

진공 기술의 기초

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포항가속기연구소 전경



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1. 진공이란?

2. 진공의 기초: 용어 및 기본개념

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- Maxwell Boltzmann distribution
- Mean free path, impingement rate, monolayer time
- Behavior of gas in different flow regime (viscous vs. molecular flow)
- Conductance, throughput, volume flow rate, pumping speed

3. 기체의 흐름과 도관에서의 저항

• 진공이란?

– 대기압보다 압력이 낮은 상태

• 압력이란?

– 단위면적 당 작용하는 힘

- 압력 낮다

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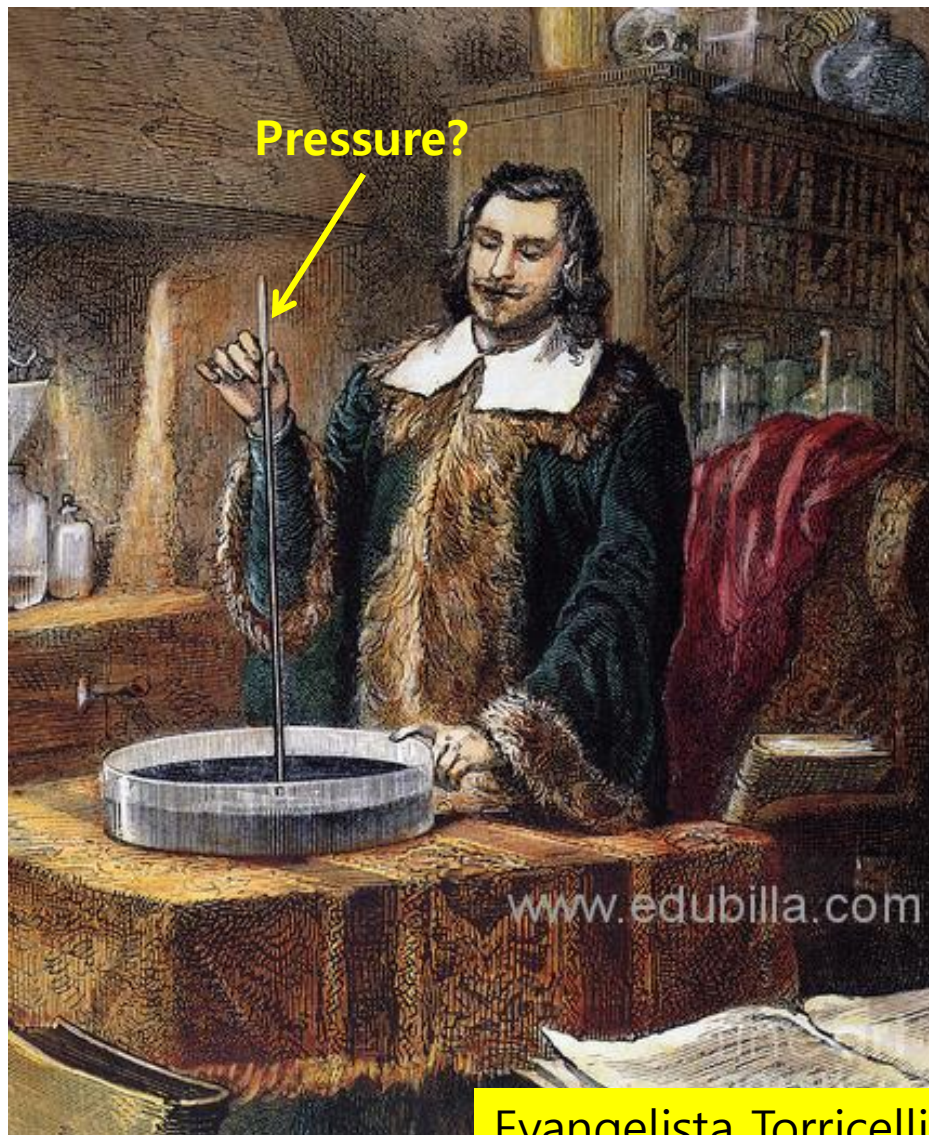
- 진공도 높다

- Low pressure

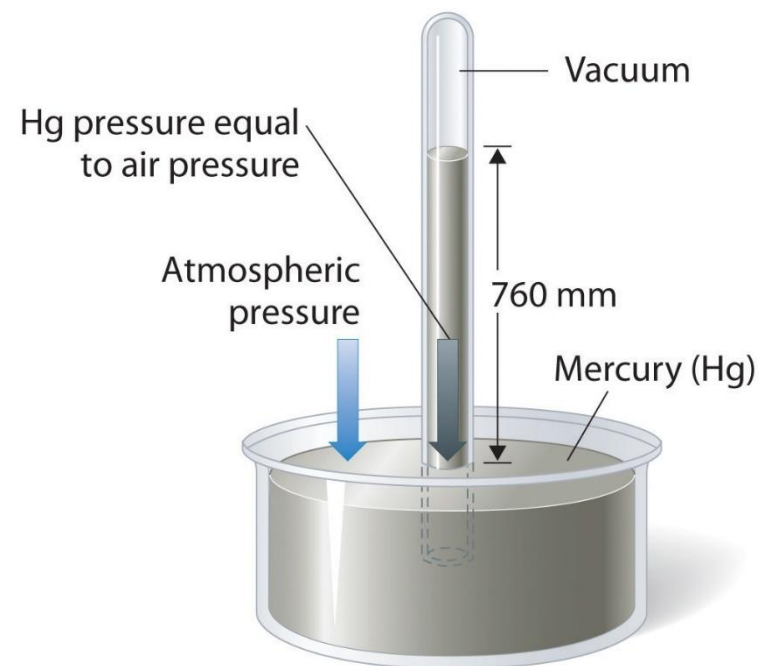
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- High Vacuum

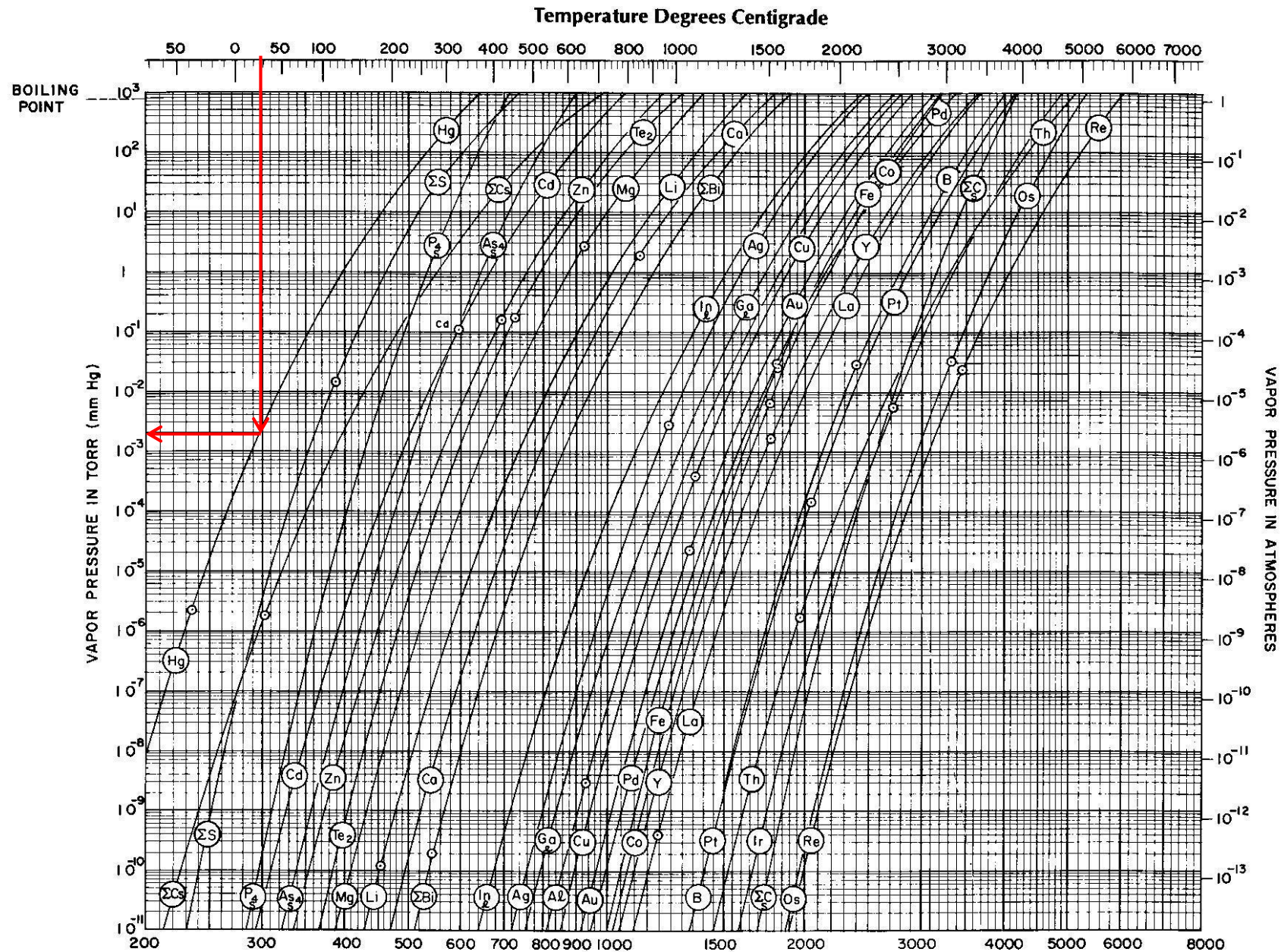
최초의 진공 실연 실험



Evangelista Torricelli (1644)

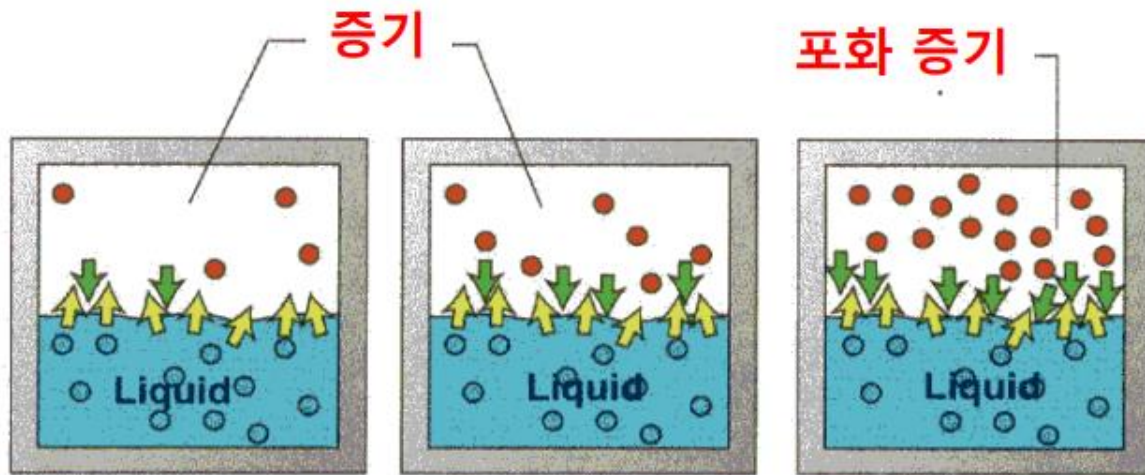
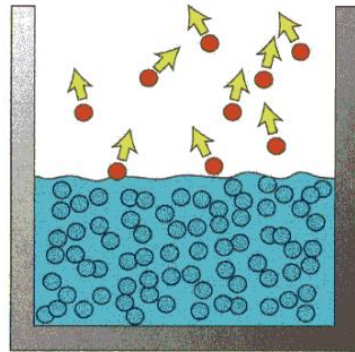


