Lecture 5 Vacuum Systems

- **Introduction of Vacuum**

1. Definition of Vacuum

A space of which the gas pressure significantly smaller than that of the surroundings.

a. The relations among pressure unit:

表 1.1 壓力單位關係表*

	托 爾 torr	千分托爾 μ	帕 Pa	大氣壓 atm	毫 巴 mbar	磅/英寸² lb/in²	英寸水銀柱 in-Hg
托 爾	1	1,000	133.322	1.31579×10^{-9}	1.33	0.019337	0.039370
千分托爾	10^{-3}	1	0.1333	1.31579×10^{-6}	1.33×10^{-3}	1.9337×10^{-5}	3.9370×10^{-5}
帕	7.501×10^{-3}	7.501	1	9.869×10^{-6}	10^{-2}	14.503×10^{-5}	2.9530×10^{-4}
大氣壓	760	760,000	101,325	1	1,013	14.695	29.921
毫巴	0.75	750	10^{-3}	9.87×10^{-4}	1	14.503×10^{-3}	2.9530×10^{-2}
磅/英寸²	51.715	51,715	6,894.8	0.068046	68.948	1	2.0360
英寸水銀柱	25.400	25,400	3,386.4	0.033421	33.864	0.49115	1

*本表採用約值 1 大氣壓＝760 托爾。

b. The classification of vacuum:

Rough vacuum: 1 atm-1 torr
Medium vacuum: 1 torr-10^{-3} torr
High vacuum: 10^{-3}-10^{-7} torr
Ultra high vacuum: <10^{-7} torr

表 1.2 眞空度的區分

	粗略眞空 Coarse vacuum	中度眞空 Intermediate vacuum	中度高眞空 medium-high vacuum	高眞空 high vacuum	超高眞空 ultra-high vacuum
壓力範圍 (托爾)	760-100	100-1	$1\text{-}10^{-3}$	$10^{-3}\text{-}10^{-7}$	$<10^{-7}$
在 20°C 時每立方厘米中的氣體分子數	2.5×10^{19} 到 3.3×10^{18}	3.3×10^{18} 到 3.3×10^{16}	3.3×10^{16} 到 3.3×10^{13}	3.3×10^{13} 到 3.3×10^{9}	$<3.3\times10^{9}$
每秒鐘在每平方厘米容器壁上的分子撞擊數	$10^{23}\text{-}10^{22}$	$10^{22}\text{-}10^{20}$	$10^{20}\text{-}10^{17}$	$10^{17}\text{-}10^{13}$	$<10^{13}$
氣流形態*	連續氣流	連續氣流	轉變爲分子氣流之過度形態	分子氣流	實際無氣流僅單一分子運動
在 20°C 時剩餘空氣分子之平均自由動徑 (厘米)	5×10^{-6} -5×10^{-5}	5×10^{-5} -5×10^{-3}	$5\times10^{-3}\text{-}5$	$5\text{-}5\times10^{4}$	$>5\times10^{4}$

*氣流形態實際與儀器的主要尺寸有關，見第 (三) 節，此處僅就一般的情況大概劃分之。

2. Vacuum system

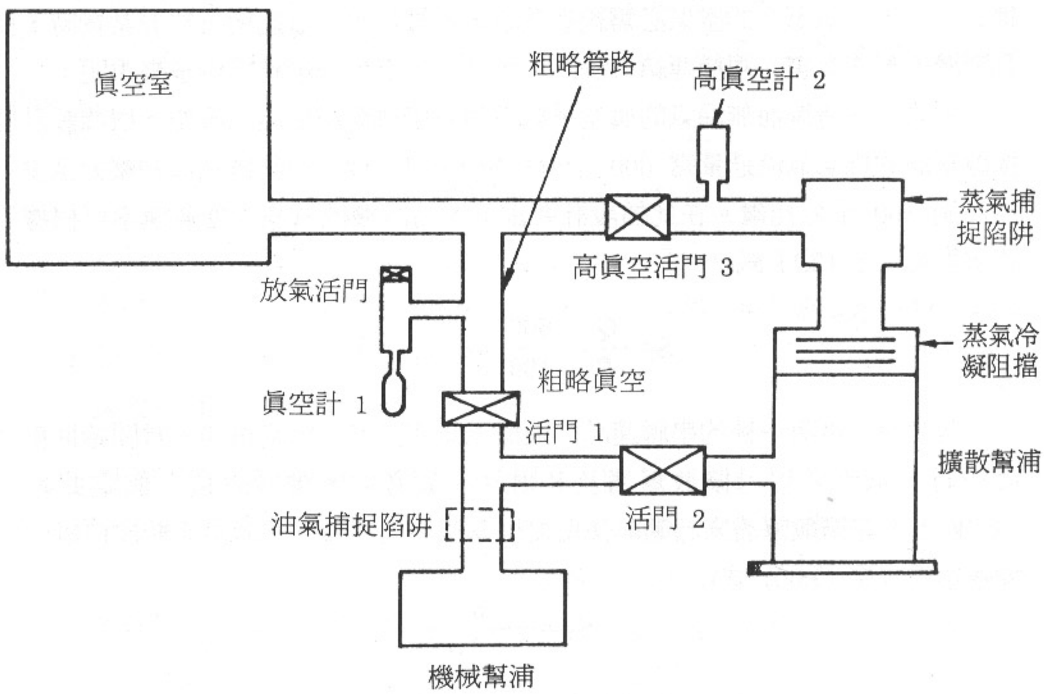

圖 3.12 擴散幫浦的連結

a. Vacuum chamber,

b. Vacuum pump (fore pump, baking pump or rough pump⇔high vacuum pump),

c. Vacuum components (pipe, connector, flange, valve, gasket or seal)

d. Vacuum gauge

e. Others (traps, electric feedthrough, mechanical feed through, cooler, safety equipments, etc…)

