_{H_2O,v} = 0.0109$ moles

In a strict sense, they should be computed iteratively.

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P_{N_2} and P_{total} are not known as this stage.

After First Cycle

$$x_{\mathsf{N_2},l} = \frac{P_{\mathsf{N_2}}}{H_{\mathsf{N_2}}} = \frac{n_{\mathsf{N_2},v} RT}{V} \frac{1}{H_{\mathsf{N_2}}}$$

Also, $x_{\mathsf{N_2},l} = \dfrac{n_{\mathsf{N_2},l}}{n_{\mathsf{H_2O},l} + \cancelto{0}{n_{\mathsf{N_2},l}}}$

$$\implies \boxed{n_{\mathsf{N_2},l} = \frac{n_{\mathsf{H_2O},l} RT}{H_{\mathsf{N_2}} V} \; n_{\mathsf{N_2},v}}$$

After First Cycle

$$x_{\mathsf{N_2},l} = \frac{P_{\mathsf{N_2}}}{H_{\mathsf{N_2}}} = \frac{n_{\mathsf{N_2},v} RT}{V} \frac{1}{H_{\mathsf{N_2}}}$$

Also, $x_{\mathsf{N_2},l} = \dfrac{n_{\mathsf{N_2},l}}{n_{\mathsf{H_2O},l} + \cancelto{0}{n_{\mathsf{N_2},l}}}$

$$\implies \boxed{n_{\mathsf{N_2},l} = \frac{n_{\mathsf{H_2O},l} RT}{H_{\mathsf{N_2}} V} \; n_{\mathsf{N_2},v}}$$

0.424×10^{-3} moles of N_2 is distributed as $n_{\mathsf{N_2},l}$ and $n_{\mathsf{N_2},v}$

$$\boxed{n_{\mathsf{N_2},l} + n_{\mathsf{N_2},v} = 0.424 \times 10^{-3}}$$

End of First Cycle

$n_{\mathsf{H_2O},l} = 55.55$ moles

$n_{\mathsf{H_2O},v} = 0.0109$ moles

$n_{\mathsf{N_2},l} = 7.18 \times 10^{-6}$ moles

$n_{\mathsf{N_2},,v} = 0.0004168$ moles

We started with

$n_{\mathsf{N_2},l} = 0.424 \times 10^{-3}$ moles

$n_{\mathsf{N_2},,v} = 0.0246$ moles

End of First Cycle

$$n_{\mathsf{H_2O},l} = 55.55 \text{ moles} \qquad n_{\mathsf{N_2},l} = 7.18 \times 10^{-6} \text{ moles}$$

$$n_{\mathsf{H_2O},v} = 0.0109 \text{ moles} \qquad n_{\mathsf{N_2},,v} = 0.0004168 \text{ moles}$$

We started with

$$n_{\mathsf{N_2},l} = 0.424 \times 10^{-3} \text{ moles}$$

$$n_{\mathsf{N_2},,v} = 0.0246 \text{ moles}$$

In one cycle of vacuum degasification, we observe reduction by 59 times of dissolved N_2 in liquid H_2O.

End of Second Cycle

$$n_{\mathsf{H_2O},l} = 55.55 \text{ moles}$$
$$n_{\mathsf{H_2O},v} = 0.0109 \text{ moles}$$

$$n_{\mathsf{N_2},l} = ??? \text{ moles}$$
$$n_{\mathsf{N_2},,v} = ??? \text{ moles}$$

We started with

$$n_{\mathsf{N_2},l} = 0.424 \times 10^{-3} \text{ moles}$$
$$n_{\mathsf{N_2},,v} = 0.0246 \text{ moles}$$

In two cycles of vacuum degasification, we observe reduction by ??? times of dissolved N_2 in liquid H_2O.

End of Third Cycle

$n_{\mathsf{H_2O},l} = 55.55$ moles

$n_{\mathsf{H_2O},v} = 0.0109$ moles

$n_{\mathsf{N_2},l} = ???$ moles

$n_{\mathsf{N_2},,v} = ???$ moles

We started with

$n_{\mathsf{N_2},l} = 0.424 \times 10^{-3}$ moles

$n_{\mathsf{N_2},,v} = 0.0246$ moles

In three cycles of vacuum degasification, we observe reduction by ??? times of dissolved N_2 in liquid H_2O.

Degassing Techniques

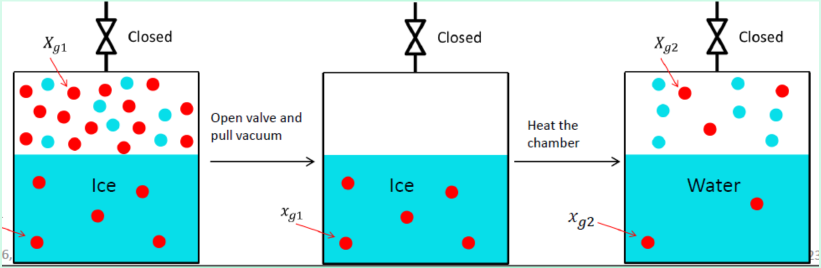
2. Vacuum degasification

- Some liquid is lost while pulling vacuum
- The chamber temperature needs to be controlled
- Needs 3 cycles to get high purity limits

Degassing Techniques

3. Freeze-pump-thaw cycling

- Very small amount of fluid is lost
- Needs 3 cycles to get high purity limits
- Less hazardous



Degassing Techniques

4. Membrane degasification

Pull vacuum through a membrane such as Gore-Tex