VAPOR PRESSURE CURVES OF THE ELEMENTS

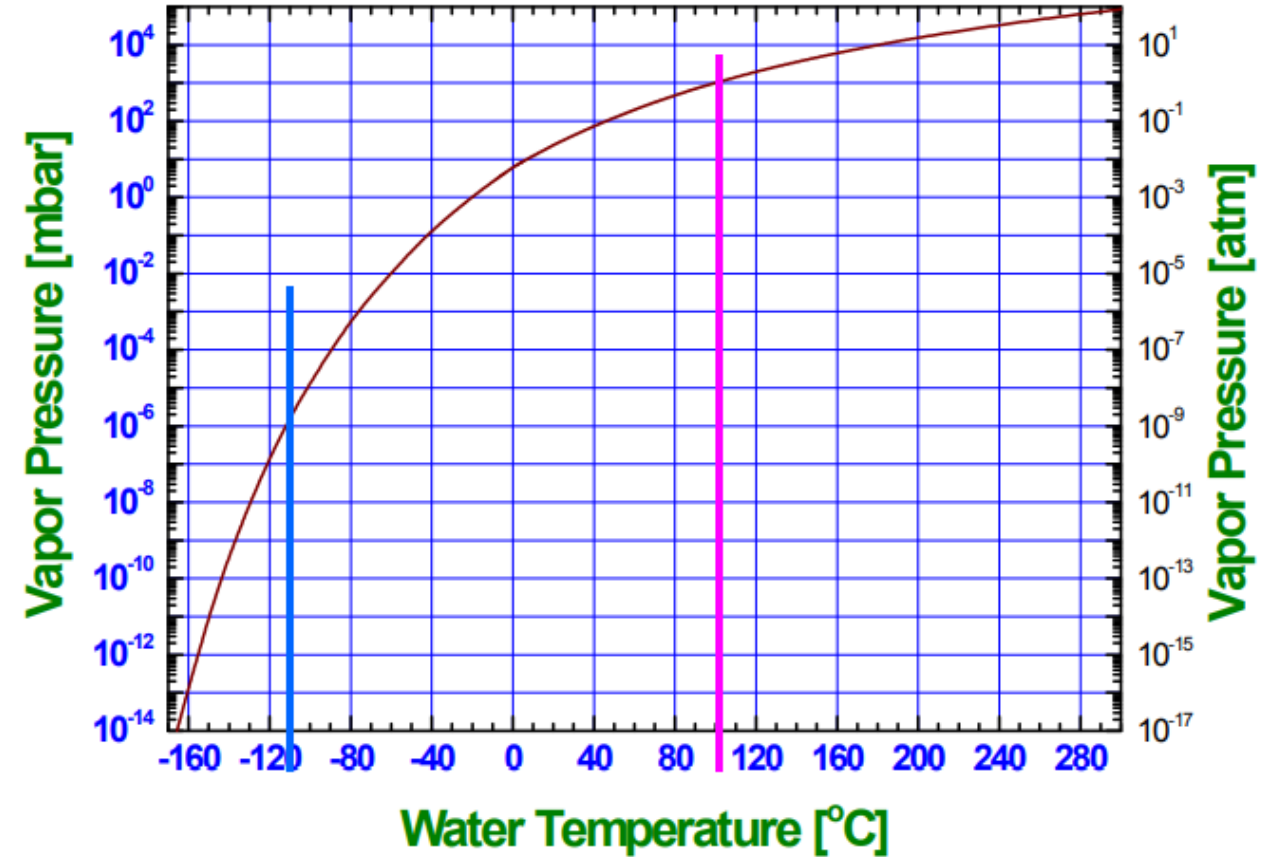


증기압

- 밀폐용기와 개방용기



- 물의 증기압 곡선



마그데부르크 반구 실험

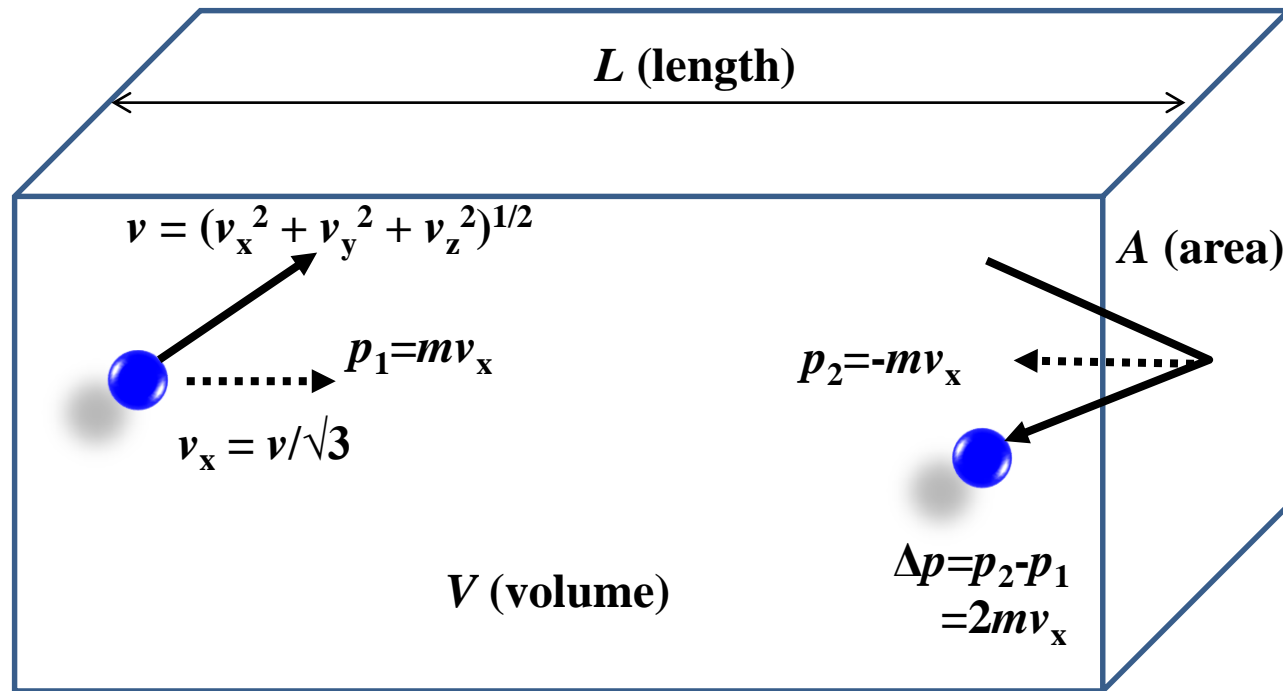
- $P = \frac{F}{A}$ [N/m²]
- 1 기압
= 수은 기둥 760 mm 압력
= 760 mmHg (Torr)
= 물 기둥 10.33 m 압력
= 1033 cmH₂O
= 1.033 kgf/cm²



진공의 영역

영역	압력	진공펌프	진공게이지	잔류기체	비고
저진공 (LV)	$\rightarrow 1$ mbar	Rotary Vane Dry pump Absorption	Manometer Bourdon CDG Pirani	Air (N ₂ , O ₂ , Ar)	Packing Vacuum cleaner Freeze drying
중진공 (MV)	$\rightarrow 10^{-3}$ mbar	Booster Ejection Dry pump	McLeod CDG SRG Ionization	H ₂ O Air	CVD
고진공 (HV, VHV)	$\rightarrow 10^{-9}$ mbar	Diffusion pump TMP Cryo-pump	SRG Ionization	H ₂ O	Evaporation Implantation Vacuum melting
초고진공 (UHV)	$\rightarrow 10^{-12}$ mbar	TMP TSP, NEG, SIP Cryo-pump	Ionization (BA type)	H ₂ CO H ₂ O	Surface analy. Accelerator
극고진공 (XHV)	$< 10^{-12}$ mbar	TSP, NEG, SIP Cryo-pump	Ionization (Filter)	H ₂ CO	Quantum device New material

기체입자와 압력 (미시적 관점)



$$F = dp/dt \quad (p=\text{momentum})$$

$$= 2mv_x / (2L/v_x)$$

$$= mv_x^2 / L = mv^2 / (3L)$$

$$P = F/A \quad (P=\text{pressure})$$

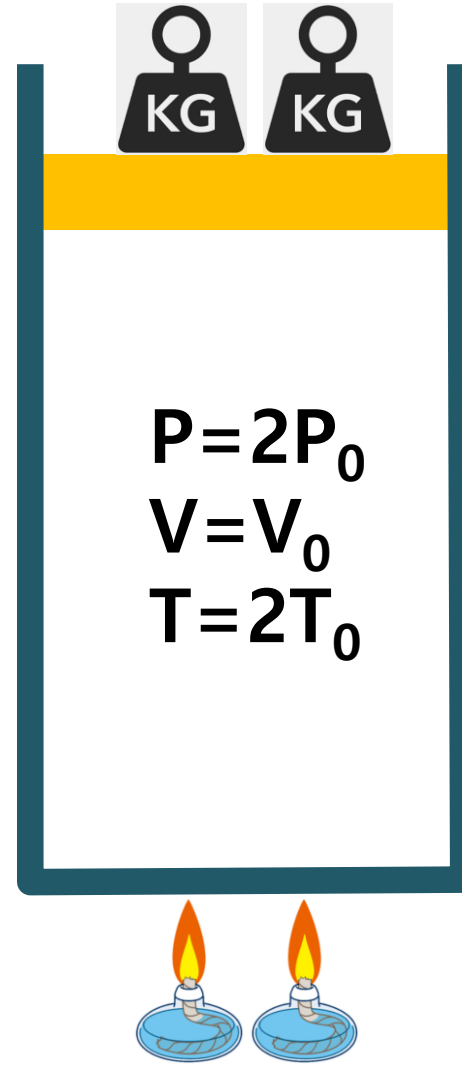
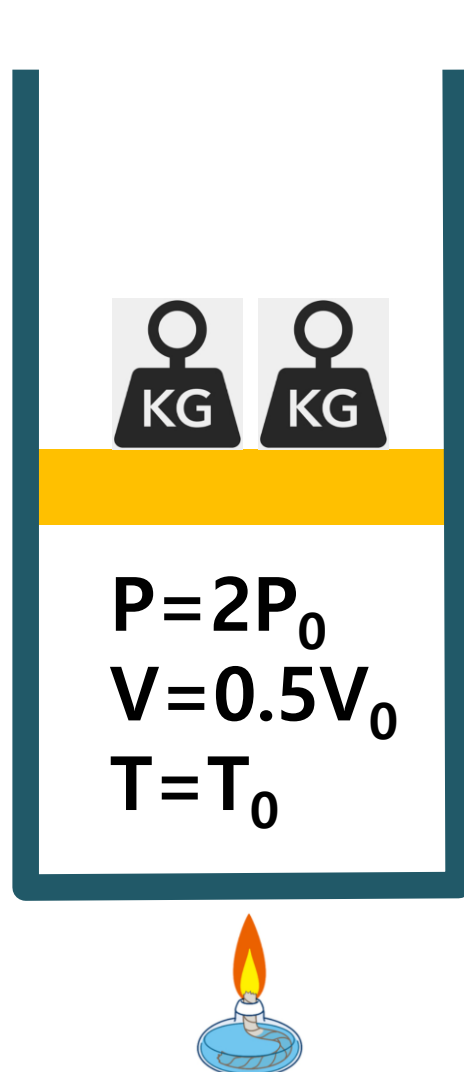
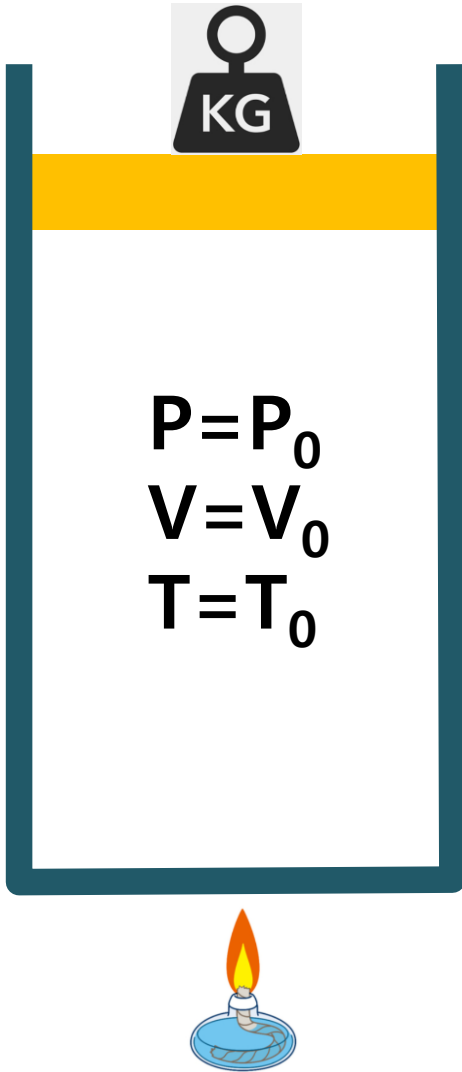
$$= Nmv^2 / (3LA)$$