3. Pump down time

$$Q = SP = -\frac{d(PV)}{dt}$$

Q: flow rate (# of gas molecules/time)

$$-V\frac{dP}{dt} + S_l = SP$$

V: Volume of the system, P: pressure of the system, S:

pumping speed (Volume/time, average value), S_l: leak rate (assume constant), if S is also constant, the pump down time can be estimated:

$$t = \frac{V}{S}\ln\left(\frac{P_0 - \frac{S_l}{S}}{P - \frac{S_l}{S}}\right)$$

- **Vacuum pumps**

  1. Classification

  a. Gas exhaust

  (a) Mechanical pump

  (b) Vapor stream pump

  b. Gas storage

  (a) Chemical adsorption pump

  (b) Sorption pump

  (c) Cryo pump

  2. Mechanical pump

  a. Rotary oil-sealed pump

  - **Thin oil film between rotor and stator**
  - **Vacuum range 10^{-4} ~10^{-5} torr, limited by oil's vapor pressure, high effeciency**
  - **Air ballast device: to help on suppressing water or alcohol liquid formation inside pump**

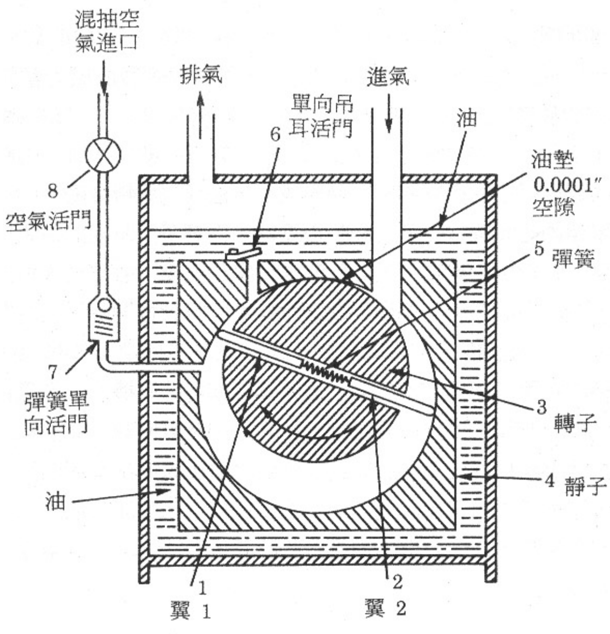

圖 3.1 迴轉油墊幫浦

b. Rotary blower pump (Roots pump, dry pump)

- **Similar to gear pump, no lubricant between rotors, count on precise machine fitting (less than 100 μm)**
- **Vacuum range: 10^{-2} -10^{-4} torr**
- **High pumping rate, from 50-5000 l/s**
- **No oil vapor, not good for the rough pumping from ATM, but better used for booster pump, however, sometimes need cooling.**

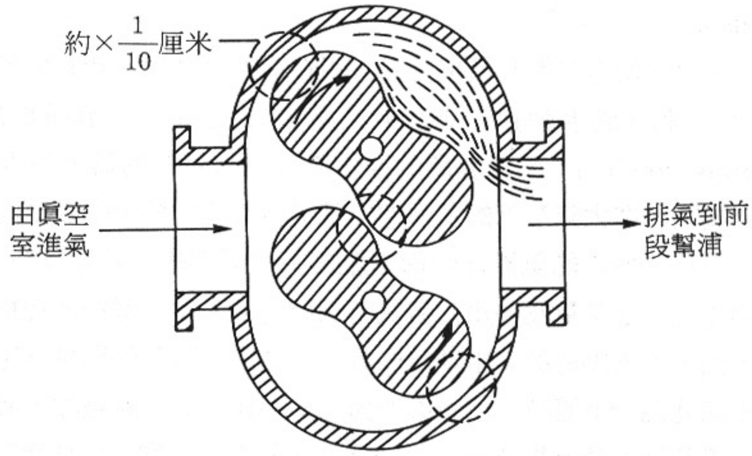

圖 3.2 迴轉吹送幫浦

c. Mechanical molecular pump

(a) Molecule drag pump

- **No lubricant between rotor and stator, precise gap (<50 μm) for large pressure drop, very clean**
- **5000-10000 rpm, 100 μm particle can damage pump**
- **No need vapor trap, be careful of over heat which cause rotor stuck.**
- **Larger molecule weight molecules (H_2O) get higher efficiency.**
- **Vacuum can be to 10^{-6} torr (need rough pump to 10^{-3} torr)**
- **Too expansive, replaced by turbo pump**