$$= Nmv^2 / (3V)$$

$$E_K = 1/2 \times mv^2 = 3/2 \times k_B T \rightarrow PV = 1/3 \times Nmv^2 = Nk_B T$$

(E_K =kinetic energy)

보일-샤를의 법칙 (거시적 관점)



$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

이상기체상태방정식

보일 샤를의 법칙 + 아보가드로의 법칙

$$(PV/T = \text{const.})$$

$$(V \propto N)$$

$$PV = N k_B T$$

or $\xrightarrow{\text{energy unit}}$

$$P = n k_B T = n_M R T$$

시간 변화율

- $d(PV)/dt = d(N k_B T)/dt$

$\xrightarrow{=0 \text{ (정상상태, } P=\text{const.)}}$

$$\text{☞ } V (dP/dt) + P (dV/dt) = k_B T (dN/dt)$$

$$dV/dt = A \cdot v : \text{부피흐름율}$$

$$dN/dt \propto P (dV/dt) \doteq Q : \text{기체흐름양(유량)}$$

P : pressure

V : volume

N : number of particles

n : density of particles

n_M : Mole

T : temperature [K]

A : area

k_B : Boltzmann const.

R : gas constant

맥스웰-볼츠만 속력 분포

1. 속력분포함수 $f(v)$ 는 속도가 v 와 $v+dv$ 사이의 영역에 있을 확률을 나타내며 곧 확률 밀도를 의미함.

2. 분포함수는 방향에 상호 독립적이므로 각 방향 별 분포함수의 곱과 같음:

$$\rightarrow f(v_x, v_y, v_z) = f(v_x)f(v_y)f(v_z)$$

3. 분포함수는 날아가는 방향에는 관계없이 그 크기에만 의존함:

$$\rightarrow f(v_x, v_y, v_z) = f(v_x^2 + v_y^2 + v_z^2)$$

4. 두 가지 함수 관계를 만족하는 함수의 형태는 지수함수가 유일함:

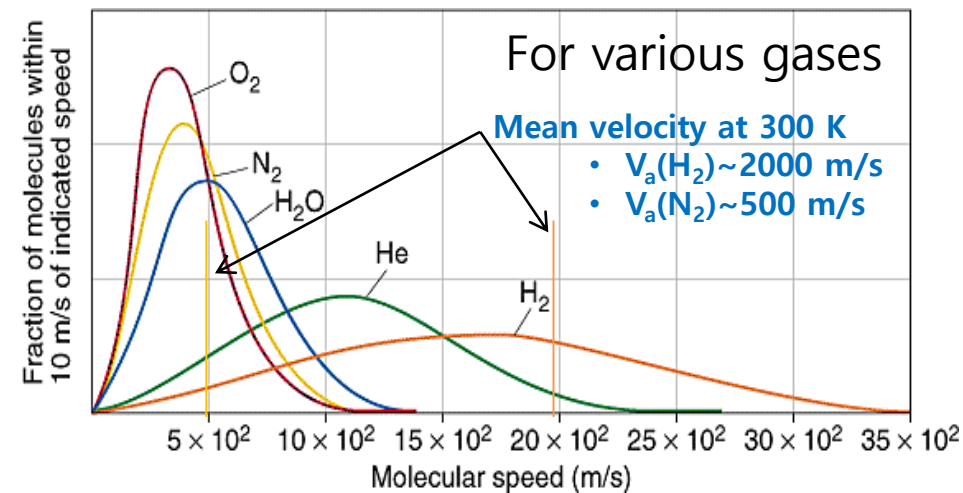
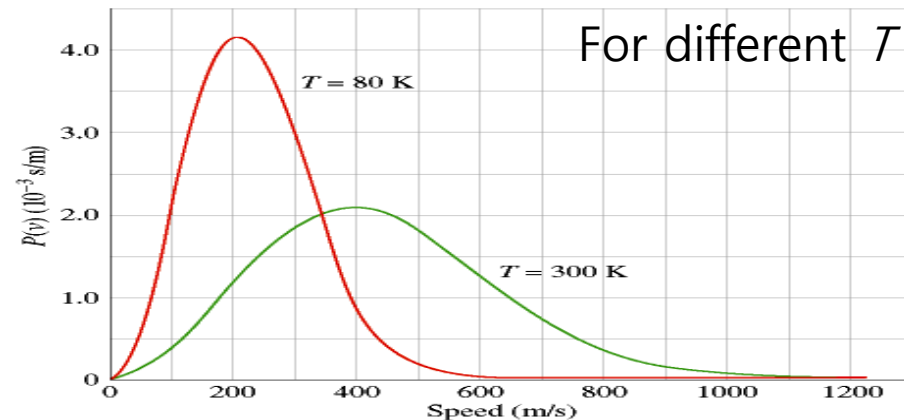
$$\rightarrow f(v) = A \exp(-\alpha v^2)$$



← 확률밀도함수의 정적분 값 = 1

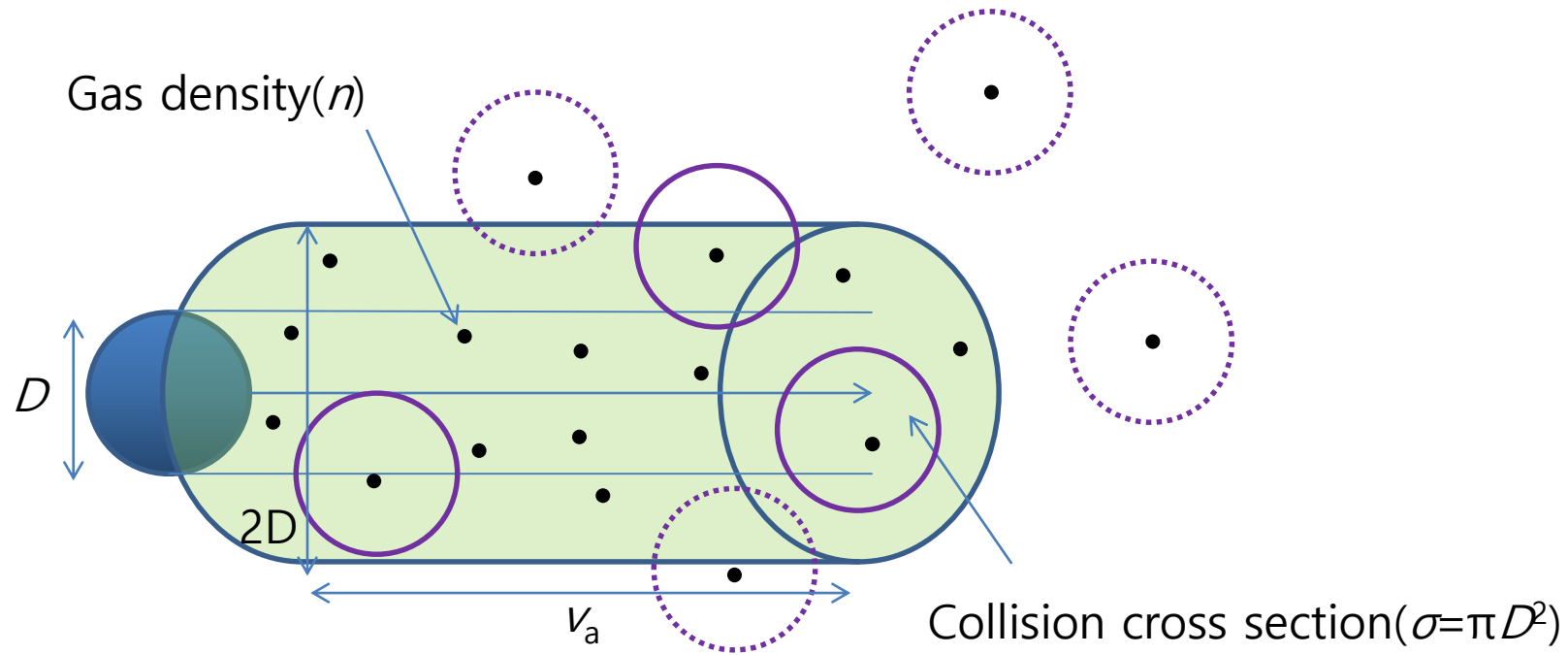
← 입자의 평균 열에너지 = $3kT/2$

$$f(v)dv = 4\pi v^2 \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{mv^2}{2kT}} dv$$



$$\left[v_a = \int_0^\infty v f(v) dv = \sqrt{\frac{8kT}{\pi m}} = 146 \sqrt{\frac{T}{M}} \quad (\text{m/s}) \right]$$

평균자유거리 (Mean free path)

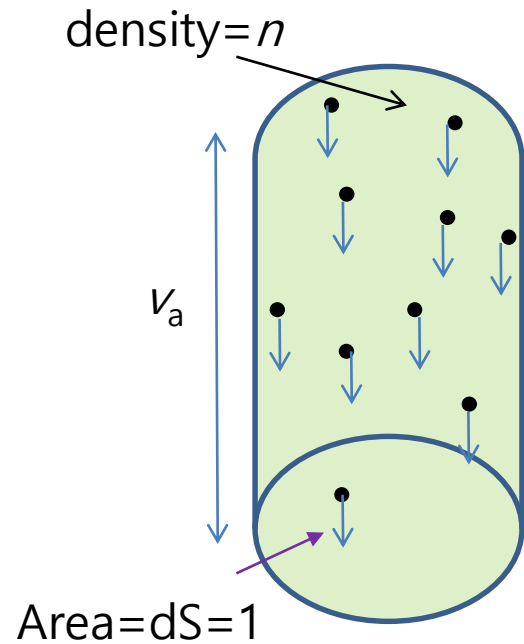


- Number of collision per second $z = n v_a \pi D^2$
- Mean free path $\lambda = v_a / z = 1 / n \pi D^2$

$$\lambda \approx 5 \times 10^{-3} / P \text{ (cm) at } 23^\circ\text{C, air}$$

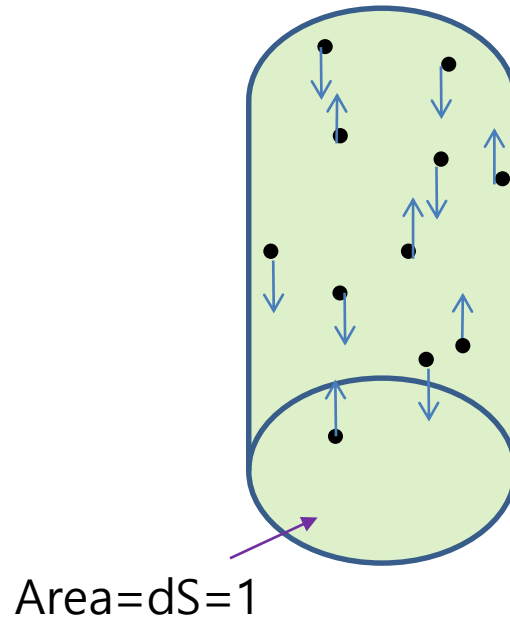
표면 충돌빈도 (Impingement rate)

- Def.) # of particles incident on unit surface per unit time



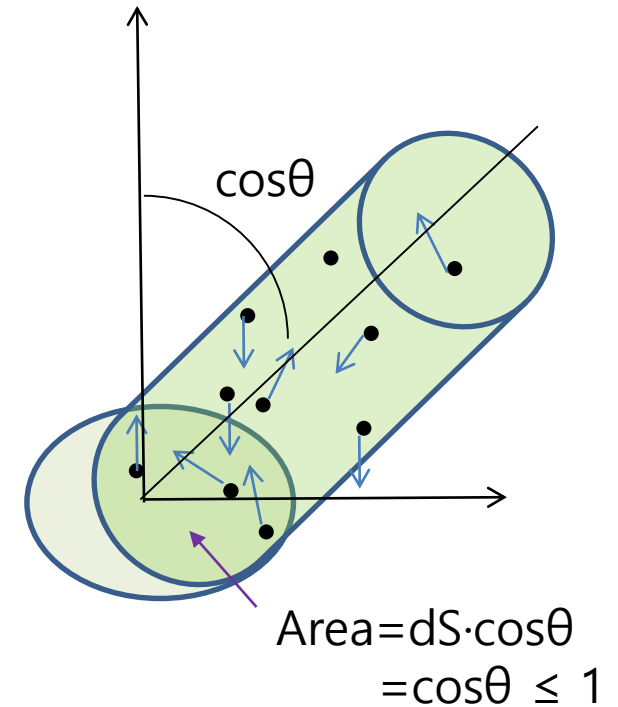
$$J = nv_a$$

(1-directional case)



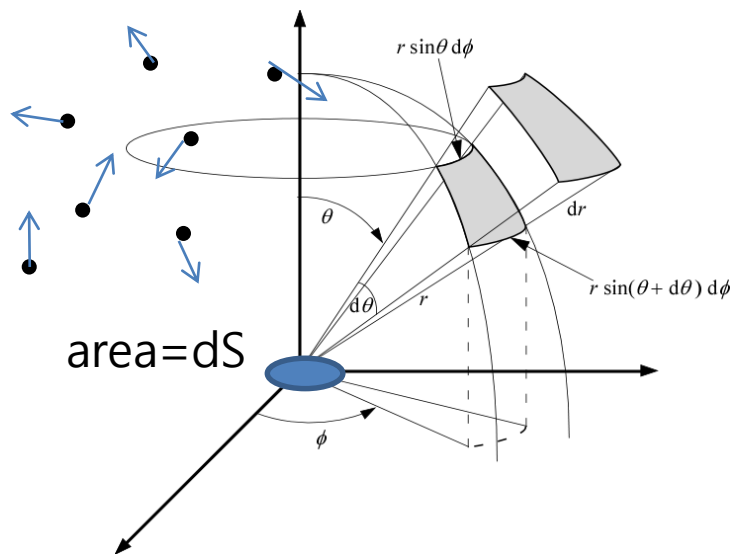
$$J = \frac{1}{2} \cdot nv_a$$

(1-dimensional case)



$$J = \frac{1}{4} \cdot nv_a$$

(3-dimensional case)



$$N_i = \left[\frac{n}{4\pi} \int_0^\infty v f(v) dv \int_0^{\pi/2} 2\pi \sin\theta \cos\theta d\theta \right] dt dS$$

$$J = \frac{N_i}{dt dS} = \frac{n}{4} \int_0^\infty v f(v) dv = \frac{1}{4} n v_a$$

$$J = \frac{P}{\sqrt{2\pi m k T}} = 3.5 \times 10^{22} \frac{P}{\sqrt{MT}} \text{ (ea cm}^{-2} \text{ s}^{-1}\text{)}$$

■ Impingement rate

$$J \doteq 3.3 \times 10^{20} P \text{ (cm}^{-2} \text{ s}^{-1}\text{) at 23}^\circ\text{C, air}$$

■ Monolayer time $\tau = 10^{15}/J = 4 \times 10^{15}/n v_a$ (Approximately 10^{15} surface sites per cm^2)

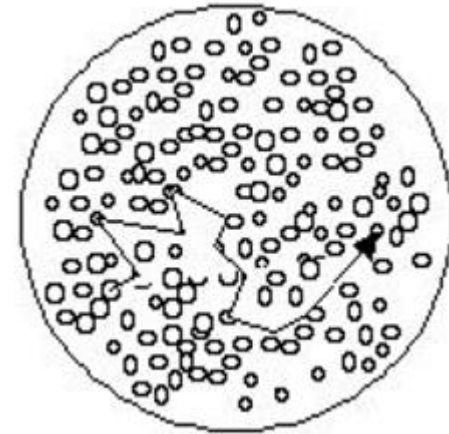
$$\tau \doteq 3 \times 10^{-6} / P \text{ (s) at 23}^\circ\text{C, air}$$

기체의 흐름 영역

1. 점성류 (Viscous flow)

$$\lambda / d < 0.01$$

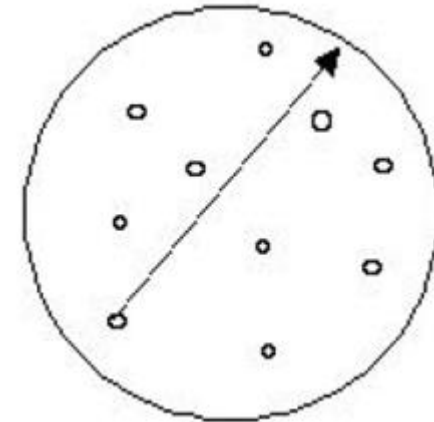
$$P \cdot d \text{ (Torr, cm)} > 0.5$$



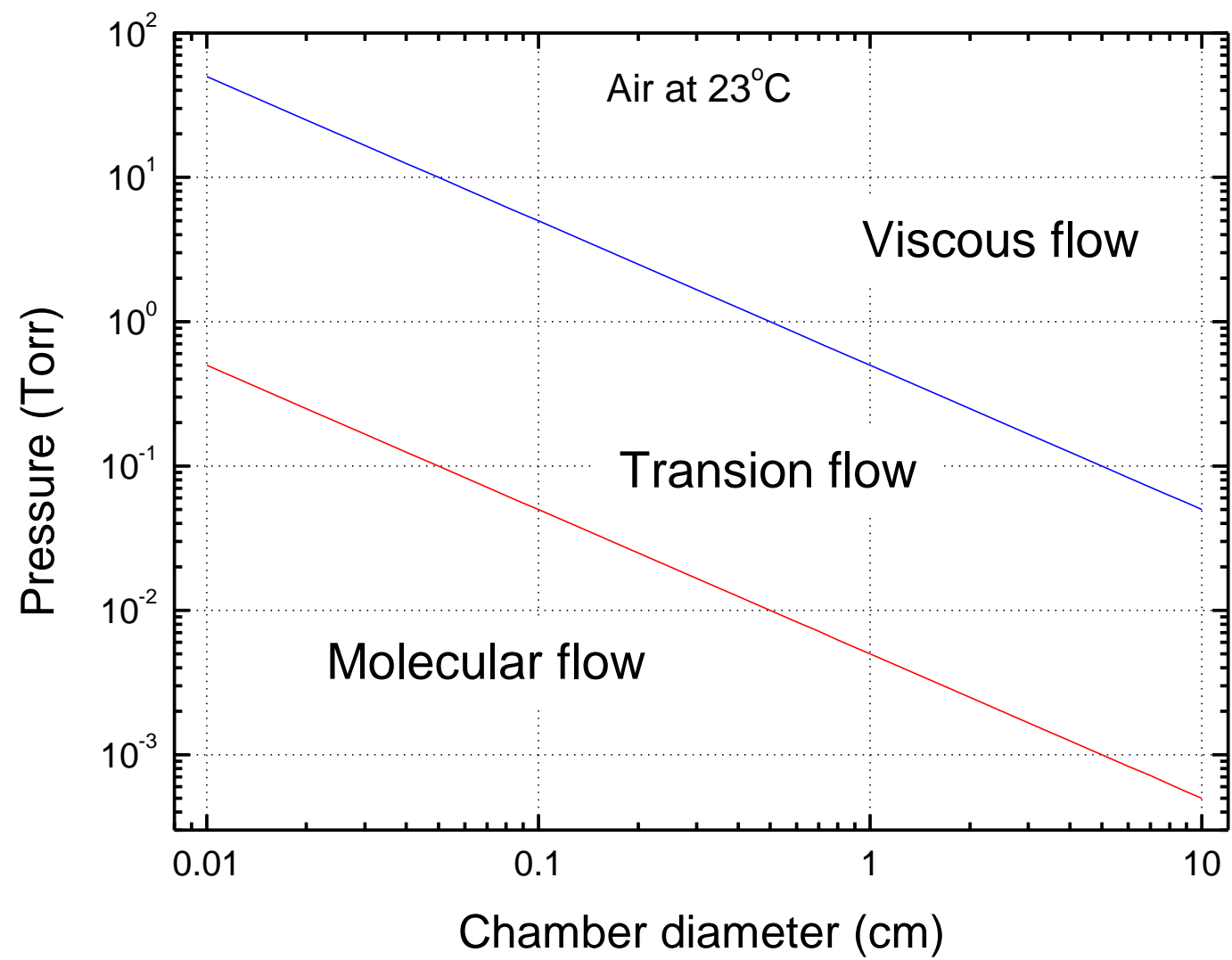
2. 분자류 (Molecular flow)