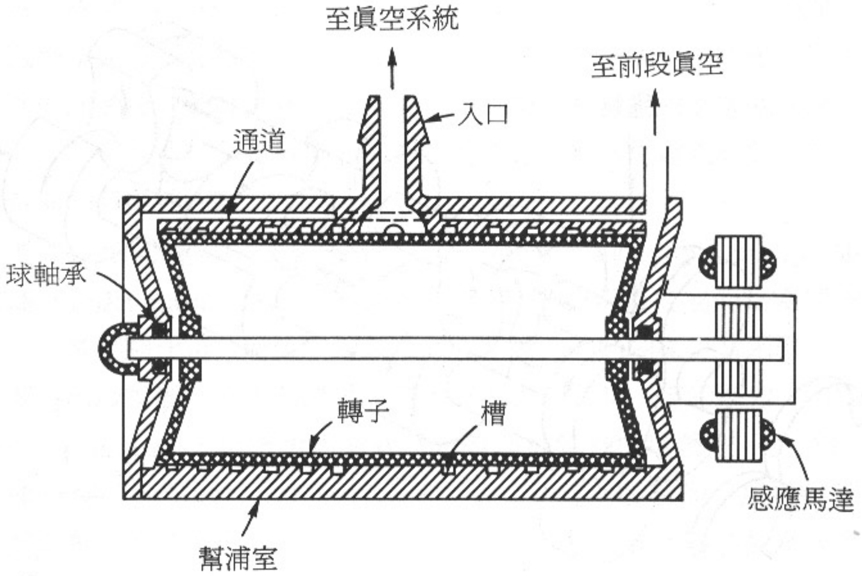

圖 3.6 分子曳引幫浦

(b) Turbo-molecular pump

- **Similar to turbine, 15000-60000 rpm.**
- **Small pressure drop between disks, which tolerate larger gap~ 1mm, multi stages to get large pressure drop.**
- **Vacuum can be 10^{-9}~10^{-10} torr (need rough pump to 10^{-3} torr), can be applied to ultra vacuum range.**
- **Larger molecule weight molecules (H_2O) get higher efficiency, very clean operation.**

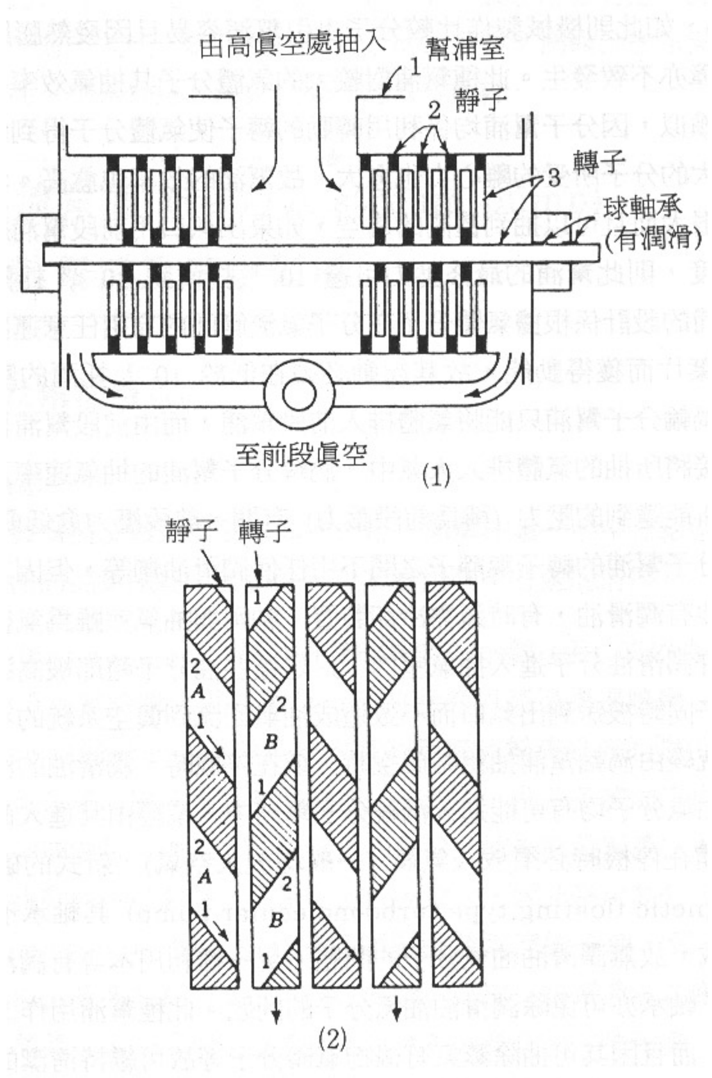

圖 3.7 渦輪分子幫浦

3. Vapor stream pump (蒸氣噴流幫浦)

a. Diffusion pump

- **Using molecular flow though nozzle in high speed to entrain gas molecules.**
- **Using Hg (higher vapor pressure usually 10^{-3} torr at room temp), for mass spectrometer, or silicone oil (lower vapor pressure) cheaper and safer, used for high vacuum (10^{-6}~10^{-9} torr under cooling).**
- **Cannot be used for ultra high vacuum because of vapor.**
- **Need rough pump to 10^{-3} torr first**
- **Using cooling baffle (freon) or traps to reduce vapor back streaming**