$$\lambda / d > 1$$

$$P \cdot d \text{ (Torr, cm)} < 0.005$$



❖ $\lambda \sim 5 \times 10^{-3} / P \text{ (Torr, cm)}$ at 23°C, air



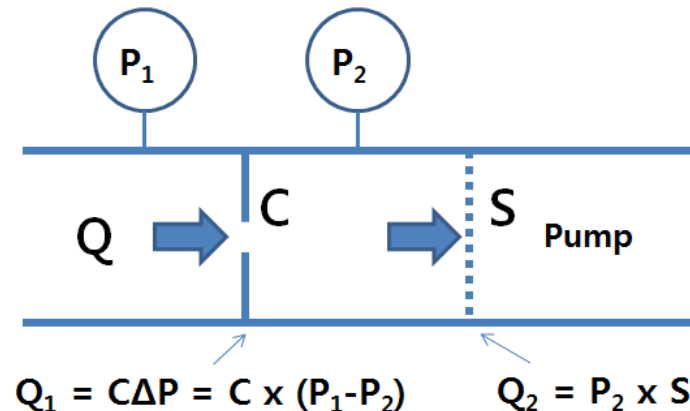
기체분자운동론적 데이터

	Pressure				
	10^3	10^0	10^{-3}	10^{-7}	10^{-11}
	7.5×10^2	7.5×10^{-1}	7.5×10^{-4}	7.5×10^{-8}	7.5×10^{-12}
	10^5	10^2	10^{-1}	10^{-5}	10^{-9}
					mbar
					Torr
					Pa
Particle density, n (cm^{-3})	10^{19}	10^{16}	10^{13}	10^9	10^5
Mean free path, λ (cm)	10^{-6}	10^{-3}	10	10^3	10^6
Impingement rate, J ($\text{s}^{-1} \cdot \text{cm}^{-2}$)	3×10^{23}	3×10^{20}	3×10^{17}	3×10^{13}	3×10^9
Collision rate, Γ_V ($\text{s}^{-1} \cdot \text{cm}^{-3}$)	10^{29}	10^{23}	10^{17}	10^9	10
Monolayer time, τ	3 ns	3 μs	3 ms	30 s	80 h
Type of gas flow	◀—Viscous— —Knudsen— ————molecular————▶				

❖ 1 atm = 760 Torr = 14.7 psi = 1013 mbar = 1013 hPa

컨덕턴스(C), 배기속도(S), 유량(Q)

- C = ratio of throughput under steady state conservative conditions to the pressure differential between two specified cross sections inside a pumping system (l/s)
- S = ratio of the throughput of a given gas to the partial pressure of that gas at the cross section of the inlet port of the pump (l/s)
- Q = amount of gas in pressure-volume units flowing per unit time across a specified cross section at a specified temperature (mbar l/s)

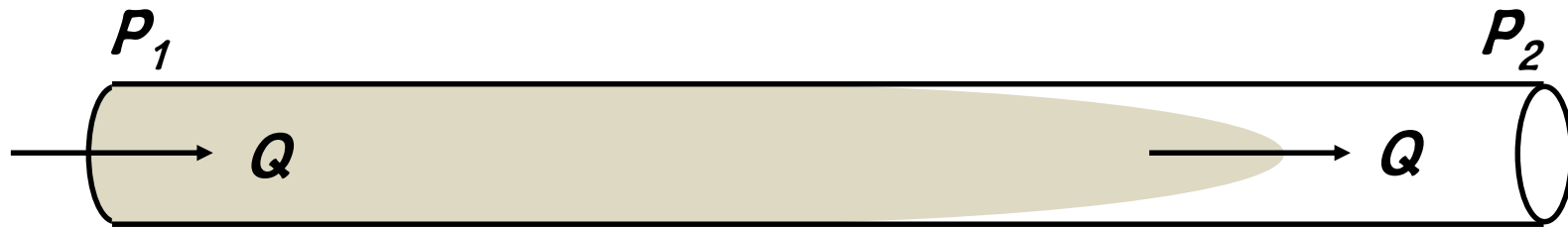


$$Q_1 = Q_2$$

$$\rightarrow S = C (P_1/P_2 - 1)$$

컨덕턴스 (Conductance)

- Definition

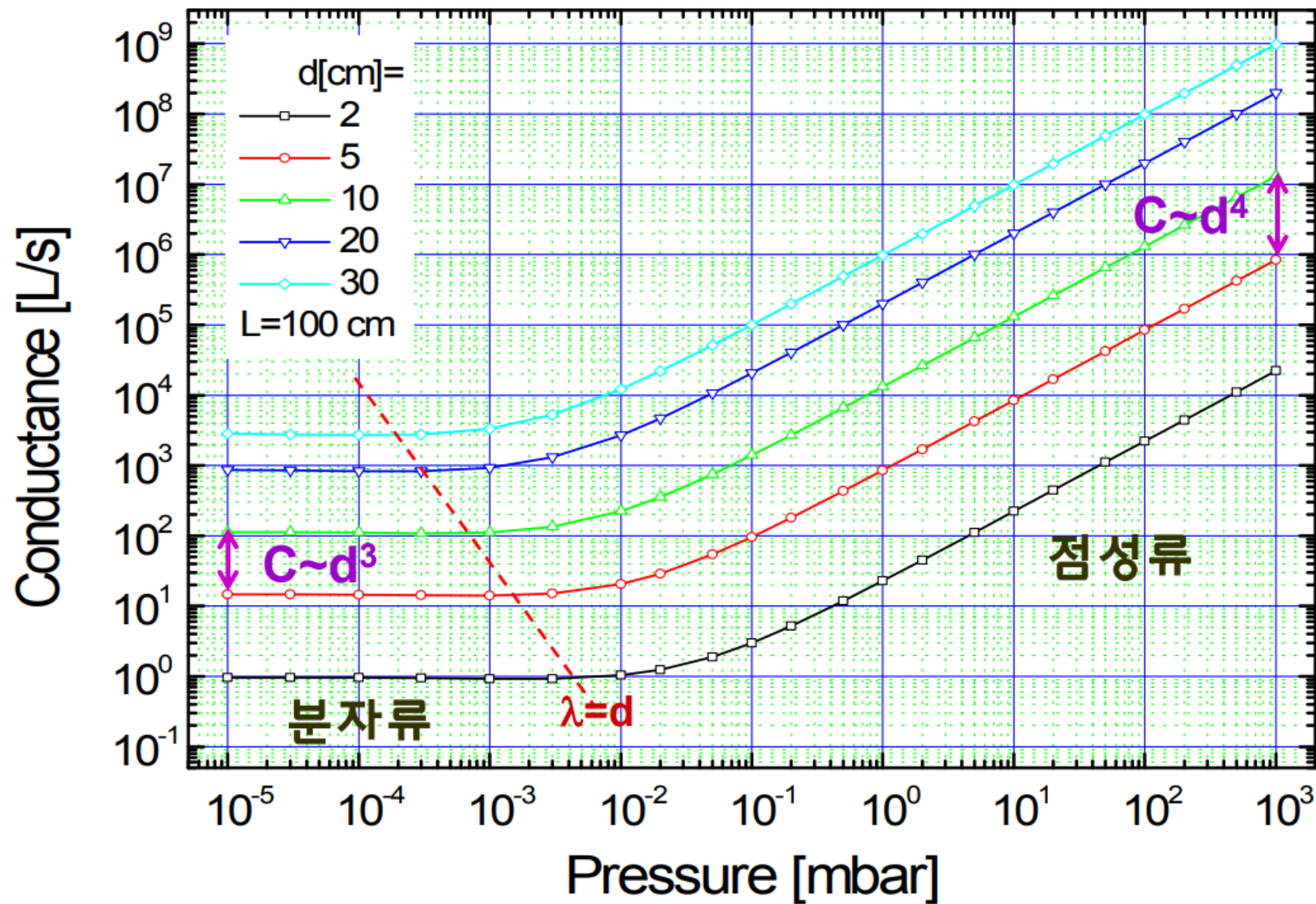


$$Q = C (P_1 - P_2)$$

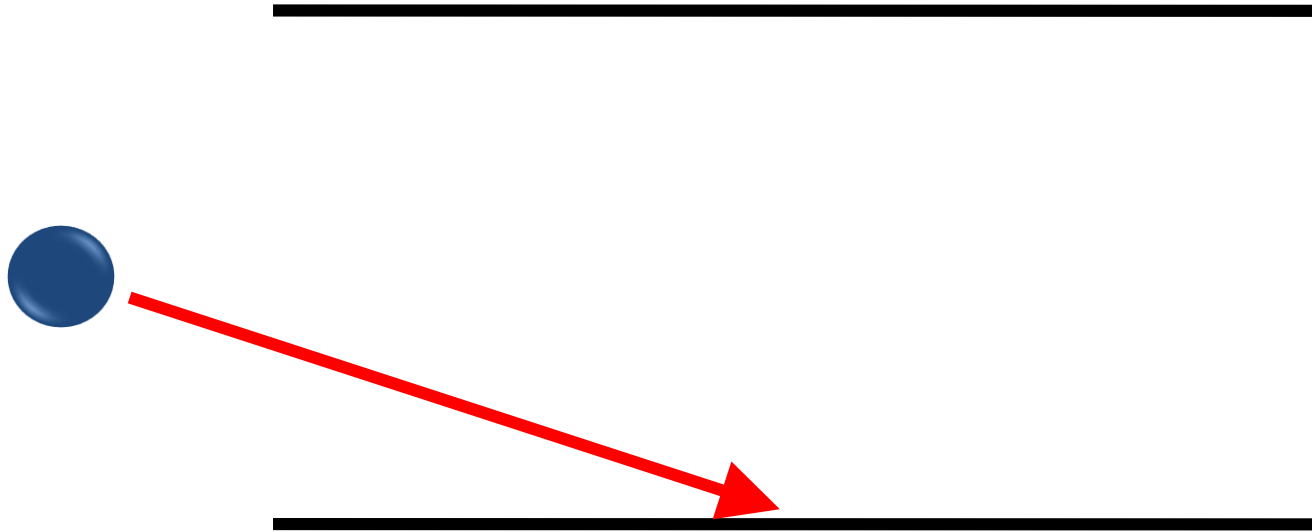
$$\rightarrow C = Q / (P_1 - P_2) \quad (\text{depends on geometry})$$

- Unit: l/s

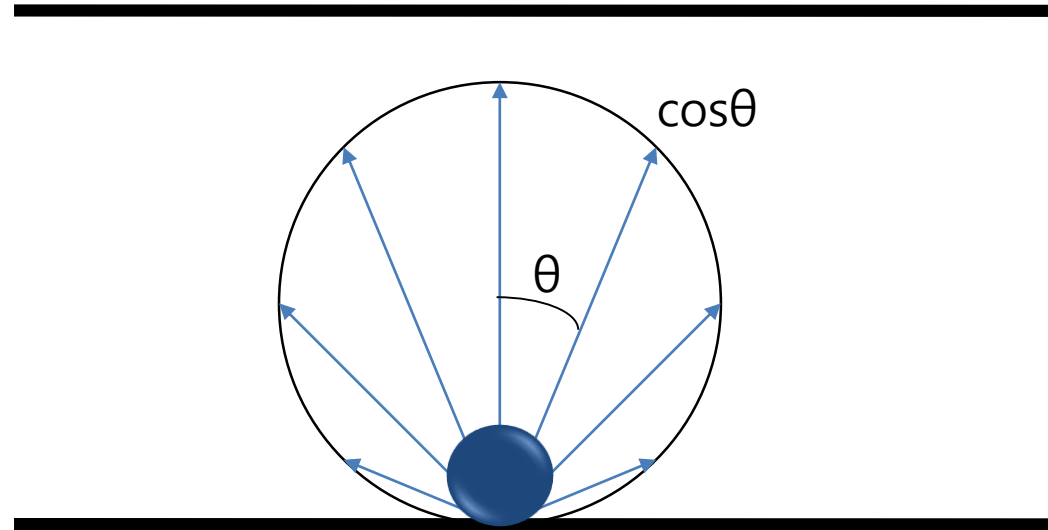
원통형 도관의 컨덕턴스



Q: 충돌 후 어느 방향으로 향할까?

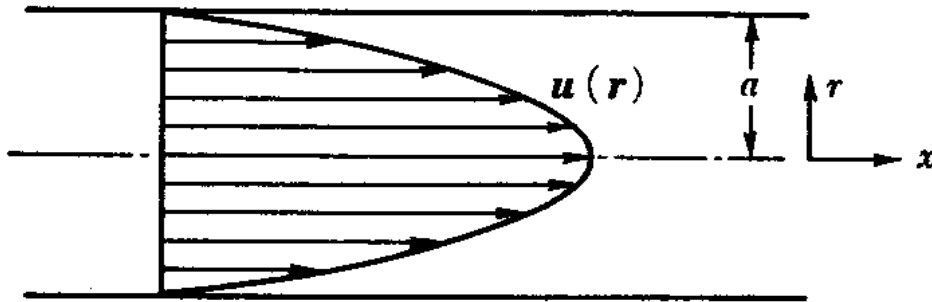


Q: 처음부터 표면에 흡착된 입자가 방출되는 방향?



점성류에서의 컨덕턴스 (원통도관)

✓ Long pipe



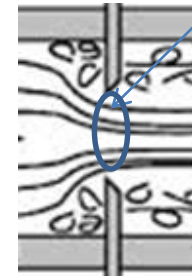
Poiseuille's law

$$Q = \frac{\pi d^4}{128\eta L} \bar{P} (P_1 - P_2)$$

$$C = \frac{\pi d^4}{128\eta L} \bar{P}$$

✓ Orifice

area = A [cm²]



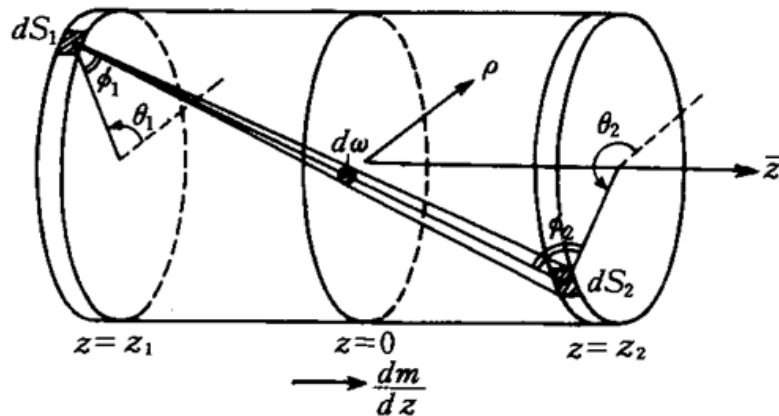
$$C_o = \frac{17.2 A}{\left(1 - \frac{P_{down}}{P_{up}}\right)} \ell/s$$

❖ **Approximation**

- 22°C, Diatomic gas. eg. Air(N₂+O₂)
- $P_{up} > 1.92 P_{down}$

분자류에서의 컨덕턴스 (원통도관)

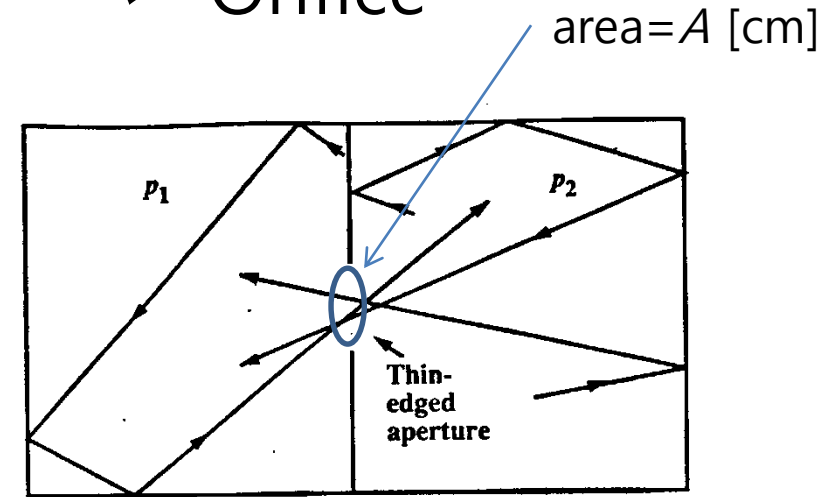
✓ Long pipe



$$Q = \frac{2\pi}{3} d^3 V_a \frac{(P_2 - P_1)}{L}$$

$$C = \frac{2\pi}{3} \frac{d^3}{L} V_a$$

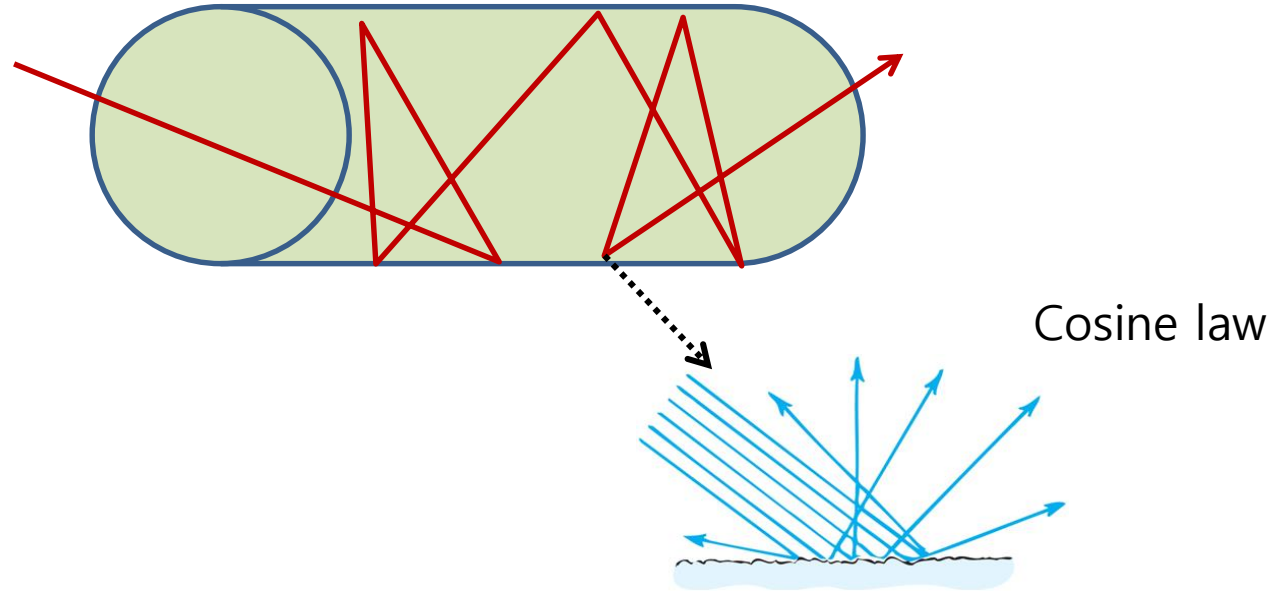
✓ Orifice



$$C_o = \frac{1}{4} \bar{v}_a A = 3.64 \sqrt{\frac{T}{M}} A \quad l/s$$

$$C_o = 11.6 A \quad (l/s, cm^2) \text{ at } 23^\circ C, \text{ air}$$

통과확률 (Transmission Probability)과 여현법칙 (Cosine Law)



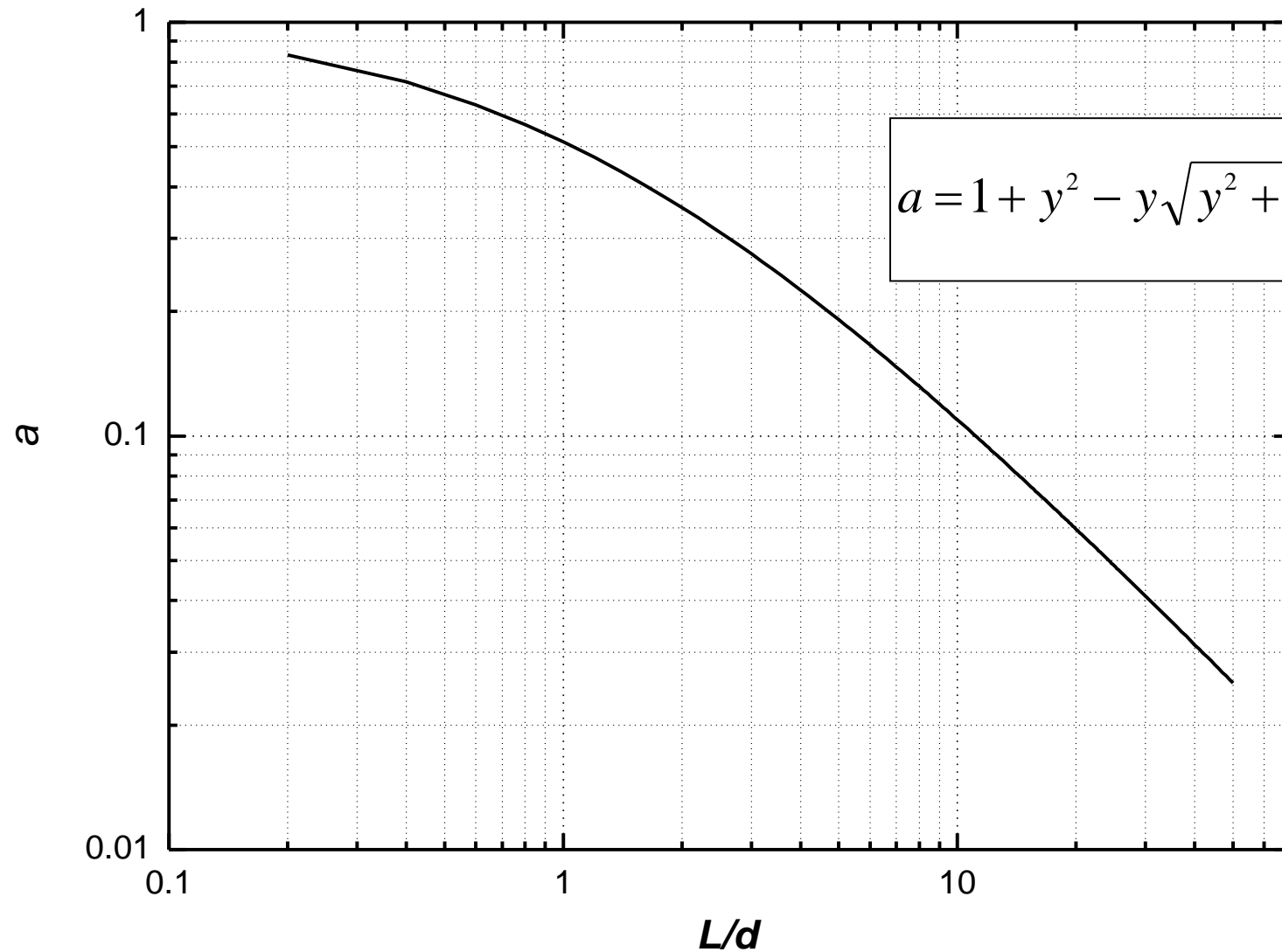
Conductance of a pipe
= Conductance of inlet (orifice) x transmission probability (a)

$$C = aC_o$$

❖ 통과확률 (Clausing coeff.)