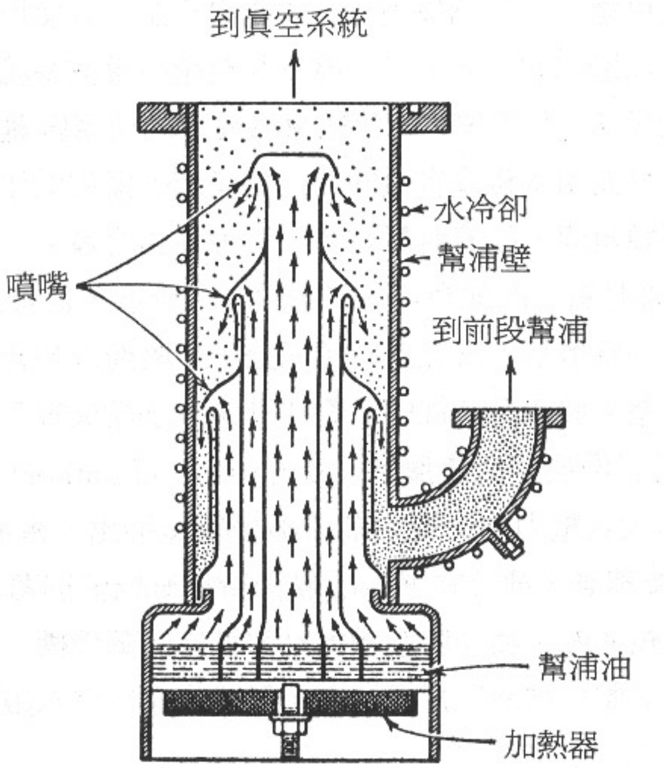

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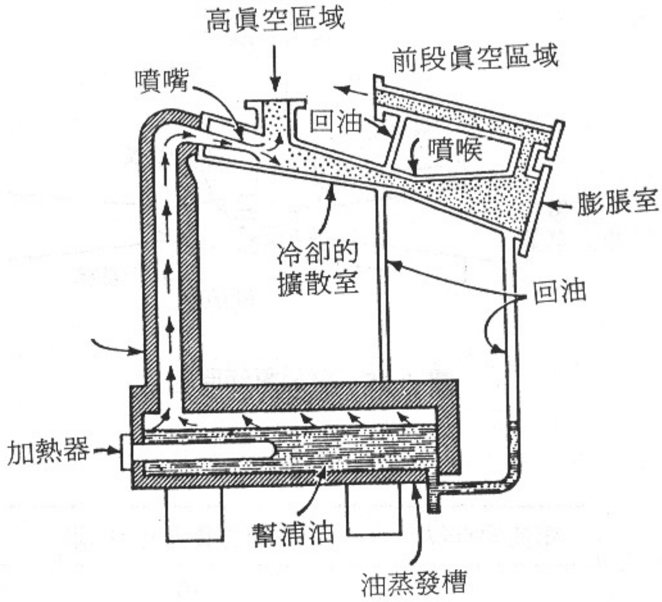
圖 3.9 分噴及不分噴式擴散幫浦

b. Stream ejector pump

- **Ejected vapor stream perpendicular to vacuum chamber.**
- **Vapor condense after passing through throat**



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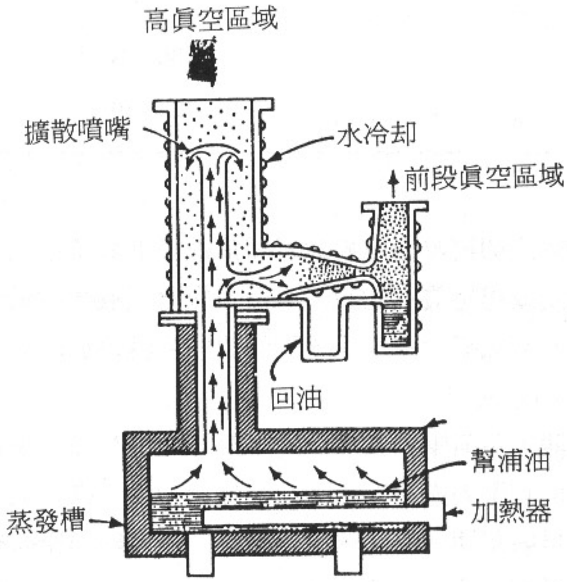

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圖 3.11 (1) 噴射幫浦；(2) 擴散噴射幫浦

4. Sorption and Cryo pump

a. Sorption pump

- **Sorption including**

  a. Absorption (gas dissolved inside solid, not easy),

  b. Physical adsorption (using Von der Waals forces on the first several molecules of solid surface, used by sorption pump),

  c. Chemisorptions (chemical bond on surface, classified into the next section)

- **Physical sorption has reversibility: to increase sorption ability: decrease temperature and increase pressure.**

  Absorbents(吸附劑) absorb Absorbates (吸附物).