L/d	a	L/d	a	L/d	a	L/d	a
0.1	0.90922	3.7	0.23824	7.4	0.1404	14.6	0.07885
0.2	0.83408	3.8	0.23376	7.6	0.13739	14.8	0.07791
0.3	0.77115	3.9	0.22945	7.8	0.13451	15	0.07699
0.4	0.71779	4	0.2253	8	0.13175	15.2	0.07609
0.5	0.67198	4.1	0.2213	8.2	0.1291	15.4	0.07521
0.6	0.63223	4.2	0.21745	8.4	0.12656	15.6	0.07436
0.7	0.59736	4.3	0.21374	8.6	0.12412	15.8	0.07352
0.8	0.56651	4.4	0.21015	8.8	0.12177	16	0.0727
0.9	0.53898	4.5	0.20669	9	0.11951	16.2	0.0719
1	0.51423	4.6	0.20334	9.2	0.11733	16.4	0.07112
1.1	0.49185	4.7	0.2001	9.4	0.11524	16.6	0.07036
1.2	0.4715	4.8	0.19697	9.6	0.11322	16.8	0.06961
1.3	0.45289	4.9	0.19393	9.8	0.11127	17	0.06887
1.4	0.43581	5	0.19099	10	0.10938	17.2	0.06816
1.5	0.42006	5.1	0.18814	10.2	0.10756	17.4	0.06745
1.6	0.40548	5.2	0.18538	10.4	0.10581	17.6	0.06677
1.7	0.39195	5.3	0.1827	10.6	0.1041	17.8	0.06609
1.8	0.37935	5.4	0.1801	10.8	0.10246	18	0.06543
1.9	0.36759	5.5	0.17757	11	0.10086	18.2	0.06478
2	0.35658	5.6	0.17512	11.2	0.09932	18.4	0.06415
2.1	0.34624	5.7	0.17273	11.4	0.09782	18.6	0.06353
2.2	0.33652	5.8	0.17041	11.6	0.09637	18.8	0.06292
2.3	0.32736	5.9	0.16815	11.8	0.09496	19	0.06232
2.4	0.31871	6	0.16596	12	0.09359	19.2	0.06173
2.5	0.31053	6.1	0.16382	12.2	0.09226	19.4	0.06116
2.6	0.30279	6.2	0.16174	12.4	0.09097	19.6	0.06059
2.7	0.29543	6.3	0.15971	12.6	0.08971	19.8	0.06004
2.8	0.28844	6.4	0.15773	12.8	0.08849	20	0.05949
2.9	0.28179	6.5	0.1558	13	0.0873	20.5	0.05817
3	0.27546	6.6	0.15392	13.2	0.08615	21	0.05691
3.1	0.26941	6.7	0.15209	13.4	0.08502	21.5	0.0557
3.2	0.26364	6.8	0.1503	13.6	0.08393	22	0.05455
3.3	0.25812	6.9	0.14855	13.8	0.08286	22.5	0.05344
3.4	0.25283	7	0.14684	14	0.08182	23	0.05237
3.5	0.24776	7.1	0.14517	14.2	0.0808	23.5	0.05135
3.6	0.24291	7.2	0.14355	14.4	0.07982	24	0.05037

❖ 통과확률 (Clausing coeff.)



$$a = 1 + y^2 - y\sqrt{y^2 + 1} - \frac{[(2 - y^2)\sqrt{y^2 + 1} + y^3 - 2]^2}{4.5y\sqrt{y^2 + 1} - 4.5\ln[y + \sqrt{y^2 + 1}]}$$

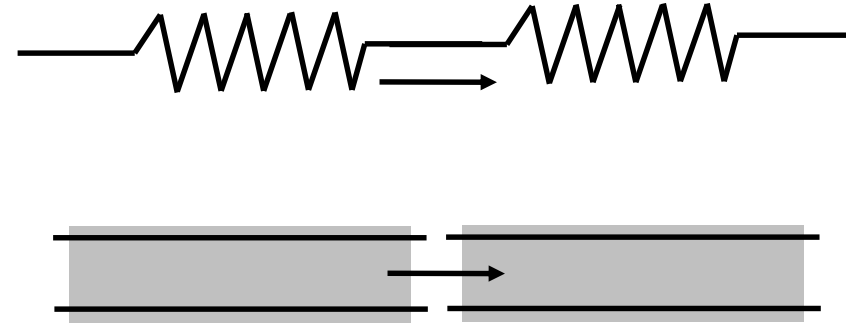
(y=L/d)

➤ Berman formula
(Error<0.7%)

컨덕턴스의 합성

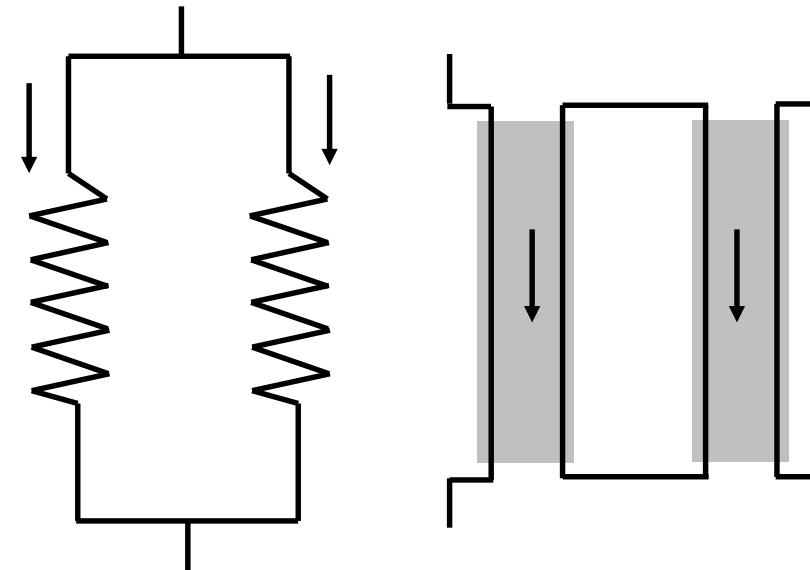
✓ 직렬연결

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$

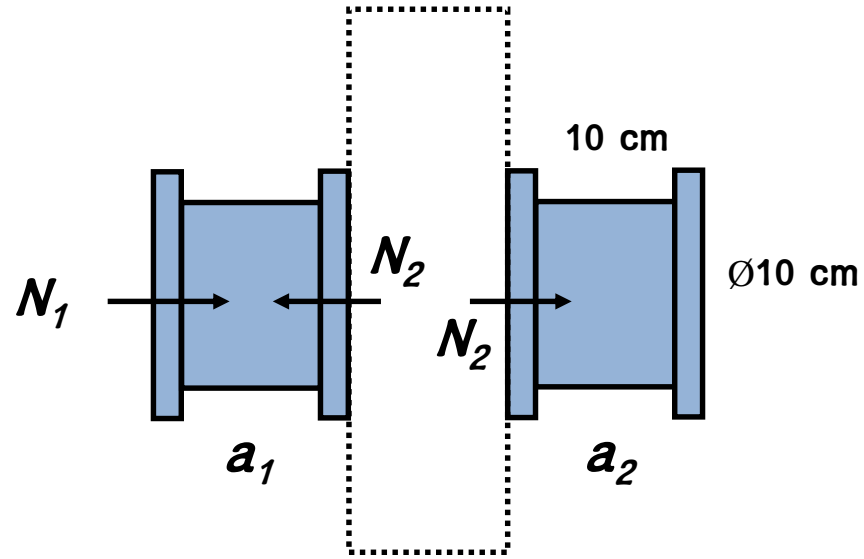


✓ 병렬연결

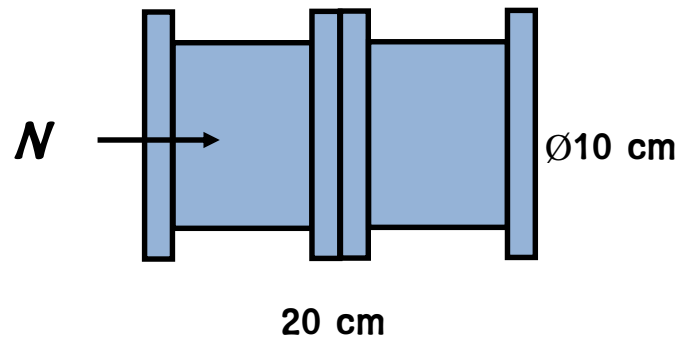
$$C = C_1 + C_2 + C_3 + \dots$$



❖ 컨덕턴스의 합성 (직렬연결)



$$\frac{1}{a} = \frac{1}{a_1} + \frac{1}{a_2}, \quad a = \frac{0.51423}{2}$$

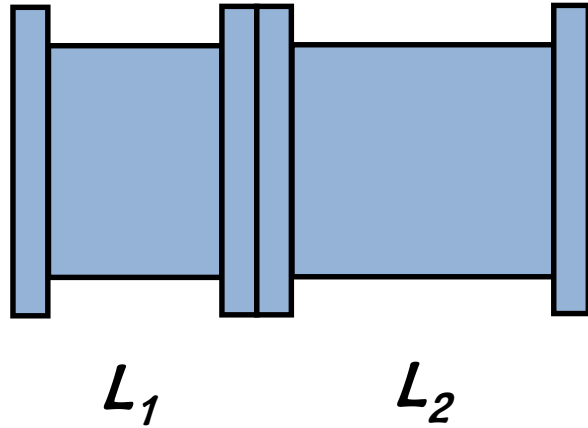


$$a_{\text{clausing}} = 0.35658 \quad (L/d = 2)$$

$$a_{\text{combi}} = 0.25711 \quad (27.9\% \text{ error})$$

Why?