- **Four important considerations for a good absorbent:**

  a. Large surface area (porosity, 多孔性)

  b. Chemical inert (化學鈍性)

  c. Integrity (固體完整性)

  d. Not hydrolysis (不潮解)

- **Popular absorbents: activated charcoal (活性碳, 10^3 m^2/cm^3), activated alumina (活性礬土), artificial zeolite (人造沸石, 600-800 m^2/g=> contained 100 cm^3/g at 77K)**

- **Usually combined with cooling system=>cryogenic sorption pump (冷凍吸附幫浦)**

- **Vacuum from 10^{-1} down to 10^{-5} (dependents on temp, usually hydrogen or helium still remained in system), need rough pump to help pump down in the first stage.**

e. Cryo pump (冷凍幫浦)

- **Using coolant to cool down and condense gas or vapor and keep them in the pump system. System cheap and simple, but the consumption is expansive, not very popular in the current industry.**
- **Solid usually has less vapor than liquid, and temperature greatly affect vapor pressure. For example: solid N_2: 32K-22K, vapor pressure from 10^{-4}-10^{-10} torr.**
- **If Use liquid N_2 (77K) as the coolant, water vapor, CO_2, organic vapor, Xe, Kr, Ar, become solid, but H_2, He, Ne, N_2 are still gas. Barely usable for cryo pump.**
- **Liquid He (4.2K) is better coolant, but expansive, liquid H_2 (10.3K) less effective and more dangerous.**
- **Considerations for cryo pump:**
  a. large cooling area
  b. thermal isolation
  c. Sealing issue when large thermal expansion happens
- **Pump start from 0.1 torr, can reach 10^{-5} torr. (higher vacuum can be obtained if the original pressure lower)**

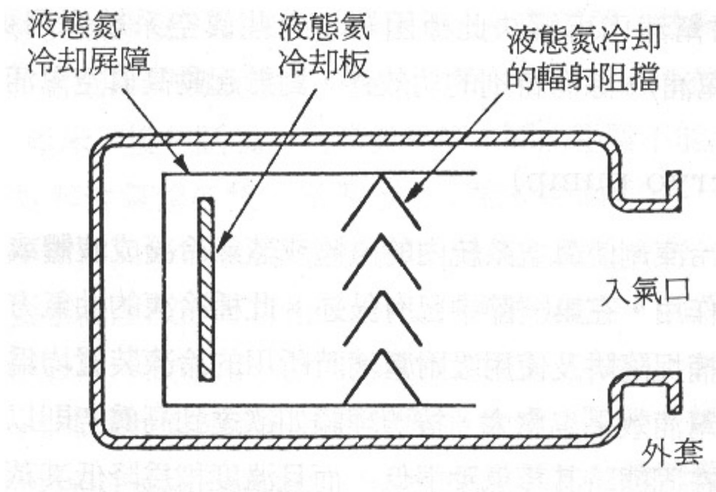

圖 3.14 冷凍幫浦

f. Refrigerator type cryopump (冷凍機式冷凍幫浦)

- **Using refrigerator to cool down system, the coolant is He.**
- **System can approach 80K in the first stage of cooling, 10 K for the second stage. H_2 and He can be absorbed by activated charcoal while not condense into solid.**
- **Most of the cryopumps using this method**

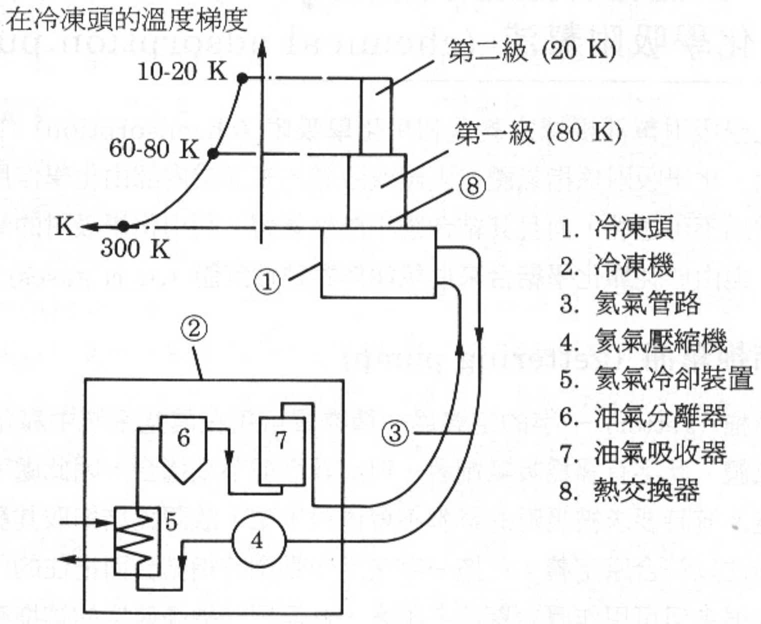

圖 3.15 冷凍機式幫浦原理

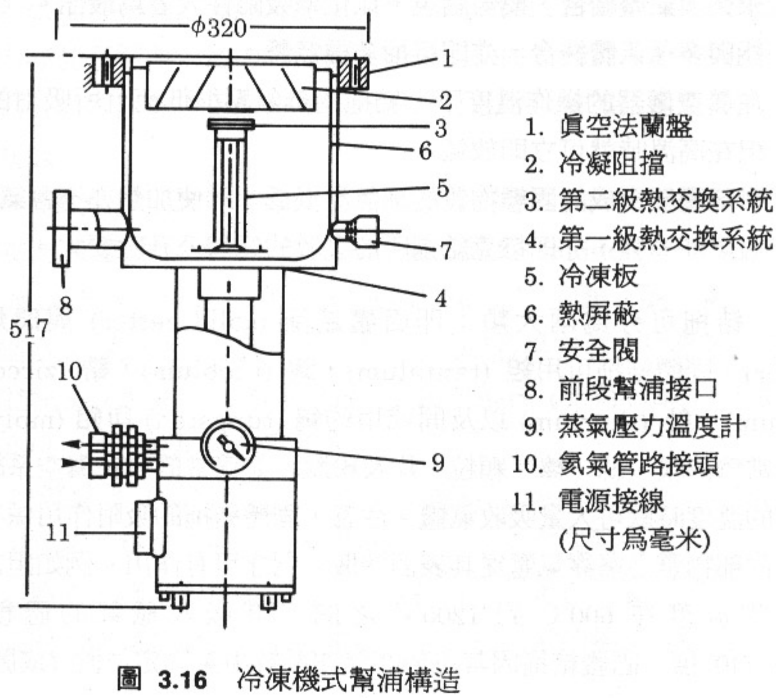

圖 3.16 冷凍機式幫浦構造

5. Chemical adsorption pumps

a. gettering pump

- **Getter: permanently adsorb gas by chemical reaction. Not effective for inert gases.**
- **Considerations for getter:**
  - **a. Permanently combined with gas**
  - **b. Can react with various gases**
  - **c. Not outgas in normal temperature and low pressure, but at high temp**
  - **d. Low vapor pressure**
  - **e. Large absorbing ratio (l/g)**
- **Types:**
  - **a. solid getter: Tantalum, Niobium, Zirconium, Titanium, Thorium, Tungsten, and Molybdenum. Absorbing gas in different temperatures, from 20-1500 °C. including bulk getter and coating getter.**
  - **b. Flash getter: active material, Mg, Ca, Cs, Ba and their alloys. Cheaper, and usually used in vacuum tube.**
- **Titanium sublimation pump.**

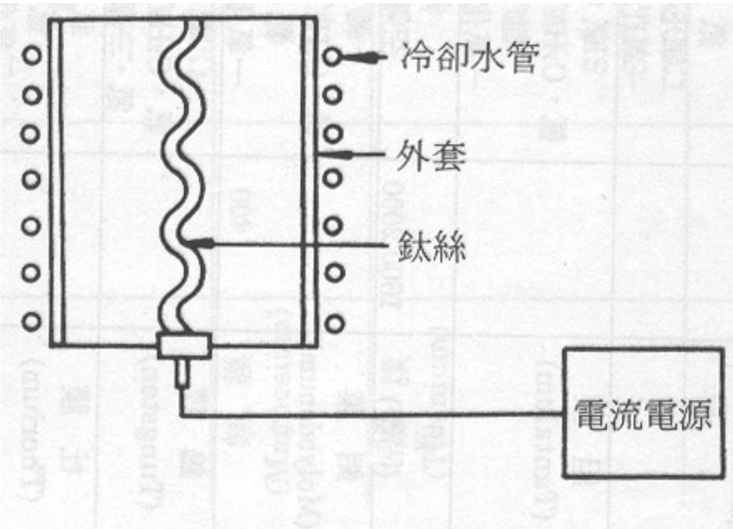

圖 3.17 結拖幫浦

b. ion pump

- **To ionize inert gases and trap them.**
- **types:**
  - **a. Gettering ion pump or evapor ion pump: using electrical discharge to ionize inert gases for gettering.**

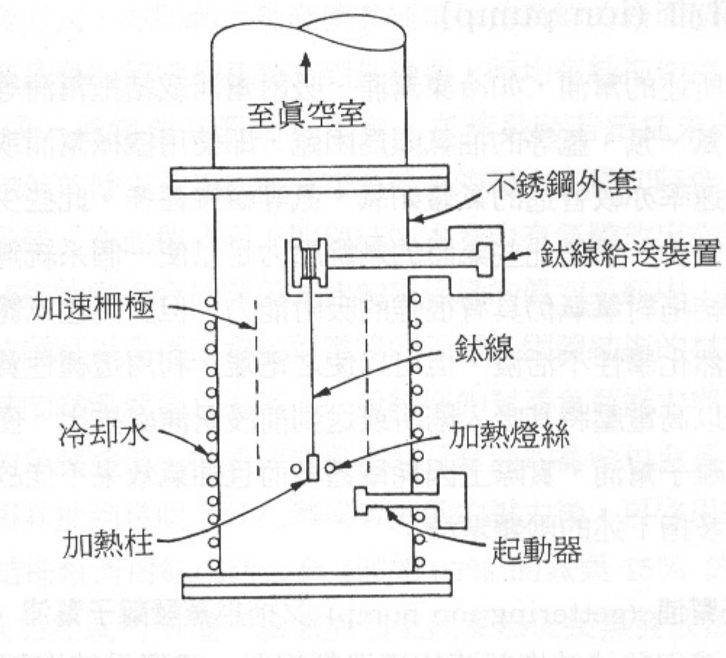

圖 3.18 結拖離子幫浦

b. Sputtering ion pump

- **Vacuum gauges**

  1. The difference between vacuum gauge (真空壓力計) and manometer (氣體壓力計): manometer usually measure pressure larger or close to ATM, the resolution is not as good as vacuum gauge. Vacuum gauge measure pressure from gas molecule in low vacuum range, but the molecular numbers in high vacuum range.