1. In case of the same cross section



$$C = C_{(L_1+L_2)/d}$$

or

$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_o} \right)$$

$$\frac{1}{a} = \frac{1}{a_1} + \left(\frac{1}{a_2} - 1 \right)$$

Oatley

(Subtract entrance
effect once at a joint)

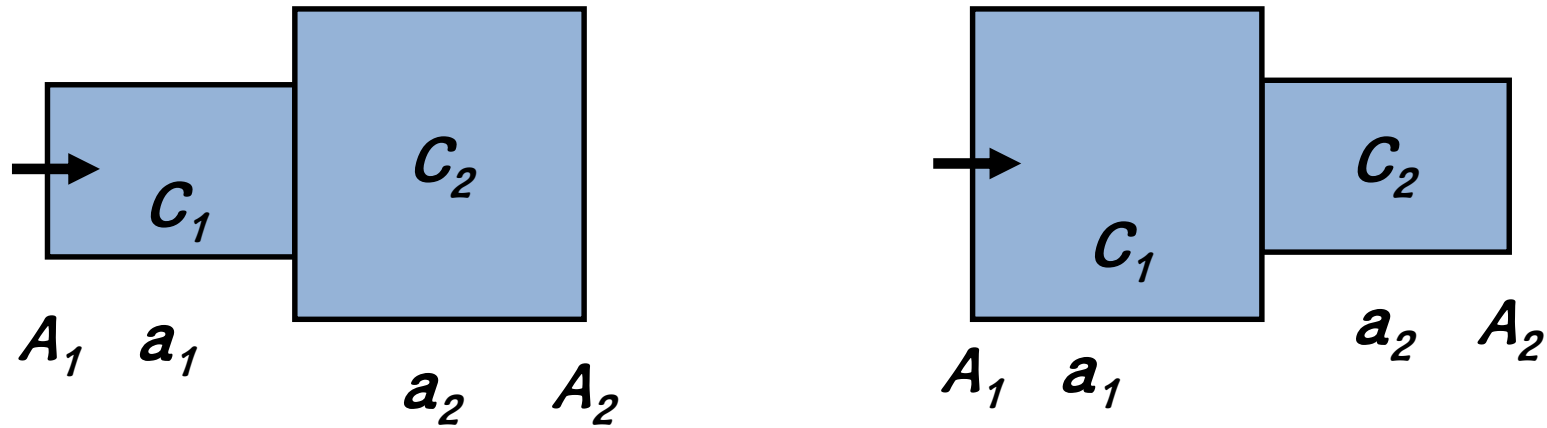
For $L_1 = L_2$:

$$a_{\text{Clausing}} = 0.35658 \quad (L/d = 2)$$

$$a_{\text{Combi}} = 0.25711 \quad (27.9\% \text{ error})$$

$$a_{\text{Oatley}} = 0.3461 \quad (2.94\% \text{ error})$$

2. In case of different cross section



$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{2o}} \right) = \frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{1o}} \right)$$

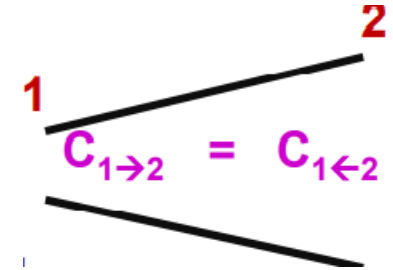
Generally,

$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{o(\max|2)}} \right) + \left(\frac{1}{C_3} - \frac{1}{C_{o(\max2|3)}} \right) + \dots,$$

컨덕턴스의 성질

❖ 무방향성

$Q_{1 \rightarrow 2} = C_{1 \rightarrow 2} P_1 - C_{2 \rightarrow 1} P_2$ 에서 만일 $C_{1 \rightarrow 2} \neq C_{2 \rightarrow 1}$ 이면 $P_1 = P_2$ 일 때도 $q_{1 \rightarrow 2} \neq 0$ 이 되어 모순



❖ 얇은꼴 도관

어떤 도관을 모든 방향으로 k 배 변화시키면 통과확률은 그대로 있고 입구 면적은 k^2 배 변하므로 컨덕턴스는 k^2 배 만큼 변한다. 예를 들어 직경 10cm, 길이 100cm인 원통도관은 직경 5cm, 길이 50cm인 도관보다 컨덕턴스가 4 배 크다.

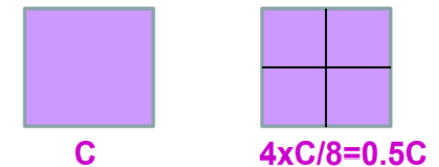
❖ 최소 둘레 길이

같은 단면적이라면 최소 둘레길이의 단면이 최대 컨덕턴스를 가진다. 직사각형보다는 정사각형이, 그보다는 원형 단면이 유리하다.



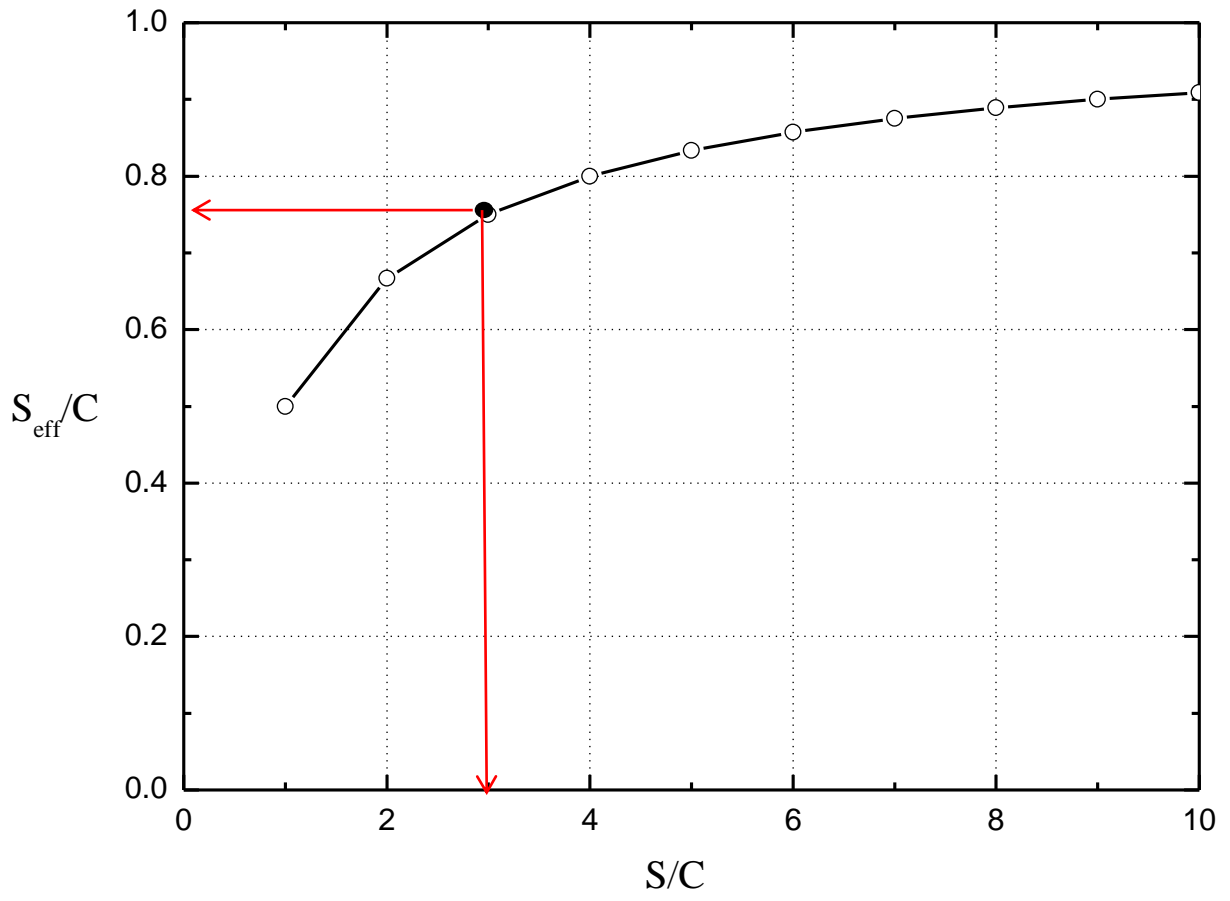
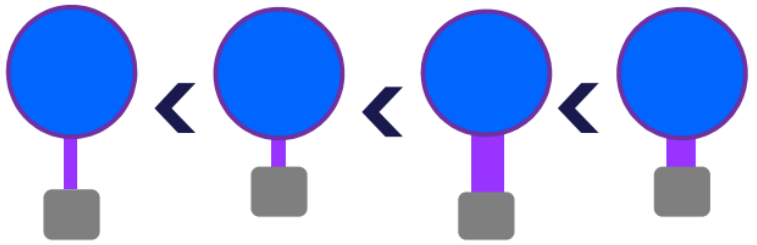
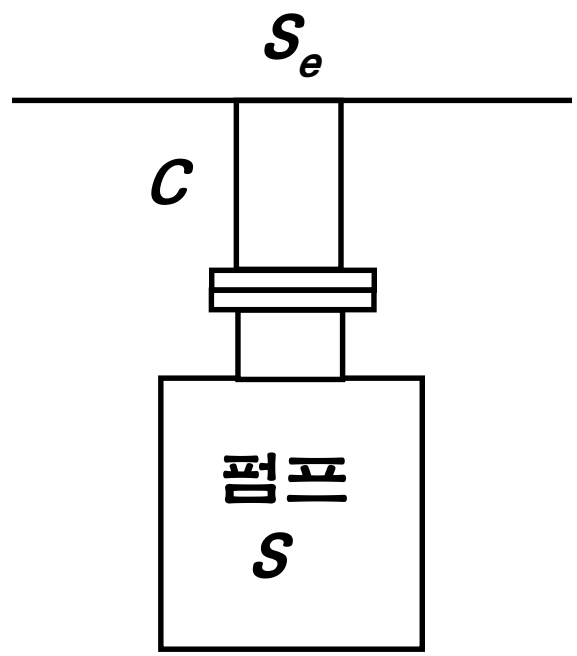
❖ 도관의 분할

도관을 분할하면 컨덕턴스가 줄어든다. 작은 도관을 여러 개 사용하는 것보다 같은 면적의 도관 하나를 사용하는 것이 좋다.

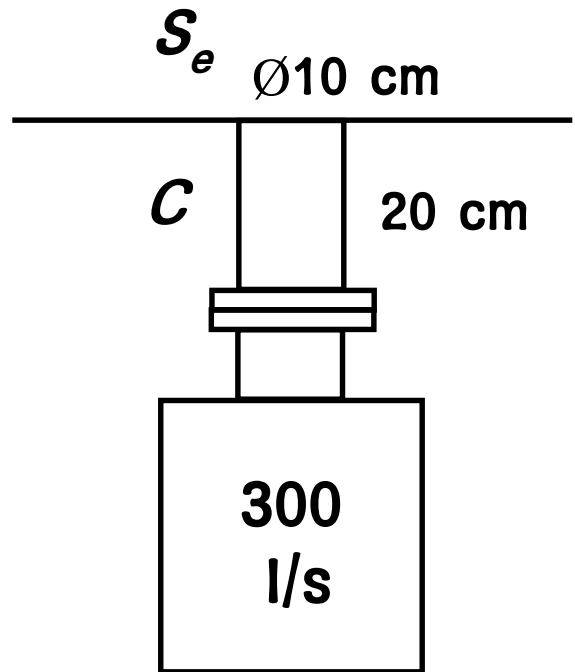


유효배기속도

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C} \quad ?$$



예제 (유효배기속도)



* 20°C, air (cm)

$$C = 11.6 (0.35658)(3.14 \times 5^2) = 325 \text{ l/s}$$

$$C_o = 11.6 (3.14 \times 5^2) = 911 \text{ l/s}$$

$$1. \quad \frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S} \Rightarrow 155 \text{ l/s}$$

$$2. \quad \frac{1}{S_{eff}} = \frac{1}{C} + \left(\frac{1}{S} - \frac{1}{C_o} \right) \Rightarrow 188 \text{ l/s}$$

• error ~18%