  2. Classifications:

<u>Low vacuum: >10^{-2} torr:</u>

a. Hydrostatic gauge (靜態壓力計)

- **Using oil or mercury tube to detect pressure change, usually 1~0.1 torr resolution.**
- **Diaphragm gauge: detect the deflection of diaphragm, resolution larger than 0.01 torr.**

<u>Middle vacuum: 10^{-2}~10^{-5} torr:</u>

b. Thermal conductivity gauge (熱傳導真空計)

- **measure the thermal gradient between the heater and the tube wall when mean free path of gas close to the heater-wall distance. Usually 1-10^{-4} torr.**
  Example, Pirani vacuum gauge:

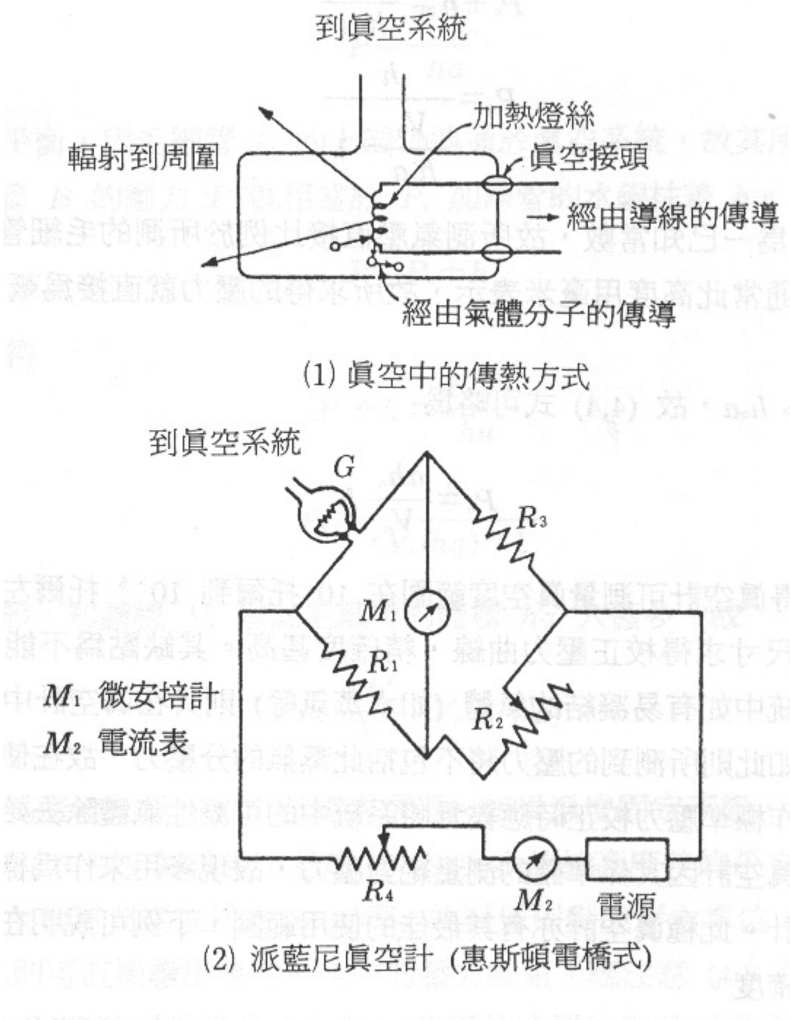

圖 4.7

c. Viscosity gauge (黏滯性真空計)

(1) Oscillating vane type (震動車葉式), 0.1-10^{-5} torr

- **measure the vibration frequency change of quartz cord.**

(2) Rotating-surface type (旋轉盤式), 10^{-3}-10^{-7}

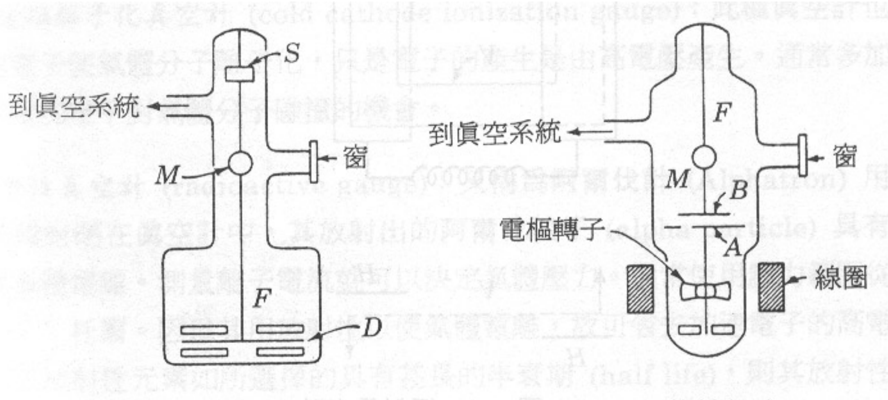

圖 4.1 振動車葉式　圖 4.2 旋轉盤式

High vacuum: <10^{-5} torr:

d. Radiometer gauge (輻射真空計), 10^{-2}-10^{-9} torr, very fragile,

used for calibration, also called Knudson vacuum gauge.

- **using radiation energy to heat up gas molecules to rotate vane inside tube.**

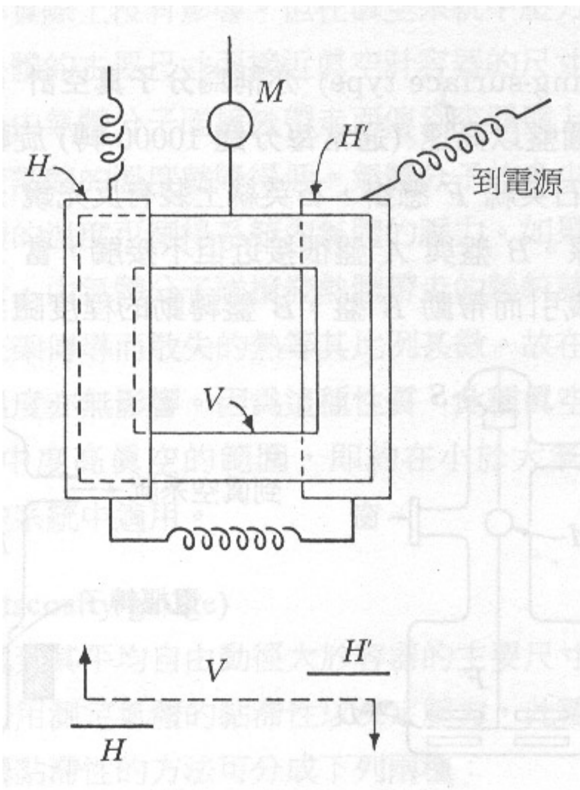

圖 4.3 輻射眞空計

e. Ionization gauges (離子化真空計)

(1) Hot cathode ionization gauges (熱陰極離子化真空計), 10^{-3}~10^{-12} torr.

• using thermionic emission to release electrons and ionize gas in the tube, and collected ionized gas to determine the current.

(2) Cold cathode ionization gauge (冷陰極離子化真空計), 10^{-3}~10^{-12} torr.

• Using high voltage to generate electrode and ionize gas.

(3) Radioactive gauge (放射性真空計), ATM-10^{-4} torr.

• Using radiation elements to release α particles to ionize gas.

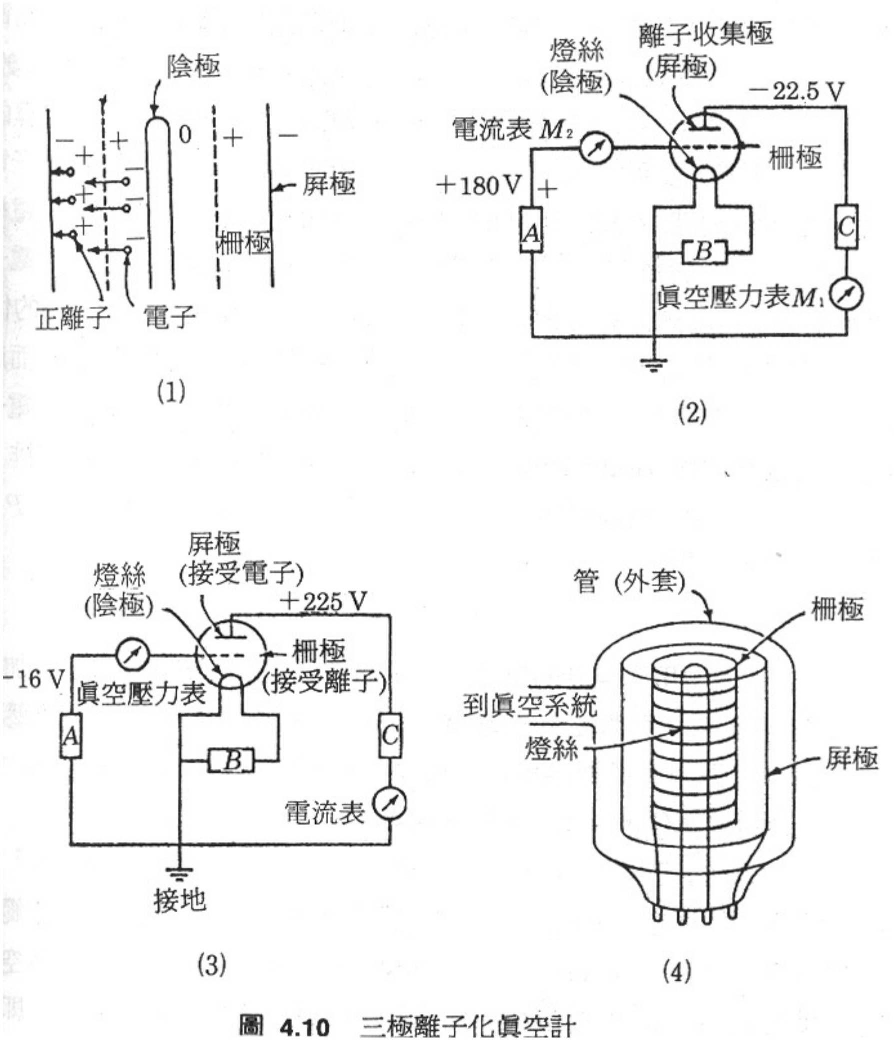

圖 4.10 三極離子化眞空計

Reference:

1. 蘇清森, “真空技術”, 東華書局, 五版, 1999.